A critical review of the hypothesis of a medieval origin for portolan charts

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A critical review of the hypothesis of a medieval origin for portolan charts

Een kritische beschouwing van de hypothese
van een middeleeuwse oorsprong voor portolaankaarten

(met een samenvatting in het Nederlands)

Proefschrift

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aan de Universiteit Utrecht
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door

Roelof Nicolai

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te Achtkarspelen

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Co-promotoren: Dr. S. A. Wepster
Dr. P. C. J. van der Krogt

He had bought a large map representing the sea,
Without the least vestige of land:
And the crew were much pleased when they found it to be
A map they could all understand.

"What's the good of Mercator's North Poles and Equators,
Tropics, Zones and Meridian Lines?"
So the Bellman would cry: and the crew would reply
"They are merely conventional signs!"

Lewis Carroll, *"The Hunting of the Snark",* 1876

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PREFACE

How it started

Like many of my fellow geodesists, I have always been interested in the history of my profession and the closely associated history of cartography. Notably the apparently chaotic criss-cross lines on Renaissance nautical charts fascinated me. However it was not until I was recovering from a serious illness some ten years ago that I discovered that the origin of these lines goes back to the Middle Ages. I was reading a book on the history of geodesy, which I had purchased before my illness. The book is called *The Mapmakers* and was written by the science journalist John Noble Wilford, who had wisely not called his book *The Geodesists*. With that title he probably wouldn't have sold many copies, as not many people know the meaning of the words 'geodesy' and 'geodesist'. I found the book fascinating and well-written, and was glad to find my mysterious criss-cross lines mentioned. I learned that they originally appeared on medieval Mediterranean nautical charts known as *portolan charts*. However, Wilford's description of the presumed construction method struck me as impossible and, with an uncooperative body but an active mind, I decided to find out more about this. Little did I realise that the subject would keep me occupied for more than ten years.

It was therefore in 2003 that I began with the statistical and geodetic analysis of what would ultimately be five charts and one portolan, a book with numeric navigation data and I read all the books and articles on the subject I was able to acquire or borrow. These investigations led to the results, reported in this thesis, which are radically different from the results of existing research. Early in 2010 I had generated enough material to give me the confidence to approach Dr. Peter van der Krogt with a proposal to document these results in the form of a doctoral thesis. He invited me to a meeting with Prof. dr. Ferjan Ormeling and himself to explain my proposal. Because of the unorthodox nature of my conclusions I entered the meeting with some trepidation and half expected to be ushered politely to the door before the scheduled end of the meeting. However I found both very open-minded and, after they had obtained further assurances that my geodetic analysis methods were in principle sound, Professor Ormeling agreed to supervise my PhD project. Regrettably his retirement got in the way of seeing the job through to the end, but I consider myself very lucky that he found Prof. dr. Jan P. Hogendijk prepared to take over.

A considerable number of pages have been required to document the results of my study. I shall not apologise for that, but do owe the reader an explanation. A large number of hypotheses for the origin of portolan charts and explanations of their presumed construction method have been put forward over the last hundred and fifty years and

I felt the need to demonstrate the flaws in these hypotheses and explanations. These ‘refutations’ take up a significant part of the thesis and may not endear me with those who are either the authors or staunch supporters of such hypotheses, but that can’t be helped; such is the nature of scientific research. It had to be done, or my own work would be at risk of being reduced to merely another opinion among many others. Also, I had to make some excursions into fields, into which few portolan chart researchers have ventured, such as the oceanographic and meteorological aspects of the Mediterranean region and the sailing characteristics of medieval ships, but notably into the history of science. Furthermore, since this study is intended for a scholarly and scientific audience that includes non-geodesists, an explanation of the geodetic analysis methods used and tools chosen for the investigation was necessary.

What this thesis is about

The subject of this doctoral thesis is the consensus view on the origin of portolan charts, nautical charts of the Mediterranean and Black Seas that appear suddenly in the maritime world of the European Middle Ages. The oldest surviving chart dates from the end of the thirteenth century. It is unclear how these charts were constructed, but a near-unanimous scholarly consensus exists that they were drawn by medieval European cartographers, based on observed distances and course directions between ports and landmarks, collected by medieval seamen during trading journeys. Because these charts are seen as cultural products of the Middle Ages, practically all researchers have stressed that they lack the sophistication of later maps. These researchers claim that they were not drawn according to any cartographic map projection and that their accuracy is good only in a relative sense, when compared to contemporary cartographic achievements. If these charts are indeed original creations of medieval European cartographers, the postulated relative simplicity of the charts becomes mandatory, as the state of geodetic and mathematical knowledge and the mapmaking skills in the Middle Ages do not permit any greater sophistication to be assumed.

The key conclusion from my study is as surprising as it is unorthodox. This study proves that, far from being primitive cartographic products, these charts are quite sophisticated: they have been designed and constructed on a geodetic map projection and their accuracy is much higher than what would have been achievable for medieval maps. For those two reasons the making of these charts would have been well beyond the capabilities of medieval mapmakers. While the results of this study do not allow the true origin of portolan charts to be established, it will be shown that they cannot be a medieval European or an Arabic-Islamic creation; this will be an upsetting conclusion for many scholars who are familiar with the subject.

One of the premises of existing portolan chart research is the (usually tacit) assumption that mapmaking is an essentially simple activity. This assumption may be justified for medieval *mappaemundi*, based as these are on a mental model of the world. However maps or charts as realistic and accurate as portolan charts can only be based on extensive measurements of distances and angles between locations. The positions or coordinates of these locations must be calculated from these measurements, which must be of sufficient accuracy. The calculations must take into account the curvature of the earth's surface and reconcile any data conflicts that will inevitably exist in a large dataset.

The consequences of the main conclusion of this study for the history of science in general are not inconsiderable. The conclusion that the origin of these charts must be pre-medieval implies that the state of geodetic and mathematical knowledge, as well as the skills of mapmaking of the originating culture must have been quite high. The originators must not only have been *capable* of executing and processing accurate geodetic measurements covering a very large area, but must have *actually executed* the mapping of the entire Mediterranean and Black Sea region, as well as the European and African Atlantic coast from the south of England to Cap Drâa in present-day Morocco.

Acknowledgements

Many people have helped me in the process to complete this study and document its results. I am very grateful to Professor Ferjan Ormeling for giving me an honest chance to prove my ideas and for the encouraging support and extensive feedback he gave me throughout the writing of my thesis. My gratitude is also due to Professor Jan P. Hogendijk, who took over the baton from Professor Ormeling with grace and provided me with many useful steers. Highly valuable feedback on the various versions of my draft thesis were also provided by my co-supervisors Dr. Steven Wepster and Dr. Peter van der Krogt, for which I cannot thank them enough; without their feedback my thesis would have been far less coherent and readable. I also thank my friends K. Lucy Parker and Roger Lott for reading the text of the thesis critically and turning it into proper English.

I am indebted to many more people, such as my colleagues Erik van der Zee and Franck Espinoza, for their help on a number of IT matters for which my skills proved inadequate. I thank my employer, Shell, for their financial support in the printing of this thesis and Anton van Woerkom of Atalanta Drukwerkbemiddeling for converting the manuscript into a professional publication. I furthermore wish to thank Dr. John Hessler and Prof. Dr.-Ing. Peter Mesenburg for making results from their research available and Mr. Tony Campbell for providing useful feedback on the narrative first chapters of my thesis.

A surprising twist was introduced in my project after I contacted Dr. John H. Pryor, professor emeritus of medieval history at the University of Sydney, to request permission to use some illustrations from his book *Geography, Technology and War*, to which I make extensive references in Chapter 4. I am very grateful to Professor Pryor for the photographs of the model of a medieval round ship which he stated he built in his

younger years, and particularly for his stimulating ideas which, combined with the key conclusion from my study, may provide new clues to the time and circumstances of the first appearance of portolan charts in the Mediterranean region.

The lion's share of my gratitude is due to my wife Annette and to my children for their unwavering support of my ambitious and sometimes seemingly endless project. We had many stimulating discussions on the subject, which have helped and encouraged me more than they probably realise.

SUMMARY

One of the most striking events in the history of cartography is the sudden appearance in the Middle Ages of realistic nautical charts of the Mediterranean and Black Sea region, so-called *portolan charts*. The oldest surviving chart dates from the end of the thirteenth century. Portolan charts appear suddenly, without any identifiable development path or predecessors, are notable for the high degree of realism (or accuracy) of the coastlines depicted and for the close resemblance of the coastline image with that of a modern map or chart. It is also surprising that they do not appear to originate in the circles of the intellectual clerical elite of that period, but come from the maritime commercial milieu.

Since the middle of the nineteenth century researchers have wrestled to find a plausible explanation for the appearance of these charts and have produced a large number of hypotheses describing their possible origin and construction method. However a common characteristic of these hypotheses is their lack of supporting evidence. They differ in the detail of who invented these charts and where and when that took place. Nevertheless, the common element in the vast majority of these hypotheses is the proposition that these charts are an original creation by medieval European mariners and cartographers. This hypothesis represents the near-unanimous consensus view of scholars and researchers and is referred to in this thesis as the *medieval origin hypothesis*.

The medieval origin hypothesis for portolan charts can be seen as being composed of four interdependent presuppositions: (1) that the charts are based on actual measurements of course direction and distance by mariners during trading voyages; (2) that multiple measurements between the same pairs of points were averaged to increase their precision and recorded in books known as *portolans*; (3) that the measurements were plotted according to the *plane charting* method, i.e. without corrections for earth curvature; (4) that the close resemblance of the charts' coastline image to that of a modern map produced by applying a map projection is accidental.

This thesis aims to test the hypothesis of a medieval origin for portolan charts by addressing the four component presuppositions separately. To that purpose numerical evidence is derived in Chapters 7, 8 and 9 from five charts and one portolan by application of geodetic and statistical analysis techniques. This is supported by surviving evidence on the history of science in the Middle Ages.

After a description of the characteristics of portolan charts, a summary is provided of the medieval origin hypothesis in its various forms and of other hypotheses for the origin of the charts.

Meteorological and oceanographic characteristics of the Mediterranean and the limitations in sailing properties of medieval ships favoured the use of maritime trade routes that predominantly followed the northern coasts. This would inevitably have led to a scarcity of measurements along the southern lee shores, compared to a richness of data along the northern windward shores of the Mediterranean. Such a misbalance in the presumed underlying navigation data is not reflected in any way by the accuracy characteristics of the charts. In Chapter 5 and Appendix III a model is developed for the best achievable navigation accuracy, based on the conjectural navigation methods in the medieval Mediterranean. This model demonstrates that the accuracy of distance and direction estimates would have been very limited. Furthermore it is unlikely that the mariner's compass, in a form suitable for making accurate quantitative measurements of course direction, was introduced in time to have played a role in the development of the first portolan chart. Calculations of the arithmetic mean from repeated measurements of the same observable in order to improve its accuracy only started to be used routinely from the middle of the eighteenth century. In the European Middle Ages until the end of the thirteenth century a practically general lack of concern for accuracy can be said to existed, apart from only a few exceptions. Viewed in this context, the application of calculations of the arithmetic mean or other statistical technique to a presumably enormous body of navigation data is so unlikely that it can be excluded as a realistic possibility.

In Chapter 7 of this thesis five portolan charts are analysed numerically: one chart from the thirteenth century, three from the fourteenth and one from the fifteenth century. The basis of this analysis is the comparison of the positions of coastal points on each portolan chart with those of corresponding points on a modern (digital) map. The results confirm that portolan charts are composed of sub-charts, with their own scale and orientation, which the cartographer 'pasted' together in such a way that no joins between them are visible. It will be shown that the sub-charts agree with modern maps on the Mercator or Equidistant Cylindrical map projection to an accuracy of the order of 10 to12 km, which is very accurate, taking into account the approximately 1:5.5 million scale of all charts. However, contrary to that which is generally assumed in portolan chart research, the boundaries of the sub-charts do not coincide with natural boundaries between Mediterranean sub-basins.

The only known medium for recording navigation data in the Middle Ages were the so-called *portolans*, written sailing guides in the European Mediterranean region, containing estimates of distances and directions between coastal points and ports; in England such documents were known as *rutters*. The oldest extant portolan, the *Compasso de Navegare*, carries a date of 1296, but is believed to be a copy of a work dating from not earlier than 1250. Chapter 8 of this thesis describes the results of a detailed statistical and geodetic analysis of the geometric data in that portolan, reported of this thesis. The analysis demonstrates unambiguously that the data has been scaled off one or more portolan charts or maps, which must therefore have been in existence before the *Compasso de Navegare* was compiled. This undermines the widespread belief that portolans represent the intermediate stage between the collection of marine navigation data and the construction of the first portolan chart.

The investigation documented in this thesis leads to the intriguing conclusion that a map projection underlies the construction of portolan charts. This is highly implausible for maps or charts that originate from the Middle Ages, as the knowledge to achieve this cannot be demonstrated to have been available in that period in Europe. Also for contemporary Arabic-Islamic civilisation, in which significant knowledge of map projections existed, the knowledge of how to reduce measurements made on the curved surface of the earth to the (flat) map plane has never been demonstrated to have existed. Previous researchers have until now explained the close resemblance of portolan charts to a modern map on the Mercator projection as an accidental by-product of the presumed simple construction method of the charts, known as *plane charting*. With this method the measurements, taken on the curved surface the earth, are treated as if the earth were flat. In existing literature on portolan charts *plane charting* is widely believed to automatically result in a map image that closely resembles the Mercator or the Equidistant Cylindrical projection. By application of geodetic analysis techniques it is demonstrated in Chapter 9 that this assumption is incorrect. Firstly, the actual accuracy of portolan charts is at least a factor of ten better than that which would have been attainable with medieval navigation methods. Secondly, plane charting would result in a coastline shape that is different from the shape on a portolan chart to a statistically significant degree. The best-fitting map projection identified in modern chart analysis cannot therefore be an accidental by-product of the plane charting method; the projection can only have been applied intentionally during the construction of the charts.

Arabic-Islamic science was considerably more advanced than contemporary European medieval science, but it will be shown in Chapter 10 that an origin in contemporary Arabic-Islamic culture is highly unlikely. Although Islamic astronomers were able to determine latitude and longitude of a location with steadily increasing accuracy, this accuracy never achieved the level of accuracy of portolan charts. Moreover locations were mainly chosen in the Arabic-Islamic world itself. One Islamic scientist, al-Biruni, designed a geodetic method of determining the longitude difference between two locations using spherical trigonometry. However the method was hardly if at all adopted by others and only one practical application by al-Biruni himself is known. Furthermore, Arabic-Islamic world and regional cartography did not benefit from these achievements, nor was the considerable Arabic-Islamic knowledge of map projections applied to terrestrial cartography. Map projections were rigorously applied to astrolabes and to the so-called Qibla-maps, from which the direction to Mecca could be scaled off in a mathematically correct manner, but the latter had a narrowly defined religious purpose. Only a few Arabic-Islamic portolan charts are extant and they appear to be copies of earlier European ones. Despite its greater scientific capabilities and achievements, Arabic-Islamic culture appears to be a highly unlikely origin for portolan charts.

The main conclusion in this thesis is, that portolan charts are not the simple medieval maps they are generally postulated to be; instead they are geodetic-cartographic products of considerable sophistication, the construction of which was well beyond the capabilities of medieval European culture.

SAMENVATTING

Eén van de meest opmerkelijke gebeurtenissen in de geschiedenis van de cartografie is het verschijnen van realistische zeekaarten van het gebied van de Middellandse en Zwarte Zee in de Middeleeuwen, zgn. *portolaankaarten*. De oudste nog bestaande kaart dateert uit het einde van de dertiende eeuw. Het verschijnen van deze kaarten gebeurde zeer plotseling; de kaarten hebben geen ontwikkelingspad of duidelijke voorgangers. Portolaankaarten zijn opmerkelijk vanwege de hoge nauwkeurigheid waarmee de kustlijnen worden afgebeeld en vanwege de grote overeenkomst die het kustlijnenbeeld vertoont met dat van een moderne kaart. Verrassend is ook dat zij niet lijken voort te komen uit kringen van de intellectuele geestelijke elite van die tijd, maar uit het maritiem-commerciële milieu.

Sinds het midden van de negentiende eeuw hebben onderzoekers geworsteld om een plausibele verklaring te vinden voor het verschijnen van deze kaarten. Dit heeft geresulteerd in een grote hoeveelheid hypothesen over hun mogelijke oorsprong en constructiewijze. Deze hypothesen verschillen in de details over het wie, waar en hoe, maar het ontbreekt alle aan voldoende onderbouwing. Het overgrote deel van de hypothesen bevat de vooronderstelling dat de kaarten een oorspronkelijke creatie zijn van middeleeuwse Europese zeelieden en cartografen. Deze vooronderstelling wordt gedeeld door vrijwel alle wetenschappers en onderzoekers en wordt in dit proefschrift de “hypothese van een middeleeuwse oorsprong” genoemd.

Deze hypothese van een middeleeuwse oorsprong voor portolaankaarten is opgebouwd uit vier onderling afhankelijke vooronderstellingen: (1) dat de kaarten gebaseerd zijn op feitelijke metingen van koersrichting en -afstand die middeleeuwse zeelieden uitvoerden tijdens handelsreizen; (2) dat gemiddelden werden berekend van series metingen tussen dezelfde paren punten om de precisie te verbeteren en dat deze gemiddelden werden opgetekend in boeken, genaamd *portolanen*; (3) dat een kaart werd getekend op basis van deze metingen, uitgaande van de geometrie van een platte aarde (‘*plane charting*’); (4) dat de grote overeenkomst van het kaartbeeld met dat van de moderne kaart, gebaseerd op een kaartprojectie, op louter toeval berust.

Het doel van dit proefschrift is het toetsen van de hypothese van een middeleeuwse oorsprong voor portolaankaarten door elk van de vier componenten afzonderlijk te evalueren. Daartoe zijn geodetische en statistische analyses uitgevoerd van vijf kaarten en één portolaan, hetgeen een grote hoeveelheid nieuwe gegevens oplevert. Deze worden aangevuld met nog bekende relevante gegevens betreffende de geschiedenis van de exacte wetenschappen in de Middeleeuwen.

Dit proefschrift begint met een beschrijving van de kenmerken van portolaankaarten en vervolgt met een samenvatting van de diverse varianten van de hypothese voor een middeleeuwse oorsprong van de portolaankaart en van enkele andere hypothesen. Meteorologische en oceanografische kenmerken van de Middellandse Zee en de beperkingen in de zeileigenschappen van middeleeuwse schepen leidden tot een voorkeur voor een handelsroute langs de noordelijke kust. Dit zou hebben moeten resulteren in een schaarste aan metingen langs de benedenwindse zuidelijke kust, ten opzichte van een rijkdom aan gegevens langs de bovenwindse noordelijke. Een dergelijk gebrek aan balans in de veronderstelde navigatiegegevens wordt volstrekt niet weerspiegeld in de nauwkeurigheid van de kaarten. In Hoofdstuk 5 en Appendix III wordt een wiskundig model uitgewerkt van de optimaal haalbare navigatienauwkeurigheid, gebaseerd op de veronderstelde navigatiemethoden in de middeleeuwse Middellandse Zee. Dit model toont aan dat de nauwkeurigheid van afstand- en richtingschattingen zeer beperkt moet zijn geweest. Verder is het onwaarschijnlijk dat het scheepskompas, in een vorm die geschikt zou zijn geweest voor het maken van kwantitatieve metingen van de scheepskoers, op tijd werd geïntroduceerd om een rol te hebben kunnen spelen in de ontwikkeling van de eerste portolaankaart.

Berekeningen van het rekenkundige gemiddelde met het doel de nauwkeurigheid te vergroten door herhalingsmetingen van dezelfde grootheid werden pas routinematig gebruikt vanaf het midden van de achttiende eeuw. In de Europese Middeleeuwen tot het einde van de dertiende eeuw was er sprake van een vrijwel algemeen gebrek aan belangstelling voor nauwkeurigheid, op wellicht een paar uitzonderingen na. Beschouwd in deze context wordt het berekenen van het rekenkundig gemiddelde of de toepassing van een andere statistische techniek op een vermoedelijk enorme hoeveelheid navigatiegegevens zó onwaarschijnlijk dat het kan worden uitgesloten als realistische mogelijkheid.

Vijf portolaankaarten worden in deze studie numeriek geanalyseerd, nl. één kaart uit de dertiende eeuw, drie uit de veertiende en één uit de vijftiende eeuw. De basis van deze analyse is de vergelijking van de posities van punten langs de kust van elk van de vijf portolaankaarten met de posities van corresponderende punten op een moderne (digitale) kaart. De resultaten bevestigen dat portolaankaarten zijn samengesteld uit deelkaarten, die de cartograaf zodanig aan elkaar heeft 'geplakt' dat er geen overgangen zichtbaar zijn. Deze studie toont aan dat de deelkaarten overeenstemmen met moderne kaarten op de Mercatorprojectie of de Equidistant Cilindrische projectie met een nauwkeurigheid in de orde van 10-12 km, wat bijzonder nauwkeurig is, in aanmerking nemende dat de schaal van de kaarten ongeveer 1:5,5 miljoen is. Echter, in tegenstelling tot datgene wat doorgaans in portolaankaartliteratuur wordt aangenomen, vallen de grenzen tussen de deelkaarten niet samen met natuurlijke grenzen tussen de deelbassins van de Middellandse Zee.

Het enige bekende medium om navigatiegegevens in de Middeleeuwen op te tekenen waren de zgn. *portolanen*, geschreven vaarinstructies in de Europese mediterrane regio, die schattingen van afstanden en richtingen tussen punten langs de kust bevatten; in de Nederlanden van de zeventiende en achttiende eeuw werden deze portolanen *leeskaarten* genoemd. De oudste nog bestaande portolaan, de *Compasso de Navegare*, draagt het jaar 1296, maar wordt algemeen verondersteld een kopie te zijn van een eerder werk, dat echter niet ouder kan zijn dan 1250. In hoofdstuk 8 van dit proefschrift wordt een gedetailleerde statistische en geodetische analyse beschreven van de gegevens in deze portolaan. Deze analyse toont onomstotelijk aan dat de gegevens zijn afgeschaald van één of meer (portolaan-) kaarten, die daarom al moeten hebben bestaan vóór de *Compasso de Navegare* werd samengesteld. Dit ondermijnt de wijd verspreide overtuiging dat portolanen de schakel vormen tussen het verzamelen van navigatiegegevens en de constructie van de eerste portolaankaart.

Het onderzoek uitgevoerd in deze studie leidt tot de intrigerende conclusie dat aan de constructie van portolaankaarten een kaartprojectie ten grondslag ligt. Dit is zeer onwaarschijnlijk voor kaarten waarvan de oorsprong in de Europese Middeleeuwen ligt, omdat het niet aannemelijk is dat de noodzakelijke kennis hiervoor aanwezig was in die periode. Ook voor de contemporaine Arabisch-Islamitische cultuur, waarin aanzienlijke kennis over kaartprojecties aanwezig was, is nooit aangetoond dat de noodzakelijke kennis bestond om waarnemingen langs het gekromde aardoppervlak te reduceren naar het platte kaartvlak. Eerdere onderzoekers hebben de grote gelijkenis van de vorm van de kustlijnen op een portolaankaart en die op een moderne kaart op de Mercatorprojectie uitgelegd als een toevallig bijproduct van de veronderstelde eenvoudige constructiemethode van de kaarten. Deze techniek staat bekend onder de Engelse term *plane charting*. De metingen, verricht op het gekromde oppervlak van de aarde, worden dan behandeld alsof de aarde plat is. In bestaande literatuur over portolaankaarten wordt algemeen verondersteld dat deze techniek automatisch leidt tot een kaartbeeld dat nauwe overeenkomst vertoont met de Mercator- of de Equidistant Cilindrische projectie.

In Hoofdstuk 9 wordt door middel van toepassing van geodetische analysetechnieken aangetoond dat die aanname onjuist is. Ten eerste is de nauwkeurigheid van een kaart geproduceerd uit middeleeuwse navigatiemetingen minstens een factor tien slechter dan die van portolaankaarten. Ten tweede zou *plane charting* resulteren in een kaartbeeld waarvan de vorm in statistische zin significant verschilt van de vorm van de kustlijnen op een portolaankaart. De optimaal passende kaartprojectie, gevonden door toepassing van moderne methoden van kaartanalyse kan daarom niet een toevallig bijproduct zijn een dergelijke analysemethode. De kaartprojectie moet daarom doelbewust zijn toegepast in de constructie van de kaarten.

De Arabisch-Islamitische wetenschappelijke traditie was aanzienlijk verder gevorderd dan haar middeleeuws-Europese tegenhanger, maar in Hoofdstuk 10 zal worden aangetoond dat een oorsprong in het contemporaine Arabisch-Islamitische cultuurgebied hoogst onwaarschijnlijk is. Astronomen in deze cultuur waren weliswaar in staat de geografische lengte en breedte van een locatie te bepalen met een gestaag toenemende nauwkeurigheid, maar deze bereikte nooit het niveau van portolaankaarten. Bovendien kozen deze astronomen voornamelijk locaties in de Arabisch-Islamitische wereld zelf. Eén Islamitische wetenschapper, al-Biruni, ontwikkelde een geodetische methode voor de bepaling van het verschil in geografische lengte van twee locaties met behulp van boldriehoeksmeting. De methode werd echter niet of nauwelijks overgenomen door anderen en slechts één praktische toepassing, die van al-Biruni zelf, is bekend. Voorts profiteerden de Arabisch-Islamitische wereld- en regionale cartografie niet van deze verworvenheden, noch werd de aanzienlijke Arabisch-Islamitische kennis van kaartprojecties toegepast in de cartografie van de aarde. Kaartprojecties werden consequent en correct toegepast in *astrolaben* en op zgn. Qibla-kaarten, waarvan de richting naar Mecca op een wiskundig juiste wijze kon worden afgeschaald, maar deze laatste hadden een nauwgedefinieerd religieus doel. Slechts een klein aantal Arabisch-Islamitische portolaankaarten zijn nog beschikbaar en deze zijn vermoedelijk kopieën van oudere Europese kaarten. Ondanks de grotere wetenschappelijke bekwaamheid en prestaties van de Arabisch-Islamitische beschaving lijkt een oorsprong van portolaankaarten in deze traditie hoogst onwaarschijnlijk te zijn.

De hoofdconclusie van dit proefschrift is, dat portolaankaarten niet de eenvoudige middeleeuwse kaarten zijn waarvoor ze algemeen worden gehouden; in plaats daarvan zijn het geavanceerde geodetisch-cartografische producten, waarvan de constructie de mogelijkheden van de middeleeuws-Europese cultuur aanzienlijk te boven ging.

INTRODUCTION

The sudden emergence of the medieval nautical charts of the Mediterranean and Black Sea known as portolan charts is one of the most significant events in the history of cartography and without doubt the most enigmatic one. It is primarily their evident accuracy, or realism, that makes these charts so remarkable. In this and several other respects they contrast sharply with contemporary European mapping, the *mappaemundi* of the intellectual clerical world. They even leave the highest cartographic achievements of antiquity by Claudius Ptolemy far behind in terms of the accuracy with which their core coverage area is depicted. Nor do the best maps that have come to us from medieval Islamic civilisation get anywhere near the accuracy of portolan charts.[1] Portolan charts appear to be even entirely unrelated to any other known map type from medieval times and classical antiquity.

Their accuracy is not their only remarkable characteristic. Perhaps even more remarkable is the fact that, despite extensive research, the origin and construction method of these charts are still entirely unclear. There is no trace of any development path, any indication of how they arrived at the degree of perfection that they so evidently possess; even the oldest extant portolan chart, presumed to date from the end of the thirteenth century[2], shows a representation of the Mediterranean coasts that is essentially correct in its key proportions. Questions regarding the how, who, where and when of the origin of these charts have so far been unsatisfactorily or only partly answered; we know for example that they emerged in the Italian maritime-commercial milieu, possibly with clerical input[3], rather than exclusively among the clerical intellectual elite of the day, but not much more than that can be established with certainty. Although an impressive cumulative amount of brain power has been applied to this problem over the past hundred and sixty years, it is still not understood in the slightest how these charts were constructed, who did that and how the underlying observational data were collected and processed.

As one writer commented:

> “Among the research problems connected with portolan charts, the question of their origin is perhaps the most intractable. … Despite the thousands of scholarly words expended on the subject, most of the hypotheses about portolan chart

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[1] A small number of portolan charts of Arabic origin from the fourteenth and fifteenth centuries are extant, but the coastlines on these charts are widely agreed to be copies of earlier Italian or Catalan charts.

[2] ‘Carte Pisane’, Bibliotheque nationale de France (BNF). Dep. des Cartes et Plans, Res. Ge. B1118. A date of 1290 is often mentioned, but that date is speculative and a date before 1250 seems unlikely.

[3] Patrick Gautier Dalché has argued for a strong clerical influence on mariners/traders who supplied the data. See Patrick Gautier Dalché, *Carte marine et portulan au XIIe siècle: Le ‘Liber de existencia riveriarum at forma maris nostri mediterranei’ (Pise, circa 1200)* (Rome: Collection de l’École française de Rome, 1995), 98-101.

> origins have remained just that. In the absence of corroborating data they often appear to be less explanations than creation myths".[4]

The eleventh, twelfth and thirteenth centuries constituted a period of awakening and expansion in Western Europe, resulting, among other things, in a doubling of its population and a strong increase in trade and manufacturing. Why should these charts not simply be one of the many achievements of that period? This is indeed the view of the vast majority of researchers, but, although it is the most obvious explanation, the extraordinary characteristics of portolan charts are inconsistent with the state of technology and knowledge of that period. The charts also contain some puzzling internal contradictions that so far have not been satisfactorily explained. This raises the question how extraordinary these portolan charts really are. I am convinced that, had only a single portolan chart survived and had their impact on later mapping not been so clearly demonstrable, that single chart would have been labelled a falsification or hoax. However, some 180 portolan charts and atlases from before 1500 are still extant[5] and their impact on later mapping is undeniable.

Research into portolan charts started in earnest in the mid-nineteenth century. Only in the late eighteenth and first half of the nineteenth century had mapmaking advanced far enough to allow geographers to understand how realistic and accurate portolan charts are. Before that, geodesy and cartography had not developed to the point that an absolute benchmark for the shape of the Mediterranean was available. The shapes of the continents and of the Mediterranean Sea region are so familiar to us nowadays that we tend to take our knowledge of them for granted, and this familiarity, as the saying goes, breeds a certain degree of contempt for the enormous effort that has been required, and the difficulties that had to be surmounted, to create accurate, realistic maps. Before the nineteenth century an accurate image of the Mediterranean coasts was simply unavailable and mapmakers could well have believed that they were still making improvements to the shape of these coasts in comparison with older maps, whereas in reality portolan charts were better than their best efforts.[6]

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[4] Tony Campbell, "Portolan Charts from the Late Thirteenth Century to 1500", in *The History of Cartography, Volume 1 – Cartography in Prehistoric, Ancient and Medieval Europe and the Mediterranean.* Ed. J.B. Harley and David Woodward, (Chicago: University of Chicago Press, 1987), 380.

[5] Campbell 1987, 373.

[6] Campbell 1987, 371. Campbell quotes Monique de la Roncière as claiming that the work of the first named practitioner, Pietro Vesconte, was so exact that that the Mediterranean outlines would not be improved until the eighteenth century. See Campbell's footnote 5, in which he adds that others made the same point even more strongly. I believe that De la Roncière was even conservative in her remark: the first thorough revision of mapping in general happens towards the middle of the 18th century with the completion of the mapping of France by Cassini (actually several generations of Cassini). There is no evidence that the Mediterranean coasts were surveyed prior to that, or shortly after that. See also: Edward L. Stevenson, *Portolan Charts – Their Origin and Characteristics with a Descriptive List of Those Belonging to The Hispanic Society of America*, Publications of The Hispanic Society of America, No. 82, (New York: The Knickerbocker Press, 1911), 1: "It is only recent times that there has been an improvement in the charting of the region to which most of them [the charts] pertain".

There is no shortage of theories about the origin of portolan charts, but hard supporting evidence is lacking in all cases. It is not even certain whether the origin of portolan charts can be established at all; some authors have expressed caution or even pessimism in that respect.[7]

One cannot avoid the impression that until now researchers have been trying to 'fit round pegs into square holes' when they attempted to explain the advent of portolan charts as an expression of medieval European culture. When none of the proposed hypotheses can be made to agree fully with the observable or deducible facts, including peripheral facts such as the historical context of the charts, the inevitable conclusion must be that something is wrong with the premises of those hypotheses, unless we are prepared to believe that the origin of these charts constitutes an unsolvable mystery. However, such an admission of defeat seems premature and goes against the spirit of scientific research.

There appears to be little mileage in a 'more of the same' research project; a radically different approach that challenges established viewpoints seems at least worth a serious attempt. That is the approach I chose for this study. The key to this approach lies in my own field of expertise, geodesy. The question of the origin of portolan charts is inextricably linked with the question how and on the basis of what measurement data they were constructed. Such questions fall in the domain of geodesy. Where the scope of cartography is the representation of spatial information in the form of maps, the domain of geodesy comprises the establishment of the geometric framework that underlies those maps, built up from surface – and nowadays surface-to-space – geodetic measurements. That distinction is rarely if ever made in existing research on portolan charts. Fundamental aspects of geodesy therefore tend to be ignored in hypothesis building or are at least imperfectly understood.

No existing hypothesis regarding portolan chart origins has so far been successfully tested, as several authors, among which Campbell, have pointed out. On the other hand, not all hypotheses may lend themselves equally well to formal testing and scholarly consensus may be the maximum achievable result, although that would condemn a hypothesis to remain a hypothesis forever. However, considerably more numerical information can be extracted from the available data than existing research has been able to reveal. This extra information may permit a more exact approach to hypothesis testing.

RESEARCH QUESTION

The key question which this thesis seeks to answer is to what extent geodetic knowledge and geodetic analysis techniques may contribute to an understanding of the origin

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[7] e.g Youssouf Kamal, *Hallucinations scientifiques. Les portulans.* (Leiden: Brill, 1937), 2;
Ramon J. Pujades i Bataller, *Les cartes portolanes. La representació medieval d'una mar solcada*, (Barcelona: Lunweg Editores, 2007), trans. Richard Rees, 506;
Gautier Dalché 1995, 16.

of portolan charts. This almost automatically leads to the intriguing and more specific question whether successful application of geodetic analysis techniques enables conclusions to be drawn on the origin of portolan charts and if so, which conclusions.

Geodetic analysis techniques can only aspire to be contributing factors in the process to discover the origin of portolan charts. These techniques alone will not lead to the desired answer; historic and cartographic knowledge are indispensable to form a complete picture.

My approach in addressing the research questions carries a strong emphasis on numerical analysis. My study is based on considerable amounts of (geodetic) mathematics, possibly to the dismay of historians and map historians, who will in general not be familiar with such techniques. I have attempted to document the mathematical and geodetic aspects in a manner that will make this study accessible to a non-mathematical academic audience, choosing a descriptive approach in the main text and, wherever possible, banishing formulas and in-depth mathematical considerations to appendices.

SCOPE

The scope of this study is limited to an investigation into a possible medieval European[8] or Arabic-Islamic origin of portolan charts. Although several authors, mainly in the past, have proposed an origin in Greco-Roman antiquity, practically all present-day researchers of portolan charts favour this medieval origin hypothesis. A medieval European or Arabic-Islamic origin indeed appears to be more obvious and I believe these theories should be thoroughly tested first and only when rejected should attention be directed to antiquity, the more so as there are no direct indicators in the charts themselves of a possible antique origin. The practical aspect of this scope limitation is that the study would have grown beyond acceptable size if it had been extended to include antiquity.

This study considers only the earliest portolan charts of the Mediterranean Sea and Black Sea. Although the nautical charts of the fifteenth century and later follow the same cartographic conventions and are therefore often also referred to as portolan charts, they have no role to play in the question of the origin and construction method of the Mediterranean portolan charts.

Not addressed are issues such as the usage of the charts, their place in medieval society, map content versus discoveries and political change, international maritime trade and other medieval historical aspects. These aspects are not relevant for the subject, but an exception has been made for historical considerations that have a bearing on the possible construction method and the accuracy of the charts.

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[8] The term ‘medieval’, when used in the context of culture, refers exclusively to European culture, not to Arabic-Islamic culture. However, when used to describe a time period, the period from the eleventh to the end of the fifteenth centuries AD is meant.

In many chapters geographic locations in the Mediterranean and the Black Sea are mentioned, with which the reader may not be familiar. For that reason two overview maps are shown at the end of this chapter, showing most of the locations mentioned in this thesis.

STRUCTURE OF THE THESIS

The text of this thesis generally follows the sequence of four basic assumptions or 'pillars', outlined below, each of which must be true if the hypothesis of a medieval origin is to be upheld. However, it is not possible to treat these subjects entirely independently; the results of an earlier chapter often have a bearing on the analysis in a later chapter and vice versa. Cross-referencing to an earlier chapter is generally not a problem, but an occasional reference has been made to later chapters, which is more awkward. I can only ask the reader to bear with me where such a reference is inevitable.

The hypothesis of a medieval origin for portolan charts is built upon the following four fundamental assumptions or 'pillars'.

1. Portolan charts are based on actual measurements by medieval sailors of course direction and distance or perhaps distance only.
2. These measurements were averaged to increase their precision, and recorded in *portolans*.[9]
3. The measurements were plotted according to the *plane charting* method.
4. The close similarity of the map image with a map projection is accidental.

The premise that portolan charts are based on actual measurements is grounded in their well attested realism and metric properties. The fact that they emerged in the maritime-commercial milieu rather than in intellectual circles has led to the assumption that the underlying raw measurements were collected by mariners. Only *they* covered the entire length and breadth of the Mediterranean, Black Sea and coastal Atlantic. The possibility of a terrestrial triangulation network covering such a large area in medieval times can be rejected a priori anyway. What remains as the only option for a European medieval origin of portolan charts is that medieval sailors made the necessary measurements during trading voyages. The role of the compass, and consequently the role of direction observations in chart construction, has been disputed by several authors who maintained that the introduction of the compass came too late to make a practical contribution to the construction of the first chart.

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[9] A *portolan*, or harbour book, is a medieval book of sailing instructions, containing courses and distances between harbours or landmarks, and providing relevant navigational information on shoals, anchorages and harbours. Numerous authors merely state that there is a relationship between the portolans and the charts, without specifying whether a causal sequence exists. However, this avoids the vital question where the underlying data of the charts came from and how this data was organised prior to the assumed next step in the hypothesis of a medieval origin, the drawing of the charts. This inevitably draws one back to assuming the causal relationship stated above.

It is widely accepted that navigational accuracy in the Middle Ages would have been insufficient to permit charts to be constructed from single measurements. From the end of the nineteenth century onwards the hypothesis has therefore been postulated that knowledge of course bearings and distances between ports had been perfected by averaging the contributions of many sailors over many voyages. This is said to have led to a shared body of cumulative knowledge of distances and possibly bearings between many ports and landmarks, which eventually enabled portolan charts to be drawn. This requires documentation and organisation of data. The only candidate available for the latter processes is the portolan. Both the assumed averaging process and the documentation of its results are therefore implicit and necessary premises of the medieval origin hypothesis.

The next question is how portolan charts would have been constructed from the measurement data documented in these portolans. The only method that can be assumed, given the state of science in this period, is the so-called *plane charting* method, in which any measurement made on the surface of the earth is plotted in the map plane without correction, apart from a fixed scale reduction of distances, a process which effectively assumes a plane geometry for the surface of the earth. This inevitable assumption thus becomes a necessary condition for the acceptance of the hypothesis of a medieval origin for portolan charts.

Cartometric analysis has shown that the coastlines in a portolan chart match the Mediterranean and Black Sea coastlines on a modern map very closely. This suggests that a map projection underlies the construction of portolan charts. However, map projections were hardly known in the Middle Ages[10], although Arabic-Islamic culture fared somewhat better than European. Claudius Ptolemy's *Geography* was not known in Western Europe and map projections were not generally accepted in Western European intellectual circles until well into the fifteenth century, when the *Geography* had become widely available. In the maritime-commercial milieu of the thirteenth century, in which portolan charts appeared, knowledge of map projections can therefore not be assumed. This again leads to the inevitable and necessary assumption underlying the medieval origin hypothesis, that any map projection of portolan charts, if it exists at all, must be an artefact, an unintentional by-product, of any method by which the charts are analysed.

Thus the medieval origin hypothesis requires all four assumptions described to be correct. This study aims to validate each of these assumptions. Since they cumulatively depend on one another, the rejection of only one would have to lead to rejection of the entire medieval origin hypothesis as it has been formulated. The sequence followed in that process is outlined in the following paragraphs with a brief description of the chapters of the thesis.

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[10] David Woodward, "Roger Bacon's Terrestrial Coordinate System", Annals of the American Association of Geographers, Vol. 80 (1990), No 1.
In his *Opus Maius* (~1267) Roger Bacon demonstrates his awareness of the fact that spherical coordinates have to be transposed to a plane coordinates by means of a map projection. Given the state of mathematics in the thirteenth century the globular map projection he proposed was graphically constructed, not mathematically.

1. THE HISTORICAL CONTEXT OF THE EMERGENCE OF PORTOLAN CHARTS

The introduction into portolan charts and the associated origin question are expanded by sketching the historical context of their emergence. A well-known adage in portolan chart research is that it is not possible to understand these charts without some understanding of the culture in which they arose. The chapter therefore starts with a brief summary of the Moslem conquests of the ninth and tenth centuries, followed by descriptions of the European awakening in the eleventh century and key events in the Mediterranean area in the eleventh to thirteenth centuries.

2. KEY CHARACTERISTICS OF PORTOLAN CHARTS

The emergence of portolan charts is described, as well as their most important characteristics. Those properties that have so far not been satisfactorily explained, or that contradict other chart characteristics, are separately described in Section 2 of this chapter.

3. EXISTING HYPOTHESES ON THE CHARTS' ORIGIN AND CONSTRUCTION METHOD

The state-of-the-art of portolan chart research is discussed, focussing on published theories, hypotheses and speculations on the origins of the charts. The chapter concludes with some observations regarding the methodology applied in the various studies and the consequences this has had for research results to date. This provides further justification for including geodetic analysis in portolan chart research.

An interesting alternative view has been voiced by Fuat Sezgin: he proposes that the origin of portolan charts lies in Arabic-Islamic civilisation and that they were constructed from a framework of astronomically determined points, filled in by maritime distance estimates.[11] Sezgin's hypothesis will only be reviewed in Chapter 10: *An Arabic-Islamic origin of portolan charts?*

4. PHYSICAL CONDITIONS OF THE MEDITERRANEAN SEA AND MEDIEVAL SHIPS

The physical characteristics of the Mediterranean basin are described, as well as the shape of its coasts, its wind and current patterns and the influence these factors have had, in addition to political factors, on the development of trade routes, the power base of the Italian maritime states and the emerging Spanish state, Aragon. The second part of this chapter contains a description of twelfth and thirteenth century Mediterranean ship types and their sailing properties, and concludes with the impact the considerations of the physical characteristics of the Mediterranean and the sailing properties of medieval ships have on the medieval origin hypothesis of portolan charts. This chapter is intended as an introduction to medieval Mediterranean navigation techniques.

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[11] Fuat Sezgin, *Mathematische Geographie und Kartographie im Islam und ihr Fortleben im Abendland. Historische Darstellung*, Teil 1, Band X of 'Geschichte des arabischen Schrifttums' (Frankfurt am Main, 2000), 309 and ibid, Teil 2, 20.

Figure A - *Overview of locations in the Western Mediterranean.*

5. NAVIGATIONAL PRACTICES IN THE TWELFTH AND THIRTEENTH CENTURIES

The medieval origin theory assumes the construction of portolan charts to be based on measurements of course direction and distance, possibly distance only, made in the process of navigating ships on trading journeys. The objective of this chapter is to get a better understanding of the constraints that would have played a role in performing such measurements. Based on those constraints an accuracy model is presented that allows quantitative estimates to be computed of achievable navigational accuracy. Given the lack of agreement on the role of the magnetic compass in the construction of portolan charts, the existing studies on the history of the introduction of the compass in the Mediterranean are summarised and reviewed.

The chapter is concluded by a discussion on relevant aspects of the history of science, in which the key question is how likely the scenario is, that assumes widespread collecting and averaging of marine measurements in the thirteenth century or even earlier.

6. CARTOMETRIC ANALYSIS; METHODOLOGY AND EXISTING RESEARCH

Chapter 6 is a preparatory chapter for the cartometric analysis of portolan charts, de-

Figure B *- Overview of Locations in the Eastern Mediterranean and Black Sea.*

scribed in Chapter 7: *Cartometric analysis of five charts*. Various methods are available to a researcher to conduct cartometric analysis and a justification of the approach followed in this study, based on the objectives of the cartometric analysis, are described. A summary of the results of existing research results is presented.

7. Cartometric analysis of five charts

This chapter describes the cartometric analysis of five portolan charts; one thirteenth, three early-fourteenth and one fifteenth century chart. The cartometric analysis of these five charts quantifies the accuracy claim made earlier in this Introduction. Also other chart characteristics are analysed, in particular the best-fitting map projection and the composition of the charts of component charts of smaller, but overlapping areas.

8. The relationship between portolans and portolan charts

Chapter 8 describes a statistical analysis of the oldest acknowledged portolan or sailing handbook of the Mediterranean, the *Compasso de Navegare*, which carries a date of 1296. An earlier study of this portolan in 1987 revealed some inexplicable characteristics that merit closer investigation.[12] This analysis specifically tests the assumption that the *Compasso*, and by implication other portolans, contain accurate averaged course bearings and distance measurements that could have formed the basis for chart construction, as is commonly assumed.

9. THE MAP PROJECTION; ARTIFICIAL OR INTENTIONAL?

The third and fourth 'pillars' of the medieval origin theory is the hypothesis that portolan charts were constructed by plane charting techniques and that any similarity of the Mediterranean coastlines of portolan charts with the coastline image on a modern map, based on a geodetic-cartographic map projection, is a purely accidental by-product, or artefact, of cartometric analyses methods. This chapter provides a description of the method and subsequent testing of that hypothesis. This involves the reconstruction of a realistic geodetic network of distances and directions that might underlie the construction of the charts. The results from Chapters 4 and 5 are used as input to this part of the study. The calculation results are compared with the properties and the degree of similarity with the depiction of the coastlines on portolan charts.

10. AN ARABIC-ISLAMIC ORIGIN OF PORTOLAN CHARTS?

The most promising alternative to a medieval European origin of portolan charts is that of an origin in Arabic-Islamic culture, which was scientifically superior to medieval European culture in the eleventh and twelfth centuries. Nevertheless, no convincing evidence has been presented yet for an origin in that culture. Fuat Sezgin has recently become a passionate ambassador for an Arabic-Islamic origin in his extensive study of Arabic-Islamic cartography and its influence on European cartography.[13] An analysis of his arguments is presented in this chapter. The reason why it is presented after my own analysis is that the results of my own study are required for an efficient treatment of Sezgin's arguments.

11. CONCLUSIONS

The conclusions drawn at the end of each chapter are recapped and the consequences of these conclusions for the four 'pillars' on which the medieval origin hypothesis rests are discussed, after which the key conclusions from this study are presented.

12. SYNTHESIS

A synthesis of the results, documented in the previous chapters, in the light of the key conclusions from this study, is presented. The study has so far focussed on what is <u>not</u> possible regarding the origin of portolan charts. A new hypothesis is presented, describing how portolan charts arrived in the medieval Mediterranean world and how they came to adopt the form in which they are now known. Recommendations for further research are presented at the end of the chapter.

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[12] Jonathan Lanman, *On the Origin of Portolan Charts,* The Hermon Dunlap Smith Center for the History of Cartography, Occasional Publication No. 2 (Chicago: The Newberry Library, 1987).

[13] See Footnote 11.

1 THE HISTORICAL CONTEXT OF THE EMERGENCE OF PORTOLAN CHARTS

This chapter provides a summary of the main political events in the late-medieval Mediterranean and their impact on the development of maritime trade, up to the end of the thirteenth century, by which time the oldest surviving portolan chart had appeared. The focus will be on aspects of Christian European history, as the Mediterranean and Black Sea were dominated from the twelfth century on by Christian European nations and city states and it is in the maritime milieu of these entities that portolan charts emerged. The possibility of an Arabic-Islamic origin is acknowledged, but the only claim that has been made for such an origin sees the charts as a product of Arabic-Islamic scientific geography, so that an analogous description of North African Islamic maritime-political history would not appear to be very relevant. Not being a historian, I have done little more than cite or paraphrase information from a number of selected sources.

1.1 THE MEDIEVAL MEDITERRANEAN – RELEVANT HISTORICAL ASPECTS

In the three centuries after the collapse of the Western Roman Empire in the fifth century AD, intellectual activity in Europe developed exclusively in the clerical world and within the confines of the doctrines of the Church Fathers. Whatever was accessible from the heritage of antiquity was captured in the form of encyclopaedic works, but no original philosophical or scientific ideas were added. Not until Charlemagne's reign was the trail of learning picked up again and under his patronage monastic schools were established, which afforded a new opportunity for the stimulation of learning and the dissemination of knowledge.[14]

Islamic civilisation blossomed contemporary with Charlemagne's empire. The unification of Europe under Charlemagne was even facilitated by the threat of the expanding Islamic world.[15] After the death of the prophet Mohammed in AD 632, Muslims vigorously expanded their territory to an enormous size in a very short time. Muslim forces were successful both on land and at sea. Whereas maritime dominance passed to the Italians at the end of eleventh century[16], the Mediterranean of the ninth and tenth

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[14] Toby Huff, *The Rise of Early Modern Science* (Cambridge: Cambrige University Press, 2003), 97;
E. J. Dijksterhuis, *The Mechanization of the World Picture*, (Princeton: Princeton University Press, 1986), 89 – 103;
A. C. Crombie, *Augustine to Galileo, Vol. I, Science in the Middle Ages, 5th to 13th Centuries*, (London, Heinemann Educational Books, 1979), 30 – 43.

[15] Armando Cortesão, *History of Portuguese Cartography*, Vol. 1 (Coimbra: Junta de Investigações de Ultramar-Lisboa, 1969), 176.

[16] See the description of the raid on Mahdia in Section 1.1.2-C.

centuries was controlled by Muslim corsairs, who carried out frequent raids on Christian ports and relentlessly attacked Christian shipping. They established strongholds on all the major islands in the Mediterranean, in southern Italy and along the Iberian and Provençal Mediterranean coast up to La Garde-Freinet (Fraxinetum) in the south of France. In the eastern Mediterranean they controlled Crete fully and Cyprus and Rhodes partly. Despite frequent battles with the Carolingian naval fleet in the west and the Byzantine fleet in the east, Muslim naval forces disrupted life and government along the North-Mediterranean coasts so effectively that Christian maritime trade sank to a nadir around the year 1000 AD. Muslim lawyers condemned trade with the infidel as unlawful and Muslims traded therefore almost exclusively in their own world.[17]

1.1.1 THE AWAKENING OF EUROPE

Around the year 1000 AD European society began to change profoundly. Agriculturally Western Europe, in particular France, saw a change from self-sufficient units to feudally managed manorial estates, which enabled a food surplus to be generated and used in trade.[18] This stimulated urbanisation and, what is relevant for this study, long distance maritime trade, which eventually resulted in European naval domination in all of the Mediterranean.

Another factor that should not be underestimated in the awakening of Western Europe is the church reform of the eleventh century, also known as the investiture controversy. This reform detached the Church from its close association with secular leadership by eliminating *simony*[19] and lay investiture. These practices were widespread and enabled noble families to exercise effective control over the Church and extend their territorial control considerably where the Church possessed extensive lands. These practices were so deeply rooted in society that some Church offices were practically considered to be hereditary by noble families. At the highest level the emperors of the Holy Roman Empire considered it their imperial privilege to appoint the Pope, expecting compliance and support.[20]

The reform resulted in a greatly strengthened Church that was able to claim spiritual leadership over all of western Christendom. It applied this leadership with considerable effect in 1095 by successfully calling all Christians to the First Crusade. A wave of religious vigour swept over Christian Europe: the number of monasteries, nunneries and new monastic orders increased steeply. One of the new orders, one that would have great impact on the development of science and scientific thought, was the Franciscan order; many great names in medieval emerging science belonged to Franciscan monks.

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[17] Balard, Michael, "A Christian Mediterranean: 1000-1500", in *The Mediterranean in History*, ed. David Abulafia, 186 (London: Thames and Hudson, 2003).

[18] David Nicholas, "Economy", in *The Central Middle Ages*, ed. Daniel Power (Oxford: Oxford University Press, 2006), 57-90.

[19] Simony is the purchase of church offices.

[20] William C. Jordan, *Europe in the High Middle Ages*, (London: Penguin Books 2002), 85-99.

Figure 1.1 *- Political division in Europe ~1200*
(© Euratlas-Nussli 2009, www.euratlas.org).

The rediscovery of the corpus of Roman civil law at the end of the eleventh century triggered a legal revolution that stimulated rational thinking as a basis of what was considered just and right.[21] At the same time the development and acknowledgement of rational thought became a fertile source of the development of science. Another important product of the legal revolution was the emergence of the corporation or *universitas* as a legal entity. This helped universities to develop as independent institutes where learning was transmitted and spread and where new knowledge was developed.[22]

European politics of the twelfth and thirteenth century were intricate and convoluted. Kingdoms, principalities, duchies and counties sometimes had rulers from the other end of Europe, who had obtained their hereditary right to rule by marriage or birth. Territorial ambitions were satisfied by marriage or war, and political influence bought or at least sought by marrying off offspring or relatives to foreign ruling families.

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[21] Charles H. Haskins, *The Renaissance of the Twelfth Century* (Cambridge, US-MA: Harvard University Press, 1927), 193-223.

[22] Huff 2007, 118 – 146.

One of the most significant factors in the political muddle was the ambition of the Papacy to establish a European theocracy under the spiritual leadership of the Pope, the Holy Roman Empire. The Papacy actively sought a ruler with imperial ambitions who would voluntarily be subservient to the Pope. Unfortunately a man who combined such contradictory character traits could not be found in the whole of Europe and the result was a long struggle for supremacy in central Europe, which saw the Hohenstaufen dynasty come and go and Charles of Anjou's empire built up and destroyed, but it also saw a steady development of national entities such as France, Spain and England in the west, in parallel with a declining Byzantine Empire in the east.[23]

1.1.2 The Italian maritime republics and Aragon

Italy was situated in the middle of the power struggle between several successions of Popes and Holy Roman Emperors and never developed as a nation in the centuries under consideration. Particularly in the north, powerful city states formed, where factionalism between the Guelfs, supporters of papal policies, and Ghibellines, who favoured a strong Holy Roman Empire, dominated political life. Four of these city states were prominent in the building up of maritime trade and Latin naval dominance and consequently they played a key role in the history of portolan charts. They are known as the *maritime republics* Venice, Amalfi, Pisa and Genoa. All four maritime republics were only ever interested in establishing and maintaining a trading empire, never in territorial gain.

A. Venice

Venice's roots lie in the Roman Empire, where the northern Adriatic land area was called *Venetia*, with Ravenna as the most important city. After the Lombard invasion of 568 AD the settlements on the islands of the lagoon absorbed many Roman immigrants and refugees. In the seventh century Venice considered itself unquestioningly part of the East-Roman or Byzantine Empire. The Lombard kingdom to the west was eventually absorbed in Charlemagne's Frankish empire. Charlemagne sent his son Pepin in 810 AD to conquer Venice, but he failed to capture the Doge and conquer Venice proper, the *Rivoalto*. The Franks withdrew; the Byzantines sent a fleet and the matter was settled by a treaty, acknowledging that the Venetian *dogado* (dukedom) would remain part of the Byzantine Empire. Soon thereafter Venice became de facto independent. The Venetians gradually changed their focus from trade with their hinterland over the river system of the Po plain and turned increasingly to the sea, over time building up a maritime trading empire.[24] With a combination of naval power and diplomacy, they achieved control over all shipping in the Adriatic, aimed at turning Venice into a staple market, i.e. ensuring that all trade ran via Venice. Venice built up a powerful and very effective navy

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[23] Steven Runciman, *The Sicilian Vespers* (Cambridge: Cambridge University Press, 2008).

[24] Frederic C. Lane, *Venice, A Maritime Republic* (Baltimore: The Johns Hopkins University Press, 1973), 1–7.

to protect its trade routes, which were initially exclusively directed towards the east.[25]

After Robert 'Guiscard' de Hauteville had wrested parts of Sicily from Muslim control with his Norman band of mercenaries, adding this area to southern Italy, which the Normans had captured earlier from Byzantium, he directed his attacks on the Byzantine Empire, intending to expand eastward. Emperor Alexis I called upon Venice's superior navy to help stop the Normans. The Venetians honoured the request, no doubt also out of self-interest, and won several naval battles against the Normans. They were rewarded for their support by extensive trade privileges defined in the so-called Golden Bull of 1082[26], but were still denied access to the Black Sea.

The Venetians established a large trading colony in Constantinople, but over time their relationship with the Byzantines soured and, when in 1171 the Venetians sacked the new Genoese trading quarter, the Byzantine emperor Manuel Comnenus arrested all Venetians in Constantinople, confiscated their possessions and withdrew the Golden Bull.[27] The affair left a deep sense of betrayal and dissatisfaction in the minds of the Venetians.

Venice's hour of revenge came with the Fourth Crusade, which marks a turning point in the city's history. Upon the initiative of French nobles Venice was contracted in 1202 to supply 200 ships for the transport of 33,500 men. The Venetians kept their side of the bargain, but the French were only able to mobilise 10,000 crusaders and were unable to pay their debts. Venice now found itself in control of a large fleet <u>and</u> an army that owed them. The story is well enough known and more complex than this space permits to tell, but the result was that the fleet attacked and conquered Constantinople for the first time in the history of that city. The Byzantine Empire was divided up among the conquerors, in which Venice acquired 3/8. The Venetians managed to secure the geographically most strategic areas and islands from the perspective of creating a string of naval bases to protect their trade routes to the East. This gave them Corfu, Coron, Modon, Negroponte (Khalkis) and Crete as staging posts and fortified strongholds on the routes to and from the East. Being able to penetrate the Black Sea now they established Soldaia (Sudak) on the Crimean peninsula. Venice had now acquired an undisputed maritime pre-eminence in the Eastern Mediterranean, which lasted until 1261 when the Greek general Michael Palaeologos, with the help of the Genoese, was able to recapture Constantinople. The Venetians were once more expelled from Byzantium and the baton of exclusive trade privileges was handed over to the Genoese, be it for a very short time, as the new emperor soon also established treaties with the Pisans and the Venetians.[28]

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[25] Lane 1973, 24–27
[26] Lane 1973, 28, 29
[27] Lane 1973, 34 – 35
[28] Lane 1973, 36, 43

B. AMALFI

Amalfi, positioned on the western extremities of the Byzantine Empire, had been active in the maritime trade on Constantinople and the Levant from the sixth century onwards, as had Gaeta and Salerno. It became independent in 839 and was able to maintain that status until it felt itself forced to ask for the protection of Robert Guiscard's Normans, who had begun their conquest of southern Italy. From 1073 on Amalfi formed part of the Norman Duchy of Apulia, but was able to retain many of its old rights. It declined to play a role in the First Crusade, not wishing to jeopardise its trade relationship with Alexandria. However, it paid dearly for its cautious policy, for it lost its competitive position to the Pisans and the Genoese, whose economies received an enormous boost as a result of the Crusades, as the Crusader states became dependent on supplies from overseas. At its heyday Amalfi housed some 70,000 inhabitants on its steep slopes. It finally lost its independence in 1131, when it rebelled against Norman rule, which resulted in the Norman King Roger II of Sicily, Robert Guiscard's nephew, conquering the city.

The considerable, and growing, political and military power of the Normans worried both the Pope and the Byzantine Emperor. This situation wasn't helped by Roger's support of the antipope Anacletus II, who rewarded Roger by crowing him king of Sicily in 1130.[29] The consequence of this conflict was a war against a coalition of the Pope, the Byzantine Emperor and the Holy Roman Emperor, backed by Genoa and Pisa. In 1133 and 1135 the Pisan fleet attacked and sacked Amalfi and nearby towns while Amalfi's fleet and fighting men were elsewhere with the Norman fleet and army.[30] Amalfi, which was already declining but still an important town in the Norman kingdom, never recovered. However, it had exerted a considerable influence on maritime commerce and navigation. Its principal claim to fame rests on its alleged invention of the mariner's compass.[31]

C. PISA

After Charlemagne's victory over the Lombards in 774, Pisa was part of the duchy of Lucca, but its subsequent expansion in maritime trade caused it to eclipse that city and in the tenth century Pisa had become the most important town in Tuscany, much to Lucca's dislike (Pisa and Lucca were in a state of war for most of the twelfth century).[32] The presence of Muslim corsairs in the northern part of the Western Mediterranean

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[29] Charles H. Haskins, *The Normans in European History* (Boston, Houghton and Mifflin, 1915), 211.

[30] William Heywood, *A History of Pisa. Eleventh and Twelfth Centuries* (Cambridge: Cambridge University Press, 1921), 84, 86.

[31] The section about Amalfi and the Normans is a composition of information from various sources: Charles H. Haskins' *The Normans in European History* and Runciman's *The Sicilian Vespers*, and the website of the city of Amalfi. It is regrettably not easy to find reliable information on this aspect of Italian history.

[32] Heywood 1921, 13, 14, 18

made it imperative for the Pisans to strengthen their naval capability, which also enabled them to embark on expansion. Pisa formed an alliance with Genoa, capturing Sardinia and Corsica in 1017, which were both important bases for the Muslim corsairs, but no sooner had the latter been ousted than the two allies turned into bitter rivals, ending in the Pisans ousting the Genoese from Sardinia, of the two islands the economically more interesting one on account of its silver mines.[33] In the 1060s their rivalry resulted in the first of many wars.

The eleventh century marks the pinnacle of Pisa's maritime and trading power. In the 1030s Pisa won several battles with Muslim corsairs off the north coast of Sicily and conquered Bona (Annaba) in North Africa. It attacked Palermo in 1063 in order to help the Norman king Roger I.[34] In 1088 it was the instigator of the raid on Mahdia in Tunisia, contributing most of the ships and men to the expedition. Mahdia had become the most important basis for Muslim corsair activities in the western Mediterranean. Now that Sicily was in Norman hands, the trade routes to the Levant were almost open to the Italians and the Mahdia corsairs were the last obstacle. Mahdia had been fortified into the then most formidable military harbour in all of the Mediterranean. Pisa organised an enormous fleet of mainly Pisan ships, which overwhelmed Mahdia completely and extracted a large ransom from the Mahdians. The raid on Mahdia – the Italians didn't occupy the fortress city – was crucial in the development of Mediterranean history, because it broke Muslim maritime dominance.[35] The Muslim half of the Mediterranean world depended on coastal shipping from Morocco and Spain to and from Egypt[36] and this Muslim trade route was now seriously compromised with the loss of Sicily and the raid on Mahdia.

The roles had now been reversed; it was now Pisa that was harassing Muslim shipping and raiding North-African towns. However, all these hostile actions never got in the way of commercial relationships: trade between all parties remained lively; the Pisans enjoyed trade privileges both in Constantinople and in Cairo and Alexandria and had a colony in Bougie (Bejaia), the most prosperous of the North-African trading cities in the twelfth century, as well as in many other cities along the North-African coast.

Pisa assumed a key role in the First Crusade with a fleet of 120 ships and played an important role in the siege and conquest of Jerusalem.[37] It founded colonies and settlements in numerous places along the Levantine coast. The Pisan quarter in Constantinople grew to about 1000 in the twelfth century and as far as the north of the Sea of

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[33] Heywood 1921, 22

[34] Heywood 1921, 27 – 29

[35] Heywood 1921, 33 – 43

[36] Steven Epstein, *Genoa & the Genoese, 958-1528* (Chapel Hill: The University of North Carolina Press, 1996), 22.

[37] Heywood 1921, 45 – 57, 217, 218. This includes chapter 4, "The First Crusade". Heywood states Pisa had the reputation of being unsurpassed in the construction of siege machinery.

Azov a 'Porto Pisane' was established. Pisa, which, like Genoa, had only had access to the Black Sea from the early 1260s, would not enjoy its position in the Black Sea for very long, for in 1284 hostilities with Genoa culminated in the naval battle of Meloria, at which the Pisan fleet was annihilated. A few years later the Genoese returned and filled up the Pisan harbour, Porto Pisane, rendering it unusable. Pisa was crippled, with its fleet and harbour destroyed, and with so many fellow Pisans in need of financial support in Genoese jails that the Pisan saying arose "To see Pisa, you have to go to Genoa".[38] Although it continued to trade, it could no longer play any role of importance in the Mediterranean world and was conquered by Florence in 1409.

D. GENOA

Genoa was in many respects the complete opposite of Venice. Whereas Venice's style of government was solid and elaborate, one might say Genoa was governed 'on a shoestring'. Genoa was the ultimate entrepreneurial city, leaving nearly everything to private enterprise, including the running of its temporary 'colonies' Tortosa and Almería. Throughout its history, Genoa was racked by civil unrest and factional strife between Guelfs and Ghibellines, although factional boundaries not always ran along those lines. Venice, on the contrary, remained a model of political stability and, despite its commercial focus, Venetians developed an appetite for art which the Genoese lacked. The historian Jacob Burckhardt describes in his classic work *The Civilisation of the Renaissance in Italy (*1878):

> "Genoa scarcely comes within range of our task [of describing the cultural changes due to the Renaissance], as before the time of Andrea Doria it took almost no part in the Renaissance. Indeed, the inhabitant of the Riviera was proverbial among Italians for his contempt of all higher culture. Party conflicts here assumed so fierce a character, and disturbed so violently the whole course of life, that we can hardly understand how, after so many revolutions and invasions, the Genoese ever contrived to return to an endurable condition".[39]

Liguria was cut off from the Po plain by a single pass, without any navigable rivers and with no arable land permitting agriculture. Even fishery was unproductive in the deep waters of the Gulf of Genoa.[40] Muslim corsairs generally left this poor area alone, but raided Genoa so thoroughly in 934-935 that the city probably lay waste for several years.[41] Considering all these facts, it is astonishing that Genoa was able to come abreast with Venice as the pre-eminent naval and trading power in the Mediterranean. Their

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[38] Heywood 1921, 268

[39] Jacob Burckhardt, *The Civilization of the Renaissance in Italy,* transl. S. G. C. Middlemore (1878), 36. http://paduan.dk/Kunsthistorie%202008/Tekster/The%20Civilization%20of%20the%20Renaissance%20in%20Italy%20-%20Burckhardt.pdf
See also Epstein 1996, 246.

[40] Epstein 1996, 11, 12

[41] Epstein 1996, 14.

differences in culture and intense rivalry made Genoa and Venice bitter enemies, who fought four wars for supremacy in the eastern Mediterranean. This is even more impressive when one realises that Genoa never had more than half of the population of Venice.

Epstein describes Islam as fundamental to Genoa's rise: Muslims were victims of Genoese corsairs as well as their main trading partners in the growth phase of the Genoese trading empire.

By violent and diplomatic coercion Genoa imposed its authority on other cities along the Ligurian coast. It eventually controlled a 330 km stretch of coast from Ventimiglia to La Spezia.[42] Genoa and the other Ligurian cities relied heavily on trade with Sicily[43], as this island was the nearest grain exporting area and a centre of trade with the Islamic world. In the twelfth century Genoa established a trade treaty with the king of Morocco and with the Muslim rulers of Majorca. By the mid-thirteenth century Ceuta had become a major centre of Genoese trade and one of its main destinations in North Africa.[44] Bougie (Bejaia) was a major trading port for Genoese, Pisans, Catalans and Provençals alike, but this did not stop the Genoese from raiding the city in 1136.[45]

Genoa was the first of the Italian cities to respond to the call to the First Crusade and the first serious Genoese war fleet participated in the siege of Antioch, where, after its conquest, they were rewarded with property and trading privileges by the new Norman ruler Bohemond.[46] At that time the Genoese already had a trading foothold in Egypt.[47]

In 1146 a Genoese fleet attacked and defeated the Muslims of Minorca and Almería. After hearing this news, Ramon Berenguer IV of Barcelona and Alphonso VII of Castile approached Genoa, promising them one third of Almería if they would help to conquer the city the next year. Ramon Berenguer IV came to a similar arrangement with Genoa regarding Tortosa. Almería, situated deep inside Muslim territory and one of the ports servicing Granada, was a serious naval force in the twelfth century, frequently attacking Genoese ships en-route from Ceuta to Majorca and Genoa. A large Genoese fleet, along with forces from Castile, Catalonia, the Provence and Pisa attacked and conquered the city in 1147. After the capture of Almería the Genoese fleet sailed to Tortosa and helped the Catalans to capture that city as well. Genoa decided to hand their share of one-third of Almería to the Genoese fleet commander for a period of

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[42] Epstein 1996, 11.

[43] Epstein 1996, 59, citing D. Abulafia, *The two Italies. Economic Relations between the Norman Kingdom of Sicily and the Northern Communes.* Cambridge (1977), 111, 119. See also Epstein, 97.

[44] David Abulafia, *A Mediterranean Emporium. The Catalan Kingdom of Majorca,* 1st paperback ed. (Cambridge: Cambridge University Press, 2002), 120, 121.

[45] Epstein 1996, 29.

[46] Epstein 1996, 29, 30.

[47] Epstein 1996, 24: In 1103 the Sultan of Egypt had all Genoese in Cairo arrested in response to Crusader actions.

30 years, which is typical for its minimum-government style. As it happened, Almería was captured back by the Almohads ten years later and remained in Muslim hands for the next three centuries. Genoa sold its share of one-third of Tortosa to the Count of Barcelona in 1153; it had stretched itself well beyond its means and was desperately short of money in the middle of the twelfth century, but it *had* emerged as a significant power in the Western Mediterranean.[48]

In the second half of the twelfth century Genoa expanded its trade on Byzantium, despite Venetian dominance. In 1155 they even reached a provisional trade agreement with Byzantium and were promised an *embolum*, a leased merchant quarter in Constantinople, which they actually established only in 1170. A year later this quarter was sacked by the Venetians, as described in the section on Venice, to which the Emperor Manuel Comnenus responded by imprisoning the Venetians and confiscating their possessions.[49]

A significant factor in the history of Genoa was their various dealings with the Holy Roman Emperors. The Papacy had felt alternatingly threatened by the power of the Normans and by that of the Holy Roman Emperors. The Pope had welcomed Frederick I 'Barbarossa' in the 1150s to counter the threat of the Normans, but, from the Pope's perspective, he soon turned out to be a remedy worse than the disease. Frederick's considerable imperial ambitions included the conquest of the prosperous Norman kingdom of Sicily and he made sweeping promises to the Genoese and Pisans if they would help him, but his ambition was frustrated because of repeated hostilities between Genoa and Pisa and by his unexpected death in 1190. His son and successor Henry VI inherited this ambition. His wife was Constance, daughter of Roger II of Sicily and heir to the Sicilian kingdom. Henry VI reminded the Genoese and Pisans of their promise for help, adding new promises to the ones his father had made. In 1195 imperial troops, supported by the Genoese and Pisan fleets, attacked and conquered Sicily. Henry VI kept none of the imperial promises he had made and the 87-year Hohenstaufen rule over the kingdom of Sicily began.[50]

Genoa continued to expand its trading empire aggressively but avoided open conflict with Venice because of the presence of their mutual rival Pisa. That changed after the death of Frederick II of Hohenstaufen in 1250, which weakened traditionally Ghibelline Pisa. After 1250 Genoa fiercely challenged Venice's control over the sea routes to the Levant, as well as its naval superiority. The intense rivalry between the two cities resulted in 1258 in the first of four wars. Peace was only made in 1270 at the insistence of the King of France, 'Saint' Louis IX, keen to hire a fleet from Genoa and Venice to go on Crusade.[51]

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[48] Epstein 1996, 49 – 52.

[49] Epstein 1996, 85. See also Section A in this chapter on Venice.

[50] Epstein 1996, 78, 79, 89

[51] Lane 1973, 73 – 77.

Although Venice emerged as the clear winner from each and every outright naval battle with Genoa in this war, the Genoese proved quick learners and after 1270 Venice lost its naval superiority in the Eastern Mediterranean[52], as Genoa continued its spectacular rise in the last quarter of the century. Although it was never overtaken by Genoa, Venice had to accept Genoa as an equal from then on. A significant factor in the shift of the power balance was the recovery of Constantinople by the Greeks, as a result of which Venice lost its trade monopoly in the Black Sea and was overtaken there by Genoa, which founded its Black Sea base at the city of Caffa (Feodosiya) in the late 1260s.[53]

The new Byzantine Emperor Michael Palaeologus had given Focaea (Foça, near Izmir), with its rich alum mines, to the Genoese merchant/adventurer and admiral Benedetto Zaccaria in the 1280s for services rendered to Byzantium.[54] The Zaccaria family was also engaged in the new trade on Flanders, importing woollen cloth.[55] Alum, needed for the dyeing of wool, was transported directly from Focaea to Flanders in large ships. Flemish woollen cloth constituted the second most important (re-)export product of Genoa and used to be transported overland until the Genoese, already used to the Atlantic through their trade with cities on the Moroccan Atlantic coast, switched to transport by sea in the last quarter of the thirteenth century.

E. THE CROWN OF ARAGON

The last key player but one in the medieval Mediterranean was Aragon, or rather the Crown of Aragon, a federation of lands of which Aragon, as a region, formed part, along with Catalonia and later Valencia, Majorca and Sicily.

The Crown of Aragon was created in 1150 by the marriage of Ramon Berenguer IV, Count of Barcelona, and Petronilla, heiress to the kingdom of Aragon. Although Aragon became a kingdom in the eleventh century, it was not a coherent political entity. Bisson states that "in 1137 Aragon was a royal-baronial confederation for the exploitation of multi-cultured lands, united by little more than name". [56] The king's authority remained a cluster of separate lordships. When dynastic succession came to depend on one daughter, Petronilla, liaison with Catalonia was sought and obtained.

The history of Catalonia was quite different. The Muslim conquests of the eighth century had inspired Charlemagne to military countermeasures, resulting in the capture of an area south of the eastern Pyrenees, known to the Franks as the Spanish March, which became the nucleus of Catalonia. Also Catalonia was a cluster of counties rather than

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[52] Lane 1973, 84.

[53] Epstein 1996, 143.

[54] Epstein 1996, 178.

[55] Abulafia 2002, 192.

[56] Thomas Bisson, *The Medieval Crown of Aragon. A Short History*, 1st paperback ed. (Oxford: Oxford University Press, 1991), 29.

a single coherent state and in this cluster Barcelona rose to predominance.[57] Although Aragon supplied its name to the federation, Catalonia was always the dominant party.

The golden age of Islam in Spain had come to an end with the collapse of the Ummayad caliphate in 1031. Muslim Spain broke up into smaller units, the so-called *taifa* kingdoms. This fragmentation made the *Reconquista* considerably easier. Both Aragonese and Catalan barons lived to a large extent on the spoils of war, which included tributary payments from the *taifa* kingdoms they harassed. Therefore they resisted the king's attempts at establishing an enduring peace, as a result of which the royal income would consist of tax revenues extracted from the same barons, whose source of income would dry up as a result of this peace. When the ruler of Aragon, Peter II died in battle in 1213, he left his five-year old son James as his successor. Raised by the Templars of Monzón, James I grew up to become one of the most famous of the kings of Aragon, earning his nickname 'The Conqueror' on account of his conquests of Majorca (1229), Minorca (1231) and Valencia (1235). He also conquered Murcia in 1266 but handed that over to Alfonso X of Castile, honouring an earlier agreement with Castile regarding the division of (re)conquered Muslim territory.

The conquest of Murcia for Castile was of great importance to Latin trade. The Alboran Sea had been a dangerous place for Christian ships, enclosed at it was on two sides by Muslim territory. The conquest of Murcia made the Alboran Sea so much safer that Majorcan and Genoese ships ventured through the Straits of Gibraltar and established a maritime connection to England and Flanders around 1277.[58] The Genoese, having more commercial and naval clout than the Majorcans, soon reduced their competitors' business share to insignificance.

F. The Sicilian Vespers

Between 1253 and 1301 Catalan trade spread over the entire Mediterranean[59] at the expense of the Genoese in the Western Mediterranean, whose trade suffered considerably from 1253 to 1270.[60] Since 1262, Catalan trade relations with Sicily had also intensified, following the marriage of James' son Peter to Constance of Hohenstaufen, daughter and heiress of King Manfred. After decades of papal attempts to thwart the imperial ambitions of the Hohenstaufen dynasty, Manfred, a bastard son of Frederick II of Hohenstaufen, rose to power in southern Italy and Sicily and, exploiting the still active Ghibelline sentiments in northern Italy, expanded his kingdom to almost all of

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[57] Bisson 1991, 19 – 23.

[58] Abulafia 2002, 192. Abulafia cites an article by Roberto Lopez, "Majorcans and Genoese on the North Sea route in the thirteenth century", *Revue belge de philology et d'histoire*, 29 (1951), 1163-1179, which he labels as controversial and which claims the Majorcans were the first to operate on the maritime route to England and Flanders, followed by the Genoese.

[59] Pujades 2007, 414.

[60] Epstein 1996, 143.

Italy and seeking further expansion across the Ionian Sea. The Pope's great worry was a revitalised Hohenstaufen empire. He had been greatly relieved at Frederick II's death in 1250 and had always considered the King of Sicily to be his vassal, but had been unable to find anyone willing to oust Frederick II during the latter's lifetime. Frederick's death offered fresh chances and the Pope started to look around for an alternative king.[61] However, one royal candidate after the other refused, among whom Charles of Anjou, who, although more than willing, was under firm orders from his brother, King Louis IX of France. The situation changed when Manfred usurped power and started to expand his lands. King Louis IX, who considered Manfred a godless interloper[62], consented to his brother accepting title to the kingdom of Sicily. Charles invaded Italy from the north and defeated Manfred's army in 1266, which left Manfred dead on the battlefield. Also Charles of Anjou turned out to have greater ambitions than the Pope considered healthy, as he persistently began to enlarge his territory eastward. His ambition was the capture of the remains of the Byzantine Empire. The rise of Charles of Anjou was bad news for Genoa, which would remain on poor terms with him for as long as he lived. This damaged Genoese trade on the Provence, traditionally the largest trading partner of Genoa, and on Naples and Sicily.[63]

"At the beginning of the year 1282, Charles [of Anjou]… was without doubt the greatest potentate in Europe", Runciman writes.[64] However, a carefully plotted conspiracy culminated in a popular uprising in Sicily, stimulated by Aragonese agents and by money from Constantinople.[65] The French garrison troops and state officials were murdered almost to a man by the angry Sicilians. The signal for the attack had been the ringing of the bells of Palermo for Vespers and this far-reaching event is therefore known as the Sicilian Vespers. Peter III, King of Aragon, later landed in Trapani with a war fleet that had been waiting at Tunis. The Catalans were welcomed warmly by the Sicilians.[66] As a result of the Vespers Charles of Anjou's empire collapsed like a house of cards. Charles did his utmost to conquer Sicily back, but the superior Catalan fleet under the brilliant admiral Roger of Lauria beat the French fleet at every encounter. He had already effectively lost Tunis to Aragon and received no help from his dominions across the Ionian Sea. In January 1285 he died, his empire withered away.[67]

The enraged Pope excommunicated King Peter III and placed Aragon under papal interdict. As the Crown of Aragon had admitted papal suzerainty in the past, the Pope felt free to offer it to Philip III, king of France, and proclaimed a crusade against Aragon. Philip invaded Catalonia with a large army, which outnumbered the Catalans, but

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[61] Runciman 2008, 56.
[62] Runciman 2008, 57. These are Runciman's words.
[63] Epstein 1996, 143, 144.
[64] Runciman 2008, 201.
[65] Runciman 2008, 201 – 213.
[66] Runciman 2008, 214 – 227.
[67] Runciman 2008, 242 – 255.

the campaign ended in disaster as the French troops were struck by dysentery. After a disorderly retreat of the crusader army, Philip III died at Perpignan, after which the army evaporated.[68]

In spite of papal enmity, Aragon had emerged victorious, and although Sicily was returned to the Holy See, it proclaimed itself independent soon after that and remained Catalan in spirit for some time to come. The Crown of Aragon had become the undisputedly dominant naval and commercial power in the Mediterranean, holding or controlling all strategically important islands in the Western Mediterranean and stepping effortlessly into the shoes involuntarily vacated by the Pisans.

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[68] Runciman 2008, 257 – 259.

2 KEY CHARACTERISTICS OF PORTOLAN CHARTS

This chapter consists of two sections, of which the first provides a purely descriptive listing of the key cartographic characteristics of portolan charts relevant to this study. The second section discusses aspects of the charts in the context of their generally assumed medieval origin, for which no satisfactory explanation exists as yet. The discussion includes aspects that indicate (apparent) internal contradictions and aspects that appear to be poorly understood.

2.1 DISTINGUISHING CARTOGRAPHIC CHARACTERISTICS

Among the innovations introduced in the eleventh, twelfth and thirteenth centuries, portolan charts are among the most surprising; they constitute a very significant step forward in cartography. Certain aspects of the charts developed over time and Campbell therefore limits his review of portolan charts to the period up to 1500[69], whereas Pujades prefers 1470.[70] Both do so for more or less the same reasons; the character of portolan charts changes in the late fifteenth century and the coverage area was greatly expanded to include newly discovered territories. Furthermore, European mapmaking changed as a result of the introduction of astronomic navigation by the Portuguese, which resulted for example in the addition of latitude scales to the charts. Gaspar discusses these developments in his recent dissertation.[71] Also the introduction of charts printed on paper influenced the mapping style, as such charts gradually replaced the manuscript charts on vellum. However, the characteristic wind rose of the Mediterranean portolan chart (see Figure 2.1 below) continued to be a feature of nautical charts until well into the eighteenth century. The description of the key characteristics of Mediterranean portolan charts from the thirteenth to the end of the fifteenth centuries provided below is largely based on Campbell's authoritative description.

A short justification of the name to be used for these charts is, I believe, appropriate. Particularly in the early days of portolan chart research there was much debate on the

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[69] Campbell 1987, 381. Campbell explains his reasons in his footnote 1 as follows: "first, the extension southward and eastward to include the Cape of Good Hope and the route to the Indies occurs close to that date, as does the first cartographic representation of Columbus's discoveries; second, the earliest surviving charts to incorporate a latitude scale – and thus in some opinions to have outgrown the term 'portolan chart' – also date from the very first years of the sixteenth century".

[70] Pujades 2007, 412. Pujades chooses the year 1470 because around that year the Portuguese reached the equator, which signified "a milestone in the history of navigation and by extension, of nautical cartography".

[71] Joaquim Alves Gaspar, *From the Portolan Chart of the Mediterranean to the Latitude Chart of the Atlantic. Cartometric Analysis and Modelling*, PhD dissertation, Universidade Nova de Lisboa (2010), 21 – 32.

name to be used. Several authors proposed a name that implied a relationship with the compass (*compass chart*) or with a map projection (*loxodromic chart* or *rhumb line chart*). *Nautical chart* was felt to be not descriptive enough. The term *portolan chart* was coined in the 1890s[72] to reflect the consensus that still exists among researchers regarding the relationship between the sailing guides known as *portolans* and the charts. The word *portolan* or *portolano* has also been used to describe the charts, but is nowadays avoided because it leads to confusion with the sailing guides. I have followed common practice in this thesis with the use of the term *portolan chart*, for no better reason than that it is a well-established term. Moreover, as long as their origin and construction method are unclear, there appears to be no point in getting too hung up about terminology, provided it creates no confusion.

There is no doubt that these cartographic products are indeed nautical charts rather than land maps, even though the majority of extant charts appears to have been created as objects of prestige and display, to be owned by wealthy merchants, princes, noblemen and even kings, and never to be taken out to sea. Nevertheless, Pujades demonstrates[73] widespread shipboard use of what was presumably an undecorated, purely utilitarian type of portolan chart, which would only have had a limited lifespan in an environment dominated by salt and water, the vast majority of which has not survived.[74] Portolan charts constitute a new genre of maps, not seen before in Europe, or anywhere else, although some authors have attempted to make a case for the existence of sea charts in antiquity, even though no such charts have survived and the possible references are ambiguous. The early usage of sea charts in the Indian Ocean seems probable, but is by no means undisputed.[75] Marco Polo refers to sea charts in his 1298 book, but whether these charts preceded Mediterranean portolan charts is a question that cannot be answered.

The area depicted on the portolan charts under consideration comprises primarily the Mediterranean and Black Sea. A fair number also portray the Atlantic coasts from Cap Drâa or even Cape Bojador in Northwest Africa up to and including southern Scandinavia and the Baltic Sea. Ireland, Britain, the North Sea coasts and Baltic Sea coasts

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[72] Campbell 1987, 375, main text and footnote 39.

[73] Pujades 2007, 428. Pujades presents a compilation of references to nautical cartography in medieval documentation spanning the period from 1315 to 1531, "confirming the existence (not counting the Venetian examples from later than 1500) of over 220 complete charts, 8 partial charts and a further twenty or so other documents, including atlases, mappaemundi in panels, charts in panels or navigational tables."

[74] Tony Campbell pointed out that some may have survived and provides a shortlist of examples on his web forum http://www.maphistory.info/PortolanColourNotes.html#plain.
One of them might be the Ristow-Skelton No. 3 chart, studied in this thesis (Tony Campbell, personal communication, 9/12/2012).

[75] Gerald R. Tibbetts, "The Role of Charts in Islamic Navigation in the Indian Ocean", in *The History of Cartography, Volume 2, Book 1, Cartography in the Traditional Islamic and South Asian Societies,* edited by J.B. Harley and David Woodward (Chicago, University of Chicago Press, 1992), 256.

are shown with little coastal detail; these coasts also lack the accuracy that the Mediterranean coasts have, but the Atlantic coasts are of the same order of accuracy as the Mediterranean, with the exception of the Carte Pisane, as will be demonstrated in Chapter 7: *Cartometric analysis of five charts*. It has been pointed out in available literature that the northern boundary of accurate charting coincides approximately with the trade boundary imposed by the Hanseatic League, or with the boundary of Roman Empire, depending of the view the relevant author takes on the origin of the charts.

Mediterranean portolan charts were almost exclusively drawn on vellum, a fine quality of parchment.[76] The entire skin of a young animal, often a lamb or a calf, was used and in most cases the dimensions of the skin dictated the scale of the chart. With nearly all charts the neck of the animal is clearly visible at the western end, but on some early charts, among which the Carte Pisane, the neck is situated at the eastern end of the map image. The charts were usually fastened to a wooden pin at the opposite side of the neck and rolled up for storage and transport. A leather thong running through the neck was used to secure them in their rolled-up position.

The most conspicuous feature of a portolan chart is the network of straight lines that covers the entire map image, as shown in Figure 2.1. These lines form a simple, yet ingenious pattern, created by marking sixteen regularly spaced points on the perimeter of a circle, which is normally not drawn, and connecting these points by straight lines. This enables the drawing of thirty-two regularly spaced directions.[77] The lines are usually extended beyond the nodal points on the hidden circle. Eight of the points on the circle perimeter correspond with the eight fundamental wind directions that the medieval sailor distinguished, consisting of the cardinal directions and their intermediate directions. These were extended by eight *half-winds* by bisecting the forty-five degree angles created by the eight fundamental winds. *Tramontana* corresponds with north; the other 'winds' can easily be deduced from the figure. Some name variations are encountered: *mezzodi* is sometimes replaced by *mezzo iorno* or *ostro*; *libeccio* is often used instead of *garbino*.

The densification from sixteen directions to thirty-two introduces the so-called *quarter-winds*. The entire pattern of lines is referred to as a *wind rose*. It is distinguished from a *compass rose* in the sense that the 'wind' originally indicated a sector of the horizon, rather than a precise direction as is the case with the 'points' of a compass rose; at least originally. A finer division beyond thirty-two points is made in portolans and will be explained in Chapter 8: *The relationship between portolans and portolan charts*.

In the early charts two of such wind roses are drawn side by side, with one common nodal point. Later charts have only a single wind rose. The lines corresponding to the

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[76] Campbell 1987, 376, footnote 48.
[77] See also Section 12.3.

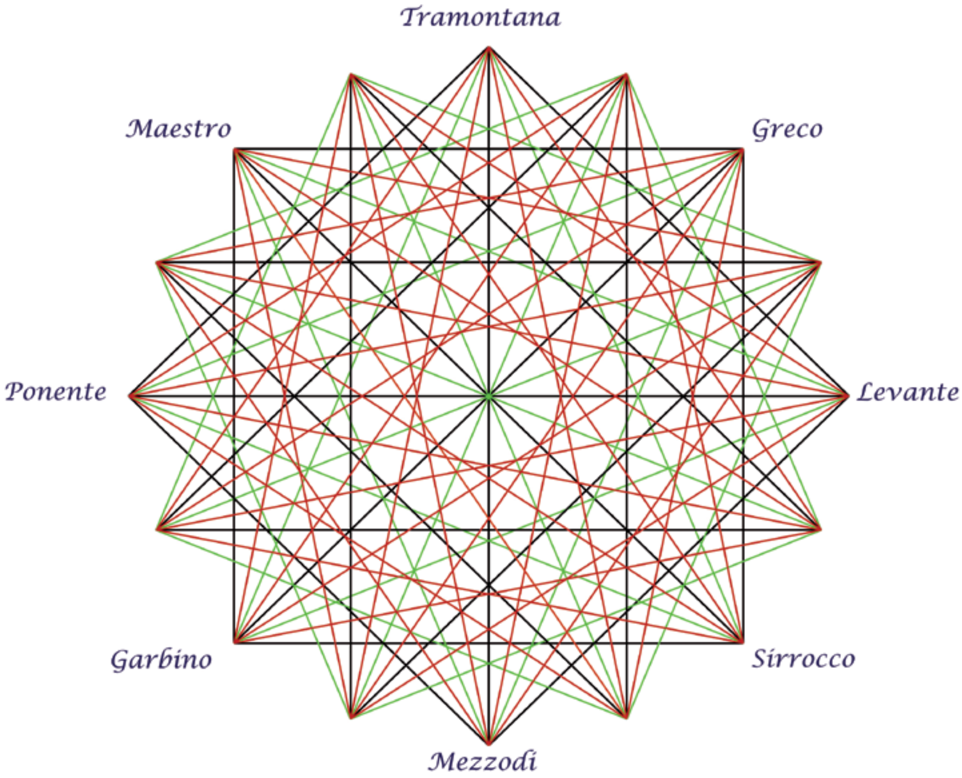

Figure 2.1 *- Wind rose with the eight cardinal winds in black, in green the half-winds and in red the quarter-winds.*

eight cardinal winds are usually shown in black, those corresponding to the eight half-winds in green and the ones defining the sixteen quarter-winds in red. The location of the wind rose's centre and its size relative to the map image are different for practically every chart. Compass roses were drawn as ornaments, typically in the nodes of the wind rose. The first compass rose appears 1375, in the Catalan Atlas (see Figure 2.2).[78]

The coastlines have been drawn in a single black line and the names of ports, prominent headlands and bays are written at right angles with the coastline. About half of these toponyms belong to ports and cities, the remainder to islands, capes, rivers and gulfs or bays. The names of important cities or geographic features are written in red ink, the remainder in black. The toponyms of islands close to the coast and of places on the islands are usually written in the opposite direction to those on the nearby coastline, so that confusion is avoided.

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[78] Campbell 1987, 395.

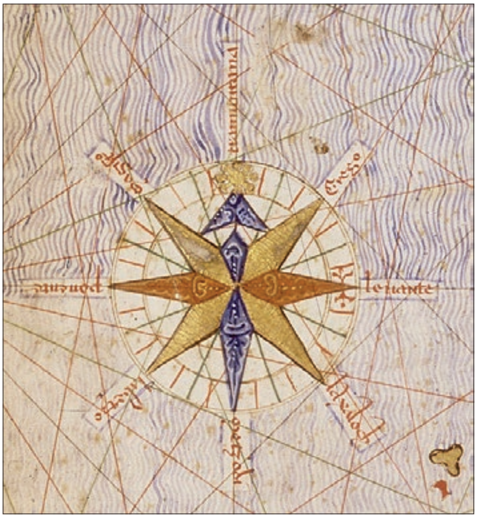

Figure 2.2 *- Compass rose from the western panel of the Catalan Atlas (1375) (Source: Bibliothèque nationale, Paris, Mss Espagnols 30).*

Visibility of islands is often enhanced by a solid colour fill, as are important river deltas. No political boundaries are indicated, but flags or pennants drawn near the locations of cities indicate their rulers. Campbell cautions against a rash interpretation of these flags, particularly as a tool for dating a chart: their design was not yet standardised, perhaps *de facto* rule was shown rather than *de jure* rule and last but not least, Christian chartmakers were quick to add Christian conquests over Islam to their charts, but in no hurry to honour the reverse. Campbell provides a table with examples.[79]

In principle portolan charts have no preferred orientation. They need to be rotated in order for all toponyms to be read. Even decorations are not drawn to a single orientation. The wind rose network establishes the relationship of the map image with the cardinal directions. From that relationship it is evident that the entire map image has been rotated anticlockwise by about nine to ten degrees. This rotation angle is usually attributed to the unknown magnetic declination in the Mediterranean, but some alternative views are discussed in the next chapter.

Portolan charts were the first maps known to be equipped with one of more scale bars showing a type of mile as length unit that is peculiar to portolans and portolan charts.[80] As is the case with the wind roses, the style of the scale bars is governed by convention; on practically all charts except the earliest the scale bars are drawn as ladder-like structures, in which the larger *spatium* between two rungs corresponds to

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[79] Campbell 1987, 399, 400.
[80] Campbell 1987, 371.

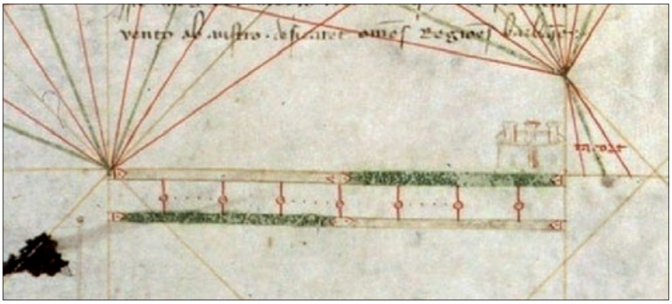

Figure 2.3 *- Scale bar on the Angelino Dulcert (1339) chart (left)*
(Source: Bibliothèque nationale, Paris, Rés. Ge. B 696).
Figure 2.4 *- Scale bar on the Pietro Vesconte (1311) chart (right)*
(Source: Florence, Archivo di Stato, CN1).

fifty miles. Every second large spatium is subdivided by dots into five small spatia of ten miles each. On the earlier charts the scale bar is often drawn in a circle, but the same principles apply. Usually two or more scale bars have been drawn on charts covering the entire Mediterranean. A key question that has troubled researchers for one and a half century is what type of mile was used for the construction of these charts and what its length was in modern units. The question of the length of this mile, which measured approximately 1250 metres[81], will be looked into in more detail during the cartometric analysis of the charts, in the statistical analysis of the *Compasso de Navegare* in Chapters 7 and 8 and in the final Chapter 12: *Synthesis*.

The nautical character of the charts, mentioned above, is demonstrated not only by the absence, or rather scarcity, of inland features, but is more clearly evidenced by the presence of hydrographic features relevant to navigation, such as shallows and reefs.[82] Shallows are generally indicated by series of red dots, reefs by black crosses or black dots, as shown in Figure 2.5. These symbols constitute two more examples of the adherence to conventions in the design of these charts.

When shown, inland features, such as for example mountain ranges and courses of major rivers, appear to reflect what the chartmaker may have believed to be reasonable assumptions about their geographic shapes and locations. However, they have clearly been drawn without recourse to actual measurements and for that reason inland features show a marked contrast with the general realism of the coastlines.

It is now generally accepted that most of the charts that have survived were intended

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[81] Campbell 1987, 389: "Even though majority opinion has settled for an approximate value of 1.25 km, the issue is far from settled."

[82] See also James E. Kelley, Jr., "Curious Vigias in Portolan Charts", *Cartographica*, Vol. 36 (1999), No. 1.

Figure 2.5 *- Reefs and shallows on an anonymous Genoese chart (1325-1350) (Source: Washington, Library of Congress, Ristow-Skelton No. 3).*

as objects of display and prestige.[83] These charts are often extensively decorated, which is particularly visible on the Catalan charts that have survived. It has long been thought that decorations were a typical feature of the products of the Catalan cartographic 'school', but Pujades concluded that the extensive decoration of surviving Catalan charts versus the austerity of surviving Italian ones should not be interpreted as a systematic style difference.[84]

Miniatures or vignettes of the major cities, such as Genoa, Venice, Rome, Cairo, etc. are often drawn at their approximate locations, their names written prominently in red ink. The amount of decoration varies by chart, with decorations becoming more lavish towards the fifteenth and sixteenth centuries, at least on the surviving exemplars.

Very characteristic of portolan charts is the stylised manner in which the coastlines have been drawn as a series of 'daisy-chained' crescents or arcs with their concave sides turned seaward (see Figure 2.6). The reason for this is not known with certainty, but Pelham attributes it to a copying method of the charts consisting of 'piercing' coastline points of an old map and then transferring the points to a new piece of vellum. This technique was originally described by Bartolomeo Crescenzio in 1601.[85] The effect

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[83] Pujades 2007, 454.

[84] Pujades 2007, 440.

[85] Peter T. Pelham, *The Portolan Charts: Their Construction and Use in the Light of Contemporary Techniques of*

Figure 2.6 *- Coastline style on the anonymous Genoese chart (1325-1350) (Source: Washington, Library of Congress, Geography & Map, No. 3).*

could then be the result of an embellishment of a 'join the dots' exercise. Although Crescenzio probably does describe an actually used technique, this does not explain how a scale change was effected, as almost every chart has its own individual scale, maximised to the dimensions of the available skin. The technique used for copying charts is as yet not understood.

Summarising, the definition of portolan charts that I have used in the context of this study is based on its key characteristics and reads as follows.

> *A portolan chart is a medieval manuscript nautical chart drawn on vellum, which covers the Mediterranean, the Black Sea and in some cases parts of the Atlantic coast of Africa, the North Sea and Baltic Sea. Its chief visual characteristic is the network of straight lines covering the chart and representing thirty-two equally spaced bearings, while it contains no graticule or other markers of latitude and longitude.*

2.2 DISPUTED, UNCLEAR AND UNSATISFACTORILY EXPLAINED ASPECTS OF PORTOLAN CHARTS

So far I have provided a purely descriptive enumeration of portolan chart characteristics. The additional characteristics, described in the remainder of the chapter, will be discussed in the context of the medieval origin hypothesis. The reason for this is that,

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Marine Survey and Navigation. Master's Thesis, Victoria University of Manchester (1980), 90; see also Campbell 1987, 391.

assuming a medieval origin of the charts, these characteristics have as yet not been explained in any satisfactory manner.

2.2.1 Exaggeration of coastal features

Although the overall coastlines show the remarkable realism referred to earlier, individual coastal features, such as capes and headlands, but also small islands, have been considerably exaggerated in size, but according to Pujades,[86]

> "… it does not matter if the least important details of the coastline are simplified; on the contrary, the dimensions are constantly and conspicuously increased of those geographical features, like capes, gulfs, islands and islets, which are particularly visible from the sea. This phenomenon, of which researchers have been talking for many years without explaining its deep meaning …"

The deep meaning to which Pujades refers is the plausible assumption that visual recognition played a key role in medieval navigation. However, the reproach he delivers to his colleagues is unwarranted; there is more to the coastline portrayal than his rather straightforward explanation suggests.

Some alternative explanations may indeed not be very realistic. For example Pelham cites unspecified authors as suggesting that feature exaggeration was introduced to "emphasize their danger to navigators and allow a greater margin of error in their circumnavigation of them".[87] That suggests that sailors would navigate their vessels on calculated position only, blindfolded as it were, whereas it is far more reasonable that they would navigate visually when possible. Why would these sailors have made life more difficult for themselves than necessary?

Lanman[88] believed that indifference of the chartmakers towards accurate depiction of coastal detail is the reason for the feature exaggeration: "No great effort to depict the coastal details was ever made" and "What the stylization[89] does show is that the chartmakers were either ignorant of coastal details or indifferent to them". This is a strange idea indeed, because most navigational dangers in the Mediterranean, as in most seas, are near the coast and not in the open sea, barring the occasional occurrences of offshore reefs. However, it is not too difficult to see how Lanman arrives at this view.

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[86] Pujades 2007, 460.

[87] Pelham 1980, 11.

[88] Lanman 1987, 6, 45. Lanman's statements should be seen in the light of his view that portolans were primarily if not exclusively intended for long-distance cross-basin navigation. I shall revisit his work in detail in Chapter 8.

[89] Lanman uses the word the word "stylization" where he describes the exaggeration of coastal features, which is not the same concept. The representation of any coastline by a series of concatenated concave arcs can be seen as stylization; the more arbitrary exaggeration of coastal feature does not represent a style choice.

Figure 2.7 *- Capo Palinuro (Roselli -1466) (Source: John Ford Bell Library, Univ. Of Minnesota).*

Figure 2.8 *- Capo Palinuro (RS-3) (Source: Library of Congress, G&M, No 3).*

Figure 2.9 *- Capo Palinuro is not visible on a 1:1,000,000 map (Source: VMAP; Digital Chart of the World).*

Figure 2.10 *- Capo Palinuro in Google Earth (Image: © 2010 Google, © Tele Atlas, © Cnes/Spot Image, © TerraMetrics).*

Figure 2.11 *- The characteristic shape of Amasra on an anonymous Genoese chart (Samalto)(Source: Florence, Bibl. Riccardiana 3827).*

Figure 2.12 *- Amasra in Google Earth (Image: © 2010 Google, © 2011 Basarsoft, © 2011 GeoEye, © 2011 Terrametrics).*

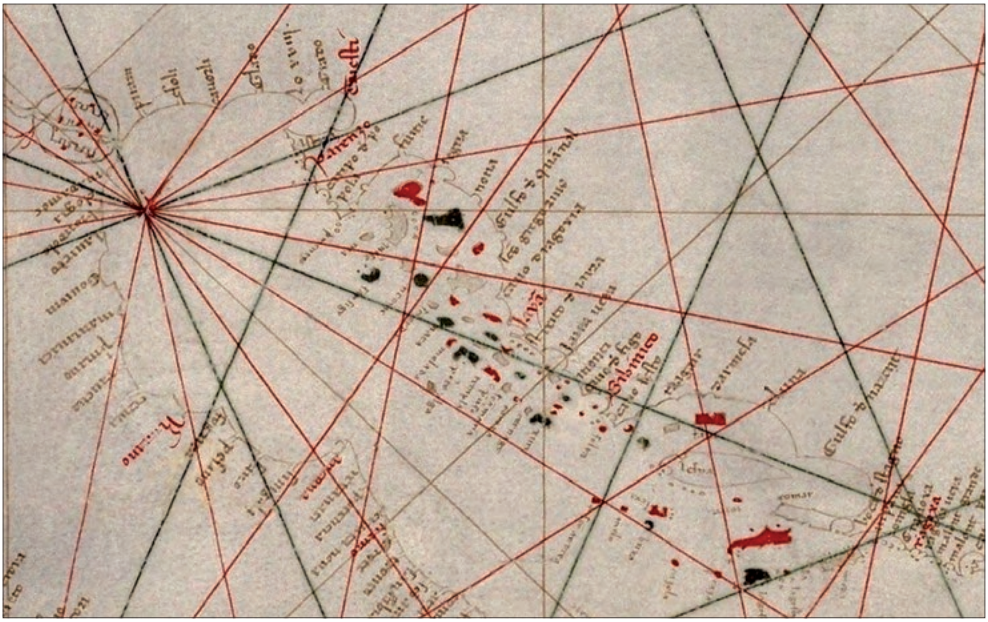

Figure 2.13 *- The Dalmatian islands on a portolan chart by Albino de Canepa (1489) (Source: James Ford Bell Library, University of Minnesota).*

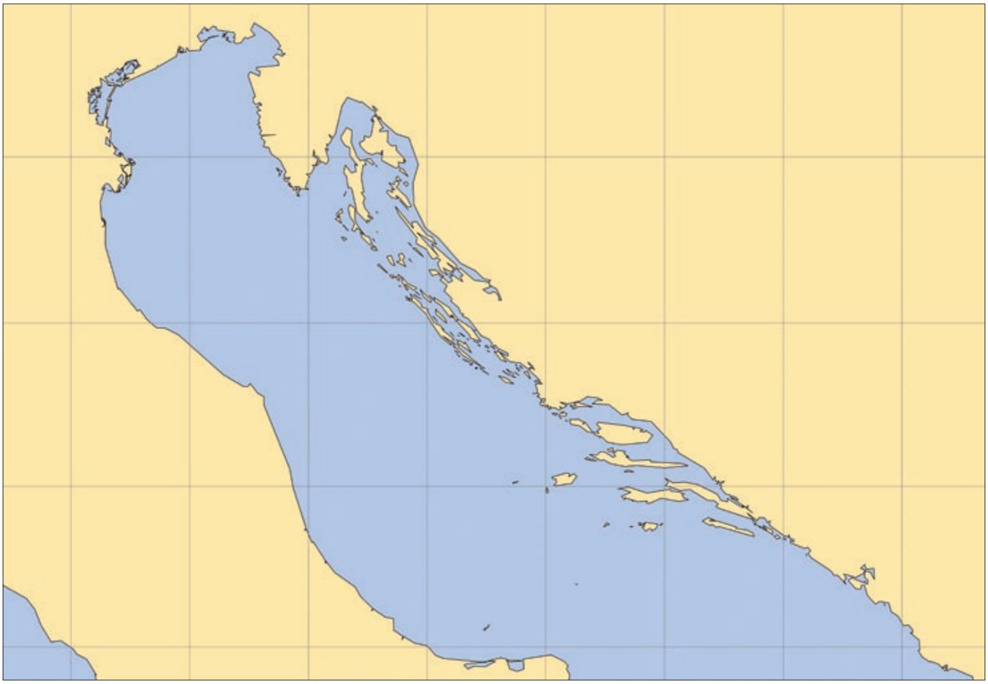

Figure 2.14 *- The Dalmation islands on a 1:1,000,000 modern map (Source: VMAP; Digital Chart of the World).*

Capo Palinuro in Italy is shown in Figure 2.7 to Figure 2.10. The feature has been enlarged on these portolan charts by more than a factor of ten. In Figure 2.11 and Figure 2.12 the town of Amasra on the southern Black Sea coast is shown, enlarged by almost a factor of ten. The exaggeration of coastal features in portolan charts is *not* a sophisticated cartographic technique, as it is not the result of a systematically applied constant scale enlargement of accurately known coastal details; instead it looks as if a rough sketch of the relevant feature has been superimposed on a coastline that was originally depicted more accurately and to scale.

Furthermore, considerable stretches of coast are in many places downright inaccurate, surprisingly without affecting the overall accuracy of the coastline over a larger area. Also the detail of islands is often very poor; whereas the centroids of most islands have been drawn in the right locations, i.e. consistent with the overall accuracy of the chart, most small islands are drawn too large and the detail of their shapes is often highly inaccurate. For example the island of Thira, one of the Cyclades, with its companion island Thirasia, is always displayed on portolan charts rotated by ninety degrees clockwise. Nowhere is this inaccuracy more apparent than in the Adriatic, where the oblong shape of the northern Dalmatian islands could hardly have escaped notice of even the most untalented navigator. The stylised portrayal of bays may be explained by assuming that trading ships bypassed those bays, sailing from headland to headland, but entire headlands and peninsulas that are lacking are harder to explain.[90]

2.2.2 A contradiction of Tobler's First Law of Geography

The measurement of an accurate geometric framework is an indispensable first step in the process of mapping. Without it, the map is unlikely to have a consistent scale and orientation. Since Willebrord Snel van Royen (Snellius) performed his degree-measurement between the two Dutch cities of Alkmaar and Bergen op Zoom by means of triangulation in the early seventeenth century[91], geodesists have used this technique until well into the twentieth century to establish *geodetic control networks*[92] as frameworks for scientific mapping. The first nationwide topographic mapping (of France) was started by Jean-Dominique Cassini and took three generations of Cassinis and an untold number of an army engineers to com-

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[90] See also Figures 8.17 to 8.20 in Chapter 8.

[91] Nico D. Haasbroek, *Gemma Frisius, Tycho Brahe and Snellius and their Triangulations*, Publication of the Netherlands Geodetic Commission, Delft, 1968. http://www.ncg.knaw.nl/Publicaties/groeneserie.html.

[92] A *geodetic (control) network* consists of a set of *control points* distributed over an area, e.g. a country, of which the relative positions have been determined by measuring angles and distances between those points. Distance measurement was difficult in the early history of geodesy, described here, and triangulation was the only technique available. The linear dimension of the system of triangles was established by measuring the length of one or more *baselines* as accurately as possible. The sides of all triangles were then computable by trigonometry. The control points were retained for future work by *monumenting* them in the field, such that they could be used as the starting points of local survey work for detailed mapping. The entire network acted as the geometric framework of national mapping.

plete. This was achieved on the basis of the first large triangulation network.[93]

Although these events obviously took place centuries after portolan charts had made their sudden appearance, one of the key questions is how such a geometric framework was established for portolan charts, as their accuracy leaves no room for doubt that such a framework would have been required. This geometric reality cannot be circumvented or avoided; it was as much valid in the Middle Ages as in the twenty-first century.

The medieval origin hypothesis assumes that this geometric framework was built up from a large body of distance – and possibly course bearing – measurements between points around the Mediterranean coasts, ports, landmarks, capes, etc.[94], averaged to achieve the accuracy displayed by the charts. Any such geodetic network[95] requires two starting points from which the network is built up through a process of accretion. This unavoidable process leads to an accumulation of random errors, so that the coordinates of the control points will show deteriorating accuracy characteristics the further away from these baseline points this accretion progresses. This holds for recent triangulation networks of the last century as much as for this (hypothetical) medieval Mediterranean network built up from bearings and distances. The key accuracy characteristic of any geodetic network is that the closer two points are located, the higher their relative accuracy will be. This may be seen as the geometric aspect of Tobler's First Law of Geography: "Everything is related to everything else, but near things are more related than distant things."[96]

However, portolan charts show the opposite relationship: the overall accuracy of the charts is very good, but the spatial relationship of near geographical features is often worse than the spatial relationship between features that are further apart. This does not refer to the exaggeration of coastal features described above. Assuming, as the medieval origin hypothesis does, that the underlying geodetic network consisted of the said (averaged) distance and compass bearing measurements, both along the coast and across the open sea, it is contradictory that the same measurements, that would have led to a high accuracy for e.g. the entire Western or Eastern Mediterranean, would have resulted simultaneously in such poor accuracy of shorter stretches of coast.

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[93] John N. Wilford, *The Mapmakers*, Revised edition (New York: Vintage Books, Random House, 2000): 132-151.
Gerald Roe Crone, *Maps and Their Makers: an Introduction to the History of Cartography*, fifth edition (Hampdon, Connecticut: Archon Books, 1978), 85-91.

[94] A separate sub-category of the medieval origin hypothesis is formed by the proposition that such a framework may have consisted of points with astronomically determined latitudes and longitudes. This option will be separately discussed: Chapter 3: *Existing hypotheses on the origin and construction method of portolan charts* contains an inventory of such propositions. Further discussion is only offered in Chapter 10: *An Arabic-Islamic origin of portolan charts?* after the details of my study have been presented.

[95] A geodetic network of this type is analysed in Chapter 9 of this study.

[96] Waldo R. Tobler, "A computer movie simulating urban growth in the Detroit region", *Economic Geography,* Vol. 46 (1970), 236.

2.2.3 FIRST APPEARANCE

The first documented evidence of shipboard use of a portolan chart is the description of the beginning of King Louis IX of France's last crusade in 1270, by his chronicler Guillaume de Nangis. The king had embarked with a large army at Aigues-Mortes on July 1st on ships supplied by Genoa, Venice and Marseilles. He had allowed himself to be persuaded by his brother, Charles of Anjou, then king of Sicily and most of Italy, to capture Tunis before sailing to the Holy Land, when the ships were caught in a storm. As Pujades translates this much-recited story:

> "Doubts began to be cast, unjustly …, on the sailors' competence. When asked what the ship's position was, they were not entirely sure of the answer: although they believed they were close to the land, they could not understand why it was not visible. So they unfolded the map (*allata mappa mundi*), determined their position and informed the king that the port of Cagliari must be very near. And so it was, for only a few hours later they sighted it some 60 miles away".[97]

An interesting but irrelevant detail is the fact that the mariners could never have determined their position so accurately after having been driven about by a storm for several days. The availability of a chart makes no difference. It looks as if they made a guess to placate the worried king, a guess that luckily turned out to be correct. Edson indeed proposes this was the case and also Gautier Dalché has pointed out this inconsistency.[98]

The date of around the middle of the thirteenth century is conventionally considered to be the approximate date of birth of the portolan chart. However, Patrick Gautier Dalché[99] has described a Pisan document, which he dates to the end of the twelfth century, *Le liber de existencia riveriarum et forma maris nostri mediterranei* and which is in essence a portolan, or written sailing guide, of the Mediterranean. His analysis casts new light on this old issue.

The preface of the *Liber* contains a startling description, paraphrased by Gautier Dalché, who admits that the text has presumably suffered over time from copying. He states:

> "The author has wanted to provide a written description of the Mediterranean … after the *cartula mappa mundi* which he had drawn …"

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[97] Pujades 2007, 458. The 'mile' to which the text refers is presumably the same distance unit shown in portolan charts and which is sometimes referred to as the 'small Italian mile' of about 1.23 or 1.25 km.

[98] Evelyn Edson, *The World Map, 1300–1492. The Persistence of Tradition and Transformation* (Baltimore: The Johns Hopkins University Press, 2007), 38.
Gautier Dalché 1995, 27.

[99] Gautier Dalché 1995.

He thus concludes that "the text thus presents itself as complementary to the chart" and furthermore that the chart must have been a portolan chart, because the geometric data provided in the *Liber* are more realistic and accurate than a *mappamundi* would be able to provide. His conclusions, and the dating of the *Liber* to the end of the twelfth century, would push back the birth of the portolan chart by up to a century. Tony Campbell has pointed out that the gap between the end of the twelfth century and the first documentary evidence of 1270 is rather large. Ramon Pujades disagrees with Gautier Dalché regarding the dating and places the composition of the *Liber* in the first quarter of the thirteenth century, which would close the gap to about half a century. More importantly, Pujades disputes Gautier Dalché's translation of the preface of the *Liber*, which is written in medieval Latin, and reverses the causal relationship between the chart and the written document, rendering the first sentence as follows.

> "We propose to write about our Mediterranean sea, about the form of the sea and its shores, in accordance with how its places are located in terms of the winds on the globe of the earth. In order to represent it on a *mappamundi* chart, I drew up this brief text on the number of miles that separate its places …"[100]

In no way am I qualified to offer an opinion on translations from medieval Latin and I shall have to leave this dispute on that subject matter to experts. However, Pujades's preconceived ideas on the relationship between portolans and portolan charts can hardly escape the reader's attention and diminish the power of his argument.

> "Thirdly, that period during which the *Liber* was compiled and the characteristics of the work itself reveal the **methodological error** committed by those who would deny the initial relationship between portolans and portolan charts … Thus, one of the authors who in recent times has **consistently denied the derivation of nautical charts from portolans** is Kelley, who alleges that in comparison to the abundance of nautical charts, portolans from the Lower Middle Ages are very few and that much of the information they contain, especially regarding fractional directions[101] must of necessity have derived from nautical charts rather than vice versa, since they could not be marked by the magnetic compass. Nonetheless, and although such observations are judicious, his arguments, which **overlook the chronological factor**, come to nothing when the directions are analysed of a more archaic work … the Liber…" (Emphasis is mine – RN).

To Pujades, the very idea that charts might have existed before portolans is apparently anathema. However, although the sequence he favours is indeed an eminently logical one, it is not actually a proven fact. Kelley pointed out some important inconsistencies

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[100] Pujades 2007, 513.

[101] Pujades 2007, 512. The English text actually states "distances" instead of *directions*. This is a translation or type-setting error; the Catalan text refers to "direccions". See page 311 of his work.

in portolan data and indeed suggested that therefore portolans may have been benefited more from portolan charts than vice versa.[102] However, this is not a methodological error; it would have been if he had chosen to ignore the facts and stick to established opinions instead. This subject will be revisited in Chapter 8: *The relationship between portolans and portolan charts*.

2.2.4 The lack of any development path

Possibly more surprising than the appearance of these realistic charts in a period when the technical capabilities for mapmaking cannot be assumed beforehand, is the fact that they appear to spring up from nowhere, without any development path being visible in historical records. Even the oldest portolan chart, the Carte Pisane, shows the coastlines of the Mediterranean more or less correctly, although it does have some obvious shortcomings and is not quite as accurate as the charts that appear from the early fourteenth century onwards. For example, the European Atlantic coast on the Carte Pisane is very sketchy.

No indications whatsoever exist that afford an insight into the positioning and charting techniques of the period, which might have led to such a realistic chart. Documentary evidence from this early period is anyway bound to be scarce, so it may be tempting to assume that a development path did exist, but is simply not visible in surviving documents. That might be a reasonable argument if the surviving charts *would* have shown evidence ongoing development from a point in time when such development had started to gain some momentum. However, the surviving charts show in essence no indication at all of on-going development. Nevertheless the toponymy in the charts *does* show development[103] and the depiction of coastal detail does change to a certain extent, but that is less improvement than simply change.[104] Coastal outlines of the peripheral area of the Mediterranean portolan charts certainly develop over time[105] but, with four exceptions, no development in the sense of improvement is visible in the overall representation of the coastlines of the core area of the charts, the Mediterranean and the Black Sea[106], despite some obvious shortcomings in the early charts, which I will describe later. The exceptions I refer to in the previous sentence are the following.

1. The change from the primitive Atlantic coastline in the Carte Pisane to the more mature form of the Vesconte charts from the first quarter of the fourteenth century and of later charts.
2. The development of the shape of the Black Sea from the Cortona chart to later charts.

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[102] James E. Kelley, Jr., "Perspectives on the Origins and Uses of the Portolan Charts", *Cartographia*, Vol. 32 (1995), No. 3: 10.

[103] Campbell 1987, 415 – 428. Campbell devotes an entire chapter and a large part of his online publication to toponymical development, which details toponymic appearances and disappearances.

[104] Campbell 1987, 403.

[105] Campbell 1987, 403-415.

[106] See footnote 107 below.

3. The correction of the orientation of the Adriatic Sea, as shown on the Carte Pisane, improving its alignment with the Mediterranean Sea in later charts.
4. The repeated attempts over time to get the scale of the Atlantic coasts correct.

Some authors have argued that, since the Carte Pisane shows a very sketchy European Atlantic coast and Pietro Vesconte's charts of only a few decades later show these coasts almost fully developed, charting of this section of coast must have taken place very rapidly indeed.[107] This conclusion is then extrapolated to apply to the charting of the entire Mediterranean. A similar argument has not been used, but might be applied to the northern shores of the Black Sea and Sea of Azov, which is shown in a squashed and crude shape on the Cortona chart (possibly early fourteenth century), but reaches its 'final' shape on, again, Vesconte's charts of the first quarter of the fourteenth century.

However, the first three modifications appear as step-changes, rather than as gradual improvements. The European Atlantic coast shows iteration without clear convergence, as shown in Figure 2.15, but *does* show a slight incremental improvement; on the anonymous Genoese chart (Ricc 3827), from the second quarter of the fourteenth century and analysed in Section 7.2, the European Atlantic coast is definitely inferior to that of the slightly later or contemporary (1339) chart of Angelino Dulcert, analysed in Section 7.4.

It is commonly assumed that a continuous feedback process existed from mariners to chart makers, allowing the latter to continuously improve their products. Campbell cites the famous text on Francisco Beccario's 1403 chart[108], which explicitly states that the chartmaker adjusted the scale of the European Atlantic coastline and the position of Sardinia, based on feedback from sailors.[109] This text is quoted by many authors as evidence that portolan charts were indeed continually updated and improved. However, this is not borne out by cartometric analysis.

Both Scott Loomer[110] and Peter Mesenburg have shown that, despite minor changes in detail and a gradually increasing effect of stylisation, the overall outline of the Mediter-

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[107] Konrad Kretschmer, *Die italienischen Portolane des Mittelalters. Ein Beitrag zur Geschichte der Kartographie und Nautik*, Veröffentlichen des Instituts für Meereskunde und des geographischen Instituts an der Universität Berlin, Heft 13, 1909, reprinted (Hildesheim: Georg Olms, 1962), 99; see also Pujades 2007, 511; Crone 1978, 17; Michel Mollat du Jourdin, M. Azard, I. Raynaud-Nguyen and M. Vannereau, *Sea Charts of the Early Explorers: 13th to 17th Century,* trans. L. le R. Dethan (New York: Thames and Hudson, 1984), 200.

[108] Beinecke Library, Yale University, New Haven; Art Object 1980.158.

[109] Campbell 1987, 427, 428.

[110] Scott A. Loomer, *A Cartometric Analysis of Portolan Charts: a Search for Methodology*, PhD thesis, University of Wisconsin, Madison (1987), 153. Loomer concluded, after analyzing 27 charts, that there is no discernible trend over time in the accuracy of the Mediterranean and Black Sea coastline representation, although "stylization" of the coast increases over time. Nevertheless, I believe that the increasing exaggeration of coastal features and its increased stylization eventually result in the deterioration of metric chart accuracy, as is e.g. visible in sixteenth and seventeenth century charts.

ranean coast does not show any evidence at all of an increasing accuracy or a resolution of defects. Loomer proved this numerically and Mesenburg demonstrated it visually in a striking manner, shown in Figure 2.15.[111] Mesenburg's set of overlays of fifteen charts also demonstrates that the correction that Beccario introduced didn't solve the scale problem of the Atlantic coast, but that repeated attempts were made to get the scale right.

The location of Sardinia and Corsica even deteriorates somewhat in Dulcert's chart of 1339, compared to earlier charts. Hermann Wagner already pointed out that Sardinia and Corsica were drawn too far south on portolan charts.[112] Beccario claimed to have corrected this. However, it is surprising to find that Sardinia and Corsica *were* shown more or less in their correct locations on the charts earlier than the Dulcert chart of 1339: the Carte Pisane, the anonymous Genoese chart (Ricc 3827)[113], as well as in the Genoese chart of the Library of Congress show these two islands in their correct locations. An analysis of the changes in the locations of Sardinia and Corsica is presented in Section 7.6.4.

One might ask why chartmakers changed this initially and why it took until 1403 before this change was noticed as an error, or rather addressed, when, as the commonly accepted hypothesis postulates, the entire Mediterranean could apparently be charted in a much shorter time frame and to a much higher accuracy.
Cape Vouxa (north-west Crete) is conspicuously missing on all portolan charts and was never added, even though the missing promontory could easily have been spotted with the naked eye on the busy route to Candia (Iraklion). Why did no cartographer ever correct this on his charts? Why was the orientation error of Thira of 90°never corrected? Lanman's explanation of indifference becomes increasingly appealing in the face of such evidence.

Most portolan charts appear to be copies of some predecessor. This led Nordenskiöld to postulate the concept of the *normal-portolano*, from which all later charts were "slavishly copied". [114] We know now that, although these charts were copied, the qualification "slavish" is inappropriate; as argued above, the overall coastline was retained, but at a lower level, a certain development, or at least on-going change, is visible in the toponymy and in the (exaggerated) coastal detail. The lack of any significant further

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[111] Peter Mesenburg, "Numerische und grafischen Analysen zur geometrischen Struktur von Portolankarten"*, Internationales Jahrbuch für Kartographie*, Vol. 28 (1988).

[112] Hermann Wagner, "Das Rätsel der Kompasskarten im Lichte der Gesamtentwicklung der Seekarten" (1895), in Wolfgang Köberer (ed), *Das rechte Fundament der Seefahrt. Deutsche Beiträge zur Geschichte der Navigation.* (Hamburg: Hoffmann und Kampe 1982): 24.

[113] See Section 6.4 for a description of these charts.

[114] Adolf E. Nordenskiöld, *Periplus. An Essay on the Early History of Charts and Sailing-Directions.* Translated by Francis A. Bather (Stockholm: P.A.Norstedt, 1897); facsimile reprint (Eastford CT USA: Martino Publishing, 2003), 18. Nordenskiöld uses the term *portolano* to describe portolan charts.

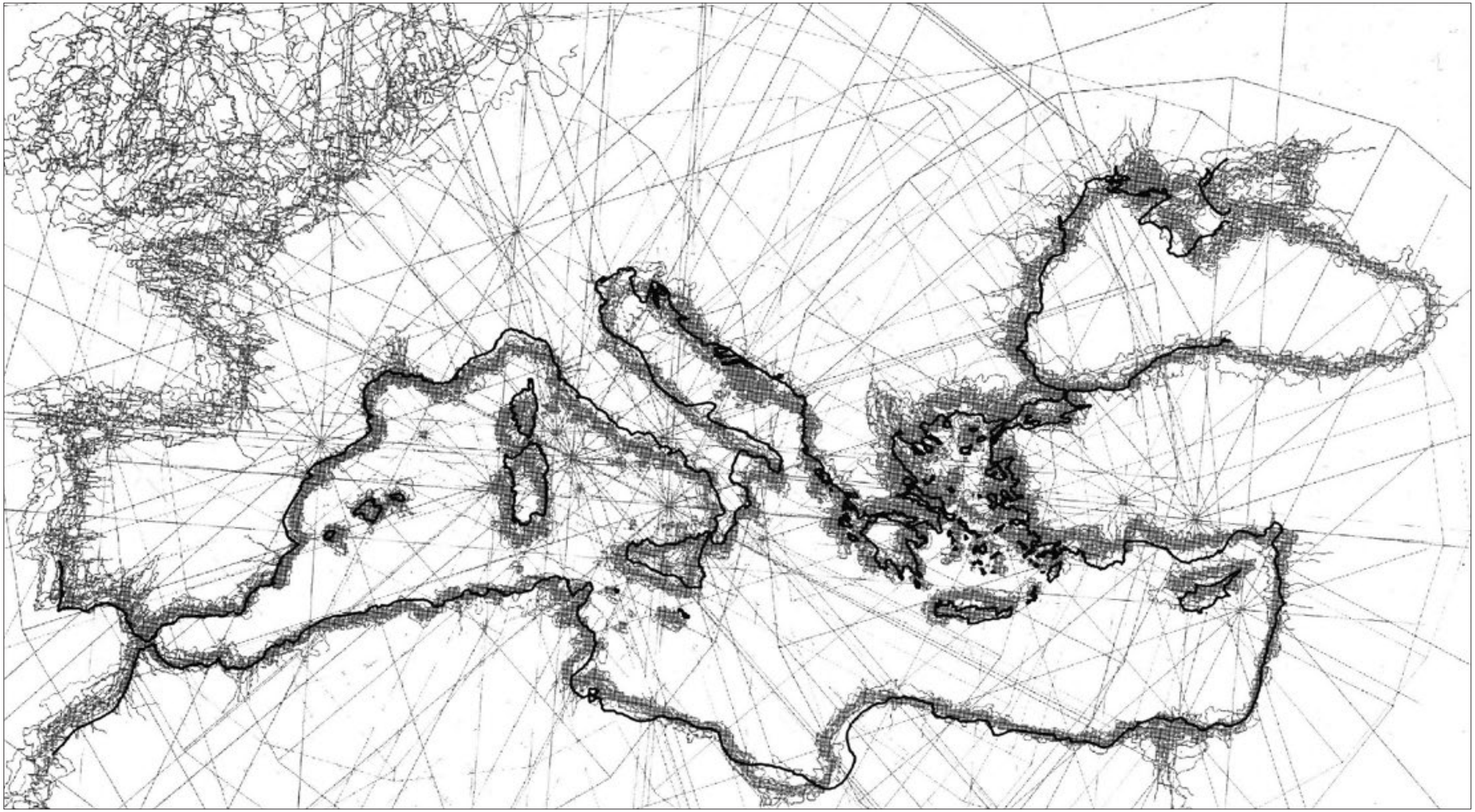

Figure 2.15 - *Overlay of tracings of 15 portolan charts*
(image by Peter Mesenburg 1988; reproduced with permission of the author).

development in the accuracy of portolan charts is as striking as the lack of a development path leading up to the creation of the charts and has as yet not been explained satisfactorily.

2.2.5 Scale variations

Portolan charts do not show a perfect representation of the Mediterranean; as mentioned in the previous paragraph they have a number of well-known 'defects' and peculiarities. The best known but still not understood defect is the varying scale of the charts. Working from the assumption that medieval mariners collected the navigation measurements from which portolan charts were drawn, it is not unreasonable to expect that different cities would use different distance measurement units and that, as a result of that, coastline data along the trade routes dominated by a particular city would show a tendency to reflect the thus dictated scale. However, the scale differences observed in portolan charts do not highlight the known trade routes. Instead, breaks in scale occur along other boundaries, in some cases between sub-basins.[115] Campbell has pointed out that there are no visible joins between the sub-basins; apparently the chartmaker has smoothed out any joins. Thus the Western Mediterranean has a different scale from the Eastern; the Black Sea scale is different again and the largest relative scale difference exists between the Atlantic coast and the Black Sea.

The reason for these systematic scale differences has eluded researchers until now. These scale variations were detected very early on in portolan chart research, in the nineteenth century. The scale consistency per sub-basin has led to the suggestion that portolan charts are composite products, resulting from 'pasting' together individual charts of the sub-basins. Wagner interprets the significant bearing error of the Adriatic Sea on the Carte Pisane in that way, suggesting that this clearly shows that a separate chart of the Adriatic was used and that therefore the Italians must have had access to pre-existing charts.[116] However, this view doesn't appear to have found wide acceptance; the early discussions on this subject all attempt to explain the varying scale by differences in the type of 'mile' used for the charting. That approach has now been abandoned.

A peculiarity that is related to these scale differences is the appearance of the scale bars on the charts. Application of a constant scale ought to be the mainstay both for the construction of the chart and its usage as a navigation tool. However, several authors have observed that scale bars tend to be drawn rather carelessly, even freehand.[117]

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[115] Western and Eastern Mediterranean, Black Sea, Aegean Sea, supplemented by charts of the Atlantic coasts.

[116] Hermann Wagner, "The Origin of the Medieval Italian Nautical Charts," in *Report on the Sixth International Geographical Congress, 1895, London*, reprinted in *Acta Cartographica* 5 (1969): 701.

[117] Kretschmer 1909, 47, 48; Nordenskiöld 1897, 21. Gaetano Ferro, *The Genoese Cartographic Tradition and Christopher Columbus*. Transl. Ann Heck and Luciano F. Farina, (Rome: Instituto Poligrafico e Zecca della Stato, Libreria della Stato, Roma, 1996), 51; Nordenskiöld 1897, 21.

The wind roses have been constructed with considerably more care and precision, and demonstrate that cartographers certainly would have had the skills to draw straight and precise scale bars. It is unclear why the scale bars display this 'carelessness'.

Pujades states that the introduction of the decimal system of numbers was crucial for the construction of portolan charts, because it enabled the cartographer to calculate a scale reduction of the measured distances.[118] However, this is a very unlikely way of drawing a map; it is far more plausible that a cartographer would start with a single scale bar and scale off the required lengths using dividers, rather than reducing all distances algebraically before plotting. This deepens the puzzle of the varying scale bars. In view of the fact that a new portolan chart was in general copied from a predecessor, it is questionable how often the process of constructing a portolan chart from raw measurement data actually took place, if it took place at all, bearing in mind Wagner's conclusion regarding the Adriatic Sea.

2.2.6 The rotation of the map image

The map image of all portolan charts has been rotated anticlockwise by about nine to ten degrees with respect to the cardinal geographic directions. Several explanations for this have been proposed. The most widely accepted view appears to be that this rotation angle, which is approximately equal to the magnetic variation in the Mediterranean in the thirteenth century, is the result of the use of uncorrected magnetic bearings for the construction of the charts. This causal relationship between rotation angle and construction method is shared by many if not most authors. In particular Crone makes short work of this problem by stating:

> "From the most cursory inspection of these early charts it is plain that the mariner's compass played a fundamental part in their construction".[119]

The surprising aspect of the anticlockwise rotation is that it remains more or less constant until about 1600[120], when corrected charts, oriented to True North, start to appear, despite significant changes in magnetic variation over that period. Although it is not contended that medieval seamen had no knowledge of magnetic variation, it is surprising that no correction was made to the charts' orientation until about 1600 if there was a feedback and adjustment mechanism in place between mariners and cartographers.

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[118] Pujades 2007, 515.

[119] Crone 1978, 12.

[120] Lanman 1987, 26; Loomer 1987, 148; Pelham, 1980, 83. All three present a table with measured skew angles. Although they use slightly different methods, the pattern that emerges is consistent.

2.2.7 CHART ACCURACY AND MAP PROJECTION

One of the fundamental questions surrounding portolan charts concerns the navigation and associated technical capabilities of the period. Did medieval sailors have the technical capabilities to make measurements, accurate enough to draw a portolan chart? The answer that they must have had, because otherwise these charts would not have been so accurate, is a circular argument too obvious to overlook. Nevertheless it is encountered in many publications, implicitly or explicitly. Taylor, for example, states:

> "Our best proof that the medieval sailor did not navigate by guesswork is afforded by the accuracy of the chart for which he had provided the material. He must have kept pretty good dead reckoning."[121]

Taylor also compared fourteen distances from the oldest portolan, the *Compasso de Navegare,* and compared them with corresponding distances, scaled off from a modern chart and, upon finding good agreement with reality, concluded: "This rules out guesswork" (i.e. in navigation).[122]

Even the most optimistic assumptions of medieval navigational accuracy cannot close the gap with the accuracy of the charts. A broad consensus exists, that averages of the distances and course bearings were developed over time and subsequently used as input for the chart making process. Some authors believe the cumulative experience of centuries to be reflected in the portolan charts[123], others believe a few decades to have been enough to arrive at satisfactory averages.[124] However, statements in literature about the

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[121] Eva G. R.Taylor, "Mathematics and the Navigator in the 13th Century." *Journal of Navigation*, Vol. 8 (1960), Issue 1, 7, 8. Crone incorrectly assumes this statement to apply to the Carte Pisane: Crone 1978, 14.

[122] See footnote 121 above.

[123] Kretschmer 1909, 59. Kretschmer claims here that the distance data in portolans, which form the basis of portolan charts in his opinion, are based on a centuries-old practice of compiling continuously improved observations. Also:
Theobald Fischer, *Sammlung mittelalterlicher Welt- und Seekarten italienischenUrsprungs und aus italienischen Bibliotheken und Archiven.* (Venice: F. Ongania 1886), 57: "Waren nun einmal solche Portolane, welche alle Kurse und Distanzen enthielten … ausgearbeitet, so war es nicht mehr schwer loxodromische Karten zu zeichnen". Both Kretschmer and Fischer believed that the uninterrupted transmission of the classical *peripli* through the Byzantines onto the Italians formed the basis of portolan charts.

[124] A. Clos-Arceduc, "L'Énigme des Portulans: Étude sur la projection et le mode de construction des cartes à rumbs du XIV^{e} et du XV^{e} siècle," *Bulletin du Comité des Travaux Historiques et Scientifiques: Section de Géographie* 69 (1956): 226. "Fifteen to twenty years of observations should provide satisfactory averages to permit accurate mapping". See also:
Heinrich Winter, "The Origin of the Sea Chart," *Imago Mundi*, Vol. 13 (1956), 39: "In respect to both direction and distance, the experience of several decades led to satisfactory adjustments". Also:
Hans-Christian Freiesleben, "The Origin of Portolan Charts," *Journal of Navigation*, Vol. 37 (1984), Issue 2, 197. According to Freiesleben, Motzo suggested the collection of the data recorded in the *Compasso de Navegare* to have required no more than fifteen years. Campbell pointed out to me that Grazioso Benincasa completed his portolan of the Adriatic, Aegean and Black Sea in 10 years, from 1435 to 1435 (Campbell, personal communication, 9/12/2012).

averaging of observations remain high-level and do not specify how such a process of averaging would have worked in the commercially and politically fragmented world of the medieval Mediterranean.

A related and unresolved subject of debate is whether the timing of the introduction of the mariner's compass allowed this new instrument to play a role in the construction of the charts. Wagner and Nordenskiöld (followed by Pelham) felt it was introduced too late and deny therefore that it played a role. In particular Nordenskiöld and Pelham concluded that the compass was evidently not required for drawing an accurate chart of the Mediterranean.

A subject that has not nearly received the amount of attention it deserves is the question why the map image on these charts fits so closely to a modern map on a map projection.[125] It is true that much effort has been spent in determining to which map projection the charts fit best, but the question how this is possible is rarely asked and even more rarely investigated in-depth. Loomer devotes his entire dissertation to an extensive cartometric analysis of a large number of charts against a significant number of different map projections and discovers a very close fit of the map image to some projections[126], but he never even asks the question how this is possible; nor does any other researcher. One has to learn from Campbell that the majority of portolan chart researchers assumes that any close fit of the map image to a map projection is an artefact, an unintentional by-product of the cartometric analysis method, and therefore non-existent in the real charts.[127] However, any map projection introduces highly systematic distortions that cannot a priori be assumed to be consistent with the assumed construction technique of portolan charts, known as plane charting. The question how the plane charting assumption can be reconciled with such systematic distortions is a very legitimate one and deserves more careful attention than to be brushed aside with this simple explanation, however broad the consensus on the matter may be.

2.2.8 Stimulus for chart development

In addition to the sudden appearance of portolan charts and the absence of any predecessors, it is unclear what provided the stimulus for the development of the portolan

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[125] This subject is addressed in Chapter 7: *Cartometric analysis of five charts*. The degree of fit of the map image to any map projection is expressed by the Root Mean Squared Error of the point positions used in the cartometric analysis, which equals approximately 11 km, or 2 mm in the actual charts. I consider that a very good fit.

[126] Loomer 1987, 148, 149. Loomer calculates figures comparable in magnitude to my figures.

[127] Campbell 1987, 385. Campbell comments here on the suggestion that portolan charts were intentionally drawn to a map projection: "majority opinion has rejected that view, considering instead that portolan charts are projectionless or that any map projection is accidental". The term *artefact* is used in this thesis in the sense of "something observed in a scientific investigation that is not naturally present but occurs as a result of the investigative procedure." See *Concise Oxford English Dictionary*, 11th ed., ed. Catherine Soanes and Angus Stevenson (Oxford: Oxford University Press, 2008).

chart. Many researchers, most recently Pujades, claim that portolan charts arose as a response to a *need*:

> "Seamen had been long awaiting this development and they received it with enthusiasm."[128]

and:

> "Once the first prototypes of the future portolan charts had been made, the seafaring world received them with open arms, since they satisfied what for some considerable time had been an imperious need."[129]

Apart from the obvious use of a poet's licence, it is very much the question whether these statements are true. What exactly constituted this "imperious need" to which portolan charts provided such a much desired response? Numerous authors, both past and present, have pointed out that navigation in the Mediterranean is not a particularly onerous process. Pujades himself cites the historian J. G. Vernet, who stated that:

> "Navigation in the Mediterranean was invariably facilitated by the special configuration of its hydrographic basin, which allows seamen to perceive from a great distance a series of very high coastal mountain ranges which reduced sailing beyond sight of land to a few days only".[130]

The relatively easy nature of Mediterranean navigation in the Middle Ages was reinforced by the trade routes along the northern coast, with frequent stopovers on the islands and staging posts. For example the Venetian trunk route to Constantinople ran along Pula, Ragusa (Dubrovnik), Levkas, Corfu, Modon or Coron, Monemvasia and Negroponte (Khalkis).[131]

> " … Vincenzo Coronelli states in his *Specchio del Mare* (1698) that since in the Mediterranean land is never long out of sight, calculation of latitude is unnecessary and experience has shown the best guide was the old rhumb-line chart. … Antonio Millo, an experienced seaman and author of an *Arte del Navegar*, roundly asserts that that in the late sixteenth century Mediterranean mariners continued to sail without either astrolabes or cross-staffs or any other kind of instrument except for the simple chart (with dividers) and the magnetic compass."[132]

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[128] Pujades 2007, 457.

[129] Pujades 2007, 521.

[130] Pujades 2007, 456.

[131] See Section 4.3.4.

[132] Pujades 2007, 458.

Pedro Nuñes (1537), Martin Cortez (1551) and Alonso de Santa Cruz (1555) likewise asserted that astronomic navigation was not used in the Mediterranean. From the fifteenth century onward the lead in navigation was taken over by the Portuguese, followed by the English, while the Dutch set a new standard in hydrographic surveying by using the Mercator projection. Seamen and cartographers in the Mediterranean never applied any innovations to their methods with the result that, by the seventeenth century, Mediterranean navigation and cartography had become distinctly backward, which, according to Texeira de Mota, inspired the cartographer Diogo Homem to leave Portugal to go to Venice.[133]

If the Mediterranean seamen saw no need to develop their methods further and medieval navigation in the Mediterranean was to a large extent visual in character, what then is the *need* that is claimed to have driven the initial development of the portolan chart?[134]

The process of constructing an accurate chart of the Mediterranean from raw measurement data is far more complex and time-consuming than is suggested in most map-historical studies. Many authors see the appearance of these charts as a natural and not particularly difficult progression from the compilation of bearing and distance information in portolans. Theobald Fischer states:

> "Once these portolans, containing all courses and distances, had been compiled, it wasn't difficult anymore to draw loxodromic charts".[135]

Pujades, however, does appear to be aware of the considerably greater complexity of mapmaking when he writes:

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[133] Avelino Texeira de Mota, "L'art de naviguer en Méditerranée du XIIIe au XVIIe siècle et la creation de la navigation astronomique dans les océans", in *Le Navire et l'économie maritime du Moyen Age au XVIIIe siècle principalement en Méditerranée: Travaux du IIème Colloque Internationale d'Histoire Maritime*, ed. Michel Mollat (Paris: SEVPEN, 1958).

[134] Pujades 2007, 459. Pujades underlines the importance of portolan charts for navigation by quoting Francesco di Marco Datini's agent at Majorca, who, upon finding that there was only one cartographer left on the island, wrote to his master "if this one dies we shall no longer be able to sail". However, in the first place this was well into the second half of the fourteenth century, by which time usage of portolan charts was probably well established. It doesn't contradict that the initial expense of the development of the portolan chart would have had to be justified by its projected gains. Secondly, one might turn the argument around and ask why, if these charts were absolutely indispensable for navigation, only a single cartographer remained active on Majorca, one of the two cartographic centres of portolan chart production. Related to this is the story of the Genoese cartographer Agostino da Noli, who, in 1438, asked the Genoese authorities for lifelong exemption from taxes and assessments on food and clothing as he could barely scrape a living out of making charts. Playing the devil's advocate, both facts might be interpreted as indicating there wasn't much of a market for portolan charts! See also Ferro 1996, 79.

[135] Fischer 1886, 75; See Footnote 123. See also:
Stevenson, 15: "But the quickened commercial activities, coupled with the discovery and use of the compass, were calculated to lead to a speedy substitution of the chart for the portolan".

> "Drawing a scale map of the entire Mediterranean implies an exercise in abstraction vastly more complicated than the act of drawing a small sketch of a sector of coast entirely visible from the deck of a ship".[136]

To the said complexities may be added the task of reconciling conflicting information and obtaining new information for gaps or areas where the available information had to be rejected. Conflicting pieces of information can coexist without any problem in a portolan, but any map image constructed from such data must have all inconsistencies, gaps and data conflicts resolved. That would have been a formidable task. Moreover, Kelley estimates that the amount of course information on a fourteenth or fifteenth century portolan chart is some twenty times greater than that contained in the most extensive surviving portolan.[137]

Hydrographic surveying of coastlines is an entirely different activity than navigating during a trading journey. The objectives are different and the techniques are different. Navigation is the process of steering a ship, aircraft or other vehicle from one place to another in the safest and most efficient manner. Hydrographic surveying aims to collect all necessary information to permit the drawing of a chart to a specified accuracy, as determined by the chart scale. Navigation may be done by visual recognition of coastal features; hydrographic surveying requires measurement of the spatial relationships of those features. Hydrographic surveying requires the position of the ship to be known continuously during its survey, if the measurement process takes place from the ship, whereas in navigation this continuity is not required, or formulated differently: in navigation the position of the ship is often only required relative to known navigational hazards and/or to landmarks. The (implied) assumption that medieval sailors conducted a complete hydrographic survey of the entire Mediterranean and Black Sea as an unintentional by-product of their trading activities is unique and exceptional; unique because there is no other example of this happening (if it happened at all) and exceptional because all other maps and charts of comparable extent and accuracy are the fruits of long and hard labour. Dedicated hydrographic departments and geodetic survey departments have toiled to create the body of maps and charts we now take for granted. Why would this be different for the Mediterranean portolan chart?

Whereas the introduction of the magnetic compass resulted in the sea to be considered open for shipping during the winter months, enabling those Italian cities trading on the Levant and Byzantium to make two round trips per year instead of one[138], the introduction of portolan charts did not inspire any change in navigational practices as far as we

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[136] Pujades 2007, 511.

[137] James E. Kelly, Jr. 1995, 10.

[138] Frederic C. Lane, "The Economic Meaning of the Compass", *American Historical Review* 68 (1963), No. 3: 608.

know.[139] It is therefore legitimate to ask what problem the portolan charts were solving. Many authors state that portolan charts arose in response to a *need*, but it is far from clear whether there was a need at all. Only a clearly perceived need could have provided the economic stimulus to develop the first portolan chart.

In summary, the development of portolan charts from navigation measurement data captured in portolans would have been a technically challenging and costly undertaking. In the absence of a clear economic stimulus, provided by an underlying need, this is an unlikely process. However, portolan charts are part of reality and a rational explanation will have to be found for this conundrum.

2.2.9 Conservatism

Another relevant issue is the often described conservatism among mariners, expressing itself through resistance at the introduction of anything new. Thus Taylor writes:

> "…the average English sailor laughed at the idea of navigating with charts and instruments. He had his compass, he knew his landmarks, and once he was in soundings he could cast the lead and feel his way into harbour blindfold."[140]

William Bourne, in his *Regiment of the Sea (1587)* describes this as follows:

> "And who doubteth but a simple Fisher-man of Barking knoweth Barking Creeke, better than the best Nauigator or Master in this Lande: so who doubteth but these simple men doth know their owne places at home. But if they should come out of the Ocean sea to seek our chanel to come vnto ye riuer of Thames, I am of that opinion, that a number of them, doth but grope as a blinde man doth, & if that they doe hit wel, that is but by chaunce, and not by any cunning that is in him.
> But I doe hope that in these dayes, that the knowledge of the Masters of shippes is very well mended, for I haue knowen within this .20. yeeres that them that were auncient masters of ships hath derided and mocked thē that haue occupied their Cards and Plats, and also the obseruatiō of the altitude of the Pole, saying that they care not for their Sheepes skins, for hee could keepe a better account upon a boord.
> And when that they did take the latitude, they would cal them starre shooters and Sunne shooters, and would aske if they had striken it. Wherefore now iudge of their skilles, considering that these two poyntes is the principal matters in Nauigation. And yet these simple people will make no small brags of themselues,

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[139] A new perspective on this will be discussed in Section 12.2.

[140] Eva G. R. Taylor, "The Dawn of Modern Navigation," *Journal of Navigation*, Vol. 1 (1948), Issue 4: 283.

> saying: that he hath ben Master this .20. yeeres, and neuer had no misfortune, and also if that they could heare of any that did vse Plats and Instruments that had any misfortune, then they woulde not a little bragge of themselues what notable fellows they themselues were."[141]

Bourne thus complains about seamen who, clinging to their old ways on grounds of their proven skills, derided the use of instruments on board such as the cross-staff and stated they didn't care for charts ("sheepskins") as they could navigate better by the traverse board[142] alone.

Richard Norwood complains about the same conservatism after the introduction of the English log by William Bourne fifty years earlier, described by Taylor as follows:

> "As to the log line, Richard Norwood, when discussing it in his Seaman's Practice in 1637 declared that many sailors were either so cocksure of their judgment that they disdained to use it, or were shamed out of doing so because they feared to proclaim themselves 'young seamen', that is to say inexperienced pilots." [143]

Also in their stubborn use of the plane chart the conservatism of seamen was evident. Gerard Mercator published his famous chart, in the projection that bears his name, in 1569, but it would take half a century or more for the new projection to be truly accepted and routinely used.[144] 'Mercator sailing' required that pilots would correct their estimates of distance sailed, either by multiplying the figures by the secant of the average ship's latitude during the run or by scaling these distances from a scale bar that showed a latitude-varying scale, and many of them didn't understand why they should 'corrupt' their day's sailing by this adjustment.

Taylor describes this eloquently with the following words:

> "The principal trouble was that sailors stuck to plain sailing by the so-called plain chart with an obstinacy at which, from these very titles, we can hardly be surprised. This led to positioning errors which these sailors … put down to sea currents, to adverse fortune or to destiny, for astrology was more to the seaman's

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[141] Citation from William Bourne's *The Regiment of the Sea* (1587) by William E. May, *A History of Marine Navigation* (New York: W.W. Norton & Co, 1973), 15, 16.

[142] The traverse board was an early tool to record the progress the ship made during half-hour intervals. At the end of the four-hour watch, course and speed thus recorded on the traverse board were consolidated and the board would be cleared, ready for the next watch. Its earliest proven use is from the sixteenth century and its existence in the thirteenth century Mediterranean is not proven.

[143] Eva G. R. Taylor, "Five Centuries of Dead Reckoning." *Journal of Navigation*, Vol. 3 (1950), Issue 3: 283. Norwood's own words are: 'Some have thought that the way which the ship maketh, may be known to an old Sea-man by experience (as they say) that is by conjecture; which opinion makes some neglect the use of the *Log*, lest they should be accounted Young Sea-men'.

[144] May 1973, 19, 184.

> taste than astronomy. A special Seaman's Astrology was, in fact, published, and was listed among recommended manuals and tutors."[145]

More interesting even is the attitude of the British Admiralty towards the newly, i.e. in 1795, established Hydrographic Service. After the end of the Anglo-French war in 1815 the Hydrographic Service was seen as a useful vehicle to retain the many now redundant naval officers as a reserve, should another war break out. The inherent usefulness of having accurate nautical charts appears to have been a minor consideration. Any vessel of no value for anything else would do for a survey ship and in 1854 Sir Charles Napier, commander of the British fleet in the Baltic during the Russian War, greeted the captain of the survey ship *Lightning* with the words: "I do not know what you have come out for, for what is the use of a surveying ship, unless to make a fire vessel of."[146]

Any changes in a repetitive activity requiring personal skill, which is brought about by the introduction of methods that measure the success of that activity objectively, will generally meet with resistance, because the skills and experience that were previously believed to be the inalienable personal qualities of those persons engaged in that activity, are suddenly stripped of their exclusiveness and personal nature. I have experienced this myself when I introduced statistical methods in the evaluation of navigation data in offshore positioning activities. The resistance comes from people who feel that they will lose out as a result of the change because their exclusive expertise is no longer needed and they will have to learn new skills in order to retain or re-acquire their old position.

Although the examples quoted are mostly from British maritime history, there is nothing specifically British or English about this process, nor is it something that is confined to a specific period in history. Human nature is the underlying driver of resistance to change and there is no reason to believe that medieval Mediterranean pilots and navigators were exempt from this trait of character.

In order to explain the extremely rapid development of portolan charts, the medieval origin hypothesis requires us to imagine highly innovative medieval sailors who applied a new instrument, the compass, and new navigation methods with surprising speed and on a very large scale. It further requires us to imagine chart makers from the same milieu who developed, in an incredibly short time frame, a new innovative genre of map. After this initial burst of innovative energy, navigational and cartographic processes abruptly stagnated and no more innovations were seen for centuries. This simply does not gel.

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[145] Taylor 1948, *Dawn of …* , 287. The titles to which Taylor refers are: *Certaine errors in navigation* by Edward Wright and the said *Seaman's Astrology.*

[146] May 1973, 191, 192.
G.S. Richie, *The Admiralty Chart. British Naval Hydrography in the Nineteenth Century*, (Durham: The Pentland Press, 1995), 298.

None of the arguments and questions in this chapter carries the weight of scientific proof, nor is it intended to. The intention is to demonstrate that the prevailing explanation of the sudden appearance of portolan charts in the history of cartography as a natural expression of cultural continuity contains enough internal contradictions and lacunae to warrant a thorough examination.

3 EXISTING HYPOTHESES ON THE ORIGIN AND CONSTRUCTION METHOD OF PORTOLAN CHARTS

3.1 SCHOLARLY VIEWS ON THE ORIGINS DEBATE

The question of the origin of portolan charts is inseparable from the question of how they were constructed. A large number of hypotheses have been formulated over the last one and a half centuries, most of them focussing on the question who made the first portolan chart and where. There are fewer hypotheses that describe how the charts might have been constructed, with even less variety in proposed construction methods.

This chapter provides an overview of most existing hypotheses, broadly grouped according to the proposed time of origin of the charts. That has resulted in two sections: 3.2 *Ideas on antique origins* and 3.3 *Hypotheses on medieval origins*. In a third section, 3.4 *Hypotheses on portolan chart construction* the aspects related to the construction of the charts are explored. The emphasis in Section 3.4 is on construction methods related to the medieval origin hypothesis. That doesn't imply antique origin hypotheses lack proposals on chart construction, although often they do, but the scope limitation of this study, explained in the *Introduction*, does not permit a detailed discussion of construction options relevant for antiquity.

One of my main objections against all hypotheses that attempt to explain the appearance and construction of portolan charts concerns the implicit supposition that the making of an accurate chart of such a large area is not a particularly onerous task. This begins with optimistic assumptions regarding the accuracy of measurements of course bearing and distance, continues by glossing over issues of data editing and outlier detection in the raw data and ends with ignoring the resolution of mismatches and data conflicts in the two-dimensional map plane, when all observation material is converted to a plane image of the coastlines. Not a single hypothesis attempts seriously to estimate the measurement accuracy that would be required to produce a map of the accuracy of a portolan chart. I will address these issues in greater detail in Chapter 9: *The map projection; artificial or intentional?*

As several authors have pointed out, the published hypotheses share the characteristic that they *all* lack supporting evidence. The whole issue of portolan charts origins has proven to be a very hard nut to crack. Tony Campbell's diplomatic summary and characterisation of these hypotheses as "creation myths" has already been mentioned in the introductory chapter. Ramon Pujades is considerably more direct and describes the origins debate as follows:

"… the issue of the origins of medieval nautical cartography, [is] a highly controversial theme in which the absence of solid grounding forces intellectual speculation to rise above desirable levels."[147]

> "Often examined only from the geographical perspective and on the fringe of any kind of historical contextualisation an extremely wide variety of opinions – often more dogmatic than scientific – have been expressed regarding the time and place of their birth …."[148]

Patrick Gautier Dalché is hardly more flattering:

> "The question of the origins of these charts has given rise to a torrent of theories, of which the essential characteristic is that none of them has a solid foundation".[149]

He illustrates his own reluctance to contribute to the origins debate with the words:

> "Concerned of not adding another conjecture to the graveyard of hypotheses that characterises the question of the origin of these nautical charts, I shall refrain from going down this thorny path."[150]

Rather than judging this phenomenon exclusively as a culpable methodological shortcoming, it is perhaps better viewed as a series of attempts to break the stalemate of the research into portolan chart origins. Regrettably some explanations have been put forward with a certainty that belies the total absence of supporting evidence, which is unfortunate, as it has created the impression outside the small circle of scholars who are aware of the uncertainties, that the origin problem of portolan charts has long been solved.[151]

In order to appreciate the findings of this study, it is necessary to be able to relate them

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[147] Pujades 2007, 413.

[148] Pujades 2007, 506.

[149] Gautier Dalché 1995, 28. Translation is mine.

[150] Gautier Dalché 1995, 16. "Soucieux de ne pas ajouter une conjecture supplémentaire au cimetière d'hypothèses qui characterise la question de l'origine des ces cartes marines, nous nous garderons de poursuivre sur cette voie mal frayée." Translation is mine.

[151] Crosby describes portolan charts as "… geometrically naive flat pictures of the curved surface of the earth …"; Alfred W. Crosby, *The measure of Reality. Quantification and Western Society, 1250 -1600* (Cambridge: Cambridge University Press, 1st paperback ed, 1998), 97. This is not a book on cartographic history, but on an aspect of the history of science. No publication on portolan charts by Crosby is known and I presume he therefore never conducted such research. He merely quotes the existing (near-) consensus on portolan charts in map-historical circles.

to the context of the established explanations and a summary of those is therefore required. The burden of evidence of any hypothesis lies first and foremost with the scholar who proposes the hypothesis; it is not the responsibility of others to supply evidence to *disprove* such a hypothesis. Nevertheless, although the general lack of evidence often makes it impossible to enter into an in-depth discussion of these proposals, I will attempt to dispel two persistent misconceptions of a technical nature, to the extent that I consider them to hamper a proper understanding of some of the characteristics of portolan charts.

Tony Campbell has provided an excellent summary using neutral, descriptive wording.[152] Although published in 1987, this summary is still correct and largely complete. The most significant new developments regarding chart origins have been made by Patrick Gautier Dalché[153] and Ramon Pujades[154]. The only new (or perhaps: revivified) hypothesis that has been added to the long list of existing ones is that of Fuat Sezgin, who advocates an Arabic-Islamic origin.

It is rather unusual in many other branches of scholarly research that are not primarily historiographical, to cite sources that go back to the nineteenth century. However, the fact that no decisive progress has been made in identifying the origins and construction method of portolan charts since the middle of the nineteenth century, makes references to such early sources inevitable and relevant.[155] Nevertheless, where possible, I will refer to more recent studies, as those ought to reflect the assimilation and synthesis of previous work done.

The nearly unanimously supported hypothesis on the origin of these medieval nautical charts is the (European) medieval origin hypothesis, which is the main topic of this study and of which the outline has been provided in the *Introduction*.

3.2 IDEAS ON ANTIQUE ORIGINS

3.2.1 NEOLITHIC ORIGINS

The hypothesis that attempts to place chart origins furthest back in time – and which is also the most far-fetched one in terms of plausibility – is that of Charles Hapgood[156], who believed portolan charts to be the products of an unknown advanced civilisation, which was destroyed at the end of the last Ice Age around 10,000 BC. He underpins

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[152] Campbell 1987, 380-384.

[153] Gautier Dalché 1995.

[154] Pujades 2007.

[155] A significant number of studies have been published in the native language of their authors. Much as I regret it, a number of those studies are therefore inaccessible to me.

[156] Charles Hapgood, *Maps of the Ancient Sea Kings. Evidence of Advanced Civilization in the Ice Age,* reprint of 1966 edition (Kempton, Illinois: Adventures Unlimited Press, 1996).

his views with as little hard evidence as any of the other writers who proposed hypotheses on chart origins, but, contrary to what most scholars believe, assumes but does not prove that medieval sailors and cartographers did not have the capability to construct such accurate charts. Fundamental problems with Hapgood's hypothesis are the facts that sea levels were much lower at the proposed time of origin, which is not reflected in the charts, and that the Black Sea was a much smaller inland sea, unconnected with the Mediterranean Sea until about 5,500 BC. Furthermore the maps would have had to bridge an enormous time gap of more than 11,000 years. His hypothesis has therefore hardly found any support. Despite these objections, Hapgood's claim that the accuracy of the charts is too high for a medieval origin is quite realistic and deserves to be taken seriously.

3.2.2 Egyptians, Phoenicians and Marinus of Tyre

The next hypothesis in the chronology of proposed origins is that of Armando Cortesão, who proposed that the development of portolan charts proceeded intermittently from antiquity, starting with the Egyptians and Phoenicians, to be transmitted from there via Marinus of Tyre and Ptolemy to the Arabs and then onwards to the Christian West via al-Idrisi.[157] He cites a statement by the tenth century Arab geographer al-Masudi, who claimed to have seen Marinus of Tyre's map and claimed it to be far superior to Ptolemy's.[158]

The name Marinus of Tyre is often mentioned in connection with an antique origin and some authors speak consistently of Marinus's *chart* or *charts*. [159] However, the nature of Marinus's cartographic product cannot be established with certainty and the tendentious usage of the word *chart* in any English translation cannot therefore be justified. Ptolemy admits that that the body of geographic data on which he based his *Geography* was essentially Marinus's compilation, be it that he, Ptolemy, corrected and supplemented Marinus's work.[160] Lloyd Brown considers the qualification *chart* purely a choice of translators and denies that Marinus's work can be considered as a nautical chart; also Kretschmer disagrees with an interpretation of Marinus's work as a chart.[161] There are no known references in ancient literature

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[157] Cortesão 1969 Vol 1, 223 footnote 218, 229 and 232.

[158] Cortesão 1969, Vol 1, 224. A pertinent question is also according to which criteria al-Masudi called Marinus's map "the best of its kind".

[159] e.g. Konrad Peters, "Zur Diskussion über die Herkunft und Entstehung der Portolankarten*", Der Vermessungsingenieur*, Vol. 5 (1985). Peters suggests Marinus's sea chart, passed on through Islamic culture, formed the basis of the proto-portolan chart. As an alternative option he sees a possible role for "Agrippa's nautical charts" reaching the West via Byzantium and the Venetians. Also Peters insists on seeing Marinus's work as a nautical chart, rather than as a world map. Also Nordenskiöld speaks of Marinus's *chart*.

[160] J. Lennard Berggren and Alexander Jones, *Ptolemy's* Geography. *An Annotated Translation of the Theoretical Chapters* (Princeton: Princeton University Press, 2000), 63 and 64.

[161] Lloyd A. Brown, *The Story of Maps* (New York: Dover Publications, 1979), 120 and Kretschmer 1909, 51.

that point unambiguously to the existence of nautical charts in antiquity and none are extant. If they did exist we have therefore no idea of their cartographic form or map content. Although it seems unlikely that Marinus's was a nautical chart, the possibility cannot be entirely excluded and it seems therefore prudent to avoid tendentious translations.

Berggren and Jones even doubt that al-Masudi saw a 'book of *Geographia'* of Marinus's and believe it ”more likely to have been a reconstruction of Ptolemy's text rather than an original work of Marinus”.[162] Any connection with portolan charts is very unlikely, but the fact that we have no idea what his map (or maps) looked like and only know of Marinus's work through Ptolemy's comments tempts some writers to place the origin of portolan charts in this blank space in the history of cartography.

Also Nordenskiöld mentions al-Masudi and claims, without providing any proof or justification, that Marinus's "charts were … of essentially the same stamp as those mediaeval charts known under the name of portolanos"[163], thereby implying that they were forerunners of the portolan chart.

3.2.3 Roman centuriation

Georges Grosjean rejects the possibility that portolan charts could be constructed from compass observations and distance estimates by medieval seamen, arguing that the accuracy of the charts could never be achieved with such observations, but he doesn't attempt to quantify this. He considers a terrestrial basis of these charts far more likely and advocates a Roman origin.[164] Together with co-author Rudolf Kinauer, he associates the creation of the charts with an extension of Roman *centuriation* and with other Roman maps.[165] Grosjean had to assume that any Roman toponyms had been replaced completely by medieval toponyms.[166] However, it has been pointed out that evidence of centuriation has only been found covering a very small part of the former Roman Empire.[167]

This has not deterred Helmut Minow, who strongly advocates a Greco-Roman origin in several articles. In his earlier articles he linked portolan charts to an extension of Ro-

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[162] Berggren and Jones 2000, 23 footnote 24.

[163] Nordenskiöld 1897, 3.

[164] Georges Grosjean ed., *Mapamundi: der katalanische Weltatlas vom Jahre 1375,* (Dietikon-Zürich: Urs Graf, 1977), 17, 18.

[165] Georges Grosjean and Rudolf Kinauer, *Kartenkunst und Kartentechnik vom Altertum bis zum Barock* (Bern: Hallweg, 1970), 29, 33.

[166] Grosjean 1977, 19. Grosjean can only relate two portolan chart toponyms with possible Roman origins, viz. *Minerba*, for *Promontorium Minervae* (the promontory opposite the island of Capri) and *Baya* (west of Naples) for the antique bathing resort *Baiae*.

[167] Campbell 1987, 381.

man centuriation[168], but in a more recent article[169] he proposes that astronomically determined coordinates of a large number of Roman lighthouses formed a kind of skeleton for an extensive geodetic network that would have formed the framework of these charts. Minow claims that an extensive geodetic survey must have been carried out between 300 BC and 100 BC (in his more recent article he mentions the first century BC) and postulates that the entire survey and its results were a (well-kept) military secret, in order to explain why no evidence of such a survey, or the resulting map, are mentioned in any documents from antiquity. Minow's proposals appear to lack realism, both in the assumption of a framework of accurately positioned Roman lighthouses and in the presumed secrecy of the hypothesised undertaking.

3.2.4 UNSPECIFIED ANTIQUITY

Richard Uhden does not attempt to be more specific in his views of portolan chart origins other than that he was absolutely convinced that portolan charts have their origin in antiquity.[170] He admitted that no sea charts from antiquity are extant, "but they must have existed", referring to a remark in Strabo's *Geography*, on the basis of which he associates the term *periplus* (pl. *periploi*) with a nautical chart as well as with a written sailing guide. Periploi served an equivalent function in antiquity as portolans did in medieval times, but periploi lacked detailed course bearing information. Uhden feels that already in early Hellenic times all conditions existed that might have led to the development of portolan charts; the compass was not required to create them. He attributes the high accuracy of portolan charts to "centuries-long experience". Only diligent study of ancient sources can reveal the true origin of the charts in Uhden's view. His article *Die antiken Grundlagen der mittelalterlichen Seekarten* is an erudite polemic well worth reading, but it contains no concrete evidence whatsoever. It appears to have convinced very few people.[171]

Most of the scholars who have attempted to place the origin of portolan charts in antiquity appear to have done so for negative reasons and not because the charts contain any positive indications of an antique origin. Mostly they see a medieval origin as incompatible with the high accuracy of the charts, to which has to be added the doubt expressed by some whether the introduction of the compass happened early enough to have played a role in their (medieval) creation.[172]

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[168] Helmut Minow, "Rätsel der mittelalterlichen Seekarten", *Deutsches Schiffahrtsarchiv*, 21.1998, 411-428, (Hamburg: Carlsen Verlag GmbH/Die Hanse, 1998) and:
Helmut Minow, "Sind die frühen Portolankarten das Ergebnis großräumiger Vermessungen?" *2. Kartographiehistorisches Colloquium* (1984).

[169] Helmut Minow, "Portolankarten" (2 parts), *Geomatik Schweiz*, 6 (2004), 372-377 and 7 (2004).

[170] Richard Uhden, "Die antiken Grundlagen der mittelalterlichen Seekarten", *Imago Mundi* Vol. 1 (1935).

[171] See for example Gautier Dalché 1995, 42, 43.

[172] Jumping back to antiquity appears to offer no solace per se to those who feel the compass was introduced too late in the Middle Ages, as this instrument was, to our best knowledge, entirely unknown

Hermann Wagner, the nineteenth century German geographer, is the only one who underpins his ideas of an antique origin of portolan charts with somewhat more substantial arguments. He is one of those scholars who believed that the introduction of the compass, in a form suitable for position-fixing[173] of geographic features, came too late to influence the development of portolan charts. Using numerical analysis methods, Wagner concluded that portolan charts are composites, consisting of accurate charts of the smaller, individual Mediterranean sub-basins, each with a slightly different scale and orientation. He also found, contrary to claims of his older colleague Arthur Breusing, that the meridians of any given sub-basin, implicit in the map image, do not converge but are parallel, which Wagner considered as proof that the magnetic compass could not have played a primary role in the construction of the charts, as spatial variation in the magnetic declination would have prevented the (hidden) meridians on the chart from being parallel.[174] He believed he had found further support for this conclusion by his incorrect reasoning that a westerly magnetic variation existed in the Mediterranean in the twelfth, thirteenth and fourteenth centuries. This would have resulted in a clockwise rotation, rather than the anticlockwise skew shown by the portolan charts, which is consistent with an easterly variation. He therefore concluded that the medieval Italians must have had access to pre-existing accurate charts of Mediterranean sub-basins from antiquity. He doesn't elaborate on this and merely refers to antiquity in general as the time of origin and, as the magnetic compass did not yet exist in antiquity, allocates only a secondary role to the magnetic compass as a tool to establish the orientations of those individual charts into a composite chart of the whole Mediterranean, a process which he does place in medieval times.[175] Unfortunately he provides no hint on how he believed these charts to have been constructed. Wagner excludes the charting of the Atlantic coastline from this hypothesis, but does not elaborate on that either.[176]

3.2.5 Ramon Pujades's views

Finally I summarise the views of a very recent author, Ramon Pujades, who rejects a possibly antique origin without reservation, putting forward a number of arguments to support his view. He points out that Greek and Roman world cartography, speculative as it was, was an occupation for a small intellectual elite. He quotes Pietro Janni[177] as

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in antiquity.

[173] The crucial innovation to the compass that in principle would have enabled position fixing was the attachment of the compass card to the needle. This is repeatedly stressed by many authors. However, Heinrich Winter held that this innovation was not required: he felt that a handheld bowl, filled with water and a magnetised needle, stuck through a straw, would have adequately controlled the effects of the ship's motion. See Heinrich Winter, "The True Position of Hermann Wagner in the Controversy of the Compass Chart", *Imago Mundi*, Vol. 5 (1948): 22.

[174] Wagner 1896 (1969), 696, 697; Wagner 1895 (1982), 20, 27, 28.

[175] Wagner 1895 (1982), 31, 32. The anticlockwise rotation of the map image is inconsistent with Wagner's belief in a westerly magnetic variation in the thirteenth century, referred to in the previous sentence. Unfortunately he glosses over this contradiction!

[176] Wagner 1895 (1982).

[177] Pietro Janni is professor emeritus in Greek Literature at the University of Macerata, Italy.

having said that "the Ancients were mistrustful of maps, preferring the written word over a drawn map" and that they favoured what Janni calls a hodological view of space, i.e. expressing spatial relationships in terms of travel times, rather than in terms of metric quantities. Pujades points to Roman itineraries in support of this view and emphasizes that no nautical equivalent can be deduced from those. This brings his story to periploi. He argues that "periploi and itineraries lack scale and orientation and are therefore unlikely parents for portolan charts" and stresses the contrast between periploi and the erudite Greek cartography of Ptolemy. If portolan charts did originate from Greek cartographic efforts, "the parentage would thus have to be a strange combination of erudite Greek world cartography and practical nautical knowledge, for which no evidence at all exists".[178]

Pujades also rejects the hypothesis of some writers that portolan charts would be a medieval cartographic rendering of classical periploi for the following three reasons: the length unit in antiquity was different, the toponymy was completely different and periploi lack all but the crudest directional information.
He finally concludes that "it is impossible to defend the hypothesis that Western nautical cartography of the lower Middle Ages directly inherited the Greek legacy when in Greek-speaking areas not a single trace of it survived until the period of transition to the modern period".[179]

3.3 HYPOTHESES ON MEDIEVAL ORIGINS

If it were possible to establish the 'true' origin hypothesis by the democratic process of majority voting, the medieval origin hypothesis would win by near-unanimous consent. However, in spite of the broad consensus, there are considerable differences in the ways in which the hypotheses are filled in with details regarding the construction method and place of origin of these charts. Also the contradictory information in the charts, described in the second part of the previous chapter, is explained in different ways, but often these contradictions are not mentioned at all.

3.3.1 RELATIONSHIP WITH PORTOLANS; BYZANTIUM

Most scholars who favour a medieval origin assume a relationship between charts and portolans. Although some do not specify what that relationship might entail, it is an inevitable consequence of the hypothesis, that the portolans were compiled first and the charts were constructed using the thus organised data. No scholar has ever attempted to make a case for the reverse relationship, as was described in Section 2.2.3. To my knowledge Patrick Gautier Dalché, James E. Kelley Jr. and Evelyn Edson are the only scholars who explicitly keep all options open regarding the relationship between portolans and

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[178] Pujades 2007, 507.

[179] Pujades 2007, 508.

charts.[180] Some authors, inspired by the degree of perfection of the charts, assume that "centuries-long experience" is reflected in the portolans. Fischer, Kretschmer, Stevenson, Taylor[181] and others assumed an uninterrupted transmission of the periploi of antiquity through Byzantium into the medieval portolans (see Pujades's comments above), but, whereas Kretschmer believed charts were not created from them before the end of the thirteenth century[182], Fischer postulated that the art of making such charts must have been practised for a long time, thereby placing their origins in the Byzantine Empire.[183] Also Fiorini allegedly held that the Italian navigators learned from the Greeks of Constantinople how to make these charts, not long after 1000 AD.[184] This, however, is all learned speculation, as there is no evidence that points to Byzantium as the place of birth of portolans and portolan charts. Gautier Dalché points out that "… the only Byzantine portolans known derive manifestly from the Italian ones".[185] Dilke states that before Maximus Planudes started his search for a copy of Ptolemy's *Geography*, there had probably been a continuing decline in mapmaking skills in Byzantium. He adds that the renewed interest in classical Greek culture in the ninth century had not resulted in any traceable interest in mapmaking. Byzantine writers of extant geographical texts "exhibit scant interest in compiling maps".[186] Dijksterhuis, speaking of the Byzantine attitude to science in general, states: "It may be an exaggeration to charge them [the Byzantines] with absolute sterility, but they did not succeed in bringing about any appreciable progress in the field of philosophy or science during the centuries separating the end of the Greek culture from the conquest of the capital by the crusaders in 1204".[187] The question how scientific the portolan charts are has not yet been answered, but an origin of portolan charts in Byzantine culture appears highly unlikely.

3.3.2 THE HOLY ROMAN EMPEROR FREDERICK II OF HOHENSTAUFEN

A fairly realistic but speculative hypothesis is Hans-Christian Freiesleben's suggestion that Frederick II of Hohenstaufen, who took a keen interest in the study of nature, might have inspired the development of the charts in support of his naval interests.[188] He is known to have visited Pisa around 1225, where he met Leonardo of Pisa (Fibonacci), who might have played an important role as scientific adviser of the presumed undertaking. However, the coverage area of the portolan charts goes well beyond the area of naval interest of Frederick II. Freiesleben adheres to the majority view that course

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[180] Gautier Dalché 1995, 77; Kelley 1995,10; Edson 2007, 40.

[181] Eva G. R. Taylor, "The Sailor in the Middle Ages", *Journal of Navigation*, Vol. 1 (1948), Issue 3, 192.

[182] Kretschmer 1909, 31.

[183] Fischer 1886, 71.

[184] Stevenson 1911, 3.

[185] Gautier Dalché 1995, 43.

[186] Oswald A.W. Dilke, with J.B. Harley and David Woodward, "Cartography in the Byzantine Empire", in: *The History of Cartography, Volume 1 – Cartography in Prehistoric, Ancient and Medieval Europe and the Mediterranean*, J.B. Harley and David Woodward, ed. (Chicago: Chicago University Press, 1987), 266.

[187] Dijksterhuis 1986, 109.

[188] Freiesleben 1984.

bearing and distance measurements would have provided the geometric basis for the construction of the charts. The timing of this presumed process conflicts with the date conventionally attributed to the introduction of the mariner's compass of around 1300.

3.3.3 LEONARDO OF PISA (FIBONACCI)

Leonardo of Pisa, and/or his pupils, had been proposed earlier by Bacchisio Motzo as the compiler of the *Compasso de Navegare*, the oldest extant portolan, and an assumed companion prototype of a portolan chart. Motzo believed the *Compasso* to be an original work. Subsequent work comparing the *Compasso* with the, roughly contemporary, Carte Pisane revealed a marked lack of correlation between the two, which has tempered the initial enthusiasm that a link might be proved. Further work by Lanman, who attempted to draw a chart from the information in the *Compasso*, showed that also in that way no strong correlation with the Carte Pisane can be demonstrated. This will be discussed in more detail in Chapter 8: *The Relationship between portolans and portolan charts*.

3.3.4 BENEDETTO ZACCARIA

Charles de la Roncière suggested that Benedetto Zaccaria, a famous Genoese merchant, adventurer-corsair, diplomat and admiral was the originator of portolan charts.[189] Zaccaria commanded not only the Genoese fleet in e.g. the battle of Meloria but also served successively as fleet commander for Byzantium, Aragon and France. He would thus have had the opportunity of seeing most parts of the Mediterranean, the Black Sea and the Atlantic coasts, shown on portolan charts. However, as Campbell rightly points out: "this theory … assumes, but does not demonstrate, the vital step from navigational experience to hydrographic innovation". That is true, but neither does any other hypothesis. This point is worth elaborating. I have argued in the previous chapter that hydrographic surveying is altogether a different activity from navigating a merchant ship, or a complete war fleet, along a predetermined or ad hoc route. It is true that many medieval seamen must have possessed detailed geographic knowledge about the waters they sailed. However, geographic knowledge is not the same thing as quantitative geometric knowledge, *geometric* in the original sense of the word as quantified spatial relationships between features on the earth's surface. A taxi driver in London or Amsterdam may possess excellent and detailed geographic knowledge of his or her city, but will not be able to draw a geometrically correct map of that city. The objection I formulated against the endemic underestimation of the complexities of mapmaking is particularly illustrated by the Zaccaria hypothesis, which assumes that a single man, although possibly aided by other commanders and navigators in the fleet under his command, would have surveyed the entire coverage area of the Mediterranean portolan chart while he was probably contracted to do other things.

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[189] Charles de la Roncière, *La découverte de l'Afrique au Moyen Age: Cartographes et exporateurs*, Mémoires de la Société Royale de Géographie d'Egypte, vols. 5, 6, 13 (Cairo: Institut Français d'Archéologie Orientale, 1924-1927), 1:40, cited by Campbell 1987, 382.

3.3.5 ARAGON

Pelham, who closely follows Nordenskiöld's ideas, but denies any link of portolan charts with Marinus of Tyre, postulates that only the Crown of Aragon had the resources to initiate a complete survey of the Mediterranean, Black Sea and Atlantic coasts.[190] Nordenskiöld himself allocates an important role to the Majorcan philosopher Ramon Llull as the author or guiding spirit of the development of the *normal-portolano*, Nordenskiöld's assumed prototype chart of which all other charts would be copies[191].

3.3.6 UNSPECIFIED MULTIPLE ORIGINS

Campbell contrasts the hypotheses that propose a specific originator of the charts with those that assume a parallel development process. As he formulates it: "A belief in multiple origins unites many scholars of past and present".[192] This shared view appears to be prompted by the well-known scale (and orientation) differences of the sub-charts, to which Wagner, and even Joachim Lelewel before him, already referred.

Several objections have been raised against this hypothesis. For example, there is no evidence of any early cartographic centre or individual chartmaker outside northern Italy and Majorca and no charts have ever come to light from such presumed sources.[193] Even if the capabilities to make such accurate regional charts existed in places other than the known ones, it is still not satisfactorily explained why the same capabilities did not allow the scale and orientation differences to be discovered and resolved, which exist between the individual basins on a complete Mediterranean portolan chart.[194] Pujades rightly points out that such charts had to have been available and in circulation in sufficient numbers to permit purchase and copying, but there is no evidence at all that points in that direction.[195] The correctness of the hypothesis of parallel development by multiple cartographic sources, spread wide apart geographically, does not appear to be likely on these grounds.

3.3.7 OTHER VIEWS

Pujades describes the currently most widely accepted idea as follows:

> "The conciliatory[196] idea has come to prevail that nautical charts are the offspring, not of a specific place, but of a Mediterranean seaborne culture in its

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[190] Pelham 1980, 111-113.

[191] Nordenskiöld 1897, 53.

[192] Campbell 1987, 383.

[193] See also Gautier Dalché 1995, 28: "… certain polygraphs allant, en dépit de tous les témoignages, jusqu'à soutenir l'existence d'«écoles» cartographiques en des endroits d'où ne provient aucune carte medievale, …"

[194] See also Hans-Christian Freiesleben, "The Still Undiscovered Origin of Portolan Charts." *Journal of Navigation*, Vol. 36 (1983), Issue 1: 126.

[195] Pujades 2007, 511.

[196] *conciliatory* in the sense of compensating for the nationalistic colouring which the debate on portolan chart origins acquired, particularly between the World Wars and which it, according to Gautier Dalché 1995, 28, occasionally still exhibits.

> broadest geographical sense; a heritage as common as the *lingua franca*, or mixture of languages that seamen used … to communicate with each other despite their vastly different provenances".[197]

Rather than also embracing the 'regional parallel development' scenario, Pujades sees Genoa or Pisa as having taken up the task of pulling all this data together and ultimately producing the first portolan chart.
He sees the emergence of literacy as key to the emergence and distribution of portolan charts, pointing out that the area displayed with high accuracy on portolan charts coincides with the "Europe of the notaries".[198] He thus envisages that:

> "by the end of the twelfth century the seamen-merchants of the Mediterranean arc that stretches between Pisa and Genoa … had accumulated a vast amount of data on the distances and directions that separated Mediterranean ports".[199]

In this statement Pujades ignores the fact that there is no evidence for such an early date for the availability and widespread use of the mariner's compass. He states that he is not convinced of the significance of the scale differences between the Mediterranean and the Black Sea at one end and the Atlantic coasts, other than that this suggests that those areas were added later.[200] However, he appears to step over this issue too lightly: although it is quite plausible that those areas might have been added later, it still provides no satisfactory explanation of the scale differences.

A suggestion – it is so non-specific that it can hardly be termed a hypothesis – is Michel Mollat du Jourdin's oblique reference to astronomic positioning as the basis of portolan charts.[201] Uta Lindgren considered Mollat's suggestion that astronomically determined points formed the geometric framework of portolan charts "a great step forward".[202] One notable supporter of a geometric framework of astronomically determined locations is Fuat Sezgin, who considers the foundation of portolan charts to be "a phenomenal achievement of Islamic geographers and astronomers".[203]

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[197] Pujades 2007, 515.

[198] Pujades 2007, 425.

[199] Pujades 2007, 520. Pujades implicitly assumes here that the compass, in a suitable form to generate useable course measurements, existed and was in widespread use in the twelfth century, which is extremely early.

[200] Pujades 2007, 511.

[201] Mollat du Jourdin 1984, 13 and 16. I am not aware that Mollat has been more explicit in other publications.

[202] Uta Lindgren, "Portulane aus wissenschafthistorischer Sicht. Ein Űberblick über Forschungsrichtungen", in: *Kartographie und Staat: Interdisziplinäre Beiträge zur Kartographiegeschichte (Algorismus)*, München (1990), p 16

[203] Sezgin 2000, Teil 1, 309 and Teil 2, 20, 26.

3.4 HYPOTHESES ON PORTOLAN CHART CONSTRUCTION

In spite of the disappointingly poor correlation of the *Compasso de Navegare* and the Carte Pisane, portolans still appear to be the most obvious intermediate source of measurement data from which proponents of the medieval origin hypothesis assume the first portolan chart to have been drawn. The main problem is that there are there no realistic alternatives, even though some authors avoid being specific on what the relationship between portolans and portolan charts may be. However, let our starting point be, for the moment at least, the presumed "*vast amount of data on the distances and directions that separated Mediterranean ports",* as Pujades describes it. How do scholars see a chart having been constructed from this raw material?

3.4.1 CONCATENATED COASTAL SKETCH MAPS

Nordenskiöld and, after him, Pelham were convinced that the compass was not required to make an accurate map of the Mediterranean coasts. The drawing of sketch maps of pieces of coast visible from a ship's deck on the basis of distance estimates only, followed by concatenating neighbouring sketch maps would have sufficed to make an accurate chart. Also Ferro believes the first portolan chart was constructed in this manner, although he does appears to allow a role for the use of the compass.[204]

Pelham extends his hypothesis with speculative assumptions of a horizontal circular "survey board", graded in degrees, with a simple alidade, laid down flat on deck and used for the intersection of coastal features from a so-called running traverse, during which the ship sails a straight course along the coast and the same coastal feature is surveyed in from successive ship's positions along that course. He repeatedly assures the reader that such simple techniques are adequate, without making a single attempt at quantification.[205] Nor does Nordenskiöld support his hypothesis of sketch maps in any quantitative way. Pelham's and Nordenskiöld's hypothesis would require the individual sketch maps to be extremely accurate to achieve the kind of overall accuracy that the portolan charts exhibit, as the concatenation process would lead to a steady accumulation of errors. This conflicts with the observable fact that small sections of coastline on portolan charts are less accurate than the overall accuracy of the sub-basin charts.

3.4.2 GEODETIC CONTROL NETWORK FROM MARINE OBSERVATIONS

Most scholars who endorse the medieval origin hypothesis assume the geometric basis of the charts to be a geodetic control network, consisting of the azimuths and distances between points along the coast, measured as a ship travelled along the coast (*per starea*) and supplemented by observations on cross-basin (*per peleio*) routes.

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[204] Ferro 1996, 45.

[205] Pelham 1980, 103-105.

Although there is general agreement that *peleio* are necessary to add strength to the framework, few attempts at quantification have been made. Most authors avoid going into any form of detailed description of how such a network might have been realised, as this would also require the description of some schema by which internal discrepancies and inconsistencies were resolved. David Woodward had the courage to be more specific and proposed the following process, which summarises most aspects of the entire medieval origin hypothesis quite well:

> "The cumulative experience of several centuries of coastal and other shipping in each of these (sub-) basins could have led to the independent recording of traditionally known distances. The average distances derived from both coastal traverses and cross-basin routes could then have been used in the construction of a series of separate charts of the individual basins. If these routes were plotted to form networks in each of the basins, each network might have assumed the form of a self-correcting closed traverse of each basin. The rigidity of this structure would, however, have depended on the availability of cross-basin distances, acting as braces to the framework. It is thus postulated that some system of empirical or stepwise graphic method of correcting these frameworks was used to achieve a 'least-squares' result."[206]

Least Squares Estimation evidently didn't exist in the Middle Ages, but Woodward uses the term loosely in the sense of achieving a result approximating an optimal fit by graphical means.

Some effort at quantification was undertaken by Scott Loomer and by James E. Kelley Jr.[207] Loomer used the idealised trilateration network proposed earlier by Kelley, comparing that with the portolan charts he analysed. However, Kelley's analysis is based on a fundamental error, which will be described in Section 3.6 below.
In the same article Kelley proposes an evolutionary development of the portolan chart, based on progressive, iterative adjustment, in which the cartographer resolved one or just a few contradiction(s) in the observation material at a time. He proposes a process, starting with simple initial approximation of the shape of the Mediterranean, e.g. al-Idrisi's map; even a simple rectangle would suffice in his view. He then proposes to make that initial map (chart) available to mariners and periodically 'harvest' their complaints about bearings and distances being incorrectly shown on the chart, working those into a next iteration step, and so on, until no meaningful further improvement can be made.

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[206] Campbell 1987, 388. Campbell states that Woodward wrote the relevant section.

[207] Loomer 1987, 133, 136, 149.
James E. Kelley Jr, "Perspectives on the Origins and Uses of Portolan Charts." *Cartographica*, Vol. 32 (1995), No. 3. It is unclear how Loomer derived the reference coordinates of his control points for this trilateration network. He doesn't describe this. Loomer used a prepublication of Kelley's work, which the latter published in Cartographica in 1995, hence the apparent discrepancy between my statement and the years of publication of the two documents.

This hypothesis looks well thought out, but it ignores an important thing: it assumes that the process thus outlined converges to a single stable shape. Turn the process around and let the cartographer start with the near-perfect shape as depicted on the charts. New measurements coming in would conflict with this shape, as a result of navigation inaccuracies and of ignoring the effects of earth curvature. The cartographer would continue to make adjustments. This process may result in an endless dithering around the perfect shape or even divergence from that shape, rather than convergence to a single stable shape. Convergence not necessarily happens automatically; not all iterative processes converge.

The assumption that the outlined process converges leads to another interesting question, viz. how the cartographer would have known when to stop making adjustments. What criterion would he have applied? Why not stop the iteration process earlier and be content with a less perfect chart, which would still have been accurate enough for navigation? How would he define or know the degree of perfection reached? As discussed in the previous chapter, it is furthermore necessary to assume that cartographers and mariners together managed to complete this process so quickly that we cannot see this iteration process towards a stable shape in the extant charts.

Notwithstanding these critical thoughts, the iterative process sketched by Kelley still appears to be more realistic than the assumption that all measurements were collected first, edited and averaged and then all this data was processed graphically in a single step, resulting in the first portolan chart. The key question is, whether such a network, in which the effects of all discrepancies and errors would have been minimised in a Least Squares sense, is "structurally indistinguishable from the surviving portolan charts", as Kelley formulates it.[208] This question will be discussed (and answered) in Chapter 9: *The map projection; artificial or intentional?*

3.4.3 GEODETIC CONTROL NETWORK BASED ON ASTRONOMIC POSITIONS

A minority of scholars has proposed that astronomically determined locations around the Mediterranean formed the core of the geodetic framework that underlies the construction of the portolan chart. Michel Mollat du Jourdin hinted at this; Uta Lindgren expressed her support and it has been recently elaborated by Fuat Sezgin. This hypothesis leads inevitably to the Islamic geodesist-astronomers, who, by the twelfth century, had made considerable advances in this field. Comparable expertise and knowledge was not at that time available in Christian Western Europe, although Crombie states that Western European astronomy started to develop independently from Arab astronomy from the middle of the thirteenth century onward.[209] A discussion is conceivable, analogous to that on the appearance of the mariner's compass, on whether Western astronomy ap-

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[208] Kelley 1995: 11.

[209] Crombie 1979, Vol 1, 104.

proached a mature state early enough to make an impact on portolan chart development. Gautier Dalché, however, feels this possibility can be excluded, as there was no interaction between the academic milieu of the astronomers and that of the mariners.[210]

The alternative to this is still Helmut Minow's hypothesis that the astronomic positioning stems from Greco-Roman antiquity, which is not supported by many and which will not be evaluated in this study.

Sezgin attributes the assumed astronomic basis of portolan charts to Islamic astronomers and assumes the infill data to come from mariners' estimates of distances and possibly directions – he speaks of "marine itineraries" – but despite the large number of arguments he produces, he does not present evidence for his hypothesis. Nevertheless, Sezgin *has* formulated a promising alternative to the established medieval origin hypothesis, which deserves more attention than it has received until now.

A more detailed discussion of the likelihood of an Arabic-Islamic origin of portolan chart construction will have to wait until Chapter 10: *An Arabic-Islamic origin of portolan charts?*, as the results of my own analysis need to be discussed first. The discussion in Chapter 10 will concentrate on Sezgin's hypothesis, as Mollat du Jourdin's hints are too vague for a meaningful discussion and Minow's proposal for such a framework in antiquity falls outside the scope of this study, although his implicit assumption that the skills (and instruments) necessary for accurate astronomic positioning existed in antiquity appear to be unrealistic.

3.5 Plane charts and plane charting

3.5.1 Other authors' views

One of the most widespread misunderstandings related to the geometry of portolan charts is the often implicitly made assumption that *plane charting* will automatically result in a *plane chart*. A plane chart, sometimes spelled as *plain chart*, is a chart of which the graticule with equal intervals in degrees of latitude and longitude forms a pattern of squares, whether explicitly drawn or implicit in the map image. Technically this map projection, for that is what it is, is called an *Equidistant Cylindrical* projection with the equator as the (only) true-to-scale parallel. Some authors[211] extend the definition of a plane chart to include any Equidistant Cylindrical projection with a true-to-scale parallel different from the equator. This produces a graticule of equal latitude and longitude intervals, consisting of rectangles instead of squares and for this reason the associated projection is also referred to as the *Equirectangular* projection. According to Ptolemy, Marinus of Tyre's map was drawn on such a projection, on which the parallel of Rhodes of 36° N was drawn true-to-scale.

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[210] Gautier Dalché 1995, 28.

[211] Wagner 1895 (1982), 27; Wagner 1896 (1969), 480; Lanman 1987, 34.

The state of science in the twelfth and thirteenth centuries only permits the assumption that a cartographer would draw a map or chart from raw measurements by *plane charting*.[212] This technique assumes a plane geometry, which ignores the curvature of the earth's surface. Geometric measurements made on the curved surface of the earth are transposed without corrections to a plane drawing surface, the map plane, apart from a fixed scale correction to the distances.

Cartometric analysis has demonstrated that the map image of portolan charts closely agrees with a modern map on either the Mercator or the Equidistant Cylindrical projection.[213] As pointed out in the *Introduction*, this property is commonly regarded as an unintentional by-product of the cartometric analysis method. Undoubtedly the name similarity has prompted many an author to assume that plane charting leads to a plane chart. Some examples of such misconceptions are provided below.

Taylor confidently states: "On a chart drawn in this style [i.e. a portolan chart] obviously the earth is treated as a plane surface (although the doctrine of the sphere was part of the master mariner's education), but the errors thus introduced were immaterial within the limits of latitude covered …".[214]

Taylor doesn't mention any map projection explicitly in this citation, but states that plane charting was used and that any discrepancies arising from plane charting are "immaterial". This is separate from the question how she could know what was part of a medieval master mariner's education and what wasn't, as no records on this exist at all. However, the discrepancies arising from plane charting are not negligible, as I shall demonstrate below.

Richard Pflederer voices majority opinion, when he states that "portolan charts are constructed on a simple, planar projection, which maintained a constant spacing for lines of latitude and longitude, ignoring the sphericity of the earth …" He adds that "errors introduced by ignoring the sphericity of the globe are relatively minor", also voicing an opinion that is often implied in other publications.[215]

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[212] Sezgin I 2000, 305. Sezgin argues that both the skills and the inclination existed in the Islamic world to draw maps on the stereographic projection and argues that this is the underlying map projection of the portolan charts. This projection was routinely applied in the design and construction of astrolabes.

[213] Loomer 1987, 146. The limited latitude range of an area such as the Mediterranean makes it difficult to distinguish the conformal cylindrical projection (i.e. the Mercator projection) from the Equidistant Cylindrical projection. This will be discussed in more detail in section 7.6.5.B – Chart Accuracy and Cartometric Characteristics.

[214] Taylor 1948 *The Sailor in the Middle Ages*, 191.

[215] Richard Pflederer,"Portolan Charts – Vital Tool of the Age of Discovery, Sailing Guides." *History Today* (2002). http://www.historytoday.com.

These two sentences contain several misconceptions: the text suggests that portolan charts were actually constructed on an Equirectangular projection, although from the context it is clear that Pflederer refers to plane charting, but believes this process creates by definition a rectangular graticule, which illustrates that the concept of a plane chart is often confused with plane charting. His statement that any errors introduced by this process are "relatively minor" is more reserved than Taylor's but is still a soothing reassurance, not proven by numerical data.

The phrase: "the convergence of the meridians is ignored", is often encountered in portolan chart literature as a supposedly conclusive argument that the earth's sphericity was ignored in their construction. This argument is incorrect and is addressed in Section 3.5.5 below.

Armando Cortesão postulates that "… the fact is that their makers considered as a plane the spherical surface represented as if the whole world were a plane disc. In fact the portolan charts belong to the class of projectionless (in a strict mathematical sense) plane maps, which the French call *cartes plates*."[216] This is another clear example of mixing up plane charting and plane charts. The product of a plane charting process is often referred to as a "projectionless" map.

Richard Uhden considered the square grid, shown in parts of the Carte Pisane outside its wind rose as "conclusive proof that portolan charts are plane charts" and "were constructed with a square grid", and describes a plane chart as a chart that "lacks any relationship with the size of the earth and its graticule".[217]

Uhden clearly didn't understand that a plane chart, in the sense of an Equidistant Cylindrical projection, is not the same as a map, constructed by plane charting (i.e. by using a square grid). He didn't understand either that a proper plane chart *does* have a very clear relationship with the graticule.

Salvador García Franco likewise maintains that portolan charts were constructed by plane charting of rhumbs and distances and are thus plane charts and he adds the puzzling statement that "Mercator's projection can reasonably be acknowledged as an extension of it".[218] I initially believed that Franco referred exclusively to charting on the basis of course bearings, which would indeed result in a Mercator chart in principle, but he explicitly mentions course bearing and distance data, which makes his statement simply incorrect.

Jonathan Lanman uses the term "square grid method" for what I have referred to

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[216] Cortesão I, 1969, 217.

[217] Uhden 1935: 16, 1.

[218] Salvador García Franco, "The 'Portolan Mile' of Nordenskiöld". *Imago Mundi*, Vol. 12 (1955): 89,90

above as 'plane charting'.[219] He justifies this with every square that can be detected in the charts. In the pattern of rhumb lines, or wind rose, squares can be discerned for directions ninety degrees apart. Lanman also observes that the two scale bars on the Carte Pisane, one drawn east-west, the other north-south, have the same length. From all these 'square' properties, he concludes that the charts were drawn by the "square grid method", i.e. plane charting and he considers the "square projection" a synonym of the Equirectangular projection, with its rectangular graticule. Lanman therefore also mixes up plane charting with a plane chart and additionally shows poor understanding of the properties of a plane chart when he describes it as "a chart in which both vertical and horizontal scales are equal and constant".[220]

The examples provided above demonstrate what appears to be a widespread incorrect or incomplete understanding of the relationship between map projections and construction methods of maps or charts.

Whereas such examples abound in portolan chart literature[221], there are fortunately also authors who do show a clear understanding of the fact that plane charting is fundamentally incompatible with *any* map projection.[222] Most recently Joaquim Alves Gaspar has drawn attention to the fact that the charts produced in the Age of Discovery cannot be regarded as proper plane charts, despite the fact that a graticule of perfect squares has been drawn on them, because the plane charting technique that was applied by the explorers both to navigate and to chart newly discovered shores would never result in a plane chart.[223] Points will be plotted in the wrong place when the spherical geometry of the earth is ignored. A square graticule drawn later by the cartographer doesn't change that fact.

3.5.2 Plane charting – a simple example

The plane charting technique would only result in a proper plane chart if the earth were flat, but it manifestly isn't. I will demonstrate this by means of an example of the impact that plane charting would have in the Western Mediterranean. Assume three ships set out to sail from Livorno to the city of Dellys in North Africa, located at approximately latitude 36.9° N and longitude 3.9° E. Departure point is 43.4° N and longitude 10.4° E, which is actually some 18 km south-south-east of Livorno. The navigators will record course and distance sailed throughout the journey and it will be assumed that their observations are error-free. It will also be assumed that the three ships will be able to find Dellys

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[219] "The simplest, almost intuitive way to plot a chart from bearing and distance data is on equicoordinate graph paper, giving a square grid". Lanman 1987, 34.

[220] Lanman 1987, 33.

[221] Apart from the examples mentioned, see also Pelham 1980, 17.

[222] Campbell 1987, 386; Stevenson 1911, 20.

[223] Gaspar 2010, 26-37;
Joaquim Alves Gaspar, "The myth of the square chart". *e-Perimetron*, Vol. 2 (2007), No. 2.

without any difficulty, purely based on the experience of their navigators; in other words, they know exactly what course to steer and what distance to sail. They will *not* scale the required course and distance from a chart; that would be the reverse process.

It will be noticed that the departure point and the target point specified lie at opposite ends of the diagonal of a square on a plane chart, spanned by 6.5 degrees of latitude and 6.5 degrees of longitude. In order to avoid introducing more error sources than just the plane charting process, it will be assumed that the length of a degree of latitude is known to be 60 NM[224], that there is no magnetic variation and that their navigation is error-free. Furthermore it will be assumed, for the purposes of this example, that the presence of land masses does not hinder the ships.

- Ship #1 will sail along the most direct compass course to Dellys.
- Ship #2 will sail due west to the point from which the skipper has learned from experience, that a due south course must be steered to reach Dellys and will steer due south from that point.
- Ship #3 will do it the other way around, sailing due south until it reaches the latitude of Dellys and then changing course to due west.

The correct course and distance measurements on the sphere, which each ship would make to get from the starting point to Dellys are shown in Figure 3.1 below. The following mental exercise will now be executed:

> *Assume that the three navigators will meet at an agreed location at Dellys and decide to chart the location of Dellys in a blank plane chart, which only shows the graticule and the section of coast near their departure point.*

The question to be answered is: where will the three navigators plot the location of Dellys using plane charting as their mapping technique? Two cases will be considered:
1. This blank chart is a plane chart, i.e. one degree of latitude spans the same length on the chart as one degree of longitude; the graticule is a grid of squares.
2. This blank chart is a chart on the Equirectangular projection with the same characteristics as a portolan chart; its true-to-scale parallel is 39.2° N.[225]

As this parallel falls roughly in the middle of the area of interest, such a chart is often called a ‘mid-latitude chart’. The graticule is a grid of rectangles.

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[224] NM = nautical mile. 1 NM = 1,852 m. The actual length of a degree of latitude is not constant. In geodesy the shape of the earth is not approximated by a sphere, but by an ellipsoid, flattened at the poles. The length of a degree varies with latitude because of this flattening and also depends on the size of the ellipsoid chosen. For this study such refinements are not required.

[225] In Chapter 7: *Cartometric analysis of five charts* it will be shown that the map image of the Western Mediterranean on portolan charts agrees with the Equidistant Cylindrical projection with the stated true-to-scale parallel. This parallel varies somewhat by portolan chart.

A. Case 1: Charting Dellys on a Plane chart

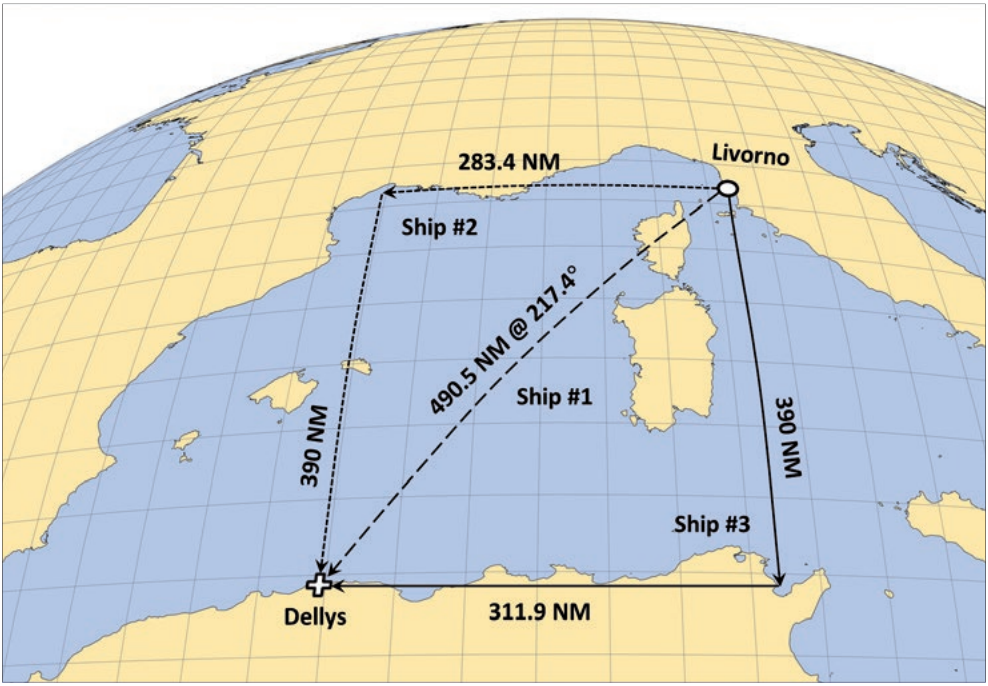

Figure 3.1 *- Distances and azimuths on the spherical earth.*

Ship #1 will have sailed 490.5 NM on a true course of 217.4° when it reaches Dellys. Ship #2 will sail 283.4 NM due west and then 390 NM south, whereas ship #3 will first sail 390 NM south and then 311.9 NM west to reach Dellys. The east-west distance is different for ship #2 and ship #3, as they sail along different parallels. The derivation of these figures is provided in Appendices I and II.

	Latitude	Longitude	Longitude error (km)
Ship # 1 (on a SW course)	36.9° N	5.438° E	137
Ship # 2 (first W, then S)	36.9° N	5.677° E	158
Ship # 3 (first S, then W)	36.9° N	5.202° E	116
Correct location of Dellys	36.9° N	3.9° E	

Table 3.1 *- Errors due to plane navigation/charting.*

The results are shown in Table 3.1. The correct latitude and longitude of Dellys have been added, so that the error due to plane charting – their navigation was error-free – can be calculated. The errors are so large because on a pure plane chart the length of a degree of longitude is what it would be on the equator, not what it ought to be in the Mediterranean. The largest error is made by ship #2, which sails west along the most northerly parallel, along which the length of a longitude degree differs most with the length of a longitude degree along the equator. The smallest charting error is made by the navigator of ship #3, which sails west along the parallel at which the error in length of a longitude degree in the plane chart is smallest. The charting error made by the navigator of ship #1 is similar to that of ship #2 during the first part of the journey but gradually decreases to the level of the errors of ship #3 towards the end of the journey and the position plotted by its navigator falls in between the two extremes.

It turns out that all three ships would have determined the *latitude* of Dellys correctly, but they would have charted the location of Dellys at an incorrect *longitude*, which also differs per ship. The charted location of a point (Dellys) thus depends on the route taken from the starting point.

B. CASE 2: CHARTING DELLYS ON AN EQUIRECTANGULAR (PORTOLAN) CHART

As mentioned above, some authors (see footnote 208) consider the concept *plane chart* also to apply to a chart on the Equirectangular projection and postulate that plane charting of any area would not produce a plane chart with a 'square' graticule, such as Figure 3.2, but a chart with a rectangular graticule, i.e. an Equidistant Cylindrical (Equirectangular) projection, such as Figure 3.3. At higher latitudes an Equirectangular projection offers a better approximation of the surface of the earth than a pure plane chart. Marinus of Tyre's map was drawn on an Equirectangular projection of which the ratio of the lengths of a longitude degree and a latitude degree was correct for the parallel of Rhodes (36° N), i.e. this parallel was true-to-scale. Its ratio is about 0.8. Although neither Wagner nor Lanman states this explicitly, it would have to be assumed that the mean latitude of the area subjected to plane charting would dictate the true-to-scale parallel. Plane charting in the Western Mediterranean on an Equirectangular chart, similar to a portolan chart, will indeed produce much smaller errors, but will not eliminate the errors, as Table 3.2 shows.

	Latitude	Longitude	Longitude error (km)
Ship # 1 (on a SW course)	36.9° N	3.997° E	9
Ship # 2 (first W, then S)	36.9° N	4.306° E	36
Ship # 3 (first S, then W)	36.9° N	3.692° E	-18
Correct location of Dellys	36.9° N	3.9° E	

Table 3.2 *- Errors on a portolan chart due to plane charting.*

If plane charting would by definition result in a plane chart or an Equirectangular chart, the longitude differences shown in Table 3.1 and Table 3.2 should not exist. However, they clearly do; depending on the path followed by the ship from the start location, the location of Dellys may be plotted in locations with different longitudes. The error is systematic and repeatable; if the same path is followed, the same error will be made.

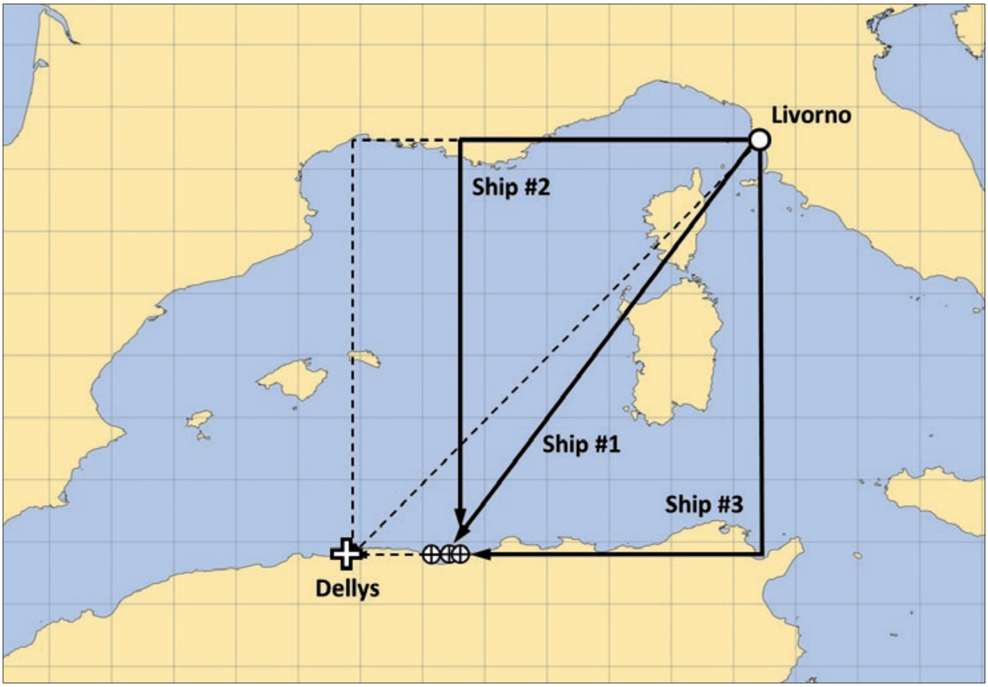

Figure 3.2 *- Correct location of Dellys on a plane chart and the three locations where it would be charted as a result of plane charting.*

The east-west distance sailed by ship #2 is converted to degrees with a degree length that is too great for the parallel along which it sailed and the longitude difference Livorno-Dellys is therefore underestimated, resulting in the plotting of Dellys 36 km too far to the east. The reverse story holds for ship #3, which overestimates that longitude difference and Dellys is consequently plotted too far west by 18 km. As in the previous case the location plotted by the navigator of ship #1 plots in the middle, but is still incorrect by 9 km.

The above example demonstrates that plane charting will result neither in an exact plane chart (proper) nor in an Equirectangular chart.

3.5.3 ANALYSIS AND FOUR MORE ARBITRARY ROUTES

An additional and somewhat more realistic example of plane charting is provided by four direct cross-sea routes from Genoa to Barcelona, Ténès, Bejaia (Bugia) and Palermo respectively.

Pure plane charting of compass course and (rhumb line) distance data, in the absence of any other errors, would result in the following charting errors in the locations of these points, on a plane chart, with respect to the location of Genoa:

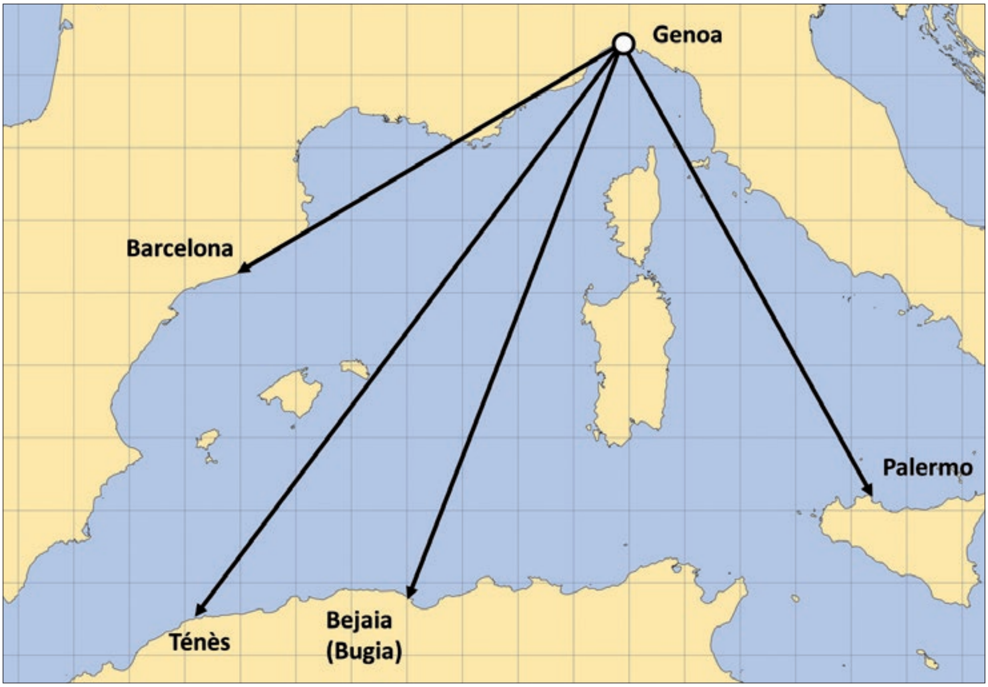

Figure 3.3 *- Four additional routes from Genoa, plotted on an Equirectangular chart.*

	Plane chart Latitude error	Plane chart Longitude error
Barcelona	0	151 km
Ténès	0	163 km
Bejaia (Bugia)	0	82 km
Palermo	0	-97 km

Table 3.3 *- Four additional routes from Genoa: plane charting errors on a plane chart.*

Comparing the charted locations on an Equirectangular projection with true-to-scale parallel of 39.2° would result in the following errors:

	Equirect. chart Latitude error	Equirect. chart Longitude error
Barcelona	0	31 km
Ténès	0	14 km
Bejaia (Bugia)	0	7 km
Palermo	0	-12 km

Table 3.4 *- Four additional routes from Genoa: plane charting errors in a portolan chart.*

These examples confirm and generalise the conclusion from Section 3.5.2 regarding the location of Dellys. A further generalisation of plane charting errors is discussed in Appendix I. It is demonstrated that the magnitude and sign of the longitude error due to plane charting depends on the course bearing and the distance sailed. This adds further complexity to the systematic errors generated by this method.

A remarkable conclusion may be drawn regarding plane charting, viz. that the errors due to plane sailing accrue entirely to the longitude difference of the target and origin points. Pure plane charting results in longitude errors only, i.e. in the absence of any other error sources, as long as the data refers to compass bearings and rhumb line lengths. If great circle distances would be included, a small latitude error would be introduced. By contrast, *usage* of a proper plane chart (with square graticule) for plotting a route, as opposed to *making* a plane chart, will definitely result in latitude errors. The same holds for a portolan chart, but the errors will be much smaller.

3.5.4 Conclusions on plane charting

The following conclusions can therefore be drawn regarding plane charting.

1. *A point feature will be charted in different locations when different routes to that point are followed and plane charting techniques are applied.*

2. *Plane charting of entire coastlines will not result in an exact plane chart or Equirectangular chart, i.e. a chart with a square or a rectangular graticule.*[226]

3. *Errors due to plane charting affect longitude differences between points only, when the lines connecting origin and target points are rhumb lines.*

4. *The magnitude and sign of the longitude error are determined by the course bearing and the length of the line sailed.*

In Chapter 7: *Cartometric analysis of five charts* it will be shown that the Root Mean Squared Error of a point in the Western Mediterranean is around 10 km. It might be therefore be tempting to add another conclusion, viz. that plane charting errors are small compared to the accuracy of portolan charts and that for that reason the Equirectangular projection may indeed be considered to be an artefact of the plane charting method. However, this conclusion would be too intuitive and premature, as plane charting errors are systematic and the quoted point accuracy of a portolan chart represents random errors.

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[226] This ignores for the moment the effects of any adjustment, presumed to be of a graphical nature, which might have been applied to raw or averaged observations to arrive at a final, coherent map image. This aspect is evaluated in Chapter 9: *The map projection; artificial or intentional?*

Any hypothesis on portolan chart construction has to assume a complex geodetic network as the underlying framework, which implies some schema for the reconciliation of measurement, plane charting and gross errors.

It is imaginable that the differences between such a reconciled plane-charted geodetic network and a reference map derived by applying an Equirectangular (or even a Mercator) map projection are so small that they will remain within the accuracy with which the coastlines are depicted on the portolan chart. In that case the derived map projection would indeed be an artificial by-product of the assumptions of the analysis method. However, this ought to be tested properly and that is indeed is the objective of Chapter 9: *The map projection; artificial or intentional?* Further examples of the non-negligible effects of plane charting will also be discussed in Chapter 8: *The relationship between portolans and portolan charts.*

3.5.5 SQUARE GRID – EARTH CURVATURE IGNORED?

A square or rectangular graticule on a chart or map that is derived from the mapped geographic features is intrinsic to the map or chart and is proof of considerably more sophistication than it is credited with in portolan chart literature. Contrary to statements that parallel, straight meridians are the result of ignoring the convergence of the meridians and hence the curvature of the earth's surface, the Equidistant Cylindrical (Equirectangular) and plane projections express a mathematical relationship between latitude (φ) and longitude (λ) on the one hand, and plane map coordinates, X and Y, on the other in the following way:

$X = R.\lambda$
$Y = R.\varphi$

and, for the Equirectangular projection:

$X = R.\ \lambda.\cos\varphi_0$
$Y = R.\varphi$

where φ_0 is the latitude of the true-to-scale parallel and R is the assumed radius of the earth, which is required to convert the angular quantities latitude and longitude into linear map coordinates X and Y. The above formulas yield coordinate values in the same unit of measure as that of the radius of the earth, i.e. when latitude and longitude are expressed in radians.

The expression of map coordinates as a (mathematical) function of latitude and longitude is the normal way of working with coordinates in geodesy. Should one wish to measure coordinates in a physical map, such as in the cartometric analysis of a map, then 'R' should be interpreted as an arbitrary number, which is the product of the radius of the earth and the (nominal) scale of the map.

However simple the above mathematical relationships may be, proper account *has* been taken of the curvature of the earth's surface, as expressed in the latitudes and longitudes of points, as long as these contain no systematic or gross errors. That is where the sophistication lies. The fact that the map distorts the curved surface of the earth considerably does not negate or annul that fact. *Every* map projection introduces its own characteristic pattern of distortions. The Mercator projection also produces a graticule of parallel, straight meridians but no knowledgeable person would consider a Mercator chart as being a simple, plane representation of the earth surface, ignoring its curvature.

A completely different situation arises when the cartographer superimposes a rectangular graticule on a map or chart that is not properly a plane chart. In that case the square grid is no more than an artefact introduced by the cartographer by means of ruler and pen. It may be considered by chart users to be a plane chart, but it isn't. This is what Gaspar means with the phrase "the myth of the square chart".

In neither of the two cases described above, i.e. an intrinsic graticule or a 'drawn' graticule, may the presence of a square or rectangular graticule in a chart be considered as an indication, and even less so as proof, that the chart was constructed by means of plane charting. The two are entirely unrelated.

Consequently the rectangular graticule that can be extracted from the topography of the coastlines in portolan charts cannot be considered as an indication or proof that plane charting is their underlying construction method. This rectangular graticule directly contradicts the common supposition that plane charting was used to construct the charts and it therefore undermines the medieval origin hypothesis, which is why this was described in the previous chapter as one of the features of portolan charts for which no satisfactory explanation has been provided as yet. Fundamentally the discovery of an underlying map projection, however simple that projection may be, is incompatible with the plane charting technique. *This is the fundamental internal contradiction of portolan charts.*

3.6 THE ROTATION ANGLE

The anticlockwise rotation angle of portolan charts has led to much speculation regarding its cause, although it doesn't appear to be as controversial as the map projection. Many authors simply attribute it to the average magnetic declination in the Mediterranean at the time the presumed collection process of course azimuth data took place and there is indeed a good correlation between this rotation angle and the estimates for magnetic declination that modern paleomagnetic models provide.[227] But is that sufficient proof and if it agrees with the charts' rotation angle, *what* exactly does it prove?

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[227] See Figure 8.10 and Appendix 4.

A small number of authors have come up with alternative explanations. One of the earliest alternatives attempted to relate the rotation angle with an error of nearly two degrees in the latitude of Constantinople in Ptolemy's maps. However, this hypothesis is nowadays virtually unanimously rejected on the grounds that the Ptolemaic error would only account for about half of the portolan chart rotation angle and cartographically there is not the slightest similitude between Ptolemaic maps and portolan charts.

Another possibility that has been suggested is that the map image would have been rotated to fit the entire image on the available animal skin. However, this seems unlikely for a number of reasons. Scale adaptation to the size of the vellum was a technique well understood and widely applied by chart makers, as all portolan charts have their own individual scale, largely determined by the size of the vellum. It therefore remains to be explained why all chartmakers would still have perceived the size of the vellum just too small to contain the entire map image, rotating it to fit. Furthermore the rotation angle of the charts is almost constant in magnitude until the late sixteenth century, whereas there is considerable variation in the dimensions of the vellum of extant charts: long, narrow shapes exist along with short, wide ones. This variation would have led to variations in the rotation angle if the shape and size of the available sheet of vellum would have been the reason. Moreover, there would be no reason at all why the wind rose would not have been subjected to the same rotation as the map image. It is unrealistic to assume that medieval cartographers would make such an obvious and gross error.

An alternative explanation that has found considerable, if not adherence, then at least favour, is James E. Kelley Jr.'s suggestion that the rotation angle is the consequence of the rotation of the underlying geodetic network.[228] Kelley analyses two scenarios: a pure trilateration network, consisting of distances only, and a network consisting of azimuths and distances. Kelley's hypothesis is unfortunately based on a fundamental error, which I will explain below.

Kelley's starting point is an idealised geodetic network of the shape shown in Figure 3.4 below. He makes use of the line Gibraltar-Antioch, which approximately coincides with the 36° N parallel, chooses the 45° N parallel as the northern boundary line and 'measures' a cross-brace every 10° of longitude, which would create the trilateration chain as shown in Figure 3.4.

Kelley reasons that, since the base of each triangle at the 36° N parallel is a bit longer than a corresponding triangle base at the 45° N parallel, because of the sphericity of the earth, the originally straight network will have a tendency of curving north, working the calculation from Gibraltar toward Antioch. This would result in the plot of the calculated network as shown in Figure 3.5.

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[228] Kelley 1995.

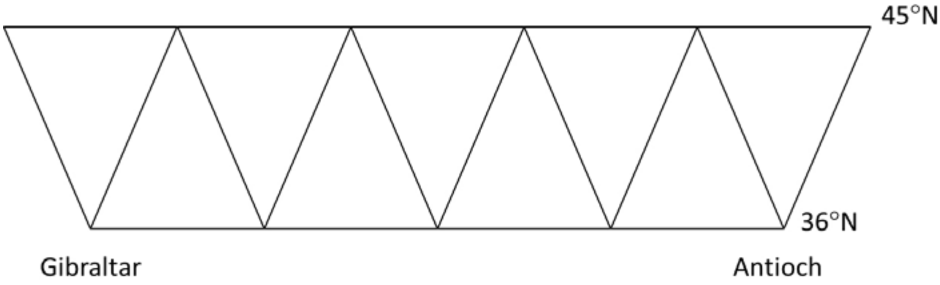

Figure 3.4 *- Kelley's idealised geodetic network.*

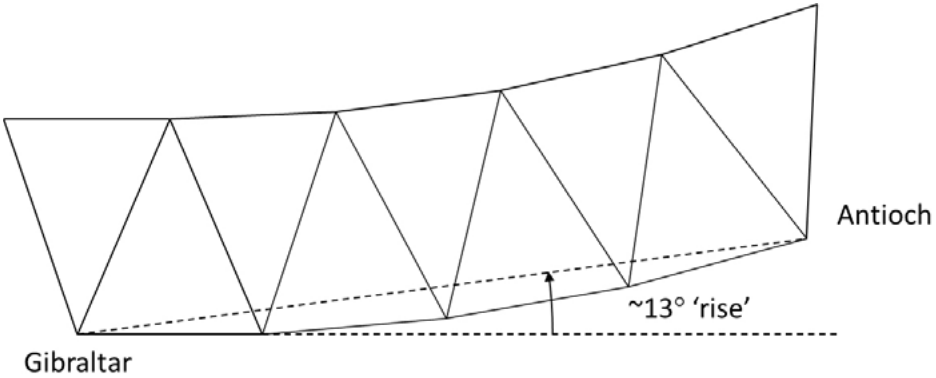

Figure 3.5 *- Kelley's demonstration of the tendency of a trilateration grid on the Mediterranean to curve northward.*

Kelley thus calculates that a trilateration network from Gibraltar to Antioch would "rise by about thirteen degrees". He measures the thirteen degrees rise from the parallel of 36°. This is where the fundamental flaw in his logic lies: he considers the parallel as a straight line. However, parallels are only straight lines on certain map projections. They are also not the shortest line connecting the two points, Gibraltar and Antioch; that would be a great circle.[229] Kelley's network is by definition asymmetrical about any east-west axis. Contrary to Kelley's asymmetrical network, a perfectly symmetrical trilateration network can be constructed about the Gibraltar-Antioch great circle in the following way. Draw two supporting great circles, one on either side of, but at the same angular distance from the Gibraltar-Antioch great circle, as the north and south boundary lines of the network and construct a symmetric pattern of cross braces between these

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[229] This formulation assumes a spherical model of the earth. Geodesists approximate the shape of the earth by an ellipsoid rather than a sphere, on which the shortest line connecting two points is a geodesic. The term 'geodesic' is the generic term for the line that provides the shortest connection between two points on any curved surface.

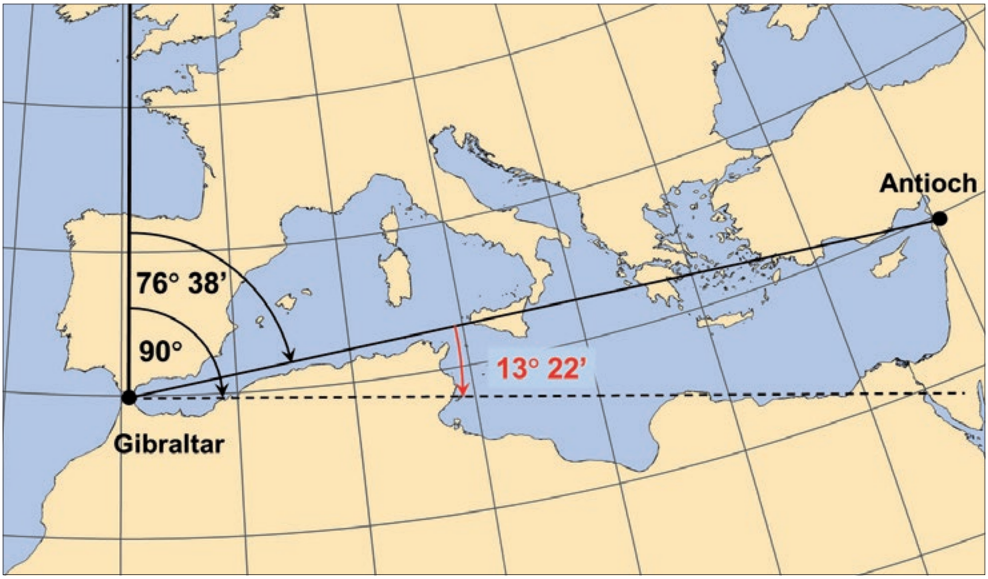

Figure 3.6 - *Stereographic projection centred on Gibraltar with the great circle to Antioch.*

bounds. Because of its symmetry the network will calculate and plot along a straight line, without any northward twist whatsoever.

What Kelley does, is to incrementally construct the parallel of Gibraltar and Antioch by his particular network and plane charting technique. As the length along the 45° N between two meridians is always shorter by the same proportion than the same length along the 36° N parallel, the constructed parallel will be an arc of a circle. Had he chosen a single traverse from Gibraltar to Antioch, consisting of legs as an imaginary ship would sail, each leg following the parallel of 36° N, i.e. with an azimuth of 90°, he would have obtained a straight line for this parallel, which is a further demonstration of the fact that plane charting does not yield a canonical[230] cartographic result, unless an identical process of charting would be repeated.

In order to demonstrate how this works, it is helpful to show the process on a map projection that projects the great circle through Gibraltar and Antioch as a straight line and parallels as arcs of a circle. This leads to an azimuthal projection and I have chosen the Stereographic projection, centred on Gibraltar, to demonstrate this in Figure 3.6. All great circles through Gibraltar will project as straight lines and all parallels (and meridians as well for that matter) will project as arcs of a circle.

The reason for the "about 13 degrees" rise of Kelley's network becomes perfectly clear now. The angle between the 36° N parallel and the meridian of Gibraltar is by defini-

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[230] i.e. independent of arbitrary choices, e.g. of routes.

Figure 3.7 *- President Gerald Ford route to Tokyo on a Mercator map.*

tion 90°, but the azimuth of the great circle from Gibraltar to Antioch equals 76° 38', which constitutes an apparent "rise" of the great circle of 13° 22'.

In other words, the special property of geodetic networks that Kelley believed to have discovered is actually an optical illusion of the geodetic kind. He did not find a generic property of geodetic networks, but a property of the particular network and the particular plane charting method he adopted. Kelley modifies his network further on in the same article by adding measured azimuths, which alters the shape of the network he computes, but not the fundamental logical flaw in his reasoning.
This is not dissimilar to that famous example of such an optical illusion, when under the administration of President Gerald R. Ford of the United States the first state visit to Japan after the Second World War was publicly announced, planned for 18-22 November, 1974. The intended route of the presidential airplane was shown on a map on television and left Americans puzzled as to why an extensive detour was scheduled via Anchorage, Alaska (see Figure 3.7).

Speculations in subsequent news analysis programmes ranged from a secret (pre-) summit with Soviet leader Brezhnev[231] to negotiations on Alaskan independence, but these

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[231] Ford and Brezhnev actually met on November 23, 1974, but not in Anchorage.

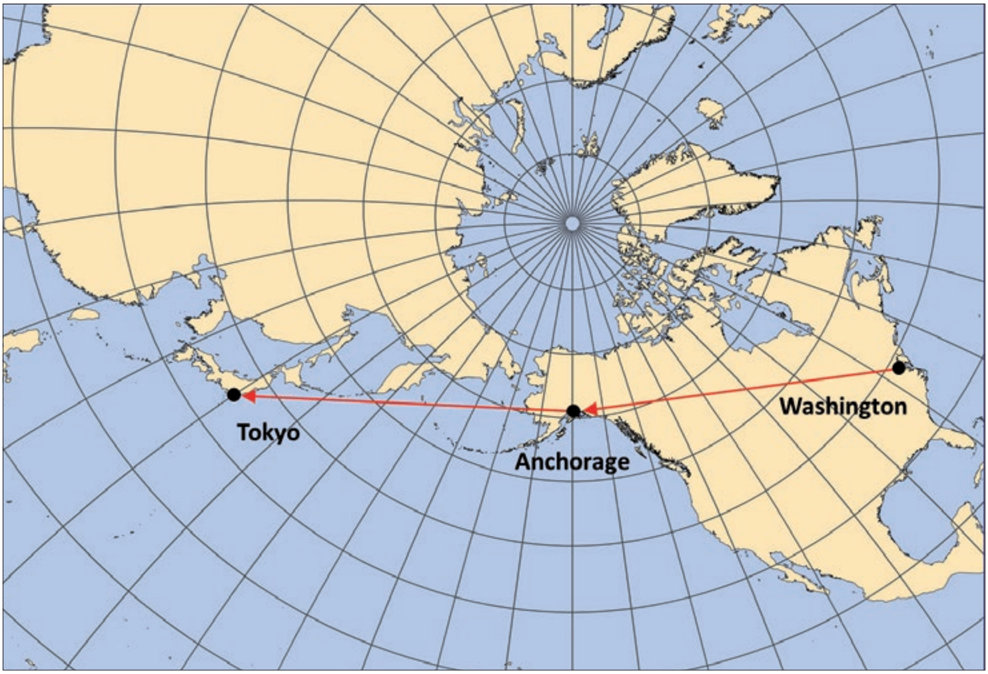

Figure 3.8 *- The same route from Washington to Tokyo on a stereographic map with Anchorage as the projection centre.*

speculations abruptly stopped when a few days later a prominent newspaper published an article by a cartographer, who showed that the whole discussion was a farce, as Anchorage practically lies on the great circle route from Washington to Tokyo (see Figure 3.8). In other words, there was no detour. This case shares with Kelley's analysis the incorrect assumption that a straight line between two points on a map represents the most direct route between those points.

Having thus eliminated Kelley's explanation, the only existing viable explanation for the anticlockwise rotation of the map image of portolan charts, which remains from the various hypotheses, is that it is somehow related to the unrecognised magnetic variation.

3.7 METHODOLOGICAL CONSIDERATIONS

A crucial requirement for all research on the Middle Ages, cartographic or historical, is to seek to answer historical questions from the frame of mind of medieval man, taking into account the historic context in the widest possible sense. What a modern researcher ought to avoid at all cost is to approach the problem as if he or she were to time-travel back into the Middle Ages and solve the problem with medieval materials but with a twenty-first century mind-set towards science and technological problem-solving.

The medieval origin hypothesis makes far-reaching suppositions about the attitude to problem-solving and the availability and widespread use of mathematical knowledge and techniques. It assumes in the first place that medieval sailors approached their navigation problems with mathematical rigour and dutifully recorded all their results. The next step assumes averaging of observations to have been applied on a very large scale and lastly the assumption that these averages were neatly organised and then used to construct the first portolan chart implies understanding and expertise in eliminating contradictions and errors. The mathematical rigour that is assumed in this sequence of activities is not extraordinary in the twentieth or twenty-first centuries, but does the same hold for the thirteenth or possibly the twelfth century? This aspect of the historical context has so far not received a great deal of attention. Pujades warns against this, pointing out that the medieval mind was entirely unconcerned with mathematical precision.[232]

The most important shared characteristic of existing hypotheses on portolan chart origins has already been mentioned and has also been identified by scholars of portolan charts themselves, viz. the total lack of corroborating evidence, which makes it impossible to test many of the hypotheses in any convincing manner.

Most authors exclusively present qualitative arguments or even revert to rhetoric and appear to be disinclined to undertake any numerical analysis. For example, Gautier Dalché states on two occasions that it is "pointless" to make any numerical analysis of the *Liber de existencia*.[233] Why he feels that it would be pointless remains unexplained, but a good numerical comparison with modern data would in my view be extremely valuable. However, he is not the only one. As early as 1886 Theobald Fischer made sweeping statements about the accuracy of data in portolans without bothering to check[234] and in the 1950s Taylor does not try very hard to come up with objective evidence, preferring rhetoric over numbers.[235] Also Mollat du Jourdin reverts to rhetoric in giving his view

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[232] See footnote 237. It is not clear to me how, simultaneous with this statement, he can entertain the idea that the observations that served as input to chart construction were the result of extensive averaging (Pujades 2007, 510).

[233] Gautier Dalché 1995, 70, 79. On page 70 he calls any comparison of data from the *Liber* with data for a modern chart pointless ('inutile'); on page 79 he uses the same argument for any numerical comparison of the *Liber* with the *Compasso de Navegare*.

[234] Fischer 1886, 64: "…at the beginning of the fourteenth century, despite the in the meantime and as one assumes, only recently introduced usage of the compass, [portolans] had reached such a degree of perfection that they could hardly be improved from that point on". No numerical data is presented to support this statement.

[235] Taylor 1960 *Mathematics* …, 7, 8: "Our best proof that the medieval sailor did not navigate by guesswork is afforded by the accuracy of the chart for which he had provided the material. He must have had pretty good dead reckoning", and: "Hundreds of cross-sea runs (peleggi) must have provided a useful framework for the chartmaker", and: "The *Compasso de Navigare* is an obvious compilation of such sources".
Eva G. R. Taylor, "Early Charts and the Origin of the Compass Rose", *Journal of Navigation*, Vol. 4 (1951), Issue 4, 351: "AD 1250 an Italian pilot could name 64 rhumbs and was finding even that

on the origin of portolan charts when he states: "… why deny thirteenth-century men a capacity for inventiveness?"[236]

However, Pujades goes more than just one step further than this attitude:

> "If we want to discover how portolan charts came into existence, how their use spread and what impact they had on medieval society, we must temper our obsession with mathematical precision – something with which the medieval mind was entirely unconcerned – and make a determined effort to fit the information the charts themselves and the scarce ancient documentation on them provide into the great jigsaw puzzle of the history of written culture and business activities of a specific era. Only in this way shall we find evidence in defence of our hypotheses. We must accept, in short, that the big questions regarding the advent of the new technique that constitutes the subject of this book pose not a purely geographical/cartographical problem (as some stubbornly insist), but rather a historical one."[237]

Summarising, Pujades effectively claims that mathematical analysis adds no value and that solution of the "big questions", among which I consider the question of their origin and construction method to be first and foremost, should be left to historians and not to cartographers or geographers. Unfortunately, in denying any role for quantitative analysis, Pujades throws away the proverbial baby with the bathwater, as he denies these charts any mathematical merit. However, it is precisely their extraordinary accuracy and their close resemblance to an image generated by a proper map projection that makes these charts so exceptional. Brazenly denying that there is anything to explain in this respect is hardly the way to solve the origin problem of the charts.

It is in particular Pujades's rejection of a role for mathematics that leads the mind to the British author C. P. Snow's lecture *The Two Cultures*.[238] Snow had been invited to deliver the Rede lecture at the Senate House of Cambridge University in 1959 and in this controversial lecture he lamented the lack of understanding and lack of communication that he felt existed between the 'sciences' and the 'humanities'. Apparently, more than half a century later, we are still wrestling with this problem. In The Netherlands both aspects of knowledge are referred to as *sciences*, the humanities as *alpha-sciences* and the

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number insufficient".

Eva G. R. Taylor, "The Oldest Mediterranean Pilot," *Journal of Navigation*, Vol. 4 (1951), Issue 1, 81: "That it was the work of an experienced sailor its language and precision leave no doubt …" (on the *Compasso de Navigare*).

See also footnote 211. None of these remarks have any supporting numeric evidence.

[236] Mollat du Jourdin 1984, 16.

[237] Pujades 2007, 506. When speaking of "the medieval mind" Pujades refers to the Christian European medieval mind.

[238] C. P. Snow, *The Two Cultures* (Cambridge: Cambridge University Press, Canto Edition, 1998).

sciences proper, as termed in English, as *beta sciences*. Generalising, *alpha scientists* tend to be good at synthesis, qualitative reasoning and languages, *beta scientists* in analysis, quantitative reasoning and mathematics and/or physics. The name doesn't solve any problems of communication or mutual understanding, but if we come across a scientific-scholarly problem that appears to straddle any gap that may exist between sciences and humanities, it helps to attempt to bridge that gap instead of, as Pujades does, emphasize it and claim ownership of the entire problem for one side or the other.

The problem of the origin of portolan charts indeed appears to straddle the boundary between these two broad categories of knowledge. It carries strong elements of some of the humanities, such as history and human geography/cartography, as well as some of the more exact elements of cartography and of geodesy. The geodetic aspects of mapmaking, i.e. the establishment of the geometric framework for maps and charts, have not been adequately taken into account in the research publications on this subject until now, as I have argued in the *Introduction*, but also the history of science has received scant attention in existing research. The latter is highly relevant for the problem of portolan chart origins, as it may provide an indication whether particular knowledge, skills and techniques, in existing research often assumed to have been present, can reasonably be expected to have existed in the period of interest. This aspect alone already straddles the gap, imaginary or real, between the humanities and the sciences. Any solution to the problem of the origin of portolan charts will not be found by searching exclusively in one domain. Symbolically that can be indicated by the overlap area in the Venn diagram in Figure 3.9.

Whereas the political-historical context was discussed in Chapter 1: *The historical context of the emergence of portolan charts*, relevant aspects of the history of science will be addressed in Section 5.10 of Chapter 5: *Navigational practices in the twelfth and thirteenth centuries*, before the core results of this study, derived using quantitative analysis, will be presented.

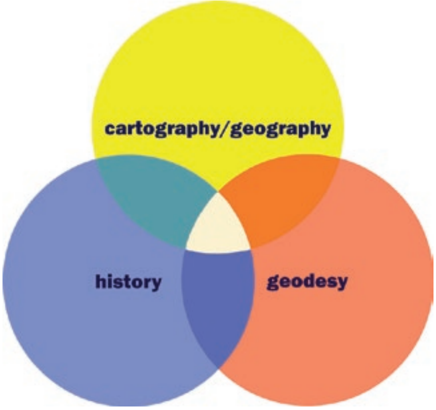

Figure 3.9 - *A multidisciplinary approach to solve the problem of portolan chart origins.*

4 PHYSICAL CONDITIONS OF THE MEDITERRANEAN SEA; MEDIEVAL SHIPS

4.1 Outline of this chapter

The current chapter discusses a number of aspects of the historical context related to the origin question of portolan charts, which establish boundary conditions for answers to this question.

Section 4.2 discusses the natural environment of the Mediterranean Sea, some of its hydrographic and oceanographic aspects, and its weather patterns. Both the prevailing wind patterns and dominant currents have exerted considerable influence on medieval shipping and on the development, or rather consolidation, of maritime trade routes that had existed since antiquity. The dominance of certain routes at the expense of others would have had a significant impact on the spread of navigation data that is widely presumed to have formed the basis for chart construction. Much of the information in this section has been extracted from John H. Pryor's work on this subject[239]; the oceanographic aspects have been summarised from Millot and Taupier-Letage[240] and supplementary information has been obtained from the Mediterranean Pilot V of the UK Hydrographer of the Navy[241].

Section 4.3 describes the two main types of ship in the medieval Mediterranean, the round ship and the galley, as well as their sailing properties. Knowledge of these properties and the insights gained in the natural conditions of the Mediterranean are important for answering the question whether these ships indeed sailed the Mediterranean on practically any course their masters desired, as is generally assumed.

4.2 The natural conditions in the Mediterranean

The purpose of this chapter is to describe factors in the geography, oceanography and meteorology of the Mediterranean area that impacted medieval navigation and shipping. These factors caused certain routes to be favoured and others to be shunned. The properties of medieval ships, to be discussed in Section 4.3 below, reinforced this se-

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[239] John H. Pryor, *Geography, Technology and War. Studies in the Maritime History of the Mediterranean 649~1571,* first paperback ed. (Cambridge: Cambridge University Press, 1992).

[240] Claude Millot and Isabelle Taupier-Letage, "Circulation in the Mediterranean Sea", *Handbook for Environmental Chemistry*, ed. Damià Barceló, Andrey G. Kostianoy, Vol. 5, Part K (Berlin, Heidelberg: Springer-Verlag, 2005).

[241] Hydrographer of the Navy. *Mediterranean Pilot, Vol. V*, Sixth Edition 1976, revised 1988 (London: Hydrographer of the Navy, 1988).

lection process. An important factor was the wind, which, during the summer months open to medieval shipping, blew predominantly from the north to north-west. In portolan chart literature the presence of currents in the Mediterranean is rarely if ever mentioned. Nevertheless surface currents exist and will have existed throughout the medieval Mediterranean and it needs to be investigated to what extent they influenced navigational accuracy. Were they predictable, so that the medieval seamen could anticipate and correct for their effects or were they random?

4.2.1 SURFACE CURRENTS

The physical characteristics of the Mediterranean, in particular the depth of its two main basins and its nearly enclosed nature, result in complicated patterns of water circulation, which are still the subject of intensive study by oceanographers. The discharge of fresh water from the few major rivers feeding into the Mediterranean, a net flow from the Black Sea and precipitation are not enough to compensate for water loss due to evaporation. Additional loss of water occurs through the Strait of Gibraltar, where highly dense saline Mediterranean water flows back into the Atlantic in a subsurface current. About 70% of the total water loss of the Mediterranean is compensated by an enormous surface influx of lighter and less saline Atlantic water through the Strait of Gibraltar. If the Mediterranean were not connected to the Atlantic, sea levels in the Mediterranean would drop by about 0.5 to 1 metre per year. The Atlantic water influx is about one million cubic metres per second. When the sea levels on either side of the Strait of Gibraltar are corrected for the effects of tides, ocean currents and atmospheric pressure variations, a dynamic height difference of several metres can be shown to exist between the Atlantic and the Mediterranean.[242] The result is an easterly[243] surface current through the Strait of Gibraltar, averaging 1-2 knots[244] and with a maximum of 5 knots, which, in antiquity as well as in the Middle Ages, was a considerable barrier for ships wishing to leave the Mediterranean through this narrow channel. Rivers and precipitation compensate for only a quarter of the water loss in the Mediterranean. The Black Sea water surplus, resulting in a current of maximum 3 knots through the Dardanelles, accounts for about 4%. Water circulation in the Mediterranean is complex and variable over time, but the general principle is that, at a basin scale, water circulates anticlockwise.[245] In the context of this study only surface currents are of interest, as

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[242] Claude Millot and Isabelle Taupier-Letage, "Circulation in the Mediterranean Sea", *Handbook for Environmental Chemistry*, ed. Damià Barceló, Andrey G. Kostianoy, Vol. 5, Part K, (Berlin Heidelberg: Springer-Verlag, 2005), 31.

[243] An easterly current is a current that flows *towards* the east, whereas an easterly wind blows *from* the east.

[244] Millot and Taupier-Letage 2005, 40.

[245] Millot and Taupier Letage state that water circulation at basin scale in the Mediterranean is anticlockwise *due to the Coriolis effect* (see footnote 6 in their book), which dictates that every moving body on the northern hemisphere experiences a deflection to the right, i.e. clockwise. Water flowing in through the Strait of Gibraltar is indeed deflected towards the right, i.e. towards the North African coast, but the constraining of the water flow by the configuration of the coasts causes circulation to

they influence shipping and navigation; vertical and subsurface circulation patterns will therefore be ignored.

The Atlantic water, when it enters the Mediterranean, is forced by the Strait of Gibraltar to flow to the north-east into the relatively shallow Alboran Sea, where it forms a clockwise gyre. Millot and Taupier-Letage add: "The inflow generally describes a second clockwise gyre in the east of the Alboran, but it can also proceed more or less directly toward Algeria, or describe a third more or less organised gyre. Out of the Alboran, the Atlantic water flow restructures itself along the Algerian coast (generally near 0° [Longitude]), mainly due to the Coriolis effect.[246] There, the Western Basin gyre starts to be clearly identified and it displays features that have justified the identification of an *Algerian Current...*" This Algerian Current follows the southern coastline up to the Sicily channel, where it bifurcates into a *vein*[247] moving north of Sicily into the Tyrrhenian Sea and one through the Sicily Channel into the Eastern Basin. The northern vein follows the Italian coast in north-westerly direction. Millot and Taupier-Letage stress the unstable character of the Algerian Current. With a velocity of up to 1.25 knots[248], it stays along the Algerian coast most of the time and generates relatively small (few tens of km in diameter) and short-lived (a few weeks/months) eddies. However, a few times a year it generates a meander growing to 50-100 km in both amplitude and wavelength, embedding a clockwise rotating eddy of 50-100 km in diameter. Larger and deeper eddies (200-250 km diameter) may cause the Algerian Current to spread and be pushed north for months.[249]

The part of the Algerian Current that continues into the Eastern Mediterranean Basin flows south-west between the south coast of Sicily and the Maltese islands. Millot and Taupier-Letage state that circulation of Atlantic water in the Sicily Channel is complex and that three distinct effects can be observed. The first is a north-eastward branch of the current which they associate with inter-annual variability, whereas other researchers have categorised it as a permanent meandering stream. "The second is the generation of mesoscale eddies that tend to drift into the central part of the Ionian Sea. The third is the more regular flow (the south-Tunisia vein) that, for most of it, follows the edge of the Tunisian shelf and for a minor (and upper) part of it, follows the Tunisian coast; both parts of this vein join off Libya". East of Ras Misratah the Libyan Cur-

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be anticlockwise, contrary to what would be expected.

[246] See previous footnote.

[247] Millot and Taupier-Letage use the term 'vein' to indicate a part of a current that follows the topography, whereas they reserve the term 'branch' for a split-off part of a current that moves seaward, unconstrained by topography.

[248] Millot and Taupier-Letage quote "several tens cm/s". The estimate of 1.25 knot comes from Mediterranean Pilot Vol V, 21 (1 knot = 1 nautical mile per hour). Pryor quotes a velocity of three to six knots in the Sicilian Channel (Pryor 1992, 13). Actual current velocities may vary.

[249] Millot and Taupier-Letage 2005, 40, 41. The paragraph on water circulation in the Western Mediterranean Basin has been summarised from these pages unless expressly stated otherwise.

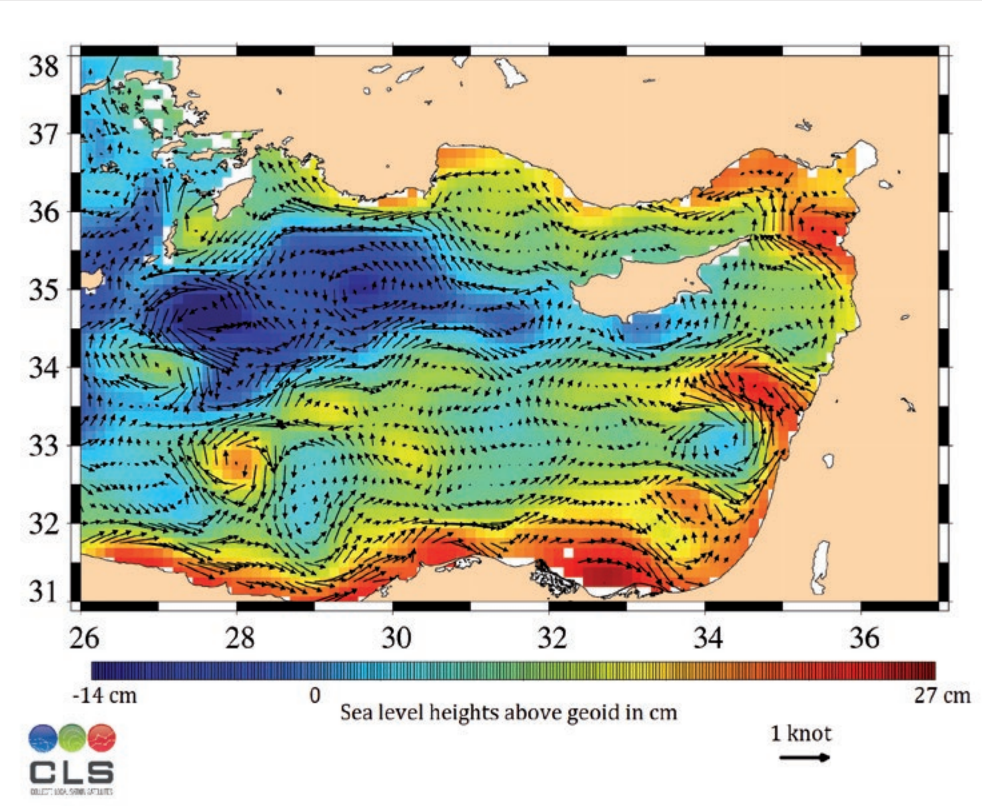

Figure 4.1 *- East Mediterranean surface currents (arrows), derived from satellite altimetry data. The sea level variation relative to the geoid can be interpreted as relative to mean sea level. This is indicated by the colour fill, of which the scale is indicated below the image. The currents have been derived from the altimetry data and do not include wind-induced effects. It is stressed that is a snapshot. (Image by courtesy of AVISO; The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes, http://www.aviso.oceanobs.com/duacs/).*

rent becomes unstable and generates mesoscale eddies, which become detached from the coast and drift into the Ionian Sea. Together with eddies that have formed immediately after the current left the Sicily Channel, they form a complex eddy field in the whole of the southern Ionian Sea. The basin-scale eastern gyre regains coherence from Ras Sem eastward, generating clockwise rotating eddies similar to the Algerian ones, up to Marsa Matruh (Egypt). These can be large, with a diameter of 150-250 km, and drift downstream with a velocity of less than ~3 km/day. To the south-west of Crete a wind-induced clockwise rotating eddy, the Iéropetra eddy, appears in summer under the influence of the *meltemi*, the strong north wind that blows in the Aegean. This eddy may survive during the winter and drift away; an additional new one may then form next summer.

Between Marsa Matruh and the Nile delta smaller clockwise rotating eddies (diameter 50-150 km) are formed and along the Levantine coast only small eddies form, drifting quickly with the main current at a rate of about 10 km per day. Along the Turkish south coast the main current meanders strongly and may thus generate clockwise rotating eddies of 50-150 km diameter. Rhodes divides the main Eastern Mediterranean current into a north-westerly and a south-westerly vein. The north-westerly current along the Turkish coast may disappear in summer under the influence of the *meltemi*. Halfway the Aegean the north-westerly current bifurcates again, forming separate anticlockwise gyres in the northern and southern Aegean. The northern one is joined by the outflow from the Dardanelles.[250]

Figure 4.1 illustrates the complexity of the surface currents, as calculated from satellite radar altimetric observations. It needs to be stressed that this is a snapshot only; the eddies that are visible are not stationary.

Tides in the Mediterranean are small. The maximum tidal amplitude of about 45 cm occurs at Gabes in Tunisia. Tidal currents periodically perturb the current patterns described above, as do variations in atmospheric pressure and surface winds. The magnitude of the currents is in general low, mostly in the order of one to two knots but less in the eastern Aegean and along the coasts of Italy and France[251]. Only in narrow passages are significantly higher current velocities experienced, e.g. at the Aegean entrance of the Dardanelles 3.5 to 4 knots, but in the Strait of Messina (tidal) flows can reach 6 knots.
The above summary can hardly do justice to the complexities of Mediterranean currents, but a more precise description is unnecessary. The objective is to demonstrate that very complex and variable currents exist in the Mediterranean and, although the basin-scale anticlockwise pattern of currents is well-known and repeatable, the detailed patterns would have been impossible to predict for medieval navigators. With modern fast-moving ships, currents in the Mediterranean will hardly be a factor in navigation at all, but with the much slower moving medieval sailing ships they would have affected navigational accuracy. This will be discussed further in Chapter 5.9. The repeatable current patterns were well-known in the Middle Ages and in antiquity and were actively used in navigation, for example when sailing against prevailing winds[252]; they were important factors in determining the selection of trade routes.

4.2.2 Wind in the Mediterranean

Another important factor is the repeatability of wind directions in summer. Summer weather in the Mediterranean is governed by the Azores High and the Indo-Persian

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[250] The above paragraph is has been summarised, paraphrased or cited from Millot and Taupier-Letage 2005, 44 – 47.

[251] Pryor 1992, 13.

[252] Pryor 1992, 15.

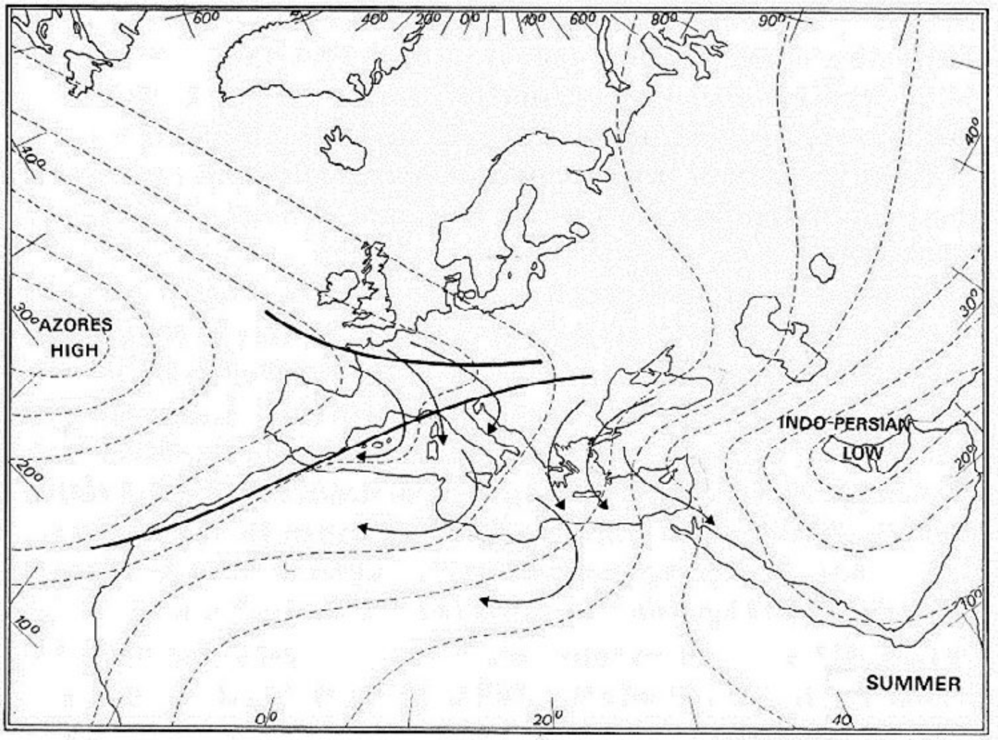

Figure 4.2 - *Typical sea-level weather patterns over the Mediterranean in summer (image by John H. Pryor 1992; published with permission of the author).*

Low. Interaction with geographical features around the Mediterranean produces complex weather patterns. The clockwise airflow generated by the Azores High combined with the anticlockwise airflow produced by the Indo-Persian Low are broadly speaking responsible for the dominance of north and north-westerly winds in summer.

Winter weather is governed by two other pressure systems, the North Atlantic Low and the Mongolian (or Siberian) High, which extends into the Danubian basin as a high-pressure ridge. Winter weather in the eastern basin is mostly influenced by the Mongolian High, while in the western basin the North Atlantic Low and the depressions it spawns are the determining factors in the weather. Although winds between north and west occur most frequently, there is no dominant wind direction in the Mediterranean in winter.[253]

According to Pryor these pressure systems "generate successive waves of pressure cells and fronts which enter the Mediterranean basin through gaps in its surrounding mountains. In general the fronts and pressure cells move in a roughly easterly direction across

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[253] Mediterranean Pilot V 1976 (1988), 17.

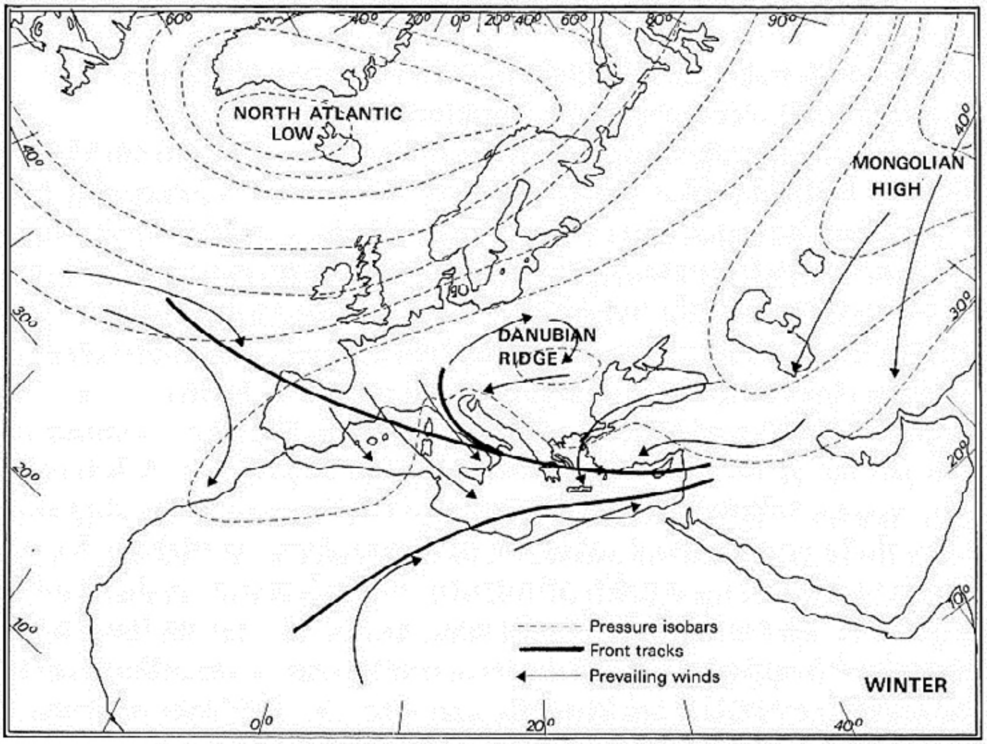

Figure 4.3 - *Typical sea-level weather patterns over the Mediterranean in winter (image by John H. Pryor 1992; published with permission of the author).*

the Mediterranean basin. Interacting with effects of the warm water of the sea and the cold highlands of the mountains surrounding it, their influences produce complex and variable local weather systems."[254]

Numerous local or regional winds of fame are produced by more detailed weather systems. The combination of a high pressure system along the north coast of Spain and a low pressure system in the Gulf of Genoa generates the *mistral,* as mutually reinforcing air flows from these systems increase in force further as the air is funnelled through the Rhone valley between the Massif Central and the Alps and/or between the Massif Central and the Pyrenees. The *mistral*, one of the most famous of the regional Mediterranean winds, can reach wind strengths of 7 or 8 Beaufort and occasionally even more.

A similar effect of mutually reinforcing air flows occurs over the Aegean Sea, where these winds are known as the *meltemi* or the *etesians* and which were an obstacle for any ship sailing north or west. The *meltemi* is a summer wind that is highly predictable; this

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[254] Pryor 1992, 16.

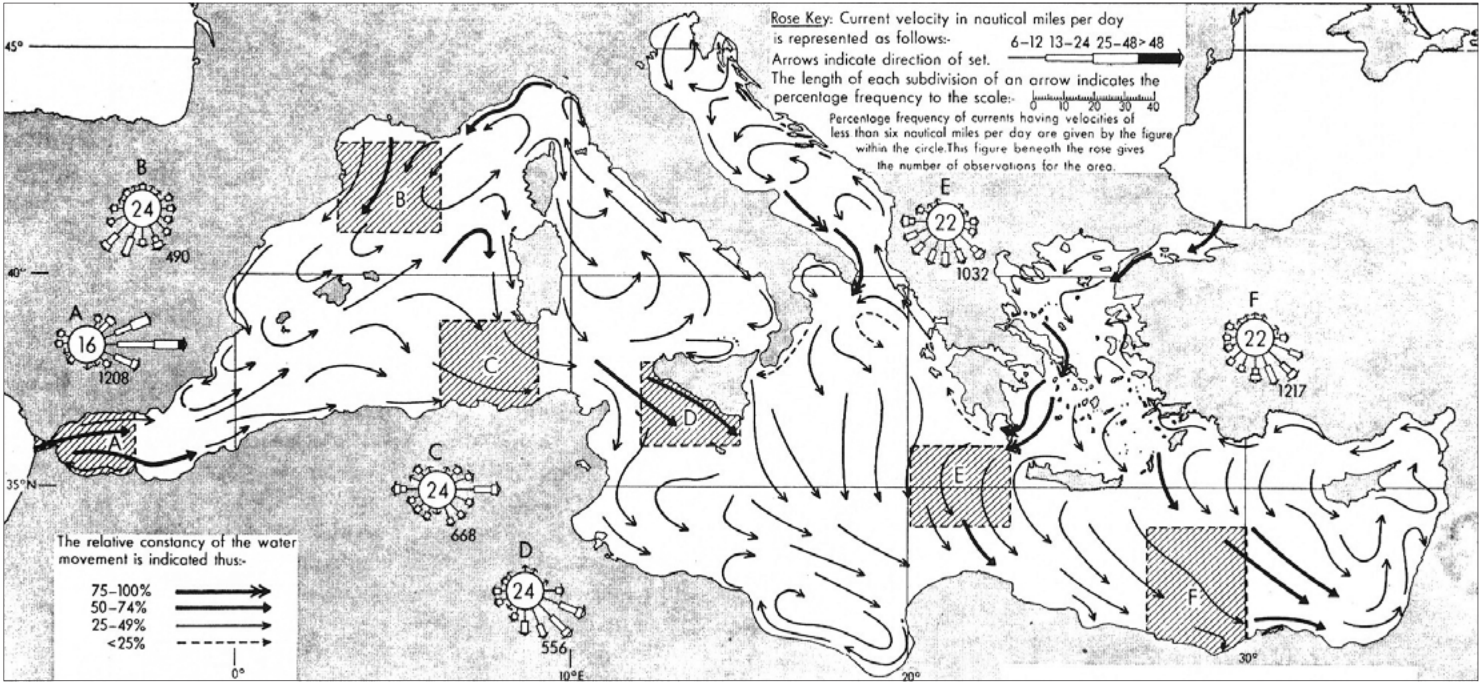

Figure 4.4 *- Predominant currents in the Mediterranean Sea - July. Note that these patterns do not include the presence of gyres and eddies!*
(source: Mediterranean Pilot V 1976 (1988), figure 1.132.2 – reproduced with permission).

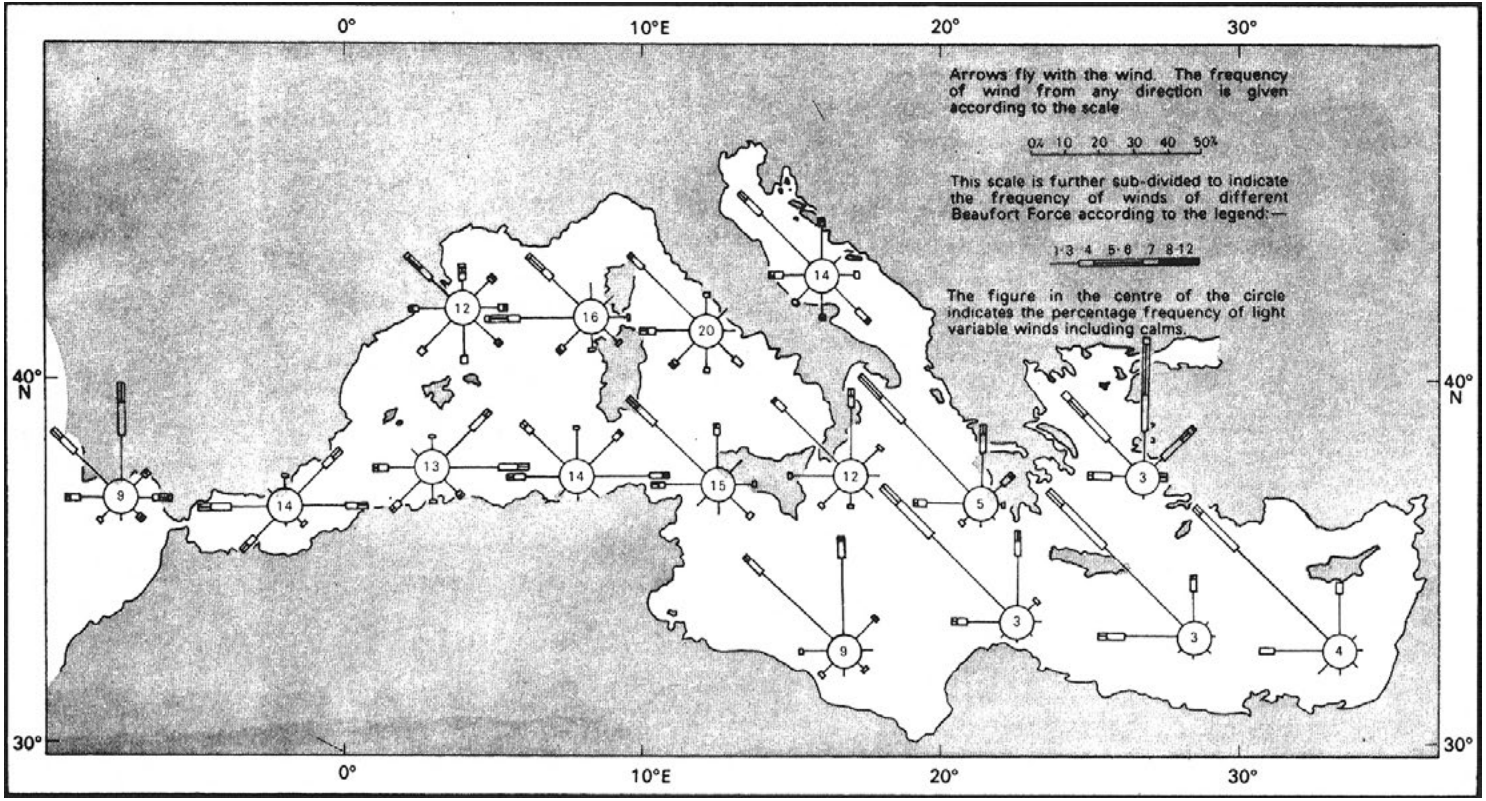

Figure 4.5 - *Wind distribution in the Mediterranean Sea - July*
(Source: Mediterranean Pilot V 1976 (1988), Figure 1.151.3 – reproduced with permission).

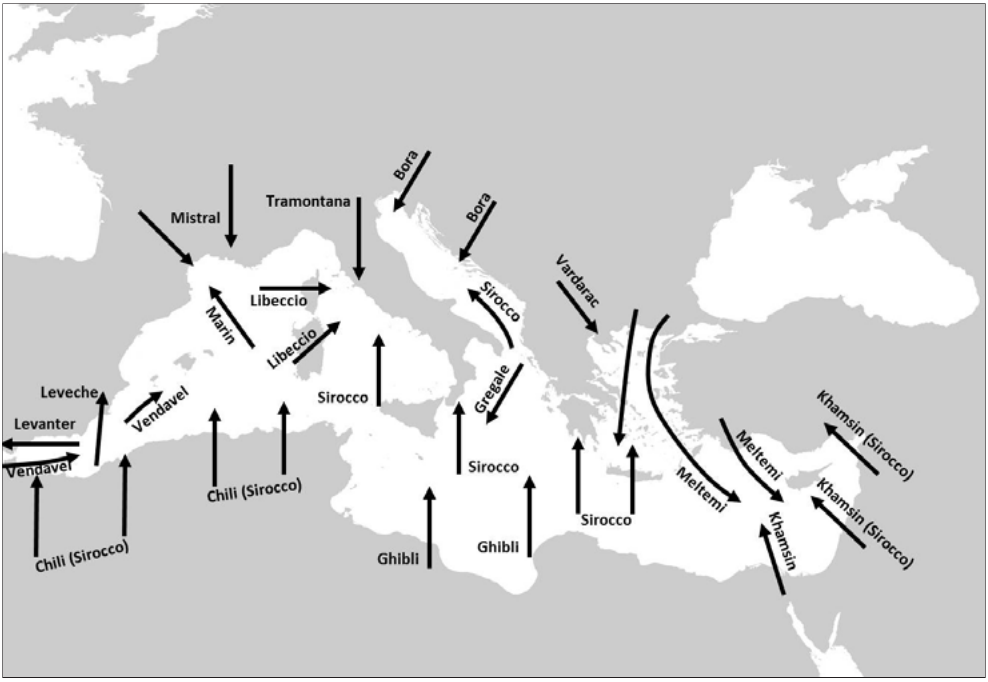

Figure 4.6 *- Regional winds in the Mediterranean*
(image is based on figure 1.151.5 of the Mediterranean Pilot V 1976(1988)).

wind can blow so steadily, that, as Pryor relates, "during the Roman period it was capable of bringing voyages from Egypt to Rome to a virtual halt for weeks on end." Pryor quotes the following numbers: "At Iraklion (Crete) its frequency at 14:00 hrs averages 75% from May to September, reaching a peak of 88% in July. At Rhodes the figures are 76.5% with a peak of 84% in August and Alexandria 83.5% with a peak of 90% in August and September."[255] Even modern sailing guides advise yachtsmen planning to sail north in the Aegean Sea to lift anchor at dawn, sail until noon and then seek a new anchorage to shelter for the *meltemi*, which can reach wind speeds of 5 to 6 Beaufort and generate considerable currents in narrow channels between islands, but usually doesn't appear until early afternoon. It is not too difficult to imagine that this would also have been the favoured medieval technique of dealing with these winds. The *meltemi* fans out as it leaves the Aegean Sea, losing in strength and becoming predominantly north-west to west in the easternmost part of the Mediterranean.

Another Mediterranean wind of fame, or rather notoriety, is the *sirocco*, which forms when tropical air from the North African deserts is pulled north by low pressure cells over the Mediterranean. This wind is very hot (~50° C) and very dry (humidity ~3%)

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[255] Pryor 1992, 20.

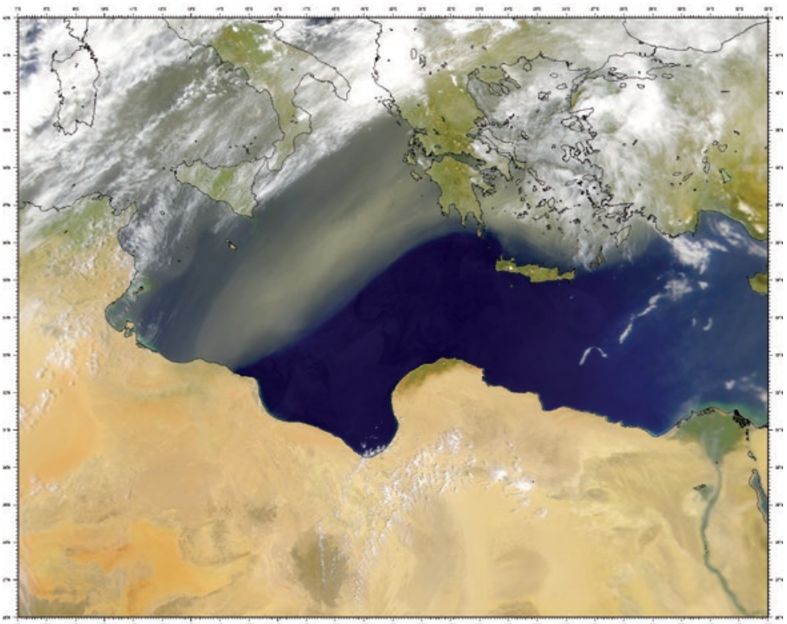

Figure 4.7 *- Dust blown over the Central Mediterranean by the Sirocco (Image taken from SeaWiFS on board GeoEye's Orb-View 2 satellite on March 26, 2001).*

along the south Mediterranean coasts, may reach gale force (7-9 Beaufort) and reduces visibility considerably due to the large amount of sand and dust it blows up. According to the Mediterranean Pilot "the intense heat and dust cause considerable distress to all forms of life". The *sirocco* blows from the south, an exception to the dominant wind patterns in the Mediterranean. It can blow from a few hours to a few days and is known under a variety of names, such as *ghibli* (Libya), *khamsin* (Egypt) and *leveche* (Algeria). It occurs mostly in late spring and autumn, but rarely in summer.[256]

Numerous other regional winds exist. One of the more useful winds in late medieval times must have been the strong easterly wind through the Strait of Gibraltar, known as the *levanter*, which would have enabled the slow sailing ships to pass the strait into the Atlantic against the current.

In addition to the general wind patterns that dominate the open sea, and the, often stormy, regional winds, diurnal thermal sea breezes (daytime) and land breezes (nighttime), caused by the difference in temperature between land and sea, are coastal effects which the medieval sailor must have put to good use. The band of these thermal winds may extend as far as 12 miles offshore.[257]

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256 Mediterranean Pilot V 1976 (1988), 18 and Pryor 1992, 20.

257 Pryor 1992, 95.

4.2.3 COASTAL TOPOGRAPHY AND HYDROGRAPHY

The prevailing north and north-west winds in summer dictated to a large extent the routes that medieval ships could follow with minimal risk of being caught en route by adverse winds. The geography of the coastline provided an additional factor for ships to seek or avoid certain coasts. The entire North African coast would, in the prevailing winds, be a lee shore, a place to avoid with a medieval ship, which had limited to no capability of beating into the wind.[258] Few good natural shelters existed along this coast that could offer refuge for ships in the event of adverse weather. All along the Mahgreb[259] coast reefs and rocks, extending offshore for miles in many places, add to the navigational dangers. Pryor quotes the fourteenth century pilgrim Ludolph van Suchem, who writes that "no one dares to sail to the south towards Barbary, for many rocks and shoals are to be found there covered by water". In spite of Van Suchem's words, merchants did it anyway, undoubtedly on the commercial principle that no gain is obtained without risk. The Christian cities in the Western Mediterranean maintained extensive trading contacts with North Africa from the second half of the twelfth century.[260] Gautier Dalché[261] relates that the customary route for Genoese and Pisan ships to Alexandria ran via the North African port(s) linked with their city. For Pisa that would have included Annaba (Bona) and Bejaia (Bugia), where Leonardo of Pisa (Fibonacci) received his mathematical training and made his acquaintance with the Hindu-Arabic number system.

The east coast of Tunisia is low and sandy, with many sandy shallows. Extensive shallows, indicated on all portolan charts, are present around the Kerkenna islands. From the Gulf of Gabes to Benghazi the coast is low lying, with rocky reefs extending a few miles seaward; it offers little help for visual navigation. Between Benghazi and Ras at Tin the coastal profile is higher, but reefs and rocky shoals continue to be a shipping hazard close to the coast.[262] From Ras at Tin to Alexandria the coast is lower, with sand hills dominating the coastal profile. Few natural harbours were available along the Libyan/Egyptian coast in the Middle Ages with the exception of Tobruk and the Marsa Matruh lagoon, the latter shown on portolan charts as Porto Alberton, but the presence of nearby reefs would have made its approach in the Middle Ages risky.

4.2.4 IMPLICATIONS FOR PORTOLAN CHART ORIGINS

Winds and currents along the North African coastline are distinctly unfavourable for westward shipping in summer. The few islands along the North African coast, including the Maltese islands, are small and were sparsely populated in the Middle Ages. They

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[258] See Section 4.3.2, *The lateen rig*.

[259] *Mahgreb* derives from the Arabic word *al Gharb,* meaning *West* and refers to the North African coast west of Bugia (Bejaia). See Heywood 1925, 31, footnote 2.

[260] Pujades 2007, 415.

[261] Gautier Dalché 1995, 66.

[262] Mediterranean Pilot V (1976) 1998, 60.

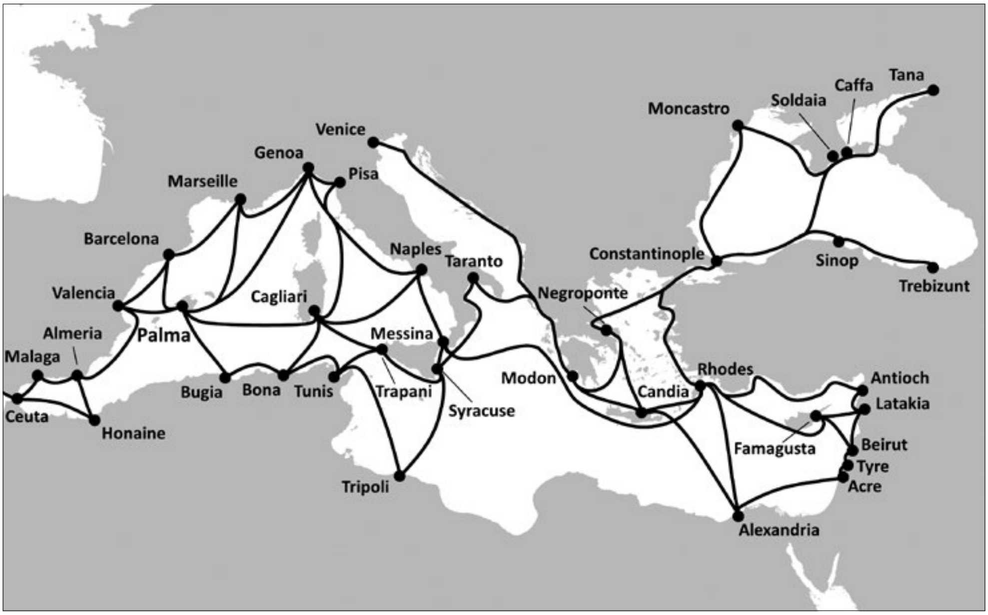

Figure 4.8 *- Dominant trade routes in the medieval Mediterranean.*

could not provide shelter and supplies to medieval ships, comparable to what the northern Mediterranean islands offered.[263] Apart from the extent and level of services on the northern islands, available to medieval ships, the number of these northern islands is much greater; they have an abundance of natural shelters, the islands are generally surrounded by navigable water and they offered opportunities for en route trade. Notably fresh water is more readily available than along the southern coast. Moreover, the high coastal profile and mountain ranges along the northern coasts provide excellent landmarks to aid visual navigation.

The interaction of these meteorological and geographic factors has therefore led to the emergence of a trunk route for Mediterranean maritime trade along the northern coast, a route that had been in use since antiquity and had lost none of its relevance in medieval times.

The implication for the construction of portolan charts from navigation data is that there would have been an unavoidable scarcity of data along the southern Mediterranean coasts, compared to a richness of data along the northern coasts. This ought to have led to a noticeable difference in accuracy or realism in the depiction of the northern and southern Mediterranean coasts, but nothing of that nature is visible on portolan charts, with the exception of the Gulf of Sirte, which is not well mapped on any portolan chart.

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[263] Pryor 1992, 24.

4.3 MEDIEVAL SHIPS

In addition to the natural factors described in the previous section, the characteristics of the ships that were used in the Middle Ages were an important factor because they reinforced the preference for established maritime trade routes. Without wishing to delve too deeply into the subject of ship characteristics, the properties of these ships that have a direct impact on navigation are highly relevant for this study.

The design of twelfth and thirteenth century Mediterranean ships ultimately derived, via the Byzantines, from the shipbuilding traditions of the Romans. An evolution from shell construction to frame construction took place, but this did not alter the fundamental shape of the Mediterranean cargo ship. War ships remained oar-driven, but the Byzantine *dromon* and medieval galley were lighter than the Roman galley and were not capable of, nor intended for, ramming the opponent. Medieval naval warfare consisted principally of boarding, followed by hand combat.

4.3.1 ROUND SHIPS

Although a large variety of ship types was used, both by Christian and Muslim states, the larger ships, used for long distance trade and transport, appear to have been similar in hull shape for both cultures. They had a rounded stem and stern and their hulls had a squat and pot-bellied appearance. At the top of the list, in terms of size, was the *navis*, according to Lane also called *buzus* or *banzonus*,[264] but in modern literature simply referred to as *round ship*.

Many other ship types were in use, but, with the exception of the galley, an appreciation of the sailing properties of the round ship is enough for an adequate understanding of what could and what could not be done with these vessels.

Not much information is available on the dimensions and shape of medieval round ships, but transcriptions of the contracts for the construction of the crusading fleet for King Louis IX are still extant and are an important source of numeric data, while iconography provides information on shape and details, be it that allowance needs to be made for the typical medieval lack of a consistent scale. Recent research into the characteristics of medieval round ships was done by John H. Pryor, who reconstructed the shape and dimensions of, what he called, an archetypal three-decked *navis*. Pryor even constructed a scale model, which allowed him to test some of the sailing properties of such ships (see Figure 4.10). It is in these ships that the evolution of the medieval round ship reached its peak.[265] In the fourteenth century the round ship was gradually

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[264] Lane 1973, *Venice*, 46. *Navis* is the Italian name for a round ship; the French referred to a round ship as *nef*, the Catalans as *naõ*.

[265] John H. Pryor, "The Mediterranean Round Ship", in *Cogs, Caravels and Galleons. The Sailing Ship 1000-1650*, ed. Robert Gardiner (London: Conway Maritime Press, 1994), 63.

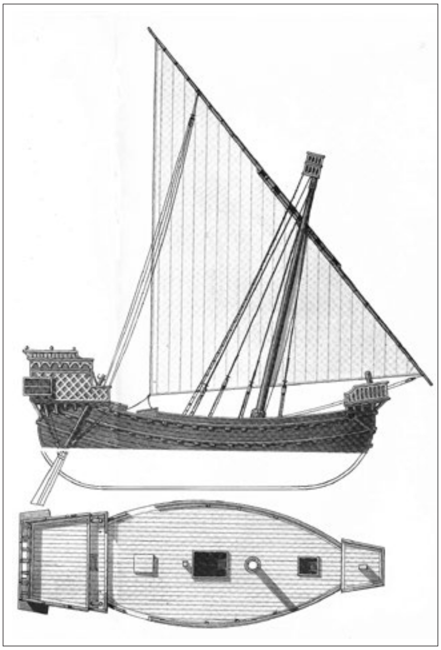

Figure 4.9 *- Reconstruction of a small one-masted round ship by Björn Landström, based on the 'St. Peter Martyr' relief in the church of San Eustorgio at Milan [Image source: Björn Landström, zeilschepen, Trans. J.G. Baggerman (Alphen a/d Rijn: Septuaginta, 1978; for Icob CV), 56-57].*

Figure 4.10 *- John H. Pryor's model reconstruction of an "archetypal" three-decked round ship for Louis IXth used in his 1270 Crusade (images courtesy of John H. Pryor).*

replaced by the square-rigged North European cog, which was already known in the Mediterranean as a ship used by crusaders from northern Europe.

The beam-to-length ratio of the *naves* or round ships was between 1:3 and 1:4 and they were steered by one or two steering oars, on starboard or on either side of the stern. For the larger medieval ships two masts was the norm, with occasional usage of three masts. The smaller ships carried only a single lateen sail, as shown in Figure 4.9. Single masts and the foremost mast on the larger ships were raked forward by about thirteen degrees.

The typical Mediterranean merchant round ship had two decks and measured around 300 metric tons (deadweight tonnage).[266] However, the three-decked ships built for Louis IX were the largest round ships constructed before the fourteenth century. Venice built two of those, Genoa three. Their deadweight tonnage was about 800 tons.

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[266] Pryor 1984, 376. Pryor describes the "archetypal" two-decked Genoese round ship as having a deadweight tonnage of 323 metric tons.

Figure 4.11 *- Kampen Cog, sailing close-hauled; the three strips that constitute the lower half of the sail are detachable 'bonnets' (©Stichting Kamper Kogge; reproduced with permission).*

They had one or more doors in the hull to allow the loading and unloading of horses; these doors were caulked before the ship sailed.[267] The stem to stern length, not counting the overhang of the superstructure, was about 35 metres and their beam about 10 metres. Two-decked round ships had an approximate overall length of 29 metres and a beam of about 7.8 metres. An interesting detail is that King Louis IX sailed to the Holy Land on his 1270 crusade on one of these three large Genoese round ships and it is from such a ship that the earliest known documented reference to a portolan chart was made, as described in Section 2.2.3.

It is difficult to estimate the speeds these ships were capable of achieving, one of the parameters required as input to the accuracy model for medieval navigation, which is presented in Chapter 5.9. The only data available is how long certain journeys took and this permits an average rate of progress to be calculated. However, since much time was spent anchoring overnight and waiting for favourable winds, actual vessel speeds can at best be a guess, unless through scientific analysis or sailing with replicas.

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[267] Pryor 1984, 192.

Perhaps it is helpful to take a look at data available for a reconstructed Dutch Hanseatic cog, which would not be much slower than a large round ship (see Figure 4.11 above). The stem-to-stern length of this *Kampen cog* is 21.6 metres, its beam 7.6 metres and its deadweight tonnage 85 tons. It is square-rigged with a maximum sail area of 140 square metres, including the three bonnets (sail extensions at the bottom of the sail), visible in Figure 4.11. Running before the wind in a strong breeze (Beaufort 6) it achieved 7.7 knots, but running in a light to gentle breeze (Beaufort 2-3) only 2.5 knots.

Braced to sail as close to the wind as possible in a strong breeze (Beaufort 6) it managed 4 knots, but at the expense of considerable leeway. Allema and Hubrechtse, who conducted a scientific analysis of the hydromechanic properties of this ship, state that it was able to point about 70 degrees to the true wind but then had a drift angle of about 20 degrees, making beating against the wind a "time-consuming if not impossible business".[268]

4.3.2 THE LATEEN RIG

The type of rig used almost exclusively in the Mediterranean was the lateen rig. Greek and Roman ships used a square rig, but the lateen rig was probably already known in antiquity.[269] A ninth century Byzantine illustration is generally regarded as the oldest representation of the lateen sail.[270]

Some writers have claimed the lateen rig to be superior to the square rig, because it supposedly allowed ships to beat into the wind. Pelham, for example, citing D. W. Waters, states that the introduction of the lateen sail "freed the sailor from the 'tyranny of the following wind' and allowed him to sail with all but directly contrary winds".[271] However, the rig is the lesser of the two factors that determine whether a ship can maintain a course-made-good close to the wind. The determining factor in the windward capability of a medieval round ship would have been the shape of its hull. The bottom of these ships was flat, with rounded bilges, resulting in an underwater ship that lacked any hydrodynamic property to resist leeway. With their high beam-to-length ratio these ships were likely to make so much leeway when they would attempt to sail close-hauled that any advantage obtained from being able to point higher would be undone. Pryor writes: "By modern standards, the round ships of the Middle Ages were poor sailers. Their lateen sails permitted them to point into the wind fairly well, but their hull design negated many of the advantages gained from the sail configuration."[272] Pryor also re-

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[268] Ir. J. Allema and ir. A. Hubrechtse. "Een kogge langs de hydromechanische lat", *SWZ Maritime* (Vol. 18), July/August 2008: 4, 5.

[269] Pryor 1994, 68.

[270] Pryor 1994, 66.

[271] Pelham 1980, 34. The phrase "tyranny of the following wind" is cited from David W. Waters, *The Art of Navigation in England in Elizabethan and Early Stuart Times* (London: Hollis and Carter, 1958), 21.

[272] Pryor 1994, 72, 73.

fers to accounts of travellers who describe how such ships had extreme difficulty not to be set back in adverse circumstances, i.e. maintaining a course-made-good of at best ninety degrees with the wind. He quotes Ibn Jubayr, a Muslim traveller from Andalusia on pilgrimage to Mecca, who, on his return voyage in 1185, boarded a Genoese ship at Acre. Ibn Jubayr wites:

> "…Steadily we sailed on, under a propitious wind of varying force, for five days. Then the west wind came out of ambuscade and blew into the ship's bows. The captain and ruler of the ship, a Genoese Rumi, who was perspicacious in his art and skilled in the duties of a sea-captain, made shift to elude this wind by tacking left and right and sought not to return on his tracks. The sea was calm and gentle. At midnight, or near to it on the night of Saturday the nineteenth of Rajab, being the 27th of October, the west wind fell on us and broke a spar of the mast, known as the *ardimun*, throwing half of it, with the attaching sails, into the sea. God saved us from its falling on the ship, for in size and bulk it resembled a mast".[273]

The yards of Mediterranean round ships could be up to one-third longer than the hull of the ship. For the large three-decked ships mentioned above, the length on the yard of the largest sail, the *artemon*, was some 45 metres. Such a yard could weigh up to eight tons, but these ships were rare.[274] For the two-decked ships a figure of three to four tons is realistic.

Another factor that would have had a further adverse effect on any ability to hold a close-hauled course was the fact that on such a course the windward steering oar would be in the turbulent wash of the ship due to its excessive leeway, which would render it useless and make the ship very difficult to steer. Furthermore, the centre of effort of the huge sails of round ships was situated significantly forward of the centre of pressure of the windward forces on the underwater ship. Whereas this would be helpful for maintaining a course with the wind dead behind, it would result in serious lee-helm on any other course, i.e. a tendency of the ship's bow to blow away with the wind. The closer to the wind the ship would try to sail, the worse this effect would become. This would make a ship, which would already be difficult to steer with only one effective steering oar, extremely difficult to handle. The lee-helm is confirmed by John H. Pryor's model of the archetypal three-decker.[275] Lee-helm would actually have been a necessary property of the ship. When sailing before the wind in a significant swell, a medieval ship

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[273] Pryor 1992, 1, quoting *The Travels of Ibn Jubayr*, trans. Roland Broadhurst (New Delhi: Goodword Books, 2007): 327. Note that Ibn Jubayr states that the sea was calm and gentle!

[274] Pryor mentions 6.5 tons to 7 tons. My figure of 8 tons assumes that ash, which has a specific weight of about 0.68 tons per cubic metre was used for the yard, and that the yard was tapered to 30 % of the diameter at the end and over half the length of the yard. The dimensions of the yards are stated in the extant contracts for the ships. This calculation is valid for the largest of the yard carried on Pryor's archetypal three-decker.

[275] Pryor 1984, 380.

would continually be overtaken by waves. A wave will pass under the stern first and as result the stern will be pushed leeward. Even modern yachts show this behaviour and when the centre of effort is not positioned significantly in front of the pressure point under water, the ship may run out of control, end up abeam of the waves and capsize, an event known as *broaching*. The significant lee-helm of a medieval ship would help to prevent this disastrous event from happening.

Vidoni concluded that the rudder, be it a stern rudder or a set of steering oars, was only the primary means of steering the ship under sail for small single-masted ships and that on larger two-masted and three-masted ships manipulation of the rig was the principal method for performing manoeuvres under sail, e.g. changing tack.[276]

Tacking with a large lateen sail was a complicated and laborious affair and was done by wearing ship and gybing. In anything but light winds the procedure was to lower the yard(s), detach the sails, hoist the yard again, bring it into a vertical position and work it to the other side of the mast, lower it again, reattach the sail to the yard, and finally hoist yard and set the sail for the new course.[277] Given the enormous weight and length of the yard on large round ships, this must have been an awkward manoeuvre at the best of times. In light winds and on small ships the sail might have been left on the yard and, prior to tacking, released far enough for the sail to flap idly before the mast, thus minimising its pressure on the mast. The yard would have to be manhandled into a vertical position and moved to the other side of the mast. With the yard in its new position the sheet, carried around the mast to the other side of the ship would be hauled in to the fairlead at the other side of the vessel and set for the new course.

The enormous rig of round ships and larger galleys alike was very vulnerable to damage by sudden squalls, as Ibn Jubayr's story illustrates, and extra vulnerable during the tacking manoeuvre. Lehmann quotes an example from the medieval pilgrim Felix Faber, who describes an event when, during tacking, the Venetian captain of the (merchant) galley, fearing the manoeuvre would end in disaster, considered it the better part of valour to get out the way and, lowering himself into the towed ship's boat, abandoned ship. However, the galley didn't capsize and with some difficulty the captain was apprehended and brought back on board.[278] Round ships carried one or more spare yards, as well as several sets of sails, the latter not only to replace a damaged sail, but also to counter variations in wind strength.

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[276] Tullio Vidoni, *Medieval Seamanship under Sail.* MA thesis (The University of British Columbia: Vancouver 1987),10.

[277] L.Th. Lehmann, *De galeien: Een bijdrage aan de kennis der zeegeschiedenis* (Amsterdam: De Bezige Bij, 1987), 117. See also: Lionel Dimmock, "The Lateen Rig". *The Mariner's Mirror*, Vol. 32 (1946), 41.

[278] Lehmann 1987, 117. Lehmann cites Felix Faber, *Evagatorium in Terrae Sanctae, Arabiae et Egypti peregrinationem* (Stuttgart: 1843), I, 155.

A factor which would limit the ability to point high with a lateen rig was the fact that the sails were not flat, but may have been cut with a considerable camber[279], as people believed for a long time that billowing sails made better use of the available wind.[280] Stretching of the cotton as a result of usage would lead to increased billowing.

In conclusion, the advantage of the lateen sail in the Mediterranean appears not so much to have existed in creating an ability to sail upwind, although medieval sailors may have believed the rig gave them that capability, as in increasing the overall sail area so that better use could be made of the lighter summer winds in the Mediterranean, more than would have been possible with a square rig. Wind speed increases with height above the water and mostly so in light air.[281]

The limited sailing capabilities of the medieval Mediterranean round ship made sailing an affair of waiting for a favourable wind[282] and sailing with it for as long as it held and, where possible, making use of known patterns of currents. Together with the geographical and meteorological factors mentioned earlier in this chapter, the limitations in sailing capabilities reinforced the sailor's preference for routes along the northern Mediterranean.

4.3.3 GALLEYS

Not yet discussed is the other important ship type of the twelfth and thirteenth century Mediterranean: the *galley*. The galley even survived, with little change to its design, until the end of the eighteenth century. Although galleys carried one or two lateen sails, they were in essence large rowing gigs. The ancestor of the medieval galley was the Byzantine *dromon*, but, unlike the *dromon*, the oars of a galley were all positioned at the same level.[283] The galley was primarily a warship, although in times of peace it might be used for the transport of low-volume / high-value goods or to carry well-paying passengers. In the fourteenth century the much larger and very seaworthy three-masted merchant galley was introduced by Venice, as the name suggests, for commercial voyages, although it turned out be a very effective warship as well. Since this is too late to have

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[279] Camber = the ratio between 'depth' of the sail and the chord distance from luff to leech (along a horizontal line). Czeslaw A. Marchaj, *Sailing Theory and Practice* (New York: Dodd, Mead & Co. 1964), 64.

[280] Pryor 1984, 363-366.
See also William Shakespeare, *The Merchant of Venice*, Act 1:
Salarino:
Your mind is tossing on the ocean;
There, where your *argosies with portly sail*, …etc
Note: 'argosy' = large merchant ship; the name probably derives from Ragusa (Dubrovnik).

[281] Marchaj 1964, 71, 72.

[282] Pryor 1984, 379.

[283] John F. Guilmartin Jr. *Galleons and Galleys* (London: Cassel & Co, 2002), 109,110: galleys before about 1200 had two vertically separated rows of rowing benches, one below deck and one above, but from 1200 onwards all rowers were positioned above deck on the same level.

Figure 4.12 *- Model of a sixteenth century Maltese galley in the Museo Storico Navale di Venezia (photo credits: Myriam Thyes).*

played any role in the possible development of portolan charts, the merchant galley will not be considered here. In the twelfth and thirteenth century galleys existed in several sizes, in descending order of size the *galee sottile*, the *galiote* and the *fusta*. The *galiote* was rowed by two rowers to the bench and generally had 18 to 20 benches on either side. *Fustas* were smaller again, with 10 to 15 benches and two oarsmen to the bench. Both *galiotes* and *fustas* were vessels preferred by corsairs.

Two oarsmen to the bench, each working his own oar, was the norm, but according to Marino Sanudo ('Torsello') a third rower and oar per bench was added at the end of the thirteenth century.[284] The oars pivoted on an outrigger, the *apostis*, clearly visible in Figure 4.13.

Galleys rode low on the water, so that the oars were as near to horizontal as possible for maximum effectiveness. The hull of a galley was closed by a deck, although the small hold could be accessed through ten[285] hatches. The 'standard' war galley was the *galee*

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[284] Marino Sanudo, *Liber Secretorum Fidelium Crucis* (Hanover:1611), LII, pars IV, caput V-XI: cited in R. C. Anderson, *Oared Fighting Ships*. 2nd ed., (Kings Langley, Argus Books: 1976), 52.

[285] Lehmann 1987, 26.

Figure 4.13 *- Reconstruction of a seventeenth century Genoese light galley in the Galata Museo del Mare, Genoa (Photo credits: Mentelocale).*

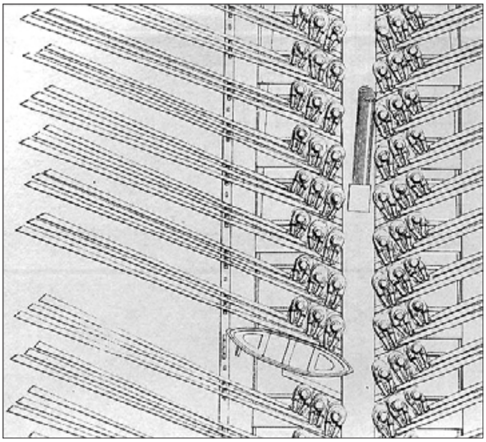

Figure 4.14 *- Rowing arrangement alla sensile (simple fashion) on a trireme galley, each rower with his own oar. Later in the fourteenth century the simpler a scaloccio was introduced, with only one (large) oar per bench, worked by multiple rowers. This became the norm.*
(image source: http://brunelleschi.imss.fi.it/michaelofrhodes/life_1401_1406.html, Dibner Institute for the History of Science and Technology).

sottile or light galley. Pryor provides the dimensions of such galleys built for Charles I of Anjou. These had a length over all of 39.3 metres, which was more or less the norm for such vessels, a hull width of 3.7 metres and a draught of only one metre. The width from starboard to port *apostis* on Charles I's galleys was 4.45 m. These galleys had two masts, carrying a lateen sail each, with the forward mast raked forward significantly. The lengths of the forward and middle masts were 16 and 11 metres and their yards 26.7 and 17.3 metres respectively. Steered by two steering oars, their deadweight tonnage was about 80 tons.[286] Also Muslim states used the galley, which they called a *kadirga* and which was quite similar to the Christian light galley, but smaller and lower in the water.[287]

It is generally agreed that galleys did not sail well. Anderson expresses surprise that only the lateen rig was used on galleys, even until their disappearance in the eighteenth century. After all, he says, "The lateen's strong point is in windward work [sic!] and it is hard to believe that so narrow and shallow a vessel as a galley ever attempted to sail to windward at all. Her sailing must always have been well off the wind and for that a square sail

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[286] Pryor 1992, 66.
[287] Pryor 1992, 68.

Figure 4.15 *- Genoese light galley: stern (Photo credits: Pete Morris).*

Figure 4.16 *- Genoese light galley: deck (Photo credits: Pete Morris).*

would have been more suitable."[288] Pryor asserts that "galleys were notoriously poor sailers" and that even merchant galleys, usage of which peaked in the fifteenth century, had great difficulty beating against the wind.[289]

A galley under sail carried its oars outboard at an angle from horizontal, so that they stayed free from the water, probably by pushing the ends under the rowing benches. Heeling, except for small angles, was impossible because of the low freeboard: the lee *apostis* would quickly become submerged, which would cause the oars to be washed away, but more importantly exposed the ship to immediate capsizing. The lateral balance of so narrow a vessel, combined with the high rig, cannot have been very good anyway. Even running before the wind in any significant breeze would be awkward, as ships under sail have a tendency to start rolling on a dead run, with the same risk. Sailing appears only to have been an option in very light conditions and in the absence of any significant waves. Galleys risked being swamped in even a modest swell.[290] The deck that covered the entire ship offered insufficient protection. Pryor quotes Marino

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[288] Anderson, 1976, 60. See my comments on the lateen rig above.

[289] Pryor, 1992, 72, 73.

[290] Pryor 1992, 69, 70.

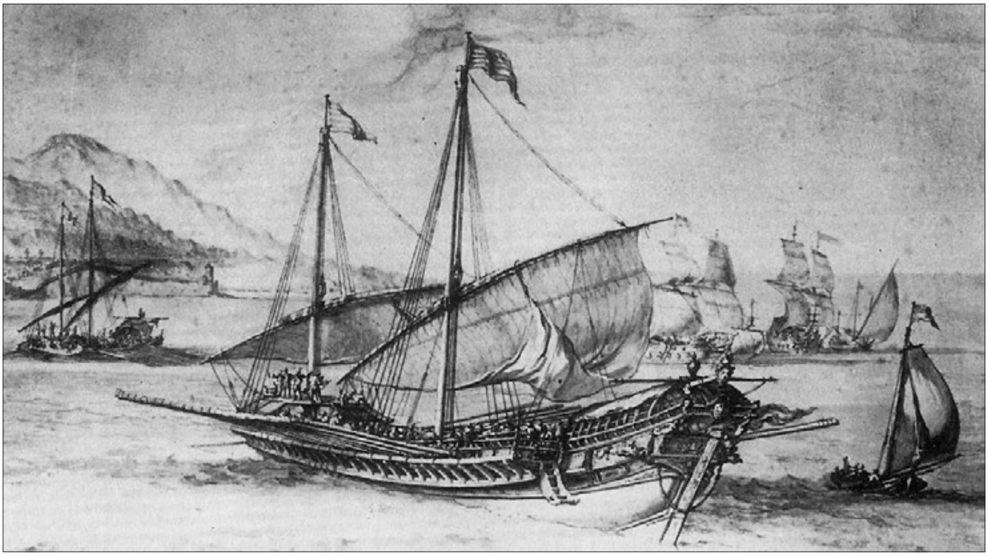

Figure 4.17 *- Galley near Marseille - Pierre Puget, 1655 (Musée des Beaux Arts, Marseille).*

Sanudo in the description of the latter's plan for a naval blockade of Egypt: "by surveillance of the sea alone, it cannot be completely prevented that anyone be able to cross by sea to the lands subject to the Sultan. The reason for which is this: that armed galleys cannot stay out to sea in winter time. And even in calm weather they are ill advised to be found out of port at night time in winter".[291]

In the twelfth century Roger of Hoveden wrote: "galleys cannot, nor dare not, go by that route [the open sea crossing from Marseilles to Acre] since, if a storm should arise, they may be swamped with ease. And therefore they ought always to proceed close to the land."[292] John H. Pryor adds to his quotations of Marino Sanudo and Roger of Hoveden, that "the history of naval warfare in the Mediterranean is replete with instances of the virtual elimination of galley fleets caught out at sea by heavy weather", and provides four examples.[293]

Galleys therefore shunned the open sea and stayed as much as possible within reach of shelter. Pryor estimates the cruising speed of a galley under oars to be on average three knots during daylight hours and that it would have to take in new water supplies after two to three weeks.[294] This determined the striking range of galleys when they operated from a home port.

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[291] Marino Sanudo, *Liber Secretorum*, I.4.2 (page 28), cited in Pryor 1992, 70.

[292] Roger of Hoveden, *Chronica*, ed. W. Stubbs (London: 1870), Vol. 3, 160, cited in Pryor 1992, 38.

[293] Pryor 1992, 70.

[294] Pryor 1992, 84.

4.3.4 IMPLICATIONS FOR PORTOLAN CHARTS ORIGINS

In the study to discover the origin of portolan charts, the above discourse on medieval ships and sailing provides necessary background information in order to assess how realistic the aspect of the medieval origin hypothesis is, which presumes that medieval ships criss-crossed the Mediterranean on whatever course their crews desired, collecting numerical data on courses followed and distances sailed.

It has been shown that summer winds in the Mediterranean, the suitability of the coasts for safe navigation, the supply of fresh water and the opportunities for en route commercial activities had tended to favour the northern Mediterranean coasts over the southern coasts.

Medieval ships had limited capability of beating into the wind, which reduced the choice of sailing routes and they would have preferred the proximity of sheltered anchorages in case they were caught by adverse winds, thus reinforcing the dominance of the trunk route along northern coasts. Travelling by ship in the medieval Mediterranean involved frequent waiting for the right wind and/or being blown off course. Galleys generally stayed within close reach of shelter anyway, avoiding prolonged exposure to open water. When deployed as a protective force for convoys of round ships, as was often the case, they therefore forced the round ships to follow the safe route through the islands along the northern coasts.

The low speed of which these vessels were capable made them, more than modern ships, susceptible to currents, which, although not strong in open water, were unpredictable. These factors would have posed limitations on the accuracy of navigation when out-of-sight of land. I shall attempt to quantify this in Section 5.9.

The characteristics of medieval ships reinforced the use of the trunk route along the northern coasts of the Mediterranean. The dominance of these routes should have led to a misbalance in the data that was supposedly collected by all these ships. Other routes were probably also sailed, but not as frequently as those trunk routes. This data misbalance ought to be visible in the portolan charts if they would have been constructed from such data, but the problem is: it isn't. It begs the question how these charts can show the correct proportions of the Mediterranean when they are based on such an inevitably misbalanced dataset.

Summarising, the following conclusion may be drawn.

5. *Geographical and meteorological factors, combined with the limitations of sailing characteristics of medieval ships, led to the strong preference of a trunk route for maritime trade along the northern Mediterranean coasts*[295].

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[295] See Pryor 1992. This is a confirmation of John H. Pryor's conclusion.

5 NAVIGATIONAL PRACTICES IN THE TWELFTH AND THIRTEENTH CENTURIES

5.1 Introduction and outline of the chapter

Very little is known about navigational practices and capabilities in the twelfth and thirteenth centuries. Navigation was regarded as a craft, a skill, not worthy of scholarly attention. It must be presumed that knowledge was transmitted orally from master to pupil. The only contemporary author to describe at least some aspects of Mediterranean navigation was the famous Majorcan philosopher Ramon Llull (~1235 - ~1315).

Nevertheless, some understanding of medieval navigation is of great importance in providing answers to questions relating to the construction method(s) of portolan charts, particularly methods that are assumed to have been used in the context of the medieval origin hypothesis.

One way to fill in the gaps in our knowledge is to deduce such capabilities from the accuracy of portolan charts. However, such an approach is only valid when it is absolutely certain that portolan charts are indeed an original creation of medieval European or Arabic-Islamic culture and as I have argued in the previous chapters, that certainty cannot be demonstrated. It would therefore carry a significant risk of contaminating any conclusions with presuppositions and this subject will therefore have to be addressed in a different way. This will consist of examining direct references to navigational aids and methods in literature, supported by the analysis of the physical environment of the Mediterranean and relevant aspects of ship design and sailing capabilities, as discussed in the previous chapter. An important contribution in this area has been made by Ramon Pujades, who, as part of his PhD study, researched available notarial documents of the period up to 1470 in the archives of Catalonia, Valencia, Majorca, Genoa, Sicily and Venice that refer to nautical cartography and navigation.

Section 5.2 discusses the 'tools of the trade' as Ramon Llull documented them and the various interpretations given to his words over time. Section 5.3 discusses a navigational tool, known as the *Toleta de Marteloio*, in particular its interpretation and misinterpretation. The *Toleta* is best described as a trigonometric reduction table to aid navigation by dead reckoning. The description of the *Toleta* forms the lead-in to a discussion on the *mathematical seaman*, a concept introduced and defended by E. G. R. Taylor in the 1950s, who suggested that medieval sailors were the first professional group of people to use mathematics in their everyday work.[296]

Sections 5.5 and 5.6 proceed with a discussion how distance and time were presumably measured on board ships in the Middle Ages, including views expressed in existing literature on, in particular, distance measurement.

Section 5.7 is a lengthy discussion on the origins of the compass. The discussion of the introduction of the compass into medieval navigational practices is still a subject that has not been concluded satisfactorily, as was mentioned in the previous chapters. Was it introduced in time? Was its usage widespread enough to have contributed to the large-scale collection of navigation data that is presumed to have constituted the observational basis for the construction of portolan charts? Or did it come too late and if so, what consequences would that have for the question of portolan chart origins? Patrick Gautier Dalché remarks drily: "The number of hypotheses on the origin of the compass are inversely proportional to the number of facts that underpin them".[297] A summary of the most relevant facts and hypotheses will be provided.

Section 5.8 summarises the implications of the foregoing on the research question of this thesis regarding the origin of portolan charts.

The sections mentioned provide the basis for the description of an error model for medieval navigation in Section 5.9. The mathematical background is provided in Appendix III. An important condition for the acceptance of any hypothesis that presumes a body of shared Mediterranean navigation data as the basis for chart construction is that this navigation data necessarily has to have been of a sufficient accuracy in order to explain the accuracy of the charts. This subject has hardly been approached quantitatively at all; it is generally presumed that the accuracy of the medieval navigation measurement data was increased to the level required for the accuracy of the charts by calculating the average of multiple estimates of the bearing and distance of the same course leg.

The navigation accuracy model in Section 5.9 represents an optimistic view on medieval navigation in the Mediterranean, optimistic because of its assumptions of widespread use of the mariner's compass and consistent application of rigorous methods for distance estimation. Both the accuracy model and the dominance of certain routes, as discussed in Chapter 4, will find their way into the geodetic control network presented in Chapter 9: *The map projection; artificial or intentional?* The accuracy model will serve as a

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[296] Taylor 1960, *Mathematics* …, 12. Apart from the question whether Taylor's claim is correct that European medieval sailors used mathematics routinely, it is definitely incorrect in the sense that Taylor overlooks the fact that e.g. the astronomers in Islamic civilisation used mathematics routinely in their work well before the twelfth century AD.

[297] Gautier Dalché 1995, 76.

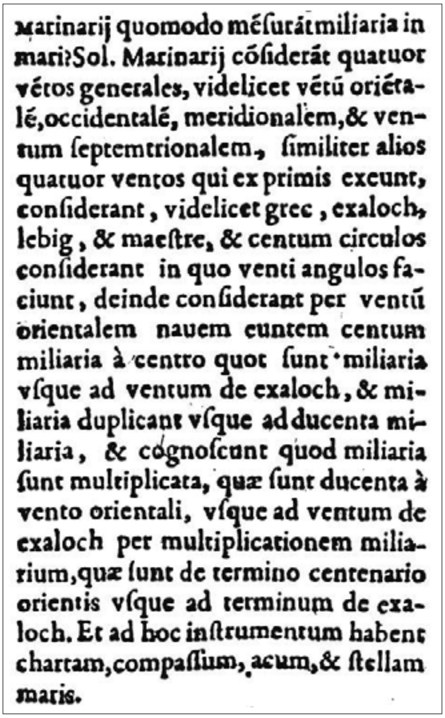
touchstone for the analysis of the course and distance data of *Lo Compasso de Navegare*, the oldest portolan covering the entire Mediterranean Sea in Chapter 8: *The relationship of portolans and portolan charts*.

In the last section of this chapter, Section 5.10, the context of the emergence of portolan charts will be discussed in the light of the history of science and the thinking about geography in the twelfth, thirteenth and fourteenth centuries. The recent study by Ramon Pujades[298] has drawn attention to the importance of the growth of literacy and the emergence of a written culture as conditional to the appearance, usage and distribution of portolan charts. Of equal if not greater relevance for the question regarding the origin and construction of these charts are certain aspects of the development of scientific thinking, such as the gradual move towards quantification of natural phenomena. The key question is: how well does an advanced mathematical approach to navigation and charting, in particular the large-scale calculation of averages of measurements, fit into the patterns of thought of this period?

5.2 NAVIGATIONAL TOOLS: CHART & DIVIDERS, NEEDLE & STAR

Ramon Llull was a Franciscan tertiary from Majorca. In his work *Arbor Scientiae* (1295-96), originally written in Catalan, he describes what is presumed to be contemporary[299] navigational knowledge. He does this, using the scholastic dialectic method, in the form of question and solution.

"How do sailors measure their mileage at sea?" *Solution*. Sailors consider four general winds, namely the east, west, south and north wind, likewise another four winds which derive from the first, namely north-east (*grec*), south-east (*exaloch*), south-west (*lebig*) and north-west (*maestre*). And they consider the centre of the circle at which the wind makes angles; next



marinarij quomodo méſurát miliaria in mari?Sol. Marinarij cóſiderát quatuor vétos generales, videlicet vétú oriétalé, occidentalé, meridionalem, & ventum ſeptemtrionalem, ſimiliter alios quatuor ventos qui ex primis exeunt, conſiderant, videlicet grec, exaloch, lebig, & maeſtre, & centum circulos conſiderant in quo venti angulos faciunt, deinde conſiderant per ventú orientalem nauem euntem centum miliaria à centro quot ſunt miliaria vſque ad ventum de exaloch, & miliaria duplicant vſque ad ducenta miliaria, & cognoſcunt quod miliaria ſunt multiplicata, quæ ſunt ducenta à vento orientali, vſque ad ventum de exaloch per multiplicationem miliarium, quæ ſunt de termino centenario orientis vſque ad terminum de exaloch. Et ad hoc inſtrumentum habent chartam, compaſſum, acum, & ſtellam maris.

Figure 5.1 *- Text from a 1515 edition of Ramon Llull's Arbor Scientiae (source: http://books.Google.Nl/books?Hl=nl&id=i64ol87ais0c).*

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[298] Pujades 2007, 420, 506.

[299] Ramon Pujades remarks that "no one has bothered to point out that the oldest manuscript that preserves this fragment is from the latter part of the fourteenth century!"
Pujades 2007, 459.

they consider, for the east wind, the ship sailing a distance of hundred miles from the centre, how many miles she makes on the south-east wind; and they double the number of miles until two-hundred, and they know how many miles are multiplied, which are two-hundred from the east wind to the south-east by multiplication of the miles, which is from the end point of the hundred miles east to the end point of south-east. And for this they have the tools: chart, dividers, needle & North Star." [300]

It is this last short sentence, *Et ad hoc instrumentum habent cartam, compassum, acum et stellam maris,* that is important to obtain an understanding of navigational aids of the end of the thirteenth century. Numerous researchers have provided their interpretation and the image that emerges is far from consistent, which underlines my statement that it isn't really known how sailors navigated in the medieval Mediterranean.[301] The remainder of Llull's text is discussed in Section 5.3.

… et ad hoc instrumentum habent …	**… cartam**	**… compassum**	**… acum**	**… stellam maris**
d'Avezac	?	portolan	?	?
Th. Fischer	chart	portolan	needle	compass rose
Breusing	chart or portolan	dividers	?	?
Kretschmer	chart	dividers	needle	compass rose
Taylor	chart	portolan	needle	Pole Star
Cortesão	chart	dividers	needle	Pole Star
Mollat du Jourdin	chart	compass or portolan	needle or compass	compass rose and Pole Star
Sezgin	chart	wind rose	needle	?
Pujades	chart	dividers	needle	Pole Star
Edson	chart	portolan	compass	Pole Star

Table 5.1 *- Translations of Ramon Llull's navigational aids.*

Theobald Fischer suggests in addition that *instrumentum* in the above Latin sentence refers to dividers. Sezgin believes that *instrumentum* refers to the wind rose and reads support in this text for his interpretation that the wind rose network and the chart were treated as two separate aids to navigation.

The association of *compassum* with *portolan* appears to be based exclusively on the name of the oldest surviving complete portolan of the Mediterranean, *Lo Compasso de Nave-*

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[300] Raymundus Lullius, *Arbor Scientiae*, 1515, 570. Available as Google e-Book, http://books.google.nl/books?hl=nl&id=I64oL87aiS0C

[301] Fischer 1886, 79; Kretschmer 1909, 50 – 51, 71, Kretschmer is the source for the information on D'Avezac and Breusing in this table; Taylor 1971, 118; Cortesão 1969, Vol I, 206; Mollat du Jourdin 1984, 16; Sezgin II 2001, 55; Pujades 2007, 458-459; Edson 2007, 51. The question mark means the author didn't mention his or her view on the meaning of the relevant term.

gare. The term *compasso* is not used in any of the extant portolan texts reproduced by Kretschmer.

Both Cortesão and Pujades go back to Llull's original Catalan text and provide convincing arguments for their interpretation. For example, Pujades points out that the Catalan text for *stella maris* reads *tremuntana*. Whereas the term *Stella Maris* (Pole Star) was also used to indicate the compass[302], the word *tremuntana* referred to the Pole Star and to the north wind, but not to the compass.[303] Secondly, the Catalan text provided by Pujades groups the terms in pairs: *carta e compàs, agulla e tremuntana*.[304] The combination chart & dividers is a logical one, as is needle & Pole Star in a period when many people believed that the behaviour of the magnetic needle was caused by its attraction to the Pole Star; Pujades discovered that the combination chart & dividers occurs many times in the body of notarial documents he analysed. The terms *compàs* and *sestes*, which he encountered frequently in these documents, are usually mentioned as inseparable companions of charts. According to Pujades, both terms refer to what is known in English as compasses or dividers. *Sestes* is an Italianism, like *bussola,* he adds.[305] In the oldest documents the magnetic compass is designated by the words *agulla, acus* or *agogia* and occasionally with *calamita*. Pujades points out that the latter term designates a lodestone.[306] What is remarkable of this short list of navigational aids is the usage of the word *acus* to indicate the compass. I shall return to this subject in Section 5.7.

5.3 THE TOLETA DE MARTELOIO

Before the last sentence of the section from *Arbor Scientiae,* discussed above, Llull describes an example of the trigonometric reduction of distance sailed. He states that, when sailing 200 miles on a south-easterly course, the distance-made good in easterly direction is 100 miles. This is incorrect; it ought to be 142 miles, but Llull corrects this error in a second work, known as *Ars Magna* and dated at approximately 1305.[307] It is not known whether Llull had the entire *Toleta de Marteloio* to his disposal. However, from the way he describes trigonometric course reduction, it does not appear to be a new technique, so, on the basis of this text, he does not appear to qualify as the inventor.

The *Toleta* consists of two separate tables of two columns each, providing solutions to two related navigational questions, of which the first one may be paraphrased as:

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[302] Taylor 1950 *Five Centuries* …, 280-281. Taylor cites Felix Faber (1480-83), who documented his journey as a pilgrim to the Holy Land.

[303] Pujades 2007, 459.

[304] Pujades 2007, 444.

[305] Pujades 2007, 442.

[306] Pujades 2007, 444.

[307] Ramon Llull, *Ars magna generalis et vltima*, per Jacobum Marechal ..., sumptibus vero Simonis Vincent, 1517, Ch. 96. Available as an e-book at: http://books.google.nl/books/about/Illuminati_Raymundi_Lull_Ars_magna_gener.html?id=rG_yINh8V1gC&redir_esc=y

> “If it is not possible to sail a desired course[308] due to an unfavourable wind, how far will I have deviated from the desired course line after having sailed a certain distance, and how far have I progressed in the desired direction?”

The deviation from the desired course line, in the sense of the shortest distance from the actual position of the ship back to the intended line, is called *alargar*. The distance-made-good in the intended direction is called *avançar*. The figures in the table are provided for the situation when 100 miles have been sailed along the actual course. The eight rows of the table provide the *alargar* and *avançar* for a difference between actual and intended course of one to eight *quarter winds*, or compass points, which is eight steps of 11¼°, thus describing a full sector of 90°.

The second (paraphrased) question addresses the complementary problem when the wind has changed and the ship can sail back to its intended course line:

> “Now that the wind has changed, how many miles do I have to sail to return to my desired course line and how much progress do I then make in the intended direction?”

The distance to sail until the original course line is reached is called *retorno* and the distance-made-good in the intended direction during this process is again called *avançar*. As in the first table, the answers are provided for stepwise increasing course differences between actual and desired bearing in steps of 11¼° (*quarter winds*). The figures refer to the situation where the *alargar* or perpendicular distance to the intended course is 10 miles.

The elements thus described constitute two right-angled triangles, as shown in Figure 5.3 and Figure 5.4.

The navigator would need to multiply the appropriate figures for his situation by multiples and fraction of the 100-mile and 10-mile unit distances in the table. That had to be done by applying the *rule of proportion* or *rule of three*: if a distance of 35 miles would have been covered with a course deviation of two quarter winds, the *alargar* and *avancar* would be calculated as:

$alargar = \frac{35}{100} \cdot 38$ miles and $avancar = \frac{35}{100} \cdot 92$ miles

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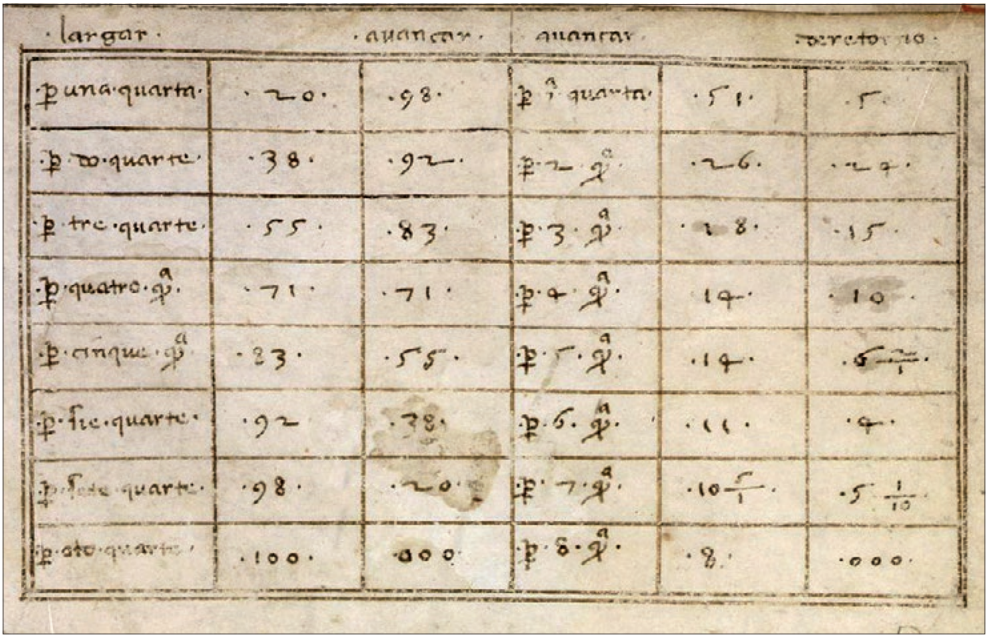
[308] According to the Concise Oxford English Dictionary (11th ed, 2008), *Course* is “the route *or* direction followed by a ship, aircraft, road or river”. In the context of this study *course* will refer only to the bearing or azimuth of the route followed by a ship, unless explicitly stated otherwise.

Cortesão and Taylor concluded that *instrument*[309] in Table 5.1 above refers to this trigonometric reduction table.[310]



largar		avancar	avancar		retorno
ꝑ una quarta	20	98	ꝑ 1 quarta	51	5
ꝑ do quarte	38	92	ꝑ 2 qª	26	24
ꝑ tre quarte	55	83	ꝑ 3 qª	18	15
ꝑ quatro qª	71	71	ꝑ 4 qª	14	10
ꝑ cinque qª	83	55	ꝑ 5 qª	14	6
ꝑ sie quarte	92	38	ꝑ 6 qª	11	4
ꝑ sete quarte	98	20	ꝑ 7 qª	10 $\frac{5}{1}$	5 $\frac{1}{10}$
ꝑ oto quarte	100	000	ꝑ 8 qª	8	000

Figure 5.2 *- Toleto de Marteloio from Andrea Bianco's 1436 atlas (source: Biblioteca Nazionale Marciana, Venice).*

Deviation from intended course Δ	**alargar = 100•sinΔ**	**avancar = 100•cosΔ**	**retorno = 10/sinΔ**	**avancar = 10/tanΔ**
1 quarter wind	20	98	51	50
2 quarter winds	38	92 (91)	26	24
3 quarter winds	56 (55)	83	18	15
4 quarter winds	71	71	14 (24)	10
5 quarter winds	83	56 (55)	12	6.5
6 quarter winds	92	38	11	4
7 quarter winds	98	20	10.2 (10)	2 [311]
8 quarter winds	100	0 (10)	8 (10)	0

Table 5.2 *- The Toleta de Marteloio (Andrea Bianco and Grazioso Benincasa).*[311]

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[309] See the text above Table 5.1.

[310] Eva G. R. Taylor, *The Haven-Finding Art: A History of Navigation from Odysseus to Captain Cook* (London: Hollis and Carter, 1971), 118; Cortesão 1969, 207.

[311] Andrea Bianco appears to write 5 and 1/10 but in other surviving examples of the Toleta the value '2' is quoted. Bianco might have meant '5 parts of 10'. However, that would be a rather roundabout way of writing '2' and Bianco doesn't do that elsewhere in the table.

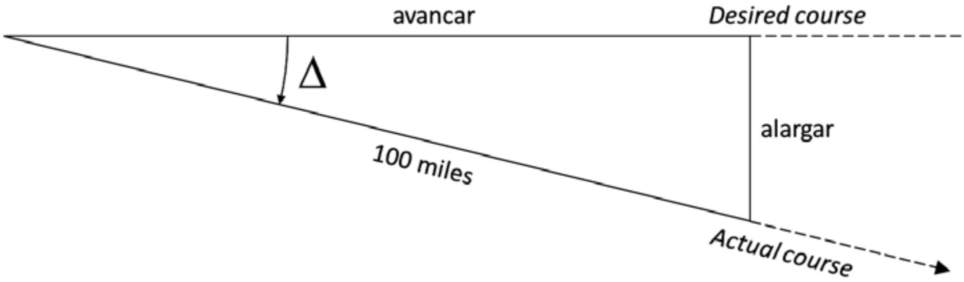

Figure 5.3 - *The left-hand side of the Toleta: distance-made-good along planned course.*

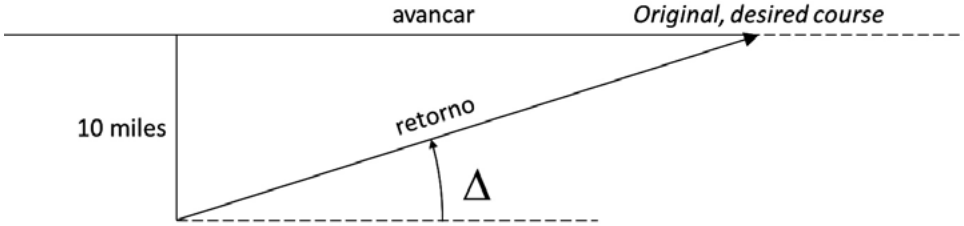

Figure 5.4 - *The right-hand side of the Toleta: distance to sail to return to a planned course line.*

The figures in parentheses in Table 5.2 are the corresponding values from Grazioso Benincasa's portolan. Benincasa doesn't provide the last column; all his figures are in Roman numerals and he doesn't provide fractions either.[312] The variations in the numbers are more likely transcription errors rather than recalculated values. Apart from those errors the figures are generally correct to the nearest mile.

Although Llull's accounts are the oldest references to the *Toleta*, the complete reduction table is only known from fifteenth century *portolans* and *taccuini*, the latter being short navigation manuals (literally: notebooks), but the most often quoted example[313] is from Andrea Bianco's atlas of 1436, which also contains a graphic version of the *Toleta*, the *tondo e quadro*, i.e. *circle and square* (see Figure 5.5). Remarkably, all surviving portolans and *taccuini* that contain the *Toleta* are Venetian; the name *Toleta de Marteloio* is Venetian dialect; in other Italian dialects it was referred to as a *Martelogio*[314]. Pujades found one reference in a 1390 Genoese notary record mentioning a (latinised) *Martilogium*.[315] Cortesão states that the Catalans referred to the table as *Raxon de Marteloio* and the Italians as *Toleta de Marteloio.*[316]

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[312] Kretschmer 1909, 358-359.

[313] Andrea Bianco's atlas is technically not the oldest; Grazioso Benincasa's portolan contains the bare contents of the table and dates from 1435. Kretschmer 1909, 358.

[314] Ferro 1996, 48;

[315] Pujades 2007, 432 (item 57); Ferro mentions the same record.

[316] Cortesão 1969, 209.

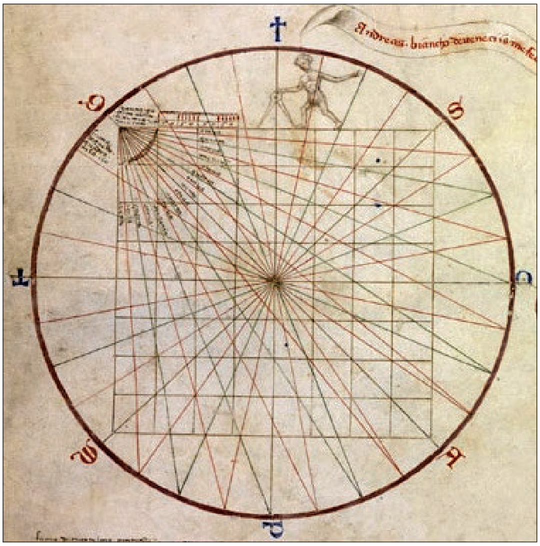

Figure 5.5 *- Circle and square from Andrea Bianco's atlas of 1436 (source: Biblioteca Nazionale Marciana, Venice).*

Most, if not all scholars who have commented on the purpose of the *Toleta* have stressed that it was used for beating into the wind by sailing as close as possible to the wind alternately on starboard and port tacks, following a zigzag course, so that the deviation Δ in Table 5.2 would be the difference between the intended course straight into the wind and the actual course. This interpretation is definitely incorrect: even a modern yacht cannot sail closer to the wind than about 45°, although the optimum angle of incidence of the wind into a modern sail, depending on its cut and camber, is about 10°, measured relative to the chord of a horizontal cross section of the sail.[317] This is caused by the forward speed of the yacht, which generates an apparent headwind that is combined with the true wind to a vector sum and is known as the *apparent wind*. The direction of the apparent wind cannot make a smaller angle than 10° with the close-hauled modern sails without the sail losing its power. The implication is that, if a modern yacht were to use the *Toleta,* its first three rows would be useless; the yacht can never sail closer to the wind than four compass points (*quarter winds*). In fact the entire *Toleta* would be useless, as the helmsman of a ship, desiring to make as much headway upwind as possible, would not willingly steer a course *less* close to the wind than that of which the ship is capable. The right-hand side of the *Toleta* becomes equally meaningless, as the ship will be able to sail just as close to the wind on one tack as on the other. If she sails 100 miles on whatever angle with the wind, the *retorno* will, because of the symmetry of the process of beating into the wind, be exactly the same, i.e. 100 miles. There is no need for a trigonometric table for a ship that is beating upwind.

Furthermore, while a modern yacht is typically able to achieve a course of 45° with the wind, a medieval ship wasn't; medieval ships could maintain a course-made-good of

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[317] Marchaj 1964, 105 – 111.

90° with the wind only with the greatest difficulty, although they would have been able to point higher[318]. Also that would render the entire *Toleta* useless. The ship might be able to point higher, but the excessive leeway would result in a course-made-good not markedly smaller than 90°. In other words, only the last line of the *Toleta* would apply in that case. Incidentally, the *Toleta*, being a purely mathematical idealisation of reality, doesn't allow for leeway at all.

Standing practice in the medieval Mediterranean was to wait for a favourable wind that allowed the ship to run before the wind and to make use of the highly predictable thermal winds along the coasts, together with predictable current patterns.[319] These thermal winds are normally at right angles with the coastline, but may merge with the gradient wind[320], which will deflect them to a more acute or obtuse angle with the coastline.

The *Toleta de Marteloio* appears therefore not to have been intended for calculating progress upwind, but to calculate progress along a planned course *downwind* when the actual wind direction made an angle with the planned course and the ship would be forced to run downwind in that suboptimal wind.

An interesting question is how much the *Toleta* was actually used. Ramon Pujades discovered a near complete absence of the *Toleta de Marteloio* in the notarial records of seamen's possessions he reviewed. The only places where it *is* mentioned occur in Venetian *taccuini* of the beginning to the middle of the fifteenth century.[321] According to Pujades, the Venetian *taccuini* that thus contain a copy of the *Toleta*, "state in one way or another that the *Toleta de Marteloio* was a technique beyond many" and Pujades arrives at the sobering conclusion that "use of the *Toleta*, portolans and lunar calendars was vastly inferior to that of nautical charts and compass, from which we can deduce that their importance as nautical instruments has been greatly exaggerated by historians." [322] Gaetano Ferro had concluded earlier that usage of the *Toleta* was not widespread.[323]

This does appear to be a more realistic conclusion than Taylor's (and others') claim that this tool was routinely used by medieval seamen. The existence of the *Toleta* doesn't

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[318] See Sections 4.3.1 and 4.3.2. The square-rigged Kampen cog can point to about 70° with the true wind, but on such a close-hauled course it makes a leeway of about 20°. Assuming that round ships with a lateen rig could point a bit higher than that but made as much or possibly a bit more leeway than the cog, which had angular bilges rather than a smooth round hull, a reasonable guess seems to be that round ships could point to about 65° with the true wind.

[319] Pryor 1992, 36 – 37 and Pryor 1994, 72 – 74.

[320] This is the wind that results from differences in air pressure, flowing from high to low pressure zones.

[321] The first three columns of the Toleta are also provided in the portolan of Grazioso Benincasa (1435), who was not from Venice, but from Ancona.

[322] Pujades 2007, 464.

[323] Ferro 1996, 48.

necessarily imply the use of trigonometric tables; it may have been scaled-off from a diagram such as the *tondo e quadro* (Figure 5.5), but a good understanding of the trigonometric relationships is certainly required. Astronomers and mathematicians may have understood those, but it is questionable whether ordinary seamen could understand that level of mathematical abstraction of reality. It is impossible for the *Toleta* to be based on experience: in open sea a sailor cannot obtain any indication how far he has deviated from his desired course line (the left-hand side of the *Toleta*), nor whether, on the way back to this line (the right-hand side of the *Toleta*), he has intersected it. This can only be visualised and quantified by theoretical analysis. Furthermore, according to Crombie, simple multiplication and division were still formidable tasks in the thirteenth century[324] and these operations were part of the calculation of proportions, or the *rule of three*, which is implied in the usage of the *Toleta*.

It appears likely that the *Toleta* was too advanced a tool to be of much practical use to the medieval seaman, for whom it appears to have been intended. The name of Leonardo of Pisa has been mentioned by a number of authors, but no concrete evidence exists that links him to the invention of the *Toleta*.

5.4 THE MATHEMATICAL SEAMAN

Despite the fact that the discussion on portolan chart origins is still fundamentally open, some scholars have felt so absolutely certain of a medieval European origin that they described conjectural navigational practices that had evidently been derived from the accuracy of these charts. In the late 1940s and 1950s, the British professor Eva G. R. Taylor followed this approach and wrote a series of spirited articles in the Journal of Navigation on medieval navigation in the Mediterranean. She succeeded in creating the image of the *mathematical seaman*, declaring that Mediterranean medieval sailors were the first professional group to use mathematics routinely in their jobs.[325]

> "The seaman was, in fact, the most accomplished technician of an age in which science and technics were otherwise completely neglected.[326] As evidence how they sailed we have a book of sailing directions drawn up about A.D. 1250 and a seachart which is dated by experts at about 1275."[327]

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[324] Crombie 1979 Vol. 2, 22: "Considerable improvements were introduced in the method of calculation in the Hindu system of numerals in the thirteenth and fourteenth centuries. The methods of multiplication and division used by the Hindus and Moslems were very uncertain. The modern method of multiplication was introduced from Florence and the modern method of division was also invented during the later Middle Ages. This made division into an ordinary matter for the counting house, whereas it had formerly been a formidably difficult operation, even for skilled mathematicians."

[325] Taylor 1960, 12.

[326] Taylor 1951, *The Oldest Mediterranean Pilot*, 82.

[327] Taylor *The Haven-Finding Art …, 1971* 98.

Taylor refers here to *Lo Compasso de Navegare* and the *Carte Pisane* respectively. She was one of the first to write in some degree of detail about medieval Mediterranean navigation practices and is still rightly considered as an authority on the history of navigation. She was one of those scholars who saw in the *Toleta de Marteloio* additional evidence of the systematic application of mathematics to navigation.

This train of thought was continued by other authors. The historian Frederic C. Lane states that:

> "Charts, tables [i.e. the *Toleta de Marteloio* – RN] and compass, used together, reduced the errors of sailing by dead reckoning. They formed a new technique of navigation which was characteristic for the Mediterranean and was so well fitted for that sea that even in the mid-sixteenth century the compass was the only instrument there considered necessary".[328]

Sixteen years later this opinion was repeated by James E. Kelley, Jr., who claimed that: "… by the end of the thirteenth century western Mediterraneans were practicing a disciplined form of navigation based on the magnetic compass, the traverse board [i.e. the *Toleta de Marteloio* – RN] and the marine chart".[329]

The method of navigation that Taylor, Lane, Kelley and others assume to have been used is called *dead reckoning*. Quantitative astronomic navigation was not used in the Mediterranean; visual navigation was probably widely used, but cannot provide the necessary geometric measurement data that is presumed to constitute the basis for portolan chart construction. Dead reckoning consists of estimating the distance sailed along a known, or rather measured, azimuth or bearing. The change in position over the lapsed time can then be calculated, or rather: plotted in a chart. In the period under consideration, only flat-earth geometry can be assumed for this process, i.e. *plane sailing* (also: *plain sailing*). That was the maximum degree of sophistication possible at the time for seaman and navigator, because the medieval sailor had no practical way of accounting for the curvature of the earth's surface.

Kelley's ideas on thirteenth century navigation methods derive from his conjectural reconstruction of late fifteenth century Mediterranean navigation methods, which he dubbed the "Italian method", or "South-European method" of navigation and which he describes in a 1987 article on Columbus's navigation[330]. Kelley draws mainly on

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[328] Lane 1963, 606.

[329] James E. Kelley Jr. "Non-Mediterranean Influences That Shaped the Atlantic in the Early Portolan Charts," *Imago Mundi*, Vol. 31 (1979), 18.

[330] James E. Kelley Jr., "The Navigation of Columbus on His First Voyage to America." *Proceedings of the First San Salvador Conference: 'Columbus and His World'*. Compiled by Donald T. Gerace (Florida: CCFL, Bahamian Field Station, 1987): 130-132. See also Kelley 1979, 18, Kelley 1995, 2, 3 and Loomer 1987, 35.

Columbus's *Journal* of his first voyage. His extrapolation backwards to the thirteenth century is based on his assumption that navigational practices did not change over the intervening period. This may or may not be true; a more pertinent question is whether Columbus's navigation method was *routinely* applied in the Mediterranean. Columbus's journey to the New World was far from a routine journey and he may have navigated more carefully than he might have done on a standard journey in the Mediterranean. Kelley describes his "Italian method" as follows.

> "At every change of watch, i.e. every four hours, or at every significant change in circumstances, the ship's speed was estimated in the following way: the pilot (probably with an assistant), used a rhythmical ditty to count the seconds it took for some flotsam or wood chip to float the distance between two marks on the ship's gunwale, separated by a fixed distance (conjecturally 50 *palms*, or about 40 English feet). Using a conversion table (possibly carved in the ship's rail), or mental arithmetic, the pilot converted the time count to miles per hour …
> The pilot recorded the relative change in the ship's position on his manoeuvring board (*toleta de marteloio* = gridiron of the hammering), a vellum sheet with a large circle of radiating rhumbs and a mile scale or embedded square grid. Using dividers, he marked off the estimated distance travelled on the course bearing from the previously marked position.
> Every 12 or 24 hours (say at sunrise and sunset) the pilot measured the distance and bearing between the end points of the traverse marked on his manoeuvring board[331] to obtain the *course made good*".

However, Columbus's *Journal*[332] doesn't provide anything like the amount of detail described by Kelley: the *Journal* does clearly indicate that half-hour glasses were used, but states rather matter-of-factly what the vessel speed was (or rather: believed to be), not how it was measured or estimated. It doesn't specify either that ship's speed was estimated at every change of watch, although it isn't unreasonable to assume so. Columbus is generally, and probably rightly so, regarded as having been an exceptionally good navigator, but be that as it may, his distance estimates must have been fortuitous, as it would have been physically impossible for him to estimate the strength of the North

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[331] Kelley equates the *Toleta de Marteloio* to a traverse board or maneuvering board, which is incorrect at any rate, but at least better than the assumption that is was used for beating upwind. A traverse board was a (wooden) tool that allowed analog recording of a series of bearing&distance pairs during a watch. At the end of the watch the components were worked into a single traverse and the vector sum was plotted on the chart. However, the *Toleta* probably had an entirely different purpose, as discussed in Section 5.2, and did not permit *recording* of bearing&distance pairs. In addition there is no evidence for traverse boards before the sixteenth century. Any suggested usage of traverse boards in the thirteenth century Mediterranean and for this usage of the *Toleta de Marteloio* are therefore entirely speculative.

[332] Christopher Columbus, *The Journal. Account of the First Voyage and Discovery of the Indies*, Part 1. Translated by Mary A. Beckwith and Luciano F. Farina. Rome: Instituto Poligrafico e Zecca della Stato, Libreria della Stato, Roma, 1992.

Equatorial current, which carried him to the New World. Columbus could not have known the existence of this current in the first place, as he was the first to sail that route. It is therefore in my opinion not justifiable either to assume routinely applied, advanced thirteenth century navigation practices on the grounds of Columbus's accuracy of navigation, as Kelley does, or to deduce such navigation practices based on reverse-engineering of the accuracy of portolan charts, as Taylor does.[333] Both appear to be examples of working towards an a priori determined result.

In the next sections I will look at the 'tools' of navigation by dead-reckoning and discuss whether it is reasonable to assume that such tools or methods were actually used in the thirteenth century.

5.5 DISTANCE MEASUREMENT AT SEA

5.5.1 THE GUNWALE LOG AND THE DUTCHMAN'S LOG

The only way to measure distance sailed in the Middle Ages was by multiplying the estimated average speed of the ship with time lapsed. We do know with certainty that the distances, travelled by ships in the Middle Ages were recorded, or at least remembered and communicated to some extent, but the initial estimates were crude and expressed distance mainly in terms of *days of sail*, as had been customary since antiquity[334].

In spite of the detail so assertively presented by Kelley, we do not really know how ship's speed was estimated in the Middle Ages. Taylor doesn't speak out on the possible method of distance estimation at all.[335] However, she is clear in her view that speed was "a matter of estimate and not of measurement".[336] After all, the so-called *English log*, which allowed proper, objective measurement of ship's speed, was only invented in the sixteenth century.[337] What Kelley describes is the so-called *gunwale log*. May and

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[333] Taylor also bases her opinion on the accuracy of fourteen distances taken from the *Compasso de Navegare* and assumed the whole Compasso reflected high accuracy navigation. In the next chapter I will analyse the Compasso in more detail.

[334] Ibn Jubayr states that a *majra* or day's sail was reckoned to be 100 miles. These would have been Arabic miles of 1921 m. A value of 192 km in a day almost certainly includes overnight sailing, as this would bring the mean speed to a reasonable value of 4.3 knots.
Ibn Jubayr, *The Travels of Ibn Jubayr,* trans. Roland Broadhurst (New Delhi: Goodword Books, 2007), 26.

[335] Taylor 1960 *Mathematics* …, 8: "What method of dead-reckoning was employed is a matter for discussion and cannot be considered here".

[336] Taylor 1950 *Five centuries of dead reckoning*, 280.

[337] David W. Waters, "The Development of the English and the Dutchman's Log." *Journal of Navigation,* Vol. 9, Issue 1 (1956), 71. See for a more extensive text: Waters 1958, 425-434. The English log was a small wooden plank that was made to stand vertically in the water, so that it would have maximum resistance; the intention was that it would remain still in the water. It was connected to the ship with the logline, which was held rolled up on a reel. When the log was dropped overboard, the sailor holding the reel would pay out the line so that as little pull as possible was exerted on the log. This continued over a preset period, nominally half a minute, measured with a sand glass, after which the

Waters refer to it as a *Dutchman's log*, which is not so named because it was invented by the Dutch, but because in the seventeenth century the Dutch apparently had a preference for this type of speed estimation.[338] See the text from *The Seaman's Tutor* below. The difference between the *Dutchman's log* and the *English log* was that the latter measured the distance sailed over a fixed time interval, whereas the *Dutchman's log* did it the other way around, using a fixed distance and measuring the time required to sail that distance. According to Waters, "many things point to the *Dutchman's log* having been Gunter's invention", but Waters appears to refer to the calculation Edmund Gunter introduced to relate the results of a such a log estimate to a value in terms of modern nautical miles per hour (knots). The gunwale log, as a crude method for speed estimation, and related to other length units than the nautical mile, is probably much older [339].

In the nautical textbook *The Seaman's Tutor* of 1662, by P. Perkins, Henry Briggs and Eysum Perkins, the following text appears:

> " …of the Estimation of a Ships way at sea [that] there's hardly any thing more necessary than to be able to make a good Estimate of the Ships way with any wind, according to all Circumstances, [and that of] the Nations now of Fame and Experience at Sea [some made it by] only guessing by the sail born, and running of the Froth or Water by the ship's side, as the Spanish and the Portuguese; others by flinging into the water a Chip, or the like; and counting how many equal timed paces they can make on the Deck, while the said Chip drives between any two Bolt-Heads or Marks on the Side, which is usual amongst the Dutch, (instead of paces you may number the Pulses while the Chip drives), but the most approved way, and now the most followed is by our English Log, and Log Line."[340]

Remarkable about this passage is the statement that the Spanish and Portuguese did not *measure* speed, but preferred to estimate it from the froth floating by, the setting of the sails with the wind and other indirect indicators. If the Spanish preference reflects the medieval Catalan methods, then presuppositions such as Kelley's that assume mathematical rigour in determining ship's speed in the medieval Mediterranean may be incorrect, unless it is further assumed that the Italians measured speed in a more exact

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amount of paid-out line was measured. To facilitate this, the logline contained knots with markers at certain distances. Hence the unit of ship speed was the *knot*, one nautical mile per hour.

[338] Hermann Wagner quotes a passage by Lucas Janszoon Waghenaer 1598, describing the log in: Hermann Wagner, "Zur Geschichte der Seemeile." *Annalen der Hydrographie und Maritimen Meteorologie, Zeitschrift für Seefahrt- und Meereskunde*, Vol. 41 (1913), 446-447.

[339] May 1973, 108 – 109 and Waters 1956, 79, 80. Edmund Gunter (1581-1626) used a rounded value of the degree measurement made by the Dutchman Willebrord Snel van Rooijen (Snellius) in 1615. Snellius had found 352,347 feet for the length of a degree of latitude and Gunter rounded this to 352,000 feet. Snellius conducted his measurement in a different length unit, the Rhineland Rod, so a conversion was required. Edmund Gunter and Richard Norwood introduced the concept of sea mile as 1/60 of a degree of latitude.

[340] Cited in Waters 1958, 428. Supplementary words in square brackets by Waters.

manner. Maintaining this train of thought would lead to the conclusion that more exact methods of measuring speed had been abandoned during the period that separates the appearance of the first portolan charts from the time when navigation started to become founded upon mathematical methods, which would appear to be unlikely.

5.5.2 Samuel Eliot Morison's adage

A more realistic opinion on vessel speed estimation is voiced by Samuel Eliot Morison, who appears to have been very influential in shaping the opinions of researchers in this aspect of navigation. In his biography of Christopher Columbus he states that the navigator on the Santa Maria would estimate ship's speed "by eye … in Roman miles per hour, by watching the bubbles or the gulfweed float by" and asserts:

> "Any seaman of good judgment and experience can estimate the speed of a vessel by this primitive method within a knot, or even a half-knot if he is used to her".[341]

Leaving aside the matter of the type of mile used by Columbus, this claim is echoed by many authors on portolan charts and on the history of marine navigation.

Both Taylor and Collinder, for example, state that an experienced sailor could gauge the speed of his ship by looking at the bow and stern wave in conjunction with the shape of the sail. Collinder describes a gunwale log as an early method in which the ship's speed was estimated from how quickly a piece of wood, thrown into the water, slid astern, but suggests it wasn't any better than the cruder method in the previous sentence.[342]

Samuel Eliot Morison was a historian who taught at Harvard University, when, shortly after the United States became involved in the Second World War, he made a proposal to his friend President Roosevelt to document US Navy operations from the inside. Roosevelt accepted and in 1942 the 54 years old Morison was commissioned as Lieutenant Commander and called to active duty. [343] He served on various assignments during the War and, as he was no armchair sailor, the claim cited above has tended to carry weight. Anyone familiar with sailing, such as Morison, who was a keen sailor all his life, will indeed confirm his claim in the sense that relatively small changes in vessel speed can be felt and seen in the ways described. However, the problem would be to convert these speed changes into knots, metres per second, or any other unit of speed. This requires calibration and that is precisely what was lacking in medieval times. One might argue that an opportunity for calibration was provided by sailing along the coast

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[341] Samuel E. Morison, *Admiral of the Ocean Sea: A Life of Christopher Columbus* (Boston: Little, Brown and Co., 1951), 190.

[342] Taylor 1950, 280 and Per Collinder, *A History of Marine Navigation*, trans. Maurice Michael (London: B.T. Batsford Ltd, 1954), 32.

[343] http://www.history.navy.mil/bios/morison_s.htm

and such an opportunity possibly existed on selected stretches where nearby Roman roads ran along the coast and milestones were still available. However, to transfer a measurement calibrated that way to everywhere in the Mediterranean and Black Sea would be a challenge. In short, medieval sailors would have been able to identify *relative* speed changes of their vessel well enough, but would have lacked the means to reliably translate these changes, indeed to translate their speed estimate, into a standardised quantity of speed.

5.5.3 DISTANCE MEASUREMENT FROM OAR STROKES

Hans-Christian Freiesleben, himself an author of a book on the history of navigation, embellishes Morison's statement and adds new elements:

"A skilled navigator can *very well* judge the speed of a ship *even at 10 knots* and *still better in sailing ships*. Furthermore, a thirteenth century galley, propelled by oars, was another important source of distance measurements because the rhythm of the stroke and the length of the vessel would provide an excellent basis for estimating the speed."[344]

The measurement of distance by oar stroke is mentioned by several authors. Campbell, for example, writes:

> "Since it was known how far a galley travelled with each oar stroke, measurement of distance run was obtained simply by counting the strokes. Bartolomeo Crescenzio describes this method in 1602."[345]

Whereas the principle of the method certainly appears viable, its practicability and accuracy must be doubted. A galley under oars is just as susceptible to variations in wind and current as any sailing ship would be and would not have been able to maintain a constant speed as a result of these variations. Moreover, the energy levels of the rowers must have been an important factor; in addition to regular fatigue in the course of a day of rowing, loss of performance due to dehydration is a known problem for athletes. The availability of drinking water was a constant source of concern for galley commanders. Also, galleys were limited in their operations to calm water, within reach of shelter.[346] It is therefore unlikely that this method of distance measurement can satisfactorily explain the collection of a large body of distance observations from which a chart could be drawn. Distance measurement by oar stroke appears practicable only for short coastal stretches.

The above discussion can be summarised as follows:

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[344] Freiesleben 1983, 125 – 126. Emphasis in this quote is mine (RN).

[345] Campbell 1987, 387. See his footnote 152.

[346] See Section 4.3.3 Galleys.

a) It cannot be established if a method of *measuring* distance was used in the medieval Mediterranean at all, or whether distances were estimated subjectively.

b) Distance measurement at sea would have been far from trivial. None of the methods mentioned in literature provides a satisfactory answer to the question how a consistent body of distances of a coherent scale (be it with small variations per sub-basin) might have been generated, as the medieval origin hypothesis presupposes. Kelley's almost scientific 'Italian method' smacks of being transposed back in time to accommodate the evident accuracy of portolan charts and the Morison 'method' cannot lead to consistent, calibrated results, i.e. in the sense of repeatable results performed by multiple sailors over the same course, but also repeatable and consistent in scale in different areas.

5.6 Early time measurement at sea[347]

Estimates of speed needed to be multiplied by time lapsed in other to obtain the distance sailed. Apart from crude estimates on the basis of the sun's daily trajectory, sand clocks were the only and probably preferred means available on a medieval Mediterranean ship to measure time.

It is reasonably certain that sand clocks were invented in the Mediterranean world of the thirteenth century, or even earlier, in support of navigation.[348] However, they were not intended to be precision measurement tools; they were primarily meant for regulation of the watches[349] on-board. For example, they are not mentioned in Ramon Llull's list of navigational aids used by seamen to estimate their mileage at sea.[350] Their accuracy was limited, as the early sand clocks simply consisted of two bottles fused together with wax and this seal was never completely moisture proof. Many attempts were made to find the ideal material, in itself a nice example of early scientific experimentation. 'Sand' was powdered marble, boiled five times in red wine (this presumably sealed the pores, making the marble less susceptible to moisture), or silver powder, Venetian sand (a mixture of charred lead and tin), ground cinnamon, powdered egg shells etc.

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[347] The most important source of information on this subject is an article by R.T. Balmer, "The Operation of Sand Clocks and Their Medieval Development", *Technology and Culture*, Vol. 19, No. 4 (1978). Supplementary information is provided in: David W. Waters, "Early Time and Distance Measurement at Sea." *Journal of Navigation,* Vol. 8 (1955), Issue 2.

[348] Balmer 1978, 615: the earliest written reference is in Francesco da Barbarini's poem *I Documenti d'Amore* (1306 – 1313); the earliest image is the fresco *Il Buon Governo* by Ambrogio Lorenzetti in Siena (~1339). This shows a fairly developed sand glass, so that an invention during the thirteenth century or earlier seems likely.

[349] 'Watch' is intended in the sense of a (reduced) 'duty crew', not in the modern meaning of a wrist-carried time-measuring device.

[350] See Section 5.2 above.

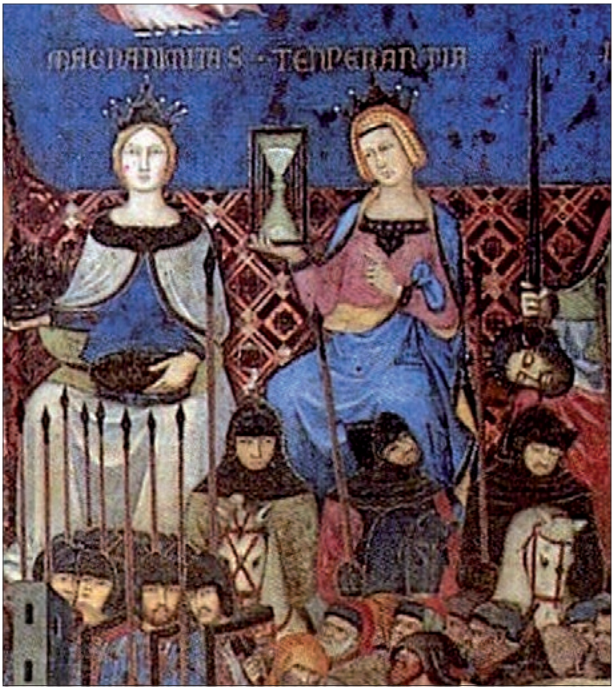

Figure 5.6 *- Detail of the fresco Il Buon Governo by Ambrogio Lorenzetti (~1339) at the Palazzo Publico, Siena.*

Waters estimates that the accuracy of sand clocks would have varied from 15 minutes to one hour per day. He bases this estimate on the accuracy of early mechanical clocks and states that sand clocks could not have been better than that. Early sand glasses did not permit graduation to estimate fractions of the running time. In Columbus's time the *ampoletta* was a half-hour glass. It is not known whether one-hour or two-hour time glasses were used in the thirteenth century, but, whatever the running time, sand glasses needed frequent turning and, as they became older, started running fast because of abrasion of the glass in the narrow neck. These factors have an impact on the accuracy with which time on board could be measured, but time measurement by sand glass, however crude the first glasses may have been, appears to have been adequately accurate for both the regulation of watches on board and for converting speed to distance. See Section 5.9 and Appendix 3 below for an estimate of the accuracy of time, measured by a sand glass.

5.7 The measurement of course bearing - the mariner's compass

The most important instrument in the history of navigation is undoubtedly the mariner's compass. It was invented in medieval times but regrettably it is not known with certainty when and where in the Mediterranean it was it first deployed.

The objective of this section is to summarise relevant research that has been carried out on this subject. Because of its importance in relation to the research question, the description takes up considerably more space than the other aspects of navigation. It is primarily the *time* of its introduction in the Mediterranean that is of importance, because the indications are that its first appearance was roughly contemporaneous with the appearance of portolan charts. Response of scholars has been threefold. Some, such as Nordenskiöld and Pelham, have concluded that a compass was evidently not required to create the first portolan chart; others, such as Wagner, concluded that, as the compass would be a necessity for chart making, portolan charts cannot be a medieval creation. The third and largest group simply ignores the timing problem.

The development stages of the compass will be discussed first, because the early types of compass are unsuitable for the accurate navigational and hydrographic survey work that is assumed to be the foundation of portolan charts. This is followed by a brief account of developments in China, from which the compass appears to originate, by sections that describe the evidence from Arabic-Islamic culture and myth and reality of its appearance in Western Europe, in which the early scientific work by Petrus Peregrinus (Pierre de Maricourt) is an important milestone.

Figure 5.7 *- First illustration of on-board use of a compass in a 1403 copy of sir John Mandeville's Travels (source: Bibliotheque Nationale de France in Paris, B MS FR 2810, fol.188V).*

5.7.1 DEVELOPMENT STAGES OF THE MAGNETIC COMPASS

The oldest form of marine compass was probably a piece of lodestone, floating, with the help of some buoyancy aid, in a bowl filled with water. This was improved by replacing the lodestone with a magnetised iron needle, stuck crosswise through a straw or placed in a lengthwise split section of reed or rush. This form of compass will be referred to as the *floating compass*. The next stage of development appears to have been the balancing of the magnetised needle on a vertical pin. This is generally called a *dry pivot compass*. The last stage is the attachment of the magnetised needle to a compass card, which was placed on a vertical pin and allowed to rotate freely with the needle. This is the *mariner's compass*, which has important advantages over the dry pivot compass. The mariner's compass underwent many changes and improvements over time, such as the submersion of needle and card in a fluid to dampen the motions transferred by the ship to the needle, but those took place well outside the Middle Ages and are therefore irrelevant for this study.

The dry pivot compass is used in the West for applications on land. The compass card is attached to, or engraved in, the housing and the needle rotates freely on a spindle above it. It is still used in orienteering. The essential improvement of the mariner's compass over the land compass is the fastening of the compass card to the needle. A *lubber line* is drawn on the outer housing and, after aligning this lubber line to the ship's longitudinal axis, the azimuth or bearing of the steered course of the ship can be directly read from the compass card.

The 'land' compass, with the compass card attached to the housing, is an impractical instrument for shipboard use. Arthur Breusing demonstrates this in clear language, which I paraphrase below.[351] He uses these arguments to support his proposition that the innovation that is claimed to have been made in Amalfi, is the fastening of the compass card to the needle, in other words, the invention of the mariner's compass.
The normal way of using the compass was to place it on a surface attached to the ship, not hand-held by the navigator. Two options are now available for working with the compass and determining the azimuth or bearing of the ship's course.

The first is to realign the *North* marker on the compass housing with the needle after every course change of the ship, which is impractical.

The second method is to align this *North* marker with the ship's longitudinal axis. If the ship sails a northerly course, the compass needle points in the direction the ship sails and the direction to the bow of the ship is North; on a southerly course the direction

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[351] Arthur Breusing, "Flavio Gioja under der Schiffskompass", *Zeitschrift der Gesellschaft für Erdkunde Berlin*, Jg. 4 (1869); reproduced in *Das rechte Fundament der Seefahrt. Deutsche Beiträge zur Geschichte der Navigation*, Wolfgang Köberer (comp), (Hamburg: Hoffmann und Kampe, 1982), 81.

indicated by the needle is South. So far all is well. However, for any other course the following inconvenient situation arises: when the ship sails e.g. an easterly course, the direction indicated by the needle will be West and vice versa. Also this is impractical, but it doesn't mean the dry pivot compass was not used on board ships: the Chinese have apparently managed to work with them for centuries and Collinder mentions that Columbus took several compasses with him on his first journey to the New World, some with the card fixed to the needle, i.e. mariner's compasses, but also some with the card fixed to the bowl under the needle, in other words: 'land' compasses.[352]

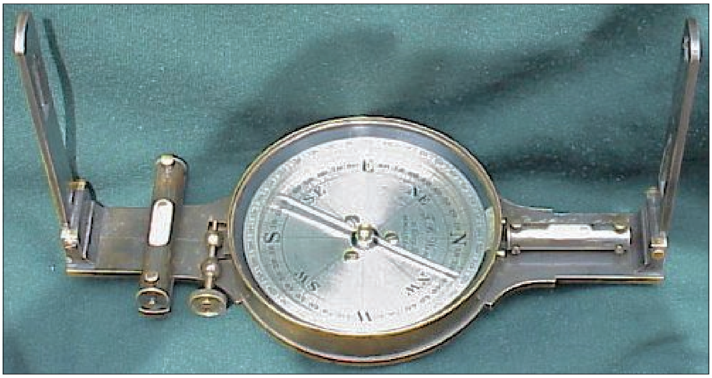

Figure 5.8 *- Mine Survey Compass, 19th century (?), England. Note the mirror-imaged compass card and the endless screw to set the magnetic declination*
(Credits: http://www.miningartifacts.org/).

This second method is the preferred method of working in mine surveying: the compass card of a mine compass is mounted such that the north-south line coincides with the viewing direction or the direction of suspension (in case of a suspended compass such as shown in Figure 5.8).

To prevent the above-mentioned problem, the compass card of mine survey compasses is mirror imaged with respect to the North-South line, to enable the measurement of the azimuth of a horizontal mine shaft, analogous to the measurement of a ship's course.

Although not much is known about European medieval navigation, mirror imaged compass cards would have merited some mention in later documents on navigation, had they been widely applied. However, this solution is neither known in Western navigation, nor in any other navigational tradition, for that matter.

The floating compass is usually referred to as *acus* in Latin texts, with equivalent words for *needle* in other languages. A document from 1294 describes an order by Charles II,

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[352] Collinder 1954, 124.

King of Naples, to return the ship *Sant Nicolau* of Messina, seized by the Genoese corsair Renier Grimaldi and sold in Taranto, including the property, stolen from skipper and crew. The description of stolen items included three charts, one *cum compasso*, two lodestones (*calamita*), of which one, the skipper's, *cum apparatibus suis*[353], which is assumed to indicate needle, straws, corks or other flotation devices and a bowl with or without markers indicating the cardinal directions. See also the listing Ramon Llull provided of navigational aids in Section 5.2.

Pelham and others, such as Kretschmer,[354] propose that the term *buxola* or *bussola* indicates the transition from the floating compass to the dry pivot compass and the mariner's compass. *Buxola*, diminutive of *box*, is believed to derive from Greek *puxos* (and Latin *pyxis*), the buxus tree or its wood.[355] This appears to be related to the widespread usage of making boxes from buxus wood or boxwood. The word *bussola* came to mean the mariner's compass itself, rather than the box in which it was contained and suggests the compass was treated as an integrated instrument rather than as a collection of components (*acus cum apparatibus suis*).[356] It seems indeed unlikely that *bussola* would apply to the floating compass.

The word *calamita* requires some explanation. This term usually indicates the lodestone, but it probably derives from the Greek word *chalamis*, meaning *reed* or *rush*. Breusing associates this with a reed, split lengthwise in two, of which one half was used as a floater for the magnetic needle.[357]

5.7.2 THE MAGNETIC COMPASS IN CHINA

Magnetism, in the sense of the iron-attracting property of lodestone, was well known both in antiquity and in the Middle Ages, in Europe, the Arabic-Islamic world as well in China. Lodestone is naturally magnetised *magnetite*, a hard iron-oxide mineral (Fe_3O_4). The Chinese appear to have been the first to discover the directive properties of lodestone. The oldest known reference is that of a lodestone spoon balancing on a highly polished Chinese chess board or diviner's board and dates from the Han dynasty (first century AD)[358]. The directive properties of lodestone were initially only used by geomancers in the Chinese art of divination, *Feng Shui*. The earliest description of a magnetic compass in China dates from 1044 AD: a thin fish-shaped piece of iron with up-

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[353] Pujades 2007, 438. This carries Pujades's reference number 132. See also Taylor 1971, 115.

[354] Kretschmer 1909, 73.

[355] Etymology of the word 'box': *Concise Oxford English Dictionary,* 11th ed (rev.), (Oxford: Oxford University Press, 2008). See also Kretschmer 1909 (1962), 73 and Amir D. Aczel, *The Riddle of the Compass* (Orlando: Harcourt Books, 2002), 36.

[356] Pelham 1980, 62.

[357] Breusing 1869 (1982), 89. Breusing credits this interpretation to D'Avezac, but provides no reference for that. The claim is repeated by Kretschmer 1909 (1962), 73.

[358] Pelham 1980, 47. Pelham claims this was proven by Wang Chen-To in 3 articles in the *Chinese Journal of Archeology,* Academia Sinica: 1) Vol. 3 (1948), 119; 2) Vol. 4 (1950), 185; 3) Vol. 5 (1951), 101.

turned edges, floating in a bowl of water.[359] The magnetic fish had been manufactured by smelting iron and casting a thin fish-shaped film. This was allowed to cool down and solidify with its 'head' pointing south. South was considered to be the imperial direction in ancient China. This process, known as *thermoremanence,* magnetises the iron. The last comment in the Chinese description is that the manufacturing process must be kept strictly secret.[360] No mention is made of its use in navigation and Needham suggests these compasses were used exclusively in geomancy.[361] Variations include a wooden fish with a piece of lodestone inside.

Figure 5.9 *- 19th century Chinese mariner's compass, Port-Louis naval museum, Brest (Credits: photograph by Rama, Wikimedia Commons, Cc-by-sa-2.0-fr).*

According to Li Shu-hua the first reference to a magnetised needle is found in the book *Meng Khi Pi Than* (*Brush Talks at Dream Brook*), dated to approximately 1088. Shen Kua describes how a geomancer may magnetise a needle by rubbing it against a lodestone. He also describes a magnetised needle made to float in a bowl of water, but states the needle to be rather "agitated" and suggests the best method is to suspend the magne-

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[359] Joseph Needham, "Navigation in Medieval China", Appendix in Taylor 1971, 267.
This appendix is a compilation from the section on Nautical Technology in Volume IV (Part 3) of Needham's *Science and Civilisation in China* (1962), made with Needham's permission.

[360] Aczel, 2002, 81.

[361] Needham, Appendix in Taylor 1971, 266.

tised needle from a silk thread. He also shows awareness of magnetic declination.[362] Cohen writes that Shen Kua also measured the Pole Star's position as eccentric from the celestial pole.[363] Shen Kua's knowledge does not appear to have filtered through into navigational practices. The first firm reference to a shipboard compass occurs in a twelfth century text, called *Pingchow Table Talk:* "The ship's pilots are acquainted with the configuration of the coasts; at night they steer with the stars and in the day-time by the sun. In dark weather they look at the South-pointing needle."[364]

Little innovation and improvement took place and floating compasses continued to be used in China, as Needham states, for nearly a millennium.

In the seventeenth century the dry pivot compass was adopted on Chinese ships under the influence of the Dutch, who had obtained a trading concession in Japan (see Figure 5.9). The dry pivot compass had been invented earlier in China[365] but, as mentioned above, was only used in geomancy. Needham states that Chinese compass makers perfected the design with a "very delicate form of suspension, which automatically corrected for variations in dip and still impressed western observers as late as the beginning of the nineteenth century."[366] However, the Chinese never made the mental jump to the far more practical innovation of fixing the compass card to the needle. Su Sung's very accurate water clock (1094) springs to mind here, a construction of ten metres high and another example of such honing-to-perfection without questioning the fundamental design.[367]

Although initially longer needles were used for the floating compass, the Chinese eventually settled for short, approximately five centimetre long needles in their dry pivot compasses[368] and continued to use both floating and dry pivot compasses until well into the twentieth century.[369] The Chinese mariner's compass uses a twenty-four-point compass rose, which to this day is still used in Feng Shui.

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[362] Li Shu-hua, "Origine de la Boussole II", *Isis*, Vol. 45 (1954), No. 2, 182;
Floris H. Cohen, *How Modern Science Came into the World* (Amsterdam: Amsterdam University Press, 2010), 42 – 43;

[363] Cohen 2010, 43, May 1973, 52, Alan Gurney, *Compass. A Story of Exploration and Innovation*. New York: W.W. Norton & Co, 2004., 37. Gurney cites Needham, *Science and Civilisation in China.* Also.

[364] Gurney 2004, 37.

[365] The three articles by Wang Chen-To, mentioned in Footnote 350, also describe a dry-pivot compass, consisting of a wooden turtle with a piece of lodestone inside, freely rotating on a spindle. The description dates from between 1100 and 1250. Reference from Aczel 2002, 84.

[366] Needham, Appendix in Taylor 1971, 267. 'Dip', a mariner's term, is better known in scientific applications as magnetic inclination, the angle between a magnetic field line and the horizontal plane.

[367] Joseph Needham, *Science and Civilization in China*, Vol. 4, Part II (Cambridge: Cambridge University Press, 1974), 449-465. See also Cohen 2010, 47.

[368] May 1973, 53.

[369] Breusing 1869 (1982), 80. Breusing mentions they were still used in his day (i.e. mid-nineteenth century); the Science Museum, London states they were used until well into the twentieth century.

5.7.3 THE MAGNETIC COMPASS IN THE ISLAMIC WORLD

The earliest reference to a compass in the Islamic world dates from 1232. The Persian historian Sadidaddin Muhammed b. Muhammed al-'Aufi describes a personal experience of a journey he made on a ship in that year, when unexpected bad weather arose. The sky became covered with clouds, but the captain of the ship fetched a hollow piece of iron in the shape of a fish, which he threw into a bowl of water. The fish turned and came to rest in the *Qibla*-direction (sic).[370] The second reference is provided by Bailaq b. Muhammad al-Qibgaqi in 1242, who writes that:

> "… in the Syrian Sea, when the night is so dark that no star can be observed, in order to orient themselves to the four cardinal directions, the seamen take a water-filled vessel which they place inside the ship to protect it from the wind. They stick a needle crosswise through a piece of wood or straw and allow it to float in the vessel. Then they take a lodestone of a size that fills your hand, or a bit smaller, and bring it close to the water surface, describe with their hand a rotation to the right, so that the needle executes a circular motion. Then they suddenly pull their hand quickly away and – verily! – the points of the needle are directed South and North … Of the seamen that sail the Indian Ocean they say that instead of a needle and a piece of wood they use some sort of hollow iron fish, which they have made such that it floats on the water surface when it is deployed, and which then shows both directions, South and North with its head and tail."[371]

It is most likely that the South-pointing, fish-shaped compass of the Arabs in the Indian Ocean originates in China. The description of the floating compass, including the details on how the needle is to be magnetised, is also found in the Latin Mediterranean. Notably Alexander Neckam mentions this in his *De Naturis Rerum*, written between 1197 and 1204.[372]

Sezgin and Schmidl[373] describe an interesting and advanced floating compass, which was originally described by the Yemenite sultan al-Malik al-Ashraf in about 1291. This consists of a needle that is kept floating in a circular bowl by mounting it crosswise on a wax-impregnated piece of fig tree wood. The lengths of the needle and the piece of wood are slightly smaller than the inner diameter of the bowl. The rim of the bowl was engraved by the four cardinal points and graduated in seventy-two parts. The latter is interesting, as this is a multiple of the Chinese division of the horizon into twenty-four parts.

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[370] Sezgin II 2000, 240 – 241. The *Qibla* is the direction to Mecca. It is presumed al-'Aufi didn't realize the compass pointed south-north instead of to Mecca.

[371] Sezgin II 2000, 241.

[372] Thomas Wright (ed), *Alexandri Neckam. De Naturis Rerum, Libre Duo, with the poem of the same author De Laudibus Divinae Sapientiae.* London: Longman, Roberts and Green, 1863, 183.

[373] Sezgin II 2000, 247. Petra G. Schmidl, "Two early Arabic sources on the magnetic compass." *Journal of Arabic and Islamic Studies* 1 (1997-1998): 81 – 132.

5.7.4 THE MAGNETIC COMPASS IN EUROPE

A. ALEXANDER NECKAM

The first documented Chinese reference to a compass used on board a ship occurs almost a century earlier than the first mention of the compass in Western Europe. Alexander Neckam (1157-1217), an English monk and scholar who studied and taught at the University of Paris, describes the use of the compass in two works, *De Utensilibus*, written in Paris between 1175 and 1183, and *De Naturis Rerum,* written between 1197 and 1204.[374] Neckam describes the use of the compass in both cases not as a novelty, but as an established practice. That is, by the way, also the case for the first references in Arabic documents. In the first work Neckam appears to describe a dry pivot compass; in his second he refers clearly to the floating compass. For the remainder of the thirteenth century only references are found to the floating compass for shipboard use; the presumed dry pivot compass of Neckam is a clear anomaly. This has puzzled researchers for a long time, as the dry pivot compass is generally regarded as the next evolutionary stage from the floating compass. It is therefore necessary to explain this apparent exception. The Latin text in Neckam's *De Utensilibus* is as follows:

> "… habeat etiam acum jaculo suppositam. Rotabitur enim et circumvolvetur acus, donec cuspis acus respiciat orientem, sicque comprehendunt quo tendere debeant naute cum cinossura latet in aeris turbacione."[375]

This has been translated as:

> "They also have a needle placed upon a dart, and it is turned and whirled around until the point of the needle looks East. And the sailors know which way to steer when the Cynosura is hidden by clouds."[376]

It is the phrase: "needle placed upon a dart" that has given rise to the interpretation that Neckam describes a dry pivot compass. The puzzling (apparent) error in his text is the statement that the needle points *East*. Wright, in the Preface of the 1857 edition of Neckam's *De Nature Rerum* is clearly puzzled by Neckam's use of the word *orientem*, moreover as, according to him "all manuscripts agree in this reading and, as it is glossed by *est*, this must be the intention of the writer".[377] Wright states he is at a loss to explain this, unless it is assumed that a cross-limb had been added to point East, "as in the twelfth century the East was the grand object of all voyages from this part of the world".

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[374] Julian A. Smith, "Precursors to Peregrinus: The early history of magnetism and the mariner's compass in Europe", *Journal of Medieval History* 18 (1992), 33, 34.

[375] Thomas Wright (ed), *A Volume of Vocabularies*. London: 1857, 114.

[376] Taylor 1971, 95. Cynosura = Ursa Minor. The Pole Star is the last star in the tail of this constellation.

[377] Wright 1857, xvii.

A century later Taylor chooses to translate *orientem* incorrectly by "North-East", in an attempt to explain the puzzle by making allowance for magnetic declination. She states that "clearly North" must have been meant and the reference is therefore probably an interpretation error made during transcription.

This interpretation appears to have been proposed by M. d'Avezac in the Bulletin de la Société de Géographie in Paris, entitled *Ancient témoignages historiques relatifs* à *la boussole* (1858). Thomas Wright mentions this in his preface to Neckam's *De Utensilibus,* published in 1863.[378] d'Avezac suggested that there were two copyist's errors: *suppositam* for *superpositam* and *orientem* for *septentrionem.*

William E. May picks up this discussion and states that: "the passage has been recently re-examined and it is now generally supposed that d'Avezac's theory has no foundation" and "*Jaculum* means a spear or dart, and could not possibly be translated as a pivot. It might very well have been applied to an arrow-headed pointer." Without quoting specific sources, May adds that the repetition of *acus* is clumsy and suggests that if there has been a copyist's error, it would be here: the second *acus* might originally have read as *eius*, resulting in:

> "… habeat etiam acum jaculo suppositam. Rotabitur enim et circumvolvetur acus, donec cuspis *eius* respiciat orientem …"

Eius would refer to the dart, not the needle. In other words, this would be a description of a dart, mounted crosswise on a needle.[379] This reminds of Sezgin's and Schmidl's

Figure 5.10 *- Compass rose on the Cantino Planisphere (1502).*

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[378] Wright 1863, xxxviii.

[379] May 1973, 104-105.

description of a Yemenite compass, described earlier. When the magnetised needle points North, the dart would point East. If this reasoning is correct, Neckam probably described a floating compass in both works, which would make it consistent with other documented references of the twelfth and thirteenth century.

In our times North is considered to be the principal direction. However, in antiquity East, the direction of the rising sun, was considered to be the most important direction. This is the origin of the word *levante* for the East wind in the medieval wind rose.[380] Homer mentions the four cardinal directions and begins with East.

In twelfth century Christian mysticism East was considered to be the sacred direction, the direction of the Holy Land and the Earthly Paradise; South signified warmth and was associated with the Passion of Christ and North with cold and evil.[381] Hugh of Saint Victor described the world as an oval, enclosing a rectangular *mystical Ark of Noah*, with the bow pointing East, the stern West. In the segment beyond the Ark and the enclosing oval in the East is Paradise. In the segment to the West resurrection will take place and the Chosen will disembark on starboard, into the southern segment. The damned will disembark to port, into the northern segment.[382]

Note that in Figure 5.5, the *tondo e quadro* diagram from Andrea Bianco's atlas, east is also shown at the top. Also Ramon Llull starts the list of *winds* in his *Arbor Scientiae* with the east wind – see Llull's text in Section 5.2 above.

The author of *Le Liber de Existencia* … describes the route to take after the passing of the Strait of Gibraltar in terms of "ascendo in orientem", which may indicate that his mental (or physical) chart was held East-up.[383]

Our word *orientation*, in the sense of reference direction, is a remnant of the former importance of East. The two cardinal directions that received special symbols on later portolan charts were East and North, the former embellished with a cross and the latter by a stylised *T* (from *Tramontana*), as shown in Figure 5.10, which in the sixteenth century evolved into a *fleur-de-lys*. It is therefore not remarkable at all that Neckam would emphasize the compass's ability to indicate East.

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[380] Compare e.g. to the English verb *to levitate.*

[381] Crosby 1998, 38.
Neckam adds a citation from Jeremiah [1:14] in his description of the compass in *De Nature Rerum:* "Ab Aquilone pandetur omne malum" (From the North is all evil spread); Wight 1863, 183.

[382] John Kirtland Wright, *The Geographical Lore of the Time of the Crusades – A Study in the History of Medieval Science and Tradition in Western Europe* (New York: Dover Publications, 1965), 153.

[383] Gautier Dalché 1995, 34.

B. Petrus Peregrinus's Epistola de Magnete

An important document in the history of medieval science is the letter which a French engineer in the army of Charles of Anjou wrote on August 8th, 1269 during the siege of the south-Italian town of Lucera, to Sygerus de Foucaucourt, a friend and neighbour in his native Picardy.[384]

This document describes experiments which this Pierre de Maricourt, or, using the Latinised form of his nickname Petrus Peregrinus, had conducted. In this letter, which was published later (~1520) under the title *Epistola de Magnete,* Peregrinus provides a detailed description of a floating compass and a dry pivot compass.

For his floating compass he describes an interesting method of calibration. The floating compass consisted of a bowl in which an oval lodestone was placed, closed with a sealed lid. This bowl floated in a larger vessel partially filled with water. The cardinal directions were inscribed on its rim, together with a division in degrees, with 0° corresponding with East. The floating bowl had a ruler with upright pins at either end attached in the middle of the lid. The next stage was the astronomic alignment of the outer rim, with the help of the sun or the Pole Star. After the bowl with the lodestone was allowed to float, the ruler on top of its lid was rotated until it coincided with the North-South line of the rim of the outer vessel. This meant that the compass eliminated magnetic declination at the place and time of its calibration, although Peregrinus was unaware of this phenomenon.

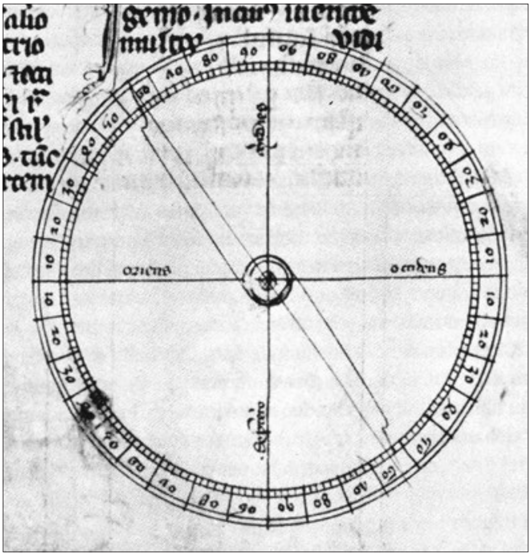

Figure 5.11 *- Alidade and degree division on Peregrinus's dry pivot compass (Source: illustration from a fourteenth century manuscript copy of Peregrinus's Epistola de Magnete, Bodleian Library, Oxford, made available through: http://en.wikipedia.org/wiki/file:epistola-de-magnete.jpg).*

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[384] Peter J. Smith, "Petrus Peregrinus' Epistola. The Beginning of Experimental Studies of Magnetism in Europe", *Earth Science Reviews* 6, A13.

Peregrinus's description of a dry pivot compass contains two remarkable things. The first is his description that the needle, which is to be placed on a spindle, should be balanced by a piece of silver wire, placed at right angles with the magnetised needle. Needle and spindle were to be placed in a box with a transparent lid, on the rim of which the four cardinal directions and a degree scale were drawn or engraved. The second remarkable aspect of the compass was the addition of an *alidade,* allowing the measurement of magnetic azimuths to stars, two and a half centuries before the azimuth compass for mariners was described by João de Castro (1514).[385] Peregrinus's compasses were intended for astronomic use, although he claims they could be used at sea. However, there is no evidence that they were ever deployed on board a ship.

C. THE FLAVIO GIOJA MYTH

The south-Italian city of Amalfi has a long-standing claim to the invention of the mariner's compass. The mythical part of this claim attributes its invention to one Flavio Gioja, a person who does not appear to have existed. Amalfi boasts a Piazza Flavio Gioja with a statue devoted to this imaginary man in the middle.

The origin of the Amalfi legend are two references, one in a description of the geography of Italy, *Italia Illustrata* by Flavio Biondo (1392 – 1463), the other in a poem attributed to the Italian poet, scholar and diplomat Antonio Beccadelli (*Il Panormita*), who lived from 1394 to 1471.

Flavio Biondo writes about Amalfi: "However, the story goes, in which we hear the Almalfitans being praised, that usage of the magnet, the application of which allows the helmsmen to be shown the North direction, was discovered in Amalfi". [386] Beccadelli's reference is shorter: "Prima dedit nautis usum magnetis Amalphis".[387]

The name *Gioja* was added to the story in the sixteenth century and the year 1300 was added in 1600 by William Gilbert in his *De Magnete*[388] and although the association of the name *Gioja* with the legend was persistent, it was questioned from the beginning.[389]

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[385] May 1973, 83.

[386] Flavio Biondo, *Italia Ilustrata*, 1474, 420.
http://www.mgh-bibliothek.de/cgi-bin/blondus2.pl?seite=420
Italia Illustrata, although published in 1474, was written around 1450. The text in question is: "Sed fama est qua Amalphitanos audiuimus gloriari, magnetis usum, cuius adminiculo nauigantes ad arĉton diriguntur, Amalphi fuisse inuentum, quicquid uero habeat in ea re ueritas, certũ est id noĉtu nauigandi auxilium priscis omnino fuisse incognitum."

[387] Breusing (1869) 1982, 80.

[388] William Gilbert, *On the magnet, magnetick bodies also, and on the great magnet the earth, a new physiology, demonstrated by many arguments & experiments.* English translation of *De Magnete*, Project Gutenberg e-book, Chapter 1. http://www.gutenberg.org/files/33810/33810-h/33810-h.htm.

[389] 'Gioia' means 'gem' and was a name used for the lodestone in the sense: 'precious stone'. 'Flavio' may have derived from the earlier reference by Flavio Biondo. This connection is so obvious that the reference was doubted very early on.

In the year 1300 the directive properties of the magnet were well-known, so if there is any substance to Amalfi's claim to fame, another explanation needs to be found. Arthur Breusing made a case for a reinterpretation of this claim to refer to the invention of the *mariner's* compass with the compass card attached to the needle. His argument rests on the interpretation of the text from Beccadelli: "Prima dedit nautis usum magnetis Amalphis". Breusing suggests this should be translated as: "Amalfi was the first to give seamen a *usable* compass". He argues that the adjective *usable* most likely refers to the attachment of the card to the needle. It cannot have been the invention of the dry pivot compass, as Peregrinus had already invented that and the practicality of using that on board a ship is questionable (see Footnote 343). Gimballed or *cardanic* suspension and fluid damping were invented much later, so by a process of elimination Breusing's interpretation is what remains. His interpretation has found wide acceptance, but it must be stressed that it concerns the interpretation of a rumour, albeit a reasonable and a persistent one, of which the time reference of 1300 has been added afterwards.

5.7.5 Wrapping up the discussion on the compass

Two questions are relevant for the origin of portolan charts, of which the most fundamental one is whether the mariner's compass would have been in general use early enough to have played a role in their construction. The question of which culture can lay claim to introducing the mariner's compass in the Mediterranean is secondary, but still relevant, as notably Fuat Sezgin postulates primacy of the Arabic-Islamic culture over that of the European Christian in the invention of the compass and links this to the origin question of portolan charts.

Many authors have seen a straightforward path for the introduction of the compass into navigation: invented by the Chinese (no one disputes that, except Sezgin), transmitted to the Arabs in the Indian Ocean (also not disputed, except by Sezgin) and from there transmitted by the Arabs to the Mediterranean (this *is* disputed, though not by Sezgin).[390] Although the Chinese were aware of the directive properties of the magnet centuries before the Arabs and Europeans, it was initially put to use exclusively in geomancy. The first documented use of a magnetised needle on-board a ship occurs about a century before the first Arab and European references. No evidence exists for the transmission of the compass from the Indian Ocean to the Mediterranean. Also the form of the floating compass in the Mediterranean is different from that in the Indian Ocean. It appears that the development of the compass in the Mediterranean took place independently of that in the Indian Ocean.[391] At any rate the first Arabic reference to the use of the compass in the Mediterranean occurs forty five years later than the earliest European reference, although that does not prove per se that the Eu-

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[390] E.g. George Sarton, *Introduction to the History of Science*, Volume II (Baltimore: The Williams and Wilkins Company, 1931), 509.

[391] May 1973, 52.

ropeans used it before the Arabs. Sezgin postulates without proof that the compass was introduced to navigation in the Indian Ocean by the Arabs in the tenth, or the eleventh century at the latest, from where it reached the Mediterranean at the beginning of the fourteenth century, but provides no evidence to support that claim.[392]
What remains is the option that the magnetic compass for maritime use in the Mediterranean was developed in Italy, or indeed in the Arabic-Islamic world. It has been suggested that the names of the Italian eight winds correspond well with the general geographic location of Sicily. Also the word *calamita* for compass or lodestone may derive from Greek, which was still spoken in the far south-east of Italy at that time.[393] On the other hand, Heinrich Winter saw no compelling reason to conclude from the geographic correspondence of the names of the eight winds with southern Italy that the mariner's compass was necessarily also invented there. In that he is probably right, because the names of the eight winds appear to have existed before 1300, the supposed time of the development of the mariner's compass. Although evidence is lacking, it is not improbable that the origin of the mariner's compass in the Mediterranean lies in southern Italy, possibly indeed Amalfi or Sicily. Whether it was introduced there by the Normans, as Bagrow and Winter suggested[394], whether it was an autonomous development by the Italians or introduced by the Arabs, cannot be established.

Ultimately it doesn't matter for this study where exactly and by whom the compass was introduced. The question whether the compass arrived in time and in a form suitable for navigation and charting is a more fundamental one. It is not realistic to believe that steady courses could be steered and recorded with sufficient accuracy using a floating compass. The Mediterranean floating compass had, as far as we can tell, no graduation at all and was, according to the surviving descriptions, only intended to be used in adverse weather conditions, as were the Chinese and the Arab variants. The dry pivot compass may not be the best choice for the recording of courses, as argued by Breusing, but it would do the job. The mariner's compass, however, is in principle the most suitable instrument for the reading and recording of a ship's course. If the appearance of the terms *buxola* and *bussola* is accepted as indicative for the appearance of the boxed compass, be it the dry pivot land compass or the mariner's compass, an approximate date can be put against this transition. Pelham does this and points out that the word *bussola* only starts to appear in the fourteenth century. Ferro mentions the first occurrence of this word in 1294, but provides no source, and, possibly in contradiction with that, claims the first description of the compass as a single unit dates from 1324.[395]

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[392] Sezgin II 2000, 264, 265. See also Chapter 10: *An Arabic-Islamic origin of Portolan Charts?*

[393] Julian A. Smith, referring to the Oxford English Dictionary, suggests *calamita* derives from *adamant,* a mythical metal or mineral of the Middle Ages, often equated to or associated with magnetite. Smith 1992, 24.

[394] Leo Bagrow, *History of Cartography*, revised and enlarged by R.A. Skelton (London: C.A. Watts & Co, Ltd, 1964), 62,
Heinrich Winter, "Who invented the Compass", *The Mariner's Mirror*, Vol. 23 (1937), 101–102.

[395] Ferro 1996, 45–46. This reads like a contradiction, if it is accepted that *bussola* refers to the compass as a single unit.

Pelham checked only literary sources and Ferro doesn't specify his. Ramon Pujades claimed to have researched, as part of his PhD work, *all* extant documents up to 1470, in particular notarial documents, that mention nautical cartography and portolans in the archives of Catalonia, Valencia, Majorca, Genoa, Sicily and Venice. Pujades found only nine records in Venice. He was able to confirm the existence of references to 220 navigational charts, 8 partial charts (*quarterons*), over 30 *mappaemundi* and about 20 miscellaneous documents, such as atlases, *mappaemundi* in panels, charts in panels and navigational tables. He concludes that, since an unknown percentage of notarial documents have survived, the total number of charts in circulation must have been much greater.

Pujades's key observation with relevance for this study is that the first mention of the word *bussola* occurs in a document from 1349. After that the term appears to gain wider acceptance, as it is used more frequently from then on, "relegating the word *agulla* to a secondary position". Pujades associates the term *bussola* with the dry pivot compass.[396]

5.8 IMPLICATIONS FOR PORTOLAN CHART ORIGINS

The conclusion to draw from this lengthy section on the magnetic compass is that it appears that either the dry pivot compass or the mariner's compass, or both, as indicated by the word *bussola*, only came into fairly widespread use in the course of the fourteenth century. I shall therefore have to draw the same conclusion that Pelham drew thirty-three years ago:

> *If the above interpretations are correct, the compass, in whatever shape of form, cannot have played a role in the construction of the earliest portolan charts.*[397]

The story of the history of the magnetic compass in navigation contains too many uncertainties, guesses and interpretations to draw this conclusion without reservations. The *Compasso de Navegare*, the oldest surviving portolan, dates from 1296 and contains a large number of bearings and the oldest portolan chart, the Carte Pisane from the end of the thirteenth century, is equipped with a wind rose showing 32 directions. These undeniable facts have led many map historians and geography historians to conclude that the mariner's compass must have been in widespread use since about the middle of the thirteenth century.[398] Pujades's results make this unlikely, but I have still included a *caveat* in my conclusion. The magnetic compass, be it as a dry pivot compass or as a mariner's compass, may have been available as early as that, but possibly in a smaller community, not as an instrument in widespread use in the Mediterranean and Black Sea.

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[396] Pujades 2007, 428 – 444. The text presented is a summary of the pages referenced.

[397] Peter Pelham drew this conclusion without the caveat: Pelham 1980, 64 – 65.

[398] Crone 1978, 16; Taylor, *The Sailor in the Middle Ages* 1948, 192; Waters 1958, 23. Waters takes the dry pivot compass described by Petrus Peregrinus as proof that seaman had a usable compass from 1269 on.

5.9 An accuracy model for medieval Mediterranean navigation

When adding up the factors discussed in the previous sections, it appears very unlikely now that portolan charts could have been constructed from an extensive data set of compass bearings and distances, collected by medieval mariners. Whatever the case may be, in the following sections and chapters I will proceed as if the mariner's compass *was* available in time to play a role in the construction of the first portolan chart, and that distances *were* estimated with mathematical rigour, so that the remaining 'pilllars' of the medieval origin hypothesis may be tested from the most optimistic perspective.

The next step in that process will be the introduction of a model to assess the accuracy of medieval navigation, assuming the most optimistic circumstances and techniques to apply. If the medieval origin hypothesis is rejected with those assumptions, no further arguments are required. Conversely, if the hypothesis is accepted under the assumed favourable conditions, additional investigation will be required to ascertain the degree of realism of those assumptions.

When considering the hypothesis that portolan charts were constructed from measurements of bearings and distances between a large number of coastal points in the Mediterranean and Black Sea (and Atlantic coast), one of the key questions is whether navigation was accurate enough to have resulted in such accurate charts.
As mentioned earlier, hardly any attempts have been made to answer this question quantitatively. Most authors repeat Morison's adage[399] like a *mantram* and state without further ado that course bearings could be determined to about five degrees, which is equivalent to about half a point on a 32-point compass. Taylor concluded from a small sample (1%) of the *Compasso de Navegare* that dead-reckoning navigation was of a high standard and Pelham merely states that "dead reckoning was simple and adequately accurate".[400]

Those unsupported claims necessitate the construction of a model that at least makes a serious attempt at approximating the accuracy of medieval navigation by dead-reckoning, in order to get a feeling of what *might* have been achievable. This model is required for the geodetic network analysis in Chapter 9: *The map projection; artificial or intentional?* but is not required for the cartometric analysis of the charts, nor for the analysis of the *Compasso de Navegare* in Chapter 8, although it may provide a useful benchmark for the latter, which is why the model is introduced at this point in the thesis. In Chapter 4 the sailing properties and natural conditions in the Mediterranean were described, for the

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[399] "Any seaman of good judgment and experience can estimate the speed of a vessel by this primitive method within a knot, or even a half-knot if he is used to her". See Section 5.5.2.

[400] Pelham 1980, 40.

purpose of assessing their impact on shipping and on the accuracy of navigation; the accuracy model implements those considerations.

Critical comments on medieval navigation in the main text aside, the model is based on course bearing measurement by means of the mariner's compass and distance measurement by the gunwale log method. The gunwale log method assumes that two marks in the gunwale or bulwark of the ship, at a calibrated distance apart, are used to time the passage of a wood chip between these two markers. The chip is thrown into the water at the bow marker by an assistant and the navigator 'measures' how quickly the chip floats past by chanting a rhyme or ditty, counting his pulse or pacing the deck. This process is assumed to be repeated after every four-hour watch until the end of the journey.

My assumption is that the markers would be about twenty metres apart, which requires a large ship, and the nominal speed of the vessel is four knots, which implies that the whole procedure of 'measuring' speed lasts about ten seconds. This is a greater distance between the markings than the twelve metres suggested by Kelley and it would lead to more accurate speed estimates.

The model presents an idealised and optimistic case, as it ignores a number of factors that would definitely have played a role if these methods would have been applied in reality, for example spatial variations in magnetic variation, the reduced or absent visibility of the wood chip in the water during overnight sailing, lapses of concentration, periods of distraction, manoeuvres en route and the possibility of lying becalmed for a certain period or set back by adverse winds. Furthermore it is likely that the assumption of normally-distributed, zero-mean random variables is not quite true. In spite of such shortcomings, the model ought to give a far better approximation of reality that the rough, intuitive rule-of-thumb Kelley and Morison present or the qualitative assertion of authors that dead reckoning is accurate enough.

5.9.1 KELLEY'S ACCURACY MODEL FOR DISTANCE ESTIMATION

James E. Kelley Jr. is the only author who makes any attempt at all at quantitative reasoning in relation to the accuracy of navigation. He presents a simple quantitative elaboration of Morison's claim, which is limited to distance estimation only, although it implies direction estimation too, where he speaks of "position estimates". The outcome of Kelley's calculation is summarised in his statement:

> "Assuming they estimated their course-made-good every four hours and could estimate speed *to within* 13.5% (average), Mediterraneans could, in theory, estimate their position *well within* 20 nautical miles unless extreme conditions interrupted the discipline needed to keep track of the ship's motion."[401]

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[401] Kelley 1979, 18. Emphasis is mine (RN). Kelley's usage of the term 'course-made-good' is incorrect

Kelley evaluated his calculation for a sailed distance of 336 NM[402]. The relationship between the 13.5% and 20 NM is not immediately obvious, but I will explain what I believe he did.

Kelley's thought process can be reconstructed as follows:

1. His departure point is Morison's claim that speed can be estimated *to within* half a knot. Kelley presumably interprets the phrase 'to within' to mean *maximum estimating error.*

2. Kelley arrives at a figure of 13.5%, considering a vessel speed in Columbus's days of 6 knots and expressing the mean of Morison's "one knot to half a knot" accuracy as a percentage of this speed. That is actually 12.5%, not 13.5%, as Kelley states.

3. Kelley transplants this speed estimation process to the slower ships of the Middle Ages and assumes a vessel speed of four knots (4 NM/hour). Furthermore he assumes speed is estimated every four hours. The ship therefore travels nominally 16 NM in that period and the maximum error in speed measurement of 13.5% translates into a maximum error in corresponding distance measurement of 13.5% of 16 NM, i.e. 2.16 NM.

4. Kelley now considers 21 successive four-hour intervals of 16 NM (total 336 NM) and adds these error estimates quadratically. The square of one maximum distance error is $2.16^2 = 4.67$ NM^2. Multiplying that by 21 and taking the square root of the resulting number will yield the maximum error after these 21 four-hour intervals, in which 336 NM was sailed.

This value equals 10 NM and Kelley thus concludes that a distance of 336 NM can be measured with an accuracy "to within" 10 NM. Apparently he feels this number to be a bit too optimistic himself and concludes: "Doubling this figure will cover the situation in most practical cases".

This is how Kelley most probably derived the number in the phrase "well within 20 NM" in the statement at the beginning of this section.

The question is how realistic his estimate is, because it all hinges on Morison's adage that "an experienced sailor can judge speed to within a knot and half a knot if he is used to the ship". Kelley stops after this analysis and makes no quantitative connection with the construction of portolan charts.

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in this context. As leeway would be unknown, only the ship's heading could be estimated.

[402] NM = nautical mile = 1852 m. 1 knot = 1 NM/hour.

5.9.2 AN NEW MODEL TO ESTIMATE NAVIGATION ACCURACY

Kelley's calculation was reconstructed in the previous section in order to compare it against the model, presented in this section and in Appendix III. This model is based on the separation of the effects of factors contributing to navigation accuracy into independent components. Appendix III contains a more detailed explanation of the model components, as well the relevant formulas.

The navigation model has been worked out numerically for a scenario that is defined for nominal values of a number of parameters, a constant vessel speed of four knots, with speed being measured or estimated every four hours in a process that takes ten seconds to complete.

The accuracy model itself consists of the calculation of the variances of these random variables and their impact on the total distance of the route sailed and the bearing or azimuth of the route, which is assumed to be constant for the route.

The model separates the *along-course* and the *cross-course* components; the first is predominantly associated with the measurement of distance sailed and the second with the bearing measurements in the dead reckoning process. The effects of spatial variations in magnetic variation are ignored in the model. These effects would definitely be systematic and repeatable on a given route, so they do not lend themselves to be 'randomised' in the way that e.g. misalignment of the compass has been modelled.

Furthermore it will be assumed that all accuracy components are normally distributed random variables with an expectation of zero. That also holds for parameters that would have a systematic effect on any given journey, such as the compass alignment. For this type of model components the assumption of a zero expectation applies to the whole population of ships, i.e. for another ship on another journey a different alignment error applies, but over the whole population of medieval ships engaged in navigation, these alignment errors would tend toward a mean value of zero.
The result of the model will be an optimistic estimate of the accuracy achievable with the assumed navigation techniques, even though the mathematical rigour in the working methods of the 'mathematical seaman' in the thirteenth century has to be doubted.

A. ALONG-COURSE ACCURACY COMPONENTS

The random variable represents the sum of the variables that affect along-course accuracy. It has the following two main components.

$$\Delta d_L = \Delta d_{speed} + \Delta d_{time}$$

Δd_{speed} is a random variable containing the cumulative effect on along-course distance generated by estimating the speed of the ship;

Δd_{time} is the random variable that quantifies the impact on along-course distance of the accuracy of time measurement by means of a sandglass.

The term *cumulative* means that although the ship's speed is assumed to be estimated every four hours with a certain accuracy, Δd_{time} contains the effect of those interval estimates on the *total* distance of the journey.

A further division into sub-components is as follows.

$\Delta d_{speed} = \Delta d_{L,1} + \Delta d_{L,2} + \Delta d_{L,3} + \Delta d_{L,4}$
$\Delta d_{time} = \Delta d_{L,5} + \Delta d_{L,6}$

$\Delta d_{L,1} =$ Random variable that quantifies the cumulative effect on the along-course distance estimate due to variations in *vessel speed* measurement *from interval to interval.* These are variations in the tempo of chanting the rhyme and variations in dropping and sighting the piece of flotsam. Variations in the latter are caused by human factors but also by the tossing about of the piece of flotsam by waves.

$\Delta d_{L,2} =$ Random variable that quantifies the cumulative effect in the along-course distance estimate due to variations in *vessel speed* measurement *between journeys and between different navigators.* Apart from the variation in the tempo of chanting the rhyme, a given navigator would have had a tendency to always recite the chant too quickly or too slowly. As short time intervals could not be measured objectively in the Middle Ages, a personal 'calibration' error is to be expected. Also the personal error in assessing whether the piece of flotsam is abeam of the navigator would contribute to this. A given navigator would therefore make this error consistently in every estimate of vessel speed he makes. The standard deviation of this variable is the spread in personal error in a large population of navigators. For simplicity it has been assumed that per journey a single navigator made all measurements. Multiple navigators for a ship, each with his own 'personal error', would be more realistic, but also more difficult to model reliably.

$\Delta d_{L,3} =$ Random variable expressing the *sampling* effect in speed measurement. The mean vessel speed over a time interval of, say, four hours, would be different from the instantaneous speed, measured at any moment during the interval.

$\Delta d_{L,4} =$ Random variable expressing the cumulative effect on the along-course distance estimate due to the (uncompensated) along-course component of *sea currents.* In Chapter 4 I argued that it would have been utterly impossible to predict currents, whether sailing along the coast or in the open sea. It is debatable whether any attempt at quantitatively estimating the effect of e.g. a coastal current would have been made. Also this random variable is assumed to be normally distributed, with a zero expectation.

The measured speed of the ship has to be multiplied with time lapsed, which is assumed to have been measured using a sandglass. This measurement is also represented by a random variable, modelling a systematic (calibration) and a random component:

$\Delta d_{L,5}$ = Random variable expressing the cumulative effect on the total distance estimate caused by variations in the measurement of time by means of a *sandglass* for the duration of a four-hour watch. It is not known what the range of a medieval sandglass was, but if it is assumed that half-hour glasses were used, as in Columbus's days, the glass would need to be turned eight times during a four-hour watch, which would introduce *random* variation in the measurement of time. Also the rolling and pitching of the vessel would result in variability of the sand flow and lastly, variations in humidity of the sand would introduce a third random element.

$\Delta d_{L,6}$ = Random variable that expresses the cumulative effect of *sandglass calibration*. This variable would have a single outcome or constant value for each journey. This calibration 'error' is assumed to have a tendency toward a mean value of zero over many journeys. Calibration of sandglasses was difficult in the Middle Ages. Furthermore, the older the sandglass would be, the more it would tend to run fast, due to abrasion of the glass by the sand. On the other hand, increased humidity of the sand would make it run slow. These two systematic effects are assumed to cancel out in the navigation accuracy model so the assumption of a zero expectation is preserved.

B. Cross-course accuracy

The random variable describing cross-course accuracy is assumed to be the sum of four independent constituent variables and to have an expectation of zero, i.e. no systematic error is assumed to be introduced in the measurement of the ship's course. Cross-course accuracy is expressed as a distance cross-course, indicated by Δd_X, and its four components are defined as follows:

$\Delta d_{X,1}$ = Variable that quantifies *random* actual variations in the vessel's *course bearing* as a result of pitch, roll and yaw, including the instability of the compass needle due to the ship's motion. Each realisation of this random error is valid for a watch interval of time duration and varies from interval to interval.

$\Delta d_{X,2}$ = Random variable that quantifies *misalignment* of the compass with the ship's longitudinal axis and by construction errors in the compass. One realisation of this variable is assumed to apply to the whole journey, but over many journeys the mean of such misalignments is assumed to tend toward zero.

$\Delta d_{X,3}$ = Random variable quantifying the *leeway* of the vessel. This is only relevant when the ship is not running due downwind. Actual leeway is assumed to vary from one watch interval to the next.

$\Delta d_{X,4}$ = Random variable expressing the cumulative effect on the cross-course distance estimate due to the (uncompensated) cross-course component of *sea currents* and evaluated in a similar way as for along-course currents.

C. ESTIMATES FOR THE STANDARD DEVIATIONS OF THE VARIABLES

The following values have been used as the standard deviations of the component random variables.

Along-course component variables		
L,1	Variation in time interval for speed measurement; nominal length of this time interval is 10 seconds	1.5 sec
L,2	Variation in time interval, nominally 10 seconds long, between multiple observers (personal error of observer)	1.5 sec
L,3	Variation in ship's speed due to sampling: average actual speed over the 4-hour interval deviates from the instantaneous speed estimate	0.5 kn
L,4	Uncompensated along-course component of currents experienced	0.5 kn
L,5	Variation in sand glass measurement of a 4 hour interval	20 sec
L,6	Variation in sand glass calibration expressed over a 4 hour interval. Constant for one sand glass; the variation is over multiple sand glasses	0.1 hr

Table 5.3 *- Assumed standard deviations of random variables contributing to along-course navigation accuracy.*

Cross-course component variables		
X,1	Variation in estimate of the ship's course over an interval of 4 hours due to pitch, roll and yaw and needle instability	7 deg
X,2	Misalignment variable of the compass with the longitudinal ship's axis, systematic for one trip; variation is over multiple compass installations	2 deg
X,3	Leeway of the vessel; only relevant when not running exactly before the wind.	3 deg
X,4	Uncompensated cross-course component of currents experienced	0.5 kn

Table 5.4 *- Assumed standard deviations of random variables contributing to cross-course navigation accuracy.*

The difficulty after having identified the various components affecting measurement accuracy evidently lies in providing realistic estimates for each component. For some components a reasonable estimate can be made, for other components an educated guess is all that is possible.

In estimating how accurate a medieval navigator would be able to estimate a time interval it has been taken into account that he would have had no means of calibration at all. A variation of 3 seconds has been assumed to cover 95% of the cases (i.e. twice the standard deviation). It should be borne in mind that this element is not only influenced by the navigator's ability to count in a consistent way, but also by *what* he was counting, i.e. the passage of a wood chip, tossed about by the waves, which had been dropped into the water by an assistant from several metres above the water surface.

The question is how representative a measurement of speed would be for the mean speed over four hours. My estimate would be that a knot more or less would cover the 95% or two standard deviation case. The currents have a slightly more solid basis. In most cases Taupier and Letage[403] speak of current speeds in the order of one to two knots in the Mediterranean. An average has been assumed over a four hour interval of 1 knot in any of the two component directions, along-course and cross-course, taking also this to represent a 95% case, thus leading to a standard deviation of half that amount. The variation in sandglass time measurement over four hours is a guess. It would be influenced by humidity and by the pitch and roll of the ship. The variation in calibration over multiple sandglasses is based on Waters, who claims that for sixteenth century mechanical clocks an error of 1 hour per day was not uncommon.[404] One-sixth of that, corresponding to a four-hour time interval, is ten minutes, which has been taken as the standard deviation, not twice the standard deviation as in the other cases. The justification for the latter decision is that sand clocks had only just been invented in the Middle Ages. Waters's figure is based on the sixteenth century and it is reasonable to assume that during the intervening three centuries these instruments had become more reliable and accurate. The estimates of the variation in bearing measurements with the magnetic compass are all subjective. The largest component would be the instability of the needle (with compass card) as a result of pitch and roll of the vessel. What would have to be added is the parallax error in reading the compass, which would be partly systematic. Yawing of the vessel would also cause the needle to deviate from the mean course bearing of the ship. This would be a significant factor, as the ships were sailing with the wind behind, and more importantly with waves running up behind. These would affect the stern of the ship first, pushing it to one side. As the wave rolled forward an opposite motion would set in and this pattern would be repeated wave after wave.

Figure 5.12 shows the standard deviation in along-track (distance) and cross-track (bearing), calculated from the navigation model with the parameter values listed in the above table. See Appendix 3 for the formulas used.

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[403] Millot and Taupier-Letage 2005.

[404] Waters 1955, 154.

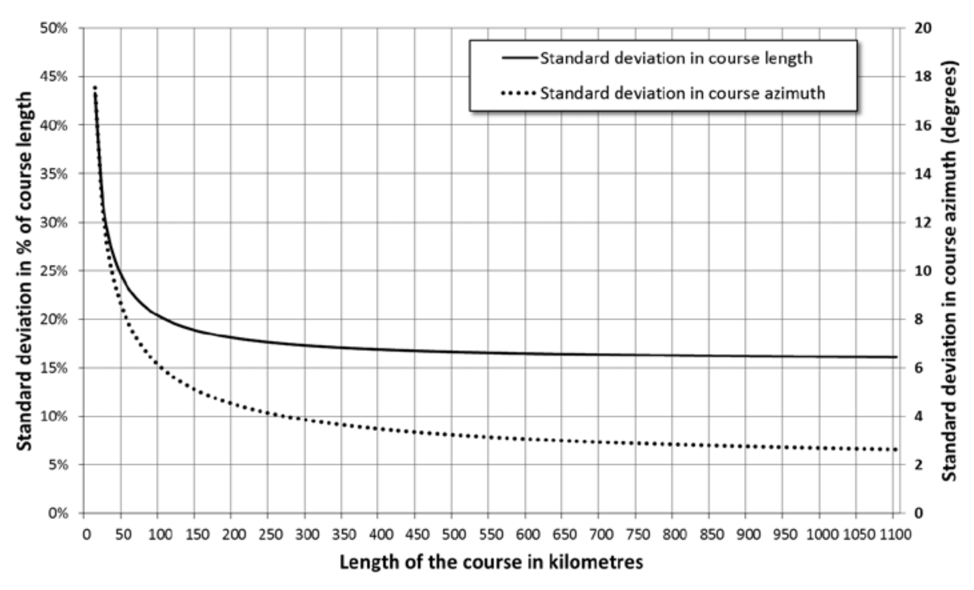

Figure 5.12 *- Standard deviation in distance and bearing of course of varying length, based on the medieval navigation model, assuming a vessel speed of 4 knots.*

5.9.3 ANALYSIS OF THE RESULTS

Figure 5.12 shows that distance and bearing measurements of short routes are relatively less accurate than those of long routes. This by caused by the fact that, the longer a route is, the more opportunity it offers for cancelling out the random components of the model. Another relevant conclusion from the navigation model is that the accuracy of distances is more than three times as poor as the measurement of bearing. Eventually the standard deviation converges to a more or less fixed percentage of the distance sailed.

Kelley estimated a standard deviation of 3.3 NM over 336 NM, or 1% for the accuracy of distance measurement. He doubled his figure to 6.6 NM, or 2%. The navigation accuracy model presented here shows a standard deviation of 16% for measured distance over 336 NM. In other words, this model leads to figures that are *eight* times worse than Kelley's, which were calculated on the basis of Morison's adage. Kelley nor Morison mentions the accuracy of the cross-course component, although Kelley speaks of "position accuracy", implying that he expects the cross-course error component to be of similar magnitude as the along-course component.

Where does this difference come from? In the first place, if Morison's figure is indeed based on practical experience; with one eye on the speed log of a modern ship and the other on the waves, his figure becomes understandable. However, that experience cannot simply be transposed to the Middle Ages, as no calibrated speed logs existed then.

Analysis of the gunwale log method shows that many factors influence the measurement process that Morison could ignore on the warships of the 1940s and on the yachts which he sailed. Kelley has done no more than packaging a figure, of which application to a medieval situation is questionable, in correct mathematics. That results in a figure that is as questionable as the value from which he started.

The single biggest error component in the medieval distance measurement process according to the model presented here is the lack of an exact time standard, more precisely, the personal error of the navigator in timing the nominally ten-second interval during which the wood chip floated by. The second factor is the random speed estimation error but the other factors are relatively insignificant.

The differences between Kelley's and my distance measurement figures are not caused because my estimates of the components are unduly pessimistic. In fact, my estimates are quite optimistic; the values of the component factors are optimistic and the model itself is optimistic. For example, spatial variation of magnetic variation has been ignored, as have any differences between daytime sailing and night sailing. Also the effects of manoeuvres en route have not been considered. Although an average speed was assumed of 4 knots, Pryor calculated from reports of medieval journeys that the average speed was often less than 2 knots, implying that much time was spent waiting for favourable winds or setbacks were experienced due to the sudden occurrence of adverse winds. Any impact these occurrences may have had on the overall accuracy of the estimates of course and distance cannot be reliably estimated and have therefore been ignored. The imaginary navigator, assumed in the model, does not suffer from distractions or lapses of concentration, but performs his duties with equal attention and precision throughout the journey. Another assumption is that the magnetic needle, which was typically made of soft iron and easily lost its magnetic properties, was promptly re-magnetised when that became necessary. Furthermore I have assumed that factors such as leeway and the effects of currents may be totally different from one four-hour interval to the next, which results in a considerable reduction of the total effect of these factors, as a significant amount of cancelling out will occur on longer journeys. In reality leeway and currents will correlate from one four-hour interval to the next, which means that this degree of cancellation or averaging-out would not happen to the extent calculated. However, such refinements are too difficult to quantify.

Conclusions from the medieval navigation accuracy model are:

- *The cross-course component of any course could be measured about three times as accurately as the along-course component. This must probably be attributed to the fact that azimuth (bearing) was measured by means of an instrument, the compass, whereas distance was essentially estimated subjectively.*
- *The longer the course, the higher the relative accuracy of both course components. This is caused by the averaging out of a number of error components as a result of the assumption of uncorrelated, successive estimates for periods of four hours.*

- *The summary conclusion from this analysis is that medieval navigation cannot have been as precise a business as is usually claimed in literature on portolan charts.*

Whether the calculated accuracy would have been adequate for drawing a portolan chart cannot be answered straight away. However, the provisional conclusion seems justified that if medieval distance and course estimates were used as a basis for portolan chart construction, averages would have been required of multiple estimates of the same course to improve precision. The assumption all authors have made regarding portolan chart construction is that the precision of the raw measurements was indeed brought to the required level – whatever that level may be – by the calculation of averages of a series of measurements for a given course leg, but the question, whether such a technique was within reach of thirteenth century cartographers has never been addressed, let alone answered. This will be done in the next and final section of this chapter.

5.10 Medieval navigation and relevant aspects of the history of science

5.10.1 Introduction

Present-day western culture has a considerable focus on measurement and precision, aimed at understanding and controlling important factors in the world around us. An important question for the understanding of the origin of portolan charts, which will be addressed in this section, is whether a similar attitude to measurement and precision existed in the Middle Ages. Existing literature suggests that not to be the case.[405] The high accuracy of portolan charts, compared to contemporary European *mappaemundi* and Arabic-Islamic cartography requires this issue to be addressed. Quantified estimates of the accuracy of portolan charts are provided in Chapter 7: *Cartometric analysis of five charts.*

The explanation provided in the medieval origin hypothesis for the extraordinary accuracy of portolan charts is the following: the accuracy of the base measurements from which portolan charts are presumed to have been constructed, has been increased to the level of accuracy reflected by the charts by averaging a large number of estimates of the bearing and distance between the same two points.

The term *averaging* is not quite specific enough and may indicate the determination of the *mean*, *median* or *mode* or even an approximate central value in the error distribution of an observation. However, from the context in which the subject is mentioned in

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[405] John K. Wright, *The Geographical Lore of the Time of the Crusades – A Study in the History of Medieval Science and Tradition in Western Europe* (New York: Dover Publications, 1965), chapter XI on cartography, 247-250; Crosby 1998, 21-126.
Crosby 1998, 21-48.

portolan chart literature, it can be established that probably the *arithmetic mean* is meant. The arithmetic mean is calculated by adding all measurements of the same quantity up and dividing the sum by the number of measurements. The resulting value has a smaller standard deviation. The theoretical relationship between the standard deviation σ of the arithmetic mean and that of a single measurement is:

$$\sigma_{\text{arithmetic mean}} = \frac{1}{\sqrt{n}}\,\sigma_{\text{single measurement}}$$

In this formula the number '*n*' is the number of measurements of the same observable. The assumptions in the above formula are that all single measurements have the same standard deviation, and that none of them contains a systematic error. Formulated in words, the standard deviation of the arithmetic mean of an observable quantity, be it a bearing between two points or a distance, is smaller than the standard deviation of a single measurement by a factor equal to the inverse of the square root of the number of measurements over which the calculation took place.

The terms *measurement* in this section refers to the resulting distance and course estimates for a seaborne route between two ports, cities, or promontories. In the case of distance, one single measurement is assumed to be the result of a complex process in which the speed of the vessel was measured at regular intervals, then multiplied by the time period of each interval to get an interval distance estimate, after which the cumulative distance of the course leg would be calculated by adding up all interval distances. For simplicity's sake it is assumed that a ship would sail a straight course from port to port.[406] The sailing of one course leg between two ports or landmarks would therefore yield two single measurements, one for direction (bearing or azimuth) and the other one for distance.

The calculation of the arithmetic mean of multiple measurements of the same route is a very convenient mechanism to explain the high accuracy of portolan charts, constructed from navigation measurements. In present-day thinking the fact that the arithmetic mean of a series of measurements of the same variable is closer to the true value than a single measurement is taken for granted. However, was this equally evident to medieval cartographer-navigators or does it reflect a *presentist*[407] attitude to assume so? That is the key question to be addressed in this section.

5.10.2 QUANTIFICATION IN THE EUROPEAN MIDDLE AGES

A simple negative answer to the above question would suffice: this was not evident to

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[406] A *straight* course is assumed to be course of constant azimuth (or bearing).

[407] *presentism* is the tendency to interpret past events in terms of modern values and concepts. *Concise Oxford English Dictionary*, 11th ed., revised (Oxford: Oxford University Press, 2008). See also the closing remarks of Chapter 3.

medieval man. Exceptions may have existed, but individual brilliant men such as Leonardo of Pisa, Robert Grosseteste and Pierre de Maricourt, were not representative for the general intellectual climate. The question is whether a climate existed that was able to foster an activity such as the large scale collection of all navigation measurements and the subsequent calculation of the arithmetic mean of repeated measurements of the same distance and, subject to the timely availability of the compass, bearing.

Up to the middle of the twelfth century the dominant classical influence on medieval thought was exercised by Plato's philosophy[408], as interpreted and promulgated by St. Augustine. However, during the twelfth century hitherto unknown works by Aristotle, translated from Arabic by Gerard of Cremona and others[409] caused Aristotelian philosophy to become the dominant philosophical influence for centuries to come. Its popularity was further enhanced by new translations of all known works of Aristotle directly from Greek by William of Moerbeke in the thirteenth century.[410] Although Aristotelian philosophy clashed with Christian thought on a number of crucial points, it was reconciled with, but also subordinated to Christian faith by Thomas Aquinas,[411] who referred to science as *ancilla theologiae*, 'handmaiden of theology', which was considered to be a "title of honour".[412] Aristotelian philosophy held scientific inquiry and scientific thinking in a strong grip throughout the Middle Ages.

Aristotle's universe was a highly qualitative, even non-quantitative universe, although it would be incorrect to see that as the cause of the qualitative thinking of the Middle Ages. In the spatial domain this non-quantitative medieval thinking is expressed most clearly in the *mappaemundi* of the period.[413]

Probably as a result of the Crusades the idea that Jerusalem is the centre of the world found expression in the later circular mappaemundi of the T-O type, such as the Hereford, Psalter and Ebstorf maps, in which Jerusalem is indeed shown in the centre of the circle.[414] Pope Urban II, calling for the First Crusade, had described Jerusalem as the centre of the world, as in Ezekiel 5:5. Associated with Jerusalem's presumed central position was the belief that the city was situated exactly at the Tropic of Cancer. David Woodward cites Adamnan, Abbot of Iona, as having written:

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[408] Crombie 1979 (1959), 50.

[409] Crombie 1979 (1959), 60.

[410] Crombie 1979 (1959), 54.

[411] Dijksterhuis 1986, 34, 38.

[412] Dijksterhuis 1986, 130.

[413] See P.D.A. Harvey, *Medieval Maps*. London: The British Library, 1991 and David Woodward, "Medieval Mappaemundi" in *The History of Cartography, Volume 1 – Cartography in Prehistoric, Ancient and Medieval Europe and the Mediterranean*, ed. J.B. Harley and David Woodward, Chicago, University of Chicago Press, 1987: 286-370.

[414] On most medieval mappaemundi Jerusalem is not shown in the centre of the world. Woodward 1987, 340.

> "A very high column, which stands at the centre of the city … It is remarkable how this column … fails to cast a shadow at midday during the summer solstice, when the sun reaches the centre of the heavens … And so this column … proves Jerusalem to be at the centre of the world … and its navel."[415]

Despite the fact that Jerusalem was in Christian hands for a considerable time, no-one apparently bothered to check this. It was a theologically obvious fact and needed no experimental verification or confirmation. In addition to the influence of theology, the awe for the authority of writers from antiquity was so great that people rather believed them than their own observations. As John Kirtland Wright observes:

> "Contemporary information from observation was seldom assimilated in the body of geographic information, taken from ancient sources, even if such observation seemed to prove old information false."[416]

Also with regard to time a lack of precision reigned; according to Alfred W. Crosby:

> "Hours were the smallest units with which people commonly concerned themselves. Shorter periods were dealt with in an improvised way: fourteenth century cooking instructions stated that an egg should be boiled for the length of time in which a *miserere* is said."[417]

But, as Crosby states, a change occurred between 1275 and 1325, which marked a move towards a more quantitative approach of reality: mechanical clocks, portolan charts, perspective painting and double-entry bookkeeping made their appearance in the Mediterranean world.[418] It is remarkable that the second element Crosby chooses to mention in this context is the appearance of portolan charts, but I shall not elaborate on that point now.

A key element of a more quantitative approach was the introduction of the Hindu-Arabic numeric system by Leonardo of Pisa, which included the place-value principle and the symbol for zero. According to Eva G. R. Taylor, in an article on navigation techniques of the thirteenth century, "the superiority of the new numerals … was immediately obvious and they soon became widely used".[419] However, evidence speaks against such a speedy uptake. As Alistair Crombie states:

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[415] Woodward 1987, 340.

[416] Wright 1965, 255.

[417] Crosby 1998, 32. This is strangely analogous to the way it is assumed vessel speed was estimated!

[418] Crosby 1998, 18.

[419] Taylor *Mathematics* … 1960, 5.

> “The Hindu numerals were introduced into Western Europe gradually from the twelfth century onward. The Hindu numerals did not immediately drive out the Roman ones and until the middle of the sixteenth century Roman numerals were widely used outside Italy, but by 1400 Arabic numerals were widely known and generally understood at least among men of learning”.[420]

Crosby underlines this observation and illustrates it with some examples:

> “The change from Roman numerals was slow and was accomplished without grace. For centuries Europeans kept jumbling various systems together… In a preface to a calendar in 1430 the year was defined as having a length of *CCC and sixty days and 5 and sex odde hours* … The year 1494 was written as MCCCC94 and 1502 as IV0II ... The painter Dirk Bouts placed on the altar at Louvain the number MCCCC4XVII (1447). Even by 1500 Hindu-Arabic numerals had not completely displaced Roman numerals.”[421]

Although the introduction of quantification started in the second half of the thirteenth century[422] Crombie summarises the work of the intellectual elite of that period with the following words:

> “Even in the midst of other excellent work, medieval scientists sometimes showed a strange indifference to precise measurements and could be guilty of misstatements of fact, often based on purely imaginary experiments copied from earlier writers, which the simplest observation would have corrected.”[423]

It is justified to conclude that, although a more quantitative outlook on the world gradually emerged from the second half of the thirteenth century, an intellectual climate in which large-scale collection of precise navigational measurements would have been a normal event cannot be said to have existed.

5.10.3 THE HISTORY OF THE ARITHMETIC MEAN

Could it be that medieval sailors and cartographers were a sub-group in medieval society that was streets ahead of the intellectual elite of its day? That is highly unlikely; however, the idea of improving the accuracy of estimates of navigation data by calculating arithmetic means may also be approached from another angle, viz. from the perspective of the history of the arithmetic mean. That idea is usually formulated in portolan chart literature in rather non-specific language, which may be summarised and paraphrased as

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[420] Crombie 1979 Vol 1, 66, 67.

[421] Crosby 1998, 115.

[422] Although this period is given by Crosby, one might consider the start of quantification in the early eleventh century with the invention of musical notation by Guido of Arezzo.

[423] Crombie 1979, Vol. 2, 26.

follows: "the emergence of a body of common knowledge of bearings and distances of repeatedly sailed routes, which led to improved estimates of these quantities." Ramon Pujades states that "by the end of the twelfth century the seamen-merchants of Mediterranean arc that stretches between Genoa and Pisa … had accumulated a vast amount of data on the distances and directions that separated Mediterranean ports."[424]

To understand that the calculation of the arithmetic mean results in a reduction of the random error, or, which is the same, a smaller standard deviation, requires in the first place some notion of the existence and the role of random errors in the measurement process.

The statistician Robin L. Plackett wrote an article devoted exclusively to the history of the arithmetic mean and reports:

> "The technique of repeating and combining observations made on the same quantity appears to have been introduced into scientific method by Tycho Brahe towards the end of the sixteenth century."

In the years from 1582 to 1588 Brahe measured the right ascension of the star α Arietis. He collected a total of 27 measurements, of which the last 24 were taken 6 months apart, such that the systematic error introduced by the annual parallax of the star was eliminated. He adopts a final value that deviates slightly (2 seconds of arc) from the arithmetic mean, but doesn't describe why he did that.[425]

Plackett continues by stating that:

> "The calculation of the mean as a more precise value than a single measurement is not far removed and had certainly appeared about the end of the seventeenth century."

Also in the emerging new science of geodesy the calculation of the arithmetic mean was applied as a technique to improve precision. Alexander R. Clarke refers to the arithmetic mean of geodetic measurements during the famous Académie Française expedition to Lapland of 1736-37 (another was organised to Peru) to establish whether the earth was flattened or elongated along its polar axis.[426]

Stephen M. Stigler summarises the situation as follows:

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[424] Pujades 2007, 520.

[425] Robin L. Plackett, "Studies in the History of Probability and Statistics: VII. The Principle of the Arithmetic Mean". *Biometrika* 45 (1958), 131, 132.

[426] Alexander R. Clarke, *Geodesy* (Oxford: Clarendon Press, 1880), 5.

> "By the middle of the eighteenth century at least one statistical technique was in frequent use in astronomy and navigation: the taking of a simple arithmetic mean among a small collection of measurements made under essentially the same conditions and usually by the same observer."[427]

The first documented experiment that demonstrated observational variation took place in 1538 on board a Portuguese ship on its way from Lisbon to Goa. The experiment was organised by Dom João de Castro, a Portuguese nobleman, one of the first to understand the importance of experiments and not afraid to dirty his hands by performing these experiments himself. He routinely observed the midday altitude of the sun by sea astrolabe but had it additionally observed by the ship's doctor, the captain, the pilot, the first mate, the ship's carpenter and at least three sailors. Teixeira de Mota provides the results of the observations, which are remarkable for their close agreement.[428] One cannot help but wonder whether the incumbents heard the values read out by the others, including D. João's before providing their own estimate. D. João was well aware of the differences in observation values by different observers and, according to R. Hooykaas, distinguished the following error sources:

a) human errors (defects of the senses; lack of skill in manipulating instruments; erroneous calculations which often are a consequence of scanty knowledge of the theory),
b) by defects of the instruments, and
c) by the influence of the environment on the phenomenon one wishes to single out.[429]

It is clear that, although he did his best to identify sources of errors in measurements Castro was not yet aware of the nature of random observational errors.

From the above summary it is crystal clear that twelfth and thirteenth century cartographers and sailors, if they had computed arithmetic means of their observations, would not just have been streets ahead of the intellectual elite of their days, they would have been centuries ahead of mainstream science, even if science in the modern sense did not yet exist. There can be little doubt that the assumption that this group of people managed to collect a huge amount of navigation observations from around the Mediterranean and Black Sea (and Atlantic for that matter) and calculated a series of arithmetic means for each geometric quantity is so unlikely that it must considered incorrect.

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[427] Stephen M. Stigler, *The History of Statistics.* The Measurement of Uncertainty before 1900, (Cambridge MS, Harvard University Press), 16.

[428] Teixeira de Mota 1958.

[429] R. Hooykaas, *Science in Manueline Style* (Academia Internacional da Cultura Portuguesa, reprint Obras Completas de D. João de Castro, Vol. IV, 231-426, Coimbra 1980), 125.

The often made claim that medieval mariners or cartographers calculated the arithmetic mean of a large number of bearings and distances spread over the coverage area of portolan charts in an attempt to explain these charts' accuracy must indeed be considered a clear example of *presentist* thinking.
The following conclusions may be drawn regarding medieval navigation techniques and the often assumed process of averaging series of measurements.

6. *The accuracy of medieval navigation, notably distance estimation, is generally grossly overestimated. A simulation model suggests a best achievable accuracy corresponding with a standard deviation of 16% of the distance sailed and a standard deviation of about 3 degrees in direction. However, this assumes a rigorous discipline was applied to navigation, which is doubtful.*

7. *The magnetic compass, as a single instrument, suitable for the measurement of course direction, appears to have come into widespread use only during the first half of the fourteenth century, which was too late to have contributed significantly to the presumed body of navigation data, shared in Mediterranean maritime circles. It is therefore unlikely that the compass could have made a key contribution to the measurement data underlying the construction of the first portolan chart.*

8. *The calculation of the arithmetic mean, or other forms of averaging, of a series of measurements of the same variable (distance or direction), with the objective of improving the precision of the resulting estimate, was a technique not known and at any rate not practiced in medieval Europe.*

6 CARTOMETRIC ANALYSIS; METHODOLOGY AND EXISTING RESEARCH

6.1 INTRODUCTION

6.1.1 OUTLINE OF THIS CHAPTER

The two most intriguing characteristics of portolan charts are their evident realism and the close resemblance of the shape of the coastlines of the Mediterranean and Black Sea on these charts to a map image generated by applying a map projection.

The accuracy of the charts and the close agreement with the Mercator and Equidistant Cylindrical projections can only be established through quantitative analysis methods, but the relative importance of such methods for portolan chart research is sometimes either doubted or unduly emphasized depending on the professional background of the researcher. Section 6.1.2 is an attempt to justify the application of quantitative analysis methods in historic map research. This is followed, in Section 6.1.3, by a brief description of how the term *map projection* is used in this thesis and, in Section 6.1.4, by a discussion on what is meant by *map accuracy* and *map distortion* and how random and systematic distortion elements in the map – a distinction made in this thesis – may be estimated.

These introductory sections are followed in Section 6.2 by a classification of cartometric analysis methods at a conceptual level and the justification of the choice of the analysis method selected for this thesis. A summary and critical review of the most relevant cartometric analysis studies is provided in Section 6.3.

Section 6.4 describes and justifies the choice for the five charts that have been analysed in Chapter 7 of this thesis. Section 6.5 explains in detail the methodology followed, describing the important aspects of the analysis method.

This chapter is supplemented by Appendix IV, in which some additional details about the creation of identical points are provided, as well as the map projection formulas used in the cartometric analysis process described in Chapter 7.

6.1.2 In defence of the cartometric method

Quantitative analysis of portolan charts was introduced in 1896 by the German geographer Hermann Wagner, who proposed the application of extensive measurements in the charts to determine their characteristics. He named this method *cartometric analysis*. He felt compelled to advocate this technique by the speculative statements of his colleagues about a possibly underlying map projection and other aspects of the charts:

> "… people have been content to express indefinite suppositions. These, repeated by one author from another without being tested, acquired the character of well-established facts, and this state of matters satisfied a large majority of the historians of geography."[430]

Wagner describes two options for cartometric analysis. The first option is the measurement of a large number of distances in the chart; the second is the drawing of a graticule based on the latitudes and longitudes of a large number of points identified in the chart.

Since their introduction by Wagner, quantitative analysis methods have been applied to portolan charts by numerous researchers, many of whom have focussed on determining the best matching map projection. However, also the accuracy of the charts may be quantified with such methods, although that is not often done; Peter Mesenburg appears to be one of the few researchers who calculated estimates of the accuracy of a number of portolan charts.

There may be a somewhat of a gap between portolan chart researchers with a background in the humanities such as history and human geography on the one hand and researchers with a more scientific background on the other and, in the 'best' C. P. Snow tradition[431], both groups may have difficulty understanding each other, accustomed as they are to their own methods and language. Proponents of the more exact approach may favour methods such as cartometric analysis, whereas those with a background in the humanities might prefer a qualitative synthesis of information from diverse sources.

It is sometimes argued that cartometric analysis does not produce consistent results and that this will undermine trust in such methods. This may even lead to rejection of mathematics as a discipline that can make a contribution to research on portolan charts, as argued for example by Pujades.[432]

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[430] Wagner 1896 (1969), 476.

[431] As in C. P. Snow, *The Two Cultures,* 1959 (1998)

[432] See Chapter 2.7 and Pujades 2007, 506

It is true that cartometric studies have failed to come up with a consistent set of conclusions, but it is unjust to blame this on the perceived inadequacy of the method. In the first place the *cartometric method* is not a single method, but rather a collection of different quantitative techniques that may be applied in the study of historical maps. 'There are horses for courses', as the saying goes, and different quantitative techniques will achieve different things. In order to get a clear result from a cartometric study it is vital to begin by asking the right question. One cannot apply a quantitative method blindly and hope it will answer a question one didn't ask.

The question, when it is asked, has to be specific enough to be answered by applying the chosen cartometric method. A negative example is the question: 'What is the area of Algeria to the nearest ten square kilometres?' The addition 'to the nearest ten square kilometres' is added to avoid any hair-splitting about the exact shape of the coastline. However, this is not enough. It is more important to know whether it is required to calculate the area on the ellipsoid or sphere or in the map plane. When that has been decided, it is necessary to know what the dimensions are of the ellipsoid or sphere and, in the case of a decision in favour of the map plane, which map projection. The last hurdle is the type of line that constitutes the border: rhumb lines, geodesics or straight lines in the map.[433] The southern borders of Algeria consist largely of lines that are shown straight on *any* map regardless of the map projection. This introduces ambiguity in the location of the border. The most extreme case is the border between Algeria and Mali/Mauretania, which is about 1200 km long. The absence of specification of the type of lines constituting the borders and the lack of specification of the precise geodetic model[434] to be used cause an ambiguity in the area of Algeria that far exceeds ten square kilometres. Should one blame geodesy or mathematics for not being able to come up with a single consistent answer? Surely not; the proper approach would be to formulate a question that is specific enough to permit an unequivocal answer.

The same holds for cartometric analysis of historic maps and charts. One can hardly blame cartometric analysis for being an inadequate method when the researcher is unclear what question the analysis is intended to answer or when the question is not specific enough. Even when the researcher is clear in his or her own mind what problem he or she is trying to solve, the question is whether the chosen cartometric method is appropriate for the task, which is why relatively much effort has been spent in this chapter to explain various methods conceptually and to justify the chosen approach.

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[433] In most map projections rhumb lines or loxodromes project as curves, with the possible exception of some special rhumb lines. For example parallels and meridians project as straight lines in any normal-aspect cylindrical projection, but all other rhumb lines in such projections project as curves. The exception is the Mercator projection, in which all loxodromes project as straight lines. Also geodesics, the shortest connecting lines on any surface, generally project as curves. Furthermore a line, shown as a straight line in one projection, will show as a curve in most other map projections.

[434] This term is explained in the next section.

6.1.3 WHAT IS A MAP PROJECTION?

Each rendering of a spherical or ellipsoidal surface on a plane surface involves some kind of projection. However, usage of the term *map projection* in this thesis is more specific.

Canters and Decleir[435] describe a map projection as follows:

> "In general mathematical terms a map projection can be defined as a one-to-one correspondence between points on a datum surface (the earth approximated by a sphere or ellipsoid) and points on a projection surface (a plane)."

The description of a map projection cited above is too general to be of practical use in the discussion on portolan charts. Mathematical functions exist that satisfy the description provided above, but are totally unsuitable for projecting parts of the surface of sphere or ellipsoid onto a plane surface. They are useless when judged against the *additional* requirement that the distortions introduced by the projections should be as small as possible, or should satisfy certain conditions, such as conformal, equidistant or equal-area conditions. These distortion requirements, which are normally derived using differential geometry, limit the number of *useful* map projections. Such map projections create very regular, systematic distortions in the map. For example, the point scale distortion of the Mercator projection is isotropic in an infinitesimal area around the point, due the conformality property of the projection, and lines of equal scale distortion are parallels. In the Stereographic projection lines of equal scale distortion are circles around the projection centre, and so on. This more narrowly defined set of *useful* projections might be termed *geodetic-cartographic map projections* or simply *map projections*. Whenever the term *map projection* is used in this thesis, an element from that set is meant.

6.1.4 MAP DISTORTIONS AND MAP ACCURACY

Accuracy, in the geodetic context of measuring geometric quantities or calculating those from measurements, is the closeness of a measured or calculated value of a quantity to its 'true' value. *Precision*, in the same geodetic context, refers to the spread of the results of multiple measurements or calculations and is an aspect of accuracy. Accuracy includes the influence of a possible systematic error or bias in the measurements, whereas precision does not. In geodesy, accuracy is often expressed as the *Root Mean Squared Error (RMSE)*[436] of a quantity; precision as its *(sample) standard deviation* and its two-dimensional equivalent, the *one-sigma error ellipse*. The quantities encountered are considered to be random variables and this approach therefore draws a researcher into the domain of statistics.

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[435] Frank Canters and Hugo Decleir, *The World in Perspective. A Directory of World Map Projections* (Chichester: John Wiley & Sons, 1989), 3.

[436] See Section 6.5.6C for a definition of RMSE.

Geometric accuracy of a map or chart, often referred to as *planimetric accuracy*[437], may be defined as the closeness of the values of geometric quantities in the map or chart, such as angles, distances or areas, to their 'true' values, compensated for the scale of the map. This requires in the first place that the features in the map are identifiable, that their values or positions are known accurately enough to consider them 'true', but it also requires knowledge of the distortions in the map caused by the map projection. For historic maps that are not based on a geodetic or cartographic map projection – they may not even be based on survey measurements – the only option the researcher has is to accept that the projective distortions cannot be separated from the other distortions and errors that are present in the map.

However, if the geodetic model of a historic map is known, the *systematic* component of map distortion resulting from this model can be calculated and taken into account. The geodetic model underlying a map consists primarily of the map projection and the ellipsoidal or spherical model of the earth.[438] The ellipsoid or sphere will generally have a smaller effect on the map distortion than the map projection, unless the dimensions of the earth are grossly under- or overestimated. Systematic distortion in this context is distortion that is either generated by the geodetic model, in particular the map projection, or it is distortion due to e.g. stretch, shrink and/or shear of the carrier material. Its magnitude and direction follows a pattern that may be estimated from measurements on the map and/or by comparison with 'field' measurements.

In addition to systematic distortions a map may contain *random* distortions. Random distortion of nearby points may correlate, but, as the distance in the map between points increases, the degree of correlation will decrease. This is Tobler's *First Law of Geography*, expressed in terms of spatial correlation.[439] Examples are data acquisition (e.g. survey) errors that affect a relatively small area of the map's coverage, incidental gross errors by the cartographer and, in the case of portolan charts, the effects of coastal feature exaggeration and localised deformations of the vellum.

The distinction of systematic and random distortion is made because these two components have to be estimated in different ways, provided they can be separated. As stated above, when the map is not based on a map projection in the geodetic-cartographic sense, systematic and random map distortions cannot be separated, but for maps that are, it is likely that separation of these two components is feasible. Whether this separation is pos-

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[437] Bernhard Jenny, Adrian Weber and Lorentz Hurni, "Visualizing the Planimetric Accuracy of Historical Maps with MapAnalyst", *Cartographica*, Vol 42, No. 1 (2007).

[438] In geography the shape of the earth is commonly approximated by a sphere. In geodesy, where higher accuracy data and larger scale maps are made and used, a more accurate model is required for the shape of the earth: an ellipsoid, which is slightly flattened at the poles.

[439] "Everything is related to everything else, but near things are more related than distant things." Tobler 1970, 236.

sible depends on the geometric quality of the data in the map. It will be clear that, if the random and gross errors in the positions of the map features approach a certain critical magnitude, they will mask the distortions caused by an underlying map projection.

Systematic distortion may be estimated by fitting a suitable model such as a map projection and/or an affine transformation to the map. However, this will not resolve all distortion; assuming the systematic distortion component has been correctly estimated, the random 'errors' or point displacements remain. These can then be characterised statistically, which is the approach followed in this thesis; map projection, scale and skew of the coordinate system are resolved and the remaining mismatches are considered to reflect the accuracy of the map.

In the case of portolan charts, existing research has already proven that separation of distortion caused by a possibly underlying map projection and distortion caused by random cartographic or navigation data errors is indeed possible; Section 6.3 provides an overview of relevant studies. However, a close fit to a map projection does not prove that the cartographer consciously applied the map projection in the construction process of the chart. Nor does it prove that the map projection in question is indeed the best-fitting one; an alternative projection may exist that will fit better. The consensus view on the relationship between map projections and portolan charts is that any map projection uncovered by cartometric analysis is an unintentional by-product of the presumed construction of the chart by plane charting. In other words, any map projection found by cartometric analysis is assumed to be not a real feature of the map or chart, but an artefact of the analysis method. The question of correctness of this consensus view will be addressed in Chapter 9: *The map projection; artificial or intentional?* However, in order to be able to address this question quantitatively it will have to be rephrased into the following two questions:

> *"Are the differences between a plane charted geodetic network and the image generated by the Mercator (or Equidistant Cylindrical) projection so small that these differences are statistically insignificant, given the accuracy of portolan charts?"*

The second question, also to be addressed in Chapter 9, follows naturally from the first:

> *"Were the geodetic capabilities of the period in which the first portolan charts were constructed commensurate with the accuracy of the charts?"*

Many of the studies on map accuracy that are described in the extensive literature on this subject do not approach map accuracy as a statistical, generalised concept. Instead these studies often focus on the actual pattern of geometric distortions of a particular map and many of the methods for the analysis of historic maps described in this literature are methods for visualising the actual pattern of distortions of a map or chart in various manners. Such methods are unsuitable for answering the two questions above; that requires quantification of the accuracy of portolan charts based on a generalised statistical concept of map accuracy.

6.2 QUANTITATIVE ANALYSIS METHODS - A CONCEPTUAL CLASSIFICATION

A bewildering array of mathematical tools is in principle available to any map historian to conduct cartometric analysis. However, most map historians are no mathematicians and it may be difficult for them to understand the presuppositions and consequences of any tool. For that reason this section is an attempt at a conceptual classification of these methods, not only to clarify the matter to the reader, but also to provide justification for the choice of the methods used in this thesis.

In 1994 Waldo Tobler published a seminal paper on quantitative analysis methods for map historical research.[440] It is difficult to estimate how many map historians have followed Tobler's ideas, but Dr. John Hessler of the US Library of Congress has professed to be inspired by them.[441]

Only one software package is widely available for cartometric analysis, viz. the open-source PC software *MapAnalyst*, which may be downloaded free of charge from the Internet[442]. *MapAnalyst* was written by Bernhard Jenny and Adrian Weber and has been available since 2006. Its algorithms are based on Dieter Beineke's PhD work.[443] The availability of *MapAnalyst* is a blessing for map historians, as it provides them with an accessible tool with a user-friendly interface, which enables them to add quantitative analysis methods to their palette of tools for the study of old maps.

Most cartometric analysis methods are based on the comparison of two sets of coordinates for corresponding points, the map coordinates (X, Y) of a point in the historical map and the coordinates of the same point obtained from a modern source, a reference dataset that is considered to be error-free. The points for which these coordinate pairs are available are usually referred to as *identical points* or *control points*.[444] The pairwise differences between the coordinates of a point in the historical map and its corresponding reference coordinates are defined as the *map error* in that particular point of the

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[440] Waldo Tobler, "Bi-dimensional Regression". *Geographical Analysis*, Vol. 26 (1994), No. 3.

[441] Hessler, John. "Bidimensional Regression Revisited: Notes toward a Characterisation of Historical Accuracy and a Theoretical Foundation for Analytical Historical Cartometry." http://loc.academia.edu/JohnHessler/Papers/161497/Bi-dimensional_Regression_Revisited.

[442] http://mapanalyst.org/ See also Bernhard Jenny, "MapAnalyst – A digital tool for the analysis of the planimetric accuracy in historical maps", *e-Perimetron* Vol. 1, No. 3 (2006). http://www.e-perimetron.org/Vol_1_3/Jenny.pdf

[443] Dieter Beineke, *Verfahren zur Genauigkeitsanalyse für Altkarte,* Heft 71, Studiengang Geodäsie und Geoinformation, Universität der Bundeswehr München, Neubiberg, 2001.

[444] This thesis uses the term *identical point*. The term *control poin*t has a different meaning in geodesy, as a nodal point in a geodetic (control) network.

historical map and are sometimes referred to as *displacement*. These differences can be calculated only after a suitable transformation of the historical map coordinates to the coordinate system of the reference dataset (or vice versa) has been applied. This transformation is either assumed beforehand or is resolved from the measurement data obtained from the map. The map errors are generally considered to be spatially correlated, i.e. two neighbouring points will have similar, but not identical errors.

However bewildering the number and complexity of (potential) mathematical methods may be, they may be divided broadly into three conceptual groups of operations on the data measured on a historical map. These three groups of methods are *interpolation*, *smoothing* and *adjustment*. They are distinguished by the way they treat the random and the systematic parts of the total map distortion. The underlying principles are illustrated for a one-dimensional case in Figure 6.1, Figure 6.3 and Figure 6.4 below.

6.2.1 INTERPOLATION

The most frequently encountered cartometric analysis method considers the map errors or displacements to be continuous over the map and to change smoothly from point to point, such that, based on the actual errors measured, an interpolated error can be calculated in non-sampled points, i.e. any point between the identical points. Interpolation methods honour the sampled data exactly, i.e. the errors in the identical points.

Interpolation determines a continuous function (graphically: a curve) from a limited set of measurements (sample) of that function (or curve). That sample, or limited set of measurements, is indicated in Figure 6.1 below as the group of black dots. Interpolation does not presume any a priori knowledge about the nature of the map errors, i.e. which part of the error is systematic and which part random. The interpolation calculation is supplemented by a variety of visualisation methods, from the simplest option of drawing the displacement vectors (error vectors) in the identical points to the calculation of distortion grids. Overviews of the various visualisation methods are provided by Forstner and Oehrli[445] and by Boutoura and Livieratos[446].

A large variety of interpolation functions are available. An often used class of such functions are *splines*, piecewise polynomial functions between successive points that have been ‘daisy chained’ in such a way that the overall result is a smooth curve with minimum curvature. Two-dimensional spline functions suitable for historic map analysis are sometimes called *thin-plate splines*. John Hessler of the Library of Congress in Washington, USA, actively looks for new ways of applying quantitative analysis methods to historic

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[445] Gustav Forstner and Marcus Oehrli, “Graphische Darstellungen der Untersuchungsergebnisse alter Karten und die Entwicklung der Verzerrungsgitter”, *Cartographica Helvetica*, Heft 17 (1998).

[446] Chryssoula Boutoura and Evangelos Livieratos, “Some fundamentals for the study of the geometry of early maps by comparative methods”, *e-Perimetron*, Vol.1, No. 1 (2006).

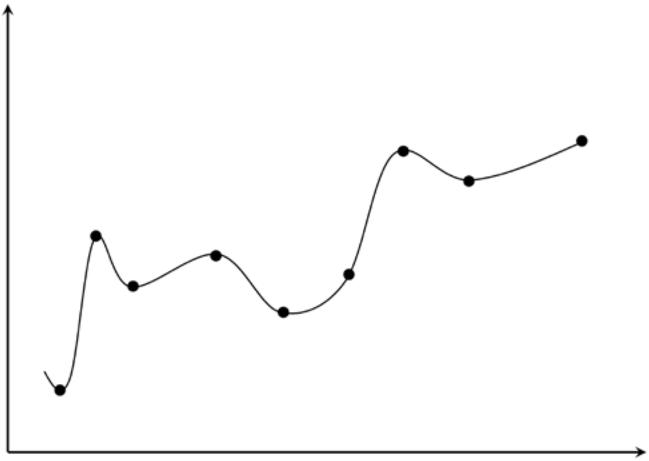

Figure 6.1 *- Conceptual illustration of interpolation.*

maps and has experimented with the application of these thin-plate splines. Balletti advocated general polynomial interpolation methods.[447]

The *MapAnalyst* programme uses an interpolation algorithm originally described by Hardy[448] and worked out by Beineke[449], who calls the method *multiquadratic interpolation*. *MapAnalyst* offers four ways to visualise the results of this interpolation calculation, viz. as:

- a distortion grid;
- displacement vectors;
- displacement circles (alternative to displacement vectors);
- iso-lines of scale and orientation (derived information from the grid).

MapAnalyst does not separate the systematic components of the map errors from the random errors computationally. Instead of calculating these systematic distortion elements from map data, the software relies on the user supplying a reference map in the appropriate map projection and thus implicitly assumes the map projection and other elements of the geodetic model of the reference map also to apply to the historic map. By default *MapAnalyst* uses a Transverse Cylindrical Equal Area projection, but, as mentioned above, it offers the option to use an alternative map projection that better approximates the projection of the historic map that is evaluated.

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[447] Christina Balletti, "Georeference in the analysis of the geometric content of early maps", *e-Perimetron*, Vol. 1, No. 1 (2006): 34.

[448] Rolland L. Hardy, "Multiquadric Equations of Topography and Other Irregular Surfaces". *Journal of Geophysical Research*, Vol. 76, No. 8 (1971).

[449] Beineke 2001, 29-31.

Jenny correctly remarks that for large-scale maps, covering small areas, the effects of the geodetic model on the distortions in the historic map, or conversely the absence of a geodetic model, can often be ignored, as other error sources will dominate the distortions in the historic map.[450]

Interpolation does not permit quantification of the accuracy of the map; the only result is the distortion grid, which provides a qualitative 'feel' for the map's accuracy, or any derived information from the interpolated grid, such as scale and orientation variations. However, the map errors that form the basis of the calculation of the distortion grid do permit quantification of map accuracy. *MapAnalyst* calculates the mean point error, i.e. the mean of the map errors in all identical points, and its sample standard deviation. Often these errors are of considerable interest or may be even the focus of map-historical investigation.

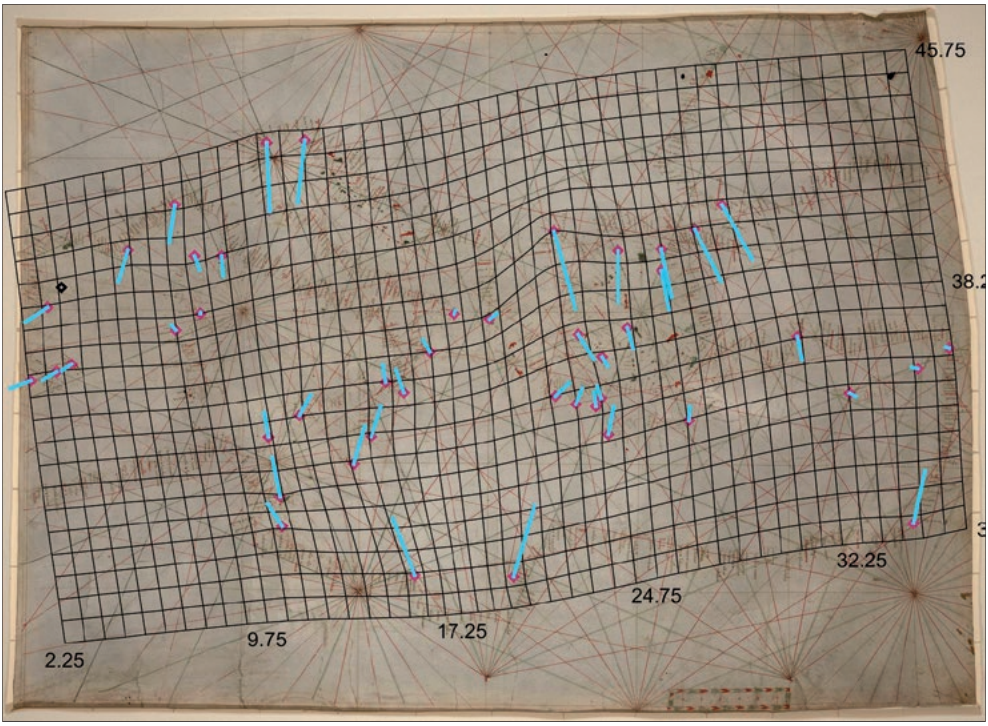

Figure 6.2 *- Distortion grid and some error vectors on the Ristow-Skelton No. 3 chart. The lines represent parallels and meridians and the numbers along the margin express latitude and longitude in decimal degrees. An assumption of regularity in the lattice of parallels and meridians even allows extrapolation of the lattice to areas outside the coverage of the (coastal) points and even outside the map (Image: courtesy of John Hessler).*

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[450] Bernhard Jenny, "New features in MapAnalyst", *e-Perimetron* Vol.5, No. 3 (2010), 179-180.

Distortion grids may contain a wealth of information about the distortions in the map and may help the map historian formulate hypotheses about the reasons for the shape of the pattern. However, deriving quantitative information from such grids may be misleading, as the inherent smoothing property of the method may mask the characteristics of the underlying historic map and patterns may become visible in the grid that do not exist in the map. The distortion grid may even be extrapolated to extend to areas of the map where no geographic features are shown, such as in the middle of sea areas or even outside the map, as may be seen in Figure 6.2.

This may for example happen with portolan charts, which are possibly composites of sub-charts of individual basins in the Mediterranean. If the sub-charts have different scales and orientations, the generation of a smooth distortion grid over the entire chart will mask the joins between those sub-charts, creating an appearance of smoothly changing scale and orientation. This is why it is risky to choose a tool for cartometric analysis without having a clear idea (i.e. a hypothesis) of what one is looking for.

6.2.2 SMOOTHING

A slightly different situation arises when the measurements, the black dots in Figure 6.1, contain random errors, which one doesn't want to see influencing the intermediate, interpolated points. In that case a smoothing algorithm, conceptually illustrated in Figure 6.3, would be appropriate.

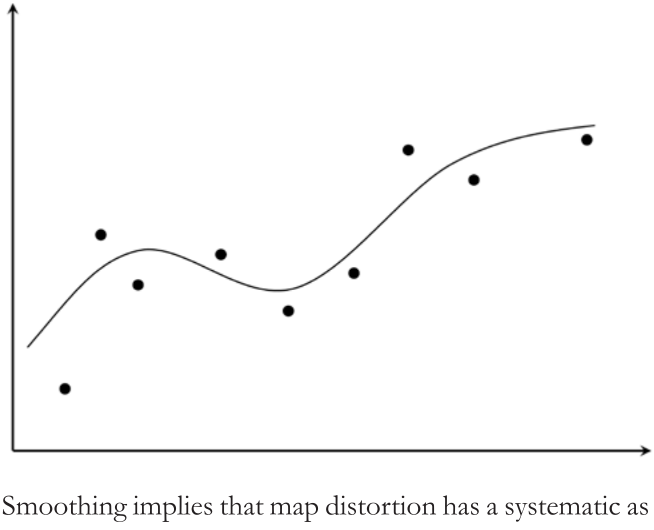

Figure 6.3 - *Conceptual illustration of smoothing.*

Smoothing implies that map distortion has a systematic as well as a random component, but the nature of the systematic component is unknown. Smoothing is an attempt to estimate the systematic distortion by filtering out random distortion (*noise*) and will result in a function (or graph) which does not exactly pass through the sampled points (the same black dots as in Figure 6.1), but will follow the trend of the errors in the sampled data. The resulting function has less 'violent' undulations as the interpolation function.

Like interpolation, smoothing can easily be extended to apply to the two-dimensional geometry of a map.

A well-known smoothing method in geodesy is Least Squares Collocation; it is applied to e.g. measurements of the gravity field of the earth and other problems where the true values are unknown but pure interpolation is inappropriate because measurements are known to be afflicted by *noise*, i.e. random errors. The fundamental problem with smoothing is that knowledge of the stochastic behaviour of the random errors is a prerequisite for successful application of the method. Although Waldo Tobler mentions collocation[451], it appears to be hardly used in the study of historic maps; perhaps not at all.

Interpolation methods honour the sampled data exactly; smoothing methods make some allowance for random measurement errors. Both types of methods are very suitable for analysing maps that have not been drawn on any intended map projection in the geodetic-cartographic sense, as they do not require the modelling of the systematic distortion characteristics of a map projection.

6.2.3 ADJUSTMENT: FITTING THE DATA TO A KNOWN FUNCTION

In some cases additional knowledge is available about the nature of the map distortions. Keeping close to the problem at hand, this is the case when the map is known to have been drawn on a map projection. The map projection, when its characteristics are known, introduces distortions that are systematic and quantifiable throughout the map. In Figure 6.4 below the systematic distortion introduced by the map projection is symbolically represented by the straight line, fitted through the data points.

The map projection can be characterised by several parameters, such as for example the (nominal) map scale and the latitude of the true-to-scale parallel. The values of such parameters may be calculated from the measurements in the map. In Figure 6.4 these parameters would be the slope of the straight line and its intersection point with the vertical axis.

This known function is referred to in geodesy as the *functional model* or *mathematical model*.[452] The coordinates of the identical points are 'forced' onto the functional model, in such a way that the result is optimised, e.g. in a Least Squares sense. In that computation

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[451] Tobler 1994, 197.

[452] 'Functional model': Peter J.G. Teunissen, *Adjustment Theory, an Introduction* (Delft: VSSD, 2003), 4 and Charles D. Ghilani, *Adjustment Computations: Spatial Data Analysis*, 5th edition (Hoboken, New Jersey: John Wiley & Sons, 2010), 182, 183.
'Mathematical model': Petr Vaníček and Edward J. Krakiwsky, *Geodesy: the Concepts* (Amsterdam: North-Holland Publishing Company, 1982), 177.
Teunissen and Ghilani consider the functional model together with the stochastic model, the a priori assumptions about the stochastic properties of the observations, to constitute the mathematical model.

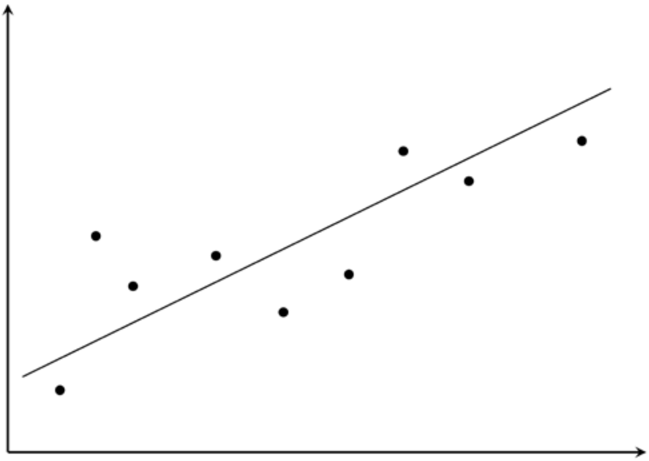

Figure 6.4 *- Conceptual illustration of adjustment: fitting a function of known shape through the data.*

the optimum values of the parameters of the functional model are determined: scale, orientation, latitude of true-to-scale parallel etc. In geodesy this approach is termed *adjustment*.

Another example, which will be presented in Chapter 9: *The map projection; artificial or intentional?*, is the application of *Least Squares Adjustment* to a geodetic network, consisting of nodal points on the coasts of the Mediterranean and Black Sea and the (simulated) bearings and distances between those points. The functional model in that case describes the measurable quantities (the bearings and distances) as a function of the unknown parameters (the coordinates of the nodal points).

Whereas the smoothing function will follow the general trend of the map distortions/errors and aims to filter out the random component of the errors, an *adjustment* process (in the geodetic sense) will apply corrections to measurements, such that the corrected measurements fit the functional model exactly. In Least Squares Adjustment the values of the parameters, which, in the conceptual example of Figure 6.4 are the slope of the straight line and its intersection point with the vertical axis, are computed by minimising the sum of the squares of the corrections to the measurements.

6.2.4 LEAST SQUARES OR ROBUST ESTIMATION?

Various options exist for the criterion according to which the measurement data, i.e. the measured coordinates of the identical points in the historical map, are fitted to the functional model. The best known criterion is probably the principle of *Least Squares*. *Least Squares Adjustment (LSA)* or *Least Squares Estimation (LSE)* minimises the sum of the squares of the corrections to the measurements that are necessary to fit them to the functional model. These corrections, with reversed signs, are commonly known as *residuals* or *residual errors*. A significant advantage of LSE is that it generates, as a by-product, statistically interpretable quality estimates of the measurement data and the calculated parameters, for example, in historic map research, the parameters that define the assumed map projection. If this presupposition (of a particular type of map projection) is correct, than the systematic component of the distortion in the map may be removed – or rather calculated, estimated – and what remains is the random component of the map errors in the form of the residuals. These random errors represent the accuracy of the map. In other words, the accuracy of the map can be quantified as a precisely defined parameter, a function of the random error components, but *only* when certain conditions are satisfied:

- the functional model is correct;
- the characteristics of the random errors have been taken into account in the appropriate way.[453]

If the functional model is incorrect, the Least Squares corrections or residuals will not only contain random errors but will be contaminated with systematic elements, and the sum of the squares of the corrections or residuals will be greater than when the correct functional model had been applied. The corrections that need to be applied to the identical points as part of the Least Squares Adjustment therefore hold the clue as to whether the correct functional model (map projection) has been applied. The sum of the squares of these residuals, calculated successively for several map projections, is a key indicator, showing which map projections fit better to the data than other projections and are thus more likely to reflect the correct functional model. This is the approach Scott Loomer adopted to determine the map projection that corresponds best with portolan charts (see Section 6.3.4).

The great disadvantage of the Least Squares method is its sensitivity to outliers.[454] Because of the squaring of the corrections to the measurements, gross errors have a disproportionally large and corrupting influence on the calculated results. Least Squares Estimation is applied extensively in geodetic surveying, but exclusively in combination with a *statistical testing* method, aimed at identifying outliers and correcting or removing them from the calculation. A good statistical testing method is able to mitigate the LSE's sensitivity for outliers very effectively.

Alternative methods that do not remove outliers, but attempt to reduce their corrupting influence on the calculated results, are collectively known as *robust estimation* methods.

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[453] This is achieved by weighted Least Squares Estimation. The observations are in this case weighted by the inverse of their variance-covariance matrix. The random errors in the map need to be normally (Gaussian) distributed. This is not a requirement for the validity of the Least Squares Estimation, but the desire to calculate meaningful accuracy estimates from the adjustment process does require the observations to be normally distributed. See Teunissen, *Adjustment Theory,* 5-60.

[454] See e.g. Frank Hampel, "Robust statistics: a brief introduction and overview", Symposium *"Robust Statistics and Fuzzy Techniques in Geodesy and GIS"*, Research Report No. 4, (Eidgenössige Technische Hochschule, Zurich: 2001) 2.

These methods usually apply a schema for iterative and progressive reduction of the impact of poorly fitting measurements. Alternatively they may use a minimising function that is less sensitive to gross errors than the Least Squares function, such as the sum of the *absolute* values of the corrections to the observations (so-called *L1 estimators*).[455] However, a side effect of robust estimation is that calculated estimates of map accuracy are much more difficult to interpret and inherently less meaningful, because the number, magnitude and impact of the gross errors in the data remain unknown. Robust methods are particularly suited to situations where the measurements are not normally distributed and to applications where exact accuracy estimates of the results are not required.

In addition to Scott Loomer, Peter Mesenburg applied Least Squares Estimation to a large number of portolan charts. Several of Mesenburg's students followed suit in a number of graduate theses under his supervision.

6.2.5 CONSIDERATIONS FOR THE METHOD TO USE

The choice for the appropriate analysis technique or the exclusion of inappropriate ones should be dictated by what the researcher intends to achieve. The application of mathematics without a clear purpose creates the possibility of seeing a result one wants to see or not seeing anything at all. Proper scientific inquiry requires prior specification of a hypothesis, followed by the design of an appropriate experiment. The outcome of the subsequent execution of the experiment will then lead to acceptance or rejection of the hypothesis. Looking into the data at random, looking for patterns (*data mining*), is a viable approach only if the objective is to formulate a hypothesis on the basis of the discovered pattern, but the researcher should avoid jumping straight from the discovered pattern to the conclusion, or mere correlation may be interpreted as functional dependency.

The researcher should seek answers to well-defined questions in order to select the appropriate analysis technique. For example, are *all* errors considered to be part of the map characteristics, including the gross errors, or should the gross errors be seen as incidental disrupting elements that may obscure the conclusions and therefore need to be excluded? How important is a statistically meaningful generalised estimate of the map's accuracy?

Previous research has shown, or at least has provided strong indications, that the portolan charts showing the Mediterranean and Black Sea are composites of sub-charts, which have their own individual scales.[456] As early as 1895 Hermann Wagner concluded

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[455] See Beineke 2001, 89-102. Beineke provides a compact but excellent description of the most popular robust estimation methods.

[456] In particular Loomer 1987. See also Campbell 1987, 383, 384 and Wagner 1896 (1969), 482, 483.

that the Adriatic Sea on the Carte Pisane "takes no part yet in the general turning of the axis of the Mediterranean."[457] Yet only Loomer has attempted to analyse portolan charts as composites.[458] A method that is able to identify these sub-charts, if their existence can be proven, is desirable.

6.2.6 JUSTIFICATION OF THE CHOSEN METHOD

In order to understand the origin of the charts, their accuracy will have to be shown to be commensurate with the geodetic capabilities of the period and the culture from which they are assumed to originate. That means that the best-fitting map projection needs to be established in order to isolate the remaining random errors, which can be used as the basis for quantifying the accuracy of the charts. Chart accuracy has to be approached as a generalised, statistical concept; the actual random distortions in a particular chart are of less interest, except where these actual distortions assist in establishing whether portolan charts are composites of coherent sub-charts and in identifying such sub-charts.

With these objectives in mind, only Least Squares Estimation of specified map projections, supplemented by statistical testing, can be considered. Interpolation or smoothing techniques are not an option, as these methods do not allow any conclusions to be drawn regarding a possible underlying map projection and cannot provide quantified estimates of the accuracy of the charts.

The addition of statistical testing as an integral part of the method distinguishes the approach selected for this thesis from other cartometric analyses of portolan charts. Statistical testing provides a means to identify sub-charts, by allowing iterative determination of coherent subsets of identical points. Outliers in the data, whether caused by poor mapping of stretches of coast or by excessive exaggeration of coastal features will have to be excluded from the calculation, as they will corrupt the estimates of scale and orientation of the sub-charts and will render the estimate of the accuracy of these sub-charts (if they can be proven to exist) unrepresentative for the total distribution of errors.

Assuming the sub-charts are real, portolan charts nevertheless show no sharp boundaries between them; the mapmaker appears to have joined the sub-charts by creating transition zones, smoothing out any discontinuities that may have existed along the joins. The statistical testing technique, used in conjunction with Least Squares Estimation should be able to reveal the transition zones between sub-charts by allowing rejection of the points that do not blend in with the main body of the sub-chart considered.

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[457] Wagner 1896 (1969), 482.

[458] Loomer 1987, 160-165.

6.3 EXISTING CARTOMETRIC STUDIES

A large amount of work has been done by numerous researchers to determine the best-fitting map projection. Other researchers are sceptical if not dismissive of such cartometric analysis methods applied to portolan charts. Why would one conduct such an analysis at all, given the broad consensus among researchers and map historians that the charts are projectionless? A method based on interpolation or smoothing would in that case be a more appropriate technique to assess chart distortions. The earlier mentioned cartometric studies failed to provide a conclusive answer regarding the best-fitting map projection, which is grist on the mill of sceptics of the application of quantitative methods. A summary of the most influential and accessible[459] studies is provided below.

6.3.1 ERNST STEGER – FIRST APPLICATION OF THE CARTOMETRIC METHOD (1896)[460]

Steger's doctoral thesis is the first study of portolan charts using the cartometric method, which had been introduced by his supervisor, Hermann Wagner. Steger is able to disprove claims by the German geographer Arthur Breusing that a conical map projection would be the best fitting projection. Breusing believed this on purely theoretical grounds, by assuming an easterly magnetic declination in the Western Mediterranean, which changed gradually into a westerly deviation in the Eastern Mediterranean. Steger concludes that an Equidistant Cylindrical projection provides the best match, i.e. the meridians do not converge towards the north everywhere in the Mediterranean, as Breusing claimed, but are more or less parallel. He also spends considerable effort in an attempt to establish the length of the mile used in the charts, producing extensive tables. This focus on the distance unit used has to be seen against the background of the *Meilenfrage* discussion in Germany at that time, in which different types of mile used in navigation were believed to provide the clue to the enigmatic scale variations in portolan charts. The scale differences between the Mediterranean on the one hand and the Atlantic coasts on the other were well-known at the time and were thought to stem from the usage of different distance units. Steger failed to provide an unambiguous figure for the length of the mile, which is not surprising in the light of the current knowledge of further scale differences between the Mediterranean and the Black Sea and between the Eastern and Western Mediterranean.

6.3.2 A.J. DUKEN'S ANALYSIS OF GIOVANNI DA CARIGNANO'S MAP[461]

The map by Giovanni da Carignano, unfortunately destroyed in the Second World War, appears to have been not so much a portolan chart, but rather a map of the Mediterranean, Black Sea and Atlantic coasts of which the coastal outlines had been copied from a portolan chart.

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[459] *Accessible* in the sense of written in a language understandable by myself.

[460] Ernst Steger, *Untersuchungen über italienischen Seekarten des Mittelalters auf Grund der kartometrischen Methode*, PhD Thesis, Göttingen: 1896.

[461] A. J. Duken, "Reconstruction of the Portolan Chart of G. Carignano (c. 1310)", *Imago Mundi*, Vol. 40 (1988).

Duken's takes an a priori position regarding the map projection. He assumes – and is the only researcher to have done so – that the Carignano map was consciously drawn on a map projection. He assumes an Oblique Stereographic projection and does not consider any alternatives, so his subsequent conclusion that the Carignano map *does* indeed correspond to this projection is a self-fulfilling prophecy.

He justifies his choice for the Oblique Stereographic projection by stating that it had been well known since antiquity. It was certainly used in the Arabic-Islamic world, but, as far as is known, for celestial mapping only, as applied to the *tympanum* of an astrolabe. It is not known ever to have been applied by the Arabs to the mapping of the earth's surface. However, Fuat Sezgin believes otherwise; his hypothesis will be discussed in Chapter 10: *An Arabic-Islamic origin of portolan charts?*

The Oblique Stereographic projection is an azimuthal projection[462] and, as such, is singularly unsuitable for the mapping of an area with the shape of the Mediterranean. In modern geodesy the suitability of a map projection type for a particular area is determined by the shape of the area and the distortion characteristics of the projection. For example, for a conic map projection the scale distortion is the same for points with the same latitude; the distortion increases in north-south direction with the distance to its true-to-scale parallel. This makes the conic projection type suitable for mapping of an area that has a dominant east-west extent, but it would be utterly unsuitable for mapping a country such as Chile, which has a very small east-west extent but considerable north-south dimensions.

In the Oblique Stereographic projection the scale distortion increases radially from the projection centre (see Figure 6.5 and Figure 6.6). This type of projection is therefore suitable for the mapping of areas that have roughly an equal extent in all directions. It is for example used in the national geodetic reference systems of The Netherlands and Romania. Lines of equal scale distortion are circles around the projection centre, or "point of tangency of the mapping plane to the sphere" as Duken calls this point. The projection centre should be chosen roughly in the middle of the area or country to be mapped, so that the scale distortion will increase equally in all directions from that point and distortion over the whole map is thus minimised. For an area with dominant east-west dimensions such as the Mediterranean area the Stereographic projection is therefore in principle unsuitable.

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[462] In an azimuthal map projection the map plane is tangent to the sphere or ellipsoid in one point, the projection centre. The general case of the Stereographic projection is usually termed *Oblique Stereographic projection*, because of the oblique angle of the map plane with the rotation axis of the sphere or ellipsoid. This name distinguishes it from the *Polar Stereographic Projection*, in which the projection centre coincides with the North or South Pole. This requires a slightly different derivation of the projection formulas in order to avoid division by zero.

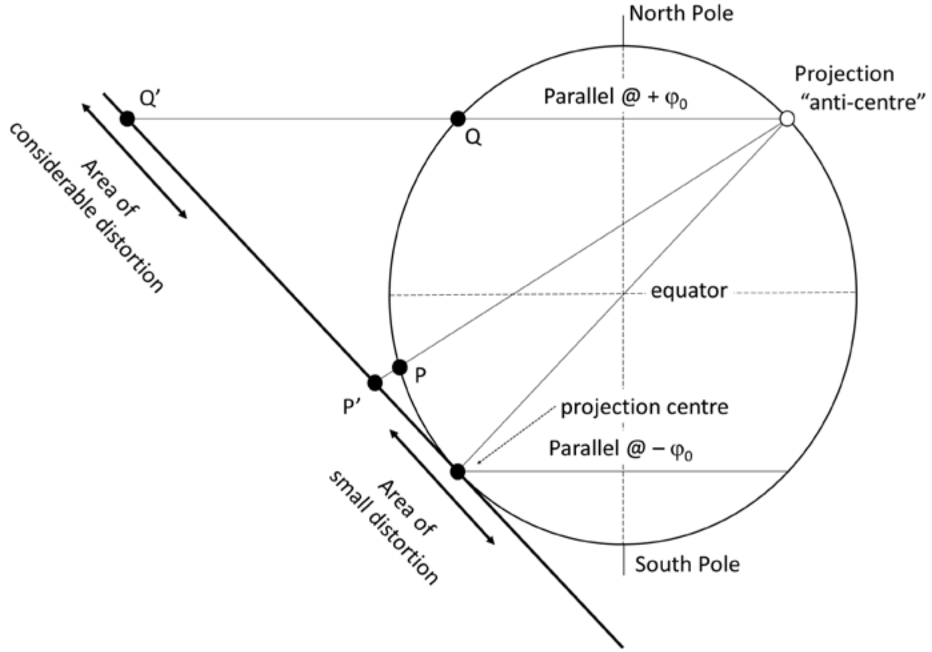

Figure 6.5 *- Principle of the Oblique Stereographic projection (meridional section).*

Duken states that he was inspired to adopt his peculiar approach when he realised that the line Tangier – Jerba Island – Alexandria is a straight line on the map and he assumes it was consciously chosen to project as a straight, horizontal line by the unknown mapmaker. The method of achieving this straightness is complicated. He assumes that that the unknown mapmaker was aware of the following property of the Oblique Stereographic projection and used this to establish the straight line mentioned: *when the projection centre is chosen in a point with latitude* -φ_0, *i.e. on the southern hemisphere, then the parallel with latitude* +φ_0 *projects as a straight line.*

Figure 6.5 and Figure 6.6 show the principle of the Oblique Stereographic projection, which, unlike the Mercator projection, can be constructed graphically. A point is chosen as the projection centre. In the example this point has latitude -φ_0, indicated as *projection centre (tangent point)* in the illustration (i.e. on the southern hemisphere).

The map plane is tangent to the sphere in the projection centre and is represented in Figure 6.5 as a single straight line. A line is now drawn from the projection centre through the centre of the sphere. This line will intersect the surface of the sphere in the antipodal point of the projection centre, indicated in Figure 6.5 with the label *projection anti-centre*.

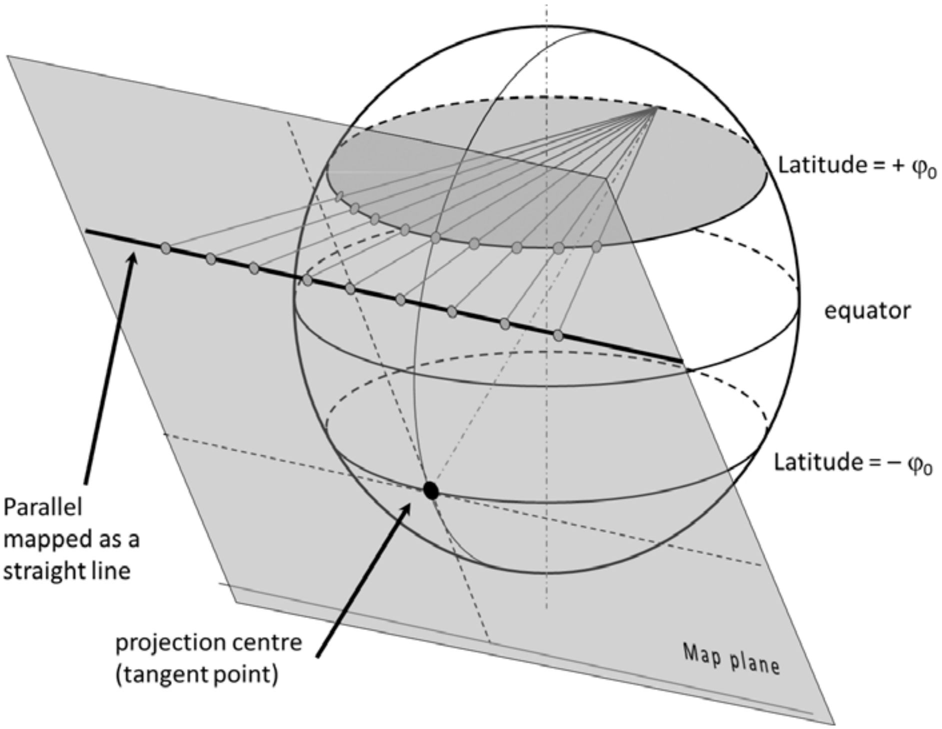

Figure 6.6 - *Perspective drawing of the line (with latitude* $+\varphi_0$*) that is projected as a straight line.*

The projection principle is as follows: an arbitrary point P on the sphere is projected as point P' in the map plane by drawing a straight line from the projection anti-centre through P and extending it until it intersects the map plane in point P'. It will be intuitively evident that the area in the vicinity (around) the projection centre is mapped with relatively little distortion. This is shown in Figure 6.5 as a single point P', as opposed to a second point Q', around which considerable distortion would be experienced; in Figure 6.6 the same arrangement is shown in a perspective drawing.

The consequence of Duken's approach is that he *must* choose the projection centre far away from the Mediterranean area on the southern hemisphere. This results in the Mediterranean and Black Sea being projected with very considerable distortions. This effect is illustrated in Figure 6.7 and Figure 6.8. A different way of expressing this distortion is to say that the parallels, as well as the meridians, *diverge* away from the projection centre. The further away from the projection centre a point is located, the stronger the divergence is. This is the mechanism by which Duken models the variations in scale in the coverage area of portolan charts, that has been observed by many researchers. In the next chapter it will be shown that the relative scale of the Eastern Mediterranean is larger than the scale of the Western Mediterranean on most charts and the scale of the Black Sea is larger again (see Figure 7.25 in Section 7.6.7). By manipulating the location

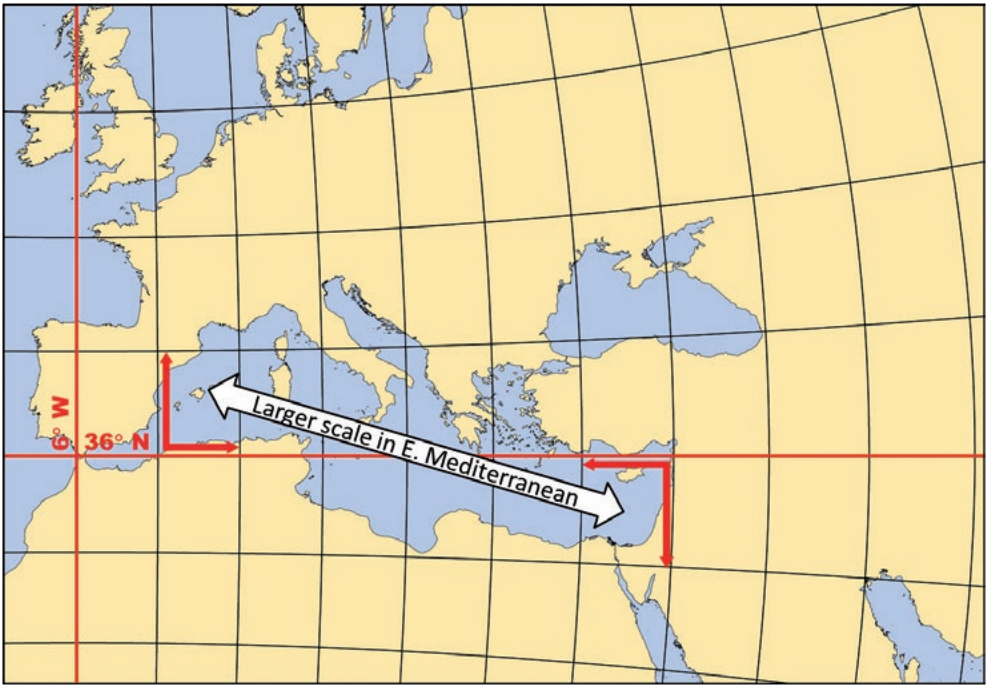

Figure 6.7 *- Oblique stereographic projection of the Mediterranean area with projection centre at latitude 36° S and longitude 6° W.*

of the projection centre, variations may be introduced in the amount of divergence of the parallels and the meridians, i.e. the amount of scale variation, until an optimum fit is found.

Figure 6.7 shows the principle of Duken's solution for the Oblique Stereographic map projection, but the scale difference between the Eastern and Western Mediterranean has been exaggerated for clarity by an even more extreme choice of the projection centre than Duken deduced. The latitude and longitude of the projection centre has been chosen at 36° S and 6°W[463]. The parallel of 36° N, which runs through the Strait of Gibraltar, is therefore projected as a straight line. The meridian of 6°W is also straight line, but for a different reason.

From the divergence of the parallels in the Eastern Mediterranean, as compared with the Western, at the longitude just west of Gibraltar, it will be clear that the map scale in the Eastern Mediterranean is larger than that of the Western Mediterranean. More divergence occurs in the Black Sea, which lies further away still from the projection centre, making the scale in the Black Sea larger again than in the Eastern Mediterranean.

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[463] In Duken's solution the latitude and longitude of the projection centre are 33.56° S and 5°E resp.

It is stressed that scale distortion increases radially from the projection centre, so the choice of the projection centre on the meridian of 6° W contributes as much to the large scale differences shown as its southern latitude. Had the projection centre been chosen at latitude 33.56° S and longitude 5° E (approximately the meridian of Marseilles), as Duken does, divergence of parallels and meridians would be slightly less and the scale differences smaller.

Had the scale differences in portolan charts shown a reverse pattern, i.e. had instead the scale of the Western Mediterranean been larger than that of the Eastern Mediterranean, a choice of the projection centre with a longitude in the extreme east of the area (and a latitude still south of the equator!) would have been appropriate, as illustrated in Figure 6.8, which shows an Oblique Stereographic projection with a projection centre at latitude 36°S and longitude 45°E.

However, Duken's solution will only work well if the scale of the chart increases radially with distance from the projection centre.

The purpose of this elaborate explanation is to demonstrate that Duken's solution is not a silver bullet that solves the problems of both the map projection and the mysterious scale differences. It is not remarkable that an Oblique Stereographic projection can be found that honours the regional scale differences of the Carignano map. Had the pattern of scale variations been different, an optimum solution could have been found by manipulating the location of the projection centre. Chryssoula Boutoura follows the same approach for modelling the increasing scale from west to east of portolan charts, but then fitting an Oblique Conic projection to several portolan charts.[464]

Key to Duken's solution is the selection of a projection centre so far away from the Mediterranean area that 'pathological' distortions are introduced in the Mediterranean area. Duken's assumption that the map projection was intentionally applied by the mapmaker leaves one with the question why such a highly skilled cartographer, who would have understood the properties of the Oblique Stereographic projection so well, would have opted for such a convoluted solution and, what is more, intentionally introduced large scale variations in the map, which every mapmaker would normally seek to avoid. The importance of the straight line Tangier – Jerba Island – Alexandria is a red herring in this respect; if the mapmaker valued straight lines that much, he could have created them in much simpler ways.

A key aspect of Duken's approach is that he considers the Mediterranean and Black Sea part of a single coherent map with a smoothly changing scale, instead of seeing it as a

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[464] Chryssoula Boutoura, "Assigning map projections to portolan maps", *e-Perimetron*, Vol. 1, No. 1 (2006).

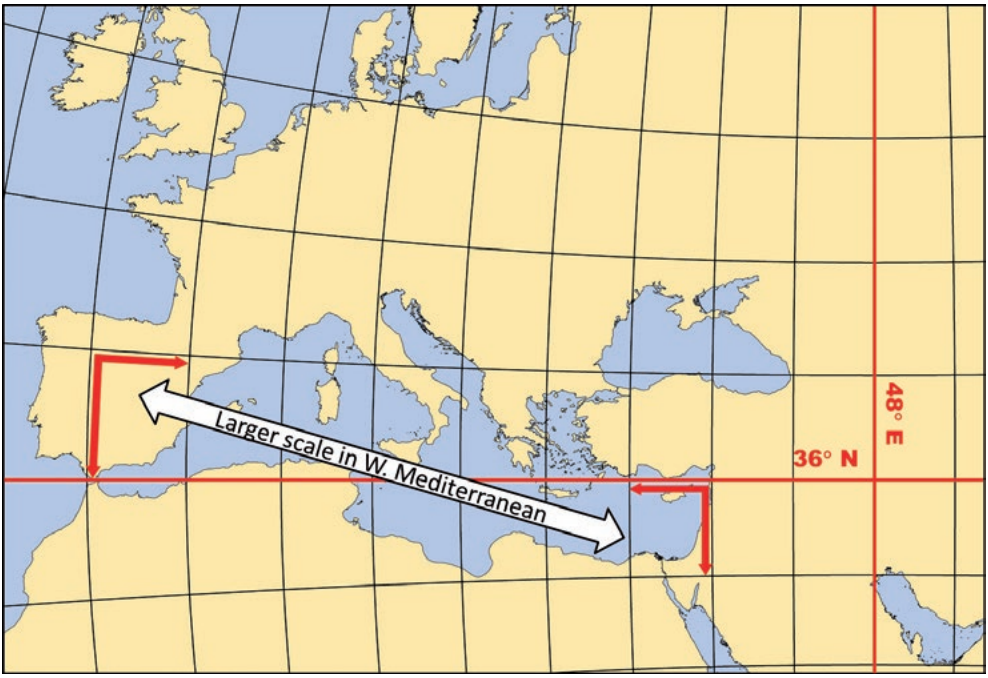

Figure 6.8 - *Oblique stereographic projection of the Mediterranean area with projection centre at latitude 36° S and longitude 48° E.*

composite of regional maps, each with their own constant scale. For the Atlantic coasts Duken's implicit assumption of a smoothly changing change as a function of distance from the projection centre doesn't hold and he concludes that the coastal areas of the Atlantic constitute two separate sub-maps. The assumption that scale increases gradually from west to (north)-east in a portolan chart is not incorrect per se, but it has to be proven by investigating the residual errors after the fitting of the Oblique Stereographic projection to the map.

The line Tangier – Jerba Island – Alexandria may be an approximately straight, horizontal line in the Carignano map, it is certainly not a line of constant latitude (parallel). Also the Carignano map exhibits the 9°-10° anticlockwise rotation of all medieval Mediterranean portolan charts. This rotation is usually explained as the result of uncorrected magnetic bearings that were used as input to the chart construction process. The angle is thus considered to reflect approximately the mean magnetic declination in the Mediterranean at the time the observations were taken. However, also in this respect Duken assumes a radically different position; he assumes that the line Tangier – Jerba Island – Alexandria *was* indeed a parallel of geodetic latitude at the time of construction of the map. He thus assumes that the geographic poles, i.e. the geographic North and South

Pole, had a physically different location on earth when the map was constructed.[465] In other words, Duken doesn't associate the anticlockwise rotation of the map in a any way with magnetic declination, as most researchers have done. Whatever his reasons may have been, the effect of this approach is more or less the same as applying the Oblique Stereographic projection without different locations for the geographic poles and then rotating the resulting map image anticlockwise.

The highly convoluted way in which he associates a map projection with the Carignano map makes Duken's work extremely unconvincing, however ingenious his solution is. The acid test for finding out whether Duken's Oblique Stereographic projection fits better than any alternative projection is to compare his solution with several alternative projections. Scott Loomer conducted such a study (see below) and concluded that the Oblique Stereographic projection does not provide as good a fit as the Mercator and Equidistant projections to the entire chart.[466] This begs the question how Loomer conducted his computation. One would expect that the way in which this application of the Oblique Stereographic projection models the scale variations would be better than the two cylindrical projections, when fitted to the entire chart.

6.3.3 Peter Mesenburg's cartometric analyses[467]

As part of his considerable amount of work on portolan charts, Peter Mesenburg analysed seventeen charts, testing several map projection types and comparing the coastal outlines of fifteen of these charts. This resulted in a very graphic illustration of the hypothesis, that the generalised coastlines of portolan charts were copied from older charts, and were not subjected to a progressive, gradual improvement over time, shown in Figure 2.15.[468]

In his 1998 paper[469] Mesenburg analyses three charts in more detail and calculates estimates of the charts' accuracy (RMSE)[470], converted to kilometres in the real world.[471] He is one of the few authors to have done so. Mesenburg treats each chart as a single,

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[465] Duken 1988, 88. He assumes the location of the North Pole to have been at the point which now has latitude 88.198° N and longitude 98.580° E. How he arrived at these figures is not entirely clear.

[466] Loomer 1987, 133. See also Sections 6.3.4 and 7.6.5.

[467] See the Bibliography section for the six publications by Mesenburg on which this short analysis is based.

[468] Mesenburg 1988, 80.

[469] This information is not in his publications, but is available on his website: http://www.mesenburg.de/Seiten/Variation_d_Abbildungsparameter.htm

[470] The acronym RMSE stands for Root Mean Squared Error. The RMSE of the map or chart is defined as the sum of the squares of the residuals of the Least Squares Estimation process, divided by the *degrees of freedom* in this adjustment. The *degrees of freedom* parameter is a number, calculated as the number of measurements, i.e. the number identical points multiplied by two, minus the number of unknowns that are estimated in the LSE process. See also Section 6.5.6C.

[471] Mesenburg presents the estimated map accuracy in kilometres; Loomer in the internal units of the photogrammetric instrument he used. See the next section.

coherent cartographic entity, rather than attempting to identify and analyse sub-charts. He tested the best fit to a variety of map projections: azimuthal, cylindrical and conic. Of each of these three classes he tested the conformal, an equidistant and an equal area variant and concludes that a conformal projection results in the best fit, but equally feels that there is no conclusive evidence to suggest which conformal projection, azimuthal, cylindrical or conic, fits best.

In three of the six papers referenced, he reports different figures for the accuracy of the charts, so he presumably analysed the same charts more than once.
Da Carignano (13xx) RMSE = 39.7 km
Petrus Roselli (1449): RMSE = 40.6 km (or 48 km, or 53 km)
Jehuda ben Zara (1497): RMSE = 40.2 km

A peculiarity of Mesenburg's method is the empirical selection of the projection centre, or origin, of the projection. Mesenburg does this by drawing contour lines of the residuals and optically identifying the minimum. These parameters could have been resolved (and thus optimised) in the adjustment along with the other parameters, but Mesenburg appears to make a conscious choice for a constrained adjustment, fixing the latitude and longitude of the projection origin to their preselected values. He proposes projection centres well outside the Mediterranean area.

In defining the functional model he uses, Mesenburg's papers (and website) are somewhat ambiguous: he refers to azimuthal, cylindrical and conic map projections, followed by a three-, four-, five-, or six-parameter transformation. The three broad categories of map projections are subdivided into conformal, equidistant and equal area projections. Regarding the three-, four-, five-, or six-parameter transformation, the reader may hazard an educated guess. For example, a four-parameter transformation is undoubtedly a similarity transformation[472], with two (X, Y) origin shift parameters, one scale parameter and one rotation parameter; a five-parameter transformation might assume one rotation and different scale parameters along the two axes of the map, but might equally refer to a solution with different rotation angles for the X and Y axis but with only one scale factor. Clarification by the author would have been helpful in this respect.

6.3.4 SCOTT LOOMER'S COMPARATIVE STUDY OF SEVERAL MAP PROJECTIONS AND MANY CHARTS[473]

Loomer conducted an excellent comparative analysis in his 1987 doctoral thesis, investigating twenty-six portolan charts of different cartographers and different time periods,

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[472] A similarity transformation is a conformal transformation that executes a shift of the origin, a single change of scale and a single rotation of the map.

[473] Loomer, 1987.

and calculating for each of those the degree-of-fit to nine different map projections. In addition he calculated the degree-of-fit of an idealised trilateration network.[474] It is unclear how he generated the reference coordinates of the identical points used for the latter network and linked them to portolan charts. This network is related to Kelley's idea that the anticlockwise rotation angle of portolan charts is caused by plane charting of a trilateration network or a mix of trilateration and triangulation.[475] In Section 3.6 it was demonstrated that the anticlockwise rotation generated by Kelley is a kind of 'optical illusion' that stems from the incorrect expectation that a parallel on the sphere ought to appear in the map as a straight line.

A very useful but taxing requirement Loomer imposed on himself was the creation of the same set of 359 identical points for each chart he investigated. That enabled him to calculate 'virtual' composites by calculating a mean position for each identical point, after due correction for differences in scales, offsets and rotations, as well as weighted by chart[476]. He thus analysed three composites of the charts grouped by period of creation: 1139-1428, 1447-1470 and 1482-1508, as well as three composites by origin: Italian, Catalan and Arabic and one composite consisting of all charts.

In addition to the parameters required for the map projection, Loomer included the four parameters of a similarity transformation in his calculations. The combination of the two transformations, i.e. a map projection with a superimposed similarity transformation, describes the relationship between map coordinates and geographical coordinates, i.e. the functional model for his analysis. He used Least Squares Estimation and calculated the degree-of-fit as the Root Mean Squared Error (RMSE).[477] Unfortunately Loomer calculated this important accuracy estimate in the internal units of the photogrammetric instrument he used for his analysis rather than in kilometres on the earth's surface, although he does mention that this internal unit is approximately equal to a centimetre on the map.[478]

Loomer concluded that the Mercator projection yields the best fit, followed closely by the Equidistant Cylindrical (Equirectangular) projection. He found that the Oblique Stereographic projection, advocated by Duken, yielded a RMSE that is 50% worse than that of the Mercator fit.

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[474] A trilateration network in this context is a geodetic network exclusively built up from distances between the nodal points of the network. No angular measurements are included.

[475] Kelley 1995, 6.

[476] Loomer does not explain in detail how he generated his 'composites'. I inferred from his description that he did it in the way described above.

[477] See Section 6.5.6C for a definition of RMSE.

[478] Loomer 1987, 123,133, 149, in footnotes. Based on a (rough) average scale of 1:5,500,000 one centimetre in the map equals 55 km.

Loomer not only analysed the complete chart of the entire Mediterranean, the Black Sea and the Portuguese and North African Atlantic coasts, but also of eight different sub-basins:

- Western Mediterranean
- West Central Mediterranean
- Tyrrhenian Sea
- Adriatic Sea
- Ionian Sea
- Aegean Sea
- Eastern Mediterranean
- Black Sea

Unfortunately he only calculated results for the Mercator projection. He did this for a 'virtual' composite, or average, of all twenty-six charts. The results of the basin by basin analysis show that the accuracy of each basin chart is considerably better than that of the complete chart and that these sub-charts have different scales and rotations. Loomer's is the first study that shows that scale and orientation do not gradually change over the Mediterranean, as Duken's model implicitly assumes, but that portolan charts are composed of sub-charts with their own scale and orientation. This is proven by the considerable increase in accuracy of the sub-charts over an evaluation of the chart as a whole.

Loomer also showed that the rotations are progressively increasing from west to east and concluded that this may be caused by the mechanism described by Kelley[479], who attributed the rotation of the charts to the assumed construction method of the charts, plane charting, which ignores earth curvature.

Loomer drew the following conclusions.[480]

1. "The portolan charts, best fitting a Mercator projection, were likely based on loxodromic data".

2. "The portolan charts were constructed by a method based on angular relationships such as triangulation rather than distances."

3. "There is no indication that the rotation of the portolan charts is related to the magnetic declination present when each chart was drafted." (Loomer found little variation of the rotation angle over time).[481]

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[479] Kelly 1995, 6. See Chapter 2.6 for an analysis of Kelley's hypothesis.

[480] Loomer 1987, 146, 146, 151 157, 157, 159, 159, 164 respectively.

[481] This is confirmed by various studies, such as that of Nordenskiöld, Lanman and Pelham.

4. "The charts were not continuously copied in direct linear descent from a single early prototype."

5. "The technology employed in constructing the charts remained essentially static during the period that the charts flourished."

6. "There is no significant difference in the accuracy of Italian versus Catalan portolan charts."

7. "Arab portolan charts are generally lower in accuracy, perhaps indicating that they are copies of European charts."

8. "The portolan charts were pieced together from charts of several individual basins that may have, in turn, been pieced together from smaller basins."

9. "The coastline rendering is subject to an increasing stylisation over time."

An important conclusion he doesn't list separately is the consistent accuracy of the charts over time: although more stylisation of the coastline is introduced in the course of time, the accuracy of the charts remains essentially unchanged.[482]

Loomer's work is a landmark study in the research on portolan charts. Apart from a few details, his methodology is clear and his investigation covers a wide spectrum: age (1339-1508), maker, location and culture of origin and nine different map projections.

6.3.5 Recent cartometric studies of portolan charts

The ready availability of the *MapAnalyst* software package for cartometric analysis appears to have inspired several researchers to approach the study of historic maps in a more quantitative way.

However, not all quantitative work on historic maps is executed with *MapAnalyst*. An example is the *Thessaloniki Project*, an extensive analysis of Ptolemy's *Geography,* undertaken at the University of Thessaloniki in Greece.[483]

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[482] Loomer 1987, 168. See also the graph on page 155 of this thesis.

[483] Several publications describe this interesting project, among which:
Evangelos Livieratos, " Graticule versus point positioning in Ptolemy cartographies", *ePerimetron*, Vol.1, No. 1 (2006);
Evangelos Livieratos, Angeliki Tsorlini and Chryssoula Boutoura. "Coordinate analysis of Ptolemy's Geographia Europe Tabula X with respect to geographic graticule and point positioning in a Ptolemaic late 15th century map", *e-Perimetron*, Vol. 2, No 2 (2007);
Evangelos Livieratos, Angeliki Tsorlini, Chryssoula Boutoura, Manolis Manoledakis. "Ptolemy's Geography in digits", *e-Perimetron*, Vol. 3, No. 1 (2008).

Several studies undertaken with *MapAnalyst* are available. Elger Heere analysed four maps of the Dutch province of Zeeland, generating distortion grids of the maps as well as the Mean Position Error and its (sample) standard deviation. He calculated these figures for each entire chart, as well as per island or peninsula[484]. A relevant conclusion in the context of the discussion of methods that Heere draws is that "*MapAnalyst* only shows patterns, but interpretation is the work of man."[485] A similar qualification is found in the analysis of a 1558 map of the province (not the country) of Holland.[486]

Joaquim Alves Gaspar[487] investigates the construction method of Mediterranean portolan charts, using software he developed as an implementation of "a generalised concept of multidimensional scaling", the latter term referring to a method proposed by Tobler. His article and method will be discussed in *Chapter 9: The map projection; artificial or intentional?*

The last study to be mentioned is, in cartometric terms, a relatively simple analysis (in the sense that no complex mathematical methods are used) of Francesco Beccari's chart of 1403 by Lepore, Piccardi and Pranzini.[488] Focus of the study is how the wind rose circle and a latitude scale, visible at the western end of the chart, might have been constructed by the cartographer. The authors show that the improvement in accuracy of the Atlantic coasts claimed by Beccari indeed constitutes real improvement rather than mere change, but their most important conclusion concerns a possible relationship between that improvement and the existence of the latitude scale, which they suggest may indicate possible early use of astronomical latitude determination.

6.4 Chart selection

6.4.1 Criteria for chart selection

The charts analysed in this thesis have been selected in accordance with the objective of this thesis to establish, if possible, the origin of the charts. It is taken as a confirmed fact that the coastal outlines of portolan charts have been copied from the earliest exemplars onward. Loomer showed through quantitative methods that the overall shape of the Mediterranean coastline does not change significantly over time; Mesenburg con-

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[484] The province of Zeeland in the sixteenth to eighteenth century consisted of a group of islands in the south-western part of the Netherlands, separated by a system of creeks and sea-arms.

[485] Elger Heere, "The accuracy of the maps of Zeeland; Accuracy measurement as part of the cartobibliography", *e-Perimetron*, Vol. 6, No. 3: (2011), 199.

[486] Bernhard Jenny and Elger Heere, "Visualisering van de planimetrische nauwkeurigheid van oude kaarten met MapAnalyst," *Caert-Thresoor*, Vol. 27, No. 1 (2008), 8.

[487] Joaquim Alves Gaspar, "Dead reckoning and magnetic declination: unveiling the mystery of portolan charts", *e- Perimetron* Vol. 3, No. 4 (2008)

[488] Fortunato Lepore, Marco Piccardi and Enzo Pranzini, "The autumn of mediaeval portolan charts. Cartometric issues." *6th International Workshop on Digital Approaches in Cartographic Heritage*, The Hague, The Netherlands, 2011.

firmed this graphically. However, at least minor changes to the coastline were made, as a result of which the exaggerated coastal features were portrayed differently over time. If clues are present in the charts themselves regarding their origin, they are most likely to be found in the earliest charts.

Loomer confirmed earlier suggestions that portolan charts are composites and added the important evidence that the sub-charts not only have their own scale but also their own orientation. This conclusion is very important, as it indicates that a portolan chart should be approached as a composite chart rather than as a single entity and it is therefore relevant that this is investigated in more detail. Loomer is the only researcher who has done this to date, but he evaluated the subsets of his data only for the Mercator projection. The requirement to investigate this deeper leads to a preference of charts that depict the entire Mediterranean and if possible the Atlantic coasts of Europe and North Africa.

The above two criteria limit the number of charts considerably, but a further limitation is necessary, as only charts that are reasonably flat and with an intact coastal outline can be considered for cartometric analysis. Charts made by the same cartographer have been avoided, as it is not improbable that the cartographer would have used a single template for his charts. However, these criteria should not be applied so rigorously that only an unrepresentative sample remains. After all, only one acknowledged thirteenth century chart survives and just a handful of fourteenth century ones. The final selection consists of the following charts:

Name in this thesis	Cartographer	Date of creation	Location	Catalogue Number
Carte Pisane	Anon. Genoese	Late 13th c.	BnF, Cartes et Plans, Paris	Ge B 1118
Ricc 3827	Anon. Genoese	1300-1325	Bib. Riccardiana, Florence	3827
Dulcert 1339	Angelino Dulcert, Palma	1339	BnF, Cartes et Plans, Paris	Ge B 696
Ristow- Skelton No 3 (RS-3)	Anon. Genoese	1325-1350	Library of Congress, Washington	?
Roselli 1466	Petrus Roselli, Palma	1466	James Ford Bell Library, Minneapolis	bell001281466 mRo

Table 6.1 - *List of portolan charts subjected to cartometric analysis in this thesis.*

The Carte Pisane is considered to be the oldest surviving portolan chart. It is usually dated to the late thirteenth century, based on its toponymy.[489] It is now held at the Bib-

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[489] The current owner of the chart, the Bibliothèque nationale de France, specifies a date of the end

liothèque nationale de France (BnF), but was previously owned by a family from Pisa, from which it derives its name. It is generally held that the chart is of Genoese origin. The north-eastern part of the chart, depicting the Black Sea, is missing due to substantial damage. Its dimensions are approximately 50 cm by 105 cm.

The chart held at the Bibliotheca Riccardiana in Florence and described simply as *Carta Nautica*, is estimated to originate in the first quarter of the fourteenth century and is perhaps the oldest fourteenth century chart that satisfies all criteria.[490]

The 1339 chart by Angelino Dulcert[491], or Dulceti, as his name has been recently reinterpreted by Ramon Pujades, is the oldest surviving chart drawn at Palma de Majorca, the location of the famous Catalan 'school'. The chart measures 75 by 102 cm and consists of two parts, joined together. The characteristic neck of the animal skin that was used to create the vellum sheet is lacking. At the eastern end some map features and toponyms are truncated, suggesting that the chart originally extended further east. However, as far as the Mediterranean, Black Sea and Atlantic coast is concerned this chart is complete and of excellent quality.

The anonymous chart believed to be Genoese and held at the Library of Congress, Washington, known as the Ristow-Skelton No. 3 chart, is currently estimated to originate in the first half of the fourteenth century.[492] Given its age, its quality is amazingly good. It appears to have been trimmed to show only the Mediterranean east of a north-south line that lies just to the west of Majorca. It has been included because of its age and quality, even though the westernmost part of the Western Mediterranean is missing.

The 1466 chart by Petrus Roselli[493], held at the James Ford Bell Library of the University of Minnesota at Minneapolis, has been added to the list of selected charts as a 'sample check' to seek confirmation of Loomer's conclusions. Loomer discovered significant differences between the charts of the individual basins (Western Mediterranean, Eastern Mediterranean and Black Sea), but provides only minimal numerical details on the orientation and scales of the sub-charts. This thesis will seek to establish these parameters and to compare them to the analogous results of the earlier maps.

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of the 13th century (see http://classes.bnf.fr/idrisi/grand/6_10.htm). This agrees with the date provided by most references in literature; e.g. Pujades 2007, 63 and Campbell 1987, 371. See also Tony Campbell, "Census of Pre-Sixteenth-Century Portolan Charts", *Imago Mundi,* Vol. 38 (1986), 67-94, available on-line: www.maphistory.info/PortolanChartsChronologicalListing.xls.

[490] Date supplied by current owner and corroborated by Campbell, 1986.

[491] The date is written on the chart by the cartographer.

[492] James E. Kelley Jr., "The Oldest Portolan Chart in The New World." *Terrae Incognitae: Annals of the Society for the History of Discoveries* 9 (1977): 22-48.

[493] The date is written on the chart by the cartographer.

6.5 CARTOMETRIC ANALYSIS APPROACH

Any cartometric analysis work for this thesis has to take into account the work that has been conducted to date, in particular Loomer's work, as that covers the time spectrum of the charts and it provides an important relative ranking of best-fitting map projections.

The key steps of the cartometric analysis described in the next chapter are the following.

1. Identification of identical points on the portolan chart and scaling off of their map coordinates (X and Y).
2. Identification of the corresponding points in the reference dataset and scaling off of their geographic latitude (φ) and longitude (λ).
3. Formulation of the hypothesis which describes how the map coordinates from step 1 are functionally related to the reference coordinates from step 2. This is the *functional model* for the analysis.
4. Calculation of the optimum values of the parameters of the functional model from step 3, by Least Squares Estimation, as well as associated quality parameters.

The workflow that was followed for cartometric analysis is illustrated in Figure 6.9; however the validation of the dimensional stability of the vellum, mentioned in Section 6.5.5, is not included in that diagram. The scaling-off of the coordinates of the identical points has been done using modern PC-based Geographical Information System (GIS) software.

6.5.1 THE REFERENCE DATASET

The reference dataset used to provide the 'true' locations of the identical points is the publicly available vector dataset VMAP, a digitised version of key geographic features from the 1 : 1 million scale Operational Navigation Charts (ONC). This is a worldwide set of charts for the support of aeronautical operations; it was formerly known as the Digital Chart of the World (DCW) and was originally published by the US Defense Mapping Agency (DMA). The absolute accuracy of this worldwide dataset is specified as 2040 m at 90% CE.[494] However, this is a value derived for the entire global dataset. The quality of the data is in the order of a few hundred metres in populated areas with adequate geodetic control, such as the Mediterranean region. The geodetic reference for the DCW is specified as the World Geodetic System (WGS), without specifying the vintage of this system.[495] Given the accuracy and the scale of the portolan charts, this ambiguity is of no consequence.

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[494] Military Specification. Digital Chart of the World. MIL-D-89009. United States National Geospatial Intelligence Agency (1992), 5.
CE stands for Circular Error. This is a military accuracy measure, meaning that the error in position is less than this value with a probability of 90%.

[495] Four progressively improved vintages of the World Geodetic System exist, each based on its own ellipsoid, WGS 60, WGS 66, WGS 72 and WGS 84. The latter is used by the Global Positioning System. The latitude and longitude of the same point in each of these coordinate reference systems differ slightly, but the differences are well within the accuracy specification of the DCW.

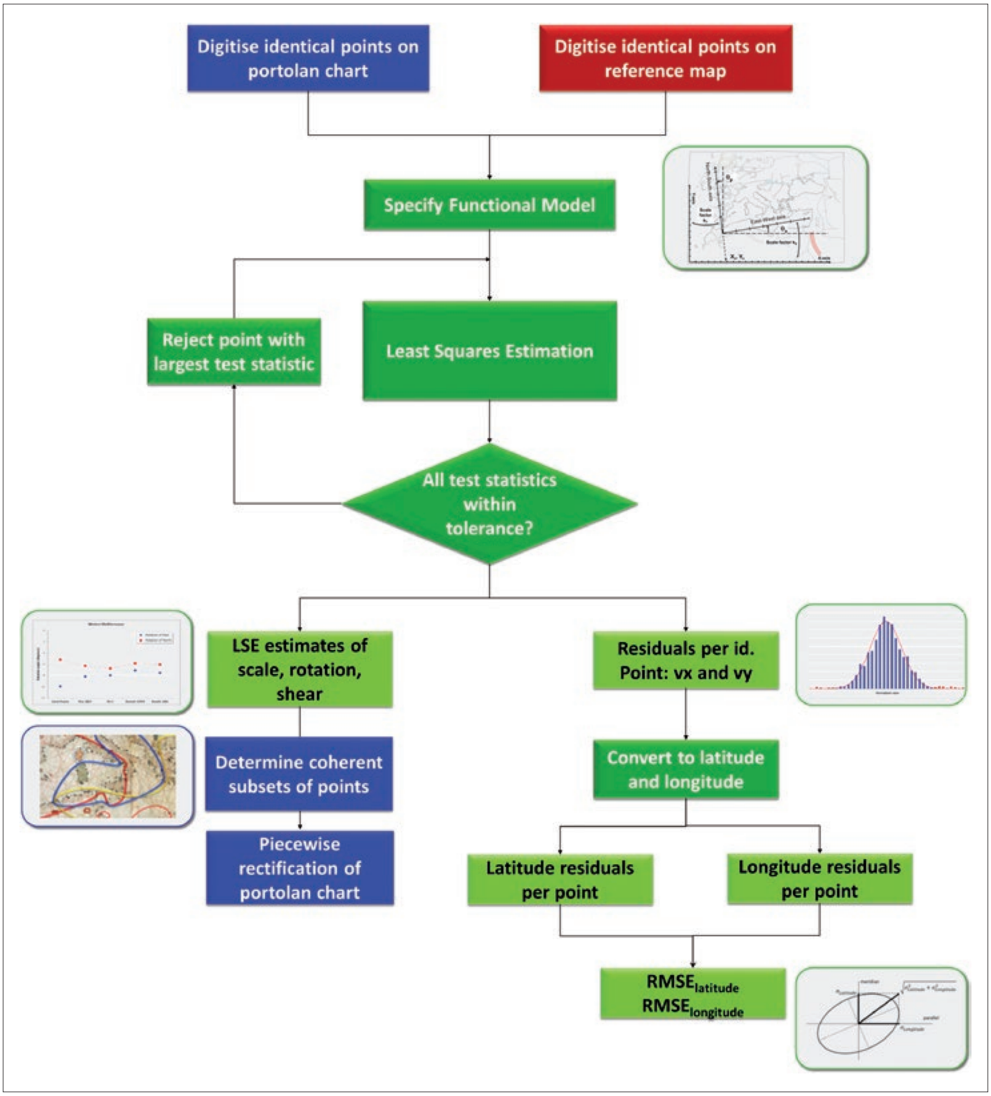

Figure 6.9 - *Workflow for the cartometric analysis in Chapter 7.*

The VMAP reference dataset defines geometric features on an ellipsoid. That implies that the more complex ellipsoidal evaluations for the map projection formulas would need to be used for the cartometric analysis. Usage of the simpler spherical map projection formulas, which was done in this thesis, is formally incorrect – spherical projection formulas shouldn't be applied to ellipsoidal latitude and longitude pairs – but the error thus introduced is negligible given the scale of the portolan charts, regardless of their accuracy. I evaluated the Dulcert 1339 chart, both with the spherical formulas for the Mercator projection and the ellipsoidal formulas, for the Western Mediterranean data-set. The geometry is subtly different with coordinate differences up to 1.2 km, but the difference between the respective key accuracy statistic, the Root Mean Squared Error of the map ($RMSE_{map}$)[496], is only 0.00009%, indicating that although the functional models are subtly different, the simplification of the model mentioned above is justified.

6.5.2 THE MAP PROJECTION

In principle any map projection, however poorly fitting, can be used in the functional model of a cartometric analysis computation. After all, this type of cartometric analysis calculates corrections to the coordinates of the identical points, required to force them onto the map image created by that map projection. However, a map projection that is not a good approximation of the optimum map projection for the portolan chart, will fit poorly and this poor fit will be reflected in the sum of the squares of the residuals. The optimally fitting map projection will have the smallest sum of squared residuals, compared with other map projections and the residuals will contain no systematic components.

Figure 6.2 shows the distortion grid calculated for the Ristow-Skelton No. 3 chart by John Hessler. This shows two patterns of parallel lines which can, after making allowance for the random errors in the map, be considered to be straight. The two patterns, corresponding with parallels and meridians, appear to be approximately orthogonal. It also shows clearly that this pattern is rotated anticlockwise. This leads to the hypothesis that the best-fitting map projection would be a normal-aspect cylindrical projection, because that type of map projection indeed produces patterns of parallels and meridians that form an orthogonal graticule of straight lines. After application of a cylindrical map projection the map image has been rotated anticlockwise to achieve the approximate map image shown by portolan charts.[497]

Loomer's study confirms a best fit for a cylindrical map projection. His 'top two' of best fits were the Mercator projection and the Equidistant Cylindrical projection, both normal-aspect[498] cylindrical projections.

It is stressed that at this point of the investigation no assumption is required as to whether these projections have been applied intentionally to the design of portolan charts or whether they are an artificial by-product of the analysis method.

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[496] For the definition of this parameter see Section 6.5.6C.

[497] Waldo Tobler proposes an Oblique Mercator projection, which is different from a normal-aspect Mercator projection of which the resulting map image has been rotated. The Oblique Mercator projection has S-shaped parallels and meridians. It is a complex map projection and its application to portolan charts would be arbitrary, rather than based on the implicit pattern of parallels and meridians. The Oblique Mercator projection would establish the projection of the earth's surface and the anticlockwise rotation of portolan charts in a single algorithm. See Waldo R. Tobler, "Medieval Distortions: the Projections of Ancient Maps." *Annual of the Association of American Geographers* 56 (1966): 351-361.

[498] For'normal-aspect' cylindrical projections, the axis of symmetry of the cylinder, on which points on the sphere of the earth are projected, coincides with the polar axis of the sphere.

6.5.3 SUPERIMPOSED AFFINE TRANSFORMATION

Figure 6.2 also shows that the meridians and parallels represented in the superimposed grid, or rather graticule, are not orthogonal everywhere. For that reason I chose a functional model in this thesis that does not enforce a right angle between the implied meridians and parallels of the portolan charts, but allows a shear angle to be computed. Furthermore, a different scale is allowed for the two axes of the portolan chart image. Mathematically, the requirements described in the previous two sentences dictate that an affine transformation is superimposed on the assumed map projection.

6.5.4 CHARTS APPROACHED AS COMPOSITES

This hypothesis that portolan charts are composites of in principle separate sub-charts is based on the systematic scale differences that many researchers found in the portrayal of the various Mediterranean sub-basins, notably Loomer.

6.5.5 PRE-ANALYSIS – DEFORMATION OF THE CARRIER MATERIAL

Before embarking on the determination of the best-fitting map projection and the accuracy of the charts, the dimensional stability of the carrier material of the charts, vellum, needs to be established. This is made possible by the useful characteristic of all portolan charts that the sixteen nodes of the wind rose have originally been drawn as regularly spaced points on the perimeter of a large circle.[499] Except for inevitable (small) construction errors the distribution of these points is highly regular. Peter Mesenburg analysed the deviations from this regularity routinely in his cartometric analysis projects; Loomer also did this for all charts he investigated.

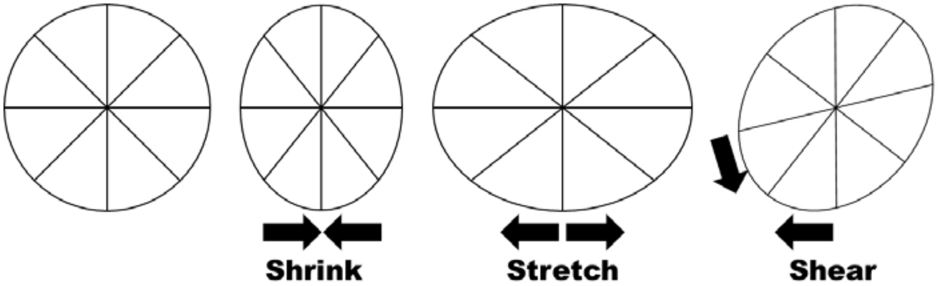

Figure 6.10 - *Conceptual illustration of the wind rose shape due to vellum deformation.*

I digitised all visible points of the wind rose(s) of each chart using GIS software and subjected the resulting digitised coordinates to a Least Squares Estimation process which resolves the following parameters.

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[499] On the Carte Pisane the diameter of the wind rose circle is about 40 cm; on the Dulcert 1339 chart about 44 cm.

1. The map coordinates of the centre of the wind rose (X_C and Y_C).
2. The radius R of the wind rose.
3. The stretch factor k of the horizontal dimension of the map.
4. The angle θ_X of the east-west axis of the wind rose with the X-axis of the map in the GIS software.
5. The angle θ_Y of the north-south axis of the wind rose with the Y-axis of the map in the GIS software.

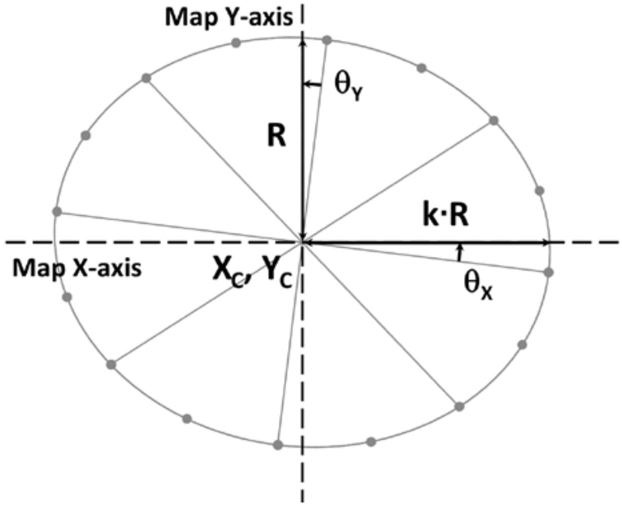

Figure 6.11 *- Parameters, estimated in the wind rose analysis.*

Whenever the terms X and Y are used in the context of this cartometric analysis, the internal GIS coordinates are meant. The unit of the internal GIS coordinate system is determined by the number of pixels in the scanned image of the portolan chart, which, in the context of the cartometric analysis, must be considered to be arbitrary. The X and Y axes directions do not automatically coincide with the north-south and east-west axis of the portolan chart. That depends on how the map was placed under the scanner or camera. High-resolution digital scans have been used for this thesis, and although the originating library staff will have done their best to orient the chart exactly with the scanner's (or camera's) principal axes, slight misalignments are to be expected.

The outcome of this pre-analysis will yield numerical estimates for the following parameters.

1. Any correction required to the height/width ratio of the chart;
2. The shear of the chart (i.e. non-orthogonality of the parallels and meridians that are implicit in the chart);
3. The misalignment of the chart. These corrections will, if numerically significant, be applied to the results of the main cartometric analysis of each chart.

In the case of the Dulcert 1339 chart two wind roses exist on the chart, one on the west and one on the east sheet. This opens up the possibility that the two halves of this chart will require a separate correction.

6.5.6 PRINCIPLES OF THE MAIN CARTOMETRIC ANALYSIS

Arguments have already been provided that the most appropriate computational method for this thesis is Least Squares Estimation supported by statistical testing.

All computations have been executed in MS-Excel software, using the available matrix calculus functions.

A. THE FUNCTIONAL MODEL

The functional model to which the scaled-off map coordinates of the identical points are forced consists of a map projection with a superimposed affine transformation.

Solutions for two map projections will be calculated for all charts:

1. Mercator;
2. Equidistant Cylindrical (Equirectangular);

The justification for the Mercator and Equidistant Cylindrical projection has been provided in Section 6.5.2 above. In addition to these two projections the Mediterranean and Black Sea sections of the Dulcert 1339 have been evaluated with the Oblique Stereographic projection, as a check on Loomer's calculation and as a check on my own reasoning in Section 6.3.2 above. The peculiarity of Duken's approach, notably with respect to his implicit assumption of smoothly changing scale and orientation in the chart warrants a check, but to do so for all five maps is unnecessary, as the results will show.

The affine transformation expresses the deformation that exists in the portolan chart in addition to the distortion introduced by the map projection:

- An origin shift along each axis: $\mathbf{X_0}$ and $\mathbf{Y_0}$ [500]
  These two parameters play no role at all in the interpretation of the results, as they are determined by the values and scale of the X and Y coordinates, which are completely arbitrary.
- Separate rotation angles for X and Y axes: θ_X and θ_Y
  This estimates the anticlockwise rotation angle of the chart as two separate rotation parameters, as the implied graticule may not be truly orthogonal (see Figure 6.2).
- Separate scale factors for the X-axis and the Y-axis: $\mathbf{k_X}$ and $\mathbf{k_Y}$

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[500] (X_0, Y_0) are the portolan chart coordinates of the intersection point of the Greenwich meridian with the equator (latitude = longitude = 0).

It has been stressed above that the map coordinates X and Y have no intrinsic meaning. The X, Y coordinate system is created automatically by the GIS software. This software aligns the X and Y axes with the horizontal and vertical direction of the available chart image. The scale of this internal coordinate system is determined by the number of pixels in the image, which is why the X and Y coordinate values of the identical points of any chart have no intrinsic meaning and are therefore, for the purposes of this thesis, considered to be arbitrary. Consequently the numeric values of $\mathbf{X_0}$ and $\mathbf{Y_0}$ that are computed have no intrinsic meaning, as are the numeric values of the scale factors $\mathbf{k_X}$ and $\mathbf{k_Y}$ which link the arbitrary unit of measure of the internal X, Y coordinate system with the unit of measure of the geographical coordinate system, which is degrees (in my calculations the unit is not even degrees, but radians). The interpretable information that can be derived from the two scale factors is their *ratio*, which indicates whether the map image has been stretched or compressed in any of its two principal directions.[501] Additionally these scale factors provide numerical information on the scale differences within the charts.

In the case of the Equidistant Cylindrical projection the scale factor along the map's vertical axis (assuming North is 'up') cannot be separated from the *standard parallel* of the projection, i.e. the true-to-scale parallel. Assuming the spacing of the meridians to remain the same, the vertical extent of the chart will appear to be more stretched when the standard parallel is chosen at higher latitude. Marinus of Tyre's map (or chart), as we know from Ptolemy's Geography, used the parallel of Rhodes (about 36° N), as the standard parallel. For the Equidistant Cylindrical projection the standard parallel φ_0 is therefore computed instead of the scale parameter $\mathbf{k_Y}$.

The Mercator projection generates a variable spacing of parallels of equal intervals in degrees and therefore does not exhibit the above problem. The six parameters enumerated above are calculated as parameters of the functional model. For the Oblique Stereographic projection the principal problem is to establish the latitude and longitude of the projection centre.

Duken derived the location of the projection centre by reasoning and introduced them into his calculation as constants. In my evaluation of the Oblique Stereographic projection the projection centre coordinates are solved as parameters in the Least Squares Estimation process. Duken considers only a single rotation parameter, i.e. he does not allow for shear in the map and he calculates a single scale factor to relate the chart to the reference stereographic map image.

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[501] It needs to be stressed that it is the stretch or shrink of the *map image* that is estimated by these scale factors, not the stretch or shrink of the map carrier material. The latter was estimated from the analysis of the wind rose circles.

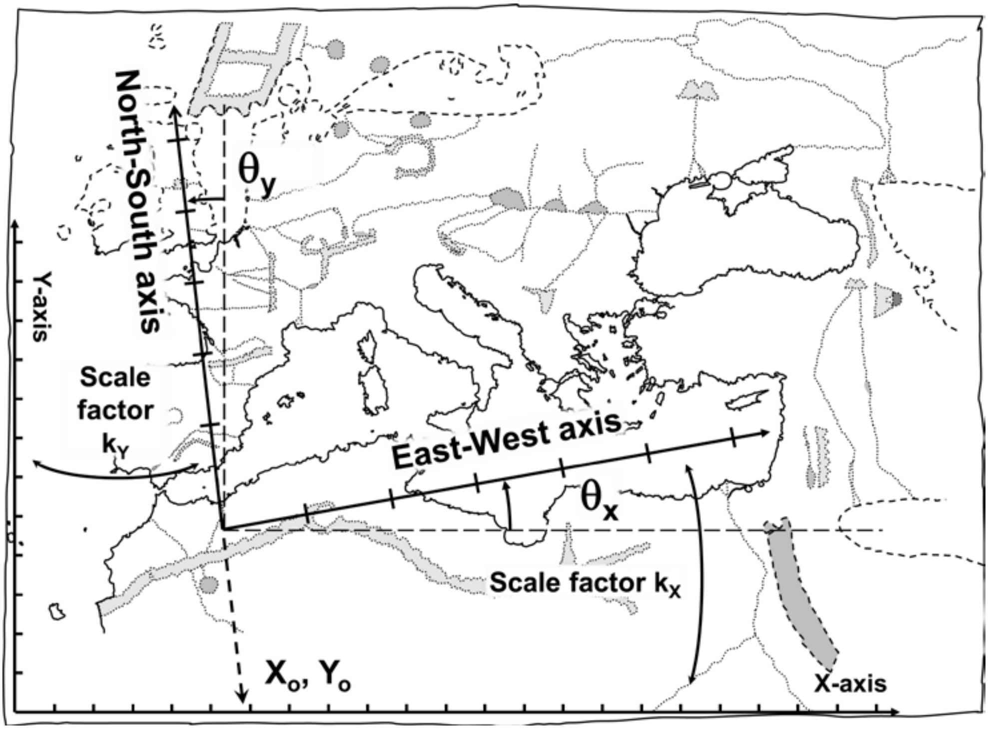

Figure 6.12 *- Illustration of the six parameters calculated in the cartometric analysis.*

B. STATISTICAL TESTING

Section 6.2.5 above contains the justification for using Least Squares Estimation with statistical testing as the processing method for the cartometric analysis in this thesis. The map coordinates of each point have been given an equal weight in the Least Squares computation.

It is assumed that the X and Y coordinates of any identical point do not correlate. Also no correlation is assumed between the coordinates of any identical point and the coordinates of nearby identical points. This will not be quite true, as the error in one particular point will definitely have an effect on the errors of nearby points because of the continuity of the coastline image, but correlation is expected to be negligible when the distance between neighbouring identical points is large enough and where they do lie closer together the arbitrary element in the exaggeration of coastal features of the chart will have a reducing effect on correlation. It is impossible to quantify this reliably, but visual inspection – also see the examples provided in Chapter 1.3.1 – suggests the exaggeration of coastal features to be of the order of 1-2 mm in the charts, which, with an approximate average scale of 1: 5.5 million equates to 5-10 km. Where possible, I have avoided selecting identical points at excessively exaggerated map features. However, in most cases no other option existed than to select the point at a recognisable geographic feature and hope the impact of the exaggeration would not be too great.

A vital aspect of the cartometric analysis in this thesis, and the second[502] distinguishing feature compared with other cartometric analysis studies, is the application of statistical testing to the results. The test statistic represents the optimal statistical test in linear systems, applied to both coordinates of a point, i.e. not to the X and Y coordinate of the point separately. This point test statistic is derived from the residuals of the calculation process and is used to reject identical points of which the value of the test statistic exceeds the tolerance, set at 99% confidence level. Although in principle two residuals are computed per identical point, one for the X and one for Y coordinate, the test statistic operates on the entire point only.[503]

An identical point is 'rejected' by setting its weight to zero and repeating the calculation. Setting the weight to zero effectively removes the point's coordinates from the Least Squares calculation.

The statistical testing process is used for two distinct purposes:

1. Exhaustive rejection of outliers in the dataset. Exhaustive rejection means that the point with the largest point test statistic is rejected, after which the Least Squares Estimation calculation is repeated. This process is repeated until all point test statistics are within tolerance.
2. The determination of the boundaries between coherent regional collections of identical points. The interpretation of such a coherent point collection is that these dictate the boundaries of the sub-charts of which the whole portolan chart is assumed to have been composed. It is clear from the onset that there will be no sharp boundaries, or these would have been very clearly visible. The cartographer has probably created transition zones between the component charts to achieve the smooth, continuous coastline visible on the charts. The following sub-basins were the starting points for the identification of the sub-charts:
    a. Western Mediterranean
    b. Adriatic Sea
    c. Eastern Mediterranean
    d. Black Sea

The method for establishing the boundary between two sub-charts is to add or remove one point at a time and to recalculate the results, until the Root Mean Squared Error of the map, $RMSE_{map}$[504], has reached a minimum for that subset of the identical points.

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[502] The first distinguishing feature is the approach of each chart as a composite of sub-charts.

[503] See Peter J.G. Teunissen, *Testing Theory, an introduction*, 2nd ed. (Delft: VSSD, 2006), 78. The test statistic I used is the two-dimensional optimum test statistic, described by Teunissen as T_q which is $\chi^2(2,0)$-distributed, when q=2. The zero inside the parentheses designates the non-centrality parameter under the null hypothesis, i.e. the test statistic is not contaminated by biases in the residuals of the point coordinates.

[504] See Section 6.5.6C for the definition of this parameter.

C. Quality estimates

The key quality estimate, which represents the accuracy of the charts, is the Root Mean Squared Error ($RMSE_{map}$) of the map (chart), defined as the sum of the squares of the residuals, divided by the *degrees of freedom* in the Least Squares Estimation (LSE) process. The *degrees of freedom* parameter is a number, calculated as the number of measurements, i.e. the number identical points multiplied by two, minus the number of unknowns, in principle six (see Figure 6.12). This estimate has been split up into two components, one for latitude and one for longitude.

The residuals, computed in the LSE process, are the corrections, with signs changed, to the X and Y coordinates of the identical points. The latter serve as the 'measurements' in this process. However, X and Y coordinates are expressed in a unit of measure that is determined by the GIS software and depends on the number of pixels in the scanned chart image that was used for the cartometric analysis. The X and Y residuals are therefore entirely meaningless for the interpretation of the accuracy of the chart and for that reason they have been converted to latitude and longitude residuals, expressed in kilometres. That can be done because after the LSE process the mathematical relationship between map coordinates (X and Y) and latitude and longitude is fully determined.

Figure 6.13 shows the error ellipse of the coordinates (latitude and longitude) of a point. The error ellipse is the two-dimensional equivalent of the standard deviation. The standard deviations in latitude and in longitude are the orthogonal projections of the extent of the ellipse onto the local parallel and meridian respectively, indicated by thick black lines. The major and minor axes of the error ellipse have been drawn at a slight angle with the parallel and meridian to indicate the correlation between the calculated latitude and longitude of the point.

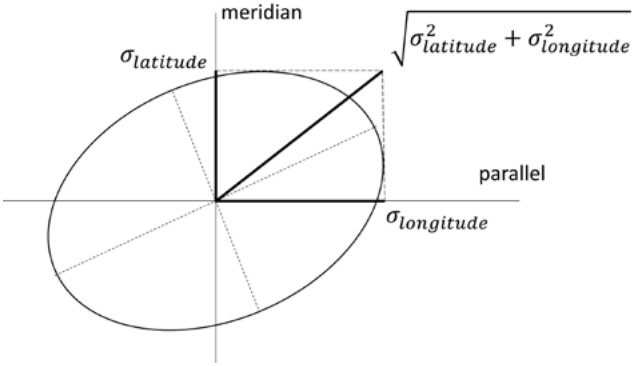

Figure 6.13 *- Error ellipse with standard deviations in latitude and longitude.*

The Root Mean Squared Errors in latitude and longitude, calculated from the LSE residuals, are estimators of these standard deviations. It is important to split up the sum of the squares of all residuals in two halves, one corresponding with latitude and one with longitude, because of the two-dimensional nature of the error distribution of the point coordinates. The error ellipse corresponds with the 39% confidence level, if the calculated latitude and longitude are random variables with bivariate normal distribution. The error ellipse at 95% confidence level is 2.45 times as large (linearly).

The square root of the sum of the variances of latitude and longitude corresponds with the length of the diagonal of a rectangle of which the sides correspond with the standard deviations in latitude and longitude. This variable is referred to in many cartometric studies as the Mean Point Error and is used to characterise the accuracy of the map. The length of this diagonal does not correspond with the 39% confidence level and it is not normally distributed. For those reasons, either the RMSE in latitude or in longitude, whichever is the larger, will be quoted when the generalised concept *chart accuracy* is mentioned.

In practical terms, correlation between latitude and longitude is negligible in the analysis of portolan charts. The correlation determines the rotation of the main axes of the error ellipse with respect the coordinate system axes (parallels and latitudes). This means that the RMSE of latitude or of longitude, whichever is the larger, is a suitable, be it a conservative, variable to express point accuracy.

Since the standard deviations in the measurements are unknown, they are computed from the spread of the observations themselves after the LSE. The calculated values therefore correspond with *sample standard deviations*, or with Root Mean Squared Errors if allowance is made for possible biases in the residuals because e.g. the wrong functional model (i.e. map projection) has been used in the calculation.

The RMSE for latitude and for longitude are computed for each subset of identical points, determined by the iterative process described in point 2 of the previous section.

Analysis of the map projection and a discussion of the accuracy results will only be undertaken after the results of all maps have been supplied.

D. The length of the portolan mile

All charts investigated contain scale bars. The portolan chart is the first known map type to be equipped with scale bars.[505] The typical characteristics of the portolan chart scale bar are explained in Section 2.2.

Cartometric analysis also offers the opportunity to estimate the length of the portolan mile. Questions to be answered are whether the scale differences in the sub-basins are reflected in the scale bars and how consistent the length of the portolan mile is across the five charts investigated. The discussion of the results is presented after the discussion of the results per chart, in Section 7.6.9.

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[505] Campbell 1987, 371.

7 CARTOMETRIC ANALYSIS OF FIVE CHARTS

Having described and justified the selected method for cartometric analysis in the previous chapter, the results of the analysis of the five portolan charts selected are presented and discussed in this chapter, Sections 7.1 to 7.5. A summary of the main findings are presented per chart, after which Section 7.6 discusses the analysis results, leading to the conclusions in Section 7.8.

7.1 Carte Pisane

The Carte Pisane is considered to be the oldest of the extant portolan charts. It is nowadays dated to the end of the thirteenth century. This is a conservative estimate, based on the chart's toponymy. One of the main indicators is provided by the toponyms for Siponto and Manfredonia on the Gargano promontory in Italy, the 'spur' of the Italian boot. King Manfred of Sicily had the new city of Manfredonia built north of the existing city of Siponto from 1256 to 1263. Once the new city, with its impressive fortress, had been finished and populated, Siponto quickly lost its importance in the region. A convention of portolan charts is that the toponyms of important cities are drawn in red ink, the remainder of the names in black. On all portolan charts the name *Manfredonia* is drawn in red ink and the name *Siponto* in black, except for two charts. The Carte Pisane shows *Manfredonia* in black ink and *Siponto* in red, suggesting that the chart was drawn at a time that Manfredonia had not yet displaced Siponto as the primary city in that coastal region. The other chart is the so-called Cortona chart, estimated to date from the early fourteenth century. The Cortona chart doesn't show Manfredonia at all, only Siponto (in black ink), which suggests it is perhaps older than the Carte Pisane.

The Atlantic European coast shown on the Carte Pisane is very sketchy. I could identify only six locations on the Moroccan Atlantic coast. The north-eastern part of the chart is so severely damaged that it was of no use for the cartometric analysis. The damage, probably due to water, has rendered many toponyms in the north-eastern quadrant of the chart unreadable.

7.1.1 Pre-analysis of chart deformation – Carte Pisane

The Carte Pisane has two wind roses and two scale bars are visible. The short scale bars, drawn inside a small circle as shown in Figure 2.4 are particular to the earliest charts only; in addition to the Carte Pisane this form is used on the Cortona chart and Petrus Vesconte's charts. One nodal point of the eastern wind rose is not visible as it is located in a physical hole in the map, but I reconstructed its location by intersecting the various wind rose lines.

The analysis of the wind rose yielded the following results:

	Wind rose west	Wind rose east	Correction applied
X-axis scale error	3.3%	3.7%	-3.5%
Misalignment X'-axis	2.1°	2.2°	-2.1°
Misalignment Y'-axis	2.3°	1.6°	-2.1°

***Table 7.1** - Results of the wind rose analysis of the Carte Pisane.*

The misalignment of the Carte Pisane under the scanner was about two degrees and there is no shear worth mentioning. The wind rose's east-west and north-south axes respectively are designated by X'-axis and Y'-axes, to distinguish these from the internal GIS axes X and Y. The difference of 0.1° in the calculated misalignment of the X'-axis and Y'-axis in the western wind rose is insignificant. The shear of 0.7° in the eastern wind rose is admittedly larger and amounts to 5 mm in linear units over the diameter of 40 cm of the wind rose, but I decided against using this figure to correct the shear calculation in the main cartometric analysis, as the figure is still small compared to the considerable shear found in the coastline data, which is around 5° (see Table 7.7 and Table 7.8).

Assuming that the wind roses were originally perfectly circular, the scale errors indicate that the Carte Pisane, when viewing it North up, as shown in Figure 7.1, is about 3.5% too wide. That *is* significant; the wind roses on the actual chart have a diameter of about 40 cm, so over the two side-by-side wind roses that scale error amounts to about 28 mm.

It seems therefore advisable to correct the east-west dimensions of the Carte Pisane before embarking on the cartometric analysis. It might be argued that such a scale correction is unnecessary, as two scale factors will be calculated in the main cartometric analysis anyway. For the Mercator projection that is indeed the case, but one of the parameters of the fit to the Equidistant Cylindrical projection is the standard parallel or true-to-scale parallel of the (sub) charts. Not correcting for the non-circularity of the wind rose contaminates the value of that parameter and that would make comparison of the results for different charts impossible. As it is not possible to obtain further information on how the scale error is distributed, I have opted to correct the X-coordinates by the mean of the values for the east and west wind rose, i.e. -3.5%.

The estimated misalignment of the entire chart of 2.1° will be used to correct the alignment angles computed from the cartometric analysis.

7.1.2 MAIN CARTOMETRIC ANALYSIS – CARTE PISANE

The results of the cartometric analysis proper, i.e. the LSE fit to for the Mercator and the Equidistant Cylindrical projections to the chart, are shown in Table 7.7 and

***Figure* 7.1** - *Carte Pisane 444 identical points, regional datasets and rejected point clusters.*

Table 7.8. The analysis is based on 444 identical points, which constitutes close to the maximum that I could confidently identify as useable identical points. This included nine points along the Moroccan Atlantic coast, starting in the Strait of Gibraltar and moving in south-westerly direction. The points and the chart are shown Figure 7.1.

The division into coherent data subsets is shown in Figure 7.1. The interpretation is that these data subsets correspond with sub-charts, from which the original portolan chart may have been compiled as a composite. The characteristics of these data subsets show clear differences in accuracy, orientation, scale and shear, the parameters that have been estimated from the cartometric analysis.

The north coast and south coast of Sicily agree well with both the Western and the Central Mediterranean dataset. A small area along the north-west coast of Tunisia fits in both the Eastern dataset and the Western Mediterranean datasets.

Both the Western and the Central Mediterranean subsets, indicated by red and blue lines in Figure 7.1 are highly consistent datasets. Of both datasets only one point had to be rejected on the grounds of the test statistic being too large. However, of the Eastern Mediterranean data subset 17 out of 163 points had to be rejected. These points are mainly located in the northern Aegean Sea and the Gulf of Sirte. Initially the suggestion presents itself that the rejections in the northern Aegean might have been caused by deformation due the nearby (water) damage, but upon closer inspection that turns out to be incorrect; that area is quite simply poorly drawn. The Macedonian peninsula, with its characteristic three ‘fingers’, is compressed in north-south direction and rotated. The same may hold for the area north-west of the island of Euboea.

The Gulf of Sirte is poorly charted on the Carte Pisane as well as on the other four portolan charts. The first problem to deal with in the Gulf of Sirte is the small number of identifiable geographic features that can be used as identical points. Admittedly the coast is notoriously featureless, but the candidate points that do exist, among which the few points that are identifiable do not fit with the rest of the data subset (and the chart).

The Carte Pisane is the ‘crudest’ of the surviving portolan charts (together with the Cortona chart). Its relatively primitive shape of the Italian peninsula has been commented on by several authors.[506] It is therefore all the more remarkable that all the islands in the Tyrrhenian, Ionian and Aegean Seas and the Maltese Islands are located in their correct positions in the respective subsets of data points. Only Thasos in the northern Aegean Sea had to be rejected, but Thasos belongs to the same cluster of rejected points commented on above. Also the large Mediterranean islands fit very well into their appropriate data subsets, including and in particular Sardinia and Corsica. The

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[506] e.g. Campbell 1987, 390.

position of notably Sardinia has long been known to show too far to the south on fourteenth century portolan charts. Hermann Wagner already pointed this out in 1895.[507] Francesco Beccari claimed to have moved Sardinia to its proper place according to the indications of sailors.[508] However, on the Carte Pisane the mispositioning is small compared to the other charts evaluated in this study. The changing location of Corsica and Sardinia in the five charts analysed in this study demonstrates that Beccari was not the first to change the location of these islands. In section 7.6.4 below the locations of Sardinia and Corsica on all five charts are compared and the possible reasons for the differences are discussed.

7.2 Anonymous Genoese chart (Ricc 3827)

The Ricc 3827 chart is presumed to be of Genoese origin and is estimated to date from the first quarter of the fourteenth century. That makes it one of the oldest surviving complete charts of the Mediterranean. Also the Ricc 3827 chart contains two wind roses. It shows four scale bars of the type shown in Figure 2.5. The chart is in very good condition and shows the Mediterranean and Black Sea as well as the Moroccan and European Atlantic coasts from Essaouira up to and including the English south coast. Some topographic detail is shown a bit further to the north, but the English south coast is where the realistic representation of coastline topography stops and the coastlines become sketchy.

7.2.1 Pre-analysis of chart deformation – Ricc 3827

The Ricc 3827 chart has retained its original dimensions much better than the Carte Pisane, as is demonstrated by the figures in Table 7.2. The values are so small that they are expressed in two decimal places to show the differences.

	Wind rose west	Wind rose east	Correction applied
X-axis scale error	0.84%	-0.04%	separate E & W
Misalignment X'-axis	-0.03°	+0.09°	-0.13°
Misalignment Y'-axis	+0.58°	-0.11°	-0.13°

Table 7.2 *- Results of the wind rose analysis of the Ricc 3827 chart.*

The scale correction obtained from the western wind rose was used to correct the X-coordinates of the identical points for the Atlantic areas, the Western and the Central Mediterranean and left the data for the Eastern Mediterranean uncorrected.

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[507] Wagner 1896 (1969), 479.

[508] Campbell 1987, 428.

7.2.2 MAIN CARTOMETRIC ANALYSIS – RICC 3827

The dataset of identical points consisted of 1015 points. The number is so large, because this chart is exceptionally clear in its coastal outlines.

On the Ricc 3827 chart the following separate coherent datasets can be distinguished, as shown in Figure 7.2:

- French Atlantic and South English coasts;
- North-West African and Portuguese Atlantic coasts;
- Western Mediterranean;
- Central Mediterranean (Adriatic and Ionian Seas);
- Eastern Mediterranean;
- Black Sea and Sea of Marmara.

The datasets show clear differences in scale and axes orientation, but their boundaries are not marked by a clear break point, but rather by transition zones, which are long and gradual in some cases and short and abrupt in others.

A relatively small overlap zone between Western, Central and Eastern Mediterranean datasets occurs around Cap Bon in Tunisia. The Dardanelles form a transition zone between the Aegean Sea and Black Sea datasets.

The joins between adjacent datasets vary from being barely noticeable to amounting to a significant shift. The first type of join leads to overlap zones between datasets; the clearest example is the Tunisian area around Cap Bon, the prominent peninsula in the north-west of the country, where a cluster of points forms part of both the Western and the Central Mediterranean datasets. On the Carte Pisane two points even fitted well in the Western, Central *and* Eastern Mediterranean datasets, but on the Ricc 3827 chart an overlap only exists between the Western and Central Mediterranean datasets. The transition zones generally extend further than the relevant joins in Figure 7.3 indicate. The second type of join, with a noticeable jump or shift, may lead to clusters of points in the middle of the transition zone between two adjacent datasets not fitting sufficiently well in either dataset. This is for example the case between the NW African / Portuguese dataset on the one hand and the Western Mediterranean dataset one the other and between the NW African / Portuguese dataset and the French Atlantic / South English dataset.

A surprising discovery was a highly accurate and coherent sub-dataset consisting of the whole of the Italian peninsula, the Adriatic and Ionian Seas, as well as Corsica and Sardinia. This Central Mediterranean dataset overlaps the Western Mediterranean dataset significantly and the Italian Tyrrhenian coast, Corsica and Sicily also fit well in the western dataset, but Sardinia doesn't. The position of the entire island has shifted by about 35 km to the south and about 12 km to the east.

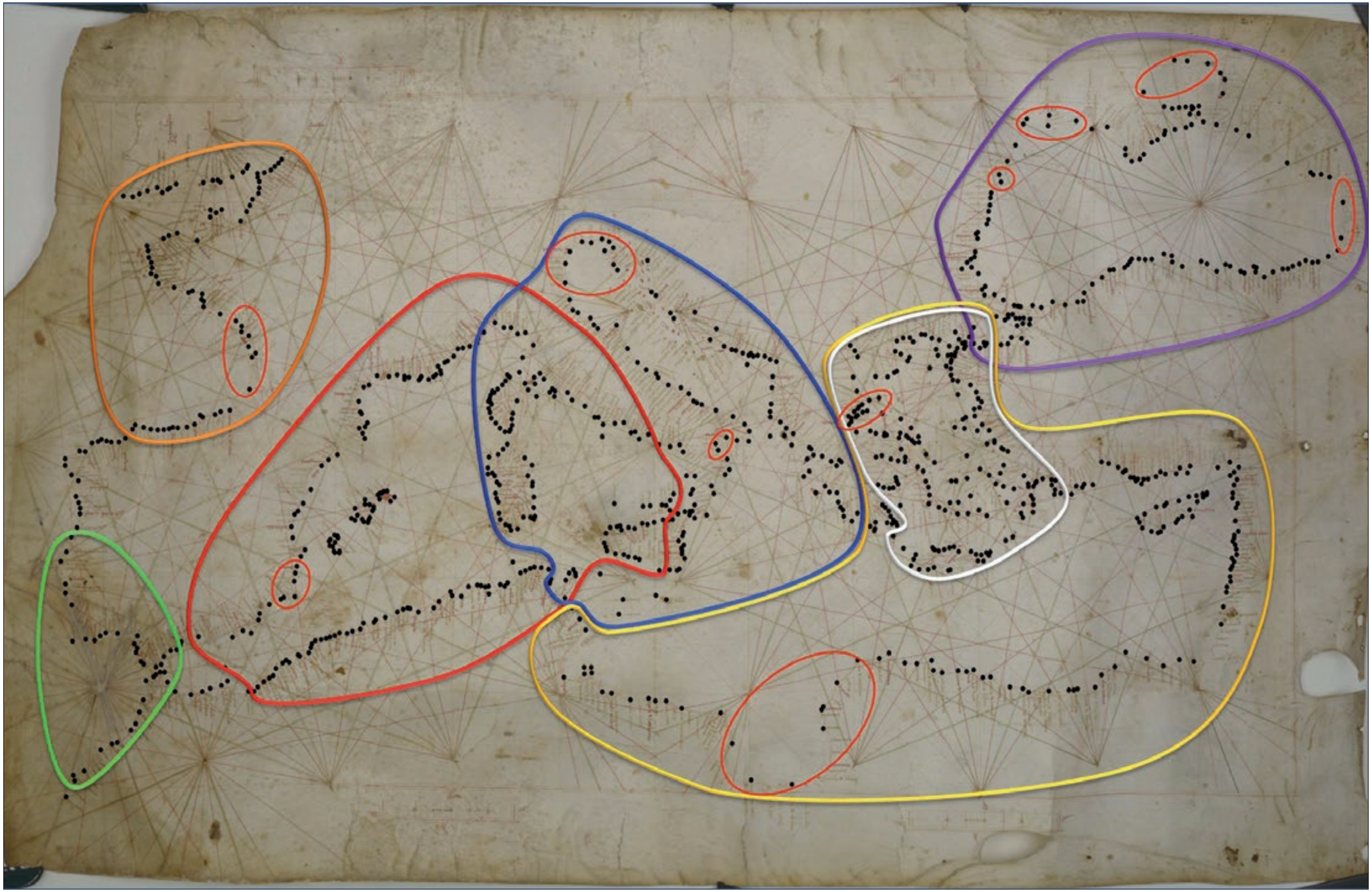

Figure 7.2 - Ricc 3827 chart with 1015 identical points, division into coherent subsets of data and rejected data points in red circles.

The coherence of the Western Mediterranean dataset is very good, relatively speaking. Only 7 of 283 points (3%) are rejected in the statistical tests and these points are mostly clustered in a short stretch of coast of eastern Spain, as shown in Figure 7.2. Of the Eastern Mediterranean dataset 31 points of 359 (9%) had to be rejected. The Ricc 3827 chart shares with the Carte Pisane the characteristic that most rejections occur in the Eastern Mediterranean.

Figure 7.3 *- Cluster of rejected points near north Euboea.*

On the Ricc 3827 chart all eight points on the Gulf of Sirte in North Africa were rejected. By comparison, the Carte Pisane yielded only two identifiable points in the Gulf of Sirte and both of those were rejected. The other significant rejection area on the Ricc 3827 chart occurs in the Aegean Sea around the northern part of the Island of Euboea, as shown in Figure 7.3. Also this is consistent with the Carte Pisane.

In addition to the point cluster in the Gulf of Sirte, a cluster of fifteen points is rejected in the Aegean Sea, that is, when analysed as part of the large Eastern Mediterranean dataset. Since an enormous number of identical points are available on the Ricc 3827 chart, analyses of smaller subsets will be reliable. Analysed separately, a subset of data in the Aegean Sea resulted in the points around the northern part of Euboea blending in well with the rest of this smaller dataset.

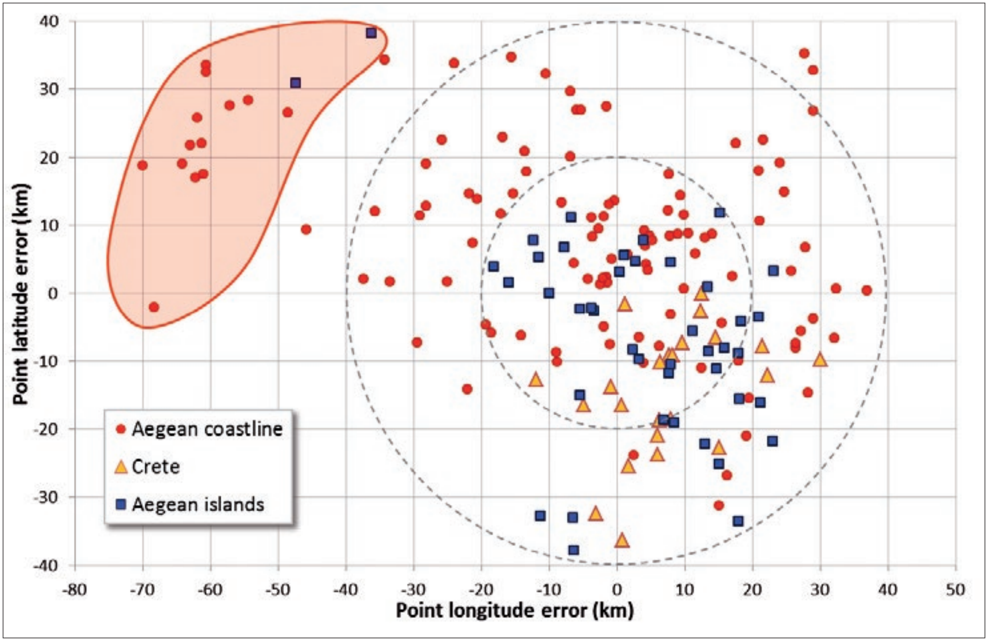

Figure 7.4 - *Errors in Aegean Sea points, evaluated as part of the large Eastern Mediterranean dataset.*

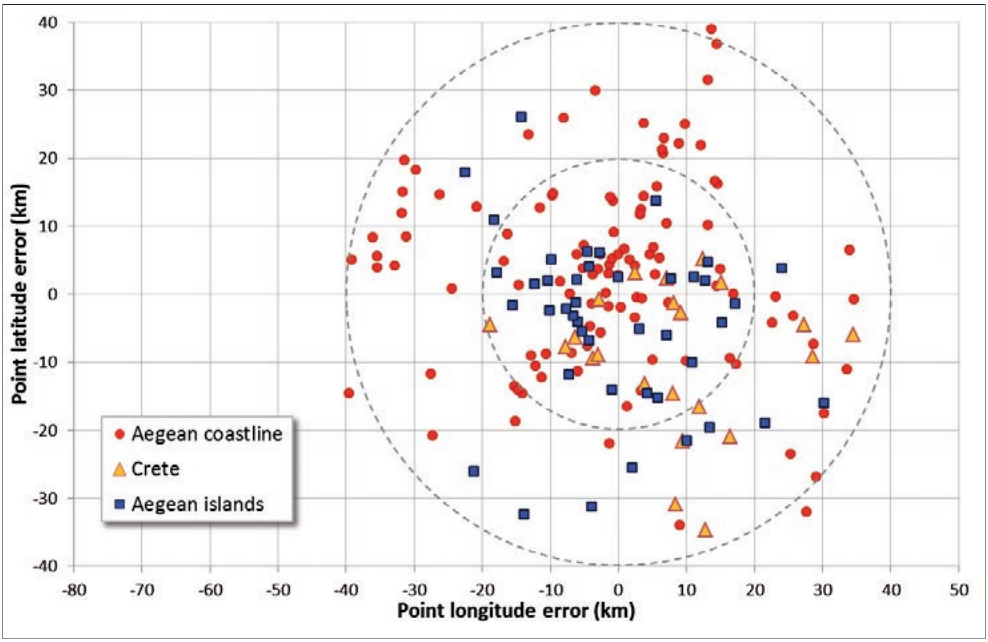

Figure 7.5 - *Errors in Aegean Sea points, evaluated as a separate dataset.*

Figure 7.4 shows a 'bull's eye plot' of the residuals, or errors, in latitude and longitude of the Aegean Sea identical points, when evaluated as part of the large Eastern Mediterranean dataset. The points have been further divided into points along the Aegean coastline, Crete and islands in the Aegean, including Rhodes. The fifteen points that were rejected are the most westerly points of the Aegean Sea dataset and are shown inside the pink shape on the left in Figure 7.4 and include two islands, Skiatos and Skopelos (the two square markers with blue fill). Apart from these outliers the plot shows that Crete plots too far to the south, whereas the Aegean coastline plots too far to the north and shows large longitude residuals. The Aegean islands plot, by and large, in the right place.

The effect of processing the Aegean Sea points as a separate dataset is shown in Figure 7.5. The outliers are generally smaller and the former outliers now blend in reasonably well with the rest of the points, although they still cluster at the perimeter of the plot on the left-hand side. The reason for the improvement is a longitude scale change.

It appears that the Aegean Sea indeed forms a separate dataset from the rest of the Eastern Mediterranean, mainly on account of its deviating longitude scale. Crete is still positioned 12-15 km too far to the south and the northern Aegean coastline shows a similar error. Another cluster of points that is clearly mispositioned in the Eastern Mediterranean is located around the perimeter of the Gulf of Sirte in Libya.

In the Central Mediterranean dataset a remarkable fact is that the cluster of points in the northern Adriatic doesn't fit in with the rest of the data.

The Black Sea shows three 'weak' spots: the Sea of Azov, the shallow north-western area of the Black Sea and two points in the Danube delta. The latter is not surprising, as the Danube delta is not shown as protruding into the Black Sea, as it is drawn on other portolan charts. The two rejected points at the eastern extremity of the Black Sea may be due to poor charting, possibly due to 'squashing' the easternmost part of the Black Sea to fit on the vellum. Several examples exist of charts where the cartographer appears to have misjudged the extent of the Black Sea, one being the Roselli 1466 chart, discussed later in this chapter.

The dataset of the French Atlantic and English south Coast shows a cluster of points in the Bay of Biscay that are rejected in the calculation. The cartographer has drawn the Atlantic coast too far to the east, cutting into the French mainland.

The accuracy of the datasets and the axes rotations are shown in Table 7.7 and Table 7.8.

7.3 The Ristow-Skelton No. 3 chart

The portolan chart, held in the US Library of Congress in Washington, D.C. and known as the Ristow-Skelton No. 3 chart, is believed to be of Genoese origin. Its creation date has been estimated to be in the first half of the fourteenth century.[509] The geography west of the north-south line (rotated by about 9°) through the Balearics are missing, most likely trimmed, possibly due to damage. Also the eastern part of the Black Sea is missing, as well as the Sea of Azov and most of the Crimean peninsula. However, what remains is a chart of excellent quality.

Only a single scale bar is present on the chart. It is likely that it originally had more than one, but any other scale bars are likely to have been lost as a result of the trimming of the chart.

The chart also has only one wind rose, part of which has disappeared as a result of the same trimming. The chart does not appear to have had a second wind rose. The centre of the wind rose is located in the middle of the Aegean, which begs the question just how much has been trimmed off at the western end of the chart. It may be that the chart never extended significantly further to the west than it does now.

In spite of the limited extent of the map image, 742 identical points have been identified on the chart.

7.3.1 Pre-analysis of chart deformation – RS-3

Only ten of the sixteen nodes of the wind rose still exist on the chart, so the adjustment is not optimal. Nevertheless it transpires that the chart kept its dimensions very well, as the X-axis scale error demonstrates.

	Wind rose	Correction applied
X-axis scale error	-0.02%	0%
Misalignment X'-axis	+0.48°	-0.37°
Misalignment Y'-axis	+0.26°	-0.37°

Table 7.3 - *Results of the wind rose adjustment of the Ristow-Skelton 3 chart.*

The misalignments indicate a small shear, but this is so small that it may be just as likely due to drawing inaccuracies as to deformations of the vellum. The average value of the two values will be applied as a correction due to misalignment of the physical chart under the scanner.

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[509] James E. Kelley Jr., "The Oldest Portolan Chart in the New World", *Terrae Incognitae: Annals of the Society for the History of Discoveries* 9 (1977): 22-48.

7.3.2 MAIN CARTOMETRIC ANALYSIS – RS-3

The excellent quality of the remainder of what appears to have been a larger chart enabled the identification of 742 identical points. This large number of points allows reliable estimates of subsets of the data to be computed despite the missing western part of the Western Mediterranean and the north-east part of the Black Sea.

The division into coherent subsets of data points is quite similar to that of the Ricc 3827 chart, except that the Atlantic subsets are evidently unavailable, but there is one notable difference. The Central Mediterranean dataset consists of the Adriatic and Ionian Seas, Sicily and the Cap Bon peninsula in Tunisia and finally and, significantly, Sardinia. The Italian west coast and Corsica are now clearly and only part of the Western Mediterranean dataset. The excellent fit of Sardinia in the Central Mediterranean dataset is illustrated in Figure 7.13, whereas it appears to have been mapped about 33 km too far to the south when viewed in the context of the Western Mediterranean dataset.

Equally surprising is the excellent fit of the eastern part of the Tunisian and Algerian coastline (up to Cap Corbelin, 125 km east of Algiers) in the Eastern Mediterranean dataset. The midpoint of the transition zone between the Black Sea dataset and the Eastern Mediterranean dataset is the same as for the Ricc 3827 chart, approximately at the boundary of the Dardanelles and the Sea of Marmara.

The Aegean Sea distinguishes itself only slightly as a separate subset from the entire Eastern Mediterranean dataset.

Of the Western Mediterranean dataset only four points do not fit in the dataset, of which three are situated around Cabo Creus just south of the French-Spanish border. In the Central Mediterranean dataset the entire northern part of the Adriatic coast is rejected, as well as the small cluster of points in the Gulf of Taranto. The latter appears to be an effect of excessive accentuation of this gulf on the chart.

The Eastern Mediterranean shows the rejection of all points in the Gulf of Sirte, plus a cluster of points in the Gulf of Gabes from Tunisia to Tripoli in Libya. Also a cluster of points around Iskenderun in the north-east corner of the Eastern Mediterranean is rejected. Although these points were not rejected in the Ricc 3827 chart, their fit into the rest of the Eastern Mediterranean dataset was also poor on that chart.

The last cluster of points to be rejected is located around Thessaloniki in Greece. This cluster is not rejected in the processing of the Aegean Sea subset of points, but it is rejected in the context of the entire Eastern Mediterranean dataset. For that reason it is indicated by a dashed line in Figure 7.6.

Figure 7.6 - Ristow-Skelton No 3 chart with 742 identical points, division into coherent subsets of points and rejected data points in red ellipses.

It will also be seen that a group of three points around Scalea (at the 'instep' of the Italian boot) doesn't fit in either the Western or the Central Mediterranean dataset. This is due to feature exaggeration of that part of the coastline. In all portolan charts this part is protruding too far seaward.

7.4 The Dulcert 1339 chart

7.4.1 Pre-analysis of chart deformation – Dulcert 1339

The Dulcert 1339 chart consists of an east sheet and a west sheet. I have been unable to find information to answer the question whether these sheets were originally one, or whether they have been drawn on separate sheets of vellum. The scale of the chart is not markedly different from that of comparable portolan charts, such as Ricc 3827, but the Dulcert chart lacks a tapered section of the vellum corresponding with the neck of the animal that provided its skin.

The abrupt truncation of the eastern extremity of the map image raises the question whether the chart originally extended further eastward, which would increase the possibility that the vellum of two sheets originate from different animal skins and may therefore have acquired different distortion characteristics over time.

The chart has five scale bars, more than any of the other charts analysed, and it has two wind roses. Analysis of the wind roses revealed the following characteristics.

	Wind rose west	Wind rose east	Correction applied
X-axis scale error	-3.31%	-3.96%	separate E & W
Misalignment X'-axis	-0.14°	-0.10°	+0.23°
Misalignment Y'-axis	-0.27°	-0.42°	+0.23°

Table 7.4 *- Results of wind rose analysis of the Dulcert 1339 chart.*

The scale distortion of both wind roses is considerable and corresponding correction of the map coordinates is therefore appropriate. I corrected the east sheet and the west sheet separately for their scale errors, rather than applying a single correction with the mean value. The difference between the two options – separate E/W and average – is very small and noticeable only in the Central and Eastern Mediterranean datasets.

The orientation differences and internal shear of the two wind roses are negligible and a single alignment correction of +0.23° was therefore applied to the entire chart to compensate for the misalignment of the chart during scanning by BnF.

Figure 7.7 - Dulcert 1339 chart with 836 identical points, division into coherent subsets of points and rejected data points in red ellipses.

7.4.2 MAIN CARTOMETRIC ANALYSIS – DULCERT 1339

The division into coherent subsets of data points in the Mediterranean and Black Sea is comparable to, but not identical to, the RS-3 chart. A Western Mediterranean dataset can be identified, which includes Sicily and the North-African coastline from Cap Bon westward, but, as with the Ricc 3827 chart, the western part of the Alboran Sea has to be excluded. Neither Sardinia, nor Corsica, fit at all in the Western Mediterranean dataset, but Sardinia does agree very well with the Central Mediterranean dataset, whereas Corsica doesn't.

The Central Mediterranean dataset overlaps the Western Mediterranean dataset along the north Tunisian and Algerian coast up to Dellys, 80 km east of Algiers. It includes all of Sicily, the Maltese islands and the Italian islands south of Sicily. The common zone along the Algerian and Tunisian coast is a well-fitting, very long transition zone, which nevertheless fits well in the Central Mediterranean dataset, although it has a slightly detrimental effect on the latitude accuracy of this dataset.

Also the Eastern Mediterranean dataset has a long overlap with the Western and Central Mediterranean datasets to approximately the same point along the Algerian coast. The boundary between the Central and Eastern Mediterranean dataset along the Greek coast occurs at the same place as it does in the RS-3 and Ricc 3827 charts. Only the Carte Pisane is different in that the Central Mediterranean dataset extends far along the Dalmatian coast. Also the join between the Eastern Mediterranean dataset and the Black Sea occurs at about the same place as in the RS-3 and Ricc 3827 charts.

The same patterns of rejected points emerge as for the earlier evaluated charts:
- the cluster of points from the Gulf of Gabes to Tripoli, Libya;
- the Gulf of Sirte;
- the point cluster near Iskenderun in the north-eastern part of the Eastern Mediterranean;
- the Sea of Azov;
- the shallow north-western Black Sea.

7.5 THE ROSELLI 1466 CHART

The Roselli 1466 chart is, despite its respectable age, a relatively young chart in the context of the objective of this study. It is an established fact that portolan charts were in principle copied from earlier exemplars, be it not 'slavishly', as Nordenskiöld believed, but sufficiently so to generate the characteristic shape of the Mediterranean and Black Sea coastlines as a recognisable common feature of all charts. One would expect that the accuracy of the charts would gradually and progressively decrease as a result of successive copying events, but Loomer found that not to be the case, although feature exaggeration does increase.[510] However, Loomer concluded this on the basis of cartometric analysis of charts as single entities, whereas the analysis in this study focusses on evaluation of sub-charts.

This different approach justifies inclusion of the evaluation of a 'young' chart in this study. The digital scan, kindly made available by the James Ford Bell Library, contains a slight irregularity in the Eastern Mediterranean. It appears that the vellum buckled while the scan was in progress. I attempted to account for this irregularity, but in the end the buckling turned out to have no appreciable effect on the results of the cartometric analysis.

7.5.1 PRE-ANALYSIS OF CHART DEFORMATION – ROSELLI 1466

Petrus Roselli's chart of 1466 is a lavishly decorated chart in the style formerly[511] associated with the *Catalan school*. It has a single wind rose, which is characteristic for nearly all later portolan charts, i.e. charts produced in the late fourteenth century onward that show the entire Mediterranean. It also has four scale bars.

The wind rose has the following distortion characteristics.

	Central wind rose	Correction applied
X-axis scale error	+0.41%	-0.41%
Misalignment X'-axis	+1.12°	-1.18°
Misalignment Y'-axis	+1.24°	-1.18°

Table 7.5 *- Results of wind rose analysis of the Roselli 1466 chart.*

As with the charts evaluated above, the difference in misalignment of the X'-axis and Y'- axis is insufficient to conclude that the chart carrier has suffered shear deformation. The only directional correction is therefore -1.18° to the entire chart for misalignment in the scanning process. A scale correction of -0.41% was applied to the X-coordinates of the 860 identical points.

7.5.2 MAIN CARTOMETRIC ANALYSIS – ROSELLI 1466

The Roselli 1466 chart shows a very similar division into coherent subsets of data points as the Dulcert 1339 and the RS-3 charts. Also the rejected point clusters are familiar: the Gulf of Sirte, the area around Iskenderun and the Sea of Azov.

The five southernmost points along the North African Atlantic coast do not fit at all in the dataset that consists of the more northerly points along that coast and points along

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[510] Loomer, 153-157.

[511] Pujades 2007, 440. Ramon Pujades argued, after investigating numerous charts of Italian and Catalan origin, that it is not justified to speak of a consistent style difference between these two 'schools'.

the Atlantic coast of the Iberian Peninsula. A notable difference is that the western part of the Alboran Sea fits better with the Western Mediterranean dataset than was the case with the other two charts.

7.6 ANALYSIS OF ALL RESULTS

The cartometric computations have yielded an enormous amount of numerical data that allows much useful information about the charts to be deduced. This data is summarised in Table 7.7 and Table 7.8. An explanation of the meaning of the various parameters listed is provided in Table 7.6.

Not only is it possible to identify coherent subsets of identical points, but also the values of the rotation and scale parameters are calculated for each subset. Furthermore, accuracy data can be extracted from the residuals of the fit to the two main map projections investigated, the Mercator and the Equidistant Cylindrical projection.

This section discusses the following aspects of the cartometric analysis results:
- the division into subsets of data points;
- accuracy of the sub-charts;
- the map projection;
- anticlockwise rotations and shear angles;
- scale;
- the length of the portolan mile.

7.6.1 DIVISION INTO SUB-CHARTS

The identical points identified in the charts may be divided into coherent subsets, which are shown in the series of figures in the previous sections. Each subset of data points does not only have its own characteristic scale, but also its own orientation and shear. The existence of different scales within a portolan chart is sufficiently known; this was discovered very early on in the history of portolan chart research, in the nineteenth century.[512] These scale differences are nowadays often believed to be caused by portolan charts being composites of smaller charts of the sub-basins of the Mediterranean.[513] The genesis of the portolan chart as a single cartographic entity is thus believed to have been a two-step process of first charting the smaller sub-basins and then creating a larger composite chart.[514] Kretschmer proposed that the scale differences were caused

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[512] Kretschmer grants the discovery of scale differences between the Atlantic and the Mediterranean to H. Wuttke in 1871 (Kretschmer, 52, 96).

[513] The discussion in available literature on scale differences focussed in the past mainly on the differences in scale between the Mediterranean and the Atlantic (Kretschmer, 52). Later it was discovered that the Black Sea also has a significantly different scale from the Mediterranean (Kelley 1977, 46-48; Freiesleben 1983,126). Pujades, on the other hand, argues against this view and attributes the scale differences to the later addition of the Black Sea and Atlantic to existing charts of the Mediterranean (Pujades, 511).

[514] See for example Loomer, 165.

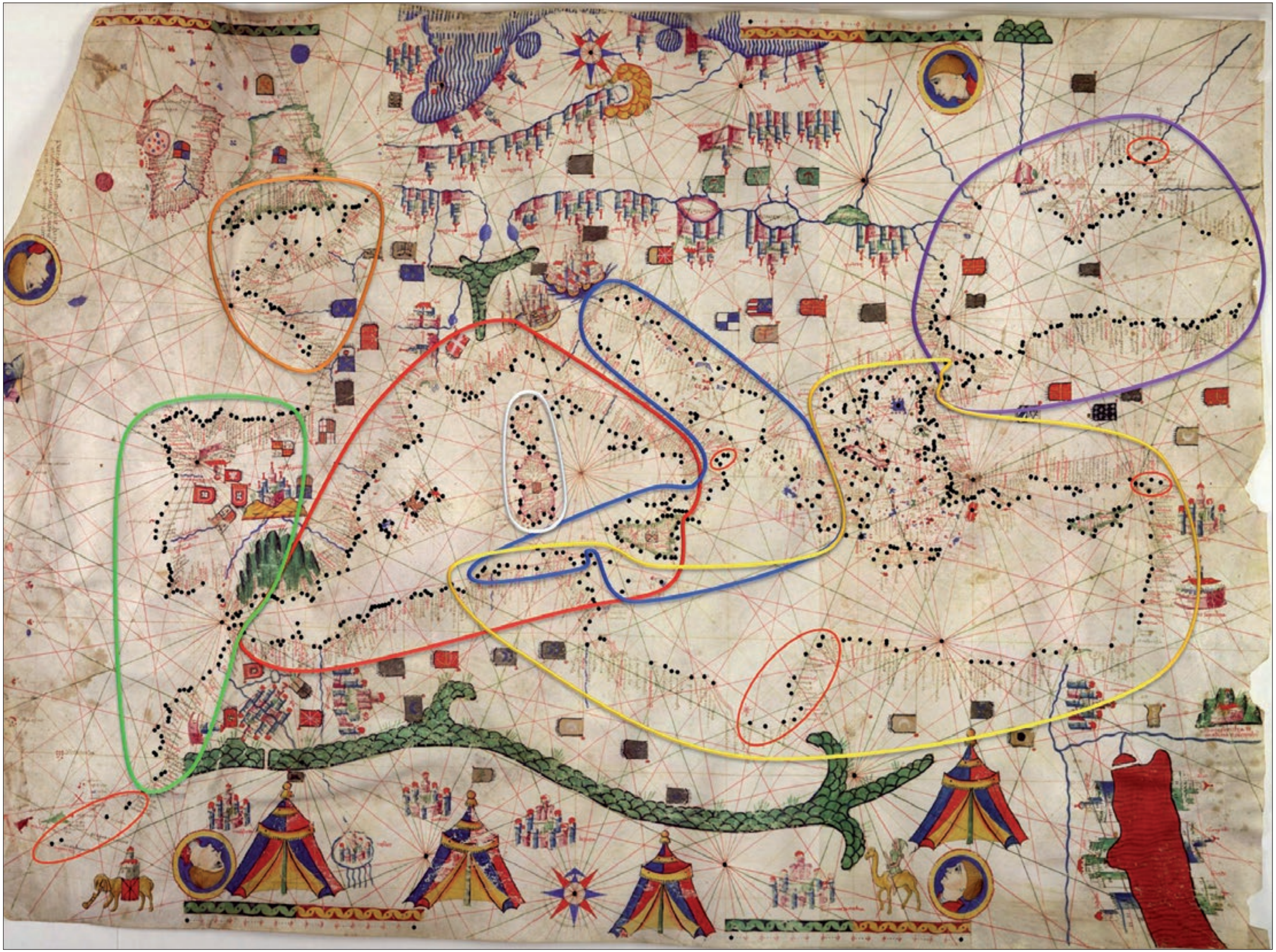

Figure 7.8 - Roselli 1466 chart with 860 identical points, division into coherent subsets of points and rejected data points in red ellipses.

by different length units being used in the different sub-basins but then adds that the Italian sailors were very familiar with the geography of all part of the Mediterranean and ”knew these waters as well as those at home”.[515] He concludes that the sub-basin charts were joined together “rather unscrupulously”.[516] To credit mariners and cartographers with the ability to make very accurate charts, as the medieval origin hypothesis does, and then to expect they would not notice or wouldn't care about the significant scale and orientation differences is not very credible.

An acceptable explanation of the scale (and orientation) differences has so far not been found, but it is justified to conclude that the various coherent subsets of data points do correspond with sub-charts, from which a composite chart has been generated. The large degree of coherence in, i.e. the high accuracy of, these subsets of data points and their scale and orientation differences support this conclusion.

However, that isn't all. In addition to the clear similarities in the compositions of the sub-charts over the five portolan charts, shown in Figure 7.1, Figure 7.3 and Figure 7.6 to Figure 7.8, there are also some intriguing differences. The most striking difference is the large section of the Dalmatian coastline that fits well in both the Central and the Eastern Mediterranean datasets of the Carte Pisane. This chart is the only one of the five investigated charts that has this characteristic and it is also the only one with such a deviating orientation of the Adriatic Sea. Furthermore the coherence of a large Central Mediterranean dataset in the Ricc 3827 charts suggests the availability of a sub-chart as source that encompassed the Adriatic Sea, the entire Italian peninsula, the Tyrrhenian Sea, Sicily, Corsica, Sardinia and the Tunisian area around the Cap Bon peninsula. The Ristow-Skelton No 3, Dulcert 1339 and the Roselli 1466 charts share a characteristic that the other two charts lack: an extension of the Eastern Mediterranean dataset along the coast of Tunisia and Algeria to about 100 km from Algiers. The join between the Aegean and Black Seas emerges fairly consistently at the location where the Dardanelles end and the Sea of Marmara begins and at the far western end a gap exists covering the western part of the Alboran Sea.

The joins between the sub-charts are never abrupt. The cartographers appear to have done their best to create a smooth appearance of the coastlines. This is visible in the cartometric analysis as *transition zones*, zones of which the identical points have a tendency of degrading the quality of the two neighbouring sub-charts. Sometimes there is an overlap, in other cases there is a gap between the optimised datasets of the sub-charts. Apart from the western Alboran Sea there is another clear gap between the datasets constituting the two Atlantic sub-charts along the north-Spanish coast. A consistent overlap area of three sub-charts exists in the Central Mediterranean around the Cap Bon peninsula. Two conclusions may tentatively be drawn from this. Firstly, contrary to what has been

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[515] Kretschmer, 96.

[516] Kretschmer, 97.

hypothesised before[517], the sub-charts do not correspond neatly with Mediterranean sub-basins. Notably the large Central Mediterranean dataset in the Ricc 3827 chart suggests that sub-charts of much larger areas may have been available.

The second conclusion concerns the meaning of the overlap zones. The process of joining the sub-charts appears to have consisted of fitting overlapping coastlines on adjacent sub-charts. This is evidenced by the large section of common Algerian coastline in the Western, Central and Eastern Mediterranean datasets in the three youngest charts. Most importantly this mechanism may explain the strange orientation of the Adriatic Sea in the Carte Pisane. The common southern Dalmatian points suggest that an existing chart of the Adriatic was best-fitted to a chart of the Eastern Mediterranean by overlaying this stretch of coast, which the two charts appear to have had in common.

The variations in the five charts suggest that the 'original' source sub-charts or copies of the originals may have been available for quite a long period, possibly until well into the fourteenth century, and that quite some trial-and-error variation in composing a complete chart was applied to improve the overall accuracy of the resulting composite.

The patterns of coherent identical points, shown with coloured lines in Figure 7.1, Figure 7.2, Figure 7.6, Figure 7.7 and Figure 7.8, indicate the main divisions into subsets of data. These graphical renderings are supported by the numerical results presented in Table 7.7 and Table 7.8. There are additional, secondary patterns of points that do not fit well in the dominant subset, but the mismatch is much smaller than that between the main subsets of data. An example is the Aegean Sea, which, on the Ricc 3827 chart, appears to have been copied from a separate partial chart. The differences between the Aegean Sea and the remainder of the larger Eastern Mediterranean dataset are smaller in the other charts. Of the Alboran Sea one would expect that the western part, which emerges as a transition zone between the Western Mediterranean dataset and Atlantic southern dataset, would have been sketched in by the cartographer. However, the entire Alboran Sea turns out to be a consistent and very accurate sub-data subset in nearly all charts, be it that on the Carte Pisane it is extremely stretched in E-W direction. The conclusion is that more partial maps or charts may have been used in the composition of a complete portolan chart of the Mediterranean and Black Sea than the primary division into coherent subsets of data suggests.

7.6.2 SUB-CHART ACCURACY

As hinted at earlier, it is rather meaningless to fit a portolan chart to a map projection as if it were a single, coherent chart, when one knows in advance that it is a composite of (relatively) poorly fitting sub-charts. Therefore no figures are presented for the whole charts in Table 7.7 and Table 7.8 with the exception of the parameter labelled as

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[517] Loomer, 159-165.

$RMSE_{map}$ in both tables. The intention of this figure is to demonstrate by which ratio the sub-charts' accuracy, expressed in the same column, has improved. A ratio close to unity would have indicated that no significant improvement was achieved by evaluating the sub-charts and would undermine the conclusion that a portolan chart is composition of such sub-charts.

The Least Squares Estimation process yields estimates for the unknown parameters of the affine transformation in the calculation, six in total:

- the origin coordinates X_0 and Y_0 of the internal GIS coordinate system, i.e. the internal X and Y coordinates of the point with latitude = longitude = 0;
- separate rotation angles for the (implicit) parallels and the (implicit) meridians in the chart relative to the chart's X and Y axis (as automatically determined by the GIS software);
- separate scale factors along the X and Y axes.

The map projection and the affine transformation complete the mathematical relationship between portolan chart coordinates and corresponding geographic coordinates. No additional unknown parameters need to be estimated for the map projection, except for the Oblique Stereographic projection, in which the latitude and longitude of the projection centre are added as parameters. However, this map projection has not been used in the cartometric analysis, except in analysing the Dulcert 1339 chart, to which it was applied to verify Loomer's conclusion that the Oblique Stereographic projection is sub-optimal.[518] In the Equidistant Cylindrical map projection the scale factor along the Y axis is interpreted as, or translated into, the latitude of the true-to-scale parallel.[519]

In addition to these parameters, accuracy estimates may be calculated from the residual errors after the Least Squares fit. The parameter $RMSE_{map}$ is a measure of the chart accuracy, but it is not immediately interpretable, as it expressed in the internal units of the X, Y coordinate system of the portolan chart image in the GIS. For that reason the residuals have been converted to residuals in latitude and longitude, from which the RMSE in latitude and in longitude can be calculated. The accuracy of a point may be represented by an error ellipse at the *one-sigma* level, which makes this ellipse the two-dimensional equivalent of the standard deviation. The larger of the two provides a slightly conservative estimate of chart accuracy, as shown in Section 6.5.6-C above.

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[518] Loomer, 133 (Table 6.3), 148 (Table 6.4), 149 (Table 6.5), 154 (Table 6.7) and 158 (Table 6.8).

[519] In Marinos of Tyre's projection the ratio was 0.8, which corresponds to the cosine of the latitude of the true-to-scale parallel, the Parallel of Rhodes at 36° N.

[520] The *degrees of freedom* in the computation is the number of measurements minus the number of parameters that is calculated. The number of measurements equals the number of points that contributed in the computation of the relevant subset of points (i.e. after subtraction of the number of rejected points), multiplied by two (each point contributes an X and a Y coordinate). The number of parameters computed equals six for both the Mercator calculation and the Equidistant Cylindrical calculation; see Section 6.5.6A.

Header	Description
	Name of the portolan chart.
Data subset	Coverage areas of identified subsets of the data.
θ_X (sd)	Rotation angle of portolan chart X-axis with its sample standard deviation from the calculation. See Figure 6.12.
θ_Y (sd)	Rotation angle of portolan chart Y-axis with its sample standard deviation from the calculation. See Figure 6.12.
θ_X-θ_Y	Shear angle; difference between values in columns 2 and 3. A positive shear angle means that the angle between the west-east axis and the south-north axis is smaller than 90°. See Figure 7.16.
$\Delta scale_{X-Y}$	For the Mercator projection: ratio of the scale along the portolan chart's longitude and latitude, calculated for the true-to-scale parallel of the best-fitting equivalent Equidistant Cylindrical projection. If the value is greater than 100% it means that the portolan chart is stretched in east-west direction. See also Section 7.6.5B.
φ_0 (sd)	For Equidistant Cylindrical projection: the latitude of the true-to-scale parallel with its sample standard deviation from the calculation. This determines the aspect ratio of a rectangle spanning 1°x 1° latitude/longitude. Because this figure may be distorted by stretch or shrink along the chart's Y-axis, this value is corrected for $\Delta scale_{X-Y}$ calculated for the Mercator projection.
Mean rel. scale	Mean scale of the sub-chart compared to the scale of the Western Mediterranean on that portolan chart. A figure greater than 100% indicates the scale is larger, i.e. a feature is shown as larger in that sub-chart than in the Western Mediterranean.
sd mean scale	For the Mercator projection: sample standard deviation from the calculation of the mean scale factor of a sub-chart.
sd scale X	For Equidistant Cylindrical projection: sample standard deviation from the calculation of the scale along X-axis. The scale along the Y-axis is included in the latitude of the true-to-scale parallel (column 6).
$RMSE_{lat}$	The sum of the squares of the residuals in latitude, divided by the degrees of freedom of the computation, expressed in kilometres on the earth's surface. The larger of the figures in this and the next column is considered to express the map accuracy of the sub-chart.
$RMSE_{lon}$	The sum of the squares of the residuals in longitude, divided by the degrees of freedom of the computation, expressed in kilometres on the earth's surface. The larger of the figures in this and the previous column is considered to express the map accuracy of the sub-chart.
$RMSE_{map}$	The square root of the sum of the squares of the residuals, divided by the degrees of freedom[520] of the computation (b), expressed in map units. As these map units are different for each chart, this variable can only be used to judge which of the two map projections tested provides the best fit and by how much.
Nr of points	The number of identical points in the dataset that is associated with the relevant sub-chart.
Rejections	The percentage of identical points in the dataset that did not fit into the solution for the relevant subset of points and was rejected (=removed from the computation).

Table 7.6 *- Definition of the meaning of the columns in Table 7.7 and Table 7.8.*

MERCATOR	Data subset	θ_X (sd)	θ_Y (sd)	θ_X-θ_Y (shear)	$\Delta \text{scale}_{X-Y}$
Carte Pisane	1. Entire dataset	–	–	–	–
	2. Alboran Sea	-11.5° (0.9°)	-10.3° (2.5°)	-4.1°	133%
	3. Western Mediterranean	-9.9° (0.2°)	-5.2° (0.3°)	-4.7°	93%
	4. Central Mediterranean	-8.1° (0.4°)	-3.4° (0.3°)	-4.7°	92%
	5. Eastern Mediterranean	-8.4° (0.2°)	-6.8° (0.3°)	-1.6°	100%
	6. Aegean Sea	-1.4° (0.7°)	-6.6° (0.7°)	5.1°	90%
Ricc 3827	1. Entire dataset	–	–	–	–
	2. Atlantic coasts North	0.2° (0.8°)	-4.8° (0.6°)	5.0°	85%
	3. Atlantic coasts South	-0.6° (0.6°)	-4.3° (0.4°)	3.7°	99%
	4. Alboran Sea	-7.3° (0.3°)	-6.0° (0.8°)	-1.3°	101%
	5. Western Mediterranean	-8.2° (0.1°)	-6.3° (0.2°)	-1.9°	99%
	6. Central Mediterranean	-12.7° (0.2°)	-5.9° (0.2°)	-6.7°	103%
	7. Eastern Mediterranean	-9.2° (0.1°)	-11.0° (0.2°)	1.8°	92%
	8. Aegean Sea	-8.0° (0.4°)	-11.3° (0.4°)	3.3°	98%
	9. Black Sea	-10.2° (0.2°)	-9.7° (0.3°)	-0.5°	105%
Ristow-Skelton 3	1. Entire dataset	–	–	–	–
	2. Western Mediterranean	-8.0° (0.2°)	-6.8° (0.2°)	-1.2°	105%
	3. Central Mediterranean	-11.9° (0.2°)	-4.6° (0.2°)	-7.3°	110%
	4. Eastern Mediterranean	-10.5° (0.1°)	-7.9° (0.2°)	-2.6°	96%
	5. Aegean Sea	-10.6° (0.2°)	-7.2° (0.3°)	-3.4°	95%
	6. Black Sea	-10.5° (0.4°)	-8.0° (0.5°)	-2.5°	112%
Dulcert 1339	1. Entire dataset	–	–	–	–
	2. Atlantic coasts North	0.6° (0.7°)	-9.1° (0.7°)	9.7°	82%
	3. Atlantic coasts South	-5.6° (1.0°)	-2.1° (0.3°)	-3.4°	110%
	4. Alboran Sea	-8.4° (0.4°)	-7.7° (0.6°)	-0.7°	114%
	5. Western Mediterranean	-7.1° (0.1°)	-5.8° (0.2°)	-1.2°	101%
	6. Central Mediterranean	-11.6° (0.2°)	-2.5° (0.2°)	-9.1°	107%
	7. Eastern Mediterranean	-10.9° (0.1°)	-9.3° (0.2°)	-1.6°	96%
	8. Aegean Sea	-10.1° (0.4°)	-7.1° (0.3°)	-3.1°	93%
	9. Black Sea	-10.4° (0.3°)	-7.8° (0.3°)	-2.6°	108%
Roselli 1466	1. Entire dataset	–	–	–	–
	2. Atlantic coasts North	0.5° (0.5°)	-5.4° (0.4°)	5.9°	96%
	3. Atlantic coasts South	0.4° (0.5°)	-3.6° (0.2°)	4.0°	97%
	4. Alboran Sea	-2.8° (0.6°)	-11.3° (0.8°)	8.5°	109%
	5. Western Mediterranean	-7.5° (0.1°)	-6.0° (0.2°)	-1.5°	102%
	6. Central Mediterranean	-9.4° (0.2°)	-3.3° (0.2°)	-6.1°	111%
	7. Eastern Mediterranean	-10.2° (0.1°)	-10.5° (0.2°)	0.2°	97%
	8. Aegean Sea	-10.4° (0.4°)	-8.9° (0.4°)	-1.5°	98%
	9. Black Sea	-13.0° (0.3°)	-10.3° (0.4°)	-2.7°	116%

***Table** 7.7 - Cartometric analysis results for the Mercator projection.*

Mean rel. scale	Sd mean scale	RMSE$_{lat}$ (km)	RMSE$_{lon}$ (km)	RMSE$_{map}$ (map units)	Number of points	Rejected points
-	–	–	–	54.9	439	9
90%	3.0%	5.5	**6.6**	15.1	23	1
100%	0.3%	15.1	**16.2**	41.9	200	1
108%	0.4%	**12.6**	11.6	35.5	126	1
96%	0.3%	**15.8**	12.3	37.1	180	17
101%	0.9%	**12.4**	11.6	32.8	78	6
-	–	–	–	43.2	1015	108
91%	0.7%	14.2	**16.6**	23.7	79	8
92%	1.0%	6.2	**6.4**	9.8	39	1
103%	0.7%	3.5	**4.3**	7.0	27	0
100%	0.2%	8.2	**9.2**	14.8	240	7
104%	0.3%	**10.2**	9.0	17.1	253	13
108%	0.2%	**12.1**	12.1	22.5	330	32
118%	0.5%	9.7	**11.1**	21.2	177	1
116%	0.3%	6.8	**9.2**	16.2	142	14
-	–	–	–	44.3	742	8
100%	0.2%	**9.6**	9.4	22.5	226	4
102%	0.2%	8.4	**9.0**	20.7	190	15
105%	0.2%	10.5	**11.1**	26.6	343	26
106%	0.3%	7.4	**7.9**	19.2	169	13
115%	0.6%	**9.0**	8.5	23.5	74	4
-	–	–	–	35.9	836	74
85%	0.8%	9.1	**9.3**	10.9	43	0
85%	0.9%	**18.1**	9.9	16.5	79	0
106%	0.7%	**4.0**	3.4	5.3	38	3
100%	0.2%	9.3	**9.8**	12.8	189	5
101%	0.3%	9.9	**11.2**	14.9	163	5
103%	0.2%	11.0	**11.4**	15.7	291	29
104%	0.5%	**7.7**	7.2	10.6	107	6
116%	0.4%	9.2	**10.9**	16.0	129	9
-	–	–	–	140.9	860	25
93%	0.5%	**9.0**	8.8	35.0	68	1
89%	0.6%	**10.6**	9.2	37.2	99	6
107%	0.9%	**5.8**	5.1	24.5	39	0
100%	0.2%	10.6	**11.9**	45.5	216	5
104%	0.3%	**9.6**	9.5	40.5	135	7
107%	0.2%	11.2	**12.4**	52.2	266	18
112%	0.5%	8.3	**10.8**	44.5	144	5
114%	0.4%	10.5	**12.1**	54.0	132	4

Bold and red figures in the columns labelled RMSE$_{LAT}$ *and RMSE*$_{LON}$ *highlight the figures chosen to represent the accuracy of the sub-charts.*

EQUIDISTANT CYLINDRICAL	**Data subset**	θ_X **(sd)**	θ_Y **(sd)**	θ_X-θ_Y **(shear)**	φ_0 **(sd)**
Carte Pisane	1. Entire dataset	–	–	–	–
	2. Alboran Sea	-15.0° (0.9°)	-1.4° (1.7°)	-13.6°	48.0° (3.9°)
	3. Western Mediterranean	-10.2° (0.2°)	-4.9° (0.3°)	-5.3°	41.1° (0.4°)
	4. Central Mediterranean	-7.7° (0.4°)	-3.3° (0.3°)	-4.4°	42.3° (0.5°)
	5. Eastern Mediterranean	-8.2° (0.2°)	-6.8° (0.3°)	-1.4°	39.0° (0.5°)
	6. Aegean Sea	-1.2° (0.8°)	-6.1° (0.6°)	4.9°	39.0° (1.0°)
Ricc 3827	1. Entire dataset	–	–	–	–
	2. Atlantic coasts North	-0.9° (1.0°)	-4.1° (0.5°)	3.2°	46.6° (0.8°)
	3. Atlantic coasts South	0.5° (0.6°)	-4.3° (0.4°)	4.8°	35.2° (1.1°)
	4. Alboran Sea	-7.0° (0.5°)	-2.9° (0.9°)	-4.1	32.4° (1.6°)
	5. Western Mediterranean	-8.1° (0.1°)	-6.3° (0.2°)	-1.8°	39.5° (0.2°)
	6. Central Mediterranean	-12.4° (0.2°)	-6.2° (0.2°)	-6.2°	39.2° (0.4°)
	7. Eastern Mediterranean	-9.9° (0.1°)	-10.1° (0.2°)	0.3°	36.6° (0.3°)
	8. Aegean Sea	-8.2° (0.4°)	-11.0° (0.3°)	2.8°	37.9° (0.7°)
	9. Black Sea	-9.8° (0.2°)	-10.1° (0.3°)	0.4°	43.2° (0.4°)
Ristow-Skelton 3	1. Entire dataset	–	–	–	–
	2. Western Mediterranean	-7.5° (0.2°)	-7.1° (0.2°)	-0.5°	40.2° (0.3°)
	3. Central Mediterranean	-11.0° (0.2°)	-4.7° (0.3°)	-6.3°	39.9° (0.5°)
	4. Eastern Mediterranean	-11.0° (0.1°)	-7.7° (0.2°)	-3.3°	36.3° (0.3°)
	5. Aegean Sea	-10.2° (0.4°)	-7.0° (0.3°)	-3.2°	39.1° (0.5°)
	6. Black Sea	-9.4° (0.4°)	-8.7° (0.6°)	-0.7°	43.1° (1.0°)
Dulcert 1339	1. Entire dataset	–	–	–	–
	2. Atlantic coasts North	0.2° (0.8°)	-7.4° (0.5°)	7.7°	48.6° (0.6°)
	3. Atlantic coasts South	-2.4° (0.7°)	-2.4° (0.2°)	0.0°	37.8° (1.3°)
	4. Alboran Sea	-7.4° (0.3°)	-8.8° (0.7°)	1.5°	36.2° (1.7°)
	5. Western Mediterranean	-6.9° (0.1°)	-5.9° (0.2°)	-1.0°	40.0° (0.3°)
	6. Central Mediterranean	-10.7° (0.2°)	-3.3° (0.3°)	-7.4°	39.9° (0.5°)
	7. Eastern Mediterranean	-11.5° (0.1°)	-8.6° (0.2°)	-2.9°	36.2° (0.3°)
	8. Aegean Sea	-10.8° (0.5°)	-6.5° (0.3°)	-4.3°	38.2° (0.6°)
	9. Black Sea	-9.5° (0.2°)	-8.5° (0.4°)	-1.1°	43.3° (0.6°)
Roselli 1466	1. Entire dataset	–	–	–	–
	2. Atlantic coasts North	-1.1° (0.6°)	-5.1° (0.3°)	4.0°	47.3° (0.6°)
	3. Atlantic coasts South	0.9° (0.6°)	-3.4° (0.2°)	4.3°	37.8° (0.7°)
	4. Alboran Sea	-2.8° (0.6°)	-12.6° (0.9°)	9.9°	36.7° (1.9°)
	5. Western Mediterranean	-7.2° (0.1°)	-6.1° (0.2°)	-1.2°	39.9° (0.3°)
	6. Central Mediterranean	-8.2° (0.2°)	-3.6° (0.3°)	-4.6°	40.8° (0.5°)
	7. Eastern Mediterranean	-10.9° (0.1°)	-10.1° (0.2°)	-0.8°	36.5° (0.3°)
	8. Aegean Sea	-14.0° (0.1°)	-9.0° (0.4°)	-4.9°	40.1° (0.4°)
	9. Black Sea	-11.1° (0.2°)	-12.3° (0.5°)	1.2°	43.5° (0.8°)

Table 7.8 *- Cartometric analysis results for the Equidistant Cylindrical projection.*

Mean rel. scale	Sd scale X	RMSE_{lat} (km)	RMSE_{lon} (km)	RMSE_{map} (map units)	Number of points	Rejected points
-	–	–	–	53.9	439	25
97%	2.9%	6.2	**8.0**	21.5	28	1
100%	0.6%	15.1	**16.4**	41.2	200	0
109%	0.5%	**14.2**	11.6	37.5	126	1
95%	0.5%	**17.1**	12.3	38.3	180	17
102%	1.0%	**12.2**	11.6	31.6	78	6
-	–	–	–	46.4	1015	40
97%	0.9%	12.9	**16.6**	23.0	79	8
91%	0.7%	**6.7**	6.4	10.2	39	1
101%	1.6%	4.0	**5.5**	8.7	33	0
100%	0.3%	7.5	**9.2**	14.5	241	7
101%	0.4%	**11.3**	9.5	18.5	231	15
112%	0.4%	**13.3**	12.6	24.3	330	29
118%	0.6%	9.1	**11.1**	20.8	177	0
112%	0.6%	6.9	**9.3**	16.5	142	13
-	–	–	–	42.1	742	12
100%	0.3%	9.4	**9.4**	22.3	221	4
99%	0.4%	**10.0**	9.8	23.2	189	15
108%	0.3%	10.1	**10.8**	25.9	338	33
110%	0.4%	7.6	**7.6**	18.7	166	12
110%	1.0%	**9.4**	9.1	24.7	74	3
-	–	–	–	35.6	836	69
96%	0.9%	8.5	**9.3**	10.4	43	0
83%	0.4%	**12.8**	9.9	13.1	80	0
100%	1.2%	**4.0**	3.3	5.3	38	3
100%	0.3%	8.4	**9.8**	12.3	189	3
97%	0.5%	11.4	**12.1**	16.0	169	6
106%	0.4%	11.0	**12.2**	16.2	255	31
108%	0.6%	**7.8**	7.3	10.7	100	4
112%	0.7%	9.6	**10.9**	16.3	129	9
-	–	–	–	123.3	860	47
97%	0.6%	**9.0**	8.5	34.2	68	4
93%	0.3%	**12.4**	9.4	41.3	99	0
104%	1.6%	**5.9**	4.9	24.2	38	0
100%	0.4%	10.1	**12.2**	45.5	213	3
99%	0.4%	**10.2**	9.5	41.6	135	10
110%	0.4%	10.9	**12.6**	52.2	268	27
114%	0.6%	10.7	**11.2**	49.4	176	5
106%	0.8%	11.9	**13.3**	58.9	139	3

Bold and red figures in the columns labelled RMSE_{LAT} *and* RMSE_{LON} *highlight the figures chosen to represent the accuracy of the sub-charts.*

Figure 7.9 shows the accuracy of the sub-charts that compose each of the five portolan charts, calculated for the Mercator projection. The vertical scale is kilometres. Figure 7.10 shows, for each of the five portolan charts evaluated, the differences in sub-chart accuracy between the fit to the Mercator and Equidistant Cylindrical projections.

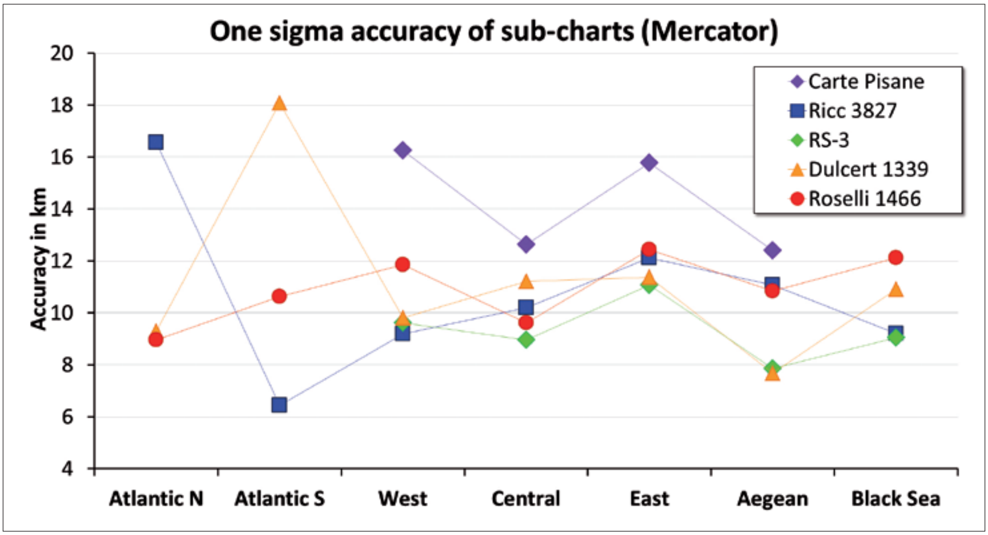


Figure 7.9 *- Accuracies of sub-charts per portolan chart (Mercator projection). The figures of sub-chart accuracy of any portolan chart have been connected by dotted lines to make it easier to identify the results of a single portolan chart. See also Table 7.7, columns 9 and 10.*
Differences with the Equidistant Cylindrical projection are shown in Figure 7.10 below.

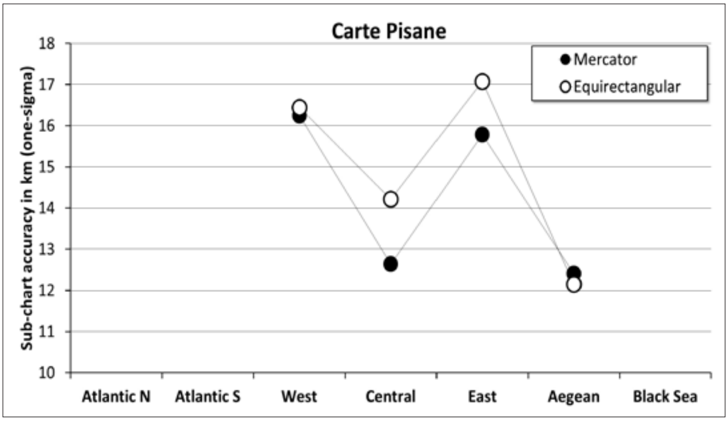
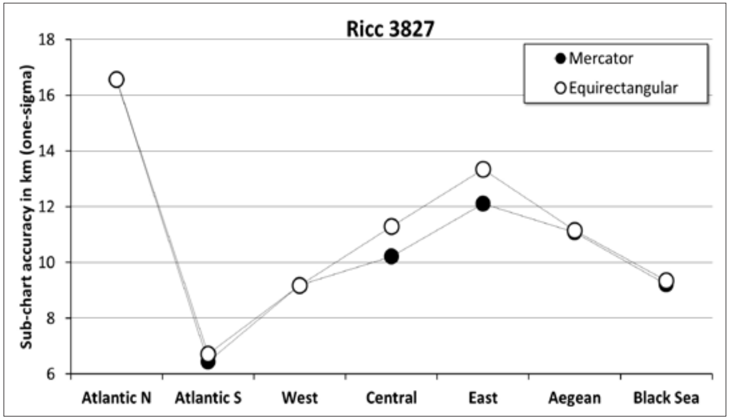
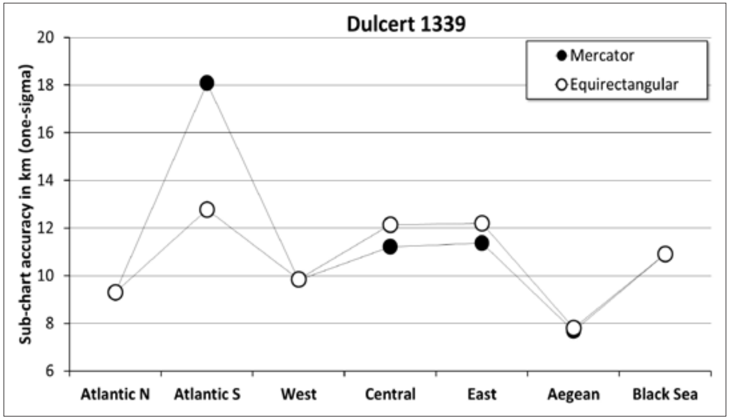


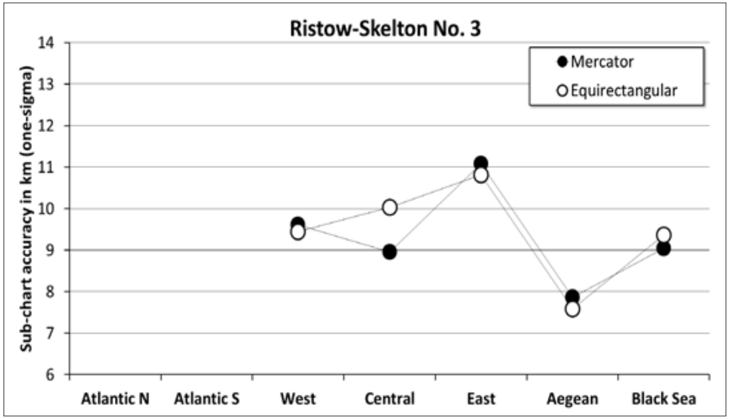
Figure 7.10 *- Comparison of sub-chart accuracies for Mercator and Equidistant Cylindrical (Equirectangular) map projections. (Figure 7.10 continues on the next page).*



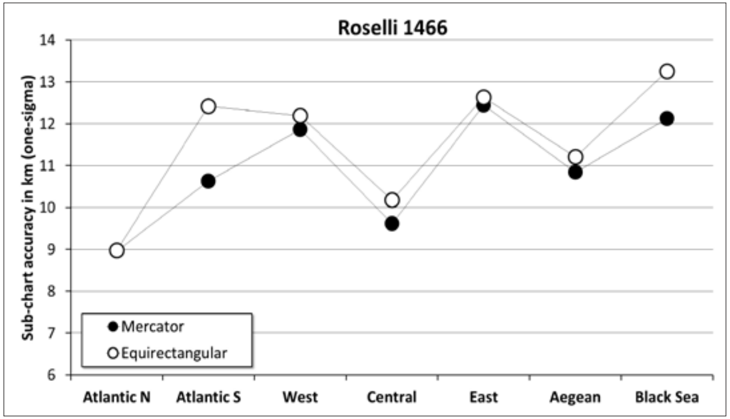
Ricc 3827



Dulcert 1339



Ristow-Skelton No. 3



Roselli 1466

The first observation to make is that the sub-charts are extremely accurate for medieval charts, but the reader is warned not to interpret these figures as "the accuracy of the sub-charts is *within* so-many km". The term *within* suggests that the larger part of the data would be *better* than the figure quoted and that is not the case. For a two-dimensional variable, such as *position* at the one-sigma level, the corresponding confidence level is about 39%. In this case the confidence level will be slightly higher because of the conservative way the two-dimensional accuracy has been summarised in a single variable, the sample standard deviation of latitude or longitude. If the values are desired at 95% confidence level the number shown need to multiplied by a factor 2.45. Based on the conservative generalisation mentioned, the actual confidence level of the number would be higher than 95%. However, it should to be remembered that these accuracy figures exclude outliers. These outliers may be caused by poor mapping, such as the zones indicated in the graphic representation of the datasets above. The former affects smaller or larger clusters of points, the latter usually single points. The rejection percentages are listed in Table 7.7 and Table 7.8, last column.

Regardless of the way chart accuracy is expressed, at the one-sigma level or 95% confidence level, the results are extremely accurate for medieval charts with an average scale of 1 : 5.5 million. A one-sigma level of accuracy of 10 km corresponds with 1.8 mm on the chart. This is close to the level of the coastal feature exaggeration!

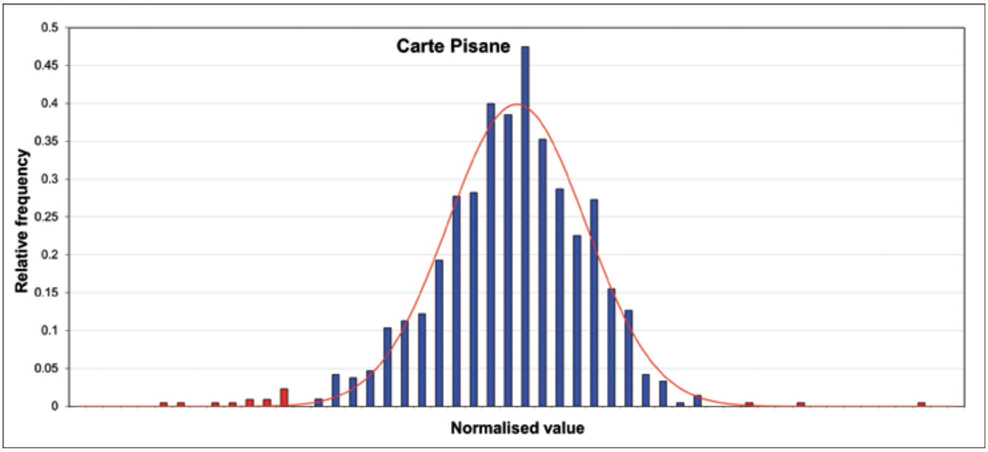
A further observation to make is the relative constancy of the pattern of accuracies over the Mediterranean and Black Sea. However, significant differences in accuracy occur for the two Atlantic sub-charts.

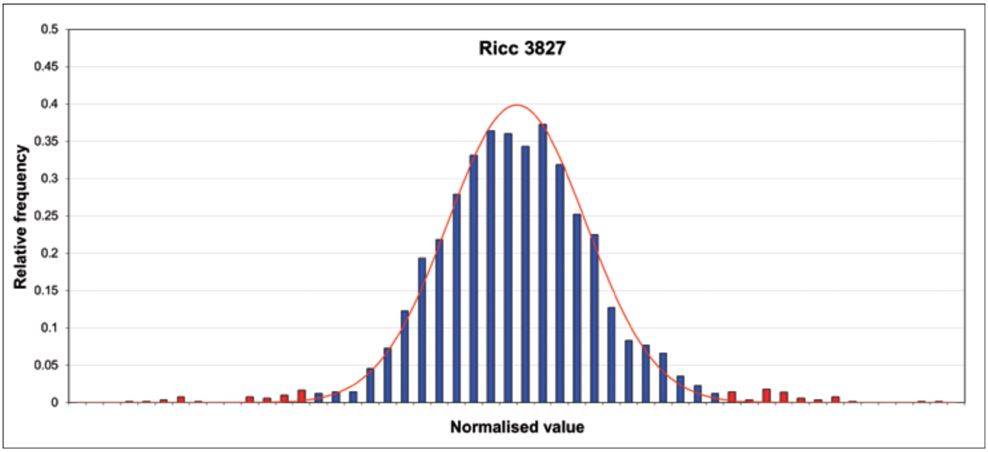
7.6.3 THE DISTRIBUTION OF THE (NORMALISED) RESIDUALS

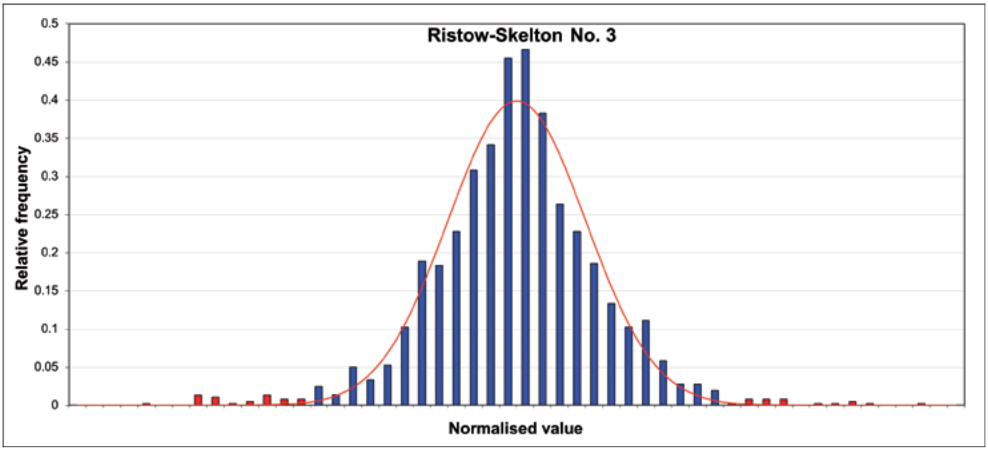
At the very beginning of the chapter the argument was put forward that points that do not fit into the 'mould' of the Least Squares Estimation process need to be rejected. The evident question to be anticipated is whether the calculated figures do not represent a flattered interpretation of the concept of chart accuracy. Should the outliers, which, after all, are part of the investigated chart, not simply be taken into account in the calculation of the accuracy figures? The answer is negative, as the inclusion of poorly fitting data would distort the values of the parameters for scale and rotation, but they should also be excluded in the accuracy estimates of the chart, which are deemed to represent the error distribution of the data. This error distribution would be the normal or Gaussian error distribution, provided the correct functional model has been applied, i.e. the right map projection has been used in the cartometric analysis calculations. Is that Gaussian distribution visible in the residuals of the calculation?

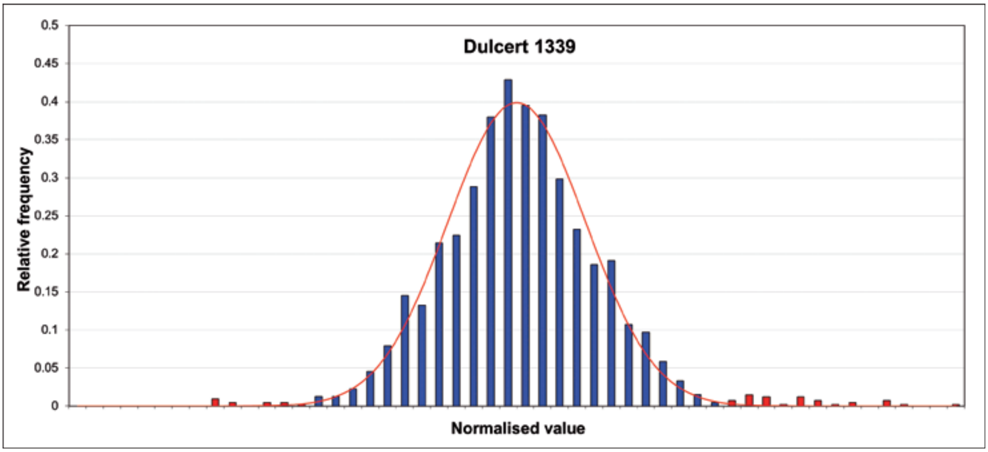
Figure 7.11 and Figure 7.13 show histograms created from the normalised residuals, i.e. the residuals in X and Y, divided by their respective sample standard deviations, of the five charts. The theoretical error distribution that this histogram should approximate on the grounds of the *Central Limit Theorem*, is the standard normal distribution, which has a mathematical expectation of zero and a standard deviation of one (unity). The curve representing that distribution has been drawn in the histograms as the solid red line. The parameter that characterises the spread of the actual data is the Root Mean Squared Error ($RMSE_{map}$). It can be seen that the histogram closely approximates the theoretical curve of the standard normal error distribution, thanks to the fact that the outliers, indicated by the red bars at the far left and right of the histogram, are excluded. Had they been included in the calculation of an estimate of the spread (or *noise*) of the data, a significantly larger $RMSE_{map}$ would have resulted, which would not have been representative for the actual spread of the errors as represented by the blue histogram.

Another conclusion may be drawn from these histograms; viz. that the functional model of the Mercator projection with superimposed affine transformation matches the map distortions of portolan charts very well. The close match to the standard normal distribution suggests that the residuals have not absorbed a systematic distortion element from the application of any incorrect functional model.









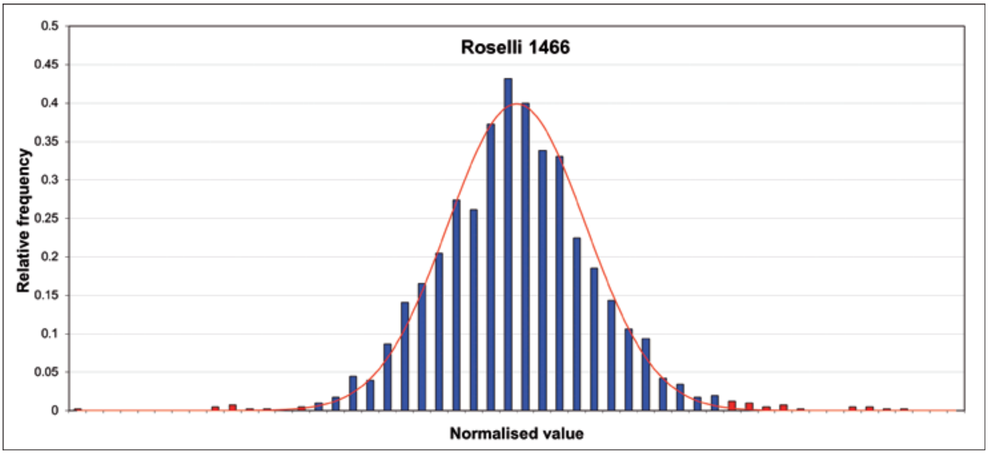


Figure 7.11 *- Histogram of normalised residuals of the analysed portolan charts after piecewise fit to the Mercator projection.*

Very similar results would have been obtained with the residuals from the evaluation of the Equidistant Cylindrical projection, because this projection is virtually indistinguishable from the Mercator projection in the mapping of the Mediterranean region.

Figure 7.12 shows the normalised residuals for the fit of the Oblique Stereographic projection to the Dulcert 1339 chart, demonstrating that an Oblique Stereographic projection may indeed be fitted successfully to a portolan chart. Only a slight skewing to the right is visible in this histogram. The similarity between Figure 7.12 and the histograms in Figure 7.11 might lead one to conclude that the Oblique Stereographic projection provides as good a fit as the Mercator projection, but that is not true. The *spread* is larger than the spread of the Mercator and Equidistant Cylindrical fit to the sub-areas. This is further discussed in Section In 7.6.5 below.

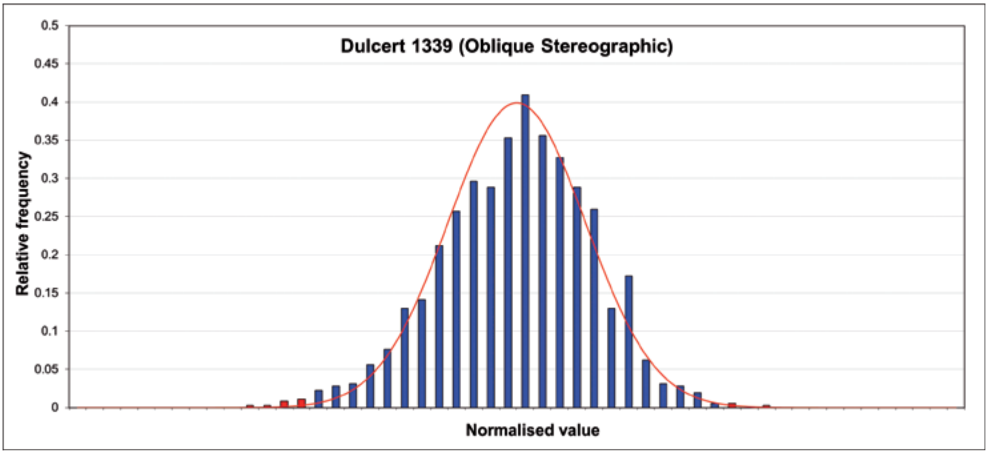


Figure 7.12 *- Normalised residuals of the Dulcert 1339 chart after fitting to an Oblique Stereographic projection.*

7.6.4 The wanderings of Corsica and Sardinia

A puzzling subject that emerged during the analysis of the five charts was the sub-chart or subset of identical points to which Corsica and Sardinia fitted best. Whereas Sicily, Crete and Cyprus are fairly consistent in their allocation to one particular, sometimes two, sub-charts, there was considerable variation in the locations of Corsica and Sardinia.

Figure 7.13 and Figure 7.14 show graphically what Table 7.9 and Table 7.10 show in numbers, viz. the variation in the locations of Corsica and Sardinia, depending on which sub-chart they are attributed to. The bold font in the two tables indicates the subset of identical points in which the respective island's points fitted best. Normal font indicates that the points didn't fit well or were even rejected.

Corsica	**Western Med. subset**		**Central Med. subset**	
	Latitude error (km)	Longitude error (km)	Latitude error (km)	Longitude error (km)
Carte Pisane	**-11.5**	**-9.8**	-65.3	-12.5
Ricc 3827	**-5.8**	**-5.4**	+13.2	-4.7
RS-3	-33.3	+3.7	**-3.6**	**-1.1**
Dulcert 1339	-16.4	-25.5	-38.5	+9.1
Roselli 1466	-36.1	-21.1	-33.9	-7.7

Table 7.9 - *Mean position errors of Corsica in Western and Central Mediterranean datasets.*

Sardinia	**Western Med. subset**		**Central Med. subset**	
	Latitude error (km)	Longitude error (km)	Latitude error (km)	Longitude error (km)
Carte Pisane	**-27.6**	**-1.7**	-65.7	+3.0
Ricc 3827	-31.1	+8.7	**-9.4**	**+9.3**
RS-3	**-14.8**	**-13.9**	+17.1	-26.6
Dulcert 1339	+3.6	-39.6	**-5.3**	**-16.1**
Roselli 1466	-16.9	-47.7	-5.4	-39.9

Table 7.10 - *Mean position errors of Sardinia in Western and Central Mediterranean datasets.*

On the Carte Pisane both islands fit best in the Western Mediterranean subset of identical points. They don't even fit at all in the Central Mediterranean dataset.

On the Ricc 3827 chart the locations of both islands have changed relative to their locations on the Carte Pisane, both with respect to the surrounding coasts of the Western Mediterranean and with respect to the Central Mediterranean dataset. Corsica fits extremely well in the Western dataset, but Sardinia in the Central.

On the Ristow-Skelton No. 3 chart it is the other way around. Sardinia lies practically in the right place in the Central Mediterranean dataset, but Corsica has moved for the worse.

On the Dulcert 1339 and Roselli 1466 charts positional correctness of the two islands gets progressively worse. On the first chart Sardinia still fits well enough in the Central Mediterranean dataset, but Corsica seems to have lost its way. It fits in neither chart and is even rejected from both datasets, i.e. the point errors exceed the 99% confidence level threshold. On the Roselli 1466 chart the two islands fit in no dataset. The mapping of the islands themselves is accurate enough, but they 'drifted' away, on average by the amounts shown in the tables.

In his ‘address to the reader’ on his 1403 chart Francesco Beccari claimed to have shifted the location of Sardinia and increased the scale of the Atlantic areas. Beccari’s text is widely regarded as an example of how portolan charts were improved by feedback from sailors. It is sometimes said that Beccari’s 1403 chart is a ‘watershed’ chart.[521] Pujades, for example, refers to a statement from Pere Rossell (Petrus Roselli) that “as from the 1430s Majorcan cartographers had abandoned their blind loyalty to the previous Dulcertan model to make their charts *de arte Baptiste Beccarii.*”[522]

The cartometric analysis undertaken in this study reveals that there is no clear ‘watershed’ between the *Dulcert model* and the *Beccari model* as templates for chart copying, as Roselli allegedly suggested in the above citation. Instead the picture emerges that successive cartographers appear to have modified the way in which the component sub-charts were fitted together, favouring the positions of Corsica and Sardinia now from one sub-chart, then from the other in, what one would assume, an attempt to arrive at a true representation of the location of the islands in the Mediterranean. The alternative would be to attribute the variation to sloppiness or carelessness, which would contradict the evident care with which the charts were drawn.

Roselli may not have used the Beccari improvement of the location of Sardinia, although that would contradict the statement Roselli himself allegedly made, or we must conclude that Beccari’s improvement of the location of Sardinia was not an improvement at all. Lepore *et al* did find a real improvement in the Atlantic distances they scaled off from Beccari’s chart, but also that appears not to have found its way into Roselli’s chart, as Figure 7.25 demonstrates.[523]

7.6.5 The map projection

A. Oblique Stereographic projection

Distortion grids generated for portolan charts, such as Figure 6.2, show that the graticule of parallels and meridians that is thus created consists of two sets of approximately parallel straight lines that may or may not be orthogonal. The ratio of the spacing of the parallels over that of the meridians appears to be approximately constant, with some variation that appears to be caused by regional scale differences, rather than by the properties of the map projection. Only two map projection types can be considered as candidates for the best-fitting map projection of portolan charts, viz. the Equidistant Cylindrical and Mercator projections. The Oblique Stereographic projection proposed by Duken may be fitted to a portolan chart, in an attempt to model the scale differences

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[521] Lepore et al 2011. Campbell 1987, 428; Pujades 2007, 461.

[522] Pujades 2007, 461.

[523] With the benefit of hindsight I have to conclude that it would have been far more interesting to analyse Beccari’s 1403 chart instead of, or in addition to Roselli’s.

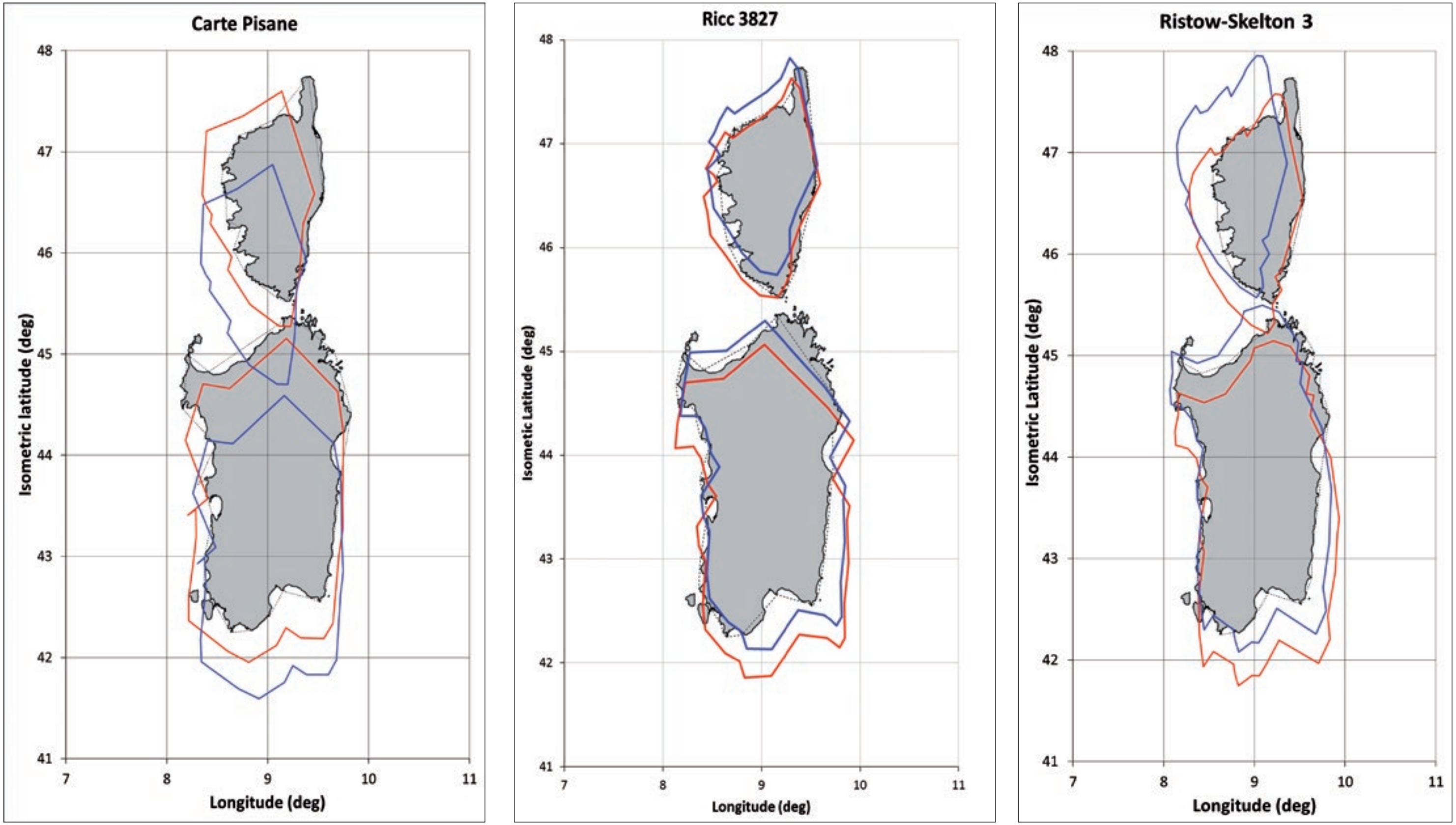

Figure 7.13 - *Location of Sardinia and Corsica in the Western and Central Mediterranean datasets on the Carte Pisane, Ricc 3827 and RS-3 charts. The faint dotted line connects the error-free identical points on the islands.*

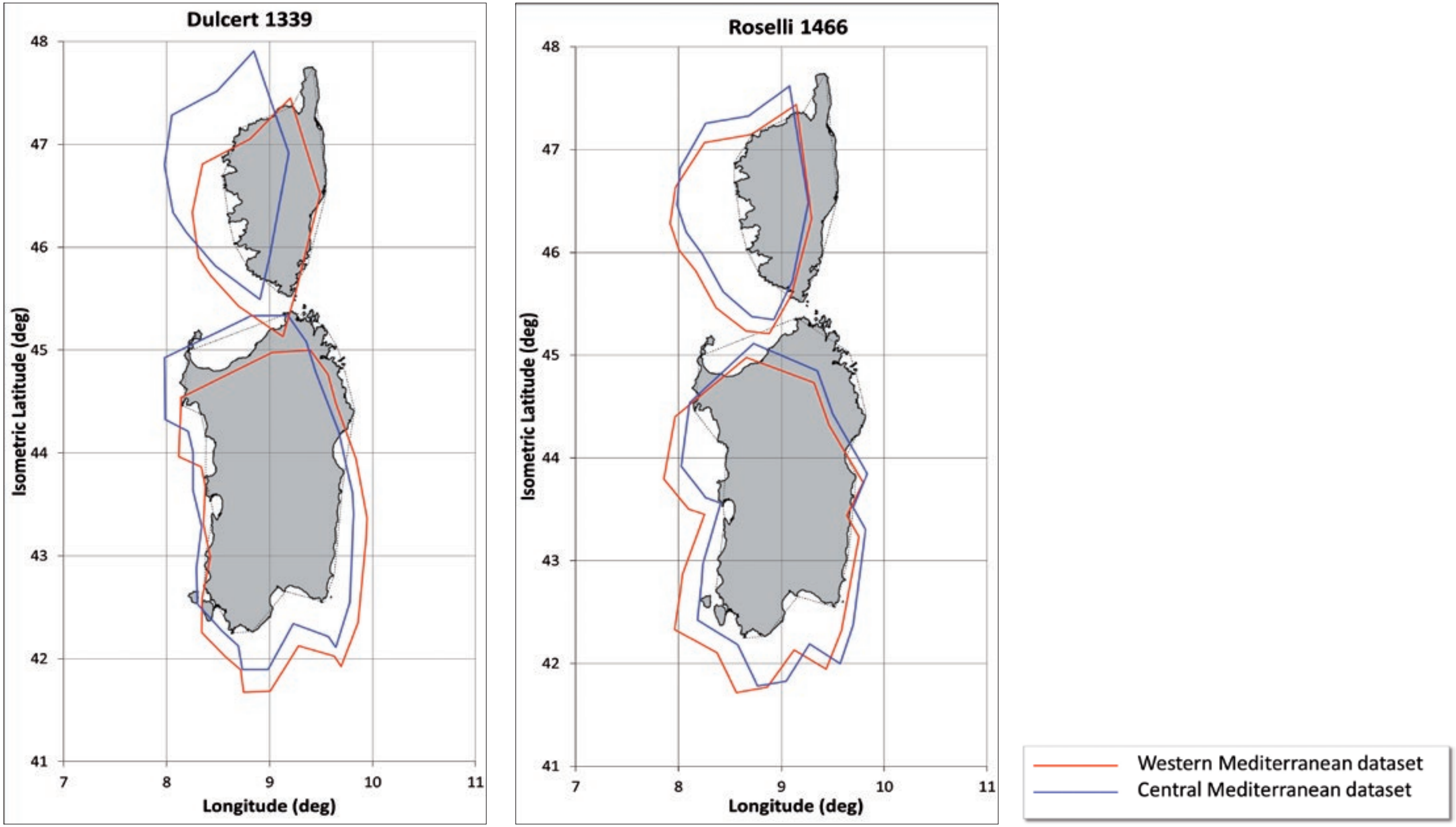

Figure 7.14 *- Location of Sardinia and Corsica in the Western and Central Mediterranean datasets on the Dulcert 1339 and Roselli 1466 charts.*

of the sub-charts in a single effort, but the result is an artificial, convoluted projection that was calculated to be sub-optimal by Loomer.[524] However, as mentioned in Section 6.3.2, Loomer's conclusion does raise a question. I applied Duken's projection to the Mediterranean and Black Sea sections of the Dulcert 1339 chart, in which the projection centre on the southern hemisphere was not derived by reasoning, as Duken did, but was resolved and thus optimised in the Least Squares process. As with the evaluation of the other two map projections a shear angle and scale difference along the portolan chart X and Y-axes were also resolved. The resulting accuracy, expressed with the same parameter in Section 7.6.2 above, is 17% *better* than the Mercator projection, but only when evaluating the chart as a single entity. The difference with Loomer's study may be caused by Loomer using Duken's empirically determined – and thus sub-optimal – projection centre. Nevertheless the Oblique Stereographic projection fits more than twice as poorly as the piece-wise fit to either the Mercator of the Equidistant Cylindrical projection.[525] No further efforts have therefore been devoted to this projection.

B. MERCATOR VERSUS EQUIDISTANT CYLINDRICAL PROJECTION

The best fitting map projection will yield the smallest value for the Root Mean Squared Error of the (sub-)chart, the parameter RMSE_{map}. The parameter used to express the accuracy of the sub-charts, the largest of the RMSE values for latitude and longitude, can therefore *not* be used to answer the question which of the two map projections evaluated is the best fitting one, as the degree-of-fit in *both* directions, X and Y (or latitude and longitude), has to be taken into account. The respective values for the RMSE_{map} are recorded in Table 7.7 and Table 7.8. The units of this parameter are the internal GIS units for the chart and are meaningless for comparing different charts, as the units are different for each chart. The only option is to compare the result of a particular sub-chart for the Mercator projection with the corresponding result for the Equidistant Cylindrical projection. For seventeen sub-charts the Mercator projection yields a better fit, eleven times the Equidistant Cylindrical fits better and in one case the results are identical. In nearly all cases the differences are small, as the two projections can hardly be distinguished from one another in an area with such limited latitude extent as the Mediterranean sub-basins. It is perhaps better to say that the Mercator projection can be approximated well by an Equidistant Cylindrical projection. The smaller the latitude extent of the area, the closer the resemblance of two map projections will be. Imagine two maps of any of the sub-basins to be drawn, one on a Mercator projection, the other on an Equidistant Cylindrical projection best-approximating the Mercator projection. If the scales were manipulated so, that northern and southern shores of the

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[524] Loomer 1987, 133.

[525] RMSE_{map} = 27.3 for the Oblique Stereographic projection, whereas the corresponding value for the Mercator projection equals 32.9. However, for the piecewise fit the RMSE_{map} for the Western Mediterranean equals 12.8. As the reader may see from Table 7.7 this value for the Western Mediterranean is representative for the entire population of sub-charts and the Oblique Stereographic projection is therefore sub-optimal.

two maps would approximately coincide, then the difference would only be found in the different way latitude would be mapped, logarithmically for the Mercator, linearly for the Equidistant Cylindrical projection. The maximum difference in latitude mapping between two maps occurs somewhere in the middle, at the true-to-scale parallel of the best-approximating Equidistant Cylindrical projection for each of the areas identified in the cartometric analysis.

Area	True-to-scale parallel of Equidistant Cylindrical	Maximum difference
Atlantic coasts north	47.38°	21.9 km
Atlantic coasts south	36.55°	48.7 km
Western Mediterranean	39.95°	22.6 km
Central Mediterranean	40.67°	22.2 km
Eastern Mediterranean	36.32°	21.0 km
Aegean Sea	38.31°	7.4 km
Black Sea and Sea of Marmara	43.58°	11.5 km

Table 7.11 *- Maximum differences between the Mercator and Equidistant Cylindrical projections.*

The figures in Table 7.11 provide an insight into the degree to which the two projections can be distinguished. Figure 7.15 illustrates this graphically for the Western Mediterranean. The greatest latitude extent of all identified sub-charts is found in the *Atlantic coast south* dataset, which covers the Atlantic coast from Galicia in north-west Spain to Cap Drâa in Morocco. With the exception of the Black Sea and Aegean Sea the remainder of the maximum differences shown in column 3 of Table 7.11 is larger than the estimated accuracy of the charts, but there are not many identical points in the middle, compared to the number of points along the northern and southern coastlines, which makes distinction of the two map projections extremely difficult. For any Equidistant Cylindrical projection with a different true-to scale parallel than the one that was computed in the cartometric analysis the differences will be greater. It is therefore not enough to conclude that a section of a portolan chart agrees best with the Equidistant Cylindrical projection; it is necessary to know what its true-to-scale parallel is.

As long as the map projection is considered to be an *apparent* by-product of a simple method of map construction (plane charting) the question which of the two, the Mercator or the Equidistant Cylindrical projection, fits best to the sub-charts of which a portolan charts is composed, is meaningless. The best-fitting projection type differs by sub-chart and nothing more is required to be known. However, when the possibility is considered that the map projection is an *intentional* aspect of the sub-charts, further evaluation is required. Admittedly this question will be addressed only in Chapter 9: *The map projection; artificial or intentional?* but some useful information, required for that evaluation can be extracted from the current cartometric analysis.

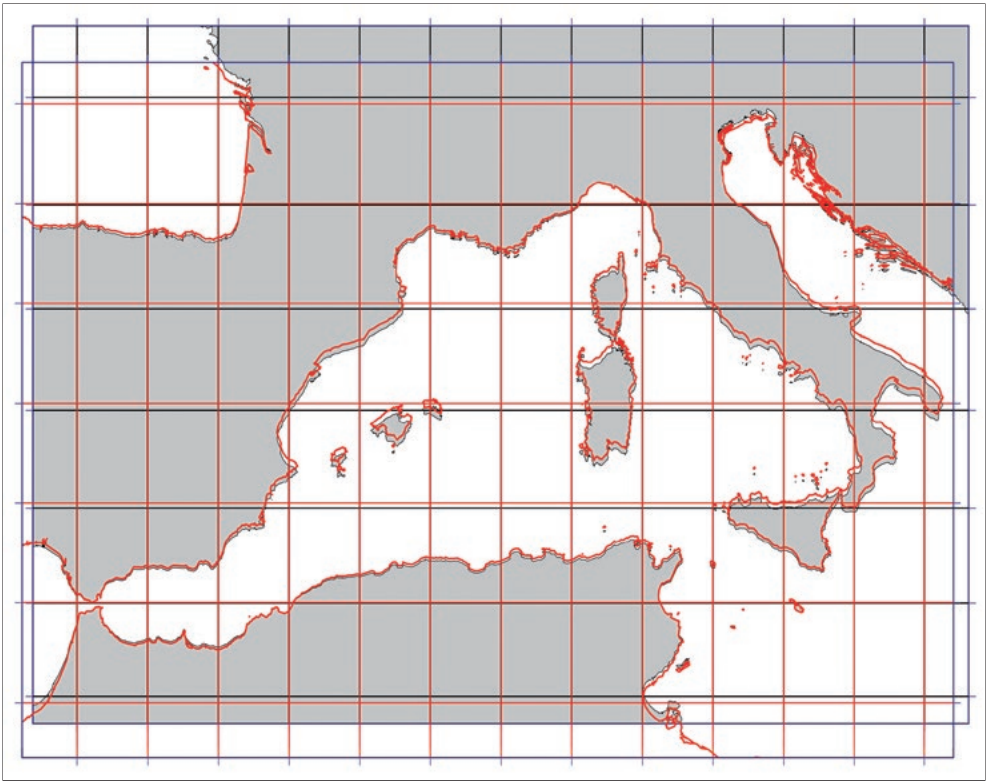

Figure 7.15 *- Illustration of the similarity between the Mercator projection (black grid; grey land masses) and the best-approximating Equidistant Cylindrical projection (red overlay). The Equidistant Cylindrical projection shows almost coincident coastlines of North Africa and Liguria. The difference between the two projections is exclusively in north-south direction and maximises at 39° 57' N (just north of Majorca).*

In the Equidistant Cylindrical projection the true-to-scale parallel determines the aspect ratio of a 1°x 1° graticule rectangle. This ratio is equal to the cosine of the latitude of this parallel. Marinus of Tyre chose the parallel of Rhodes of 36°N as the true-to-scale parallel, which yields an aspect ratio of 0.8. In the Mercator projection the aspect ratio of a 1°x 1° rectangle in the graticule varies with latitude and is entirely determined by the projection formulas. If the value on an actual chart is found to be 0.76 instead of 0.8, one might conclude a north-south scale that is 5% larger than Marinus' chart or map. The map will indeed appear to be stretched in north-south direction compared to the Marinus map. However, this can only be concluded if one knows in advance that the mapmaker used the 36° N parallel as the true-to-scale parallel. If one doesn't know that, the only conclusion possible is, that the true-to-scale parallel is 40° 32' 09" N, i.e. the parallel of which the cosine equals 0.76. The latter is the situation with portolan charts. This means that in the Equidistant Cylindrical projection only the scale factor along the X-axis *and* the latitude of the true-to-scale parallel can be resolved, but *not* a second scale factor along the Y-axis. However, for the Mercator projection separate scale factors are computed for the X-axis and the Y-axes, but no latitude of the true-to-scale parallel. The differential scale parameter Δscale_{X_Y} therefore only appears in column 6 of Table 7.7 (Mercator projection) and not in Table 7.8, which shows the results for the Equidistant Cylindrical projection. Table 7.8 shows instead the scale factor along the X-axis and the latitude of the true-to-scale parallel, labelled φ_0.

Area	Carte Pisane	Ricc 3827	RS-3	Dulcert 1339	Roselli 1466	Mercator approx.
Atlantic coasts N		46.6°		48.6°	47.3°	**47.4°**
Atlantic coasts S		35.2°		37.8°	37.8°	**36.6°**
Western Med.	41.1°	39.5°	40.2°	40.0°	39.9°	**40.0°**
Central Med.	42.3°	39.2°	39.9°	39.9°	40.8°	**40.7°**
Eastern Med.	39.0°	36.6°	36.3°	36.2°	36.5°	**36.3°**
Aegean Sea	39.0°	37.9°	39.1°	38.2°	40.1°	**38.3°**
Black Sea		43.2°	43.1°	43.3°	43.5°	**43.6°**

Table 7.12 *- Latitudes North of true-to-scale parallels of the Equidistant Cylindrical projection that best approximate a Mercator projection in each region listed (bold font) and the true-to-scale parallels computed in the cartometric analysis of the five charts. These values correspond with the values in the column labelled* φ_0 *in Table 7.8.*

Table 7.12 shows the latitudes of the true-to-scale parallel calculated per region, corresponding with the sub-charts identified and in the last column it shows the latitude of the true-to-scale parallel of the Equidistant Cylindrical projection that yields the best approximation of the Mercator projection for that section of the chart. In itself this table shows nothing new. The results in Table 7.7 and Table 7.8 already demonstrated that the two projections cannot be distinguished well enough and that is repeated and emphasized by the information in Table 7.12. The latitude values of the true-to-scale parallel correspond well with the optimum values, calculated to achieve a best fit with the Mercator projection, except perhaps for the central and Eastern Mediterranean datasets of the Carte Pisane.

If the map projection is an unintentional by-product of a simple construction method, the information in Table 7.12 is irrelevant. However, it is not irrelevant if the map projection is *not* an accidental by-product but was an intentionally applied element of the chart's construction. From the results in Table 7.7 and Table 7.8 it cannot be concluded whether the Mercator projection is the more likely of the two or the Equidistant Cylindrical. However, another clue may be provided by splitting the datasets in a northern and a southern section. If the appropriate map projection is the Equidistant Cylindrical, than the creation of two halves should have no effect on the true-to-scale parallel of each half, apart from some variation caused by the random properties of each half-dataset. If, on the other hand portolan charts exhibit more the characteristics of the Mercator map projection, the southern half, when evaluated for the Equidistant Cylindrical projection, would have a more southerly true-to-scale parallel than that for the entire sub-chart and the northern half would have a more northerly true-to-scale parallel than the entire dataset would have. This exercise was only executed for the Western, Central and Eastern Mediterranean and for the Black Sea (when available on the chart), because:

- For smaller datasets the two projections are less distinctive and the results are more likely to be dominated by random errors;
- The Atlantic datasets lack an even distribution of points both in latitude and in longitude, which would increase the risk of contaminating the results with computational artefacts.

The dividing parallels I used were the following.

- Western Mediterranean:	41°N
- Central Mediterranean:	41°N
- Eastern Mediterranean:	35°N
- Black Sea:	43°N

The resulting true-to-scale parallels of the Equidistant Cylindrical projection fit are shown in Table 7.13.

Columns 2 and 3 of Table 7.13 show the RMSE_{map} for each sub-area per chart and are intended as an *aide memoire*; these values are repeated from Table 7.7 and Table 7.8 and indicate which of the two projections yielded a better fit. Columns 4 and 5 are the actual calculation results of the true-to-scale parallels of the northern and southern subsets and columns 6 and 7 provide the approximate mid-latitudes of the data subsets for reference; they list the expected values of the true-to-scale parallels for an 'ideal' dataset.

Some unexpected results appear in Table 7.13; the Black Sea areas in the Ricc 3827 and RS-3 charts are anomalous in that the true-to-scale parallel of the southern half of each dataset is more northerly than the corresponding parallel for the northern half. This would imply that the parallels in the southern part of the Black Sea on those two maps have a greater spacing that the parallels of the northern halves. This quite conceivable, but it is surprising that in both cases the entire Black Sea shows a marginally better fit to the Mercator projection than to the Equidistant Cylindrical. I cannot explain this.

A similar effect is shown for the Western Mediterranean dataset of the Dulcert 1339 chart and the Eastern Mediterranean dataset of the Roselli 1466 chart, except that for the Dulcert chart the Equidistant Cylindrical projection emerges as the better fit and in the case of the Roselli chart both projections provide the same result.

	RMSE$_{map}$ (map units)		True-to-scale parallel		Approximate mid latitude	
	Mercator	Equirect	South	North	South	North
Carte Pisane						
West	40.8	41.2	36.2°	42.5°	38.0°	42.0°
Central	34.6	37.5	34.1°	47.3°	38.5°	43.3°
East	36.2	38.3	34.3°	39.4°	33.0°	38.0°
Ricc 3827						
West	14.8	14.5	41.4°	42.0°	38.0°	42.0°
Central	17.1	18.5	37.2°	44.9°	38.5°	43.3°
East	22.5	24.3	29.1°	40.0°	33.0°	38.0°
Black Sea	16.2	16.5	**39.5°**	**37.9°**	41.5°	45.0°
RS-3						
West	22.5	22.3	36.8°	41.5°	38.0°	42.0°
Central	20.7	23.2	36.4°	45.7°	38.5°	43.3°
East	26.6	25.9	34.2°	37.1°	33.0°	38.0°
Black Sea	23.5	24.7	**37.6°**	**34.9°**	41.5°	45.0°
Dulcert 1339						
West	12.8	12.3	**41.6°**	**39.0°**	38.0°	42.0°
Central	14.9	16.0	36.6°	43.1°	38.5°	43.3°
East	15.7	16.2	34.7°	37.7°	33.0°	38.0°
Black Sea	16.0	16.3	38.4°	41.1°	41.5°	45.0°
Roselli 1466						
West	45.5	45.5	39.9°	41.7°	38.0°	42.0°
Central	40.5	41.6	38.7°	48.3°	38.5°	43.3°
East	52.2	52.2	**36.6°**	**35.7°**	33.0°	38.0°
Black Sea	54.0	58.9	36.9°	41.1°	41.5°	45.0°

Table 7.13 - *True-to-scale parallels for northern and southern halves of the sub-areas.*

For the more 'well-behaved' datasets the true-to-scale parallel of the northern half is indeed more northerly than that of the southern half of each dataset, which is a characteristic to be expected of the Mercator projection but not of the Equidistant Cylindrical projection. However, whether this is the result of pure chance (i.e. the random errors in the identical points) or is indeed an indication of the Mercator projection is impossible to say with certainty.

In conclusion it may be said that, although portolan charts exhibit to a greater extent the characteristics of the Mercator projection than of the Equidistant Cylindrical projection, it is impossible to draw an unequivocal conclusion as to which of two the possibly underlying projection is. The qualification 'possibly' is used in the previous sentence because it has not been established yet whether the map projection should be treated as an artificial or as an intentional cartographic element.

7.6.6 ANTICLOCKWISE ROTATIONS AND SHEAR ANGLES

The anticlockwise rotation that most early Mediterranean portolan charts exhibit – only from about 1600 onwards were portolan charts 'de-skewed' – has been well known for as long as the charts have been studied. The values computed in the cartometric analysis of this study have been corrected for the misalignment of the wind-roses for each chart, as documented in Sections 7.1 to 7.5 above. The shear angles computed from the wind roses have *not* been applied as corrections to the cartometric analysis results as shown in Table 7.7 and Table 7.8, only the misalignment angles of the wind roses. The shear angle is the difference in rotation between the calculated rotations of the (implicit) parallels and meridians.

Rotation angles are negative if the rotation of the parallels or meridians is anticlockwise. Rotation of the parallels is indicated with respect to the internal X-axis ('portolan chart east'); rotations of the meridians with respect to the internal Y-axis ('portolan chart north'). The values of the angles are shown in Table 7.7 and Table 7.8 as the parameters θ_X and θ_Y for the two map projections that have been evaluated.

Shear is the difference between the rotations about the X-axis and Y-axis. It is a *positive* angle if the implicit parallels and meridians pointing east and north respectively span an angle *smaller* than 90°.

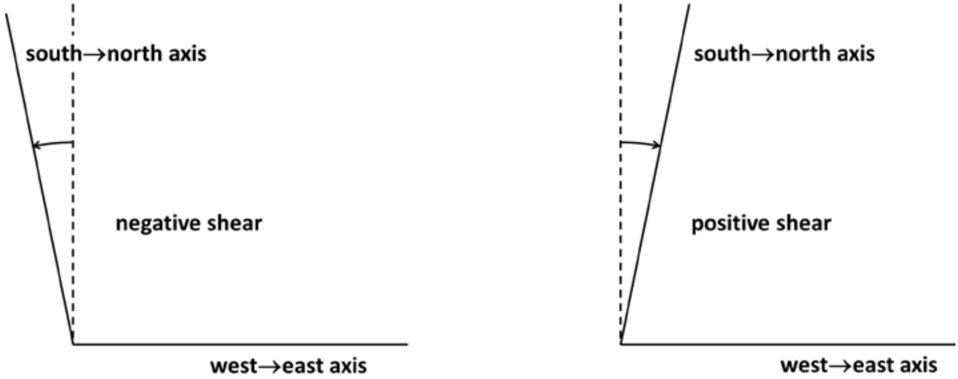

Figure 7.16 - *Positive and negative shear angle.*

These angles may be studied in two main ways. One may look at:

1. The rotation angles and their difference (shear) of the various sub-charts within a single portolan chart;
2. The development of the rotation angles and shear angles of the same sub-charts across the five portolan charts.

In previous cartometric analysis projects the only angle analysed was the total rotation angle, often expressed as the deviation from the parallel of 36° N, which runs approximately through Gibraltar and Antioch. This yielded remarkably stable results.[526] However, considerable variations exist between the rotation angles of the three main component charts of the Western, Central and Eastern Mediterranean (see notably Table 7.7). With the variations in the rotations of the sub-charts that have come to light in this thesis, the question arises how the total angle, measured from Gibraltar to Antioch, can be so constant. The variation in the angles of sub-charts demonstrates that chartmakers allowed the relative positions of the sub-charts to vary. They may have considered the total dimension and orientation of the Mediterranean's longitudinal axis as a given, which might explain why the line Gibraltar-Antioch shows such a constant orientation.

Figure 7.17 shows the mean rotation angles (i.e. mean of X-axis and Y-axis rotation angles) of the sub-charts of each of the five portolan charts analysed. It can be seen clearly that the Carte Pisane is anomalous, compared with the other four charts, particularly in the rotation angle of the Aegean Sea. Interesting and clearly visible in the graph is the extra rotation of −2° of the Black Sea on the Roselli 1466 chart.

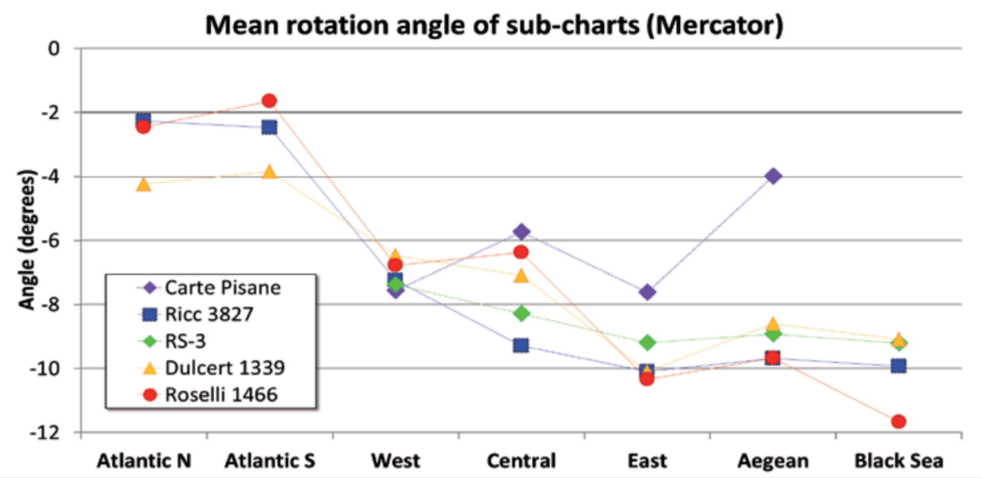

Figure 7.17 *- Mean rotation angle of the sub-charts of each portolan chart.*

A more puzzling aspect is the shear which exists in the various sub-charts and which is not constant for the same sub-chart over the five portolan charts analysed. If all the

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[526] Pelham provides the rotation angle of 28 charts (mean = -9.8°; standard deviation = 0.6°)
Lanman lists 19 charts (mean = -8.3°; standard deviation = 1.1°);
Loomer calculates the rotation angle from his more extensive cartometric analysis of 27 charts (mean = -9.8°; standard deviation = 0.5°).
The differences in the mean values are probably caused by the use of different reference points. For example, Lanman calculates for the Dulcert 1339 chart -8.8°, Loomer -9.8° and Pelham -10.5°). See Pelham 1980, 83; Lanman 1987, 25; Loomer 1987, 148.

chartmaker did was rearranging the sub-charts in a way he may have believed to be an improvement, then the shear should remain constant. It seems likely that variations in shear angle are computational artefacts caused by the copying process from old chart to new chart. This implies that the copying process of portolan charts, which is as yet not understood, may have taken place by copying one discrete section of coastline at a time. A slight misplacement of such sections would immediately show up as shear in the calculation executed in this study. For instance, an east-west shift of 1 millimetre on a 1 : 5.5 million scale portolan chart of the south Turkish coast relative to the Egyptian North coast would result in a shear angle of one degree. The variation in shear angles, calculated for any sub-chart on the five portolan charts, therefore probably reflects the effects of progressive copying.

Figure 7.18 to Figure 7.24 show the rotation angles of the five portolan charts by sub-chart. The difference between two corresponding markers for any sub-chart is evidently the shear angle. Dotted lines have been added, connecting the markers of the same type, which makes it easier to spot similarities and dissimilarities between charts. However, the values represented by the markers are all unrelated. It is clear that the Carte Pisane and to a lesser extent the Ricc 3827 show more considerable variations in comparison with the other charts. This may indicate immaturity on account of their relatively early age. Variations between the later charts are generally smaller. On the Carte Pisane the Aegean Sea is rotated by some five to six degrees compared to other four charts, suggesting that a separate source chart was used. A significantly deviating value exists in the rotation of the parallels for the Atlantic coast south dataset in the Dulcert chart. However, it should be pointed out that this dataset has a very small east-west extent and consequently the direction of the parallels cannot be determined reliably. A slight displacement of parts of the coastline may result in a large difference in the value for the orientation of East direction (the parallels). The effect of relatively minor shifts of stretches of coast on shear has been discussed above. The same holds for the rotation angles of the axes in general (shear is of course a derivative of those angles). Variations in the order of 1 to 2 degrees should therefore be considered insignificant.

The larger the dataset, both in terms of number of points and in terms of latitude and longitude extent, the more reliable the calculation of axes orientations will be.

The two Atlantic datasets are especially vulnerable to such variations as identifiable points along the coasts only exist on one side. Nevertheless the variations of the rotation angle values does show that trial-and-error modifications in getting these outlines right had been applied well before Beccari made his claim on his 1403 chart. Nevertheless the shear angles in e.g. the Western Mediterranean and Black Sea sub-charts and even the large shear angle of the Central Mediterranean sub-chart are remarkably stable. This may either indicate a very early copying error or the existence of this shear angle in the original sub-charts used for composing complete portolan charts.

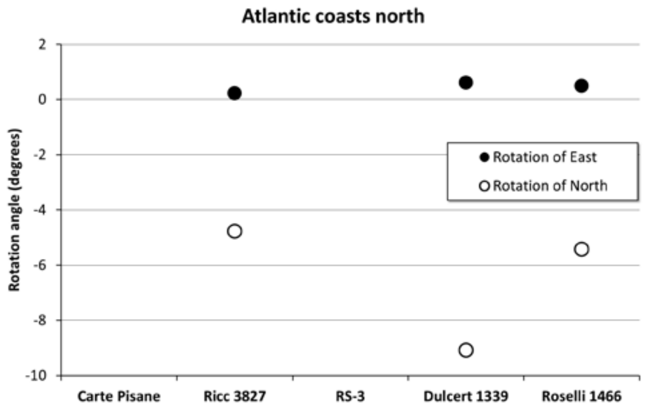

Figure 7.18 - *Changes in the rotation angles of the Atlantic coasts North sub-chart over the analysed portolan charts.*

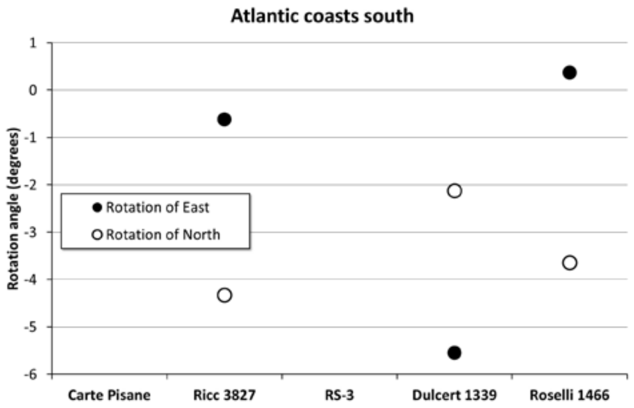

Figure 7.19 - *Changes in the rotation angles of the Atlantic coasts South sub-chart over the analysed portolan charts.*

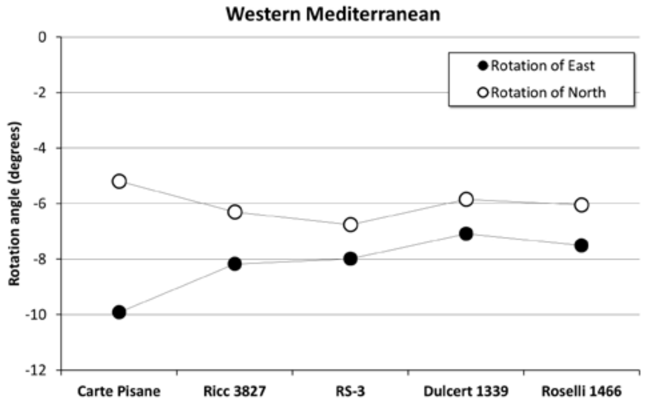

Figure 7.20 - *Changes in the rotation angles of the Western Mediterranean sub-chart over the analysed portolan charts.*

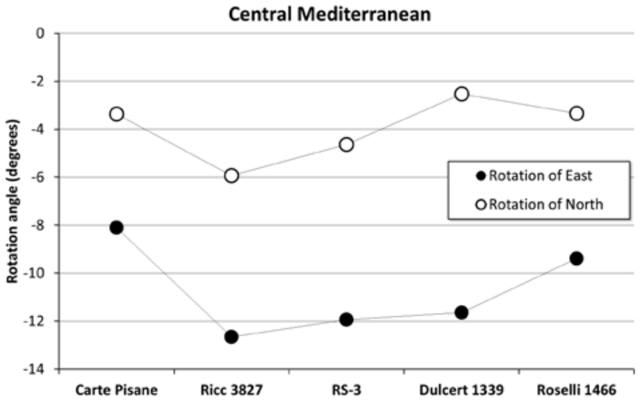

Figure 7.21 - *Changes in the rotation angles of the Central Mediterranean sub-chart over the analysed portolan charts.*

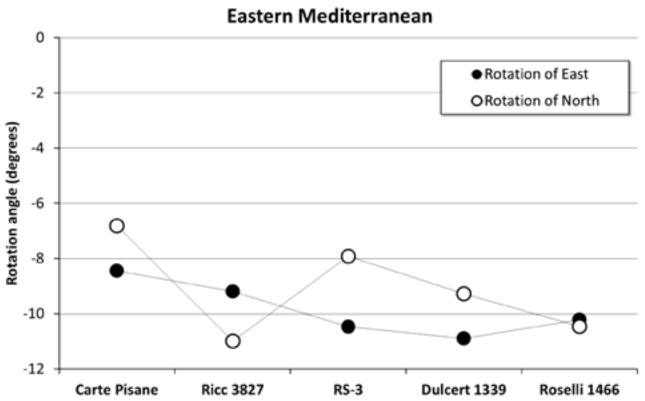

Figure 7.22 - *Changes in the rotation angles of the Eastern Mediterranean sub-chart over the analysed portolan charts.*

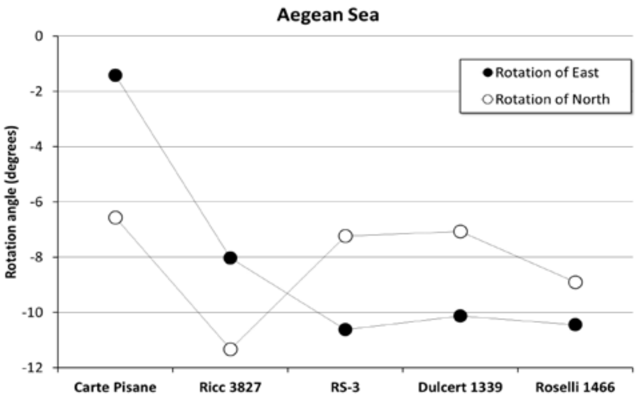

Figure 7.23 - *Changes in the rotation angles of the Aegean Sea sub-chart over the analysed portolan charts.*

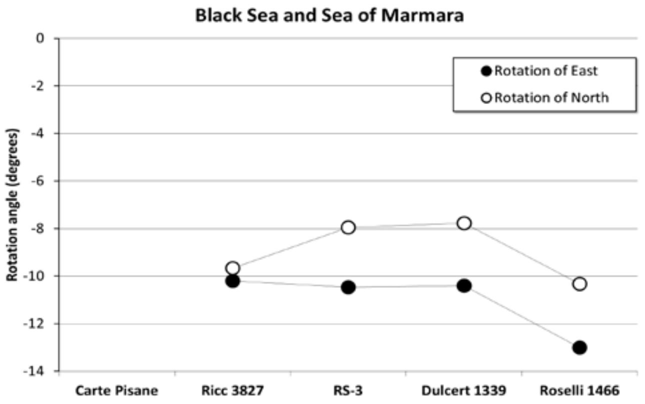

Figure 7.24 - *Changes in the rotation angles of the Black Sea sub-area over the analysed portolan charts.*

The (very) large shear angle of the Central Mediterranean sub-chart is not caused by the inclusion of Italian and Tunisian data points in the extreme south-west of the sub-chart, but by the Adriatic coastlines. It appears as if the Dalmatian and Italian coastlines are shifted lengthwise relative to one another, i.e. in the main direction of the Adriatic Sea.

7.6.7 SCALE

The scale differences between the sub-charts are well-known, but not well-understood. Kretschmer's view, from the beginning of the twentieth century, that these differences indicate the use of different length measures in the various sub-basins has largely been abandoned. However, no convincing alternative explanation has been presented yet for this chart characteristic. The consensus view, that portolan charts are composites of smaller charts of sub-basins of the Mediterranean, is borne out to some extent by the current cartometric analysis, be it that significant overlaps between those charts appear to have existed, which appear to have been used to compose the complete portolan chart by overlaying common sections of coastline. The presence of shear angles in the original charts would have made this a complicated process, for which no canonical solution would have existed. This may account for some of the variation that exists between charts.

Another complicating factor would have been the presence of partial maps or charts at different scales. It may be evident to a modern researcher that the sub-charts of portolan charts had different scales, the medieval chartmaker would almost certainly not have been aware of these different scales, but even if he would, he had no means of confirming and even less so of quantifying any scale differences between the component charts.

The calculation of scale data from the five portolan charts may be divided into two categories. The first is a scale mismatch in portolan chart north and east directions per sub-chart. As explained above, this can only be calculated for the Mercator projection, because that projection prescribes a fixed relationship between latitude and longitude scales. For the Equidistant Cylindrical projection a stretch in north-south direction has the same effect as choosing the true-to-scale parallel at higher latitude; both cause the aspect ratio of a 1°x 1° rectangle from the graticule to reduce. The mean scale for the relevant sub-chart has been calculated as the geometric mean of the scales in the two main chart directions:

$$\text{mean scale} = \sqrt{(\text{scale}_X \bullet \text{scale}_Y)}$$

The mean scale for any given sub-chart is still a meaningless figure. It is only useful in comparison with the mean scales of other sub-charts. The Western Mediterranean mean scale has been chosen as the reference for comparison, because in all charts investigated the Western Mediterranean is a good quality dataset with very few rejected points, when compared with the Eastern Mediterranean, which would have been one alternative, and the number of points and coverage area are larger than the Black Sea, which would have been a third option. Compared with both alternatives, the Western Mediterranean is expected to yield a more stable 'baseline value'. The mean scale of each sub-chart in any of the five portolan charts is thus expressed as a percentage of the scale of the Western Mediterranean sub-chart on that portolan chart. This relative scale of each sub-chart is listed in Table 7.7 and Table 7.8 under the heading 'Mean relative scale'. A sub-chart with a relative scale greater than 100% will show a geographical feature larger than in the Western Mediterranean sub-chart.

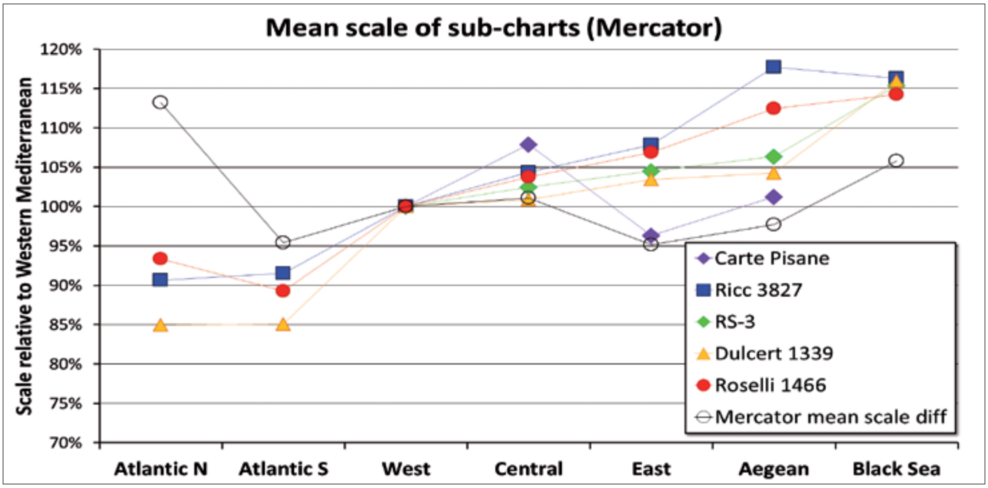

Figure 7.25 - Mean scale per sub-chart relative to the Western Mediterranean sub-chart (calculated for the Mercator projection).

Figure 7.25 shows the relative scales of the sub-charts for each portolan chart, i.e. relative to the scale of the Western Mediterranean, which therefore has the value of 100% for each chart. In addition the theoretical mean Mercator scale for each sub-chart, which is a function of the mean latitude of the coverage area, is shown. Dotted lines have been added, connecting the markers of the same portolan chart to enable easy identification of the results of a single portolan charts. However, the values represented by the markers are all unrelated.

The graph shows differences per portolan chart, confirming that each portolan chart was not an exact copy of a predecessor. With the exception of the relative scale of the Black Sea, which does not appear to have changed at all over time relative to the Western Mediterranean, variation is visible in the Mediterranean and Atlantic areas. Also in the relative scales the Carte Pisane reveals itself as deviating from the rest, which is probably due to its immaturity as an 'agreed' cartographic product. The Atlantic coasts also show in this graph as not matching with the rest of the portolan chart, which is not a new conclusion. The Aegean Sea also shows quite some variation, but this covers a relatively small area in which a modest shift of a piece of charted coastline would have equated to a relatively large scale change.

The question may arise, whether these scale differences by sub-chart are caused because all stem from a single source chart on the Mercator projection. For that reason the theoretical scale differences of the sub-charts' coverage areas, relative to the Western Mediterranean, are shown, as derived from single Mercator chart. The assumption of a single Mercator source chart would explain only half of the scale of the Black Sea in relation to the Western Mediterranean and the scale of the Eastern Mediterranean and Aegean Sea ought to be smaller than the scale of the Western Mediterranean, instead of larger. Interesting though that idea may be, it must therefore be rejected.

A relevant common feature of four of the five studied charts – the Carte Pisane is the outlier – is the increasing scale from west to east for the Mediterranean areas and the Black Sea. This stepwise increasing scale enabled Duken to formulate a map projection that approximates this pattern as a continuous increase. The increasing scale from west to east does not appear to have been resolved over time. The Ricc 3827 chart shows an improvement over the Carte Pisane and the Ristow-Skelton No 3 is more homogeneous in scale again, while the Dulcert 1339 has the least inhomogeneity in its scales. However, the Roselli 1466 chart shows a marked increase of scale differences between sub-charts.

This leads to the conclusion that chartmakers made, what appears to be, ad hoc changes in the relative positions, scales and orientations of the sub-charts in, what may be presumed, attempts to increase the quality of the entire portolan chart.

7.6.8 Conjectural coverage of source charts (or maps)

Despite the many differences in the apparent composition of the five portolan charts, a tentative estimate may be made of the coverage areas of the source maps or charts. It is impossible to state anything with certainty about those coverage areas, as it is not known what parts of the source charts the cartographer used or what criteria he applied for considering one source chart more reliable than another.

1. The European Atlantic coast from the north Iberian coast up to and including the south coast of England. Ireland is clearly not included.
2. The Portuguese, south-west Spanish and African Atlantic coasts down to approximately Cape Drâa. The western part of the Alboran Sea may have been visible on this chart.
3. The Alboran Sea may have been a separate chart or may have featured on both the Western Mediterranean chart and the Portuguese – North African Atlantic chart.
4. The Western Mediterranean up to the Sicilian Channel and including the Cap Bon peninsula in Tunisia and possibly (part of) the Gulf of Gabes.

5. The Central Mediterranean, covering the Adriatic and Ionian Seas up to Cape Akritas in Greece and the eastern part of the Western Mediterranean, including Corsica, Sardinia, Sicily, the Italian Ligurian and Tyrrhenian coasts and part of the Tunisian-Algerian coast. The Libyan coast appears not to have featured on this map or chart or was ignored by all cartographers.
6. The Eastern Mediterranean, possibly without the Aegean Sea but possibly with part of the Adriatic Sea and part of the Western Mediterranean, up to at least 100 km west of Algiers. It is questionable how much of Corsica and Sardinia would have been visible.
7. The Aegean Sea and the Dardanelles up to the Sea of Marmara.
8. The Black Sea and the Sea of Marmara.

7.6.9 The length of the portolan mile[527]

Portolan charts are the first known maps to contain scale bars. These scale bars show the application of what appears to be a cartographic convention in portolan charts. Only the very first deviate from the later style; both styles are described in Chapter 2.2. The availability of these scale bars allows estimates to be computed of the length of the portolan mile, the length unit used in portolans and apparently in the charts too. Campbell states that the length of the portolan mile has been estimated to be around 1.25 km by various authors, but that the matter is far from settled.[528]

Any estimate extracted from the portolan charts will be inherently inaccurate, although it may be calculated very precisely. The inaccuracy is caused in the first place by the scale variations in the charts, which show a relative range of as much as 25–30% (see Figure 7.25) but also because of assumptions that need to be made to what latitude the scale bars apply. After all, the actual scale varies with latitude, both on a Mercator chart and on a chart on an Equidistant Cylindrical projection. Over the full range of latitudes from Alexandria to the Sea of Azov this makes a difference of 26%. It seems prudent to exclude the Atlantic coast areas from any analysis, as these areas are clear outliers.

The typical portolan chart scale bar looks like a ladder, of which the rungs are separated by fifty miles. This larger *spatium* is subdivided into five smaller *spatia* of each ten miles by means of four equally spaced dots. The only exception in the investigated charts is the Carte Pisane, in which the smallest spatium does not equal ten miles but five.

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[527] The term *portolan mile* acquired a specific meaning after Nordenskiöld's work. Nordenskiöld believed the basic unit of the portolan chart to be the *portolan mile*, equal to five *spatia* on the scale bar of the charts. That enabled him to link this unit to the Spanish *legua*, supporting his idea of a Catalan origin of the charts. His idea has not found many followers and the *Compasso de Navegare* actually proves his idea to be wrong, where it specifically speaks of *millaria* (miles). It is this *millarium* (of around 1230 m) that I have referred to as *portolan mile* in this thesis, in line with what has become customary after Nordenskiöld.

[528] Campbell 1987, 389.

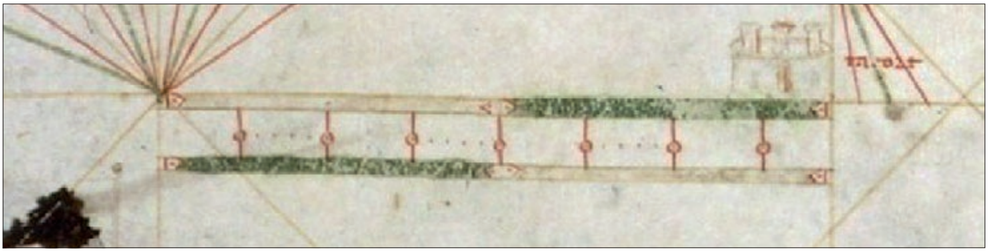

Figure 7.26 - *Scale bar on the Dulcert 1339 chart.*

I have interpreted the length of the scale bars on the five charts to apply to the latitude of 39°57' N, which is the latitude in the Western Mediterranean for which the Mercator projection is best approximated by an Equidistant Cylindrical projection. This may be seen as the optimum *mid-latitude* for the Western Mediterranean. I furthermore corrected the measured lengths of the scale bars that are parallel to the portolan chart's X-axis by the appropriate scale correction derived from the analysis of the chart's wind rose(s).

This resulted in the following comparison of mile lengths deduced from the available scale bars, as shown in Figure 7.27. The colours of the bars indicate the chart from which they originate; the text on the left indicates the scale bar from which each value has been derived. The terms *top left* (TL) and others have to be interpreted with the chart facing north-up.

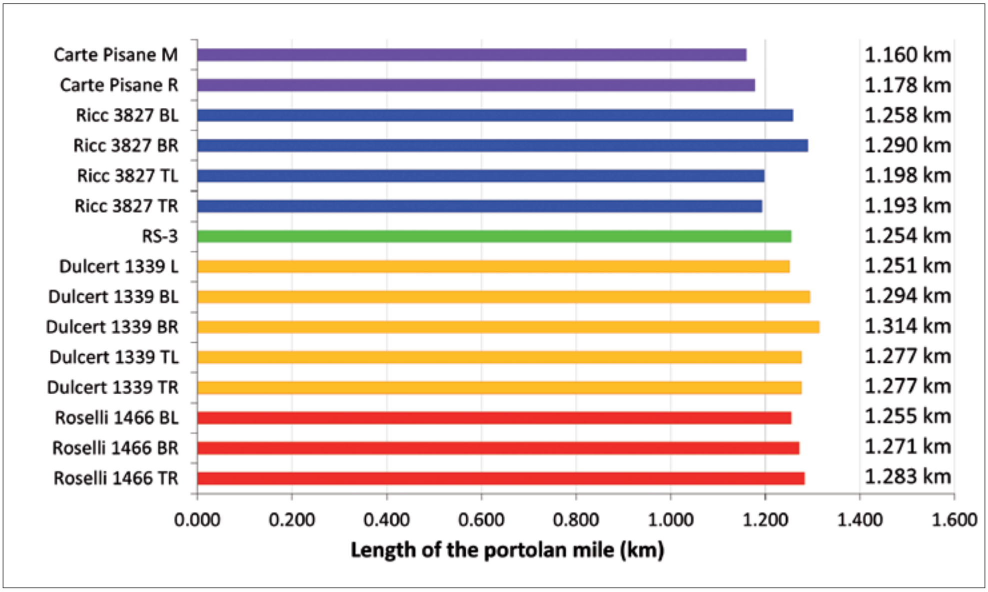

Figure 7.27 - *Length of 'portolan mile' standardised for latitude 39° 57' N (the numbers on the right are the lengths of the relevant portolan mile in km; 'BR' means Bottom-Right, 'TL'= Top-Left, etc.).*

Two observations should be made:

- The varying length of the scale bars in a single chart may be considered to be a measure of the care of the chartmaker, since it has been established in the wind rose analysis that the vellum of all five charts has not been significantly deformed.
- The variations in the average length of the portolan mile over the five charts are considerable.

The Carte Pisane clearly yields the shortest average portolan mile of 1160 m and the two scale bars do differ in length by 1.6%, which equates to half a millimetre over the approximately 3 cm long scale bars in the chart.

The Ricc 3827 chart shows considerably more variation. The two scale bars at the bottom of the chart are significantly longer than the two at the top, the largest variation being about 8%. The length of the scale bars, over which I took measurements, is nominally about 5 cm. The longest of them is about 4 mm longer than the shortest. This is large enough to have been noticeable to a medieval cartographer. The average mile length is 1235 m.

The Dulcert 1339 chart yields the longest mile value of all charts with 1314 m. The average mile length over all five scale bars is 1282 m. The longest and shortest scale bars differ by 5%, which, with a nominal length of each scale bar of about 6.5 cm, equates to 3.2 mm in the chart.

Petrus Roselli, on the other hand, drew 16 cm long scale bars on his 1466 chart. As a rule, scale bars become longer for the later charts. The difference in length between the longest and shortest scale bar is 3.6 mm.

The variations in three charts (Ricc 3827, Dulcert 1339 and Roselli 1466) between the longest and the shortest scale bars amounted to 3-4 mm, variations the draughtsman could easily have spotted and prevented.

The mean length of the portolan mile of these five charts computes ironically as 1250 m, or, if the Carte Pisane is excluded as an outlier, 1263 m. One might argue that the existing estimate, supplied by Campbell, is spot-on, but it shouldn't be forgotten that this value is valid for one specific latitude in the Western Mediterranean. A totally different value would emerge for the Eastern Mediterranean, the Black Sea etc. as a result of the scale differences in the sub-charts of these areas and the different latitudinal range of those areas. It can therefore not be concluded that this was the length the medieval cartographers used for the construction of their charts and less so that this was the length of the mile used by medieval seamen!

No correlation can be discerned between the length of the scale bars and their location on the charts. The variation in the scale bars is clearly not related to the scale differences of the sub charts.

In Chapter 2: *Key characteristics of portolan charts*, section 2.2.5, 'carelessness' was mentioned in connection with the drawing of some scale bars. Some authors even observed that scale bars appeared to have been drawn 'freehand'.[529] Ramon Pujades shows 44 scale bars[530] from as many charts, but only a few of them can be considered as having been drawn with lack of appropriate care. Most of them look as having been carefully drawn. The conclusion that remains is that the cartographers appear to have had only an imprecise idea of the scale of the charts. How the approximate scale was known in the first place is another matter. The medieval origin hypothesis postulates that this scale emerged because high-accuracy mean values of distances were used for the construction of portolan charts, but cannot then explain why any scale differences would exist in the charts. In Section 5.10 it has been demonstrated that the improvement of accuracy by means of calculation of the arithmetic mean of multiple observations of one distance was a technique that wasn't known and therefore cannot have been practiced in the Middle Ages. Further discussion on the origin of the scale of portolan charts will have to wait to Chapter 12: *Synthesis*, as the relationship between plane charting and the map projection has yet to be investigated.

7.7 How difficult is it to make an accurate map?

With modern software it is easy to correct a portolan chart for the characteristics resulting from the cartometric analysis and to produce a rectified chart on the Mercator projection. The result is shown in Figure 7.29 for the Dulcert 1339 chart.

Whereas the contrast between portolan charts and contemporary medieval maps, the *mappaemundi*, is evident at a glance, two characteristics stand out in the explanations that are usually provided for this remarkable difference; the accuracy of portolan charts is generally downplayed and the effort required to make accurate maps is underestimated.

The downplaying of the accuracy of portolan charts is for example expressed by qualifications of portolan charts as being *relatively* accurate (i.e. when compared against *mappaemundi*). H. Floris Cohen refers to the charts as follows: "… mariners drew Mediterranean coastlines as they saw them"[531] and Alfred Crosby is downright depreciative when he describes the charts as "geometrically naïve flat pictures of the curved surface of the earth"[532]. Neither author can be blamed for consciously writing untruths; neither of

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[529] Kretschmer 1909, 47, 48; Ferro 1996, 51; Nordenskiöld 1897, 21.
[530] Pujades 2007, 220, 221.
[531] Cohen 2010, 129.
[532] Crosby 1998, 97.

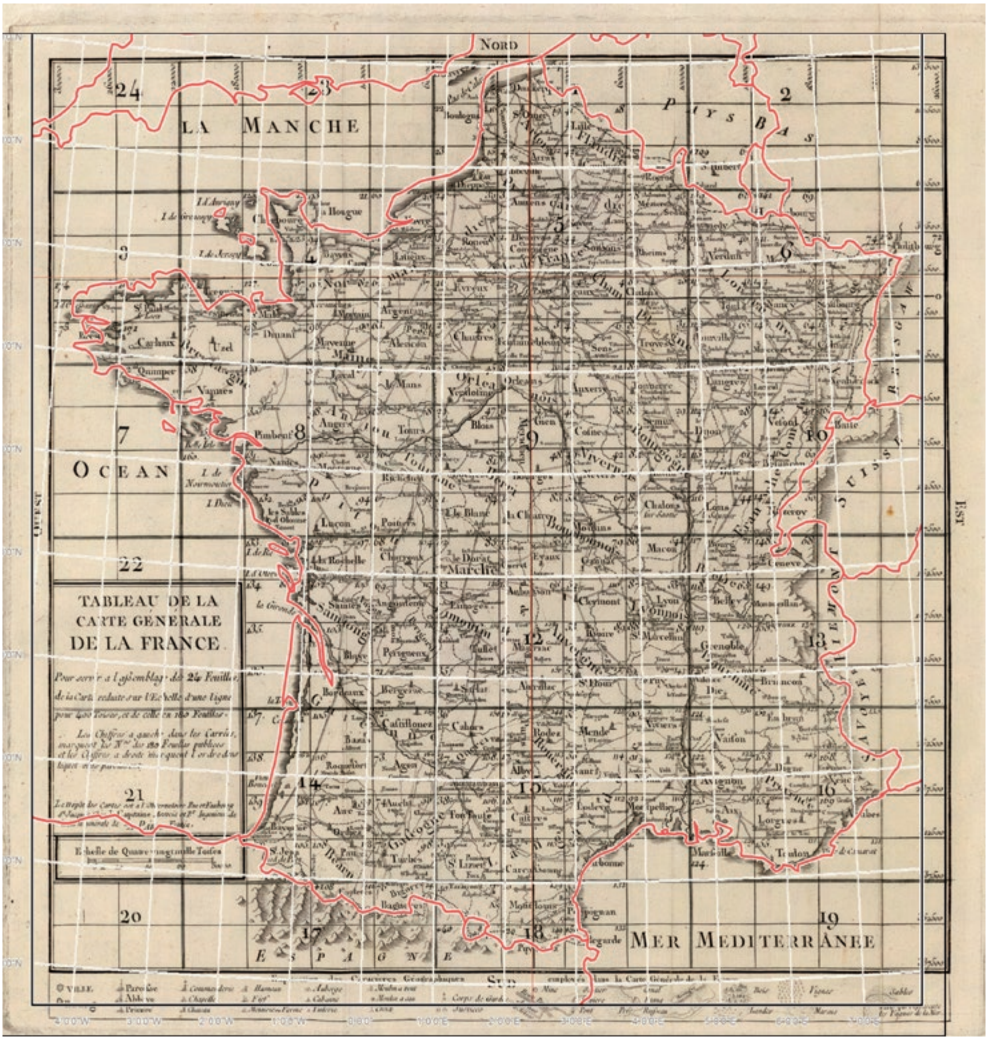

Figure 7.28 - *Index of the Cassini map of France (1747), superimposed by the modern outline of France.*

them is a map historian or geodesist and they have done no more than paraphrasing the established map-historical consensus on portolan charts. A description of the proper characteristics of these charts, as derived in the earlier chapters of this study, would have been utterly incongruent in the context of the development path of scientific inquiry described by each author.

In Section 3.1 I referred to "the implicit supposition that the making of an accurate chart of such a large area is not a particularly onerous task" in most portolan chart literature. This assumption is generally not made explicit; the only explicit statement I could readily find was Theobald Fischer's claim that "Once such portolanos, contain-

Figure 7.29 *- Piecewise rectified core coverage area of the Dulcert 1339 chart (coastlines traced in blue) and modern Mercator map (red outline).*

ing all courses and distances … had been worked out, it was no longer difficult to draw loxodromic charts."[533]

How easy or difficult the making of an accurate map of a large area is, is best illustrated with the famous Cassini map of France, the first map entirely based on a country-wide geodetic survey. The index map of the Cassini map series is shown in Figure 7.28 and dates from 1747. The map had been drawn using, what was at the time a revolutionary new approach to mapping: first establishing a countrywide framework consisting of a triangulation network and then filling in the topographical detail, i.e. the actual mapping of geographic features. Additionally numerous astronomically determined locations were included, of which the longitude differences had been measured using the Jupiter moon method, which had been proposed by Galileo. An enormous amount of manpower went into this enterprise and it took four generations of Cassinis and countless surveyors to complete the project. This was the pinnacle of scientific achievement of the first half of the eighteenth century. In Figure 7.28 the Cassini map has been overlaid with a modern map, drawn from the same dataset as used for the analysis of the five portolan charts in this study. The modern outline of the coasts has been projected using the Cassini projection, the projection on which the Cassini map was constructed. I determined the exact scale by using the grid values in the map in the unit of measure used by Cassini, the *toise*, and forced the maps to coincide at the location of the Paris observatory, the origin of the network and starting point of the mapping.

Closer inspection of the map and comparison with the modern outline shows errors in the Cassini map of 25 to 30 km. Errors not much larger are found in the portolan charts of almost five centuries earlier. This should not be read as a claim that portolan charts were as good as the Cassini map. The purpose of Figure 7.28 is to demonstrate that accurate mapmaking is *not* a trivially simple process.

7.8 CONCLUSIONS

9. *The vellum sheets on which the portolan charts have been drawn were found to have retained their original shapes very well.*

10. *Portolan charts are composites of smaller charts that have their own cartometric characteristics, such as scale and orientation. The division into coherent (first-level) sub-charts is reasonably consistent across the five investigated charts. The scale and orientation variations are statistically significant. Scale differences between sub-charts are about 25-30%, with the Atlantic coasts exhibiting the smallest scale and the Black Sea the largest. Orientations of sub-charts range on average from -7° to -11°, from the Western Mediterranean to the Black Sea, with the Atlantic coasts having a deviating rotation angle of -2° to -4°.*

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[533] Fischer 1886, 75; see also Section 2.2.8.

11. *In some cases, smaller entities, such as the Alboran Sea and the Aegean Sea may be identified. The scale and orientation differences between such a second-level sub-chart and the first level sub-chart are smaller than the differences between the first-level sub-charts.*

12. *Sub-charts appear to have been fitted together by matching overlapping stretches of coastline. This is notably evident in the Carte Pisane, the only chart in which a long stretch of Dalmatian coastline is shared by the Central and Eastern Mediterranean sub-chart and the only chart with a deviating orientation of the Adriatic Sea.*

13. *The joins between the sub-charts do not always coincide with the natural boundaries of sub-basins in the Mediterranean. Considerable overlaps may have existed between sub-charts. This is evident in the Carte Pisane (see conclusion 12) and in a stretch of Tunisian-Algerian coastline in the RS-3, Dulcert 1339 and Roselli 1466 charts that fits well both in the Western and the Eastern Mediterranean datasets of each chart.*

14. *The scale bars in the charts show variations of several percent, both within a single chart and between charts. These variations are five to ten times smaller than the scale variations in the map image within a single portolan chart and there is no correlation between the two. This appears to indicate that the cartographer was not entirely sure of the scale of the charts and the scale variations within them. It also indicates that the charts were not built up from the scale bars.*

15. *The accuracy of the sub-charts, generally 10-12 km (one sigma), is very high for medieval charts of the approximate portolan chart scale of 1 : 5,500,000.*

16. *The accuracy of the Carte Pisane sub-charts is consistently worse than of those in the other charts. Also the other characteristics of the chart, such as the orientation of the Adriatic and Aegean Sea differ clearly from the other charts and appear to indicate that the Carte Pisane is an early chart, created before an approximate cartographic consensus emerged about the relative positions, orientations and scales of the component sub-charts.*

17. *Although the sub-charts exhibit to a greater extent the characteristics of the Mercator projection than of the Equidistant Cylindrical projection it is impossible to conclude with confidence that either of the two projections fits better to the charts than the other.*

18. *Considerable successive adjustments appear to have been made in the relative positions of the sub-charts. The islands of Corsica and Sardinia fit optimally with the Western Mediterranean sub-chart in one chart and with the Central Mediterranean sub-chart in another. Also the considerable changes in the Atlantic sub-charts indicate ad hoc adjustments. Francesco Beccari, in his 1403 chart, was therefore not the first cartographer to attempt to optimise the charting of the Mediterranean.*

19. *Apart from its individual scale and orientation, each sub-chart also exhibits shear. This shear angle varies in the five portolan charts and appears to be an artefact of the cartometric analysis, indicating differential shifting of pieces of coastline in that sub-chart, introduced by the copying process from portolan chart to portolan chart.*

8 THE RELATIONSHIP BETWEEN PORTOLANS AND PORTOLAN CHARTS

8.1 Introduction

In his book *A History of Marine Navigation* Per Collinder calls the study of portolan charts "a real feast for the eyes".[534] The same cannot be said of the study of *portolans*, written sailing books without any literary merit, which contain dry lists of courses and distances, information about ports and anchorages, including depths, all of which would be relevant only to a practically minded medieval seaman.

A relationship with portolan charts is immediately suspected. Portolans are widely considered to be the forerunners of the Mediterranean portolan charts and the obvious medium for recording a body of collective and shared information on measured Mediterranean course directions and distances. This suspected relationship is also the justification for the name *portolan chart.*

This chapter reassesses the relationship between portolans and portolan charts and comprises a mini-thesis in its own right, which may be read separately from the remainder of this thesis. A review of the results of existing research in Section 8.2 is the necessary starting point, and consists of a summary of Konrad Kretschmer's work[535] (1909) and a detailed analysis of Jonathan Lanman's study[536], published in 1987.

Section 8.3 describes my own analysis of the oldest extant complete portolan, *Lo Compasso de Navegare,* starting, after an introduction, with an explanation of the methodology behind this new analysis and other prior considerations (Section 8.3.2). Section 8.3.3 then forms the starting point of the analysis proper, beginning with the controversial conclusion by James E. Kelley Jr. that portolans have possibly benefited more from portolan charts than vice versa, which was based on the existence of course legs that appear to show evidence of having been scaled from a chart.[537]

Sections 8.3.4 and 8.3.6 describe the analysis of bearings and distances as separate quantities. These bearings and distances belong to *peleio*, or *peleghi*, which are open-sea routes and *per starea*, or coastal routes respectively, with an interlude in Section 8.3.5 on the correct way to calculate the length of the portolan mile from the data. Section 8.3.7

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[534] Collinder 1954, 85.
[535] Kretschmer 1909 (1962).
[536] Lanman 1987.
[537] Kelley 1995,10.

describes an analysis of so-called high-resolution data, a concept that will be explained below, and Section 8.3.8 concludes this part by a summary and analysis of the separate course components.

Section 8.3.9 presents the results of traverse calculations, in which course legs along the coast are 'daisy-chained' into traverses that constitute closed circuits around the Mediterranean and the Black Sea. A traverse, in the context of this study, is defined as a contiguous sequence of bearing and distance pairs. Each bearing and distance pair constitutes what will be termed a *course leg*, or *leg* for short.

Sections 8.4 and 8.5 discuss a synthesis of the results and the final conclusions respectively.

8.2 EXISTING RESEARCH

Research by James E. Kelley Jr. succeeded in casting some measure of doubt on the widely held and apparently self-evident view that portolans provided the source data for the charts. He pointed out that data inconsistencies exist in some portolans. Some course legs cut across land; others are stated to pass within a certain number of miles of a reef that ought not to be visible from a ship on that route. Peleio*,* open sea course legs, are often organised in regularly spaced fans from a point on one coast to multiple points on the opposite coast, which appear to have no relevance as destinations for medieval trading journeys. In the earlier portolans, such as the *Compasso de Navegare*, "non-standard bearings", as Kelley calls them, are recorded, bearings which have a higher resolution than one compass point (11¼°). The *Compasso* contains a relatively high percentage of these high-resolution bearings, 21% according to Kelley, but in the later portolans the percentage of these high-resolution bearings drops significantly. According to Kelley the Pietro de Versi portolan (1444) contains 8% of these courses, but the Rizo portolan (1490) only 3%, the implication being that these bearings had been scaled off and turned out to be too fine-graded for practical use.[538]

E. G. R. Taylor, on the other hand, hails these high-resolution bearings uncritically as proof of the high standard of navigation in the thirteenth century[539], but Kelley is more cautious and asks: "Can it be concluded that portolans may have benefited more from the charts than vice versa?", in other words, can it be that the major part of portolan data has been scaled from a pre-existing chart? This triggered the strong response by Ramon Pujades cited in Section 1.3.3.

Often cited in favour of the argument that portolans contain truly observed data is the following text from Grazioso Benincasa's portolan (1435):

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[538] Kelley 1995, 10.

[539] Taylor 1951, *Early Charts and the Origin of the Compass Rose*, 351: "A.D. 1250 an Italian pilot could name 64 rhumbs and was finding even that number insufficient".

> “I quali porti et senbianze di terre non sono tratte niuna de la charta, ma sono tochate chon mano et vegiute cholli ochi” (The ports and landmarks are not drawn, none of them, from the chart, but are touched with the hand and seen with the eye).[540]

Kelley reads this the other way around, suggesting that Benincasa, by emphasizing that his data is genuine, hints at an existing practice of deriving portolan data from a chart. Evelyn Edson leaves the nature of the relationship between portolans and portolan charts entirely open whilst still acknowledging that a relationship between the two is likely.[541]

With the possible dating of the *Liber de existencia* to the end of the twelfth century and the indication that its data may have been scaled from a portolan chart, Patrick Gautier Dalché has succeeded in stirring up the discussion on the origin of the charts, despite his stated preference to steer clear of that debate.

Kelley was not the first to point out that the relationship between portolans and portolan charts may be more complex than is usually assumed. Kretschmer was already aware of this, but, having access to mainly fifteenth century portolans, he reasoned that these later portolans might have been ‘enhanced’ by bearings and distances, scaled from charts, whereas the original data content would stem from observations. He states for instance that many peleio in the Rizo portolan (1490) have apparently been scaled from the charts, such as one that runs right across Sicily, but adds that this does not necessarily invalidate the assumption that the first portolan chart had been drawn from data supplied in portolans.[542] Kretschmer’s reasoning is correct, but does make one curious to find out if the same issues are found in the oldest portolan, *Lo Compasso de Navegare*, which was not yet available to Kretschmer.

Considering the elusive origin of portolan charts and the unclear nature of the relationship between portolans and portolan charts, it is rather surprising that not more research into portolans has been conducted. Although a large number of charts have been subjected to detailed cartometric analysis, only one serious quantitative analysis of portolans has been made in addition to Kelley’s half-page summary on this subject. Jonathan Lanman analysed the only two surviving portolans that describe an entire ‘round trip’ of the Mediterranean, *Lo Compasso de Navegare* and the so-called *Parma-Magliabecchi* portolan.[543]

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[540] Kelley 1995, 10. See Also Campbell 1987, 433 and Gautier-Dalché 1995, 44. The original text is available in Kretschmer 1909 (1962), 358, just before the listing of the *Toleta de Marteloio*, mentioned in Section 5.3.

[541] Edson 2007, 40.

[542] Kretschmer 1909 (1962), 94-95.

[543] The *Parma-Magliabecchi* portolan which Lanman analysed is based on Kretschmer’s consolidated text constructed from the five codices of the text that exist. See Group I under section 8.2.1.

Before looking into the results of Lanman's analysis, Konrad Kretschmer's work, *Die italienischen Portolane des Mittelalters* (1909), needs to be mentioned, because it contains an important classification of portolans, as well as the texts of seven extant ones. This work was published before the most famous of medieval portolans, *Lo Compasso de Navegare*, became known through Bacchisio Motzo's book in 1947.[544]

8.2.1 KRETSCHMER'S CLASSIFICATION OF PORTOLANS

Kretschmer observes that the contents of surviving portolans can be classified in groups, the members of which have more or less numerically identical contents, with editorial differences only.

He distinguishes the following three groups:[545]

I. Parma-Magliabecchi group
  1) Portolano Parmense (middle 15th century)
  2) Portolano Magliabecchiano – variant 'Ma' (15th century)
  3) Portolano Magliabecchiano n. XIII, 72,1 – variant 'Mb' (second quarter 15th century; this is a collection of documents containing two portolans)
  4) Portolano Marucelliano (nearly identical to Mb; 15th century, but after Mb)
  5) Portolano Casanatense (end 15th – early 16th century)

II Uzzano group
  1) Portolano Sanudino (early 14th century)[546]
  2) Portolano Riccardiano (15th century)
  3) Portolano Magliabecchiano, n XIII, 72,2 – variant 'Mc' (date unknown)
  4) Portolano Uzzano (1442, but only known as a printed version from 1765)

  Lo Compasso de Navegare (1250-1296), which was unknown to Kretschmer, belongs to the Uzzano group (see comment Gautier Dalché below).

III Rizo group
  1) Portolano Magliabecchiano, n. XIII, 71 – variant 'Md' (1480)
  2) Portolano Rizo (an *incunable*; printed in 1490) – totally different from the other portolans, except Md.

In addition to these three groups the following portolans are individual works:
  1) Portolano Gratiosus Benincasa (1435)
  2) Portolano Pietro de Versi (1445)
     (Bibiotheca Marciana, Venice, Mss.Italiani, Classe IV, n.170)

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[544] Bacchisio R. Motzo, "Il Compasso da Navigare, opera italiana della metà del secolo XIII." *Annali della Facoltà di Lettere e Filisofia della Università di Cagliari* 8, 1947.

[545] Kretschmer 1909 (1962), 173.

[546] Kretschmer writes: "Sanutino".

The Portolano Sanudino is included in Marino Sanudo's *Liber secretorum fidelium crucis*.

Kretschmer has left the so-called Marciana fragment[547] out of this classification. This fragment describes the route from Acre to Alexandria and Venice. He doesn't explain why he didn't include it – perhaps because it is so short – but he does provide the text on pages 235-237 of his book. According to Gautier Dalché this fragment dates from between 1211 and 1270 and this early date would make it very interesting from the perspective of the study into the origin of portolan charts.

Gautier Dalché writes that Marino Sanudo's portolan, a member of the Uzzano group, is no more than a translation (into Latin) of the *Compasso de Navegare*[548] and Kretschmer stresses that the members of the Uzzano group have practically identical numerical contents.

The most important conclusion that may be drawn from Kretschmer's classification and text analysis is that, although portolans may not have been copied to the degree of detail that portolan charts were copied, the copying practice of portolans continued to well beyond the fifteenth century. If portolans do reflect a collectively shared body of geographic knowledge, gradually increasing in accuracy and acquired from practical observations, one would not expect to find numerically identical copies after two centuries.

This is a convenient point to switch to Jonathan Lanman's numerical analysis of two portolans. Because Lanman's work is the only large quantitative analysis of portolans available to date, I have provided an extensive summary with comments below.

8.2.2 Lanman's analysis of two portolans

Lanman's work appears to have been inspired by the suggestion, originally made by Taylor, that it would interesting to find out if a chart could be drawn from the *Compasso de Navegare* that would be sufficiently similar to the earliest portolan chart to demonstrate that portolans provided the source data for the construction of portolan charts.

His report was published in 1987, which means that his analysis was done earlier, at a time when personal computers were not yet widely available. His methods reflect the inevitable limitations that the absence of the usage of a computer poses.[549]

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[547] Bibliotheca Marciana, Venice, Mss. Italiani Classe XI, Cod. N.87.

[548] Gautier Dalché 1995, 67. He refers to Kretschmer 1909 (1962), 202-203, who states that Sanudo's portolan is a literal translation from a common ancestor portolan in the Uzzano group. As an example Kretschmer provides six courses and distances from Sanudo's portolan and the Uzzano portolan. This data is identical to that from the *Compasso*.

[549] I conclude that Lanman didn't use a computer because he analysed only six small samples of data, three samples of coastal courses and three samples of *peleio*; if he did use a computer after all, he didn't make full use of its potential.

Lanman analysed two portolans, *Lo Compasso de Navegare* ("CdN") and the *Parma-Magliabecchi* ("P-M") portolan. The former carries a date of 1296, but is assumed to be a copy of an older version dated to 1250 at the earliest. The *Parma-Magliabecchi* portolan dates from the late fifteenth to mid-sixteenth century and exists in five codices, four of which appear under that name in Kretschmer's classification table; the fifth is also in the list, but under the name *Portolano Casanatense*. As mentioned earlier in footnote 543, Lanman conducted his analysis on the basis of Kretschmer's text, which consists of a consolidation of these five versions, with any relevant differences explained in footnotes. He extracted the numerical data of the *Compasso* from Motzo's book.

Lanman states the objective of his analysis to be the following:

> "The CdN and P-M offered an opportunity to test a relationship of portolani and portolan charts and perhaps cast further light on the origins of the latter … If recognisable charts could be made [from the bearing and distance data in the two portolans - RN], they could then be compared both with the portolan charts to reveal similarities and disparities, and with each other to show the difference that two centuries' further experience in Mediterranean sailing had made on the accuracy of the portolani."

This reflects an open-minded approach, but unfortunately he spoils that impression a little later by excluding a priori the possibility that charts preceded portolans: "If a chart were the primary source, where would it have come from?"[550] As early as page 7 of his 54-page publication Lanman excludes any other conclusion as that portolan charts are based on observation data recorded in portolans. His work thereby presents yet another example of a priori reasoning.

A. PERIMETER DATA (*PER STAREA*)

Lanman separates his work into an analysis of coastal perimeter and pelagic course legs. From both the *Compasso* and the *Parma-Magliabecchi* a complete round trip of the Mediterranean can be extracted, which permits a misclosure[551] to be calculated.

For the *Compasso* Lanman calculated the complete round trip to have a total length of 7,824 NM (14,490 km) and to consist of 426 bearing and distance pairs of which 14

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[550] Lanman 1987, 7.

[551] *Misclosure* is a geodetic term. A misclosure is the accumulated error in survey observations that can be shown to exist:
a) in the internal geometric relationships of the observations, e.g. if the sum of the angles in a plane triangle is 182°, rather than 180°, as mathematics prescribe, the misclosure equals +2°;
b) in the calculated position at the end of a closed traverse of survey observations, where the end point is the same as the starting point, or in an interpolated survey traverse between two points of which the coordinates are known.

were defective (12 distance-only; 2 bearing-only). Lanman indicates he omitted the defective sections, but it is unclear whether he used the available half of each incomplete pair or substituted each incomplete section with a fully calculated one.[552]

In the *Parma-Magliabecchi* portolan the round trip consisted of 310 bearing-distance pairs, of which only 7 were distance-only. He calculates the length of the perimeter as 7,663 NM (14,192 km).

In all calculations, Lanman used a length for the portolan length unit, the *mile,* of 1230 m, as proposed by Hermann Wagner.[553]

In the course of his analysis Lanman claims he encountered a presumed error in the data for the Adriatic Sea in the *Compasso*. A closed traverse can be calculated in the Adriatic, because, in addition to course legs along the coastline, a cross-sea bearing and distance pair is provided from the island Othonoi, northwest of Corfu, to Cap Leuca, the southernmost point of Italy's 'heel'. This reveals a significant error, which Lanman corrected by inserting a computed section to Othonoi on the Adriatic east coast, compensating for this error. Although he doesn't acknowledge this, he therefore effectively excludes the Adriatic from the calculation of the perimeter misclosure.

Figure 8.1 *- Lanman's 'raw data' plot from the Compasso de Navegare, showing the point where he inserted a computed course leg of about 120 NM in the Adriatic. This is Lanman's Plate 1 (© The Newberry Library, Chicago; reproduced with permission).*

Also in the *Parma-Magliabecchi* portolan Lanman encountered problems with the Adriatic data, but of a different nature than in the *Compasso*: he discovered incorrect sequences of towns, impossible courses and an apparent confusion in the location of Brindisi.

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[552] Lanman 1987, 5.

[553] Lanman 1987, 5 and Wagner 1913, 397.

Lanman calculates the following parameters to estimate the accuracy of the two portolans:

1. The *misclosure at Ceuta*, i.e. the location of Ceuta after the round trip:
   Compasso misclosure: 77 NM (143 km) too far north (= 1% of the total length of the traverse, 7,824 NM, not 0.9%, as Lanman calculates);
   Parma-Magliabecchi misclosure: 75 NM (139 km) south-east of 'True' (=1% of the total length of 7,663 NM, not 0.8%, as Lanman calculates).
2. The *length and width* of the Mediterranean:
   Compasso: length 10% too long; width 3% too short;
   Parma-Magliabecchi: length 1% too long; width 1% too short.
3. *Mean error and spread in bearing and distance* data, calculated for three sample stretches of coast.

Point 3 requires slightly more explanation. Lanman uses sample data from three stretches of coast: southern Spain (~90 NM = ~170 km), southern Italy (150-200 NM = ~280-370 km) and North Africa (~340 NM = ~630 km). Each stretch of coast consists of a number of bearing-distance pairs, on average about eight, and Lanman calculates the mean error and the standard deviation in bearing and in distance. Bearing errors and their standard deviations are in degrees; distance errors and their standard deviations are expressed as percentages from true. The length of each section is short, ranging from 12 to 39 NM (22 – 72 km). He presents the results in a table, which I reproduce below.

				Bearing deviation from True		Distance deviation from True	
Location	**Source**	**N**	**Mean section length (NM)**	**Mean error**	**Standard deviation**	**Mean error**	**Standard deviation**
Southern Spain	CdN	7	12	19°	25°	39%	49%
	PM	7	14	20°	23°	18%	25%
Southern Italy	CdN	9	22	26°	36°	22%	31%
	PM	6	25	12°	16°	23%	33%
North Africa	CdN	11	30	30°	40°	22%	29%
	PM	9	39	18°	30°	52%	52%

Table 8.1 *- Bearing and distance errors in two portolans (=Table 2 in Lanman 1987, 13).*

The parameter Lanman calculates for the spread of the data is not the standard deviation, but the Root Mean Squared Error (RMSE). This is a measure for the spread of a parameter about its *mathematical expectation* , i.e. about its 'true' value, whereas the sample standard deviation indicates the spread about the *mean* value of the parameter in the data sample. Lanman indeed calculates each error as the difference of the *Compasso* bearing or distance with its 'true' value computed from his reference chart. The formula he presents for the calculation of the standard deviation (or rather: RMSE) is incorrect, but I am convinced this is a typesetting error rather than a calculation error.[554]

Although he doesn't explain this, the mean error he calculates is probably the mean *absolute* error, which cannot be directly related to the RMSE. Its inclusion in the results suggests that the mean error and the 'standard deviation' contain independent information, but that is not the case; both describe the spread of the data. For the small samples that Lanman uses, the mean absolute error is probably a more meaningful parameter than the RMSE.

The conclusions Lanman draws from this data are interesting. Immediately after presenting the comparison of the length and width of the Mediterranean (see point 2 above), Lanman concludes that the *Parma-Magliabecchi* portolan shows superior accuracy with respect to the *Compasso de Navegare*, claiming that, "with time and experience, the portolans improved in accuracy".[555]

Unfortunately, this isn't confirmed by the misclosures in the position of Ceuta, nor in any convincing way by the figures in Table 8.1 above (Lanman's Table 2). Lanman acknowledges that, but deals with it by calling it "remarkable". Making matters worse, he states later on: "One would suppose the accuracy of short coastal courses could have been readily improved with time, but the directions in the mid-sixteenth century *Parma-Magliabecchi* portolan are no better than those in the thirteenth century C de N".[556] With this remark he contradicts his earlier conclusion that "with time and experience, the portolans improved in accuracy". On the grounds of the improved gross dimensions of the outline of the Mediterranean in the *Parma-Magliabecchi* portolan, Lanman jumps to the generalised concept of *data accuracy* too quickly: the poor quality of the coastal stretches conflicts with the apparent greater accuracy of the outline of the Mediterranean of the Parma-Magliabecchi portolan. However, that contrast is also visible in the *Compasso* outline. The observation that the gross dimensions of the *Parma-Magliabecchi* outline are better than those of the *Compasso* is correct, but it detracts from the more important question why relatively poor coastal observations of bearing and distance can lead to such correct overall dimensions of the Mediterranean.

Although some improvement is visible in the charts that Lanman drew from the two portolans, the *Parma-Magliabecchi* portolan data cannot, on the basis of these maps, be

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[554] Lanman explains the formula he has used for the calculation of his standard deviation on page 12 of his document $\sigma = \frac{\sqrt{(x - \tilde{x})^2}}{n - 1}$, in which $\tilde{x} = E\{x\}$ is the *mathematical expectation*, or 'correct' value of the relevant distance or bearing.
The correct formula is: $RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - E\{x_i\})^2}{n}}$.

[555] Lanman 1987, 12.

[556] Lanman 1987, 19.

regarded as superior in accuracy with respect to the *Compasso* data. Lanman also concludes that the *Compasso de Navegare* overestimates the length of the Mediterranean by about 10%, but misses a more puzzling characteristic. The 10% error in the length of the Mediterranean along the northern coast of the Mediterranean is almost exactly compensated by a similar error along the southern coast. Observed bearing and distance data along the two coasts ought to be independent, which would make this cancelling out a very unlikely phenomenon. Also the *Parma-Magliabecchi* portolan shows errors in the Mediterranean north coast that are cancelled out by errors in the south coast. In the *Compasso de Navegare* the largest errors occur along the Levantine coast; in the Parma-Magliabecchi portolan in the Italian peninsula.

Figure 8.2 *- Lanman's plot of the data in the Compasso de Navegare; this is Lanman's Plate 4 (©The Newberry Library, Chicago, reproduced with permission).*

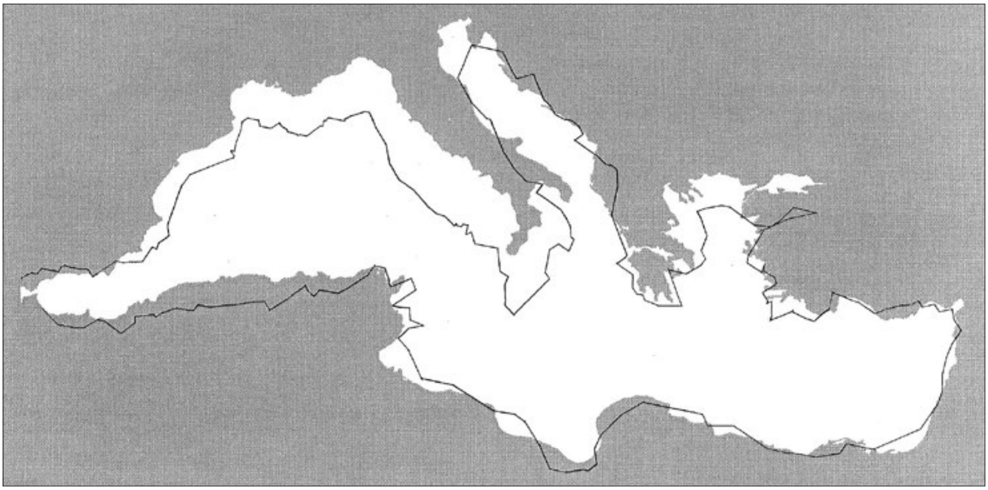

Figure 8.3 *- Lanman's plot of the data in the Parma-Magliabecchi portolan; this is Lanman's Plate 5 (©The Newberry Library, Chicago; reproduced with permission).*

Lanman observed that the charts he drew from the portolan coastal data, shown in Figure 8.2 and Figure 8.3 above, showed the coastline image rotated by 9° (*Compasso*) and 10° (Parma-Magliabecchi) respectively. He concluded that this "indicated that the bearings had been measured with an uncorrected compass".[557]

Note that Lanman's outlines in Figure 8.2 and Figure 8.3 above do not begin at Gibraltar, but that he shifted the entire outline slightly to the west, apparently to spread the errors more evenly over the entire coverage area.

B. LONG-DISTANCE OPEN-SEA ROUTES (*PER PELEIO*)

Lanman observes that the majority of data in the *Compasso* describe per starea, i.e. coastal, course legs, but that it contains a section with some 200 pelagic course legs (peleio or peleghi). He doesn't evaluate the peleio in the Parma-Magliabecchi portolan, only those in the *Compasso*, but provides no explanation. He analyses 129 peleio, of which the results are summarised in Table 4 (page 19) of his report, reproduced below.

			Bearing deviation from True		Distance deviation from True		
Site	**N**	**Mean section length (NM)**	**Mean error**	**Standard deviation**	**Mean error**	**Standard deviation**	**Magnetic Declination**
Western Med.	48	167	7.8°	10.9°	8.9%	11.9%	5.1°E
Central Med.	59	255	6.8°	9.4°	12.3%	15.7%	4.6°E
Eastern Med.	22	233	10.4°	12.3°	9.0%	11.4%	6.0°E

Table 8.2 - *Accuracy of peleio in (=Table 4 in Lanman 1987, 19).*

Also the figures in Table 8.2 result from evaluating the data relative to their 'true' values. The magnetic declination column shows the average error in the bearings, which Lanman *interprets* as the magnetic declination, whereas the columns entitled "mean error" probably again contain mean *absolute* errors. Lanman doesn't explain this. He doesn't calculate corresponding estimates for "magnetic declination" for the short coastal per starea course legs (see Table 8.1) but doesn't elaborate on that either.

Lanman correctly concludes that the pelagic courses (peleio) are of superior accuracy compared to the coastal data, which is the reverse of what he expected. He concludes that the pelagic course legs appear to constitute a separate population of data from the coastal course legs.

He also claims that it is not true that peleio cut across land and concludes that they "are clearly intended to be practical sailing routes and obviously derived from experience".[558]

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[557] Lanman 1987, 13.

[558] Lanman 1987, 20-21.

The implication of this interpretation – the words "clearly" and "obviously" mask the fact that this concerns an interpretation and not a conclusion supported by objective evidence – is that the magnetic compass, in a form that would have enabled the recording of accurate bearings, would have been in widespread use before this data was recorded in the *Compasso*. This leads to his conclusion: "And so the large number of remarkably accurate long-distance courses must have been assembled in no more than half a century" (i.e. between the dates of 1250 and 1296 mentioned in relation to the age of the *Compasso de Navegare* – see Section 8.3.1 below).

Lanman believed, like many other writers, that the peleio had been used to construct a framework to control the overall dimensions of the Mediterranean image on portolan charts. He attempted to draw this framework from the peleio in the *Compasso* and was surprised to find that there isn't enough data available to construct a trilateration/triangulation network: "… there were very few opportunities to construct triangles with shared sides."[559] This left him with a puzzle he could not solve. He considered it unlikely that any additional peleio would have been kept outside the portolans, which seems reasonable; no other sources of navigation data have come to light. Additional peleio might have been recorded in other portolans, but that appears to be an unlikely option because of the extensive copying of portolan contents, described in Section 8.2.1 above.

Lanman's main conclusions are:

1. Readily recognisable charts, apparently of reasonable accuracy, can be drawn from portolan data. The charts were skewed in the same direction and by the same amount as portolan charts, indicating that the sailing directions had been determined with the use of an uncorrected compass.
2. A major, if not *the* major, purpose of portolans and of early portolan charts was to provide the course data for safer open-sea sailing, made possible by the introduction of the compass.

He also draws a few conclusions on the application of plane charting which have been discussed in Section 3.5.1 and will not be repeated here.

C. ANALYSIS AND COMMENTS

Lanman's a priori reasoning is very unsatisfactory and his presupposition that the data in the *Compasso de Navegare* are bearings and distances observed from a ship colours his conclusions to an unacceptable degree. His rash conclusion that the skewing of the charts, drawn from the two portolans, indicates that the bearing data was collected with an uncorrected compass, demonstrates this. If the data would have been scaled from a portolan chart, the same skewing would emerge; so on the grounds of the skew angle alone one cannot conclude one thing or the other. It *would* be justified to draw the conclusion Lanman draws if

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[559] Lanman 1987, 23-24.

the bearing errors show a clear correlation with the magnetic declination at that location, but the *Compasso* data isn't good enough to show that, as evidenced by Figure 8.45 below. Lanman's objectives were to find out if recognisable charts could be drawn from data in portolans and to use the similarities and disparities with portolan charts to investigate the relationship between the two.

Apart from the fact that the charts from the two portolans may show sailing courses along the coast rather than showing the coastline itself, the question is how 'recognisable' these charts have to be to conclude a close relationship with portolan charts. I am not advocating that there is no relationship, but in my view the most striking feature of the charts drawn from the two portolans is the *dis*similarity between them and portolan charts. There is still a wide gap between the realism and accuracy shown by portolan charts and the graphically rendered portolan data. Lanman's a priori assumption that portolan charts are based on data, recorded in portolans, is not confirmed by the 'recognisability' of the charts drawn from the portolans. The accuracy of the data in the two portolans investigated is of a different order than that of the portolan charts. In my opinion Lanman glosses over this dissimilarity.

Lanman also uncovered some contradictions, or apparent contradictions, in the portolan data. In a number of ways the data refuse to comply with his a priori conclusion. Lanman acknowledges that fact, in most cases describing it as "remarkable" or "surprising", but he never questions his premises.

a) On the poor data of the Adriatic: "So gross an inaccuracy in an area that must have been well known to Italian, or at least Venetian, sailors, was *surprising*".
b) In describing the depiction of the Italian peninsula and errors around Brindisi in the *Parma-Magliabecchi* portolan: "These mistakes *go beyond the expected errors* in bearing and distance …"
c) "Bearing and distance errors appear large in view of the relative accuracy of the charts made from them".
d) On the very small misclosure in the round trip of the Mediterranean and the lack of steady build-up of errors along this perimeter: "While errors would be expected to cancel each other to some extent, the degree to which this seems to have occurred was *remarkable*."
e) On the misclosure in the location he found after the roundtrip of the Mediterranean: "…the final error, … 0.9%, was *remarkable*".
f) On the peleio: "... the large number of *remarkably* accurate long distance courses …"
g) On discovering that the peleio in the *Compasso* are not sufficient to draw a framework for a chart: "It is possible that the chartmakers had available additional course data that would have obviated this difficulty, but their omission from the *Compasso*, in which pelagic courses occupied such a prominent place, would have been *surprising*."

A striking conclusion that Lanman does *not* draw is that no convincing improvements in the numerical data are visible in the Parma-Magliabecchi portolan, compared with the *Compasso de Navegare*.

Lanman's conclusion, based on the higher standard deviations he calculated for the shorter coastal courses compared to the *peleio,* was that "the main, if not the only purpose of portolans was to provide accurate pelagic courses".[560]
This conclusion is unsatisfactory, as the *peleio* constitute only 28% of the numeric course content of the *Compasso*.

The popular image that portolans contain the base observations, gradually increasing in accuracy, for the drawing of the first portolan chart, is certainly not borne out by Lanman's analysis. Additionally the data appears to be afflicted by intriguing contradictions that beg further investigation. In my opinion, Lanman does not respond to these issues in a satisfactory manner, which is why I decided to conduct my own analysis of the *Compasso de Navegare*, described in the sections below.

8.3 A NEW ANALYSIS OF *LO COMPASSO DE NAVEGARE*

8.3.1 ORIGIN OF THE SOURCE DATA

The original manuscript of *Lo Compasso de Navegare*, as its name is in medieval Italian, is held under the name *Hamilton codex 396* in the *Staatsbibliothek zu Berlin*. The manuscript itself carries the date 1296 (see Figure 8.4, second line), but the document is considered to be a copy of an older original, thought to date from around 1250. In Section 7.1 above the origin of the city of Manfredonia was mentioned and the consequences its construction had for the existing city of Siponto. By 1296 Manfredonia would have displaced Siponto in importance and would have been mentioned instead in such a document. However, in the *Compasso de Navegare* only Siponto is mentioned and the origin of the *Compasso* must therefore lay further back in time.

An indication of the lower time limit is provided by the reference in the *Compasso* to the port of Aigues-Mortes, which was constructed by King Louis IX and was the embarkation point for his crusades of 1248 and 1270.

I have used the text reproduced in Motzo's book[561] to extract the numerical course information, a tedious process, as I am not a master of medieval Italian and could therefore do little with the additional descriptions provided in the text. My serendipitous discovery of a German translation by Christian Weitemeyer was of great help in decod-

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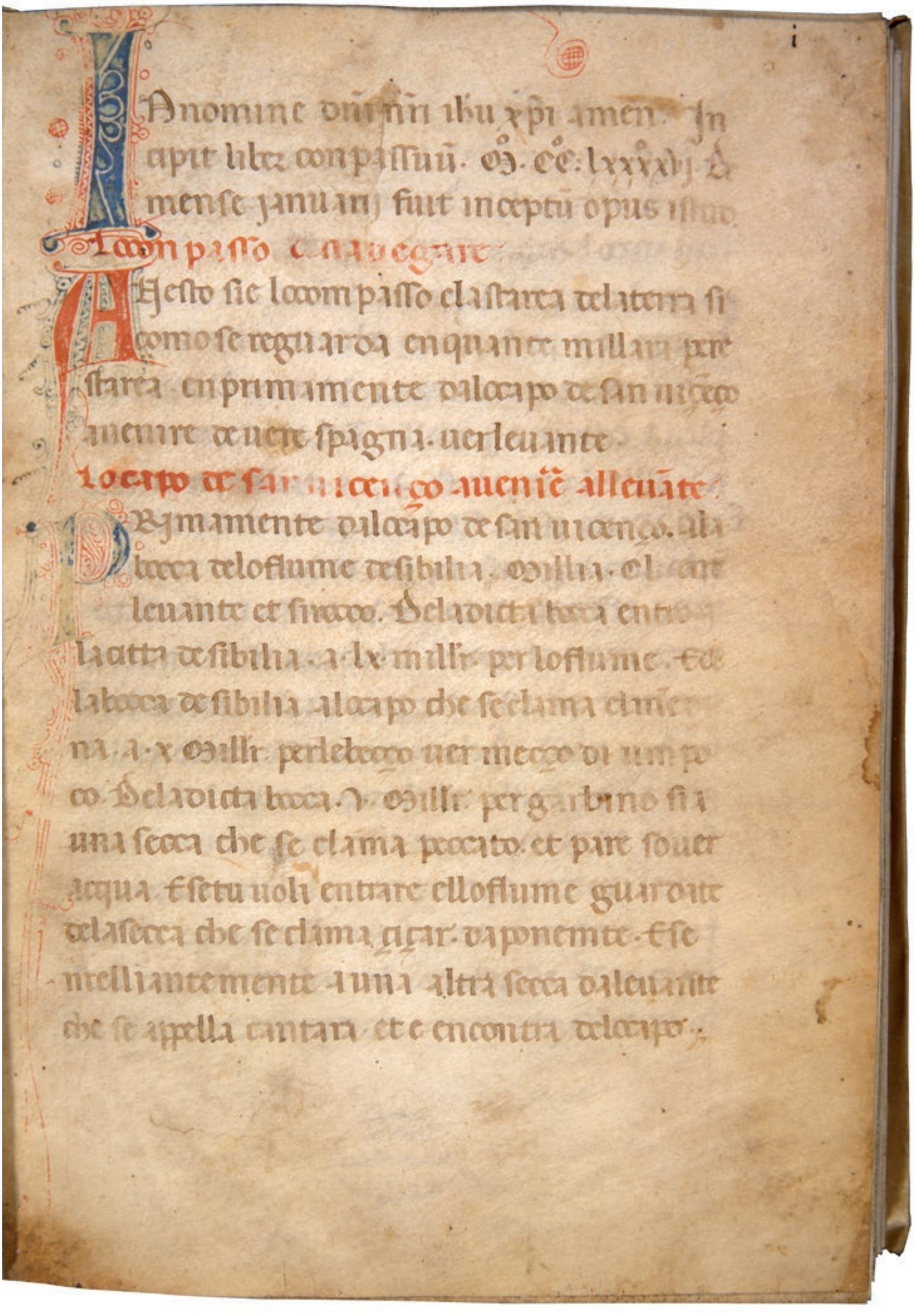
[560] Lanman 1987, 20.
[561] Motzo 1947.



In nomine dñi nři ihu xpi amen. In
cipit liber conpaſſuum. M°. CC°. lxxxxvj. de
mense januarij fuit inceptũ opus iſtud

Lo compaſſo de navegare.

Queſto sie lo compaſſo e la ſtarea de la terra ſi
como ſe reguarda en quante millara per
ſtarea. en primamente da lo cavo de ſan viçenço
avenire de vere ſpagna. ver levante.

Lo cavo de ſan viçenço avenĩẽ alleuãte.

Primamente da lo cavo de ſan viçenço. ala
bocca delo flume de ſibilia. Millia. el [illegible]
levante et ſiroco. De la dicta bocca entro
la citta de ſibilia. a. lx. millr. per lo flume. Et
la bocca de ſibilia alo cavo che ſe clama elm[illegible]
na. a. x. Millr. per le boçço ver meço di un po
co. De la dicta bocca. v. Millr. per garbino ſta
una ſecca che ſe clama peocito. et pare ſouer
acqua. E ſe tu voli entrare ello flume guardate
de la ſecca che ſe clama çiçar. da ponente. E ſe
ſimelliantemente a una altra ſecca da levante
che ſe appella cantara et e encontra de lo cavo.

Figure 8.4 - *First page of Lo Compasso de Navegare*
(Image: courtesy of Staatsbibliotek zu Berlin - Preussischer Kulturbesitz, MS-Ham 396).

ing the second half of the *Compasso*.[562] Weitemeyer's translation has been published as a private initiative, presumably in a limited edition. I have checked the numbers against those in Motzo's book and, apart from one minor difference, discovered no errors.

The *Compasso* begins at Cape St Vincent, follows the clockwise coastal route initially eastward around the Mediterranean, and finally back through the Strait of Gibraltar, to end at Safi on the Atlantic coast of Morocco. This coastal route or 'perimeter' is interspersed with course legs that are shortcuts between two perimeter points, or short 'hanging' traverses.[563] Roughly in the middle of the entire text a large number of course data between the Aegean islands are listed. A further listing of data between these islands, duplicating some of the earlier data, is provided at the end of the Mediterranean section of the *Compasso*, which concludes with a chapter that is explicitly named "peleio". These long-distance course legs are described in groups, fanning out from a limited number of source points.

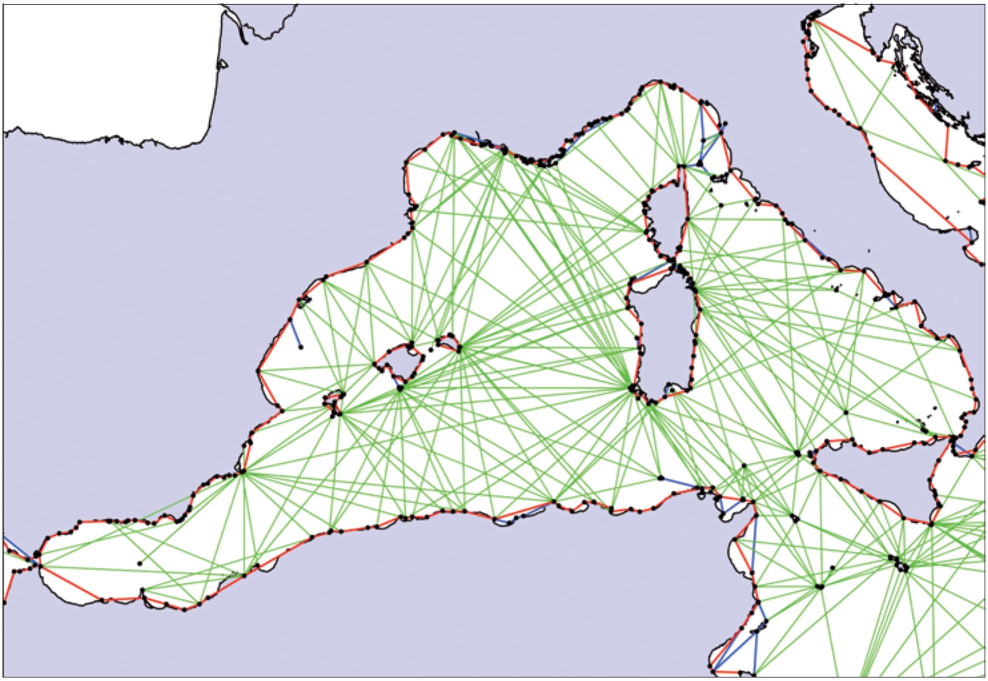


Figure 8.5 - *Compasso de Navegare: course legs in the western Mediterranean.*

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[562] Christian Weitemeyer, *Compasso de Navegare, erstes Seehandbuch Mittelmeer aus dem 13. Jahrhundert* (Nienburg: Betzel Verlag, 1996).

[563] A hanging traverse is a sequence of bearing-distance pairs that is only connected to the perimeter data at one end. The correctness of those bearings and distances can therefore not be verified against other bearing and distance data, as no misclosure can be computed.

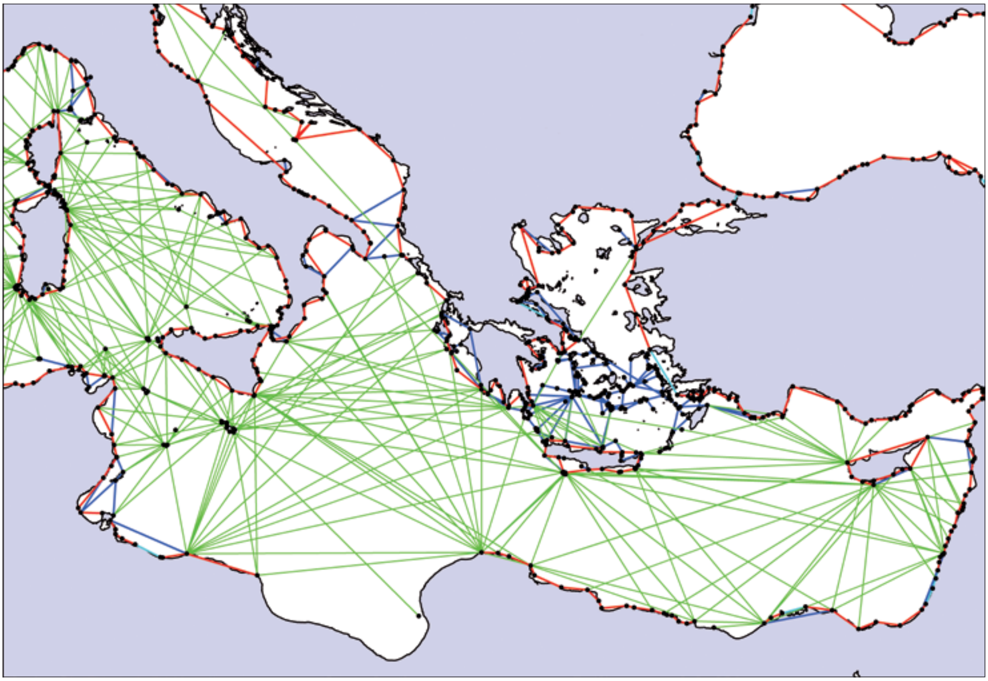

Figure 8.6 - *Compasso de Navegare: course legs in the eastern Mediterranean.*

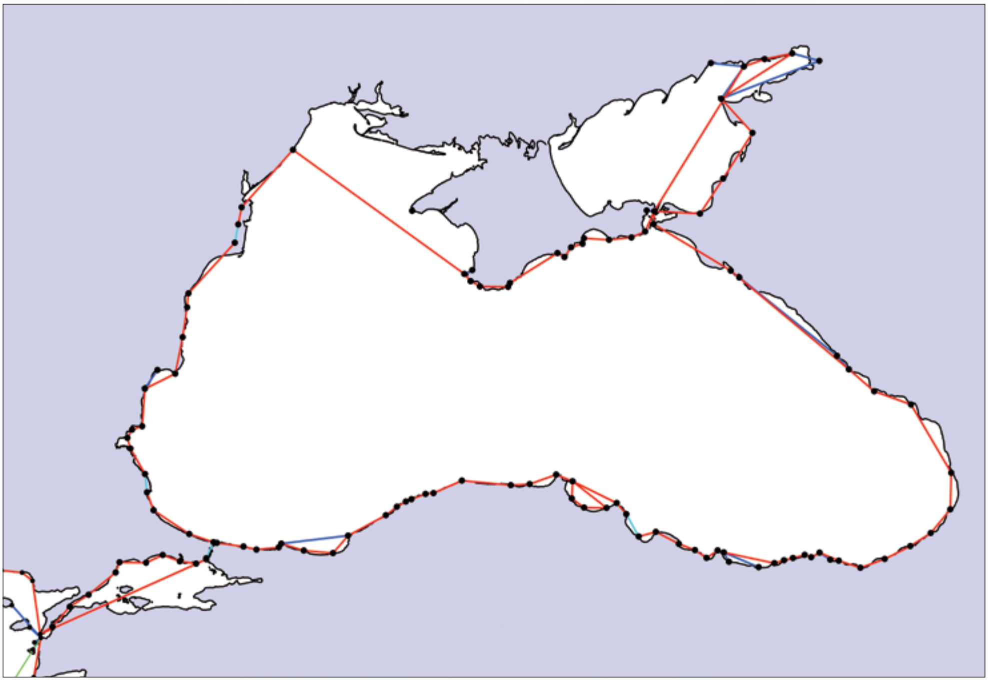

Figure 8.7 - *Compasso de Navegare: course legs in the Black Sea.*

The last part of the *Compasso* consists of two listings of course data in the Black Sea, both starting at the Bosporus, one going east and the other going west.

The two traverses meet at Cape Khersones at the Crimea peninsula. It seems evident that these lists have been added after the rest of the *Compasso* had been compiled. No peleio are recorded for the Black Sea.

Figure 8.5 to Figure 8.7 show all the course legs I used in my analysis. They have been colour-coded as follows:
- Green: *per peleio* course legs;
- Red: *per starea* course legs used for the perimeter calculations;
- Blue: additional *per starea* course legs, decribed as hanging traverses and shortcuts; the inter-island course legs in the Aegean Sea belong to this category.
- Cyan lines indicate two or more course legs, combined into a single leg.

8.3.2 METHODOLOGICAL CONSIDERATIONS

The analysis of the *Compasso de Navegare* turned out to be an enormous bookkeeping exercise. In the course of my analysis I realised that the 426 bearing and distance pairs of the perimeter plus the 129 *peleio* that Lanman analysed constitute less than half of the entire contents of the *Compasso*.

My analysis eventually comprised 369 *peleio* and 958 *per starea* course legs, of which 661 were bearing and distance pairs along the perimeters and 297 remaining course legs, which neither belong to the perimeter data nor to the *peleio*. An additional 42 bearing and distance pairs were rejected because they involved unidentifiable points or turned out to be duplicates; 25 of those constitute a traverse from the Aegean mouth of the Dardanelles to the mouth of the Bosporus at the Black Sea. A further 19 *Compasso* entries were decoded, but not used in the analysis because they were circumferences, whole or partial, of islands.

Before embarking on the analysis itself, relevant aspects of the approach I have followed need to be discussed. The first is the question what dataset I have used as the benchmark to judge the quality of the *Compasso* data. Also required is an explanation and partly a justification of the geodetic aspects of the analysis, including the geodetic calculations that were required to conduct the analysis and in particular the dual use of the Mercator projection, which I have attempted to explain in Section 8.3.2E below.

The remainder of this section describes aspects of the *Compasso de Navegare*, relevant for this analysis, such as the system used in the *Compasso* to describe bearings and distances (section 8.3.2F), how I interpreted course data in the *Compasso* and dealt with incomplete data and unidentifiable points (sections 8.3.2GI). Finally I describe what I consider useful additional aspects of data (section 8.3.2J).

A. REFERENCE DATASET AND SOFTWARE USED

After having identified the locations recorded in the *Compasso de Navegare*, i.e. associated those locations with present-day locations, I scaled off latitude and longitude of each point in a reference dataset by means of Geographical Information System (GIS) software. This reference dataset was again the publicly available vector dataset VMAP, described in Section 6.5.1.

B. OBSERVED OR SCALED OFF DATA? TWO MAIN STRANDS OF ANALYSIS

James E. Kelley Jr. managed to 'rock the boat' in which the medieval origin hypothesis was comfortably seated by suggesting that portolans may owe more to portolan charts than vice versa.[564] In view of the facts Kelley mentions, his suggestion deserves a better fate than being called a "methodological error"[565] and I have therefore analysed the data in the *Compasso* for two different hypotheses.

1. The *Compasso* contains observed data.
2. The data in the *Compasso* were scaled from a portolan chart.

C. GEODETIC CALCULATIONS

Most techniques used in my evaluation of the *Compasso* are standard mathematical and statistical techniques, such as the calculation of the sample standard deviation of a dataset. Key in the evaluation of errors in the bearings and distances are the ordering of the errors as a function of the length of the course leg and the treatment of the distance errors as *relative* errors, i.e. as a proportion of the length of the course leg. The latter is justified by the principle of distance measurement assumed, i.e. estimation of vessel speed, integrated over time. That principle implies that errors will increase with course length.

Specific geodetic aspects are introduced by the reduction of observations, made on the surface of the earth, to the map plane. These reductions are standard ingredients of geodetic calculations performed in the map plane, an approach that is usually adopted because of the simpler Euclidean geometry compared with the more complex geometry of the ellipsoid. My earlier evaluation of the characteristics of plane charting in Chapter 2.5 will be extended in the current chapter to the analysis of the *Compasso de Navegare*.

These same geodetic aspects play a key role in my evaluation of the per starea or coastal perimeter data. It makes a significant difference to the calculated shape of the Mediterranean perimeter whether the data in the *Compasso* are considered to have been observed from a ship or whether they are assumed to have been scaled from a pre-existing chart.

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[564] James E. Kelley, Jr., "Perspectives on the Origins and Uses of the Portolan Charts", *Cartographia,* Vol. 32 (1995), No. 3: 10.

[565] Pujades 2007, 512.

Data that have been scaled from a chart will be afflicted by the inevitable distortions the map projection of the source chart possessed. We know now that a portolan chart agrees closely to a Mercator chart, so the distortions inherent to the Mercator projection will have to be taken into account in the evaluation of the *Compasso* data.

It is incorrect, as Lanman did, to plot the course legs from the *Compasso* by plane charting and compare the result with a reference chart on the Mercator projection. This amounts to comparing apples with oranges, as I shall demonstrate later in this chapter.

The reference dataset of bearings and distances has been calculated from the locations of the points associated with the toponyms of the *Compasso,* identified in the VMAP dataset and shown diagrammatically in Figure 8.8 as *Nodal points (Lat, Lon).* In view of the two strands of analysis mentioned in the previous section, I converted all geographic coordinates (latitude and longitude) of the points identified to Mercator Easting and Northing (E, N), using a custom Mercator projection with a true-to-scale parallel of 39° 57' N, the reference latitude used to express the scale results of the cartometric analysis of the charts in Chapter 7. The values for the length of the portolan mile, computed from the *Compasso* data, are therefore directly compatible with the values, calculated from the scale bars on the charts in Section 7.6.9. The earth model underlying the calculations is assumed to be the World Geodetic System 1984, which is based on an ellipsoid with a semi-major axis of 6,378,137 m and a flattening of 1/298.25722.

The analysis strand that assumes the *Compasso* to contain data, *scaled* from a pre-existing portolan chart, allows direct scaling from a modern Mercator chart to establish the reference values for the compass bearings. For this hypothesis also the distance between start and end points of each course leg may be calculated directly from the (modern) Mercator chart coordinates using simple plane geometry (Pythagoras's rule).

For the analysis strand that assumes the *Compasso* to contain *observed data*, the same reference values of the bearings of all course legs may be used, due to the bearing-preserving properties of the Mercator projection. Ships that would have contributed their navigation measurements would have sailed along rhumb lines as they sailed the course laid by means of the compass. The reference values of the lengths of these rhumbs were calculated using the method described in Appendix II.

The two paragraphs above describe how the reference or benchmark values for the analysis were derived. Section 8.3.9 below describes the calculation of the errors in the nodal points of the traverses around the Mediterranean and the Black Sea. Lanman calculated only the misclosure of the closed traverse around the Mediterranean, using the plane charting method.

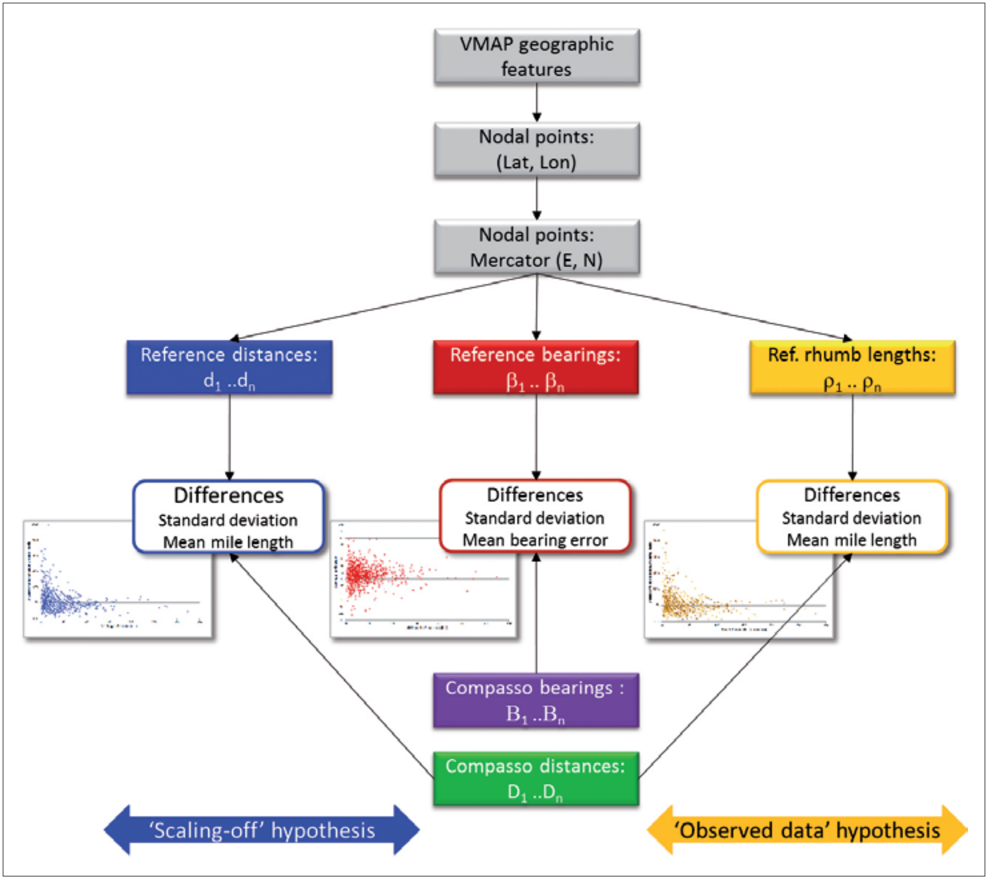

Figure 8.8 - *Schematic representation of the processing streams for the analysis of bearing and distance errors.*

However, as has been demonstrated in Chapters 2.5.2 and 2.5.3, the plane charting method introduces systematic deviations, additional to the random measurement errors that will be present in the data. To eliminate or rather avoid these plane charting deviations, the observations need to be corrected in the same way any sailor who navigates by dead reckoning will have to correct his estimates when plotting the ship's position on a Mercator chart. This *Mercator sailing* requires the estimated distance sailed to be corrected for the linear scale distortion of the projection. Compass bearings do not need to be corrected in Mercator sailing.[566]

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[566] It might be argued that compass bearings need to be corrected for magnetic variation, but although that correction should be applied, it has nothing to do with the distortion of the map projection, hence should not be associated with Mercator sailing.

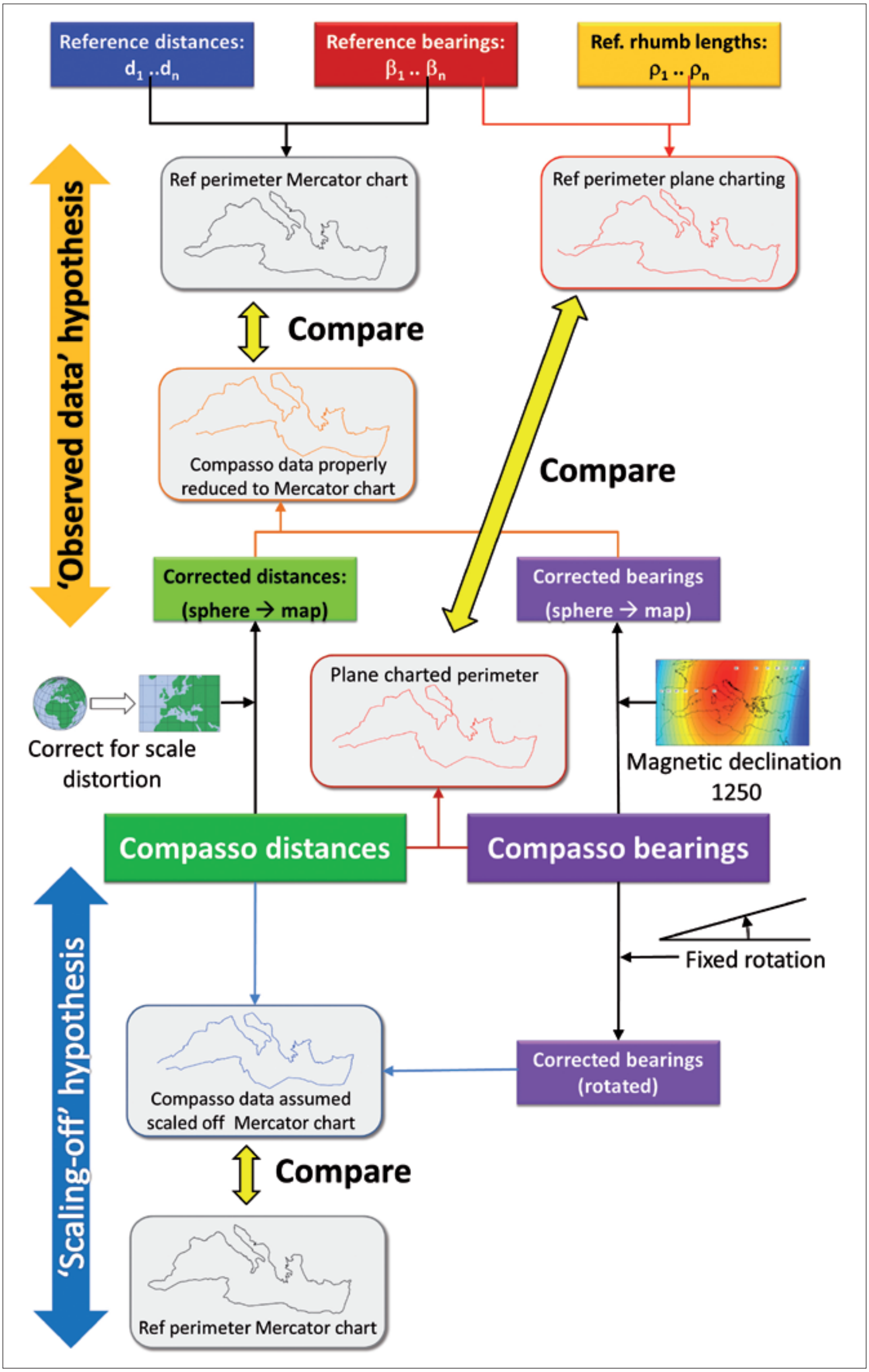

Figure 8.9 - *Schematic representation of the processing options for the calculation of the perimeter of the Mediterranean.*

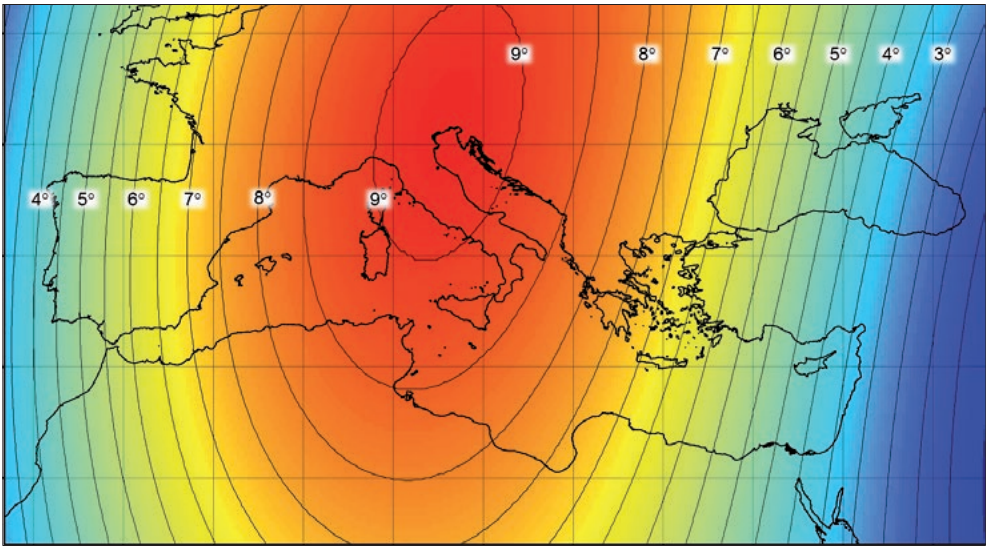

***Figure 8.10** – Magnetic declination from CALS7k.2 for the year 1250 (the positive values correspond with an easterly declination).*

In past publications magnetic declination has always been a phenomenon that was difficult to quantify for the Mediterranean region in the Middle Ages. Luckily much geophysical research has been done on magnetic field properties of the past and this has resulted in several generations of archaeomagnetic models. I have used the CALS7k.2 model, which models the earth's magnetic field from the present to 5000 BC.[567] Calculated for the year 1250, Figure 8.10 shows the pattern of magnetic declination over the area of interest.

The CALS7k.2 model is based on magnetic field data, extracted from lake sediments and archaeological artefacts. The model calculates a representation of the earth's magnetic field, strongly smoothed both in space and in time. Uncertainty estimates associated with CALS7k.2 model predictions are not well defined, but a more recent and much improved model, CALS3k.4b, does contain accuracy estimates.[568] Installing the

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[567] M. Korte, M., A. Genevey, C.G. Constable, U. Frank and E. Schnepp. "Continuous Geomagnetic Field Models for the Past 7 Millennia I: A New Global Data Compilation." *Geochemistry, Geophysics, Geosystems,* Vol. 6 (2005), No. 2: 1 28. Q02H16, doi:10.1029/2004GC000800.
M. Korte and C.G. Constable. "Continuous geomagnetic field models for the past 7 millennia: 2. CALS7K." Geochemistry, Geophysics, Geosystems, Vol. 6 (2005), No. 1: 1-18. Q02H16, doi:10.1029/2004GC000801.

[568] Monika Korte, personal communication, 11th July 2012. For a description of CALS3k.4: M. Korte, and C. Constable, "Improving geomagnetic field reconstructions for 0 - 3ka", *Phys. Earth Planet. Int.*, 188, 2011, 247-259.

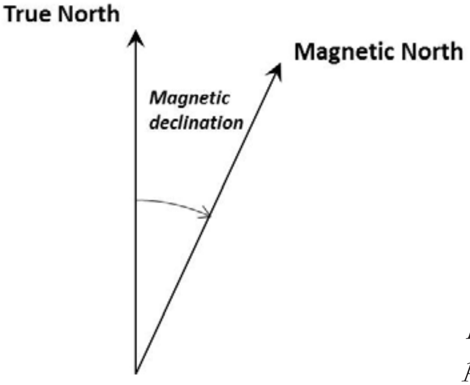

Figure 8.11 - Magnetic declination is the clockwise-positive angle from true north to magnetic north.

new model and re-doing all calculations at this stage would cause unacceptable delays, so I have opted for providing estimates of the quality of CALS7k.2 magnetic declination values, by providing comparisons with CALS3k.4b predictions in a number of locations around the Mediterranean Sea, Black Sea and along the North Atlantic coast. *Appendix V – Reliability of the CALS7k.2 archaeomagnetic model* shows time series of magnetic declination per location for both models covering the period 1100 AD to 1280 AD. An uncertainty band at 95% confidence level is shown around the values generated with CALS3k.4b. The curves have been generated using the online GEOMAGIA database.[569]

It is quite evident from the comparison that the figures from CALS7k.2 are heavily smoothed temporally. Figure 8.10 shows that they are also heavily smoothed spatially. Nevertheless such smoothed figures are more useful for showing a pattern over a large area than the raw magnetic declination details for one particular location, as quoted for example by Pelham.[570] These introduce the risk of focussing on non-representative values, leading to incorrect generalisations on magnetic declination for the entire Mediterranean area.

Figure 8.10 a magnetic declination pattern for the year 1250 that has a relatively small easterly (positive) value in the western Mediterranean (+6.2° at Gibraltar), increasing towards the east and reaching a maximum in the central Mediterranean (+9.7° at Venice). From the central Mediterranean towards the Levantine coast magnetic declination decreases to a minimum of +3.7° around Tartus in Syria.

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[569] http://geomagia.ucsd.edu/geomagia/index.php
F. Donadini, K. Korhonen, P. Riisager, and L. Pesonen, "Database for Holocene geomagnetic intensity information", *EOS, Transactions, American Geophysical Union*, 87(14), 2006, 137.
K. Korhonen, F. Donadini, P. Riisager, and L. Pesonen, "GEOMAGIA50: an archeointensity database with PHP and MySQL", *Geochemistry, Geophysics, Geosystems*, 9, 2008. doi:10.1029/2007GC001,893,

[570] Pelham 1980, 84.

The CALS3k.4 model shows the same pattern of magnetic declination with a ridge or peak in the central Mediterranean. However, it also shows that CALS7k.2 underestimates magnetic declination at Gibraltar by about 2°, is roughly correct in the central Mediterranean, but then overestimates the declination along the Levantine coast by 1° to 1½°, that is, for the year 1250. The error margin around the CALS3k.4 model in the Mediterranean varies, depending on location, from 4° to 6° (95% confidence level).

Both the CALS3k.4 and the CALS7k.2 models show a generally decreasing magnetic declination in the Mediterranean over time in the period of interest of this study, after a peak at about 1160, which is revealed by CALS3k.4 but is missed by CALS7k.2.

The Black Sea data show that CALS7k.2 overestimates magnetic declination in the entire Black Sea by about 0.8° to 1°, with a 95% confidence level of the CALS3k.4 model values of about 4°.

The comparison demonstrates that detailed conclusions cannot be drawn on the basis of magnetic declination estimated from these archaeomagnetic models, but that the general trend and magnitude of magnetic declination as calculated with CALS7k.2 is sufficiently accurate for the purposes of this study: the possible errors in the estimation of magnetic declination are an order of magnitude smaller than the errors found in the bearings of the *Compasso de Navegare* (see also Figure 8.45).

E. THE MERCATOR PROJECTION

A fundamental question concerns the role of the Mercator projection in this analysis. Superficially there appears to be a potential conflict between the use of the Mercator projection in the analysis of the *Compasso* data and the relationship of the *Compasso* with portolan charts. In Chapter 7 it has been shown that the coastline image of the Mediterranean and the Black Sea on portolan charts agrees piecewise with both the Mercator projection and with the Equidistant Cylindrical projection. These two projections are virtually indistinguishable in an area of limited latitude extent such as the Mediterranean region.

In order to test the hypothesis that the data in the *Compasso de Navegare* have been scaled from a portolan chart, one of these two projections *must* therefore be used in order to replicate the specific distortions the projection would have introduced into the data.[571]

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[571] Strictly speaking this would require the reference Mercator chart to be cut up into sub-charts, analogous to the composition of a portolan chart, each sub-chart with its own scale and with its own shear angle. I have done that, using the average results over all five charts from the cartometric analysis in Chapter 7. However, whereas the errors in the bearings reduce, the errors in the distances show a mixed pattern. These results suggest that those mean shear angles and scale differences cannot be uniformly applied to the *Compasso* data. Calculation of the optimum value of those parameters appears to go beyond the limited or even poor quality of the *Compasso* data, which is why I have not further pursued this line of inquiry.

I have used the Mercator projection rather than the Equidistant Cylindrical projection because the data reductions due to map projection distortion are much simpler to calculate for the Mercator projection than for the Equidistant Cylindrical projection, although the reductions would be numerically almost identical for the two projections, because of their similarity in an area of limited latitude extent.

An issue that is entirely separate from these considerations is the question in which coordinate space the analysis of the *Compasso* is best executed. The options are to analyse the data on the sphere (or ellipsoid), or in the map plane. As long as the appropriate reductions to the data are made, it doesn't really matter which of the two is chosen. Analysis in the map plane is computationally more convenient, as Euclidean geometry is much simpler than spherical or ellipsoidal geometry. I have therefore opted for analysis in the map plane. That choice having been made, the next question is *which* map projection to use. In principle any map projection will do, again, as long the appropriate data corrections are applied.

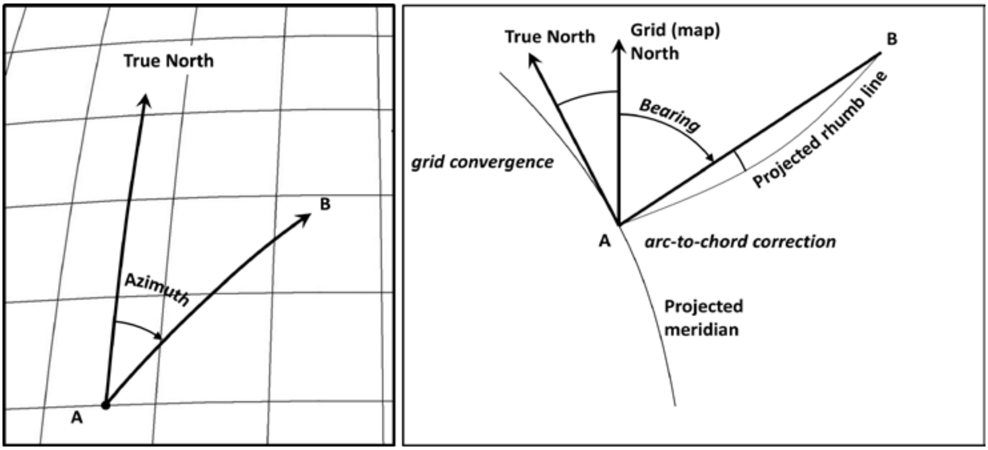

Figure 8.12 *- Relationships between azimuth (sphere or ellipsoid) and bearing (map plane).*

Distance corrections

In an arbitrary map projection a rhumb line will generally project as a curve. Additionally the length of that curve is generally affected by the scale distortion of the map projection. In a limited area the first error may be negligible, but not the second. In the Mercator projection a rhumb line projects as a straight line, but the *length* of a rhumb line section on a Mercator chart is different from the corresponding length of the rhumb line section on the sphere or ellipsoid, so the length does need to be corrected. The ratio of the two is the latitude-dependent scale factor of the Mercator projection. The method for calculation of the Mercator scale distortion is explained in Appendix II. Figure 8.9 shows where this correction has been applied in the reduction process.

Azimuth (bearing) corrections

As stated in the previous paragraph, in an arbitrary projection a rhumb line section projects generally as a curve. The bearing of the projected rhumb line in the map plane, i.e. its angle with grid or map north, is then different from the azimuth[572] of the rhumb line, i.e. its angle with the meridian on the sphere or ellipsoid. A small correction is therefore required, known as the arc-to-chord correction.[573] The exception is the Mercator projection, where the arc-to-chord correction for rhumb lines is zero.

These correction properties for rhumb lines and azimuths make the Mercator projection so exceptionally suitable for navigation purposes.

The above considerations are only relevant for the evaluation of the data with the *observed data* hypothesis. For the *scaled off data* hypothesis no corrections need to be applied to the data at all if they are compared to reference data from a Mercator chart. Usage of the Mercator projection for the analysis of the *Compasso* data therefore offers computational simplicity. I stress that the use of the Mercator projection for analysis of the *Compasso* data does not prejudice the conclusions in any way, that is, as long as the appropriate corrections are made to the data.

F. THE SYSTEM OF BEARING AND DISTANCE DESCRIPTION

The Compasso lists all distances in *millara* or *millaria*, i.e. miles, and all bearings in terms of winds, using the eight-wind system described in Chapter 1.2. Any bearing halfway between two of the eight main winds is termed a *half wind* and the terminology, e.g. for the half wind between Greco (= north-east) and Levante (= east) is: "enter greco et levante", or simply "greco ver levante". The order of the two main winds in the designation of such a half wind is arbitrary. The division into half winds creates a wind rose of sixteen points; a further division in two creates the thirty-two point wind rose with quarter winds as the smallest unit.

The angle between a half wind and the adjacent main wind is 22.5°. The *Compasso* divides any sector of 22.5° into eight equal parts of about 2.8°, that is, I have *assumed* the subdivision to be in equal parts; the *Compasso* itself does not state that at all.

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[572] Within the context of this thesis 'azimuth' refers in principle to an angle on the sphere (or ellipsoid), whereas 'bearing' refers to the corresponding angle in the map plane. However, in geodetic and navigational practice the terms 'azimuth' and 'bearing' are generally considered synonyms and the term 'compass bearing' is therefore also used in this thesis, in line with common usage, instead of 'compass azimuth'. The term *azimuth from A to B* normally refers to the azimuth of the *geodesic* from A to B, i.e. the shortest line connecting A and B. In the context of this thesis only the azimuths of rhumb lines are considered, unless explicitly stated.

[573] Guy Bomford, *Geodesy*, 4th ed. (Oxford: Oxford University Press, 1980), 186, 187.

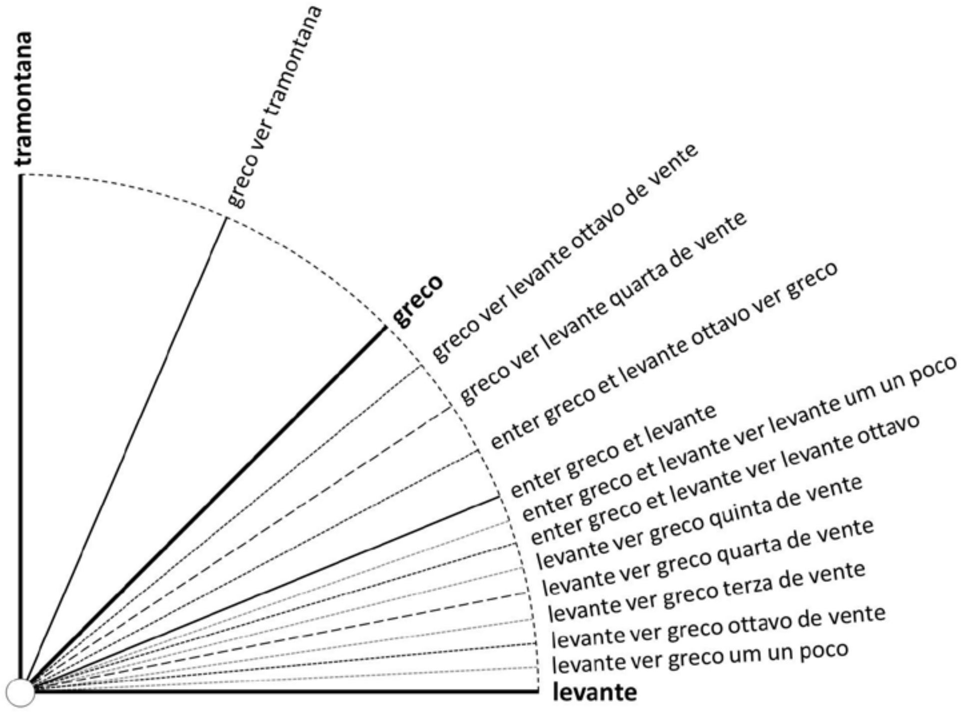

Figure 8.13 – *Principle of the naming system for course bearings in the Compasso de Navegare.*

About 17% of all bearing values provided in the *Compasso* use a finer resolution than a quarter wind. I have referred to these values as *high-resolution bearings*.

The distance values are all written in Roman numerals, in rounded figures, i.e. about 70% of them are multiples of ten miles and 20% are odd multiples of five miles. I consider the remainder of about 11% to be *high-resolution distances* and will analyse them separately from the high-resolution bearings. A high-resolution distance is usually not paired with a high-resolution bearing. Some 54% of the high-resolution bearings occur in peleio.

The mile appears to be the same unit of measure as the one used on portolan charts, but this needs be confirmed by the numerical analysis of distances.

G. IDENTIFICATION OF TOPONYMS

Identification of all toponyms of the *Compasso* proved to be a time-consuming and difficult activity. I used the list of toponyms provided by Piero Falchetta[574] as a starting

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[574] Piero Falchetta, "Manuscript No.10057 in the Biblioteca Marciana, Venice. A possible source for the Catalan Atlas?" *Imago Mundi* Vol. 46, 1994, 19-28; transcription of toponyms: http://geoweb.venezia.sbn.it/cms/images/stories/Testi_HSL/10057.pdf.

point and corrected and extended this list on the basis of the *Geonames* database[575] and Konrad Kretschmer's listing[576]. Occasionally I correlated the location description in the *Compasso* with 3D views and photographs of coastal geography in Google Earth. An additional and very useful extra source was a reproduction of a portolan chart by Petrus Roselli (1449) that came with a publication of a cartometric analysis of this chart by Peter Mesenburg.[577] The reproduction was on a large enough scale to permit reading of most toponyms. I gained access to Tony Campbell's web based list of toponyms[578] and Alberto Carpacci's "*La toponomastica nella cartografia nautical di tipo medievale*" well after I had completed my analysis of the *Compasso de Navegare* and the five portolan charts. A check of my interpretation of toponyms against Campbell's and Carpacci's turned out to be too time-consuming. A complicating factor is also that Carpacci lists the toponyms in alphabetical order instead of sequentially by geography, as Campbell does. I did cross-check my interpretation of the toponyms against Weitemeyer's, finding disagreement in only a few cases.

H. Interpretation of inter-island course legs; artificial legs

One of the differences between Lanman's analysis and mine is that I have attempted to identify *all* points mentioned in the *Compasso*, whereas Lanman didn't. That enables my calculation not only of the position error after a full round trip, as Lanman did for the location of Gibraltar, but also the errors in all intermediate points.

A second important difference is the following: although his report does not mention this, Lanman appears to consider each toponym mentioned in the *Compasso* to be associated with a single point. That is a reasonable, practical approach to the question how to associate the descriptions of locations in the *Compasso de Navegare* with actual Mediterranean coastal geography, but it is most probably incorrect where islands are involved. Certainly when it is assumed that the *Compasso* contains actually observed data, it is more likely that the distances are not measured between the centroids of islands, but rather describe the width of the amount of water separating these islands along the route sailed. Alternatively they might run from cape to cape or from port to port. I have assumed the *Compasso* data to specify the minimum distance between the islands. This necessitated the creation (in the GIS dataset) of several points per island, particularly in the Aegean Sea with its many islands, although in some straightforward cases of small islands I created a single point per island and applied a correction to the distances to that island. Lanman did not include the course legs between the Aegean islands in his dataset, but this principle *does* affect the courses along the Dalmatian coast he includes in his perimeter analysis. Lanman found that he was short of a significant amount of

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[575] http://www.geonames.org

[576] Kretschmer 1909 (1962), 559-687.

[577] Peter Mesenburg, *Kartographie im Mittelalter – Eine analytische Betrachtung zum Informationsinhalt der Portulankarte des Petrus Roselli aus dem Jahre 1449*, Karlsruher geowissenschaftlichen Schriften, Reihe C, Band 1. Karlsruhe: Fachhochschule Karlsruhe, 1989.

[578] http://www.maphistory.info/ToponymyMenu.html

length along that coast and corrected that by inserting an artificial course leg of the right bearing and distance to obtain a zero misclosure for the Adriatic Sea (see Figure 8.1 above). With the approach I have chosen, the insertion of an extra, computed course leg is unnecessary; the misclosure in the Adriatic I calculated is compatible in magnitude with other misclosures in the *Compasso* data.

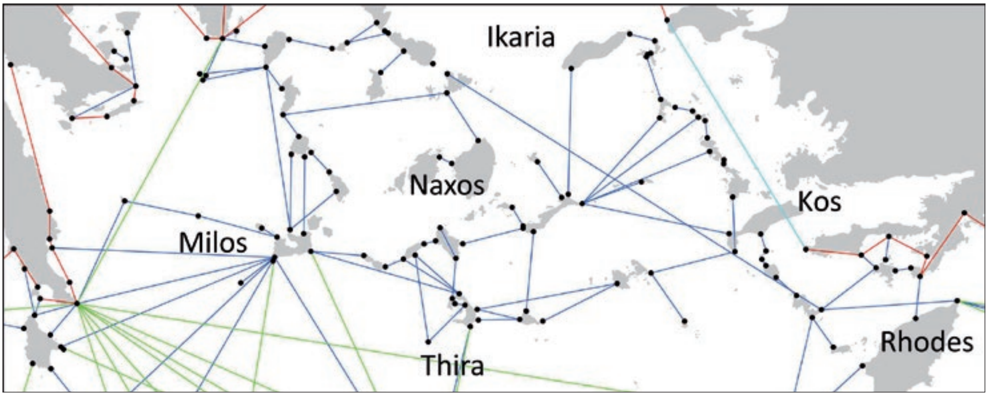

Figure 8.14 - *Example of the interpretation of inter-island course legs (Cyclades and Dodecanese islands in the Aegean Sea).*

The approach just described necessitates the insertion of calculated, 'synthetic' course legs covering the lengths of islands and is also required to close any gaps in the data in order to make the perimeters of the Mediterranean and Black Sea complete. In such cases I have calculated the bearing and distance from the coordinates in the reference chart, applying the appropriate kilometre-to-mile ratio for the inserted distances and correcting the calculated bearings with a fixed rotation angle or with the magnetic declination for 1250, depending on the type of calculation executed (see Sections 8.3.2B and 8.3.2C). Twenty-three synthetic bearing and distance pairs were thus inserted in the dataset for the perimeter calculation. Because of their calculated values (with appropriate corrections) they do not contribute to the calculated misclosures. They have also been excluded from calculations of the other statistics.

For thirty incomplete course legs that were part of the perimeter, i.e. course legs of which either the distance or the bearing was missing, the missing component was substituted by a calculated value.

I. Unidentifiable points; vector sums

Where I was unable to identify points in the perimeter of the Mediterranean or Black Sea, I combined successive bearing and distance pairs into a single vector. This happened on ten occasions, seven in the Mediterranean and three in the Black Sea. Nine of the ten vector sums were composites of only two courses, but from Khalkis to the

Knimis Channel between the island Euboea and the mainland of Greece, I was forced to combine four successive course legs into a single one. This combined leg is visible as the cyan coloured line in Figure 8.21.

Course legs with an unidentifiable start or end point that were not part of the perimeter have been ignored in the data analysis.

A particularly awkward sequence of bearing and distance pairs, which I could not analyse because of the many unidentifiable locations, occurs on pages 46 and 47 of Motzo's text. This text describes the passage from the Dardanelles to Istanbul. Attempts to plot these courses on a chart to give possible clues to the location of the nodes turned out to be futile; they appear to have been scaled off in a very roughshod manner, as many of them cut across land.

J. Recording of additional attributes

Apart from the distinction of the two main categories mentioned earlier:

1) peleio,
2) per starea data, further divided into:
    a) perimeter data,
    b) hanging traverses and shortcuts,

I recorded several useful aspects of the data in separate attributes:

- incomplete course leg;
- ignored course leg (duplicate or unidentifiable start and/or end points);
- impossible or improbable course leg;
- high-resolution bearing or distance.

K. Overview of the data

Table 8.3 provides a summary of the vital statistics of *the Compasso de Navegare*.

The *incomplete course leg* category refers to course legs of which either bearing or distance was missing. I found 58 of those, but for one of them neither distance nor bearing was given and this leg therefore also features in the *ignored course leg* category, which contains data of which I was unable to identify the start and/or end point of the leg and which were not part of the perimeter calculation, as mentioned above.

An important category is the *impossible or improbable course legs*. This category is composed mainly of course legs that cut across land. They will be discussed separately in Section 8.3.3 below. Also important are the high-resolution bearings and/or distances, mentioned in Section 8.3.2F above and analysed in Section 8.3.7 below.

The sub-basins listed in Table 8.3 are shown in Figure 8.15.

Data by category	**Number of legs**	**Comments**
perimeter	664	3 peleio double as perimeter course leg. See Section 8.3.9
inserted bearing-distance pairs	23	
vector sums	10	… consisting of 22 individual courses, counted in the perimeter
peleio	369	See Section 8.3.3
hanging traverses and shortcuts	297	
invalid or duplicate	42	Excluded from above. Includes a traverse of 25 legs between Aegean and Istanbul
Valid course legs by sub-basin		
Atlantic	24	See Figure 8.15
Western Mediterranean	547	See Figure 8.15
Central Mediterranean	416	See Figure 8.15
Eastern Mediterranean	221	See Figure 8.15
Black Sea	119	See Figure 8.15
Data aspects		
Incomplete	57	bearing or distance missing
Improbable or impossible	67	See Section 8.3.3
High-resolution bearings	227	… of which 123 are part of peleio See Section 8.3.7
High-resolution distances	151	See Section 8.3.7

Table 8.3 - *Dimensions of the Compasso de Navegare.*

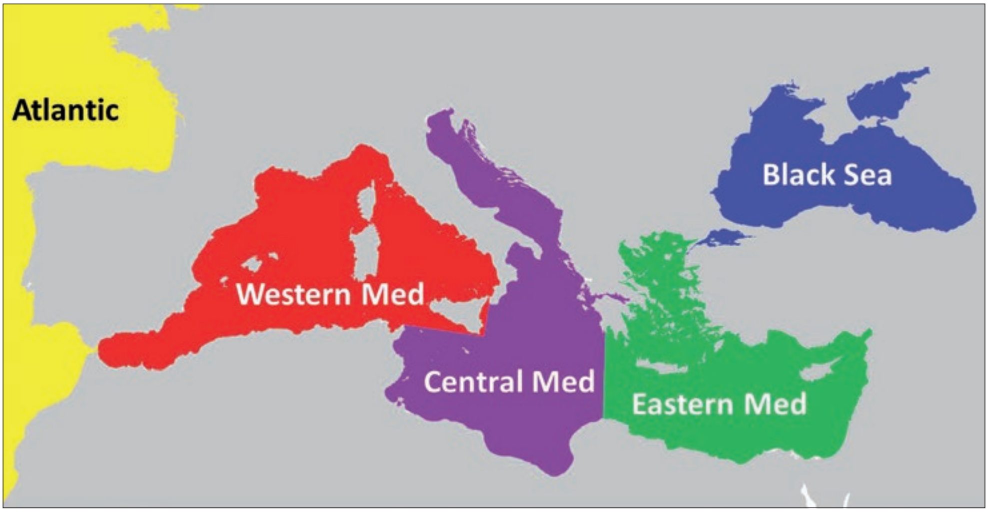

Figure 8.15 - *Division of the Mediterranean region into sub-basins.*

8.3.3 UNLIKELY OR IMPOSSIBLE COURSE LEGS

It is not new that portolans contain some strange data. Both Kretschmer and Kelley noticed this, but differ in their interpretation.[579] Kretschmer, speaking of the fifteenth century Rizo portolan, saw no reason to change his opinion that portolans in principle contain observed data, possibly enhanced with scaled off bearing and distance pairs that would have been added at a later date, after charts had become available. Kelley's interpretation is more far-reaching in that he questioned that portolan charts derive from portolans, the consensus view of which Kretschmer was an unwavering believer. Jonathan Lanman, aware of these opinions, claims that it is not true that courses cut across land, which would have been an indication of scaling off.[580]

Most of the course legs that I have labelled *impossible or improbable* are legs that cut across land in a significant way or cut off promontories that would have required the course leg to have been broken up in two or more legs with significant bearing differences. More course legs than the 66 labelled as such actually cut across land, but this often happens along a slightly concave coast. I have not counted those as *impossible*, assuming that, if they resulted from actual observation, the ship may have been out at sea by some distance, thus avoiding the coast. Furthermore, capes or promontories close to a port might have been counted as the start or end point of the course leg rather than the actual location of the port. After discounting those, 66 course legs remain which I consider impossible or at least suspect.

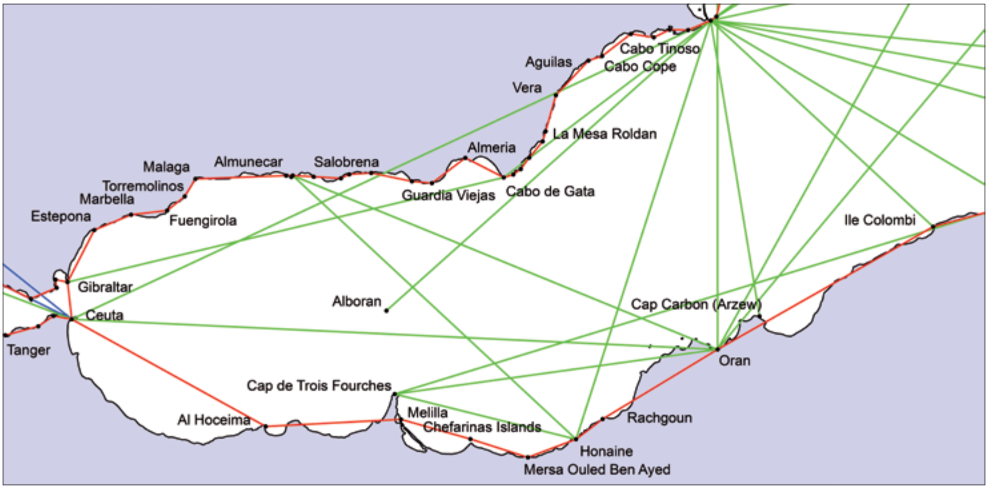

***Figure 8.16** – The Alboran Sea.*

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[579] Kelley 1995, 10 and Kretschmer, 94, 95.

[580] Lanman 1987, 20, 21: "It has been said that the pelagic courses sometimes cut across intervening land, suggesting that they may have been derived from charts rather from sailing experience. However, examination of the courses shows this not to be true. Considerable care seems to have been taken to select origins and destinations that give single, straight, unobstructed courses." Lanman also feels that the mentioning of navigation hazards en route is proof that these pelagic courses "obviously derive from experience".

Figure 8.16 provides a reasonably representative sample of *Compasso* course legs in the Alboran Sea and demonstrates what I have called *significantly cutting across land*. I did not mark the course from Oran to Honaine (red) as a course that cuts across land, assuming it may have been counted from Cap Falcon (northwest of Oran), but the *peleio* (green) from Cabo de Palos to Ceuta cuts across land too much and has been marked as an *impossible course*, as has the course leg from Melilla to Al Hoceima (red), in the latter case because Cap de Trois Fourches features separately as start or end point in other course legs.

Gautier Dalché has suggested that course legs that cut across land mean nothing, as they may be the result of combining several course legs into a single resulting one. This argument is far from convincing. The computation of a combined course leg would have been complex in the Middle Ages, but one might argue the compiler could have done that graphically. However, such combined course legs, particularly if they cut across land, achieve the opposite of providing a seaman with practical information on how to steer his ship to its destination. Instead they would have added to the navigational dangers that threatened a medieval ship. This may be illustrated with an anecdote from the 1970s in The Netherlands, when a foreign yachtsman, on holiday in Dutch waters, asked an old fisherman what course to steer from the mainland to the island of Schiermonnikoog, across the Waddenzee. The fisherman merely pointed to where the island could be seen temptingly close, about eight kilometres to the north. The motorboat captain followed this 'advice' and laid a straight course to Schiermonnikoog, instead of following the marked channel. The tide was falling and the hapless but naive skipper found himself stuck on the mudflats of the Waddenzee for a number of hours, his ship no doubt heeling at an uncomfortable angle. In short, it is not a good idea to combine courses, but whereas a seaman in the Dutch Waddenzee deals with sand and mud, the Mediterranean seaman would have to cope with rocks.

I provide some examples of impossible course legs, the first one in the Saronic Gulf near Athens in Greece. The course legs in Figure 8.17 have been colour-coded as explained in Section 8.3.1, *red* meaning perimeter courses, *blue* hanging traverses or shortcuts and *green* refers to *peleio*. The map is oriented north-up. The course leg from Megara to Piraeus cuts right across the island of Salamis in Greece. The one from Vidhion to Examilia, the westernmost location on this small map cuts across the Methanon peninsula. On the eastern side of the map the course leg from Akra Sounion to Akra Mandili, the southernmost point of the island of Euboea (not shown on the map) runs across the island of Makronisi. The course leg from Akra Sounion to Akra Mavroneri runs entirely over land.

However, the most interesting part is yet to come, viz. what these course legs look like on a portolan chart. That is shown in Figure 8.18. Plotting the same courses on the early fourteenth century Ricc 3827 chart shows that they hardly meet any obstacle at all. The excerpts from portolan charts shown in Figure 8.18 to Figure 8.20, as well as Figure 8.21 are oriented north-up.

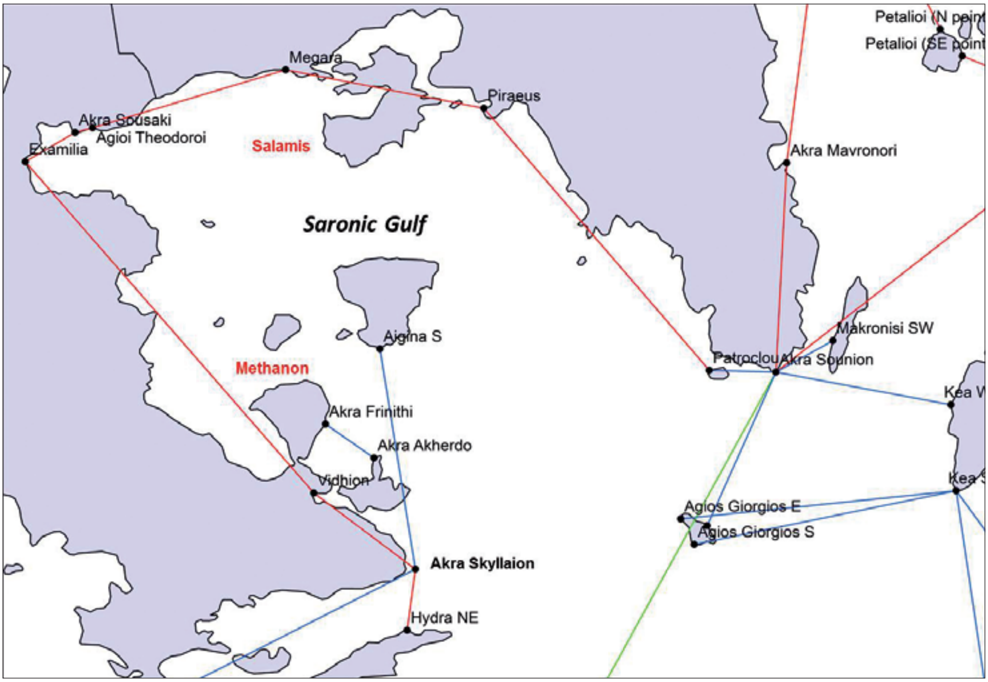

Figure 8.17 *- Impossible course legs in the Saronic Gulf.*

Figure 8.18 *- The same course legs on the Ricc 3827 portolan chart.*

The entire Methanon peninsula is missing, as is the island of Salamis, at least at the place where it is supposed to be. Megara does not feature on portolan charts; it does in the *Compasso de Navegare* under the name *Porto de Migra* and on the portolan chart the course from Megara to Piraeus is unobstructed. The course leg from Akra Sounion (*Capo de Colonne*) and Akra Mavroneri (*Capo de la Fata*) runs close to, but on the correct side of the coastline and finally Makronisi (dark red on the chart) does not obstruct the course to Akra Mandili. The same situation may be observed on the Carte Pisane and the Ricc 3827 chart, shown below.

Thus the initial question why on earth anyone would want to scale off a course that runs so obviously across land acquires an answer indicating a rational process when one looks more closely at these course legs on a portolan chart.

However, this is not always the case. Sometimes course legs do run conspicuously over land, even on a portolan chart; for example a direct bearing and distance pair is provided in the *Compasso* from Akra Artemision, the northernmost point of the island of Euboea to Akra Mandili, the south-easternmost point of Euboea. On the Ristow-Skelton No. 3 chart (Figure 8.20) and on the Ricc 3827 chart (Figure 8.18) this course leg runs diagonally across the island, but on the Carte Pisane it might be interpreted as nearly running parallel to its north-east coast.

That last course leg is shown on a modern chart to run diagonally across the island of Euboea in Figure 8.21. The cyan-coloured course leg between Nisis Passas and the mouth of the Rema is a vector sum of four bearing-distance pairs of which I could not identify the intermediate points, so it isn't surprising that two promontories are cut off and I have therefore not marked it as *impossible*.

Four peleio are stated to pass within 20, 20, 25 and 30 miles respectively of Skerki Bank (northeast of Tunis; see Figure 8.23). The direction to the reef at closest approach is provided for each. Skerki Bank is an extensive area of shallow sea and includes some notorious reefs. It is a rich source of artefacts from antiquity on account of the number of shipwrecks from that period. However, for an observer in the tallest mast of a large medieval ship, twenty meters above the water surface, the horizon is about sixteen kilometres away and 20 miles (~25 km) would be well beyond it. These course legs have therefore almost certainly been scaled off, contrary to Lanman's belief that it proves that this information stems from observation; unless one would wish to maintain that the information has been added after the charting of the first portolan charts from original medieval measurements had been completed.

A similar comment with the *peleio* from Capo Carbonara, the southeast point of Sardinia, to Capo Circeo between Rome and Naples states that the shoals of Scortezeto remain 80 miles away to the north-east. This is also impossible to observe; 80 miles (~100 km) is a very long way beyond the horizon of a medieval ship!

Figure 8.19 *- Course legs in the Saronic Gulf and across Euboea on the Carte Pisane.*

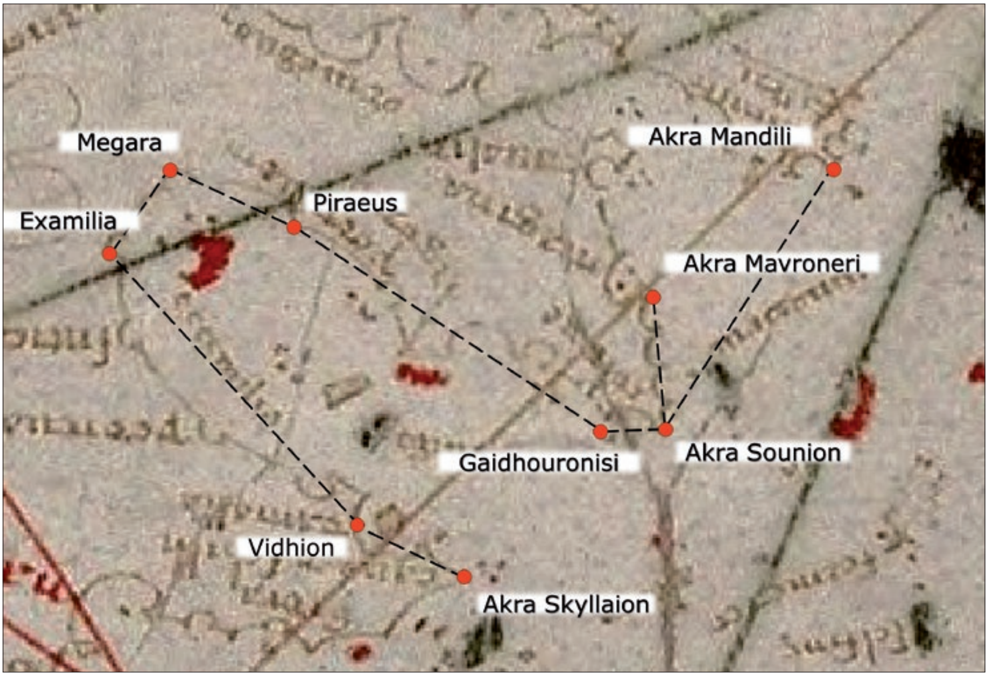

Figure 8.20 *- Course legs in the Saronic Gulf on the anonymous Genoese chart Ristow-Skelton No. 3.*

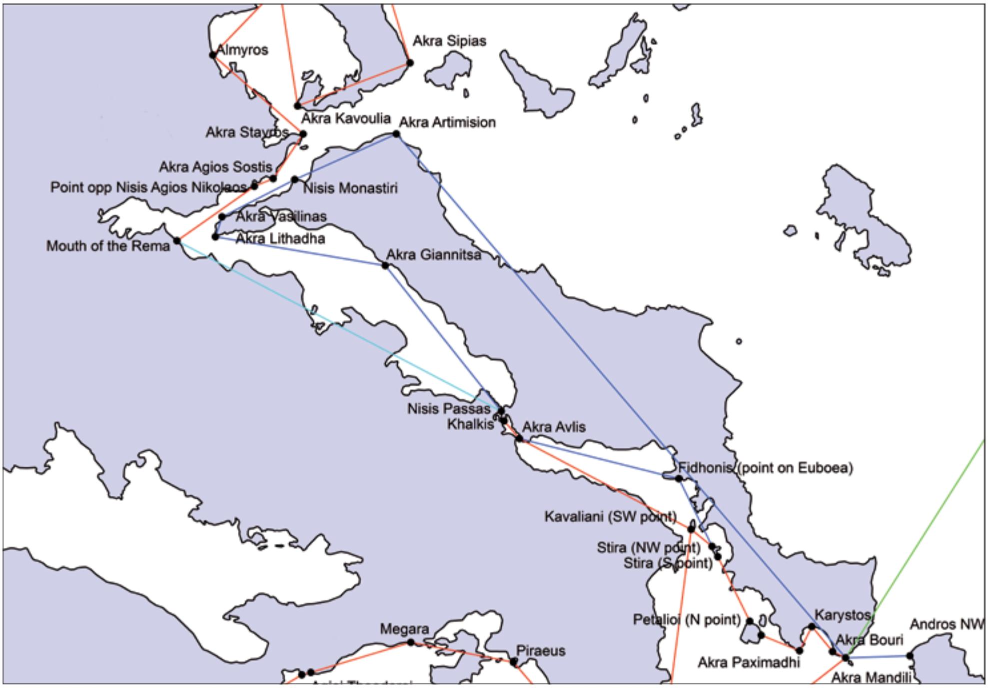

Figure 8.21 - *Course leg running across the island of Euboea.*

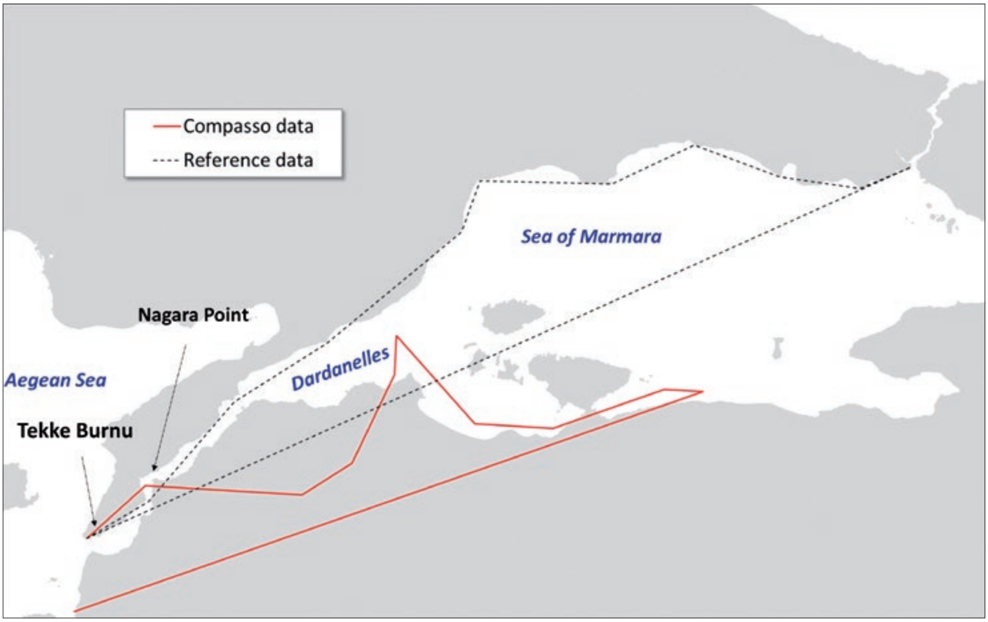

Figure 8.22 - *The courses through the Dardaneles to Istanbul and back.*

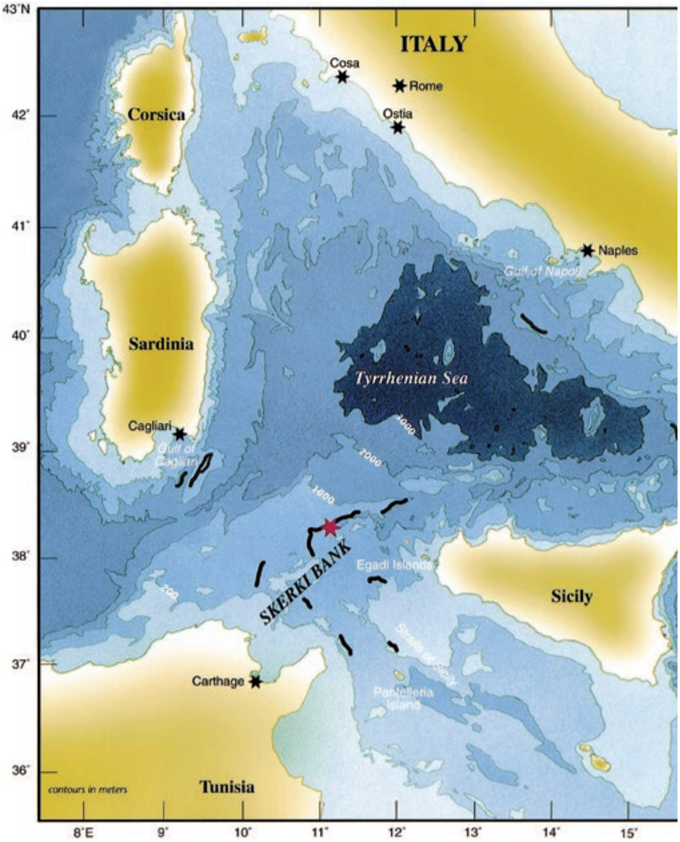

Figure 8.23 *- The location of Skerki Bank*
(image source: R.D. Ballard et al: The discovery of ancient history in the deep sea using advanced deep submergence technology,"Deep-Sea Research Part I", Vol. 47 (2000), 1591-1620. http://www.journals.elsevier.com/deep-sea-research-part-i-oceanographic-research-papers/ reproduced with permission).
The red star marks the location of Skerki Bank Deep Sea Archaeological Project. The black lines indicate original exploration in 1988 by the R/V Starella.

More evidence of scaling off is found in the course data between the Dardanelles and Istanbul. To begin with, a single bearing and distance pair is provided from Istanbul to Tekke Burnu (Cap Greco), the northern point of the Aegean mouth of the Dardanelles, as shown in Figure 8.22. In this figure I applied the same mile length and the same fixed rotation correction as for the Eastern Mediterranean and Aegean. A single direct course leg from Constantinople to the Aegean would have been of no practical use at all to a medieval ship, apart from the fact that it is 40% too short as well. The other course legs shown in Figure 8.22 look more realistic, but omit the navigation around Nagara Point, at which an almost 90° course change is required. However, the main problem appears to be the scale of the distances, which are all about 40% too short.

Alternatively one might hypothesize that it is just a coincidence that these courses all have large negative distance errors, but that seems not very likely. Less likely still is the possibility that a 40% longer mile than in the Aegean Sea was used by the medieval navigators for the stretch between the Aegean and Constantinople. The most likely explanation is that they have been scaled off by a person with an entirely incorrect notion of the scale and orientation of the chart he was using.

8.3.4 PER PELEIO, OR OPEN-SEA COURSE LEGS

Most of the peleio in the *Compasso de Navegare* are listed at the end of the *Compasso* in a number of sections that explicitly state that these course legs are peleio. This concerns a total of 331 bearing and distance pairs. Two of those are duplicates of others and have been excluded from the analysis. Another forty, occasionally labelled as peleio, but more often simply embedded among other data, are spread throughout the text. These are open sea course legs that are longer than 150 km. I analysed these two categories separately, but no systematic differences came to light, so my further analysis concerns the entire population of 369 peleio.

A. Bearings

Table 8.4 shows the sample standard deviation and the bias, i.e. the mean error of all peleio data and for three groups of data for the Western, Central and Eastern Mediterranean. Bearing values that deviate more than three times the sample standard deviation were rejected prior to calculating the standard deviation and bias. Interestingly many of the rejections were close to either 90° or 45°, i.e. the errors constitute one or two whole 'winds'. As mentioned above, the *Compasso* contains no peleio for the Black Sea.

Dataset	Number of peleio	Standard Deviation	Bias	Rejections
All data	369	9.4°	-5.5°	3.8%
Atlantic	2	-	-	
Western Mediterranean	202	8.7°	-3.9°	4.0%
Central Mediterranean	80	10.7°	-7.7°	2.6%
Eastern Mediterranean	83	8.7°	-7.9°	4.9%

Table 8.4 *- Peleio bearing statistics.*[581]

Figure 8.24 shows the bearing errors for all peleio data in degrees, ordered by length of the course leg. In accordance with Section 8.3.2C above, Figure 8.24 is valid for both hypotheses, i.e. that they may represent either scaled off or observed data; numerically that makes no difference. The rejected values are visible in this plot as having the largest values in absolute sense.

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[581] Three of the 392 peleio had no bearing information, only distance.

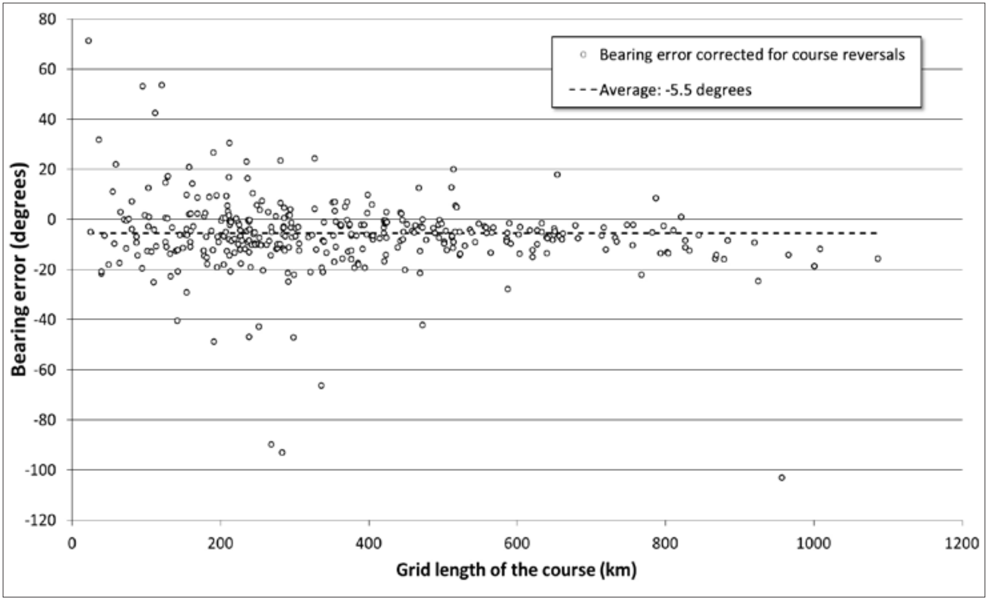

Figure 8.24 *- Bearing errors in the peleio.*

What immediately strikes the eye in the above figure is that the error is comparatively small for the longer course legs. At first sight this appears to agree reasonably well with the theoretical accuracy model formulated in Section 5.9. Based on the physics of the measurement process the navigation model shows higher *noise* up to about 100 NM (~200 km), then asymptotically approaches a more stable value. However, that is where the correspondence stops, because in the model the standard deviation of the bearing converges to about 3° for the longer courses, which is some three times smaller than the peleio in the *Compasso*.

B. DISTANCES

When the distances in the *Compasso* are considered to represent observations, they should be treated as estimates of the lengths of rhumb lines between points. However, when they are considered to have been scaled from a portolan chart, they should be compared with distances, scaled from a map that approximates portolan charts best, which is a map on the Mercator projection. With the naked eye it is hardly possible to discern any differences from the graphical rendering of the data, as is demonstrated by Figure 8.25 and Figure 8.26. I have therefore not reproduced the graph belonging to the *observed data* hypothesis in the following sections.

Whereas for the bearings a bias, or mean error, can be calculated, any bias or mean error in the (relative) distance errors is effectively a scale effect and is shown as a corrected value for the km-to-mile ratio. These values are listed in Table 8.5. For the calculation of the sample standard deviation I iteratively rejected any observations that were more than three times this standard deviation until no more values exceeding this threshold were flagged. I applied this principle not only to the peleio, but also to the per starea course data and the high-resolution bearings and distances.

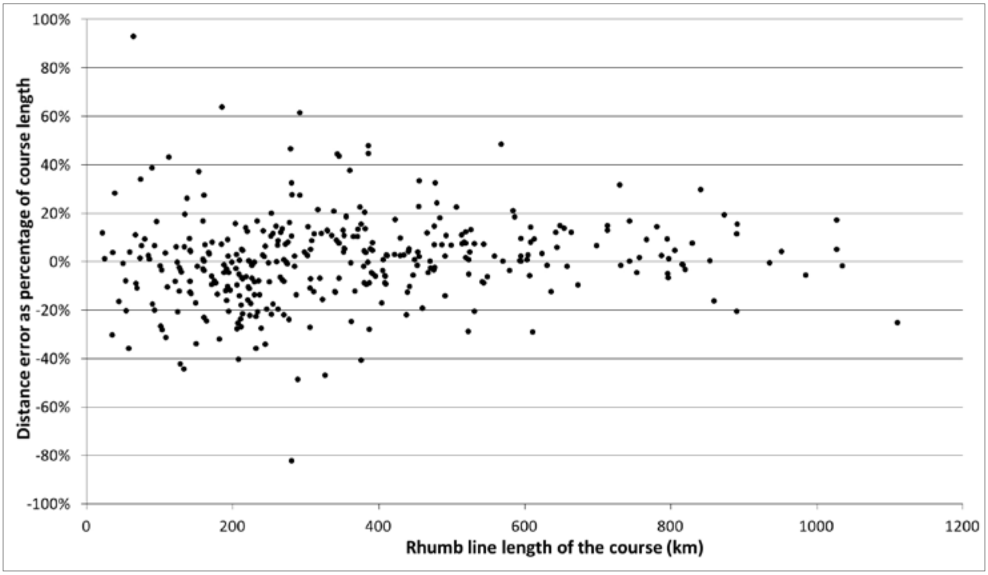

Figure 8.25 *- Distance errors in the peleio when treated as observed data.*

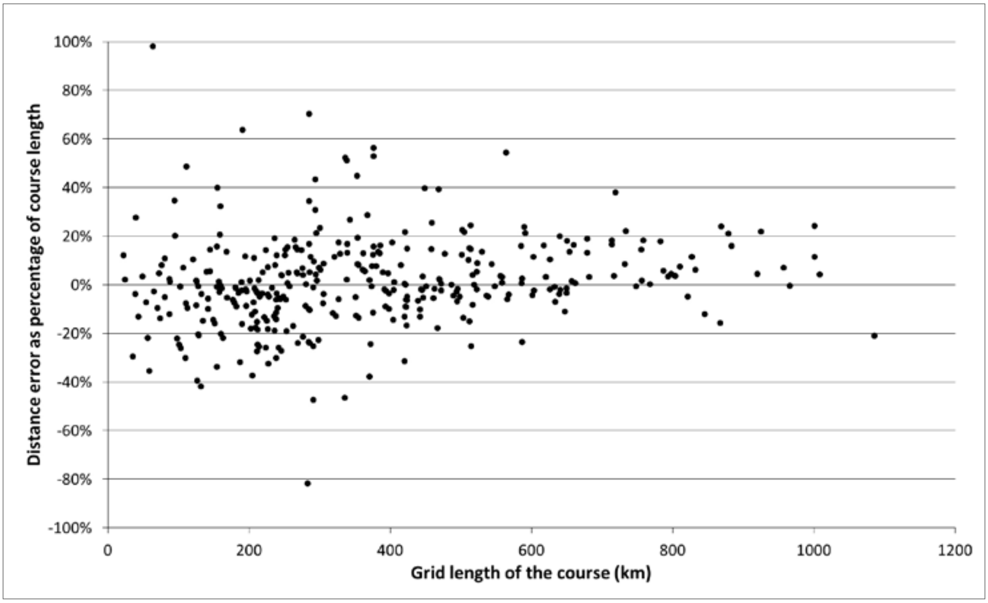

Figure 8.26 *– Distance errors in the peleio when treated as scaled off.*

	Standard Deviation (% of course length)	Length of portolan mile	Rejected observations
Observed	15.3%	1.177 km	2.4%
Scaled off	15.0%	1.214 km	3.3%

Table 8.5 *- Comparison of summary statistics of the peleio distances.*

8.3.5 INTERLUDE ON THE CALCULATION OF THE LENGTH OF THE PORTOLAN MILE

One of the pieces of information that may be derived from the wealth of data in the *Compasso* is the length of the mile used in medieval Mediterranean navigation. I describe three methods for calculating this length, but there may be more.

1. Compute the sum of all distances ($\mathbf{D}_i$, i = 1 ... n) in the *Compasso*, possibly split up in categories such as peleio, and divide this number by the sum of these distances computed from reference data ($\mathbf{L}_i$, i = 1 ... n):[582]
   $1 \text{ mile} = \sum_{i=1}^{n} L_i \Big/ \sum_{i=1}^{n} D_i$ km.
2. Calculate the km-per-mile ratio for each distance ($\mathbf{D}_i$, i = 1 ... n) in the *Compasso*, by dividing that by the corresponding correct reference length ($\mathbf{L}_i$, i = 1 ... n) and compute the mean of all ratio values thus computed:
   $1 \text{ mile} = \frac{1}{n} \sum_{i=1}^{n} \left(L_i \big/ D_i \right)$ km.
3. Calculate the mile-to-km ratio, i.e. the inverse to the ratio computed under point 2, for each distance in the *Compasso*:
   $1 \text{ km} = \frac{1}{n} \sum_{i=1}^{n} \left(D_i \big/ L_i \right)$ mile.

At first sight it seems to make no difference how it is done, but that is deceptive: the three methods yield three different figures for the length of the mile. For example, calculation of the length of the mile for the all the per starea distances in the Western Mediterranean yield the following different figures: 1.218 km for method 1; 1.406 km for method 2 and 1.210 km for method 3.

I suggest that the optimum way of calculating the mile length is method 3. This is best understood when approaching the problem from the formalism of the Least Squares Estimation method, which offers a structured way of formulating the problem and makes it quickly evident how the calculation should be done.

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[582] The Σ symbol in these formulas is a summation symbol. Hence $\sum_{i=1}^{n} D_i$ means that summation takes place over index ‘i’. $\sum_{i=1}^{n} D_i = D_1 + D_2 + D_3 + \ldots$ etc.

The random variable that is subject to measurement is clearly the distance $\mathbf{D_i}$ in miles. Assume that $\mathbf{D_i}$ is normally distributed with a standard deviation proportional to the corresponding true length $\mathbf{L_i}$. Each measurement value $r_i = L_i / D_i$ $(i = 1 \ldots n)$ may then be treated as a realisation of a normally distributed random variable and is an estimate of the kilometre-to-mile ratio. The best estimator of the kilometre-to-mile ratio, according the Least Squares criterion, is then simply the arithmetic mean of all r_i $(i = 1 \ldots n)$:
$r = \frac{1}{n}\sum_{i=i}^{n} (L_i / D_i)$, which corresponds with method 3.

Method 2 is suboptimum, because, when the inverse ratio is computed, i.e. the mile-to-kilometre ratio, the corresponding random variable $\mathbf{L_i} / \mathbf{D_i}$ is not normally distributed and consequently the arithmetic mean of the values $\frac{1}{n}\sum_{i=i}^{n} (L_i / D_i)$ for $(i = 1 \ldots n)$ is suboptimum for the mile-to-kilometre ratio.

Method 1 is equivalent to calculating the length of the portolan mile in such a way, that the sum of the residual errors in the measured mile values equals zero.[583] If that is not the case – and that would be the normal situation – also a suboptimal value for the conversion ratio will be computed.

8.3.6 Per starea, or coastal course legs

The majority of course legs in the *Compasso de Navegare* follow the coastline (per starea or *perimeter* data). In addition there are numerous single bearing and distance pairs or short traverses that either provide a secondary, usually shorter, route along the perimeter or do not 'tie back' into the main perimeter (see also footnote 563 on page 286). I have called these *shortcuts and hanging traverses*. The per starea course legs in the *Compasso* can be divided into a total of 673 bearing and distance pairs along the perimeter and 266 shortcuts and hanging traverses, several of which are incomplete, i.e. bearing only or distance only.

A. Bearings

A total of 883 valid bearing values were analysed. Seven bearings were most probably in error by 180° and were corrected for direction reversal.

A summary of the sample standard deviation (SD) of an individual bearing[584] and the bias (mean error) is provided in Table 8.6. For the *scaled off data* hypothesis these biases will correspond with the rotation angle of the sub-chart used. In Chapter 5.6 it has been shown that these rotation angles are different for the sub-basins distinguished above. However, for the *observed data* hypothesis, the bias or mean value ought to correspond with the average magnetic declination at the time of observation.[585]

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[583] Expressed in a formula:

[584] An individual bearing is a random variable and such it has a standard deviation.

[585] I did not compute the magnetic declination for every course leg mentioned in the *Compasso*, but only for the perimeter course legs. See Figure 8.45.

Dataset	Number of per starea measurements	Sample SD of an individual bearing	Mean (or bias)	Rejections
All data	883	28.8°	-6.8°	1.8%
Atlantic	16	21.3°	-1.9°	0
Western Mediterranean	319	24.1°	-9.1°	1.3%
Central Mediterranean	116	28.7°	-5.9°	3.4%
Eastern Mediterranean	322	24.4°	-4.1°	2.2%
Black Sea	110	23.1°	-9.1°	0.9%

Table 8.6 - *Summary of bearing statistics for all per starea data.*

The first row concerns all data, the next five show the results for subsets of the data grouped by sub-basin.

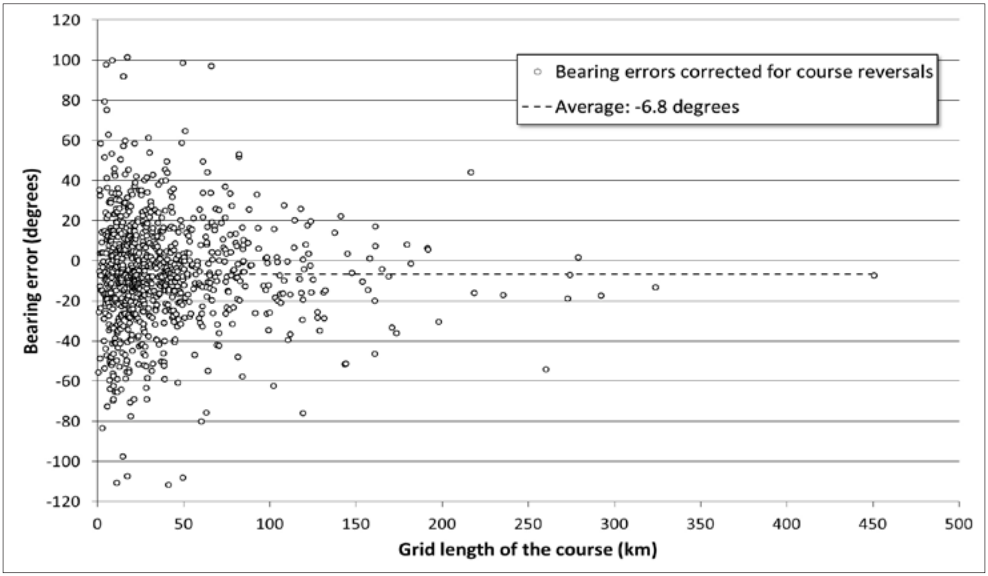

Figure 8.27 - *Bearing errors in all per starea data, ordered by grid length of the course (this graph includes the rejected values).*

B. DISTANCES

The distances may be analysed as observed or as scaled off data, as explained above. A comparison of the main statistics for the entire dataset is shown in Table 8.7 below.

	Standard Deviation (% of course length)	Length of mile	Rejected observations
Observed	37.3%	1.163 km	5.6%
Scaled off	37.3%	1.211 km	5.6%

Table 8.7- *Comparison of summary statistics of distances of per starea courses.*

In order to investigate whether any scale differences might exist for the *scaled off data* hypothesis I grouped the distances by sub-basin in the same way as the bearings. I calculated the length of the mile in a similar way, but expressed the result as a percentage of the scale of the Western Mediterranean data and the sample standard deviation (SD) for the scale differences has been calculated analogously to that of the mean bearing values in Table 8.6.

Dataset	Length of the mile	Relative scale	SD of relative scale
Atlantic	1.311 km	92%	8.1%
Western Mediterranean	1.210 km	100%	1.9%
Central Mediterranean	1.316 km	92%	3.8%
Eastern Mediterranean	1.196 km	101%	2.2%
Black Sea	1.179 km	103%	3.6%

Table 8.8 - *Scale differences per sub-basin in all distances of per starea data (hypothesis only).*

Figure 8.28 shows the distance errors in all per starea distances for the *scaled off data* hypothesis, expressed as a fraction of the length of the relevant course leg. The largest errors occur in the shortest legs. A remarkable feature is the series of arc patterns. These are artefacts (artificial by-products) of the distance values in the *Compasso* being mostly provided to the nearest five or ten miles. They are also visible in Figure 8.30 but in that case the artefact is caused by the high-resolution distances being provided to nearest mile. See Figure 8.33 below for a confirmation of this explanation.

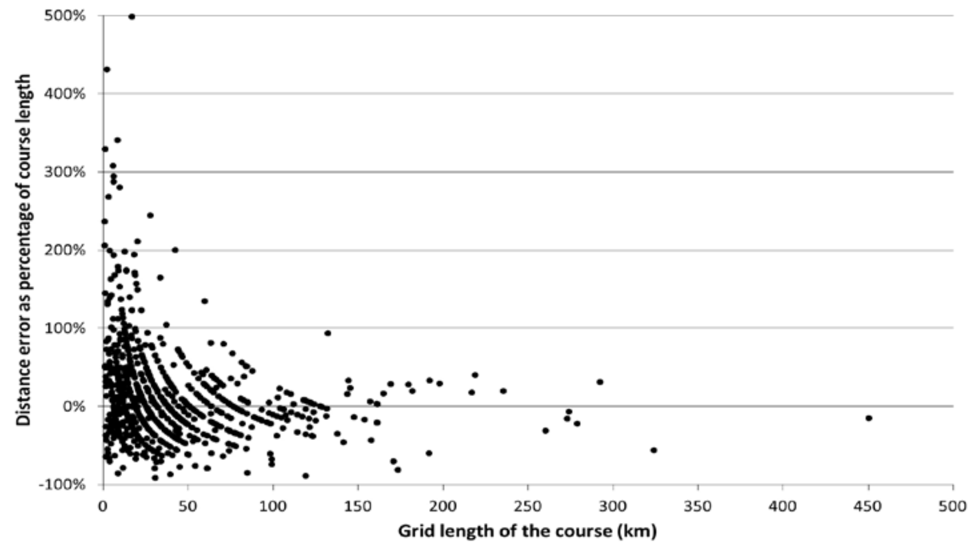

Figure 8.28 - *Distance errors in all per starea data, treated as scaled off (based on different mile lengths per sub-basin).*

8.3.7 HIGH-RESOLUTION BEARINGS AND DISTANCES

About 17% of the data in the *Compasso de Navegare* consists of high-resolution bearings. Kelley arrived at a figure of 21% of "non-standard bearings", as he called them, but his percentage was based on a sample of data only.[586] The definition of a *high-resolution bearing* used in this study is any bearing described to better than a quarter wind (11¼°). This is based on the fact that the smallest unit on a thirty-two point wind rose is a quarter wind.

Most distance values (about 70%) in the *Compasso* are multiples of ten miles; approximately 20% are odd multiples of five miles. The remainder of the distances contained in the *Compasso*, which rounds to 11%, have a greater resolution than five miles.

The peleio and per starea data form separate, non-overlapping datasets, but the high-resolution bearings and distances are composed of members of those two categories; each high-resolution element also features as a peleio or as a per starea course leg. Of the high-resolution courses 54% are peleio, the remaining 46% are per starea course legs. The numerical summary of the data is shown in Table 8.9.

Dataset	Standard deviation	Bias	
Distances	46.5%	Km / mile ('observed')	1.297
		Km / mile ('scaled off')	1.359
Bearings	17.5°	Mean error	-8.6°

Table 8.9 - *Accuracy summary of high-resolution data.*

Figure 8.29 shows the errors in the high-resolution bearings. The relative errors in distances with a finer resolution than five miles are shown in Figure 8.30 below.

In Figure 8.30 the three highest values of 700%, 257% and 225% have been omitted; they plot beyond the range of the vertical axis.

As indicated in Section 8.3.4B above, only the distance errors compared to the (correct) *grid* distances are shown, i.e. corresponding with the *scaled off data* hypothesis. That doesn't mean I did not consider the *observed data* hypothesis, but the differences between the grid lengths and the rhumb line lengths of these relatively short course legs are so small that the graphs would be practically identical.

Comparison of the bearings with the length of the respective course legs reveals that the high-resolution bearings are associated with some very long course legs, up to nearly 1100 km, whereas the high-resolution distances occur only in short courses of up to 90 km. 54% of high-resolution bearings occur in *peleio*.

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[586] Kelley 1995, 10.

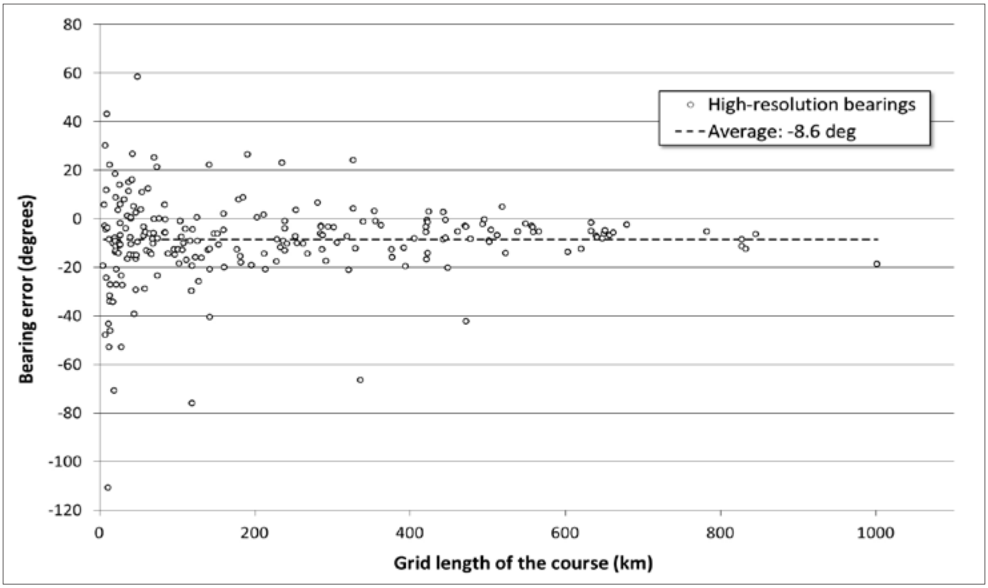

Figure 8.29 - *Bearing errors in high-resolution data.*

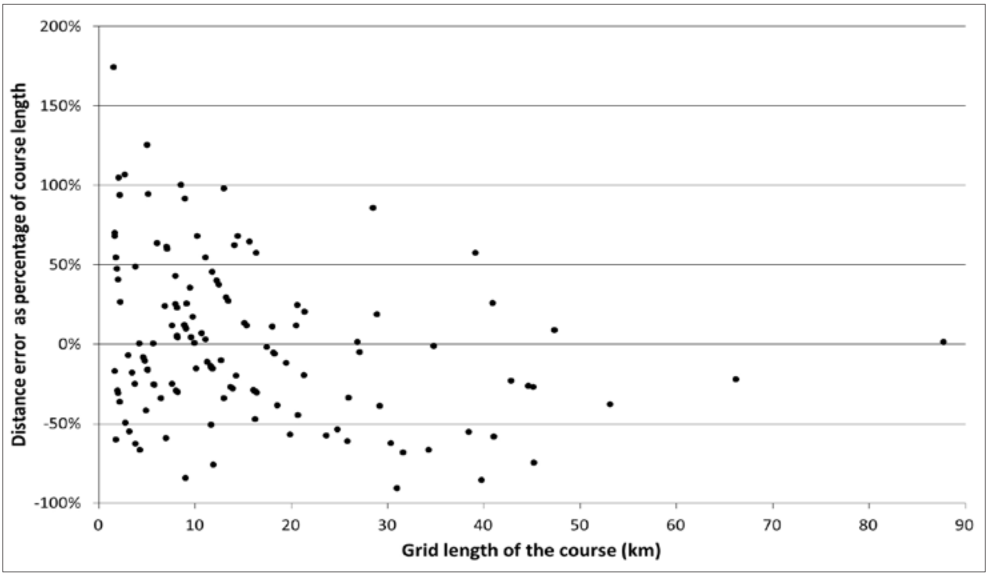

Figure 8.30 - *Relative errors in high-resolution distances, treated as scaled off.*

The higher resolution of the data in this subset compared to the remainder of the data invites the interpretation that their accuracy is higher, that they have observed, or scaled off, with greater care than the rest of the data. However, Table 8.10 demonstrates that this is not the case: their accuracy is not at all superior to the other data in the *Compasso.*

The standard deviation of the bearings is worse than that of the *peleio,* but better than the remainder of the data. It will have to be borne in mind that 54% of the high-resolution bearings belong to *peleio.*

Sample standard deviations of:	per peleio	per starea	hi-res data
Distances	15%	37%	47%
Bearings	9.5°	24.8°	17.5°

Table 8.10 *- Summary of high-resolution data accuracy, compared with the other data. The values for the distances have been rounded off to the nearest integer values.*

The accuracy of the high-resolution distances is considerably worse than that of the other distances. Even more striking is the fact that the biggest relative errors are in the four shortest distances: the shortest, a distance of 700 m in reality, was estimated to be 4 miles, or about 5.2 or 5.5 km, which constitutes the 700% error mentioned above. Although the error model presented in Chapter 5 suggests a lower accuracy of very short distances, the errors of the high-resolution distances are considerably larger than the values computed with this model.[587] Apart from distances less than 10 km I cannot see much difference in the relative errors in shorter and in longer distances.

The calculated length of the mile of 1.359 km for the high-resolution distances is quite different from the value calculated from both the *peleio* and all the *per starea* distances (the distances with the four largest errors have been excluded from the calculation of the km-to-mile ratio). This deviating value is almost certainly caused by the errors in this dataset.

Summing up, the accuracy of the high resolution bearings and distances is worse, rather than better than that of the rest of the data.

8.3.8 SUMMARY AND ANALYSIS OF THE ERRORS IN BEARINGS AND DISTANCES

A. ERROR SUMMARY

The following three tables contain a repetition of the data provided in the previous sections to save the reader having to page back through the thesis.

Table 8.11 summarises the sample standard deviations, computed for the bearings (in degrees) and for the distances (as a ratio of the distance). The first and second rows provide the results for that *Compasso* data, treated as a single dataset. The remaining five rows are valid only for the *scaled off data* hypothesis. The bearings are not affected by the

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[587] See Figure 5.12.

difference between these hypotheses because of the bearing-preserving properties of the Mercator projection.

Dataset	bearings		distances	
	per peleio	per starea	per peleio	per starea
All data (observed)	15.0°	28.1°	15.3%	37.6%
All data (scaled off)	15.0°	28.1°	15.0%	37.5%
Atlantic	--	21.3°	--	34.4%
Western Mediterranean	15.3°	24.1°	12.9%	35.3%
Central Mediterranean	11.8°	27.1°	18.9%	41.6%
Eastern Mediterranean	15.5°	24.8°	16.4%	38.7%
Black Sea	--	21.9°	--	37.3%

Table 8.11 *- Sample standard deviations in per peleio and per starea course legs.*

	mean bearings		length of the mile and relative scale differences by area			
	per peleio	per starea	per peleio		per starea	
All data ('observed')			1.177		1.163	
All data ('scaled off')	-5.5°	-6.8°	1.214		1.211	100%
Atlantic	--	-1.9°	1.282	90%	1.311	92%
Western Mediterranean	-3.9°	-9.1°	1.238	100%	1.210	100%
Central Mediterranean	-7.7°	-5.9°	1.214	102%	1.316	92%
Eastern Mediterranean	-7.9°	-4.1°	1.153	107%	1.196	101%
Black Sea	--	-9.1°	--	--	1.179	103%

Table 8.12 *– Provisional biases in per peleio and per starea course legs bearing biases in degrees and length of the mile in kilometres.*

Table 8.12 contains the same row division as Table 8.11, but the data displayed are the *biases* in the respective data categories. For bearings this refers to the mean error, which should be interpreted differently depending on the hypothesis under consideration. For the *scaled off data* hypothesis they are estimates of the different rotation angles of the component charts, but for the *observed data* hypothesis, the mean bearing values are likely to reflect the effects of magnetic variation over the different regions. The biases in the per starea data are provisional; the final values will only be determined after the perimeter calculations in Section 8.3.9.

For the distances the story is a bit more complicated. Because the length of the mile used in the *Compasso de Navegare* is unknown and needs to be calculated from the data itself, any bias in the distance data results in a different mile length. The variations in the mile length have been calculated for the *scaled off data* hypothesis. As such these differences may be explained from scale differences in the component charts. The percentages shown behind the mile length figures in Table 8.12 reflect the *relative* scale differences of those component charts. These percentages are only valid for the column in which they are shown and are relative to the scale of the Western Mediterranean, which is therefore shown in both columns as 100%. As with the bearing biases, the values for the per starea data are provisional. Final values are determined after the perimeter calculations of Section 8.3.9.

B. SHORT VERSUS LONG COURSE LEGS

The first observation to make from Table 8.11 is the evident poor accuracy of both bearings and distances. The peleio data are considerably more accurate than the other data, as Lanman had already observed, and appear to comprise a separate dataset. This is underlined by the differences between the biases in the *peleio* and *per starea* bearing data per sub-basin, shown in Table 8.12 above. However, the accuracy of both data categories is poor and compares unfavourably with the navigation accuracy model presented in Chapter 5.9.2.

What is most striking about all data, per peleio and per starea data alike, is that shorter course legs tend to have larger errors both in bearings and distances. Whereas the navigation accuracy model from Chapter 5.9.2 does indeed indicate a poorer accuracy over shorter distances, the actual errors in the *Compasso* are *extremely* large for short distances, so large, that it is very improbable that these values are the results of observations. Distances of 10 km are so short that no sailor who is not seriously geographically challenged will overestimate them by the amount seen in the data, i.e. by a factor from two to six. The same holds for the bearings: short course legs within line of sight ought not to end up with errors of forty degrees or more. Any medieval sailor making such errors would have been completely clueless as a navigator. However, these errors *do* make sense for data that have been scaled from a pre-existing portolan chart, with its exaggeration of coastal detail. The same pattern is visible in the bearings of the peleio, although not in the distances. This stands to reason, as there are by definition no very short peleio.

To verify that this *short distance* effect may be caused by scaling from a portolan chart, I calculated bearings and distances from the series of coastal points of the Carte Pisane, scaled off for the cartometric analysis in Chapter 7: *Cartometric analysis of five charts*.

I rounded the bearings to the nearest quarter wind and the distances to the nearest multiple of ten miles and compared them against reference values calculated from the Mercator coordinates of the same points on the reference map.

A sample section from the Aegean Sea, scaled from the Carte Pisane, is shown in Figure 8.31 and Table 8.13 as an example. I have made no effort to select navigable traverse legs along the coast; hence, some legs cut across land. For the calculation and the point I am trying to make this makes no difference. The bearing and distance errors of this sample, shown in Table 8.13, have *not* been rounded to the nearest quarter wind and ten miles respectively, the values shown for the entire Carte Pisane in Figure 8.32 and Figure 8.33 have.

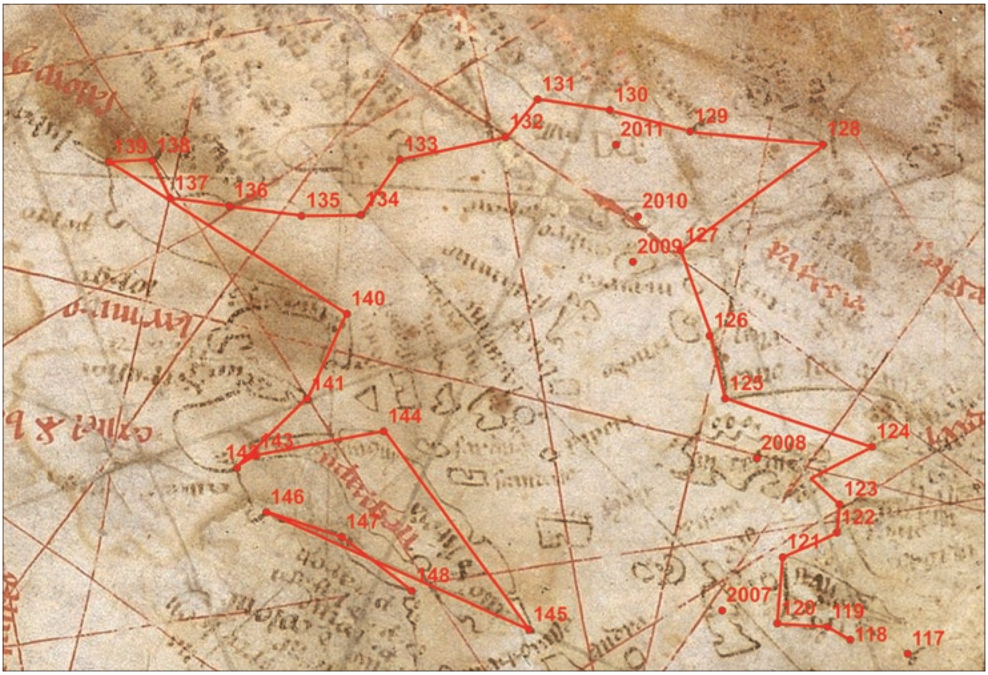

Figure 8.31 *- Fragment from the Carte Pisane showing the Aegean Sea with a calculated traverse.*

All results for the Carte Pisane (431 bearing-distance pairs) are summarised in Figure 8.32 and Figure 8.33 and are presented in the same manner as the *Compasso* data, i.e. ordered by length of the course leg.

The similarity with the *Compasso* data is unmistakable: the same pattern and the same order of magnitude of the errors are visible in the shorter distances. Also the arc pattern, caused by the rounding process, is visible. A version of the graph using scaled off values that were *not* rounded didn't show this arc pattern, but is omitted here. The Carte Pisane shows less exaggeration of coastal detail than later charts, but given the fact that it is roughly contemporary with the *Compasso de Navegare,* I felt no other portolan chart could be used for this comparison.

A conclusion that the bearings have been scaled off would be consistent with the conclusion from Section 5.7-D that potentially suitable compasses only became more widely used in the first half of the fourteenth century.

From	Name	To	Name	Bearing error	Distance error
118	Teke Burnu	119	Kocak Burnu	-4.6°	-25%
119	Kocak Burnu	120	SW point opp Chios	-23.1°	39%
120	SW point opp Chios	121	NW point Karaburun	-10.2°	-17%
121	NW point Karaburun	122	Deve Burnu (Foca)	-28.3°	-7%
122	Deve Burnu (Foca)	123	Aslan Burnu	7.9°	32%
123	Aslan Burnu	124	Egribucak Burnu	40.0°	-42%
124	Egribucak Burnu	125	Karanlik Burun	-7.3°	55%
125	Karanlik Burun	126	Tuzla Burnu	-25.8°	10%
126	Tuzla Burnu	127	Tekke Burnu	-24.1°	51%
127	Tekke Burnu	128	East point Gulf of Saos	9.9°	11%
128	East point Gulf of Saos	129	point east of Sultanice Deresi	5.5°	19%
129	point east of Sultanice Deresi	130	Nisida Thasopoula	2.0°	-66%
130	Nisida Thasopoula	131	Akra Apollonias	22.0°	-34%
131	Akra Apollonias	132	Cape Monte Santo	65.5°	-64%
132	Cape Monte Santo	133	Akra Ambelos	17.5°	24%
133	Akra Ambelos	134	Akra Paliourion	-51.0°	129%
134	Akra Paliourion	135	Akra Kassandras	-5.1°	-8%
135	Akra Kassandras	136	Akra Pirgos	-69.1°	125%
136	Akra Pirgos	137	Akra Epanomi	-35.8°	-35%
137	Akra Epanomi	138	Kato Karaburnu	4.1°	79%
138	Kato Karaburnu	139	Loudhias Potamos	-17.2°	88%
139	Loudhias Potamos	140	Akra Sipias	-36.0°	-6%
140	Akra Sipias	141	Akra Stavros	-31.7°	71%
141	Akra Stavros	142	Akra Knimis	7.3°	51%
142	Akra Knimis	143	Akra Lithada	41.7°	162%
143	Akra Lithada	144	Akra Artemision	18.5°	45%
144	Akra Artemision	145	Akra Mandili	4.4°	-17%
145	Akra Mandili	146	Akra Theologos	-10.8°	10%
146	Akra Theologos	147	Point opposite Khalkis	-15.2°	2%
147	Point opposite Khalkis	148	Akra Agia Marina	1.4°	-4%

Table 8.13 *- Errors in scaled off bearings and distances on the Carte Pisane in the Aegean Sea. The numbers correspond with the point numbers in Figure 8.31.*

For the longer course legs in the *Compasso de Navegare* it is impossible to tell from the bearing and distance values whether they result from observation or from scaling off, but one thing is evident: in either case an extremely poor job was done. Distances of around 100 km come out reasonably well, but bearings do not and bearing should have been the more accurate observable of the two according to the accuracy model presented earlier.

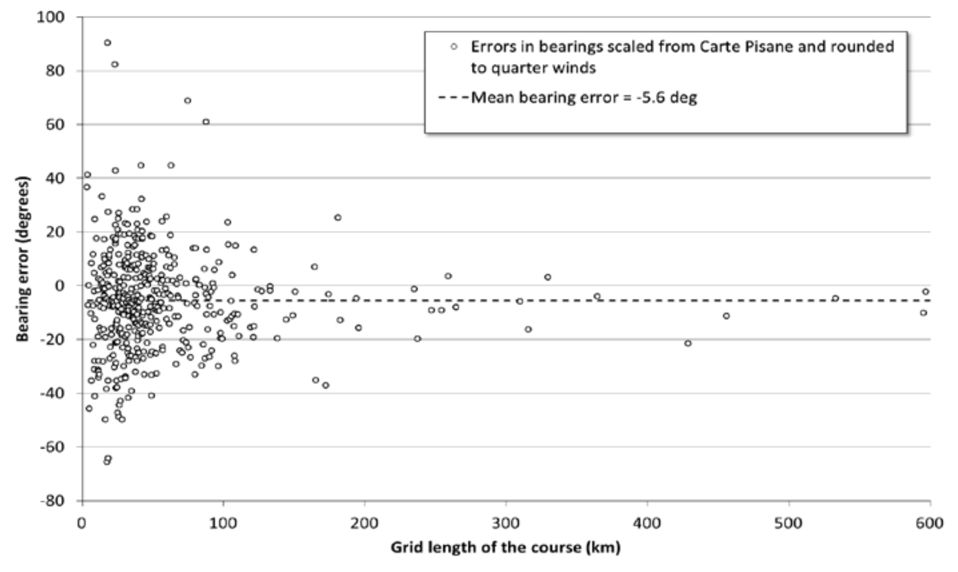

Figure 8.32 *- Bearing errors of courses, scaled from the Carte Pisane.*

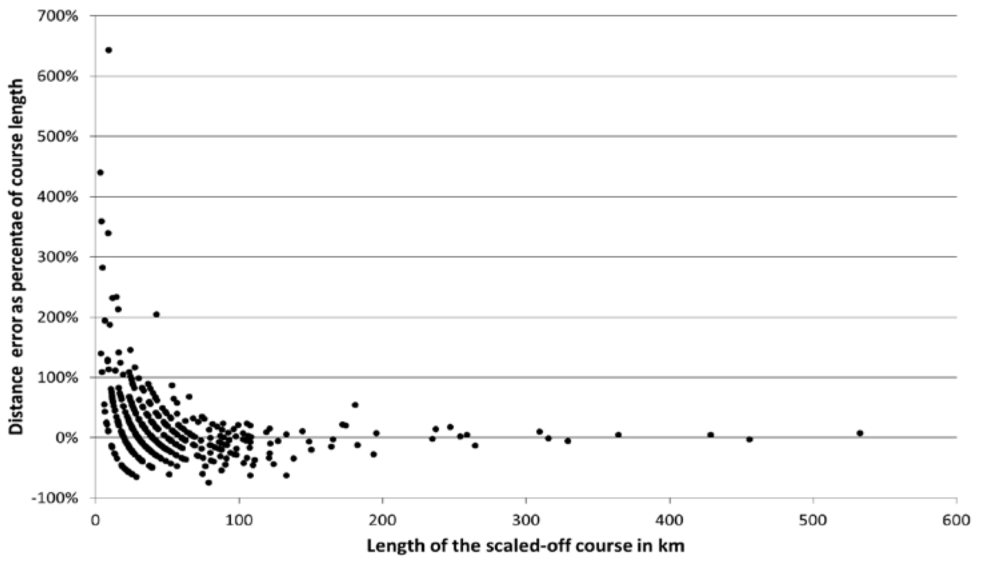

Figure 8.33 *- Relative distance errors of courses, scaled from the Carte Pisane.*

It cannot be established whether the high-resolution data has been generated with the *intention* of creating more accurate data. This data is less, not more accurate than the other data. For the distances, which mostly belong to short, coastal course legs, the low accuracy can be explained by the scaling off process, as the exaggeration of coastal detail on a portolan chart would have made any attempt to scale off accurate data a priori futile. However, the high-resolution bearings belong to a large extent to peleio and for such longer course legs it ought to be possible to scale off data more accurately than the *Compasso* data shows. Figure 8.32 demonstrates this quite clearly. The most likely explanation for the gap between achievable and achieved accuracy of bearing data is the medieval attitude to accuracy which John Kirtland Wright summarised in the title of his chapter "Accuracy not deemed necessary".[588]

The following two provisional conclusions may be drawn from the separate analysis of the bearing and distance errors.

1. The *Compasso de Navegare* does not contain averages of many measurements of the same bearing or distance, as has been hypothesized in much portolan chart literature. The magnitude of the calculated standard deviations, 28° and 37.5% for bearings and distances of the coastal perimeter data respectively, are simply too large and leave no room for the option that these figures are averages, calculated or estimated from multiple measurements of a single bearing or distance.[589]
2. Much if not most of the data in the *Compasso* appears to have been scaled off and the scaling off process was of a very poor quality.

8.3.9 PERIMETER TRAVERSE CALCULATIONS

From a contiguous sequence of bearing and distance pairs in the *Compasso de Navegare* the coordinates may be computed of the nodes of the traverse, relative to its first point. These may then be compared with their known reference coordinates, provided that each node has been correctly associated with its corresponding point in the reference dataset.

The *Compasso de Navegare* even contains several closed traverses (round trips), of which the last point is the same as the first. This enables the calculation of the misclosure of the traverse, independently of whether any of the traverse nodes have been identified.[590] This was Lanman's approach for the round trip of the entire Mediterranean in the two portolans he evaluated.

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[588] Wright, 248, 249.

[589] A single bearing or distance is a random variable and as such it has a standard deviation. The average, calculated from multiple observations of the bearing or the distance between the same two points, will have a smaller standard deviation than a single bearing or distance. See Section 5.10.

[590] An *approximate* identification of each node is required for the various processing methods presented in this study. Such approximate locations are required in order to associate each course leg with a value of magnetic declination that can be considered to be correct within the limits of the magnetic model used. Furthermore an approximate location is required to be able to compute the scale factor of the assumed map projection. Lanman only considered the plane charting method, for which neither the magnetic declination, nor the map projection scale factor is required to be known in any of the traverse nodes.

Occasionally a leg is missing from a traverse; in that case I have inserted a *synthetic* course leg, calculated from the known reference coordinates of the start and end point, so that no errors are added to the traverse. A total of sixteen legs were thus inserted in the main Mediterranean perimeter, none in the Black Sea and seven in the perimeters of the main Mediterranean islands.

Whereas the previous section contained what might be termed a one-dimensional analysis of each of the two course leg components, the traverse calculations in this section enable the two-dimensional spatial characteristics of the data to be quantified and visualised. This may provide additional information for the evaluation of the two main hypotheses regarding the origin of the data in the *Compasso*: *observed* or *scaled off*. The different calculation methods of the traverse node coordinates for the two hypotheses are explained in the remainder of this section.

A. PROCESSING FOR THE *OBSERVED DATA* HYPOTHESIS

Because of its computational convenience I have opted for calculation of the traverses in the Mercator map plane. However the plane geometry of the map surface is different from the spherical (or ellipsoidal) geometry, assumed for the surface of the earth. Therefore corrections need to be applied to the *Compasso* data to correct for the inevitable distortions introduced by the Mercator projection. No correction is required for the bearing data, because of the bearing preserving properties of the Mercator projection, but the bearings do need to be corrected for magnetic declination. Note that no correction for magnetic declination was made in the analysis of the bearing data in the Sections 8.3.4, 8.3.6 and 8.3.7 above.

Each distance is assumed to be the length of the rhumb line section connecting start and end point of the traverse leg. Rhumb lines project as straight lines in a Mercator chart, but are longer in the Mercator map plane than on the curved surface of the earth by the mean scale factor along the line in the Mercator map plane. This process is explained in Appendix II. In other words, the consequence of the choice of using the Mercator projection as the analysis 'space' is that 'Mercator navigation' is required in order to process 'observed' perimeter data correctly.

B. PROCESSING FOR THE *SCALED OFF DATA* HYPOTHESIS

With the *scaled off data* hypothesis no corrections are required to the bearings and the distances from the *Compasso*, as the values for these parameters are assumed to originate from such a chart. However, the *Compasso* bearings do need to be corrected for the rotation angle of about nine degrees of the (assumed) source portolan chart so that they may be compared to a modern Mercator chart. The rotation angle applied is different per sub-basin, as determined from the analysis of the per starea data in Section 8.3.6. Also the mile length assumed is different per sub-basin, honouring the scale differences found in the Mediterranean sub-basins in Section 8.3.6. See also Table 8.6 and Table 8.8 for a summary of these values.

A closed traverse, scaled from a Mercator (or any other) chart has by definition a theoretical zero misclosure, as the scaling off ends in the same point on the chart as it has started. The term *theoretical* implies the absence of any scaling off errors.

C. PROCESSING FOR THE *PLANE-CHARTING* HYPOTHESIS

Jonathan Lanman applied a third method of processing, as he wanted to test the hypothesis that the first portolan chart had been constructed by means of *plane charting* of observed bearings and distances. I will refer to his hypothesis as the *plane charting* hypothesis.

With this hypothesis no corrections are applied to either bearings or distances, although Lanman rotated the resulting outline of the Mediterranean by 9° to achieve a visual best-fit, in order to be able to compare the results with his reference Mercator chart (see Figure 8.2 and Figure 8.3).

In other words, there is very little difference between the ways the *Compasso* data is processed for the *scaled off data* hypothesis and for plane charting: in principle no corrections are applied to the data. However, the differences between Lanman's plane charting processing and my 'scaling off' processing are the following:

1. Lanman assumes a single, fixed portolan mile length of 1.230 km; I have calculated the values per sub-basin from the *Compasso* distances themselves.
2. Lanman applied a single rotation to the entire perimeter outline generated from his plane charting calculation to visually achieve a best fit with the Mercator reference chart. I applied rotations to the *Compasso* bearings by sub-basin, determined from the bearings themselves.
3. Additionally I carried out Least Squares Adjustment to achieve a best-fit with the Mercator reference chart, correcting the mile lengths and rotations used in steps 1 and 2 respectively and applying a horizontal shift to the entire outline. Lanman shifted and rotated the perimeter to achieve a best-fit visually but did not correct his assumed mile length.

It is evident from the above numbered list that there are no fundamental differences between the processing of the *Compasso* data for the *scaled off data* hypothesis and for the *plane charting* hypothesis. The reductions I applied to the data are differentiated by sub-basin and calculated from the data, whereas Lanman's values are based on a single, assumed value for the mile length and a visually determined rotation, but those are differences of degree, not of principle.

For my plane charting solution (Figure 8.43) I adopted a mile length of 1.122 km and a rotation of 6.1° to the entire outline resulting from the plane charting, the results of the Least Squares fit for the *observed data hypothesis* (Figure 8.35), as opposed to Lanman's

1.230 km for the mile length and 9° rotation. The difference in rotation is quite large, but, not knowing how Lanman did his perimeter calculation, I cannot explain this difference. The difference in mile length explains the large discrepancy Lanman's results show for the Levantine coast (see Figure 8.2).

However, the real difference between the *scaled off data* hypothesis and the *plane charting* hypothesis lies in the reference data against which the computation results have to be compared. For the *scaled off data* hypothesis this is the perimeter on the reference Mercator chart, but for the *plane charting* hypothesis it is the theoretical perimeter of the Mediterranean obtained by plane charting of error-free 'measurements'. A plane charted, closed traverse will *not* have a zero theoretical misclosure; it was demonstrated in Section 3.5.2 and Appendix I that plane charting will result in a theoretical misclosure in east-west direction.[591] The actual misclosure will in practice not only deviate because of random observational errors, but also because of variations in magnetic declination along the perimeter and by any errors in the assumed curvature of the earth's surface.

D. PROCESSING STEPS APPLIED IN THIS ANALYSIS

The three processing options described above are shown symbolically in Figure 8.34. Each processing option requires different corrections to be made to the *Compasso* data. These corrections are summarised in Table 8.14. In the following sections all three options will be evaluated.

Corrections to:↓	Observed data hypothesis (Mercator sailing)	Scaled off data hypothesis	Plane charting of (assumed) observations
Bearings	Magnetic declination	Rotations per sub-basin	Single rotation for all data
Distances	Scale correction for Mercator projection. Single value for mile length.	No correction. Different mile lengths per sub-basin	No correction. Single value for mile length.

Table 8.14 *- Corrections to bearings and distances for the three processing options.*

The processing of the perimeter data is a two-step process, for both the *scaled off data* and for the *observed data* hypotheses.

1. Calculation of the coordinates of each traverse node from the coordinates of the previous node and the bearing and distance to the next node. The coordinates of the starting point, Gibraltar, are assumed to be (X =0, Y=0), so the coordinates calculated are *relative* Mercator coordinates.
2. Correction of the thus computed perimeter outline for residual rotation, residual scale and a horizontal shift. This results in a best-fit outline to the reference outline, i.e. the Mercator chart.

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[591] See Section 3.5 and Appendix I.

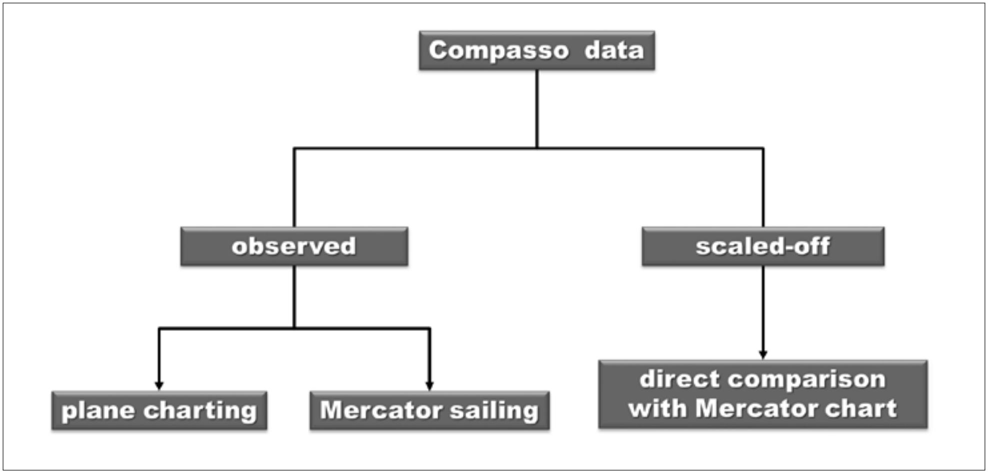

Figure 8.34 - *Possible origins of, and corresponding processing procedures for the perimeter data.*

Step 1 is executed, applying:

- for the *scaled off data* hypothesis: the mile lengths and bearing biases per sub-basin from the per starea course legs;
- for the *observed data* hypothesis: the mean mile length for the entire Mediterranean, calculated from all per starea course legs, together with magnetic declination per point from CALS 7k.2.

The relevant values are listed in Table 8.6 and Table 8.8.

After executing Step 1, both the Mediterranean and Black Sea perimeter outlines show a residual scale and rotation effect. This is, at first sight, somewhat mystifying, since mile lengths and bearing biases have been calculated from the most appropriate subset of the data, the per starea data. These residual effects are caused by the mean bearing biases having been computed from the bearing data only and the mean mile lengths from the distance data only, independently of one another. However, this one-dimensional data view fails to reveal the interaction effects between bearings and distances in the position calculations of the perimeter. For example, a bearing error for a short course leg has a much smaller effect on position than the same error in a long course leg. Corrected values for both the bearing bias and the mile length should be obtained by a best-fit calculation of the perimeter shape to the reference shape.

For the above reason an adjustment is required, best-fitting the calculated outlines from Step 1 to the reference outlines. It will be remembered that both the length of the mile and the rotation of the dataset are in essence unknown and need to be estimated from the data itself. This best-fit calculation has been executed as a Least Squares Estimation of the parameters of a similarity or Helmert transformation. This is a transformation that induces a shift, a rotation and a scale change of the entire outline, but leaves the shape of the outline unchanged. Exhaustive statistical testing has been conducted at a confidence level of 99%, to prevent unrealistic outliers from influencing the estimates of rotation and mile length. This led to rejection of one point for the *scaled off data* hypothesis and 32 points (8%) for the *observed data* hypothesis.

The third method of processing executed is for the *plane charting* hypothesis, i.e. the approach taken by Lanman. The only objective of including these results in this thesis is to also demonstrate visually where the flaw in Lanman's approach lies.

E. COMPASSO DATA FOR THE *OBSERVED DATA* HYPOTHESIS

Figure 8.35 shows the two-dimensional quality of the *Compasso* data, i.e. the interaction between bearings and distances, for the *observed data* hypothesis. The correct, or reference, perimeter created by the course legs described in the data, is shown as the dashed black line. The best-fit outline has received an additional rotation of 0.7°, i.e. reducing the magnitude of the average magnetic declination correction applied by that amount to a total rotation of 6.1°. A scale correction of 3.5% was required for a best fit, reducing the applicable mile length to 1.122 km. Figure 8.36 is based on the same information as Figure 8.35, but displayed as position errors per point, split up in an east-west and a north-south component. These components are *not* Mercator coordinate differences, as those would be affected by the scale distortion of the projection, but 'real-world' errors in km, i.e. I have corrected them for the Mercator scale distortion. The X-axis shows the cumulative sum of the lengths of the legs, from Gibraltar, clockwise around.

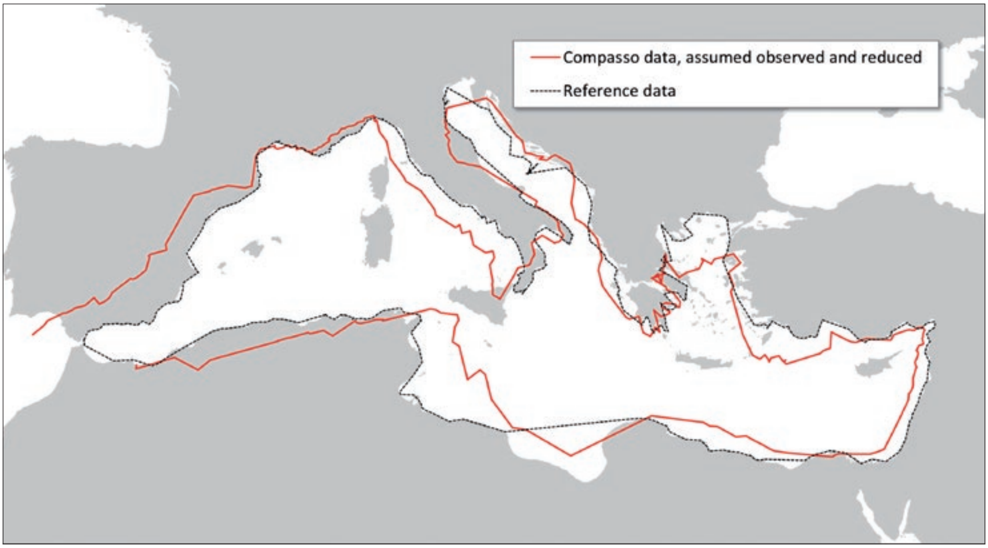

Figure 8.35 - *Compasso main perimeter for the 'observed data' hypothesis.*

The misclosure at Gibraltar, after the best-fit adjustment, is 455 km east and 131 km south. The errors in east-west direction range from -247 to +309 km and the errors in north-south direction from -196 to +182 km.

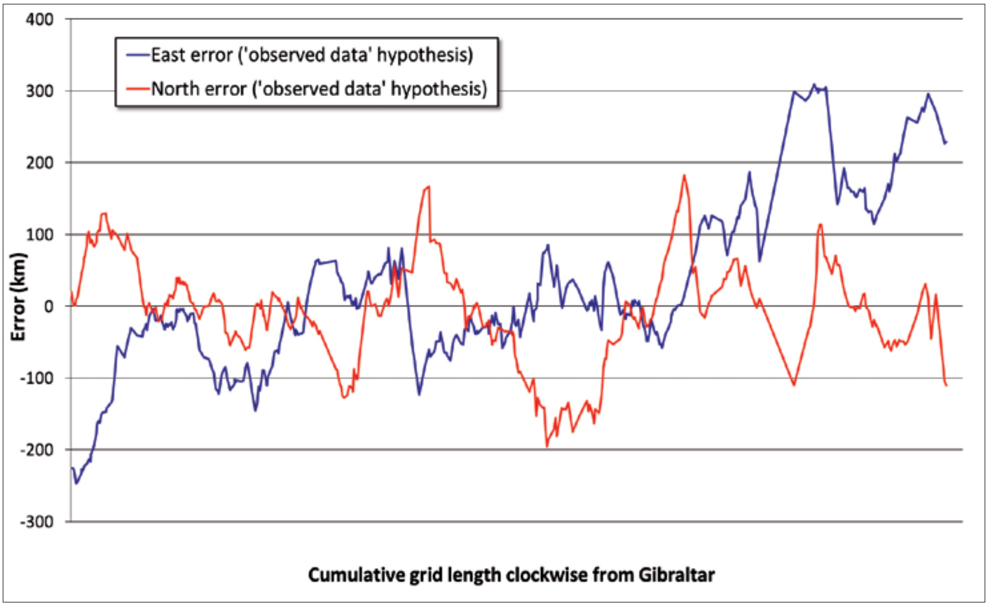

Figure 8.36 *- Position errors in the Mediterranean perimeter for the 'observed data' hypothesis.*

Closed traverses may also be calculated for the main islands in the Mediterranean, but these do not add relevant new information. However, of considerable interest are the traverses in the Black Sea. The Black Sea course data appear in a chapter at the end of the *Compasso*. It appears that the medieval compiler(s) of the *Compasso* has (have) added the bearings and distances of this area after the main document describing the Mediterranean course legs had been completed. In the *Compasso de Navegare* the Black Sea data have been divided into two traverses, one clockwise and the other anticlockwise from the mouth of the Bosporus. The two meet at Cape Khersones, the cape slightly west of Sebastopol on the Crimea peninsula. The lengths of the anticlockwise and clockwise traverses are 3051 km and 1098 km respectively.

Figure 8.37 shows the result of the perimeter calculation for the *observed data* hypothesis and after the Least Squares best-fit. However, the mile length was kept fixed to 1.122 km, the value calculated from all distances in the Mediterranean, as it is unlikely that observed distances in the Black Sea would be based on a different type of mile than the distances in the Mediterranean. The maximum error occurs in the Sea of Azov and is about 150 km.

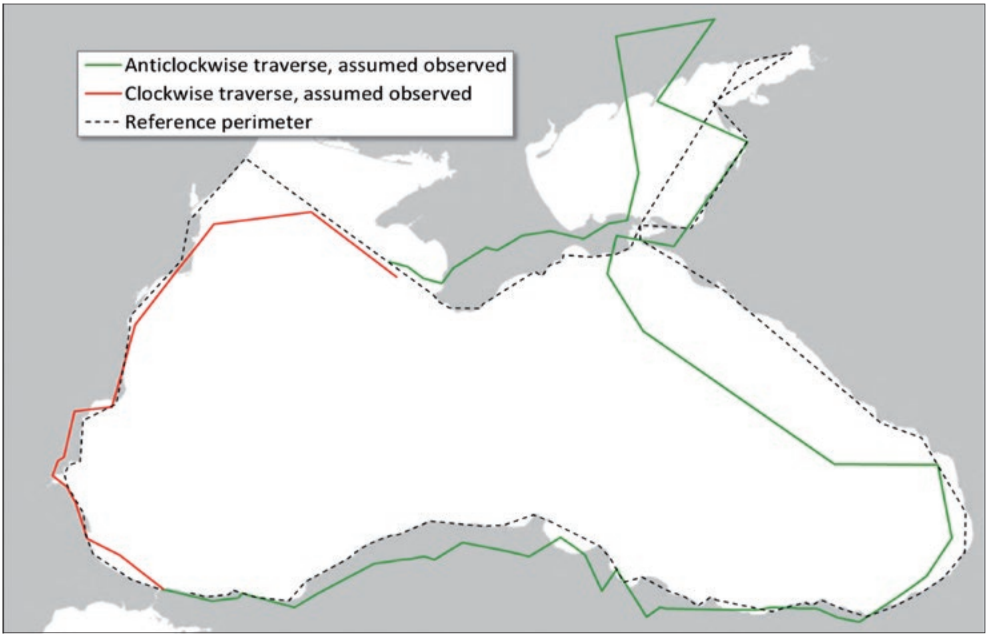

Figure 8.37 *- Black Sea perimeter assuming observed data.*

Before analysing these results the same perimeters will be plotted for the *scaled off data* hypothesis.

F. COMPASSO DATA FOR THE *SCALED OFF* DATA HYPOTHESIS

The two-dimensional representation of the perimeter of the Mediterranean for the *scaled off data* hypothesis involves the correction for a fixed rotation of the presumed portolan chart that was used for that process. No distance corrections need to be made to those data in order to compare them against data scaled from a modern Mercator chart. In order to stay true to the results of the analysis in Chapter 7 that showed portolan charts to be composites of charts of the sub-basins, rotation angles have been applied per sub-basin. These values have been calculated as the mean biases in the bearing data of all per starea course legs. In addition I have assumed the mile-length values as computed by sub-basin. Both sets of values are shown in Table 8.12.

The resulting perimeter is shown in Figure 8.38 below and the corresponding east-west and north-south errors in Figure 8.39.

The misclosure at Gibraltar is 147 km east and 215 km south, considerably less than the misclosure for the *observed data* hypothesis. This also holds for the errors in the other points of the perimeter, as is demonstrated by comparing Figure 8.36 against Figure 8.39. This is confirmed by the RMSE value in position after the best-fit calculation: 72 km for the *scaled off data* hypothesis against 97 km for the *observed data* hypothesis.

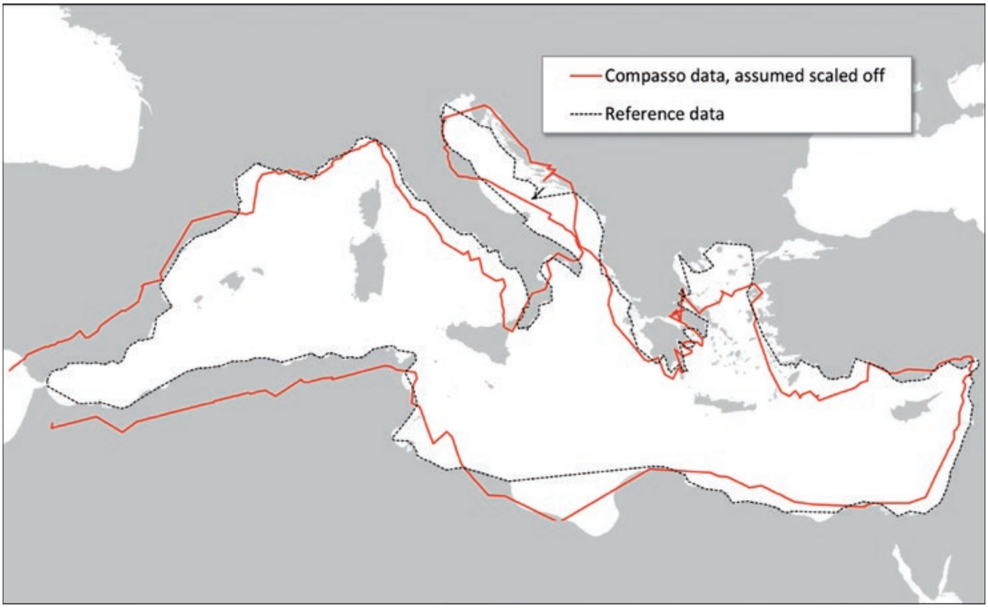

Figure 8.38 - *Compasso main Mediterranean perimeter; data treated as scaled off.*

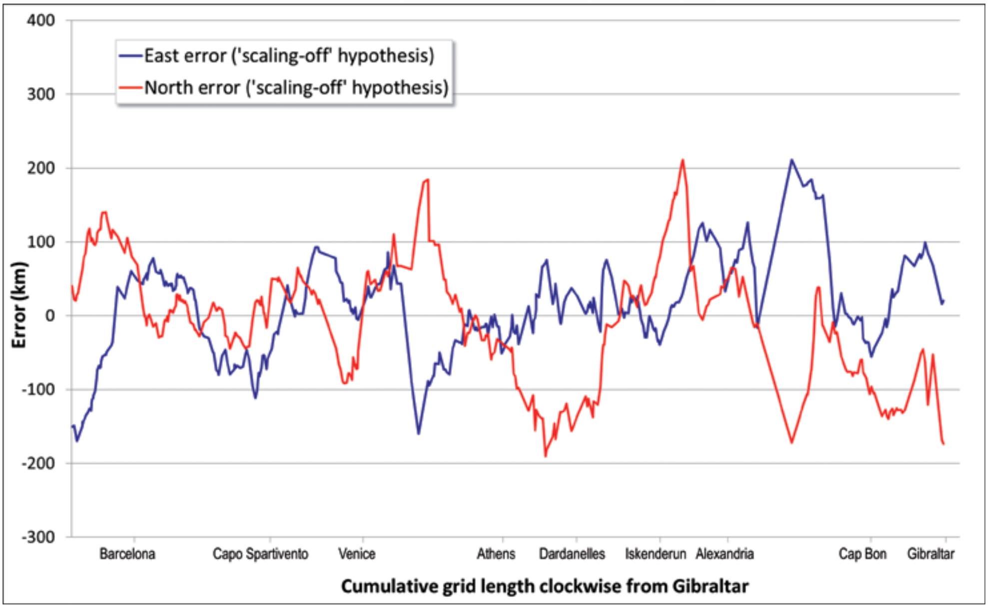

Figure 8.39 - *Position errors in the Mediterranean perimeter for the 'scaled off data' hypothesis.*

The results for the Black Sea traverse for the *scaled off data* hypothesis are shown in Figure 8.40. The maximum error now occurs at Cape Khersones for the clockwise traverse, but is reduced to 117 km, compared to the 150 km error in the Sea of Azov for the *observed data* hypothesis. The mile length value used is 1.163 km and the rotation angle applied was -11.7° (see Section G below).

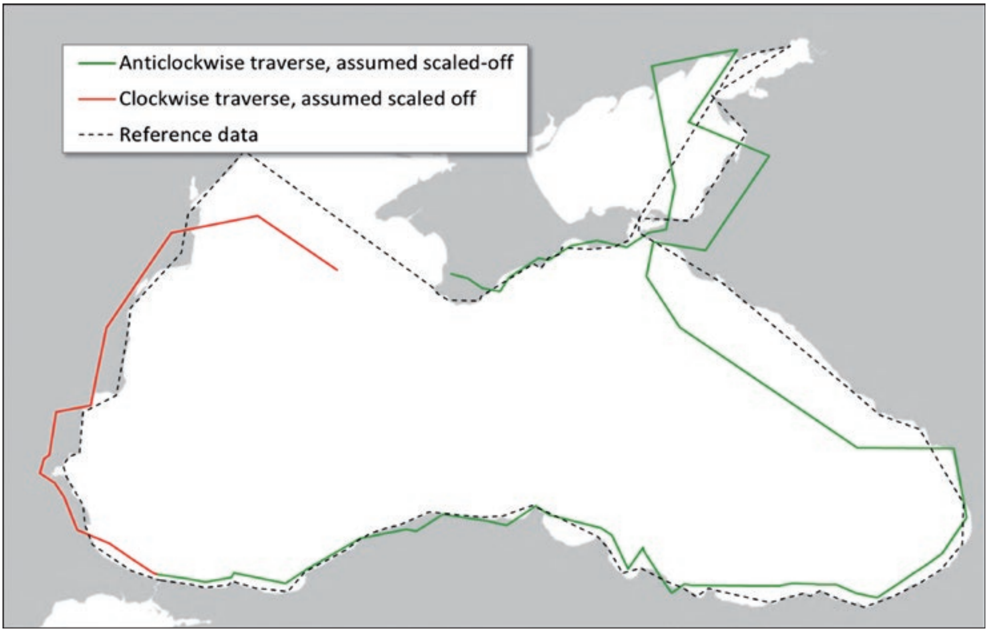

Figure 8.40 *- Black Sea perimeter; data treated as scaled off.*

G. SUMMARY AND ANALYSIS OF PERIMETER CALCULATIONS

The Least Squares Adjustment of the perimeter outlines, best-fitting them to their theoretical shapes, has resulted in corrected values for sub-basin rotations and the estimated length of the portolan mile.

The corrections that have been applied to scale and rotation are the following:

Observed data hypothesis	Correction to magn. declination	Scale correction	Corrected mile length
Mediterranean	-0.7°	-3.5%	1.122 km
Black Sea	+8.8°	-1.8%	1.142 km

Table 8.15 *- Corrections after Least Squares 'best-fit'; 'observed data' hypothesis.*

For the final calculation of the perimeter of the Black Sea, as shown in Figure 8.37, I constrained the length of the mile to 1.122 km instead of the 1.142 km that resulted from the Least Squares fit. The result is that the Black Sea perimeter has been scale-corrected by twice the amount of the correction determined by the optimal fit. Instead of a scale correction of 1.8% as shown in the table above I have applied the scale correction of -3.5% for the Mediterranean, because I have assumed the same mile length would apply to the Mediterranean and the Black Sea in the case of observed distances.

Scaled off data hypothesis	Rotation correction	Corrected rotation	Scale correction	Corrected mile length
Western Mediterranean	+0.8°	-8.3°	-4.0%	1.162 km
Central Mediterranean	+0.8°	-5.1°	-4.0%	1.264 km
Eastern Mediterranean	+0.8°	-3.3°	-4.0%	1.148 km
Black Sea	-2.6°	-11.7°	-1.4%	1.163 km

Table 8.16 *- Corrections after Least Squares 'best-fit'; 'scaled off data' hypothesis.*

The results for the *scaled off data* hypothesis are shown in Table 8.16. The reader is reminded that the *scaled off data* hypothesis implies that different values for rotation and mile length are used per Mediterranean sub-basin.

The length of the portolan mile, which can be deduced from the figures in Table 8.16, is, with the exception of the Central Mediterranean, shorter than what is generally believed. Lanman used a 'consensus' value of 1.230 km. Again with the exception of the value for the Central Mediterranean, the figures are nevertheless fairly consistent with the two portolan mile values extracted from the Carte Pisane, 1.160 km and 1.221 km respectively. The portolan mile length deduced from later charts is longer than those. This appears to confirm that the portolan mile used in Compasso de Navegare is the same as the one used on portolan charts. Nevertheless, the distances for the Central Mediterranean have a significantly different scale.

Table 8.15 and Table 8.16 constitute corrections to the data, calculated for the per starea data shown in Table 8.12. Only a single rotation correction and scale correction have been calculated for the Mediterranean perimeter; the scale and rotation differences between the sub-basins, determined from the per starea data therefore remain the same.

The question may rightfully be asked why I did not execute the Least Squares fit by sub-basin and apply the thus determined corrections. I did do this, but it results in an unrealistic rotation of the Western Mediterranean. This is caused by the fact that the Least Squares computation operates on the calculated traverse coordinates, in which the total misclosure of the entire Mediterranean is compounded at Gibraltar. Isolating the Western Mediterranean therefore causes unrealistic parameters to be computed for that sub-basin.

Limited conclusions may be drawn from the values of the Least Squares corrections to rotation and scale of the data. The residual rotation for the *observed data* hypothesis can only be interpreted as a correction to the values for magnetic declination, determined with the CALS7k.2 model for the year 1250. The correction of 0.7° is well within the error margin of the model and can therefore not lead to any conclusions. However, for the Black Sea an additional rotation of +8.8° is required to bring the *Compasso* in line with the reference data. This is well outside the error margin of the magnetic declination values calculated with the CALS7k.2 model. CALS7k.2 furthermore appears to overestimate magnetic declination in the Black Sea by about 0.5° (see Appendix V). This increases the discrepancy with the *Compasso* data to more than 9°. The 95% confidence level of the CALS3.4 values is about 4° in the Black Sea, which would make this mean rotation error in the *Compasso* bearings for the Black Sea statistically significant. The rotation correction calculated for the Black Sea for the *observed data* hypothesis is therefore a strong indicator that this data has not been observed, but has been scaled off.

The corresponding correction of 2.6° to the mean of 9.1° calculated earlier for the Black Sea for the *scaled off data* hypothesis brings the total anticlockwise rotation of the presumed portolan chart underlying the data to 11.7°, which would imply that the chart, used for scaling off was misaligned with true north by that amount. This is quite conceivable. The scale correction of the Black Sea distances for the *observed data* hypothesis is half the corresponding correction for the Mediterranean distances (-1.8% vs. -3.5%), which is too insignificant to lead to any reliable conclusions. If the data had been observed, it should theoretically result in the same scale correction as for the Mediterranean data, as the same length unit should have been used in both areas. However, the discrepancy is too small to be considered as evidence that the data cannot have been observed.

Both the Mediterranean perimeter and the Black Sea perimeter agree better with the reference perimeter (i.e. the Mercator chart) for the *scaled off data* hypothesis than for the *observed data* hypothesis. It may be visually evident in the range of illustrations from Figure 8.35 to Figure 8.40 and it is computationally confirmed by the RMSE[592] values of position for these calculations, shown in Table 8.17.

	Scaled off	**Observed**
Mediterranean	73	97
Black Sea	30	37

Table 8.17 *- RMSE in kilometres of the perimeter data adjustment for the two hypotheses.*

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[592] RMSE of position is the square root of the sum of the squares of the X and Y residuals after the Least Squares Adjustment, divided by the degrees of freedom, i.e. the number of residuals minus the number of unknowns, four in this case: two translations, one rotation and one scale difference.

If the *Compasso* data had been observed, it would, in practical terms, be impossible that a better fit with the reference outline would emerge after corrections had been applied to the data for scaling off. The following corrections were made to the data for the *scaled off data* hypothesis.

1. Correction of the bearings by a single rotation of the data per sub-basin instead of an estimate of magnetic declination per course.
2. Correction of the distances with the scale factor of the Mercator projection.

If the data had been observed, these corrections would be totally inappropriate and would introduce errors (biases) into the data. The first 'erroneous' correction would destroy the pattern of spatial variation of magnetic declination and the second correction would introduce latitude-dependent scale errors to the distances.

The key question is whether the differences between the two pairs of figures in Table 8.17 are statistically significant. What is the probability that that the inappropriately applied corrections would have a net beneficial effect on the data? Or, what is the probability that the difference is significant in statistical terms?

The appropriate statistical test for these questions is the so-called F-test on the ratios of the squares of the figures in Table 8.17 for the Mediterranean and the Black Sea respectively. The datasets are in both cases quite large: the Mediterranean dataset consists of 422 points, the Black Sea dataset of 87 points.

In testing these datasets, two options are open: to reject outliers or to leave them in the dataset. I have opted to leave them in the dataset for this test, because exhaustive rejection of outliers leads to rejection of the entire North African coast from Ras Amir westward. This would result in testing only part of the Mediterranean coastline. The results are the following.[593]

The probability that the better fit of the *scaled off* perimeter of the Mediterranean compared with the *observed data* perimeter can be attributed to sheer coincidence is indeed negligibly small. The computed value is $3*10^{-16}$, or, for non-mathematicians: 0.00000000000003%. For the Black Sea the same probability computes as 0.57%.

The conclusion must therefore be that the perimeter calculations confirm overwhelmingly that the data in the *Compasso de Navegare* have been scaled off. This confirms the earlier provisional conclusions drawn from the individual analysis of bearing and distance data.

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[593] I used the Microsoft Excel function F.DIST.RT (x, df1, df2), where df1 and df2 are the degrees of freedom of the numerator and the denominator of the Fisher distribution respectively. The function returns the right-tailed probability that value x is exceeded.

H. COMPASSO DATA FOR THE *PLANE-CHARTING* HYPOTHESIS

The matter of the origin of the data in the *Compasso de Navegare* may be considered to be settled at this point. However, there may still be a lingering doubt with some people that plane charting, which adds its own characteristic errors, might somehow compensate for the differences in error characteristics that led to the final conclusion at the end of the previous section. For that reason this section on plane charting has been added.

The characteristics of plane charting have been described in Section 3.5.2 and it was shown that plane charting introduces errors in *east-west direction*. For the entire Mediterranean the differences between plane charting and a proper Mercator chart are shown in Figure 8.41 and Figure 8.42.

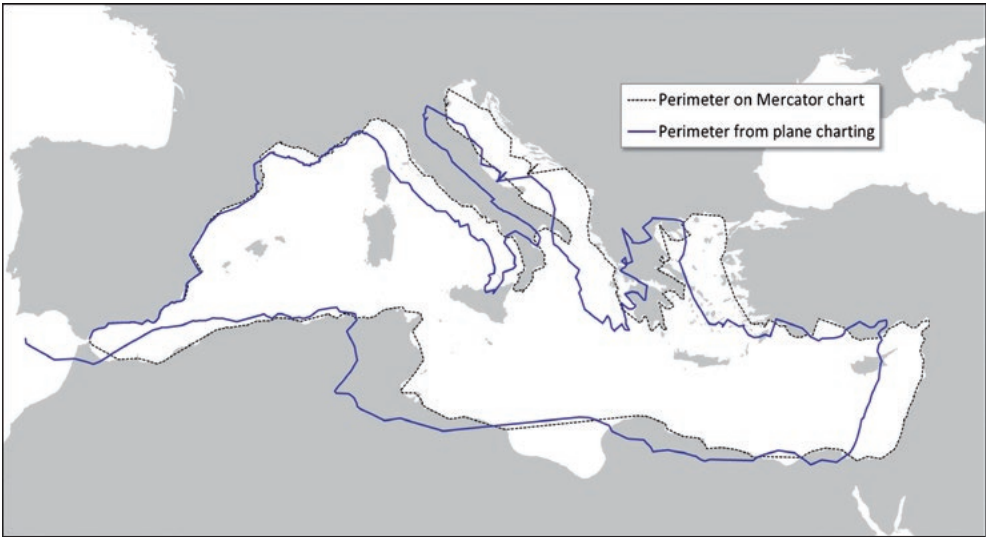

Figure 8.41 *- Differences between plane charting from Gibraltar clockwise around and a Mercator chart (error-free data).*

For the plane charting perimeter outline in Figure 8.41 error-free data was used. The intention is to illustrate what happens when one draws a map of the entire Mediterranean by plane charting, starting from Gibraltar. It will be seen in various points along the northern coast, but in particular at the location of Venice at the northernmost point of the Adriatic, that there is also an error in latitude in the plane charting outline. This appears to contradict what I stated earlier regarding plane charting, but it doesn't: this error is due to the fact that the data is displayed on a Mercator chart, which 'stretches' the Northing of points logarithmically. Plane charting would not introduce an error in Northing on a plane chart, as shown in Section 3.5, but it will on a Mercator chart. The larger the latitude difference with Gibraltar, the larger the Northing discrepancy will become.

It will also be seen that the east-west error due to plane charting is not an error that uniformly increases from Gibraltar, to maximise at the end of the traverse back at this starting point. Instead the error shows a more complex pattern as a result of the indentations of the coastline and the varying latitude offset from the latitude of Gibraltar of 36° N. Figure 8.42 shows the north-south and the east-west error, starting from Gibraltar on the left of the graph and then progressively 'charting' clockwise around the Mediterranean until Gibraltar is reached again on the far right of the graph.

The locations of the areas that have the largest latitude offset from Gibraltar's latitude are clearly visible in the graph. The maximum error in the Mediterranean purely due to plane charting is about 300 km. So much for earlier claims that plane charting errors in the Mediterranean are negligible!

The obvious question is what will happen when a perimeter chart is drawn from the the *Compasso* data by means of plane charting. This is the only option that Jonathan Lanman verified.

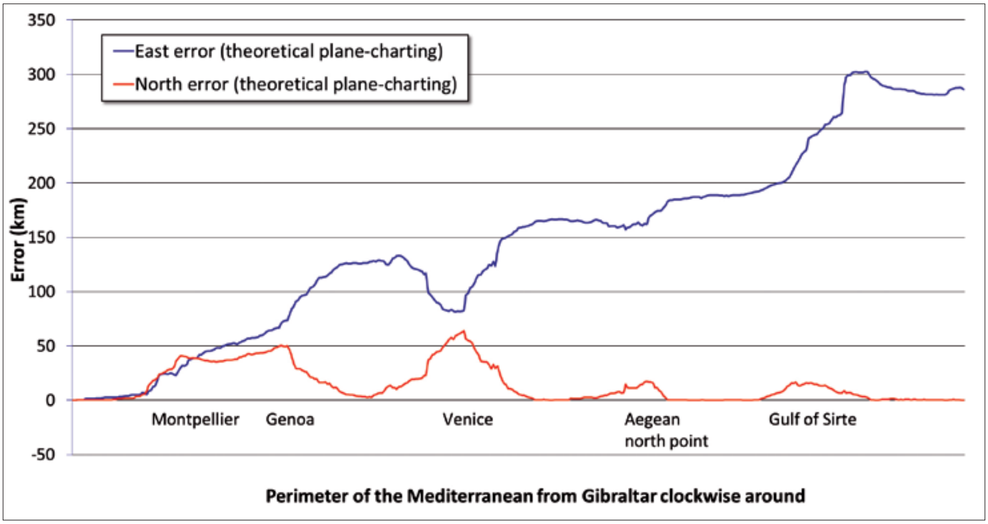

Figure 8.42 *- Error due to plane charting of the Mediterranean coastline from Gibraltar clockwise around, compared with a Mercator chart.*

In Figure 8.43 the perimeter from the *Compasso* data has been calculated by plane charting (red outline) and with a mile-length of 1.122 km, which is the value resulting from best-fitting the Mediterranean data to the reference outline assuming the data had been observed. In addition the *Compasso* outline has been rotated by 6.1° to achieve a visual best-fit with the Mercator chart.

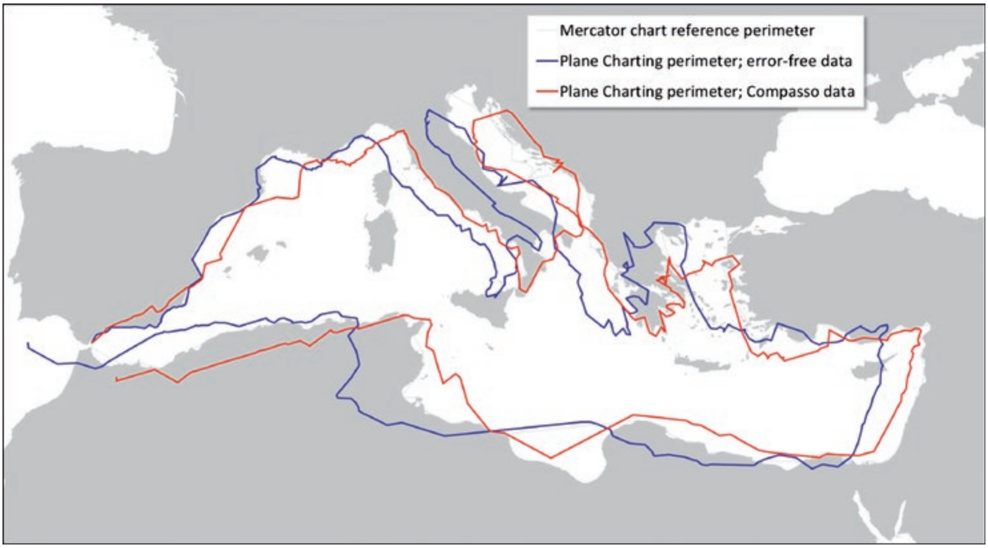

Figure 8.43 *- Plane charting: outline from data (red) and theoretical plane charting outline (blue), based on portolan mile length of 1.122 km and a rotation of 6°.*

Lanman found the similarity of the *Compasso* plane charting outline and the 'real' outline good enough to conclude that portolan charts are indeed the result of plane charting of real observed bearings and distances. However, apart from the question how close the similarity has to be in order to justify such a conclusion, Lanman compared apples

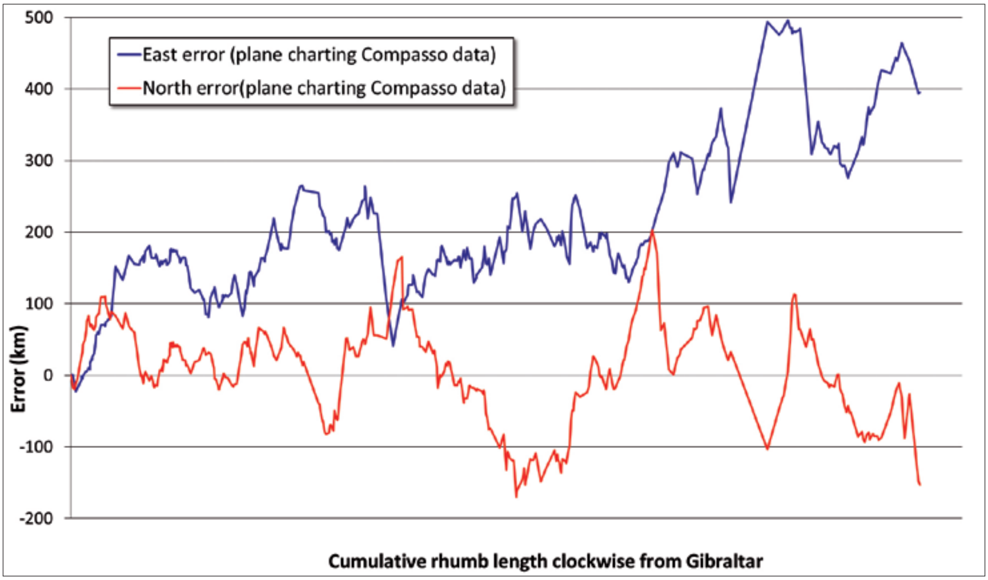

Figure 8.44 *- Errors as a result of plane charting of actual course data from the (the errors are larger than the theoretical plane charting errors!).*

with oranges. He should have compared his equivalent of the red outline in Figure 8.43 with the theoretical (blue) outline of the Mediterranean obtained from plane charting of error-free bearings and distances and *not* with the grey Mercator reference chart. Had he done that, he would have been left with the question how the plane charted outline from *Compasso* data can deviate so much from its theoretical plane charting outline and yet be so close to the true Mediterranean outline on the Mercator chart, as evidenced by the east-west errors, especially along the northern coast.

Figure 8.43 and Figure 8.44 demonstrate that plane charting does not compensate errors in the data and cannot coincidentally result in a good agreement with a Mercator reference chart. The differences are systematic; plane charting of error-free data would lead to a significantly, i.e. up to 300 km maximum, different outline of the Mediterranean Sea.

The conclusion is that the Mediterranean perimeter data in the Compasso cannot be explained by plane charting of observed distances and compass bearings.

8.4 SUMMARY OF THE ANALYSIS

8.4.1 CRITIQUE OF LANMAN'S ANALYSIS

In Section 8.2.2 above I labelled Jonathan Lanman's analysis as unsatisfactory; he works exclusively from the assumption that the *Compasso de Navegare* contains observed data, rejecting other options a priori. He furthermore processes the coastal (per starea) course legs by plane charting, compares them with the outline of the Mediterranean on a modern Mercator chart and declares the visually observed agreement of the plotted coastline with a modern Mercator reference chart to be proof of the hypothesis that portolan charts were constructed from real observed data and by means of plane charting. His method is faulty, as he should have compared the outline created from the *Compasso* data with the theoretical outline resulting from plane charting instead of with a Mercator chart.

Lanman furthermore bases his conclusions regarding the accuracy of the data on six small samples only, three sequences of coastal courses and three samples of peleio. He deals with any inconsistencies in the data by calling them "surprising" or "remarkable", but does not investigate further or question his premises.

8.4.2 NEW ANALYSIS OF THE COMPASSO DE NAVEGARE

A. ERROR ANALYSIS OF BEARINGS AND DISTANCES SEPARATELY

Calculating the standard deviations and mean errors in the course components separately reveals few differences between the two hypotheses. However, together with graphs of the errors as a function of course leg length the following notable characteristics are revealed.

1. The accuracy of the data, both bearings and distances, expressed in their sample standard deviations, is very poor.
2. The largest errors, both in bearings and in distances, occur in the shorter course legs.
3. High-resolution bearings and distances are not more accurate than data expressed to a resolution of quarter winds (11¼°) or integer multiples of ten miles.

The errors in the shorter courses exceed reasonably expected error levels by far; an actual distance of 700 m is recorded as being 5 km. Bearing errors on shorter course legs of 40° and more are common. Such poor quality observations could never have led to high-accuracy portolan charts and are even quite improbable for poor quality navigation observations. The effect is particularly noticeable in the coastal course legs, but is evident even in the peleio, by definition long routes. Inexplicable as this effect is for the assumption that the data have been observed, the poorer quality of relatively short courses is entirely consistent with the scaling of these courses from a pre-existing portolan chart. The pattern of errors was replicated by scaling a series of course legs from the Carte Pisane (late 13th century), shown in Figure 8.32 and Figure 8.33, and is caused by the exaggeration of coastal details in the chart. This explains why the high-resolution course legs have such a poor accuracy; even when they have been scaled off with care, the dominant error source would be the portolan chart's exaggeration of coastal details.

B. COASTAL PERIMETER TRAVERSES

The series of course legs recorded in the *Compasso de Navegare* that run along the perimeter of the Mediterranean and Black Sea enable the calculation of the perimeter or coastline shape of the Mediterranean.

The perimeter plots (Figure 8.35 to Figure 8.43 for the Mediterranean) show better agreement with the *scaled off data* hypothesis than with the *observed data* hypothesis; the difference is statistically significant. The level of agreement of the perimeter outline, calculated for the *observed data* hypothesis with the reference perimeter outline, shown in Figure 8.35, does not in itself permit any conclusion to be drawn. The bearing and distance data have already been shown to be of poor accuracy, so no good-quality perimeter outline is to be expected on those grounds. If the data in the *Compasso* were observed data, this outline would reflect the random errors in the observed bearings and distances. These bearings and distances would have resulted from independent measurement processes and apart from perhaps a short sequence of successive courses, bearings and distances of different course legs should not correlate. Due to its random nature it is impossible for the perimeter outline to agree so well with the reference perimeter when processed with the assumption that the data result from navigation measurements. The statistical test of the data after a Least Squares fit to the Mercator reference perimeter shown in Table 8.17 confirms unambiguously that the Mediterranean data have been scaled off. This is visually supported by Figure 8.38 and Figure 8.40.

The coastal outline created for the Black sea confirms this conclusion: the outline computed for the *scaled off data* hypothesis fits better with the data than the outline for the hypothesis of observed data. The difference is again statistically significant. Further support of the *scaled off data* hypothesis is provided by the calculated rotation of the Black Sea outline: for the *observed data* hypothesis a rotation of 8.8° is required over and above magnetic declination to provide a best-fit with the reference data. Taking into account that CALS7k.2 overestimates magnetic declination in the Black Sea by about 0.5°, the discrepancy would increase to more than 9°, which is well outside the error margin of the available magnetic models.

The conclusion on the scaling off of bearings is consistent with the conclusion from Section 5.7 that the mariner's compass only came into widespread use in the course of the fourteenth century.

C. Individual course legs with evidence of having been scaled off

Further evidence of scaling off is found in the 'impossible' course legs, which cut across land masses. Some course legs cut across land on a modern map, but run across water on a portolan chart, which supports the conclusion that they have been scaled from such a chart. Lanman stated that no pelagic courses cut across land, which is almost true; two pelagic courses cuts across land significantly (from Rhodes port to Cape Chelidonia and from Cabo de Palos to Ceuta). Furthermore, 64 coastal course legs cut across land significantly.

Six course legs are stated to pass within a number of miles of a reef that couldn't have been visible from a medieval ship and can therefore not be based on actual observation; only on scaling from a chart.

One might argue that this doesn't prove that the data have been scaled off. However, if the course legs that cut across land would be vector sums of course legs that go around promontories and peninsulas, one will have to ask what purpose was served by combining those course legs. That argument also holds for the possibility that the original data *did* include proper courses around such promontories and peninsulas and that the 'impossible' courses have been scaled off after the charts had been constructed. There is no reason at all why good quality navigation data would be substituted with impossible data.

Kelley pointed out that peleio in the *Compasso* are grouped in the form of 'fans' from a point on one shore to a series of adjacent points on the opposite shore, where neither the start points nor the end points appear to have any significance for medieval trading journeys. He concluded that this suggests that these peleio have been scaled off. Whereas Kelley is certainly right regarding the fans – a number of them can be observed in Figure 8.5 and Figure 8.6, it is a matter of argument whether these points had significance in medieval trading journeys or not. They may have been relevant, not in their own right as port of origin or destination point, but as waypoints on a longer journey. However, one would expect the frequently sailed trading routes and the prevailing winds to be reflected in the pattern of peleio, but that is certainly not the case. That makes these peleio indeed 'suspect', or even unlikely, but I feel this suspicion does not provide sufficiently solid ground for firm conclusions.

D. Analysis of data differences by sub-basin

Grouping of the data by sub-basins of the Mediterranean, both for distances and for bearings, has been shown to result in differences in data statistics per sub-basin. It is becoming increasingly clear from the analysis so far that the data in the *Compasso de Navegare* is the result of scaling from a pre-existing portolan chart. This raises the question to what extent the *Compasso* data reflect the regional, or sub-basin characteristics of portolan charts.

Table 8.18 and Table 8.19 show the corrected rotation angles of the *Compasso* data per sub-basin, together with the rotations determined from the cartometric analysis of the five portolan charts in Chapter 7.[594] Although the two tables do show the results for the peleio, care should be taken to include them in the comparison, as they were excluded from the final correction of the perimeter data and are therefore likely to contain unknown biases. The *CdN starea* data (second numerical column) have been derived from Table 8.16; the per starea data for the Atlantic and the data for the peleio from the separate analysis of bearing and distances, shown in Table 8.12.

A weak correlation may be observed between the mean rotation angles and mean scales of the *Compasso* data with the corresponding results from the analysis of the five charts investigated.

For example in Table 8.18 and Table 8.19 the rotation and scale differences of the Atlantic dataset with the Western Mediterranean dataset agree very well with the results of the cartometric analysis, which is consistent with the pattern seen in the five charts. On the other hand, the data of the Eastern Mediterranean basin show the least agreement with the results for the five charts. Also the results for the Central Mediterranean do not agree well with the characteristics of the charts, but both Central and Eastern Mediterranean data show quite some variation among the charts. The Black Sea data in the *Compasso* does reflect the significant rotation, but not the larger scale of the five charts.

However, as can be seen from Table 8.6 and Table 8.8 the sample standard deviations in the data are so high that these small variations cannot be statistically significant. This isn't helped by the considerable variation between corresponding sub-basin data in the

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[594] See Chapter 7.6.6.

	CdN peleio	CdN starea	Carte Pisane	Ricc 3827	Ristow-Skelt. 3	Dulcert 1339	Roselli Bell Lib
Atlantic	--	-1.9°	--	-2.0°	--	-3.8°	-1.7°
West	-3.9°	-8.3°	-7.6°	-7.3°	-7.4°	-6.5°	-6.7°
Central	-7.7°	-5.1°	-5.7°	-9.2°	-7.9°	-6.9°	-6.5°
East	-7.9°	-3.3°	-8.1°	-10.0°	-9.3°	-10.0°	-10.1°
Black Sea	--	-11.7°	--	-10.2°	-9.6°	-9.2°	-12.0°

Table 8.18 *- Mean bearing bias (CdN) and mean chart rotations in degrees by sub-basin.*

	CdN peleio	CdN starea	Carte Pisane	Ricc 3827	Ristow-Skelt. 3	Dulcert 1339	Roselli Bell Lib
Atlantic	--	-1.9°	--	-2.0°	--	-3.8°	-1.7°
West	-3.9°	-8.3°	-7.6°	-7.3°	-7.4°	-6.5°	-6.7°
Central	-7.7°	-5.1°	-5.7°	-9.2°	-7.9°	-6.9°	-6.5°
East	-7.9°	-3.3°	-8.1°	-10.0°	-9.3°	-10.0°	-10.1°
Black Sea	--	-11.7°	--	-10.2°	-9.6°	-9.2°	-12.0°

Table 8.19 *- Relative data scale (CdN) and chart scales by sub-basin.*

charts themselves. The limited accuracy of the *Compasso* data makes it therefore impossible to draw reliable conclusions from the comparison of regional data differences in the *Compasso* with regional differences in portolan charts.

An analysis of scale differences per sub-basin has deliberately not been provided for the *observed data* hypothesis. As stated above, the division of the data into sub-basins does not make sense for the *observed data* hypothesis. This holds for distances and bearings alike. There is no reason at all why raw distances would exhibit regional scale differences. The same ships, with the same seamen, sailed to all corners of the Mediterranean and Black Sea and it is unrealistic to assume that navigators would not have spotted such scale differences, given their astuteness and competence that have to be assumed if they really generated the raw data for such accurate charts.

Whereas the *scaled off data* hypothesis assumes a fixed rotation angle per sub-basin, the *observed data* hypothesis implies that the bias in observed compass bearing would be approximately equal to the average magnetic declination for that course leg, assuming that no other biases are present in the bearing data. The question arises whether the spatial variation in magnetic declination is visible in the bearing errors of the *Compasso* data.

The answer is provided conclusively by Figure 8.45, which shows the errors in the bearings of the perimeter courses around the Mediterranean, as well as the magnetic declination, calculated from CALS7k.2, for the year 1250. No pattern is visible in the green dots which might have suggested that the bearing errors 'follow' magnetic declination;

the errors are far too large for that. The Root Mean Squared Error (RMSE) in a single bearing *before* correcting the bearings for these magnetic declination values is 29.8°. The RMSE *after* correction for magnetic declination is 28.8°, which is only a marginal improvement and which may be explained because the correction for magnetic declination goes some way to remove the constant rotation error due to the bearings having been scaled from a rotated chart.

The sample standard deviations in a single bearing after correction for a fixed rotation angle per sub-basin, shown in Table 8.6, are in all cases considerably smaller (21.3° to 24.8°) than the figures in the previous sentence, demonstrating that the bearing data in the *Compasso de Navegare* agree better with the *scaled off data* model than with the *observed data* model.

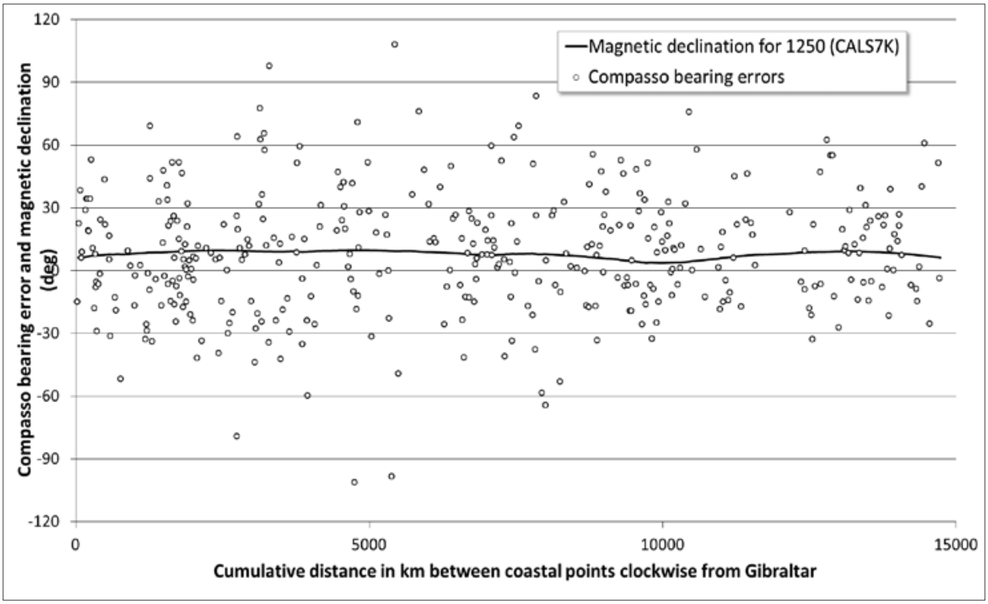

Figure 8.45 - *Bearing errors and magnetic variation in 1250 (CALS7K) along the Mediterranean perimeter.*

The comparison of regional subsets of data by sub-basin with corresponding regions on portolan charts does not provide conclusive insight into the question whether the data has been scaled off or observed, because of the limited accuracy of the data and the variations between the portolan charts. Nevertheless some correlation can be shown between the error patterns in the *Compasso* and the variations in scale and orientation found on a portolan chart for the same sub-basin (see Table 8.18 and Table 8.19). However, no conclusions should be drawn on the basis of this data alone.

E. EXTENSION OF ANALYSIS TO OTHER PORTOLANS

Lanman's study, despite its shortcomings, has demonstrated that the Parma-Magliabecchi portolan is of a quality comparable to the *Compasso de Navegare*. Furthermore Kretschmer's analysis shows that portolans were copied to such an extent, that it is possible to group them into 'families' of which the members show editorial differences only. This suggests that the *Compasso de Navegare* is representative for the entire body of extant portolans, at least within its own 'family'. It seems highly unlikely that the *Compasso de Navegare* and the *Parma-Magliabecchi* portolan analysed by Jonathan Lanman are merely unfortunate exceptions that mask the existence of highly accurate bearing and distance data in other portolans. The conclusions from this study can therefore be generalised to apply to all Mediterranean portolans. It seems even more unlikely that highly accurate bearing and distance data, from which a portolan chart might conceivably have been drawn, would have been available outside the body of portolans.

8.5 CONCLUSIONS

20. *The bearing and distance data in the Compasso de Navegare and, by implication, in other extant medieval Mediterranean portolans, have been scaled from one or more existing charts. On the basis of our current knowledge, this can only have been done from portolan charts. No other candidate cartographic documents have come to light.*

21. *The accuracy of both the distances and the bearings in the Compasso de Navegare is very poor. It is much worse than one would expect for scaled off data and even for observed data. Although the peleio are of considerably higher accuracy than the per starea course data, both regarding the bearings and the distances, to speak of "superior accuracy" of the peleio, as Lanman does, is unjustified, even if it only describes the accuracy relative to the per starea data.*

22. *The portolan mile used in the Compasso de Navegare appears to be the same unit of measure as shown in the scale bars of portolan charts. This is the logical consequence of conclusion no. 20 and it is confirmed by the calculations of its length for the Compasso data. The portolan mile of the Compasso is somewhat shorter than the mile on the portolan charts, analysed in Chapter 7, with the exception of the Carte Pisane, with which it agrees reasonably well. However, the central Mediterranean distances in the Compasso deviate significantly.*

The first conclusion resolves the apparent contradiction that bearings were recorded before a compass, suitable for accurate navigation, had been introduced in the Mediterranean.[595]

It is not improbable that the *Compasso de Navegare* also contains some distances that were estimated from experience, notably *peleio*. However, these cannot be identified in the data.

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[595] See Sections 5.7 and 5.8.

The generation of bearing and distance data by scaling them from a pre-existing portolan chart has most probably not taken place in a single effort, but in several unconnected efforts. Evidence for this is found in the different error characteristics of the *peleio* and the other data and it is supported by the repetition of inter-island data in the Aegean Sea and by the likely later addition of the Black Sea data. The scale difference between *peleio* and the other data can thus be understood to have been caused by successive operators having different ideas about the scale of that chart or charts. It is not improbable that also the per starea course data would have been affected by the different ideas of successive operators. However, it is impossible to establish where the boundaries of any separate batches of coastal data would lie and in the case of the coastal data the situation will anyway be muddled because of the scale variations within any single chart from which the data were scaled off.

The question that forces itself inexorably upon one is why, when data in portolans have been (largely) scaled off, it is not of comparable accuracy to the portolan charts. That may have several reasons, but the most important one is probably the medieval attitude to accuracy.

With the caveat that our knowledge is necessarily constrained by the availability of extant portolans and portolan charts, the following key conclusion is drawn from this analysis:

23. *Portolans of the Mediterranean and Black Sea were scaled from portolan charts. Therefore portolan charts must have existed before the extant portolans of the Mediterranean were compiled.*

9 THE MAP PROJECTION; ARTIFICIAL OR INTENTIONAL?

9.1 INTRODUCTION AND CHAPTER OUTLINE

Numerous cartometric studies have shown close agreement between the coastline image on portolan charts and the corresponding image on a modern map, produced by applying a geodetic map projection, i.e. a map projection as defined in Section 6.1.4. That does not agree well with the medieval origin hypothesis, because adequate knowledge about geodetic map projections cannot be assumed to have been available in the putative period of the origin of portolan charts. The question is therefore justified whether any underlying map projection, which is revealed by cartometric analysis, is an intentional aspect of the portolan chart or an accidental by-product of the cartometric analysis method.

Conscious, a priori application of a map projection to navigation data requires more than knowledge of the bare map projection, the latter term referring to the relationship between latitude and longitude on the one hand and map coordinates (X and Y) on the other. It requires reduction of spherical or ellipsoidal[596] distances and azimuths to the map plane. Alternatively the coastline geometry may be computed entirely on the sphere, after which the map projection is applied, converting latitude and longitude of each coastal point to map coordinates. However, the latter approach is more complex than the former.

In the case of the Mercator projection, an azimuth[597] on the sphere transfers without correction to a corresponding bearing in the map plane. It is this property that Gerard Mercator had in mind when he published his famous 1569 map of the world. The correction of the spherical rhumb line distance between two points to a plane distance on a Mercator chart consists of dividing the spherical distance by the cosine of the mean

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[596] Whether a sphere or ellipsoid is used as a geodetic earth model depends on the purpose of the model. In this chapter I use the terms ‘sphere’ and ‘spherical’ frequently and have omitted to refer explicitly to the ellipsoidal model for ease of reading. Applicability to an ellipsoidal model is implied in those cases.

[597] See Footnote 560 in Section 8.3.2. and Figure 8.12. Within the context of this thesis ‘azimuth’ refers to an angle on the sphere (or ellipsoid), whereas ‘bearing’ refers to the corresponding angle in the map plane. In geodetic and navigational practice the terms ‘azimuth’ and ‘bearing’ are generally considered synonyms and the term ‘compass bearing’ is therefore also used in this thesis, in line with common usage, instead of ‘compass azimuth’.

latitude of the line between the two points.[598] This knowledge can definitely not be assumed to have been available in the thirteenth century.

The consensus view of researchers is that the map projection found in portolan charts is an artefact, or accidental by-product, of the cartometric analysis method to which the charts have been subjected and not an intrinsic property of the charts themselves. The charts are considered to lack an a priori applied map projection, because they are presumed to have been constructed by means of *plane charting*. This is usually formulated by describing them as *projectionless*. In the plane charting technique geometric measurements made on the surface of the earth are transferred to the map plane without making any corrections for differences in geometry between the curved surface of the earth and the flat map plane.

Despite the fact that the consensus among researchers is as near to unanimous as it can possibly be, it is still only a hypothesis that has never been properly tested. It will be clear from the two preceding paragraphs that any proof that the map projection is *not* accidental would imply that it is intentional, which would lead to outright rejection of the medieval origin hypothesis, regardless of the veracity of the other three 'pillars' of the medieval origin hypothesis.[599] The construction of a chart with an a priori intended map projection would definitely be well beyond the capabilities of medieval sailors, cartographers and even the intellectual elite of that period.

It is very difficult to prove that a geodetic map projection has been intentionally applied a priori to any map or chart. When it concerns a modern map or chart the claim that some map projection has been applied by the cartographer in the design of the map will not be contentious, but for a medieval chart the situation is different. In that case it may be assumed, as stated above, that the cartographer could not have had the required knowledge as to how to correct surface geodetic measurements prior to map construction.

However, the proposition that the map projection of portolan charts is an artefact of the cartometric analysis method should not be seen as an *ad hoc* argument that was only wheeled in to shore up the plane charting hypothesis in the face of adverse evidence; it has been part of map-historical reasoning since the first studies of these charts in the nineteenth century. The hypothesis allows itself to be reformulated as follows:

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[598] This is an approximation. The correct way to proceed would be to multiply the spherical rhumb line distance with the mean point scale factor over the latitude range between the two points, as shown in Appendix II. However, for practical applications and small latitude ranges the approximation described in the text of this chapter is adequate.

[599] In shorthand the four 'pillars' of the medieval origin hypothesis are: 1. The 'mathematical seaman'. 2. Improved accuracy of distances (and azimuths) by averaging. 3. Chart construction by plane charting. 4. Any map projection is only apparent or accidental.

> *It is assumed that the differences between the coastline image on portolan charts and the corresponding coastlines on a modern Mercator or Equirectangular chart are insignificant compared with the accuracy with which the coastlines have been charted by means of plane charting of measurements of distance and possibly of azimuth between coastal points.*

The accuracy of portolan charts has been estimated in Chapter 7*: Cartometric analysis of five charts*. The above formulation leads to two distinct questions:

a) Was medieval navigation good enough to have produced the *accuracy* of portolan charts, as that has been estimated in Chapter 7?

b) Assuming that the charts have been constructed by means of plane charting, does the *shape* of the map image fit well enough to the Mercator or Equidistant Cylindrical projection, after having made allowance for the accuracy of portolan charts as estimated in Chapter 7?

Plane charting is a prerequisite for question b), but additionally question a) needs to be answered affirmatively, otherwise question b) doesn't even make sense. In the process of testing the above hypothesis these two questions will be addressed separately.

The concept of a geodetic network (or geodetic control network) has been explained in footnote 92 in Chapter 2: *Key characteristics of portolan charts,* and is repeated for convenience in the next paragraph.

A *geodetic network* consists of a set of points, distributed over an area to be mapped, together with measured geometric relationships between those points, such as angles, distances and/or azimuths. The points form the nodes of the network. In the case of portolan charts the points are distributed along the coasts of the Mediterranean and its principal islands. Their relative positions may be calculated from the measurement data. The coordinates of the network nodes together are the geometric framework for the map or chart. When more geometric relationships between the nodes are measured than are strictly required to determine their coordinates, the network is said to be *overdetermined* and contains *redundant* measurements. The computation of the coordinates of the nodal points from all measurements may then be established by e.g. Least Squares Estimation. The redundancy in the measurements has the effect of improving the precision of the calculated coordinates, but may additionally be used to detect any gross errors in the measurements.

OUTLINE OF THIS CHAPTER

Some a priori geodetic objections may be raised against the hypothesis to be tested and these are discussed in Section 9.2. Existing research is summarised in Section 9.3, after which the workflow and method followed in this chapter are described in Sections 9.4 and 9.5, notably the different ways in which the two elements of the hypothesis, expressed in questions a) and b) above, will be tested.

Section 9.6 describes some introductory details of geodetic network analysis, which is a prerequisite for understanding the analysis results presented later.

Section 9.7 contains a description and justification for the composition of the three geodetic networks, covering the Western and Eastern Mediterranean and the Black Sea. The results of the geodetic network calculations are finally presented in Sections 9.8 and 9.9; the conclusions are summarised in Section 9.10.

9.2 A PRIORI GEODETIC OBJECTIONS

In the case of portolan charts, with their large coverage area, the hypothesis, which assumes their construction from measurements of direction and distance, must also assume that an enormous number of such measurements has been used for that construction and that the reconciliation of all measurement values resulted in the map image that is seen on the charts. Such reconciliation would be necessary, as raw measurements would contain not only a random error inherent to any measurement process, but also a systematic error or mismatch, introduced by the plane charting technique. It is further to be expected that gross (human) errors would have been present in such a large dataset.

A clear difference exists between the simple examples of plane charting that have been discussed in Section 3.5.2 of this thesis and the application of plane charting to course and distance measurements in a complex geodetic network. In the simple examples of Section 3.5.2 the plane charting error could be isolated as a single systematic mismatch. In a complex geodetic network with a large number of measurements, the reconciliation process of mismatches in the network would cause the systematic plane charting mismatches and the random measurement errors to merge in an unpredictable and arbitrary manner. Gross errors, when not identified and removed, would further add to this spreading of errors.

David Woodward, cited earlier in Chapter 2.4.2, was one of the few map historians who attempted to describe to some level of detail how this process might have worked.

> "The cumulative experience of several centuries of coastal and other shipping in each of these (sub-) basins could have led to the independent recording of traditionally known distances. The average distances derived from both coastal traverses and cross-basin routes could then have been used in the construction of a series of separate charts of the individual basins. If these routes were plotted to form networks in each of the basins, each network might have assumed

> the form of a self-correcting closed traverse of each basin. The rigidity of this structure would, however, have depended on the availability of cross-basin distances, acting as braces to the framework. It is thus postulated that some system of empirical or stepwise graphic method of correcting these frameworks was used to achieve a 'least-squares' result."[600]

Woodward's hypothesis is echoed by Joaquim Alves Gaspar.[601] Another researcher was James E. Kelly Jr., cited earlier in Section 3.4.2, who proposed a progressive iterative adjustment, starting from a simple shape and proposing that with the addition of each new measurement, an adjustment to the shape of the Mediterranean was made. Kelley postulates that this process would result in a steady improvement of the charted shape of the Mediterranean "until no meaningful improvement could be made".[602] Kelley's proposal does not go beyond the conceptual level and the objections against his idea have already been described in Section 3.4.2. The most important of these are the implicit assumptions that the shape of the Mediterranean will converge to a stable shape and that new measurements will not alter the shape of the map image.

Woodward, in the above citation, does not mention compass bearings, presumably because he was well aware of the contentious nature of their assumed availability at such an early date (he speaks of "the cumulative experience of several centuries", which would take data gathering well into the 'pre-compass' era). He doesn't mention the issue of the map projection either.

Although the consensus view on the map projection and Woodward's explanation above may seem very reasonable and satisfying, the existence of a map projection is considerably less self-evident from a geodetic perspective and from the perspective of the history of science. To begin with the latter, in Section 5.10 significant objections were raised against the assumption of the calculation of the arithmetic mean of a series of measurements. The implied second step in Woodward's conceptual construction process, the two-dimensional graphic reconciliation of the conflicts between those average measurements, is a further step along the path of presentist thinking. Despite the apparent plausibility of Woodward's last sentence, the implied process is of considerably greater complexity than the calculation of the arithmetic mean of a series of measurements of the same distance.

The geodetic objections against the consensus view are the following: "self-correcting traverses", as Woodward proposes, exist neither in practical, nor in theoretical geodesy. What Woodward describes is a geodetic trilateration network that would consist not of traverses, but of triangles, which would have to be more complex than his descrip-

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[600] Campbell 1987, 388. Campbell states that Woodward wrote the relevant section.

[601] Gaspar 2010, 7.

[602] Kelley 1995, 7, 11.

tion suggests. In a coastal 'traverse' consisting of distances alone the coordinates of the nodes cannot be computed; a very large number of cross-braces would have to be available in order to enable the construction of triangles – hence the word 'trilateration', so that coordinates of all nodes may be computed. They do not just add strength or rigidity to the network; they are a necessity for the calculation of coordinates of the positions of all nodes. Straight,[603] unobstructed lines over water would have to exist between all connected nodes. Distances along the coast would therefore have a limited length, as sections of coast protruding into the sea would otherwise be in the way, but to make triangles, many long cross-basin distances would have to exist This is illustrated in Figure 9.1 for only a few of the required number of nodes in the Western Mediterranean.

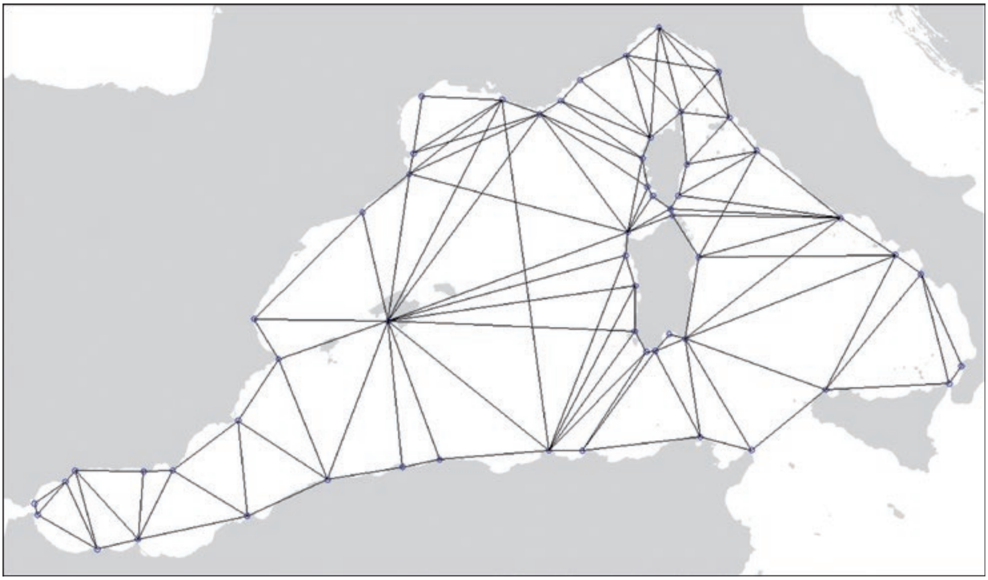

Figure 9.1 *- Conceptual trilateration network in the Western Mediterranean.*

In the conceptual trilateration network of Figure 9.1 the coastal legs are unrealistically long. In many cases a headland would be in the way, and Majorca is treated as a single point. However, the objective is to demonstrate that a trilateration network completely depends on peleio, long-distance, cross-basin routes, to form triangles, and an enormous number of them is required in order to be able to calculate the coordinates of all network nodes. This is the weak point of the assumption of a distances-only approach. It may easily be imagined that in order to chart the Black Sea coasts, many peleio in all directions, between many coastal points, would be essential. This dependence on

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[603] 'Straight', in the presence of a compass, would be defined as a line of constant compass bearing. The ship then sails along a rhumb line.

peleio in all directions conflicts with the presence of prevailing summer winds and the limited sailing capacities of medieval ships. One might further care to ask how medieval mariners would be able to steer long straight courses without a compass, in whatever way one defines 'straight'. The assumption of distances-only positioning is therefore unrealistic from a geodetic and from a practical perspective.

Even a geodetic network consisting of distance and direction pairs would be very complex and the more complex a network becomes, the easier gross errors will be able to 'hide' and be spread out by the adjustment or graphic reconciliation process. Only sophisticated statistical techniques are able to reveal gross errors, but such detection methods have only been available in modern geodesy. The detection of errors in a geodetic network is complex and requires iterative adjustment of the network. Error removal or error neutralisation will not occur automatically, as Woodward suggests.

Another geodetic objection may be raised against Woodward's 'least-squares' result. The objection is not so much that the method of Least Squares was only discovered or developed around 1800 and was therefore not known in the Middle Ages; the parentheses in Woodward's text indicate he was well aware of that. What he clearly means is that a graphical reconciliation process was executed, resulting in a best-fit solution, not identical to a Least Squares solution, but at least tolerably close to this theoretical optimum. The objection against this assumption is that a progressive, graphic adjustment or reconciliation is not likely to succeed. Graphic adjustment implies that the cartographer would have started from one location in the network and as he proceeded to construct new points from available distances and bearings he would have to reconcile the inevitable conflicts and redraw all the network nodes he had drawn earlier. By the incorporation of a single bearing or distance measurement, the whole network, or chart, would have to be changed. That is a process, so complex and laborious for a large network, that it cannot be considered a realistic option. Least Squares Estimation, on the other hand, computes a best-fit in a single integrated step.

Furthermore a geodetic map projection introduces a distortion in the resulting map image that is highly regular. For example, the scale distortion of both the Equidistant Cylindrical and the Mercator projection is constant for a given parallel of latitude; it varies only as a function of latitude.[604] The adjustment or reconciliation process described above would have distributed all mismatches and conflicts in the measurements across the whole chart in an arbitrary manner. This random or arbitrary spreading of distortions over the entire map image conflicts with the systematic nature of the distortions created by a geodetic map projection (or a close approximation of such a projection).

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[604] The Equidistant Cylindrical projection is equidistant along the meridians. A line along a meridian has no scale distortion. The scale distortion in east-west direction is a function of latitude.

Despite these critical notes I will assume that it would have been possible to execute such an optimal graphic reconciliation process. The best achievable result would have been realised by Least Squares Estimation, as this method distributes all data conflicts evenly over all points of the geodetic network and this method will therefore be used to test the assumptions of plane charting and accidental resemblance to a map projection, which are key elements of the medieval origin hypothesis.

9.3 Existing research

Only a few researchers have attempted to *prove* that portolan charts are the product of plane charting; the vast majority assumes that to be a self-evident fact. Jonathan Lanman's work has been discussed in the previous chapter. James E. Kelley's proposal was mentioned above. A more recent study by Joaquim Alves Gaspar[605] sets out to prove the plane charting hypothesis. Gaspar applied a technique known in literature as *multidimensional scaling (MDS)*. Waldo Tobler proposed to apply this technique in 1977 to cartographic problems.

Multidimensional scaling is statistical technique, used mainly in social sciences; a considerable body of literature exists on the subject.[606] The technique matches two images or surfaces by means of Least Squares Estimation. Multidimensional scaling may for example be used to express similarities or dissimilarities in the images of two human faces and is therefore used in automatic image-matching algorithms. However, multidimensional scaling uses exclusively distances, measured between points on the two surfaces that are compared.

When applied to cartography, the two images to be compared might be the geometry of the Mediterranean coastlines on a modern map and the same coastlines on a portolan chart, or the geometry of the Mediterranean coastlines created from the plane charting of a network of distances and bearings measured on the earth's surface and a modern map.

Geodetic networks, consisting of distances, angles, azimuths and (astronomically determined) latitudes and longitudes of points on the earth's surface have been processed by Least Squares Estimation since that method was developed independently by Carl Friedrich Gauss and Adrien Marie Legendre[607]. Multidimensional scaling is merely a special case of that method. However, whereas multidimensional scaling is restricted to distances between points, geodetic networks allow *any* measured geometric variable to contribute to the solution. Also the ways of expressing the results are different in geodesy and in the application areas of multidimensional scaling in the social sciences.

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[605] Joaquim Alves Gaspar, "Dead reckoning and magnetic declination: unveiling the mystery of portolan charts", *e- Perimetron* Vol. 3, No. 4 (2008).

[606] E.g. Trevor F. Cox and Michael A. A. Cox, *Multidimensional Scaling*, 2nd ed. (Boca Raton: Chapman&Hall/CRC, 2001).

[607] Stigler 1998, 11 – 61.

Part 1 of Steven R. Stigler's three-part book *The History of Statistics* bears the title 'The Development of Mathematical Statistics in Astronomy and Geodesy before 1827'[608] and focuses on the application of Least Squares Estimation in those disciplines. A recommendation from Tobler to apply LSE techniques to cartography is therefore hardly necessary, when geodesy is defined as "the science of the measurement and mapping of the earth's surface".[609] Although Tobler does refer to specifically geodetic literature[610], he does not mention the extensive geodetic tradition on this subject. It is not clear why he didn't exploit the obvious synergy between geodesy and cartography, but chose to make a detour to the application of these statistical techniques in the social sciences.

In his doctoral thesis Gaspar formulates a number of "study hypotheses", one of which is the following:

> "The geometry of pre-Mercator charts can be numerically replicated by simulating the charting method of the time, taking into account the routes supposedly used to construct them and the spatial distribution of the magnetic declination."[611]

Gaspar furthermore states that:

> "By applying the concept of multidimensional scaling, here generalized to rhumb-line directions and distances measured on the spherical surface of the Earth, the geometry of the charts is simulated. The comparison of the model's results with the interpolated grids of the originals is used to validate the a priori assumptions and to clarify the details of the construction methods."[612]

The "interpolated grids of the originals" to which Gaspar refers have been generated with the programme MapAnalyst of two portolan charts, the chart of Angelino Dulcert (1339) and a chart by Jorge de Aguiar (1492). He clarifies his test criterion as follows:

> "The hypothesis is considered to be confirmed if the most significant geometric characteristics of the original charts, revealed through their implicit grids of meridians and parallels, can be replicated by the model. By 'significant geometric characteristics' it is here understood the general orientation and spacing of meridians and parallels, and the distortions caused by the uncorrected magnetic declination and by the distortions inherent to the charting process."[613]

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[608] Stigler 1998, 9.

[609] Wolfgang Torge, *Geodesy*, third completely revised and extended edition (Berlin: Walter de Gruyter, 2001), 1. The definition is from Friedrich Robert Helmert (1880).

[610] Waldo R. Tobler, "Surveying Multidimensional Measurement." In *Proximity and Preference*, edited by Reginald G. Colledge and John W. Raynor. Minneapolis: The University of Minnesota Press, 1982: 9. His literature references 2, 3, 7, 8 and 11 are scientific works on geodesy.

[611] Gaspar 2010, 7. This is Gaspar's Hypothesis 5.

[612] Gaspar 2010, 5.

[613] Gaspar 2010, 7.

Although Gaspar's formulation includes the phrase "…taking into account the routes supposedly used to construct [the charts] …" he does not actually do that.[614] Instead he constructs a network from a series of 55 regularly spaced nodes with latitudes from 30° N to 50° N, and longitudes from 10° W to 40° E, with a 5° increment for both. Gaspar proceeds to treat the connection between each pair of nodal points as a simulated ship's route, for which rhumb line distance and azimuth are calculated, which would have resulted in a total of 1485 distances and azimuths, assuming he used each pair of nodes only once and not twice to include the reverse azimuth as well. The azimuths are corrected for magnetic declination derived from the CALS7k.2 model[615] for the year 1300. He then executes a Least Squares Adjustment of these simulated measurements with the plane charting assumptions, generating, as output, four maps of the adjusted grid with the Mediterranean, Black Sea and Atlantic coastlines.[616]

Gaspar limits the maximum distance to about 900 NM. He uses a relative weighting factor *w* between distances and azimuths; *w* = 0 means only distances are used in the LSE process and *w* = 1 only azimuths. He arrives at the best result for a factor *w* = 0.8, and draws the conclusions that:

- both azimuths and distances were used in the construction of the charts;
- a larger weight was given to observed azimuths than to the observed distances.[617]

However, it stands to reason that when both distances *and* azimuths are used in a network calculation the precision of the result, which is what he computes, will be better than when only distances or only azimuths are used, because twice or possibly even three times as many measurements are used in the calculation. An optimum value of the weight factor between 0 and 1, reflecting that both types of measurement are included, is therefore to be expected.[618] *Any* geodetic network would show that result. Furthermore these numbers only show the comparison between several *simulation* calculations; it is unclear how Gaspar connects the simulations to the chart construction process and is able to arrive at his first conclusion.

The relatively larger weight of the azimuths in the optimal simulation calculation cannot be translated into a conclusion that the medieval cartographer would also have done that, quite apart from the questions whether a thirteenth century cartographer would have been *able* to do that and if so, *how* he would have done that. Distances and azimuths have different units. One unit of distance makes a different contribution to a position calculation than one unit of azimuth does; the optimum relative weighting factor *w*

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[614] It is not entirely clear how Gaspar generated his results.

[615] See also Section 6.3.1D.

[616] Gaspar 2008, 195.

[617] Gaspar 2008, 199.

[618] Three times if both the forward and the reverse azimuth of each line connecting two nodes is used, twice if only the forward azimuth was used.

therefore reflects primarily the units used. In a proper geodetic network adjustment the weight of each quantity would be equal to the inverse of the (estimated) variance[619] of that quantity. This has the effect of converting azimuths and distances into computationally compatible quantities and it also offers a mechanism to deal with variations in measurement precision, as it allows longer distances to have a larger variance and thus a correspondingly lower weight. No conclusions can therefore be drawn from Gaspar's optimal weight factor value.

Gaspar's concluding remark is:

> "The results show that the geometry of the charts is well explained by the use of uncorrected magnetic declination and estimated distances, plotted in a plane with a constant scale, as if the Earth were flat."[620]

It is unclear how he arrives at this conclusion, as he does not specify what quantitative criteria he uses for the comparison of the "significant geometric characteristics" of portolan charts against the same characteristics of his simulated network and when this comparison would lead to either acceptance or rejection of his hypothesis. It is unclear how Gaspar's calculation results support his conclusion.

9.4 Conceptual workflow and test criteria

Testing of the hypothesis formulated in Section 9.1 will be approached by mimicking the charting process that is presumed to have been executed for the construction of portolan charts. The preparatory work will be done in the following three successive steps.

1. Selection of a series of points along the coast of the Mediterranean and its large islands that will constitute the nodes of a geodetic network.
2. Calculation of simulated data of rhumb-line distances and magnetic azimuths between these points, taking into account the trading routes, notably in the selection of the cross-basin bearing and distance pairs. The theoretical azimuths between any two points will be corrected by the magnetic declination for the year 1250, calculated from the CALS7k.2 model introduced in Chapter 8, hence the reference to 'magnetic azimuths'. Note that the calculated values are error-free and defined on the sphere. Together with the nodal points these simulated distances and directions constitute a geodetic network.
3. Calculation of the coordinates of the network's nodal points by means of plane charting, i.e. treating the synthetic data as if the earth were flat, using Least Squares Estimation. The synthetic directions and distances may be free from random measurement errors, but the plane charting process introduces mismatches, i.e. discrepancies in the distances and directions, as these are spherical quantities and not plane

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[619] The variance is the square of the standard deviation.

[620] Gaspar 2008, 202.

quantities. LSE is deemed to approximate the presumed graphic reconciliation process of the medieval cartographer, even though the hypothetical medieval cartographer would have had to reconcile the random measurement errors *and* the plane charting discrepancies. The essence of plane charting is that he would have treated the combined effect of these two in a single graphic reconciliation process, which is simulated in this chapter by LSE. Therefore, even though the synthetic data is free from random errors, LSE is still appropriate to reconcile the plane charting distortions in the synthetic data.

The positions of the coastal points thus determined will serve as the identical points of a 'synthetic portolan chart', i.e. a series of coastal points of which the positions have been computed from the synthetic distances and directions.

The two aspects of the hypothesis to be tested were related to the following two questions, which are repeated here for convenience:

a) Was medieval navigation good enough to have produced the *accuracy* of portolan charts, which has been estimated in Chapter 7: *Cartometric analysis of five charts*?
b) Does the *shape* of the map image in the 'synthetic' chart described above fit well enough to the Mercator or Equidistant Cylindrical projection, making allowance for the accuracy of portolan charts estimated in Chapter 7?

The 'synthetic chart' contains the errors that resulted from ignoring earth curvature, i.e. from the plane charting process, but it does not contain the effects of random measurement errors, as it has not been constructed from real measurements, but from error-free azimuth and distance values on the sphere. The accuracy of the coordinates of the nodal points will be assessed by quantifying how the estimated standard deviations in the navigation measurements propagate into the accuracy of the coordinates of these points. This will enable the first question, related to the *accuracy* of the charts, to be answered.

In order to find out whether the map projection is an accidental by-product of the cartometric analysis method, the 'synthetic chart' will be subjected to the same cartometric analysis process as the real charts, described in Chapter 6: *Cartometric analysis; methodology and existing research*. The outcome of that analysis will permit a direct test whether the *shape* of the coastlines of that synthetic chart fits well enough to the Mercator or Equidistant Cylindrical projection. If it does, the map projection can justifiably be considered as an artefact of the cartometric analysis method and not as an intentional element of chart construction.

No formal statistical test will be executed to the find the answer to question a) above. The justification for this will be become clearer later in this chapter.

However, question b) may be approached in a more exact manner. The accuracy of portolan charts, as estimated in Chapter 7, can be argued to contain at least three independent components, expressed in the Table 9.1, for the hypothesis that the charts were constructed by plane charting techniques.

	Description	
1	The effects of the random navigation errors on the accuracy of the charted coastal point positions, caused by the stochastic (random) nature of the measurements	MSE_{nav}
2	The effects of the coastal feature exaggeration	MSE_{feat}
3	The contribution of the mismatches of the plane charting network with the charts best-fitting map projection	$MSE_{p\text{-}ch}$
	Chart accuracy = sum of the above 3 components	$\mathbf{MSE_{map}}$

Table 9.1 *- Error components of a portolan chart if the map projection is an artefact of the cartometric analysis method.*

These three independent components can be considered as the Mean Squared Errors (MSE) of the respective error source. These error sources are independent of one another, for which reason the MSEs of these error sources may be added. The sum of these three component MSEs constitutes the value for the Mean Squared Error of the charts, MSE_{map}, computed in the cartometric analysis process of Chapter 7. The effects of any local warping of the vellum would also be a contributing factor, but it is impossible to quantify that factor reliably and separate it from the other factors, so it has been omitted in Table 9.1 and in the subsequent analysis. Of the four quantities listed in Table 9.1 three are known in the sense that they have been or may be estimated.

$\mathbf{MSE_{nav}}$ will not be estimated exactly (see footnote 621), but it will be shown later that an exact estimate is not required.

$\mathbf{MSE_{feat}}$ can be quantified crudely as follows. Some examples of feature exaggeration were shown in Section 2.1.1. One millimetre exaggeration in a 1 : 5,500,000 scale map equates to 5.5 km. A standard deviation in feature exaggeration in the chart of 1 mm seems justifiable; it many places feature exaggeration exceeds this figure. A notional value of 5 km as a standard deviation to estimate this component will therefore be adopted. This sets a conservative value for this effect as $MSE_{feat} = 25\ km^2$.

$\mathbf{MSE_{p\text{-}ch}}$ will be estimated in this chapter by subjecting the ‘synthetic chart’ described above to the cartometric analysis process of Chapter 7.

$\mathbf{MSE_{map}}$, the resultant sum of all components, has been estimated in Chapter 7.

The values for all figures need to be expressed in the same units. As the calculations in this chapter have been executed in the coordinate system of the Dulcert 1339 chart, rescaling of the figures for MSE_{map} and $MSE_{p\text{-}ch}$ to kilometres squared is therefore required. This will be explained later in this chapter.

For the process described above to be executed, the following arguments against the creation and adjustment of such a network of navigation measurements will have to be temporarily suspended:

- arguments from the perspective of the history of science that the implied statistical and geodetic techniques were not yet available;
- the historical argument that the magnetic compass, in a form that was suitable for accurate measurement of the ship's course, was not yet available or at any rate not yet widespread enough to generate a large body of measurements.

9.5 Design principles for a 'medieval' geodetic network

A geodetic network will be analysed in this chapter, consisting of rhumb line distances and magnetic azimuths between points along the coast of the Mediterranean and the Black Sea, supplemented by a number of cross-sea distances and azimuths. The network design takes into account the findings on prevailing winds, dominant trade routes and sailing characteristics of medieval ships discussed in Chapter 4: *Physical conditions of the Mediterranean Sea; medieval ships*. This is therefore a network that aspires to be a realistic approximation of a network that might have been used for the construction of the charts, as assumed as an element of the medieval origin hypothesis.

The points along the perimeter of the Mediterranean and Black Sea that have been used for the cartometric analysis of the Dulcert 1339 chart form the core of this network. Prominent headlands have been selected as the nodal points, with distances in the order of fifty to one hundred kilometres, a distance a medieval ship might be expected to cover in a day's sailing. A chain of coastal course legs has thus been created and for each course leg the rhumb line distance and azimuth have been computed from the coordinates of these points. The bearings or azimuths have been corrected for magnetic declination for the year 1250, derived from the CALS7k.2 model and introduced in the previous chapter. The coordinates of the network nodes will thus be computed from synthetic, error-free measurements, in the sense that they do not contain random measurement errors, but in the plane charting model they will contain a mismatch, resulting from ignoring earth curvature. Least Squares Estimation will be used to mimic the presumed graphic reconciliation process of the medieval cartographer. The coastal course legs have been supplemented with peleio or long-distance, cross-basin routes, as seemed reasonable to assume, based on trade routes and prevailing winds.

The network will be processed in three discrete partitions, for the Western and Eastern Mediterranean and the third for the Black Sea. The division into sub-charts as concluded in Chapter 7: *Cartometric analysis of five charts,* which would call for a separate Central Mediterranean network, has not been mimicked. As was demonstrated in Chapter 7, the sub-charts are not sharply delineated, which would make the translation into separate networks rather arbitrary.

A. TWO ADJUSTMENTS FOR EACH NETWORK

Each network has been computed twice, in order to address the two different aspects of the problem described above: *accuracy* of the charting process and *shape* of the chart resulting from plane charting. The difference of the two computations, which will be termed Network Adjustment Nr 1 and Network Adjustment Nr 2, is explained and justified below.

Because azimuths and distances are different quantities, their contribution to the Least Squares Estimation process needs to be *normalised* by taking into account their standard deviations, or rather their variances.[621] A convenient way of viewing this is to say that instead of kilometres and degrees, all measurements are expressed as multiples of their respective standard deviations. The standard deviation will be different for different measurement types and e.g. for shorter and longer courses, but this process normalises the contributions of all measurements, taking into account their different units and their different precision.

NETWORK ADJUSTMENT # 1

The first network adjustment will be aimed at finding out how accurate such a network would be when the achievable measurement accuracy of medieval navigation, described in the navigation accuracy model presented in Section 5.9.2, is used in a *weighted* Least Squares Adjustment. The resulting coordinates of the nodal points are of little interest in this case, but network statistics, expressed in the one-sigma error ellipses of the nodal points and the sensitivity of the network for gross errors are the output of interest of this calculation.

NETWORK ADJUSTMENT # 2

It goes too far to assume that a medieval cartographer would have been able to perform a graphic adjustment that approximates a weighted Least Squares Adjustment. Therefore the following assumptions are made:

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[621] The associated LSE process is often referred to as 'Weighted Least Squares'. The generalised way of taking the different metric and stochastic characteristics of the various measurements into account is to express those characteristics in the variance-covariance matrix of the measurements. The inverse of this matrix is the *weight matrix* of the adjustment. In the network calculated here the weight matrix is assumed to be a diagonal matrix, i.e. no correlation is assumed to exist between any two measurements.

1. The medieval graphical reconciliation process would not have favoured either distances or azimuths in their impact on the estimated position of the ship.
2. The medieval cartographer would treat all distances and course bearings as equally accurate.

These two assumptions are illustrated in Figure 9.2. They translate into a stochastic model of the measurements, i.e. they define the properties of the measurements as random variables and are the basis of network adjustment # 2, which will yield the coordinates of the points that will be subjected to the matching process with a map projection, as was explained in Section 6.5.

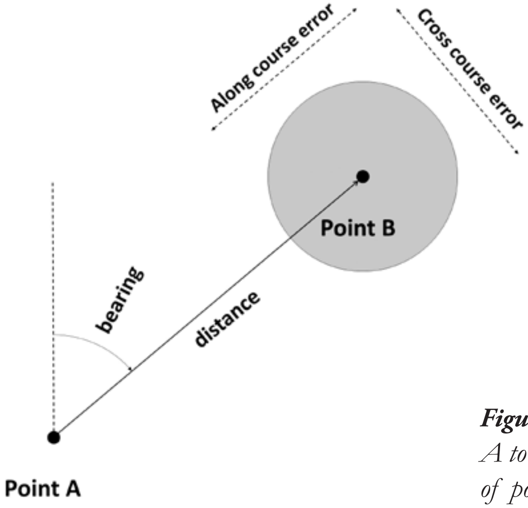

Figure 9.2 *- The random error in the bearing from A to B has an equal effect on the computed position of point B as the random error in distance AB.*

9.6 INTRODUCTORY INFORMATION ON GEODETIC NETWORK ANALYSIS

My criticism described in Section 9.3 on Tobler's reference to *multidimensional scaling* referred to Tobler not mentioning the rich and long tradition in the design, analysis and processing of geodetic networks. The next section is intended to provide a brief introduction into the most relevant aspects of geodetic networks.

9.6.1 THE NEED TO DEFINE A BASELINE

Coordinates are manmade quantities, in contrast with angles and distances, which are measurable geometric quantities.[622] This results in the following problem. Assume four points in a Euclidean plane geometry that span an irregular quadrangle. The shape

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[622] Strictly speaking distances are only observable as multiples and fractions of a unit of measure, which is again a manmade quantity. In geodetic theory the problem may be avoided by considering distance ratios. In practice it is resolved by including a scale parameter as an unknown quantity, to be resolved in the LSE process.

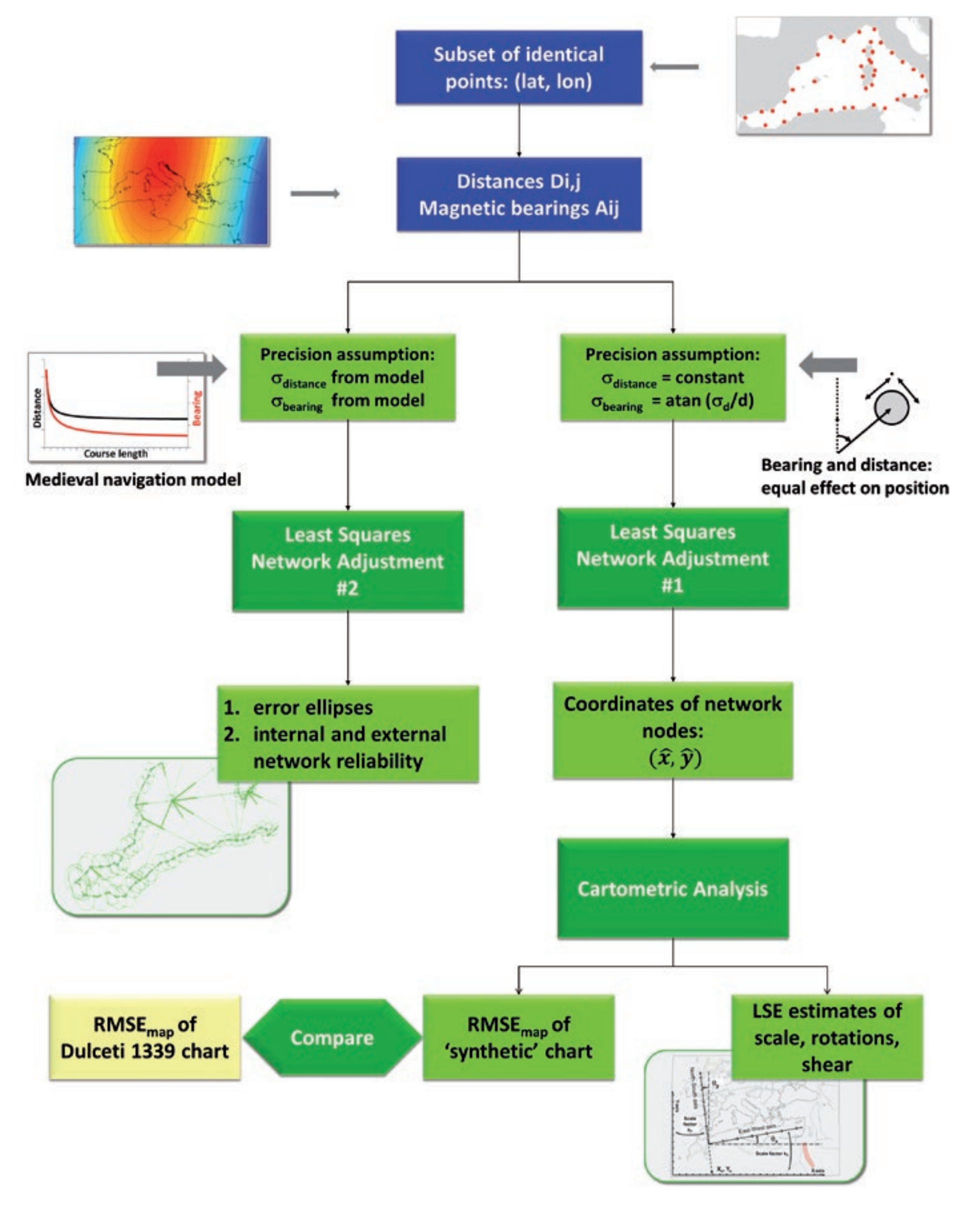

Figure 9.3 *- Workflow of the geodetic analysis of Chapter 9.*

and size of that quadrangle are fully determined when the five distances shown in Figure 9.4 are measured. These *five* distances determine the figure fully; two angles and three distances, or even four angles and one distance would do the same. However, to express the shape of the quadrangle by means of plane coordinates requires *eight* coordinates.

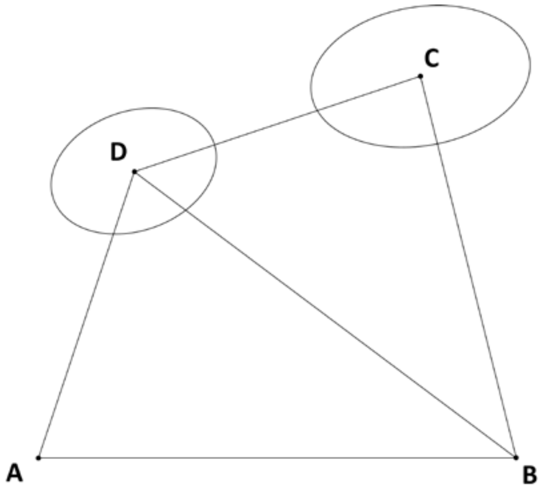

Figure 9.4 - *A simple quadrangle determined by five distances.*

Mathematically, the conversion from measurements to coordinates is therefore a singular operation at this point. It cannot be executed without knowledge of the directions of the coordinate axes and their unit of measure or scale. The origin, axes directions and unit of measure of the coordinate system need to be chosen; only then can the coordinates be computed from the measured distances. It is stressed that the unit of measure of the coordinate system needs to be chosen too. Even when one assumes that the unit of the coordinate system is the *metre*, as derived from the measured value of distance d_{AB} between A and B, this embodies a choice regarding the scale. There is no law of nature that dictates that the unit of measure of the coordinate system must be same as the unit in which the distance measurements took place; that is a choice. One option would be to choose point A as the origin of the coordinate system, i.e. $X_A = Y_A = 0$, and to choose the coordinates of points B to be $X_B = 10$, and $Y_B = 0$. Assuming a Cartesian coordinate system with the positive Y-axis being defined in a direction 90° anticlockwise from the positive Xaxis defines the entire coordinate system.

An alternative choice would be to select the measured value of the distance AB to be the abscissa of point B. Summing up, a total of four parameters need to be chosen to fully define a coordinate system capable of expressing the geometry of the quadrangle. One might also say that Euclidean 2D coordinate space contains four *degrees of freedom*. These may satisfied by choosing the coordinates of two points (the baseline); alternatively one may choose the origin of the coordinate system (2 degrees of freedom), the direction of the X-axis (1 degree of freedom) and the unit of measure of the coordinate system to be equal to that of the distance measurements (1 degree of freedom). The four degrees of freedom are found back in the classical Helmert or similarity transformation between two 2D Cartesian coordinate systems: an origin shift, consisting of two components, a rotation and a scale difference.

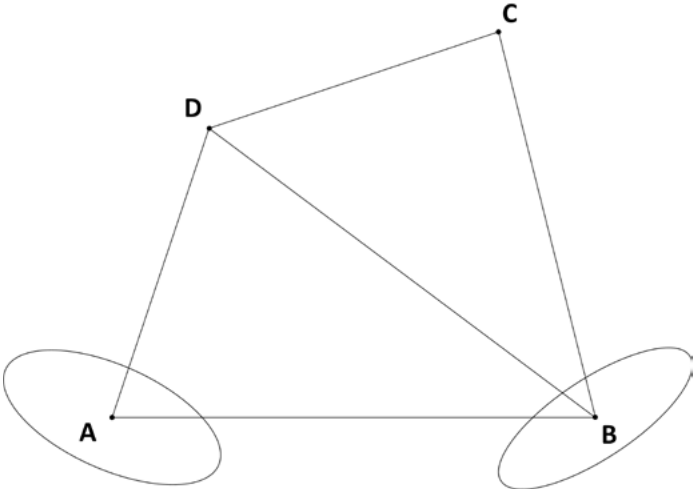

Figure 9.5 *- The same quadrangle as in Figure 9.4, but with points C and D constituting the baseline.*

These apparently trivial facts from 2D Euclidean geometry have some profound consequences in geodesy. The measurements, i.e. the distances and angles, are random variables. They are commonly (and realistically) assumed to be normally distributed variables. These stochastic properties of the measurements propagate, through the computational process, into the coordinates, which, as result, are also random variables. When the measurements are normally distributed, so will the coordinates.[623] However, because coordinates belong together in pairs, a coordinate pair will have a *bivariate normal probability density function*, the two-dimensional extension of the normal or Gaussian distribution. As described in Section 5.5.6C the two-dimensional distribution of a pair of coordinates can be characterised by means of the *standard* or *one-sigma error ellipse*, the two-dimensional equivalent of the standard deviation. One would expect the coordinates of all four points of the quadrangle to have error ellipses, but that is not the case. Points A and B in the example of Figure 9.4 have coordinate values that have been *chosen* and chosen values cannot exhibit random behaviour. The coordinates of points A and B are not random variables and points A and B therefore have no error ellipses.[624] They span the *baseline* of the geodetic network.

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[623] The calculation of coordinates from e.g. distances and angles is rarely a linear operation. However the variation in the measurement values, as expressed in the standard deviations of those measurements, is generally small. The propagation of error characteristics from distances and angles into coordinates is therefore generally modelled as a linear(ised) relationship. In a linear process the output parameters (the coordinates) are normally distributed if the input parameters (angles and distances) are normally distributed.

[624] A more abstract mathematical approach to this phenomenon is to focus on the variance- covariance matrix of the coordinates, which is calculated in the Weighted LSE process. A prerequisite is that the variance-covariance matrix of the measurement variables has been used as part of the input to the LSE process. The problem sketched above manifests itself in the variance-covariance matrix of the coordinates being a singular matrix with a rank deficiency of four, i.e. equal to the four degrees of freedom. This problem may be solved in various ways: either two baseline points are chosen, which

Alternatively one might select points C and D as the baseline points. This results in the coordinates of points A and B being treated as random variables, whilst the coordinates of points C and D are constants, which results in the error ellipses as shown in Figure 9.5.

9.6.2 Error ellipses

The concept of error ellipses is probably relatively unknown in cartography[625] and certainly in map history, so it may be helpful to dwell for a moment on their meaning. Assume that one hundred complete sets of five distances have been measured in the quadrangle shown in Figure 9.4, each set of five distances having identical random error properties as the other sets. Assume further that the coordinates of the points of the quadrangle are computed in the same way, i.e. points A and B have the same coordinates for each of the one hundred calculations. If each calculated point were to be plotted as a dot, one would see a cloud of points around the locations of point C and D that would take the shape of the error ellipse shown in Figure 9.4, such that roughly 39% of the one hundred 'realisations' would plot inside that node's one-sigma error ellipse. This *does* assume that these 100 sets of five measurements in this example do not contain any gross errors.

The one-sigma error ellipse has a confidence level of about 39%; the error ellipse at a confidence level of 95% is 2.45 times larger (linearly).

The choice of baseline is important for the error ellipses; error ellipses of points near the baseline will be small, those of points far away from the baseline will be larger. However, the choice of baseline has no effect on the *shape* of the network that is computed. The network is simply 'pinned' to the chosen baseline and realisations of the geodetic network for different baselines will show a different scale and orientation of the network but the network shape will not change. The coordinates of the two points of the baseline are considered error-free in one network realisation.

9.6.3 Statistical testing and minimal detectable bias

It is stressed that Least Squares Estimation is only sensible[626] when a geodetic network

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have chosen values and as such must be considered to be free from random errors, or a generalised inverse of the singular variance-covariance matrix may be calculated and used in the LSE process and that may be done in various ways. Calculating a generalised inverse of a matrix has the effect of 'thinly spreading' the singularity of the matrix over the entire network. This is far beyond the scope of this thesis and will not be discussed any further. In this thesis the first solution has been chosen: the selection of a baseline that is free from random errors. See Vaníček and Krakiwsky 1982, 272 – 276.

[625] An error ellipse should not be confused with Tissot's Indicatrix, which is also an ellipse. Tissot's Indicatrix does not describe random error behaviour, but distortion introduced by a map projection. Assuming an infinitesimal circle on the sphere or ellipsoid, Tissot's Indicatrix shows how that circle would be rendered, in general as an ellipse, when projected in the plane through a map projection.

[626] When a geodetic network contains just enough measurements to calculate the coordinates of the nodes, Least Squares Estimation is technically possible, i.e. the algorithm will in principle not fail, but

contains redundant measurements, i.e. more measurements have been made than are strictly required for the calculation of the location of all network nodes. For example the small 'network' shown in Figure 9.4 has no redundancy. Although it is possible to compute the error ellipses of the two points C and D, no gross error, be it a human blunder or an instrumental error in any of the measurements would ever be detected.[627]

The assumption of the absence of gross errors, often referred to as *biases*, *outliers* or *blunders*, is implicit in the concepts of error ellipse and standard deviation. However the presence of gross errors in a large dataset consisting of measurement values is an inevitable fact of life. Such gross errors have a large disturbing effect on the calculated Least Squares Estimators and some method of detecting and removing or correcting gross errors is therefore always used in the processing and analysis of geodetic networks by LSE. Therefore a well-designed geodetic network will contain an adequate number of redundant measurements[628], i.e. measurements that are not strictly necessary for the calculation of the coordinates of the network nodes, but serve as check measurements. However, in Least Squares Estimation no distinction is made between 'required' and 'check' measurements; all measurements are resolved in a single integrated calculation and the geometric relationships between the measurements provide the internal 'checks and balances' that enable the detection of any gross errors. The (Least Squares) residuals of the measurements are the basis of all statistical testing methods. The theory behind statistical testing is complex and the reader is referred to specialised literature for the details.[629]

The application of statistical testing to the results of Least Squares Estimation processes does not guarantee that all gross errors are discovered. Statistical testing is not unlike fishing with a net: big fish are easily caught, but small fish have a good chance of escaping through the mesh. 'Small' gross errors may therefore go undetected, despite the statistical testing process, but the question is how small is 'small'? Furthermore multiple gross errors may cancel each other out in the 'checks and balances' and thus never be discovered. However, provided certain assumptions are made, such as the supposition that one measurement contains a gross error and the rest does not, the threshold level

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there is no sum of squares that can be minimised.

[627] Some classifications of gross errors distinguish incidental errors (occur only once), systematic errors (occur in all measurements of the same type) and human blunders. In geodetic network quality control, too fine a distinction is not meaningful. A gross error is considered to be any error that introduces a bias to the first moment of the (measured) random variable, in other words, it introduces a bias to the mathematical expectation of the random variable. Only in the formulation of alternative hypotheses for statistical testing scenarios may a finer distinction be helpful. Errors in the n-th moment of a random variable, with $n>1$ (e.g. the variance, for $n=2$) are *not* considered to be gross errors in the context of this study.

[628] Ghilani states that 'good' is this context means more than 50% of the measurements are redundant. Ghilani 2010, 455.

[629] Ghilani 2010, 70 – 85.
Peter J. G. Teunissen, *Testing Theory, an Introduction* (Delft: VSSD 2006).

of error detection can be quantified exactly. The question may thus be asked what the minimum magnitude of that error needs to be before it is caught with near certitude, i.e. a sufficiently high probability, which, in the calculation executed for this thesis has been set to 80%.[630] This leads to the concept of the *Minimal Detectable Bias (MDB)* in a measurement and this concept requires a focussed optimum statistical test on the correctness of that one measurement.[631] Alternatively one may assume that a number of measurements all contain a gross error, but that the exact pattern is not known. In the cartometric analysis of Chapter 7 the statistical test executed assumed an error in both the latitude and the longitude of a single identical point, both of unknown magnitude.

In the so-called Delft-method[632] of geodetic network analysis a MDB is computed for the assumption that only one specified measurement contains a gross error. The collection of MDBs thus computed is a measure of the internal strength of the geodetic network, i.e. its ability to allow gross errors in the measurements to be detected. This concept of strength of a geodetic network is called *internal reliability*. A further question is to what extent the coordinates of the nodal points of the network (and other parameters) may be affected by undetected errors in the measurements. This leads to the complementary concept of *external reliability*. If a geodetic network contains, say, 200 measurements, the impact is computed of an assumed error in one measurement on the coordinates of the network nodes; the magnitude of this assumed measurement error is assumed to be equal to its MDB. In the example of a network with 200 measurements, this is repeated 200 times, i.e. for each available measurement. This process results in 200 sets of coordinate 'errors' per point, of which only the maximum 'error' in point coordinates is recorded; the rest is discarded. These maximum 'errors' in each network node together quantify the concept of *external reliability*.

In the analysis of the three geodetic networks in this chapter this maximum error per network node is divided by the semi-major axis of the error ellipse of that point. This yields a *Bias-to-Noise Ratio (BNR)* for each node, which reflects the magnitude of the errors in the coordinates of the network nodes that cannot be detected from the internal 'checks and balances' in the network in a statistically reliable manner. This Bias-to-Noise ratio *does* presume that the optimum statistical testing is used to detect any errors.

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[630] For the statistically inclined reader: the value of 80% is known as the *Power of the Test* $\mathcal{P}$.

[631] The *Minimal Detectable Bias* (*MDB*) is the bias or error that is detected with a probability of $\mathcal{P}$, the *Power of the Test*, in a statistical test with significance level α. The MDB is computed for a chosen value of the Power of the Test, that is sufficiently large, e.g. 80%. The *significance level* of the test α determines the critical value, which, when exceeded by the test statistic, will lead to rejection of the *Null Hypothesis* (i.e. the assumption that no gross error or bias has occurred). The significance level of the test is chosen sufficiently low, e.g. 1% or 0.1%. The significance level of the test is the probability of incorrectly rejecting the *Null Hypothesis*. The Power of the Test $\mathcal{P} = 1 - \beta$, in which β is the probability of incorrectly accepting the *Null Hypothesis*, i.e. assuming that no gross error or bias has occurred while in reality it has. See Vaníček and Krakiwsky 1982, 220-225 and Ghilani 2010, 435-463.

[632] Peter J. G. Teunissen, *Network quality control* (Delft: VSSD, 2001)

9.7 NETWORK DEFINITION AND ANALYSIS

9.7.1 COASTAL ROUTES AND PELEIO

In Section 9.5 the design principles were listed for the geodetic network. This section will detail the actual coastal stretches and peleio selected per basin that constitute the three networks for the Western and Eastern Mediterranean and the Black Sea.

The question is how to mimic the process by which a medieval cartographer might have constructed the network, i.e. drawn the framework of the chart. It is most likely that chart construction would have begun from the 'home base' of the cartographer and that he extended the network from there. That would lead to a construction in which a baseline in the supposed area of origin of the charts is adopted. The baseline would have to be 'measurable', i.e. a line that medieval sailors could have measured (at least hypothetically) with some degree of confidence. Given the likely origin of portolan charts in either Genoa or Pisa, a baseline along the Ligurian coast would seem justifiable. A very short baseline would result in large error ellipses[633] at the far end of the geodetic network, at Gibraltar and Ceuta; a very long baseline, e.g. Genoa – Ceuta, would be the baseline of choice for a modern geodesist, but this is an impossibly long distance for the Middle Ages. A baseline between e.g. Genoa to Piombino would be realistic, as this route might have been sailed very frequently in the twelfth and thirteenth centuries and it may be sailed in one single course leg. However, for the calculations in this chapter I have selected the baseline between Genoa and Palma (de Majorca), which would result in smaller error ellipses in all non-baseline points, but which is not very realistic for a late medieval setting. This calculation will therefore be too optimistic as a 'benchmark', but I will nevertheless use this baseline in order to prevent the accuracy results of the geodetic network calculation appearing unduly pessimistic.

Tony Campbell suggested that the most likely process would be that the ships sailed from headland to headland and register course details only for those course legs.[634] The intermediate coastline details might have been sketched in later freehand. I have implemented this principle in the design of the networks analysed in this chapter. These headland points therefore constitute the nodes of the geodetic network. Corsica and Sardinia have been included in the Western Mediterranean geodetic network and I represent the Balearics as a single point at the location of Palma de Majorca. The Western Mediterranean network terminates at the line from Cap Bon to Marsala on Sicily, includes the north coast of Sicily and picks up mainland Italy from Capo Vaticano. The westernmost point of the network is Tarifa, west of Gibraltar.

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[633] See the discussion on the principles of geodetic networks in Sections 9.6.1 and 9.6.2.

[634] Tony Campbell, personal communication. Campbell also suggests this in his Foreword to the book by Richard Pflederer, *Finding their Way at Sea* (Houten: Hes & De Graaf 2013), 9. This book was published as I wrote this chapter.

Having thus described the principle that governs the choice of the course legs along the coastline, the question is which peleio would have to be included. Where coastwise sailing is concerned, one may assume that medieval ships would always be able to pick up a favourable wind, including the diurnal thermal winds that occur in a relatively narrow strip of water along most coasts in summer. However, that cannot be assumed for peleio. The successful completion of a long-distance offshore course leg requires a fairly steady wind along that course. A limited number of peleio have therefore been chosen to run:

a) between major ports or headlands;
b) along courses that are favourable only with the prevailing winds, which vary between north and north-west (see Chapter 3).

This leads to the network for the Western Mediterranean that is shown in Figure 9.6. The choice for the peleio in this network design doesn't imply that other routes were not sailed, merely that other routes were probably sailed less frequently than the ones shown.

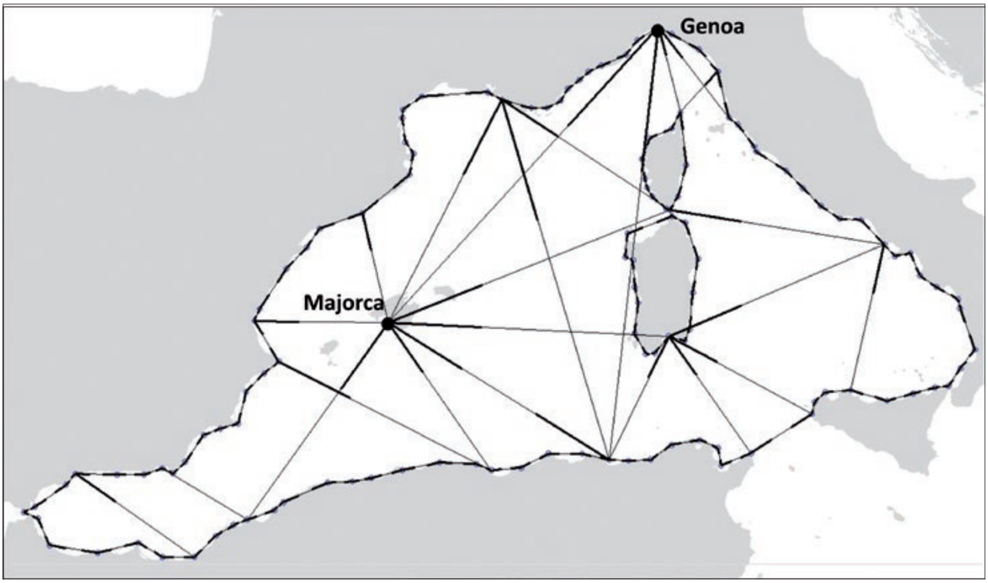

Figure 9.6 - *Western Mediterranean geodetic network.*

The thin lines indicate where distances would have been measured, the thick short lines the direction in which each course leg was sailed. The coastal points were taken as a subset from the identical points of the cartometric analysis of the Dulcert 1339 chart, which enables a direct comparison of this network with the portolan chart, as will be shown later. The points were chosen to be prominent headlands, spaced at about 50 to 100 km, to reflect approximately a day's sailing as a minimum.

A network in the Eastern Mediterranean can be defined along similar lines, except that in the Eastern Mediterranean the summer winds blow predominantly from the north-west with much greater consistency than in the Western Mediterranean. This is reflected in the scarcity of peleio. The peleio from the Strait of Messina to the south-western tip of Crete requires some explanation. Crete was in Venetian hands during much of the thirteenth century and the Genoese avoided direct contact with the Venetians where possible unless for acts of piracy. On their route to Constantinople the Genoese followed the southern coast of Crete, after which they made for Rhodes, and worked their way north along the Anatolian coast from there. The Venetians, on the other hand, would normally call at their bases at Modon or Coron (the current towns of Methoni and Koroni on the Peloponnisos peninsula) and sail either coastwise to their base at Negroponte (Khalkis on the island of Euboea) or call at Candia (Iraklion on Crete) first. On the Levantine coast the normal route west was via Cyprus. Note that the Gulf of Sirte is by-passed in the network. A realistic baseline would be between Corfu and Modon, however I have chosen an overly optimistic baseline between Messina and Alexandria, which is too long to have been measured accurately enough in medieval times. For network adjustment No 2 the data in the Adriatic was excluded in order to enable an 'honest' comparison with the cartometric analysis for the Eastern Mediterranean, which also excludes the Adriatic. However, for the precision and strength analysis in network adjustment No 1 the Adriatic data was included.

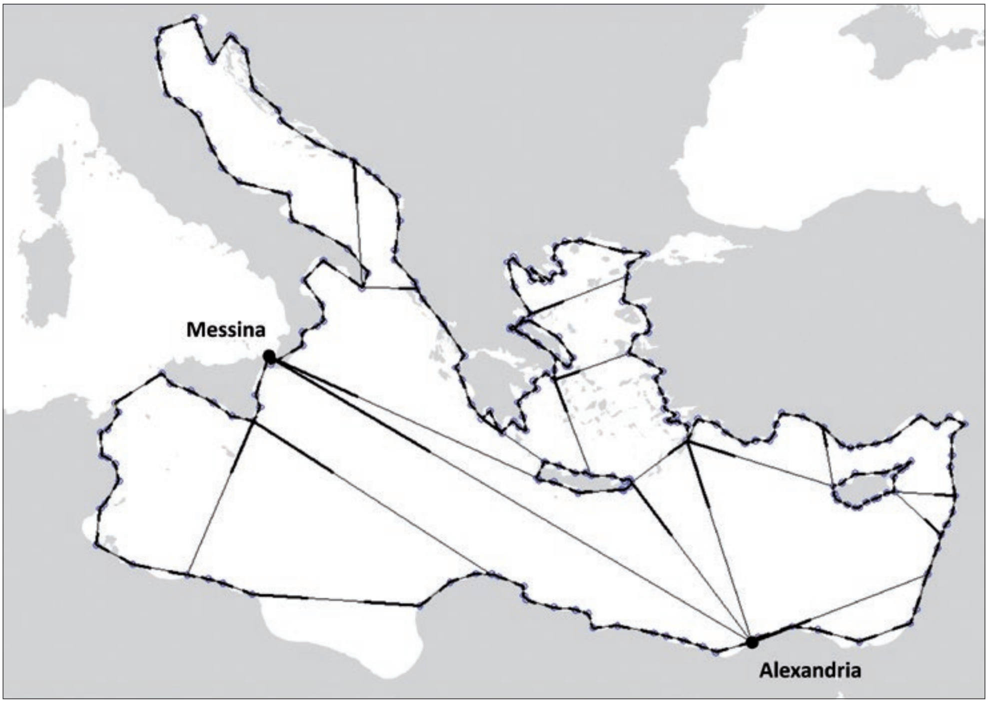

Figure 9.7 *- Eastern Mediterranean network.*

The prevailing summer winds in the Black Sea are north-easterlies, which is why only two peleio have been drawn, viz. the direct route from the Crimean peninsula to the Bosporus. The reverse route would not have been possible. Even in the present day yachtsmen are advised to make for the Bulgarian coast after leaving the Bosporus. It would therefore stand to reason to choose a baseline in that direction, but, to stay true to my intention to perform the calculations for an optimistic configuration I carried out the network computation using a baseline from the southernmost point of the Crimea peninsula (Cape Lapsi) to the Bosporus.

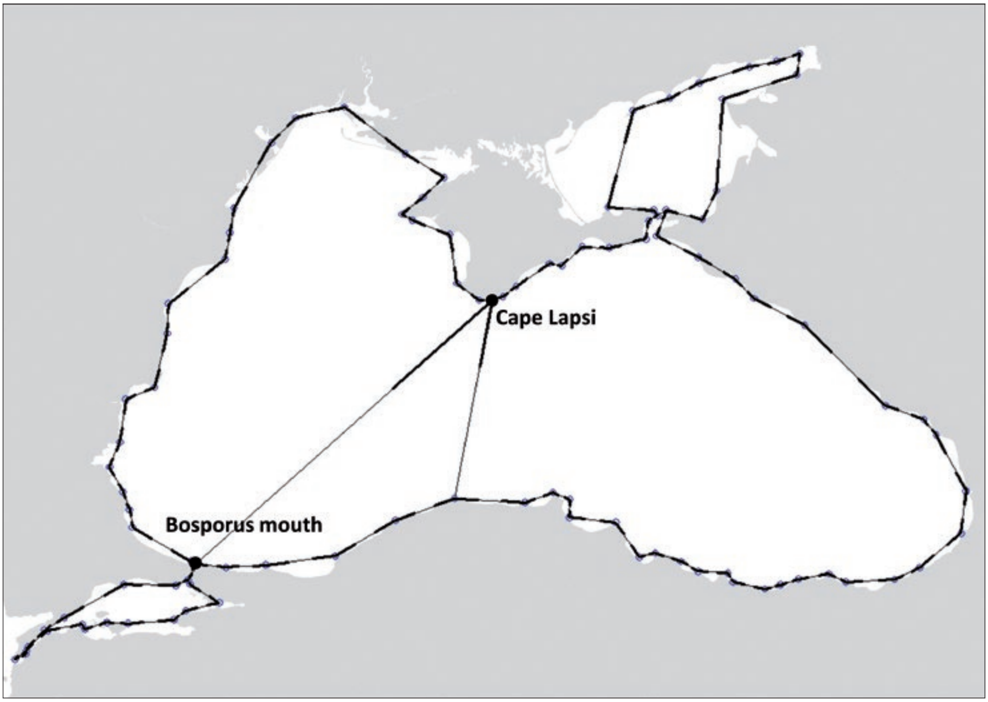

Figure 9.8 *- Black Sea geodetic network.*

9.8 NETWORK ADJUSTMENT # 1 – ACCURACY

In Section 4.10 a model was presented that quantifies navigation accuracy based on the presumed navigation techniques in the thirteenth century. The parameter values of the model were chosen such that they reflect the most optimistic case. A graphical representation of the model was shown in Section 5.9 as Figure 5.12. This figure is repeated here as Figure 9.9.

The errors in rhumb line distances and course bearings propagate into the computed coordinates of the coastal points or network nodes through the computation process of the coordinates, the Least Squares Adjustment of the geodetic network.

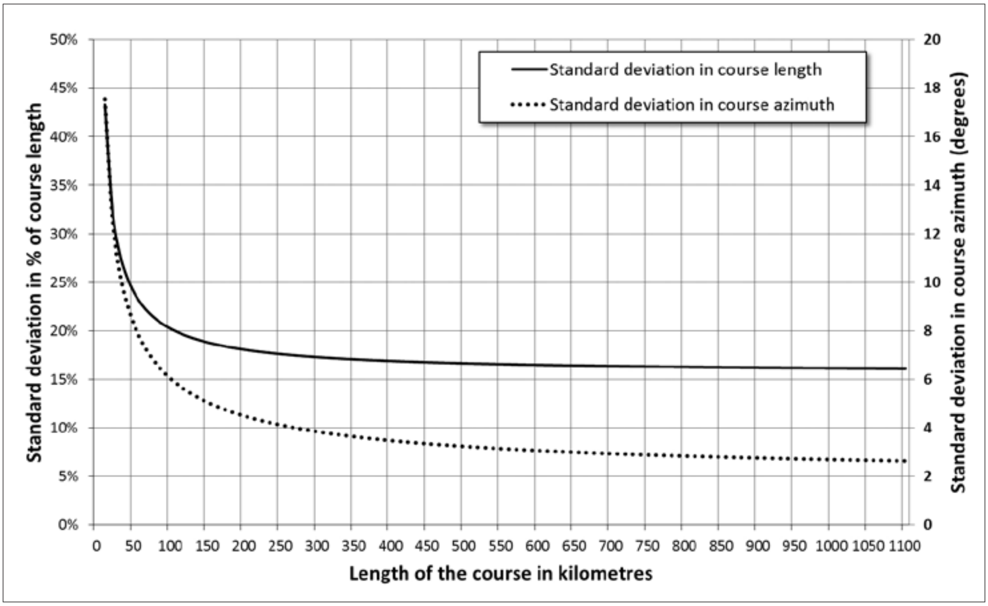

Figure 9.9 *- Standard deviation in distance and bearing of course of varying length, based on the medieval navigation model, assuming a vessel speed of 4 knots.*

The current section will assume geodetically correct processing of all distance and bearing measurements in a *weighted* Least Squares Adjustment. This is the optimum processing method and the results of the adjustment will therefore reflect the theoretical optimum chart accuracy that is achievable when charting is assumed to have taken place based on the three networks discussed in the previous section.

The output of this calculation consists of the following information:

1. Error ellipses of all points (except for the baseline ends);
2. Minimal Detectable Bias (MDB) of each distance and each bearing measurement;
3. Maximum impact of undetected errors on the coordinates of the network nodes along the coast, expressed as a Bias-to-Noise ratio.

The error ellipses for the three networks are shown in Figure 9.10, Figure 9.12 and Figure 9.14. Their distribution holds no surprises. However, the size of their semi-major axes is large in all cases except the area in the vicinity of the baseline point Genoa (there are no points close to Majorca). In the Western Mediterranean network the semi-major axes of the one-sigma error ellipses range from zero (the baseline points Genoa and Majorca) to 126 km in the far western end of the network.

Figure 9.11 shows the semi-major axes of the error ellipses of Figure 9.10 in kilometres (left-hand vertical axis of the graph), whereas the black dashes show the external reli-

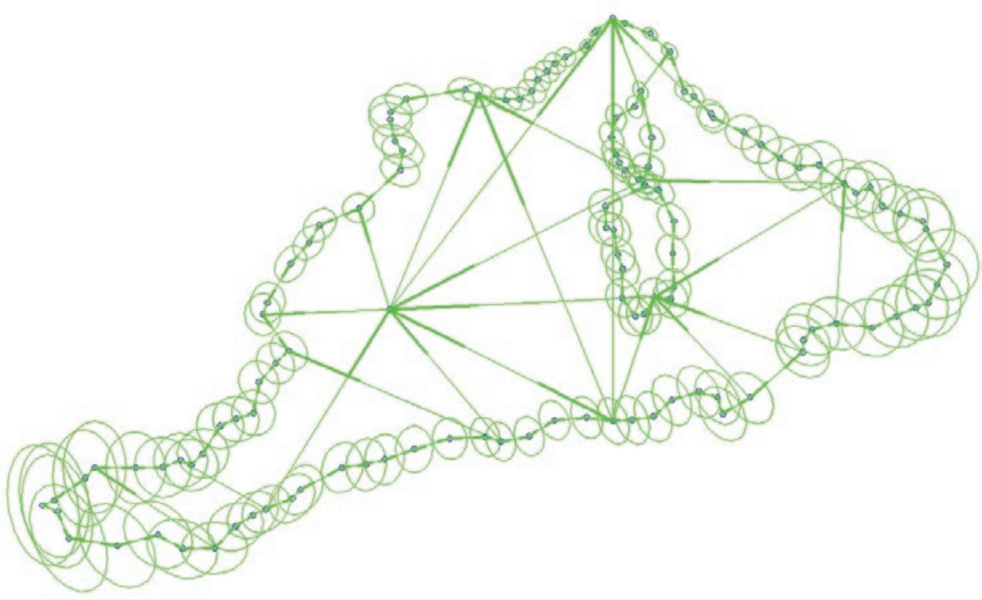

Figure 9.10 - *Error ellipses Western Mediterranean network.*

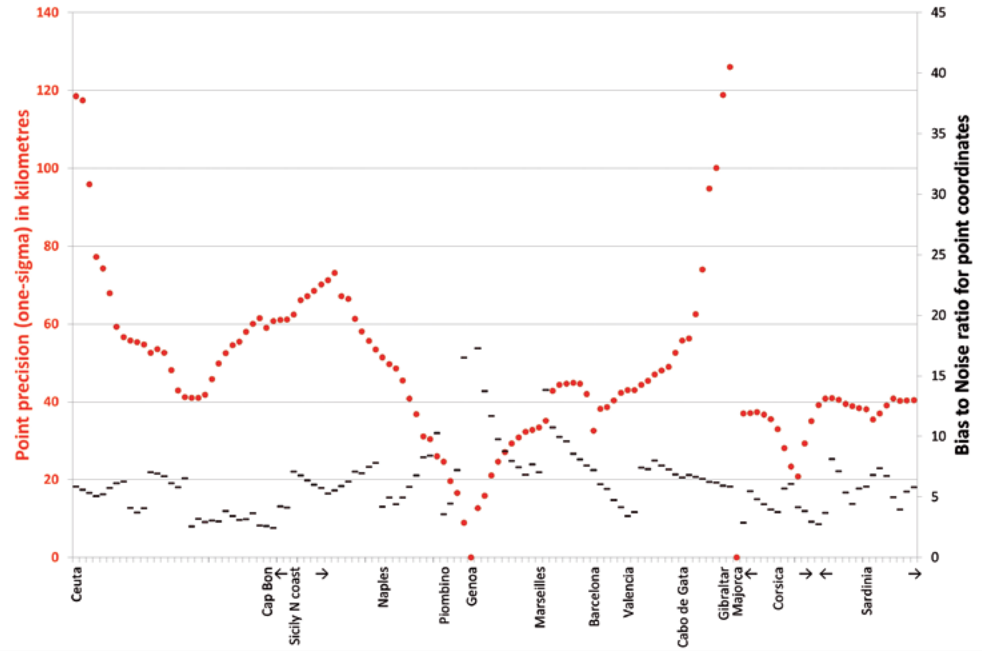

Figure 9.11 *– Western Mediterranean network: semi-major axes of one-sigma error ellipses and Bias-to-Noise ratio for the point coordinates.*

ability of the geodetic network in the form of the Bias-to-Noise ratio of the coordinates (right-hand vertical axis in the graph). The latter is a multiplication factor to apply to the semi-major axis of the point, indicating the maximum impact on the coordinates of a given point of a gross error in one of the measurements that may be detected with a probability of 80%.

This does not allow one-to-one comparison with the accuracy estimates ($RMSE_{map}$) computed from the cartometric analysis in Chapter 7. However, a rough averaging to an overall accuracy of about 50 km does permit such a comparison. Actual portolan chart accuracies for the Western Mediterranean are approximately five times better. This implies that all bearing and distance measurements would have to be more than five times better than the optimistic navigation model indicates, but this is still under the assumption of ideal LSE processing of geodetic network with an optimistic baseline. A realistic multiplication factor would therefore be much larger than five.

What is also highly revealing is the sensitivity of the Western Mediterranean network for undetected gross errors in the measurements. Taking the MDBs[635] of the measurements as the threshold for detection, the impact of undiscovered errors may on average be about five times greater than the semi-major axis of a point indicates. In a well-designed geodetic network more than twice as many geometric quantities are measured than are strictly required to compute the network coordinates. The two Mediterranean networks and the Black Sea network do not satisfy this requirement by a long way because the check measurements provided consist almost exclusively of peleio. Because of the predominance of coastal trading routes in the Middle Ages, these networks would necessarily have been very weak. Konrad Kretschmer stated in 1909 that only a handful of cross-basin courses would be adequate for providing network strength. Proper geodetic analysis, not yet possible in Kretschmer's days, proves that to be definitely incorrect.[636] It would have been nearly impossible to detect any error at all in such a network. As the black hyphens in Figure 9.11 indicate, the threshold for error detection is of the order of five times the precision of the coordinates. The Bias-to-Noise Ratio (BNR) in the area around the baseline points Genoa and Majorca is much higher because the error ellipses in that area are much smaller than elsewhere in the network. As the effects of undiscovered errors in the point coordinates error are divided by the, much smaller, semi-major axes of the error ellipses, the BNR factor is correspondingly greater for those points.

On the following pages the results are shown of the Eastern Mediterranean network and the Black Sea network.

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[635] The Minimal Detectable Biases in the bearing and distance measurements and consequently the Bias-to-Noise Ratios of the point coordinates have been calculated for a significance level of 0.1% and a power of the test of 80%.

[636] Kretschmer 1909 (1962), 87.

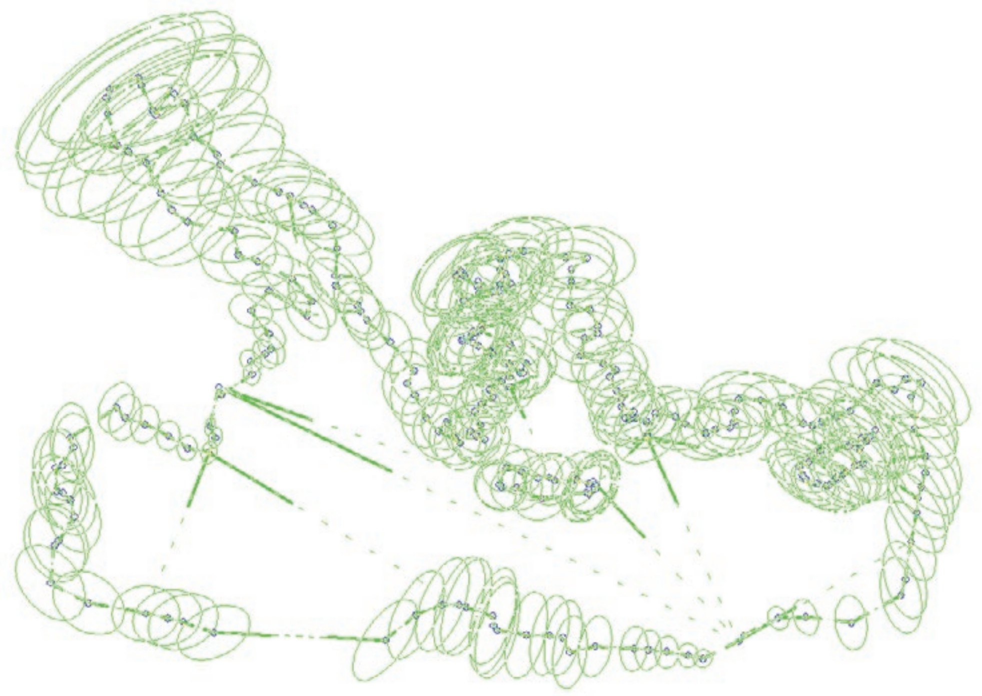

Figure 9.12 - *Error ellipses Eastern Mediterranean network.*

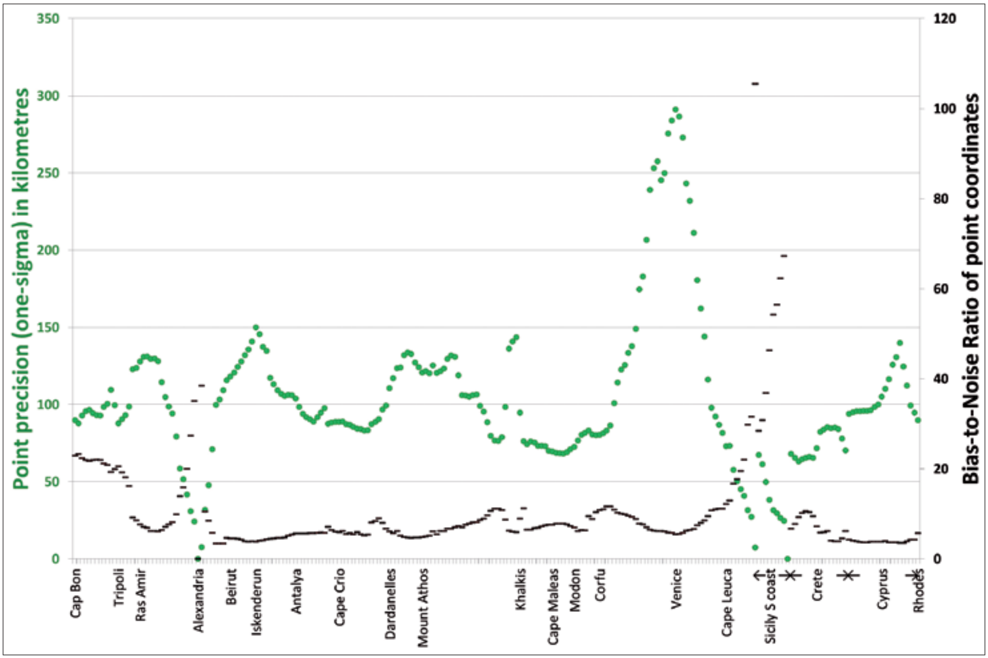

Figure 9.13 - *Eastern Mediterranean network: semi-major axes of one-sigma error ellipses and Bias-to-Noise ratio for the point coordinates.*

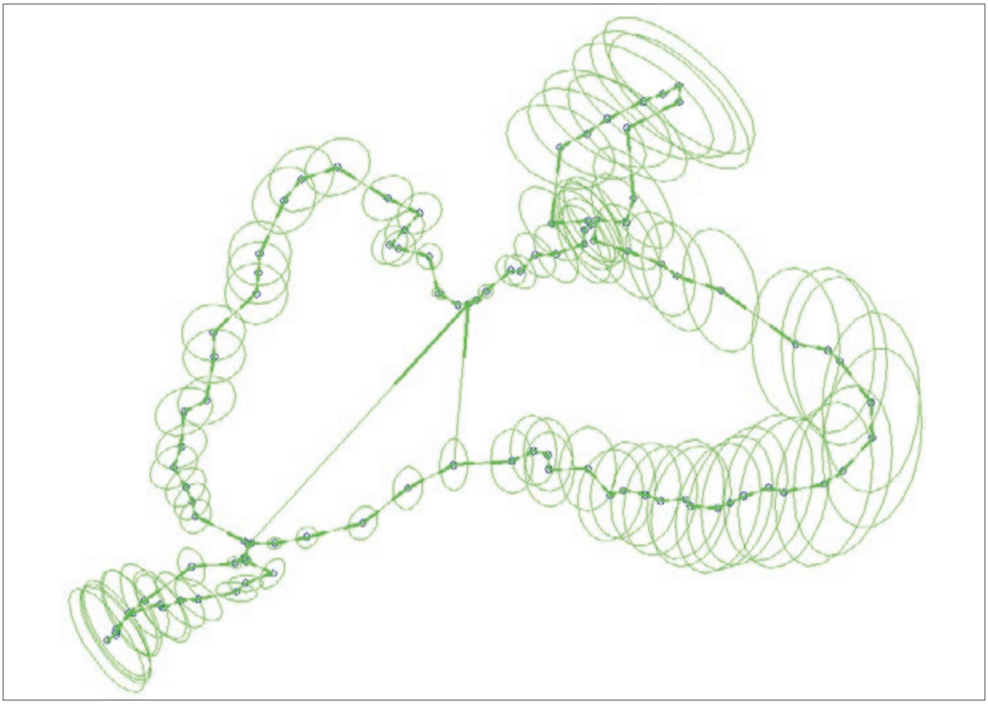

Figure 9.14 *- Error ellipses Black Sea network.*

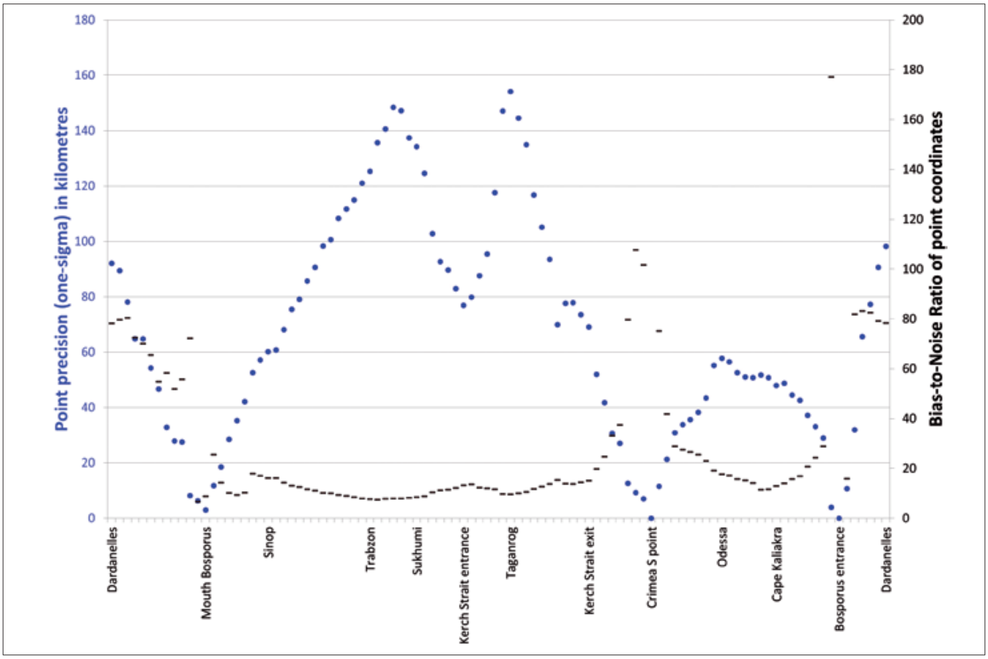

Figure 9.15 *- Black Sea network: semi-major axes of one-sigma error ellipses and Bias-to-Noise ratio for the point coordinates.*

The external reliability of the Eastern Mediterranean network is approximately twice as bad as that of the Western Mediterranean network, a BNR of about ten. Also, the precision is about twice as bad, if the large error ellipses of the Adriatic relative to the Messina-Alexandria baseline are ignored. The Adriatic lies well away from that baseline and the narrow configuration of that sea does not yield the best results for the points at its north-western extremity. The average point precision of the Eastern Mediterranean points is about 100 km one-sigma.

The Black Sea network is much smaller in coverage, but not as many peleio and other check-measurements are possible in that sea, so that the resulting average precision is still only around 70 km one-sigma. The BNR factor on the other hand, is, much larger than for the other two networks, which reflects the general lack of redundancy. The BNR factor is in the order of 15 to 20.

It is stressed that a medieval cartographer would not have had the benefit of computer programmes with such powerful processing and statistical testing techniques. Furthermore I stress again that the baselines selected are overly optimistic and over and above that, the estimated measurement precision is (too) optimistic. A *realistic* assessment of the geodetic capabilities of and possibilities in the thirteenth century for the creation of a geodetic framework that might serve as basis for charting would therefore yield considerably worse results than the network analysis results show, as presented in this section.

The method followed in this entire analysis of geodetic capabilities of the period was to adopt an optimistic position at every point where a choice needed to be made, the idea being that if a highly optimistic approach would yield results that fall short of explaining the accuracy of portolan charts, no further arguments would be required. That turns out to be the case. The following conclusion may therefore be drawn.

Even with highly optimistic assumptions for achievable navigation accuracy and processing capabilities, the achievable accuracy of realistic geodetic networks, built up with distances and bearings on routes, collected by trading ships, falls far short of the accuracy exhibited by the portolan charts that are supposed to have been constructed from such data.

9.9 NETWORK ADJUSTMENT # 2
THE MAP PROJECTION, ACCIDENTAL OR NOT?

Network adjustment# 2 attempts to mimic the hypothetical charting process as Woodward described it – see Section 9.2 above – with the additional assumption that a medieval cartographer would not have treated bearings and distances in different ways. The precision and reliability characteristics of the network, the error ellipses and Minimal Detectable Biases (MDBs), are not relevant for this calculation, as the assumed standard deviations of distances and bearings in the LSE are intended to reflect the cartographer's presumed actions in constructing the framework of the chart rather than the achievable accuracy in the network. Network adjustment #2 generates the outline of a 'synthetic chart', outline in the sense of a string of points along the coasts.

The key question to be answered is: are the *shapes* of the three geodetic networks covering the Western and Eastern Mediterranean and the Black Sea indeed sufficiently similar to the shapes of respective areas on portolan charts? One way to get an indication whether that is the case would be to overlay the Dulcert 1339 portolan chart with the plane charting network nodes after due correction for the scale and orientation differences. However the interpretation of the position differences of the network nodes would be subjective.

The proper question to ask is how similar the 'synthetic' outline chart is with a Mercator or Equirectangular reference map. This will reveal how closely the 'synthetic chart' resembles either of these two map projections. If the resemblance is very close, the map projection may indeed be considered to be an artefact, an artificial by-product, of the cartometric analysis process.

The way to answer the latter question is to subject the 'synthetic chart' to the same cartometric analysis process as the portolan charts in Chapter 7. This has the added benefit that any remaining scale and orientation differences between the plane charting network and any portolan chart are eliminated in this cartometric analysis process; these parameters are resolved as unknowns in the Least Squares Adjustment. In other words, the $\mathrm{MSE}_{\text{p-ch}}$, resulting from the cartometric analysis of the plane charting network, reflects exclusively the *shape* differences between the plane charting networks on the one hand and the coastlines of the reference map on the other. $\mathrm{MSE}_{\text{p-ch}}$ reflects the agreement of the 'synthetic' portolan chart with the reference map, without any disturbing influences such as feature exaggeration, vellum deformation or the propagation of navigation data accuracy contributing to the result. If the map projection is indeed an artefact and not a real characteristic of the chart, that match will be very close and $\mathrm{MSE}_{\text{p-ch}}$ will be close to zero.

If the hypothesis is correct, that the map projection is an artefact of the cartometric analysis process, the total error budget of the Dulcert 1339 chart, as computed in the cartometric analysis, can be considered to consist of the three main components shown in Table 9.1.

In this analysis I have used the cartometric analysis results of the Dulcert 1339 chart. The parameter to be used to reflect the accuracy of the Dulcert 1339 chart should be the sum of the squares of *all* residuals, $\mathrm{MSE}_{\text{map}}$, rather than the parameter used to quantify the overall chart accuracy, $\mathrm{MSE}_{\text{lat}}$ or $\mathrm{MSE}_{\text{lon}}$, whichever is the larger – see also

Tables 7.6 and 7.7. However, MSE_{map} is expressed in internal map units squared, which is not very meaningful. The MSE_{map} parameter has therefore been scaled to kilometres squared by appropriate scaling factors for the Dulcert 1339 chart, as determined in the cartometric analysis of Chapter 7 and shown in Table 9.2 below.

Basin	Km per map unit
Western Mediterranean	1.035
Eastern Mediterranean	1.0004
Black Sea	0.893

Table 9.2 *- Scales of the three main basins of the Dulcert 1339 chart expressed as kilometres per internal map unit.*

Network adjustment # 2 yields the following results:

Accuracy component	Western Med.	Eastern Med.	Black Sea
MSEnav: Navigation errors	…	…	…
MSEfeat: Feature exaggeration	25.0	25.0	25.0
MSEp-ch: Plane charting mismatches	177.2	663.1	60.3
MSEmap: cartometric analysis Ch. 7	176.3	247.9	203.6

Table 9.3 *- Results of the cartometric analysis of the 'synthetic' chart and the Dulcert 1339 chart in* km^2.

The figures listed in Table 9.3 are crucial, as they provide the answer to the fundamental question that forms the subject of this chapter: "Is the map projection found in the cartometric analysis of Chapter 7 an artefact of the cartometric analysis process?" Table 9.3 demonstrates that the answer to this question must be negative.

The Mean Squared Error of the map, MSE_{map} was described in Table 9.1 as being the sum of three independent components, with the assumption that the charts result from plane charting of marine navigation data.

1. MSE_{nav}, the contribution of the accuracy of the bearings and distances.
2. MSE_{feat}, the contribution of feature exaggeration.
3. $MSE_{p\text{-}ch}$, the contribution of plane charting mismatches.

$$MSE_{map} = MSE_{nav} + MSE_{feat} + MSE_{p\text{-}ch}$$

The three component effects are all defined as squares, hence they are all positive numbers. Nevertheless Table 9.3 shows that for the Western and the Eastern Mediterranean networks the contribution made by plane charting mismatches is already *larger than* the total Mean Squared Error of the Dulcert 1339 sub-charts, as determined by cartometric analysis in Chapter 7.

It isn't even necessary to add a realistic estimate of the contribution of navigational accuracy to the MSE of the map, hence the dots in the first row of Table 9.3. It is clear from the large contribution of the plane charting mismatches, that portolan charts cannot have been constructed by means of plane charting. The interpretation of the figures in Table 9.3 is that the plane charting network has a *significantly different shape* than the coastal outlines on the actual portolan charts. The coastal outlines on a portolan chart agree closely to a map image generated by applying a map projection; the plane charting network yields significantly different results and well outside the accuracy 'band' of the portolan chart, as quantified by $\mathrm{MSE}_{\mathrm{map}}$.

Only in the case of the Black Sea network do the figures in Table 9.3 not immediately lead to a conclusion that the charts cannot have been constructed by plane charting. This is caused by the much smaller extent of the Black Sea network, as a result of which the plane charting mismatches are smaller. For the contribution of navigation accuracy of the Black Sea network, a Root Mean Squared Error of 10.9 km remains from the error budget in Table 9.3. The accuracy calculation of network adjustment #1 yielded a standard deviation in the order of 70 km and, as emphasized several times before, that is based on an optimistic model for medieval navigation and for processing the measurements into a charting framework.

Therefore it may be concluded that the map projection of portolan charts cannot be an artificial by-product of a cartometric analysis method that calculates the best-fit of that map projection to the chart.

The map projection must therefore have been intentionally and a priori designed into the construction of the chart. Plane charting mismatches in the Mediterranean are clearly not negligible, as is usually postulated. This has been demonstrated earlier in Chapter 3.5 and Appendix II and it is confirmed by the figures in Table 9.3.

The differences between the plane charting network, of which the three components have been rotated and scale-corrected by best-fitting them to the Dulcert 1339 portolan chart are shown in the form of a map in Figure 9.16 and in the form of radial differences expressed in kilometres in Figure 9.17.

In the above comparison each of the three plane charting networks was corrected for scale and rotation, determined from a Least-Squares fit of the network to the Dulcert 1339 chart, so that only the shapes of each network and the portion of the Dulcert 1339 chart it covers are compared. The entire plane charting network was then 'pinned' to the location of Genoa, which consequently shows no error.

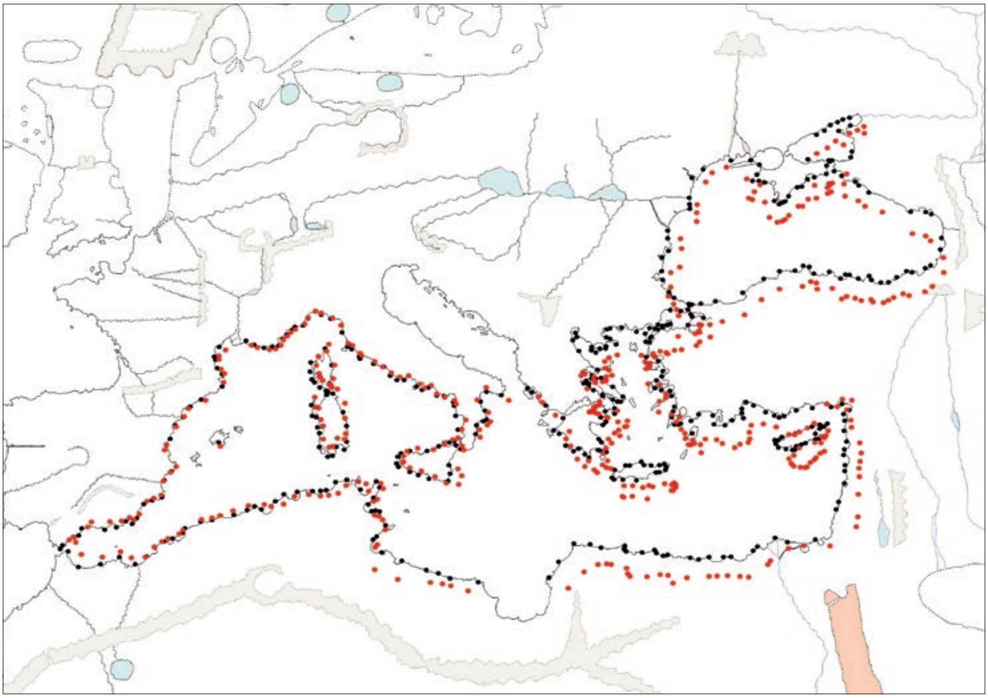

Figure 9.16 *- Tracing of the Dulcert 1339 chart with points used in the plane charting network (black dots) and the positions of the same points from the plane charting calculation (red dots).*

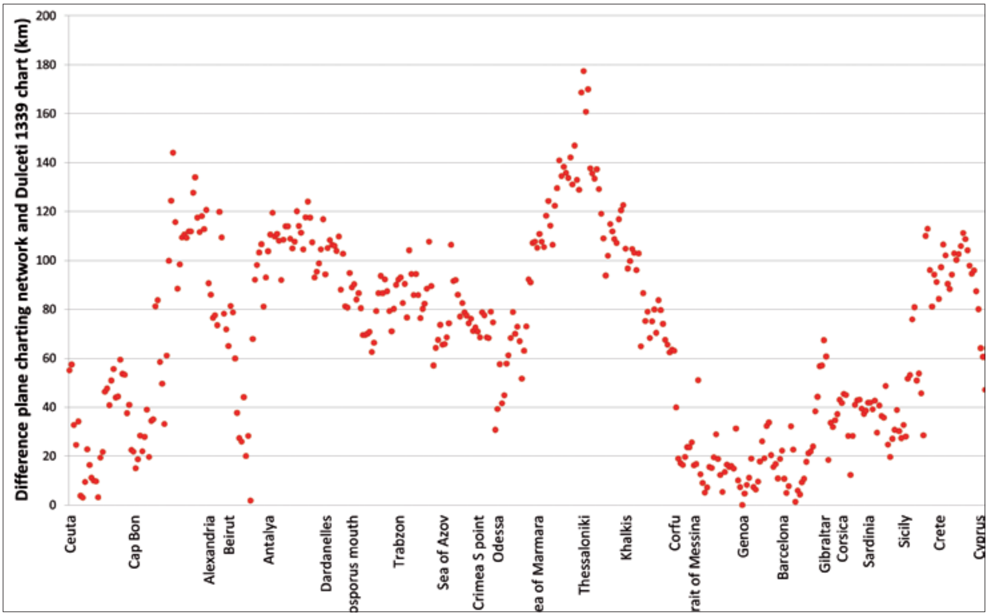

Figure 9.17 *- Point differences in kilometres between the Dulcert 1339 chart and the plane charting network.*

Figure 9.16 and Figure 9.17 illustrate the differences that would occur between a plane charting network proposed in the medieval origin hypothesis and an actual portolan chart. Admittedly the differences cannot be seen in Figure 9.16 with the naked eye, which is why simple visual inspection of the results is not enough to draw reliable conclusions. The proof that a plane charting network will not result in a portolan chart is provided by Table 9.3, which demonstrates in a single figure that the shapes of the two do not match.

9.10 ANALYSIS AND CONCLUSIONS

The network accuracy analysis in Section 9.8 demonstrates that a geodetic network consisting of uncorrected magnetic bearings and rhumb line distances falls short of the precision displayed by portolan charts by approximately:

- a factor five for the Western Mediterranean,
- a factor ten for the Eastern Mediterranean and
- a factor six for the Black Sea.

A question which readers may wish to ask is how the achieved point accuracy compares with the accuracy of distance and direction measurement. In the Western Mediterranean the distance from the baseline point Palma to Ceuta is about 840 km. If that distance could have been measured directly it would, according the accuracy model derived, have a standard deviation of about 80 km (see Figure 9.9). Direction could have been measured about three times better, i.e. equivalent to about 27 km cross-course. The one-sigma point accuracy of Ceuta and Gibraltar relative to the baseline point Majorca is about 120 km (see Figure 9.10 and Figure 9.11).

In the Eastern Mediterranean the distance from the baseline point Alexandria to Acre on the Levantine coast is 527 km, which would, for a direct measurement of that distance, result in a standard deviation of about 90 km and a standard deviation in the direction measurement of 30 km cross-course. In contrast with those figures, the semi-major axis of the one-sigma error ellipse of Acre is about 120 km (see Figure 9.12 and Figure 9.13).

One might expect the accuracy of any point to correspond linearly with the distance to the baseline, but the geometry of the network is the intermediate factor between the measurement precision of distance and direction and the precision of the computed positions of the network nodes. Depending on the quality of the geometry of the network the effect may be favourable or unfavourable. The poor geometry of the Eastern Mediterranean network may be blamed for the poor precision of the coordinates of the nodal points. It is rarely realised that the accuracy of measured distances and other geometric quantities do not propagate one-to-one into the accuracy of the points of which the positions are computed. The geometry of the geodetic network introduces a 'loss factor' into the accuracy of these point positions.

The above multiplication factors represent a highly optimistic view of the achievable precision with a geodetic network consisting of azimuth and distance measurements, taken on board of medieval ships. It should be realised that the following factors would have reduced the quality of such a network:

1. The results in Sections 9.8 and 9.9 are based on Least Squares Estimation and associated optimum statistical testing. The inevitably cruder methods of graphic adjustment that would have been available to a medieval cartographer would have resulted in a sub-optimum network, i.e. a network of poorer accuracy. Notably the vulnerability to undetected errors, which is already very considerable in the LSE analysis of the three networks, would have been far greater and it is unrealistic to assume that medieval seamen would never have made errors in their (presumed) estimates of distance (and direction).
2. In Section 5.8 it was concluded that the magnetic compass cannot have played a role in the construction of the first portolan charts, because it would not have been available widely enough in a suitable form that would allow the measurement of directions (azimuths or bearings). Since the navigation accuracy model developed in Chapter 5.9 and Appendix III concluded that a compass bearing could have been observed about three times more accurately than distance, any geodetic network consisting of distances alone – as Woodward[637] suggested – would firstly require an immense number of distances to construct the network (i.e. to determine the position of all nodes) and secondly would have been considerably less accurate than the networks computed in Section 9.8.
3. In Section 4.10 it was concluded that the possibility that the accuracy of any azimuth or distance was improved by the calculation of the arithmetic mean from multiple estimates of that quantity must be excluded, as this technique was unknown and hence not available in the Middle Ages.
4. The navigation accuracy model, populated with the chosen values of the model parameters, presents an optimistic view of medieval navigation and was intended to describe the best achievable result.

The analysis of a plane charting network in Section 9.8 demonstrates that the shape of a plane-charted geodetic network is significantly different from the coastal outlines on a portolan chart and from the coastline shapes of a modern map on the Mercator or Equidistant Cylindrical projection.

It might be argued by die-hard proponents of the consensus view (projectionless portolan charts), that a *different* plane charting network than the one tested, e.g. with more cross-basin routes, may confirm the consensus idea. However, that must be doubted. The reason for the MSE_{plane_ch} being as large as it is for the Western and Central Medi-

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[637] Campbell 1987, 388. See also Section 9.2.

terranean networks is the fact that earth curvature is ignored. More or different cross-basin routes will simply add their own systematic discrepancies; they will not make the effects of ignoring earth curvature disappear.

It is also highly unlikely that the adjustment or graphic reconciliation process will, by sheer coincidence, distribute all data conflicts in such a way that the resulting shape of the coastlines agrees well with a Mercator chart. That would require the following unlikely pattern of corrections:

- Compass bearings would have to receive a correction that would eliminate on average the spatial variation in magnetic declination only, because the bearing from one point to another in a Mercator chart is the same as the corresponding azimuth measured on the spherical earth.
- Distances would have to receive a correction such that, on average, the corrected distance would be $1/\cos\varphi$ times the distance measured, in which φ is the mean latitude of the two points between which the distance was measured (this would equate to accidental 'Mercator sailing').

In short, given the arbitrary graphic reconciliation process, mimicked by a Least Squares Adjustment, a highly regular pattern of corrections, as described above, would accidentally have to be applied to the measurements and the probability of this happening in any of the sub-basins of the Mediterranean must be considered negligibly small. It is even less likely to have happened in every sub-basin that was investigated.

The conclusions from the dual analysis of geodetic networks in this chapter have to be as follows.

24. *The constructional basis of portolan charts was <u>not</u> a plane charted geodetic network consisting of magnetic bearings and rhumb line distances.*

25. *The map projection found in portolan charts is not an artefact of the cartometric analysis process.*

26. *The map projection must, in the absence of any other realistic explanations, be considered to have been designed into the charts intentionally.*

27. *The achievable navigational accuracy in the Middle Ages fell far short of being able to supply the base data from which a portolan chart could be constructed.*

10 AN ARABIC-ISLAMIC ORIGIN OF PORTOLAN CHARTS?

10.1 Introduction

In the Introduction of this thesis I stated that I would only consider a possible Arabic-Islamic origin of portolan charts after having completed my analysis of the charts and the related material. It is more efficient to deal with the subject in that order, because the cartometric data generated, as well as several of my arguments, apply in equal measure to a possible Arabic-Islamic and a possible European origin.

Very few researchers have proposed an Arabic-Islamic origin of portolan charts, but this idea recently acquired a passionate ambassador in Fuat Sezgin, who wrote a very extensive work in two volumes on Arabic-Islamic cartography, with a separate third volume containing map reproductions.[638]

Sezgin's rather unorthodox views have hardly drawn any responses from map historical circles. The only reference I have been able to find is by Evelyn Edson, who, after describing some of Sezgin's arguments regarding the origin of portolan charts, comments cautiously that "Sezgin is more plausible when he cites Arabic influences on later European world maps …"[639]

Arabic-Islamic science was probably the most advanced in the world in the eleventh and twelfth centuries.[640] The name that stands out in geodesy is Abu al-Rayhan Muhammad ibn Ahmad al-Biruni[641]; in astronomy and astronomical geodesy (position determination) many more men made significant contributions. These arguments do indeed make Arabic-Islamic culture a more likely candidate for the origin of portolan charts than late-medieval European culture.

However, map-historical consensus holds that portolan charts did not originate in Arabic-Islamic civilisation and that consensus is based on three good arguments.

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[638] Fuat Sezgin, *Geschichte des arabischen Schriftums*, *Mathematische Geographie und Kartografie im Islam und ihr Fortleben im Abendland*, Band X, XI & XII (Frankfurt am Main: Institut für Geschichte der Arabisch-Islamischen Wissenschaften an der Johann Wolfgang Goethe-Universität, 2000).

[639] Edson 2007, 43.

[640] Huff 2003, 52, 53.

[641] See Jamil Ali, *The Determination of the Coordinates of Positions for the Correction of Distances between Cities*, a translation from the Arabic of al-Biruni's 'Kitab Tahdid Nihaya al-Amakin …' (Beirut: American University of Beirut: 1967)

1. Portolan charts have nothing in common with typical Arabic-Islamic cartography.
2. No early Arabic-Islamic portolan charts are extant.
3. The few Arabic-Islamic portolan charts that are known appear to be poor copies of European portolan charts.[642]

Regarding the first point it might be argued that portolan charts have nothing in common either with European clerical cartography (*mappaemundi*) and that this has never stopped researchers from assuming that portolan charts have a European origin. Although that is entirely true, "two wrongs don't make a right". The dissimilarity of portolan charts and Arabic-Islamic cartography becomes a relevant argument in the light of the current study, which has demonstrated that portolan charts, far from being a primitive map type, are actually sophisticated cartographic and geodetic products.

Scholars who have advocated Arabic-Islamic roots in the past appear to have been led by the argument that Muslims had early access to Claudius Ptolemy's *Geography,* which constituted the pinnacle of cartographic achievement in antiquity. However, it has since been proven that portolan charts and Ptolemaic cartography share no characteristics.

Sezgin attempts to show that cartography, or rather mathematical geography, developed far beyond the Ptolemaic basis in Arabic-Islamic culture, exerted considerable influence on European mapping in general and led to the development of portolan charts.

10.2 Ibn Fadl'allah's map – the 'Mamun geography'

Fuat Sezgin makes a spirited effort to reconstruct the geographic work that took place under caliph al-Mamun in the early ninth century AD. Key to his reasoning is a world map, discovered in 1985 in a copy of a 27-volume encyclopaedia by Ibn Fadl'allah al-Umari (1301-1349), which shows the results, according to Sezgin, of the geographic work undertaken by a group of scientists assigned by the caliph to improve on Ptolemy's *Geography.* Sezgin refers to the results with the term 'Mamun geography'. The map is reproduced in Sezgin's map annex as Map No. 1a and is also reproduced by Gerald Tibbetts in *The History of Cartography* series, Part II, Book 1 as Figure 6.14, unfortunately in black and white only.

Sezgin believes this map, which is equipped with a graticule, to be based on the Stereographic projection and dates it without providing justification to "about 1340", which would make it an original of Ibn Fadl'allah, although he admits at the same time that the map is the result of multiple successive copying of an original map by Ibn Fadl'allah.

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[642] Scott Loomer's analysis of two extant Arabic portolan charts showed that the accuracy (RMSE) of these charts was worse than that of the European charts he analysed. In Table 6.4 Loomer lists the RMSE of all 27 charts he analysed in order of ascending RMSE, from 0.30 to 0.76. The two Arabic charts are found on places 25 and 26, with a RMSE of 0.63 and 0.67. See Loomer 1987, 148.

The extant map copy would therefore have to date from much later than 1340. Sezgin adds later in his book that the map is the product of a painter rather than a cartographer, because of the "deformed outlines" of notably South-East Asia, which raises the question from where Sezgin obtained that information, when this is the only cartographic remnant of the Mamun geography.[643] Tibbetts points out that there are several copies of Ibn Fadl'allah's encyclopaedia in the Topkapi Sarayi Museum in Istanbul and that none of the dated ones is older than 1585. Tibbetts believes the graticule to be a later Ottoman addition to the extant map copy. The graticule appears to belong to the so-called Globular projection, which, according to Gerald Tibbetts, was invented or at least described by al-Biruni.[644] It was subsequently described by Roger Bacon, but became popular in Europe only in the fifteenth and sixteenth centuries. The Globular projection is a simple map projection that creates a globe-like visual impression of the earth. It exists only in the equatorial aspect: the earth is shown as a circle and all parallels are straight, equidistant horizontal lines; the meridians are arcs of circles that intersect the equator at equal intervals.

However, Sezgin is convinced that the meridians on Ibn Fadl'allah's map result from the application of the Stereographic projection, whereas the parallels, which would also be arcs of circle in the Stereographic projection, have been replaced by equidistant straight lines by an "ignorant copyist". Sezgin is convinced that justification for his view is found in a surviving document by Abu Abdallah az-Zuhri (twelfth century AD), which describes aspects of the Mamun geography. Sezgin cites the following statement by az-Zuhri: "They transposed … [the spherical geometry of the earth] to the plane, as they have done with the astrolabe …" He takes the phrase " … as they have done with the astrolabe" to mean that al-Mamun's geographers rendered the results of their labour in a map on the Stereographic projection, since the *tympanum* of an astrolabe shows a Stereographic projection of the celestial globe.

The postulated Stereographic projection is key to Sezgin's claim on portolan chart origins. Citing Duken that portolan charts were consciously drawn on a Stereographic projection, Sezgin concludes: "When the configuration of the portolan charts leads us to the conclusion that they are originally based on the Stereographic projection, we may assume that they are indirectly linked to the Mamun map."[645]

In Section 6.3 B and Section 6.7.5 I demonstrated that the Stereographic projection is a highly unlikely map projection to underlie portolan charts, although it is of course quite possible to evaluate a portolan chart cartometrically against that projection, as Duken

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[643] Sezgin I, 2000, 112, 305.

[644] Gerald R. Tibbetts, "Later Cartographic Developments." In *The History of Cartography, Volume 2, Book 1, Cartography in the Traditional Islamic and South Asian Societies,* ed. J.B. Harley and David Woodward (Chicago, University of Chicago Press, 1992). 142.

[645] Sezgin I, 2000, 305.

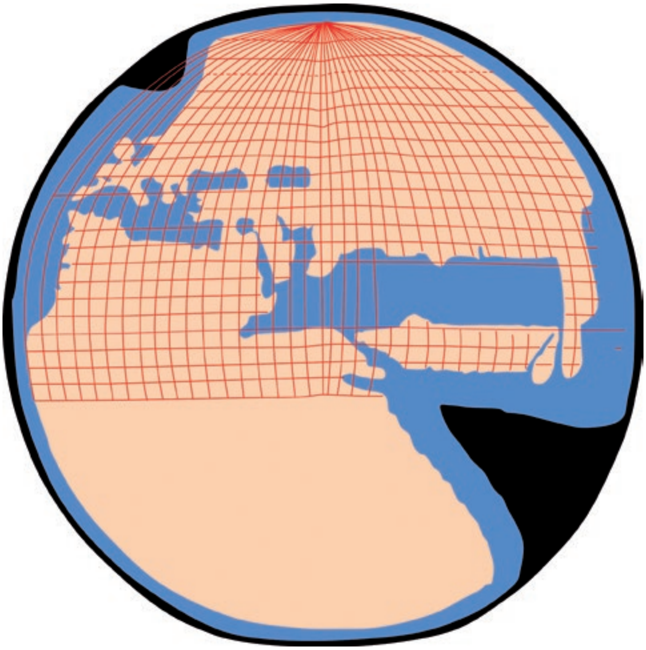

Figure 10.1 *- Tracing of the copy of Ibn Fadl'allah's map (Sezgin: map 1a).*

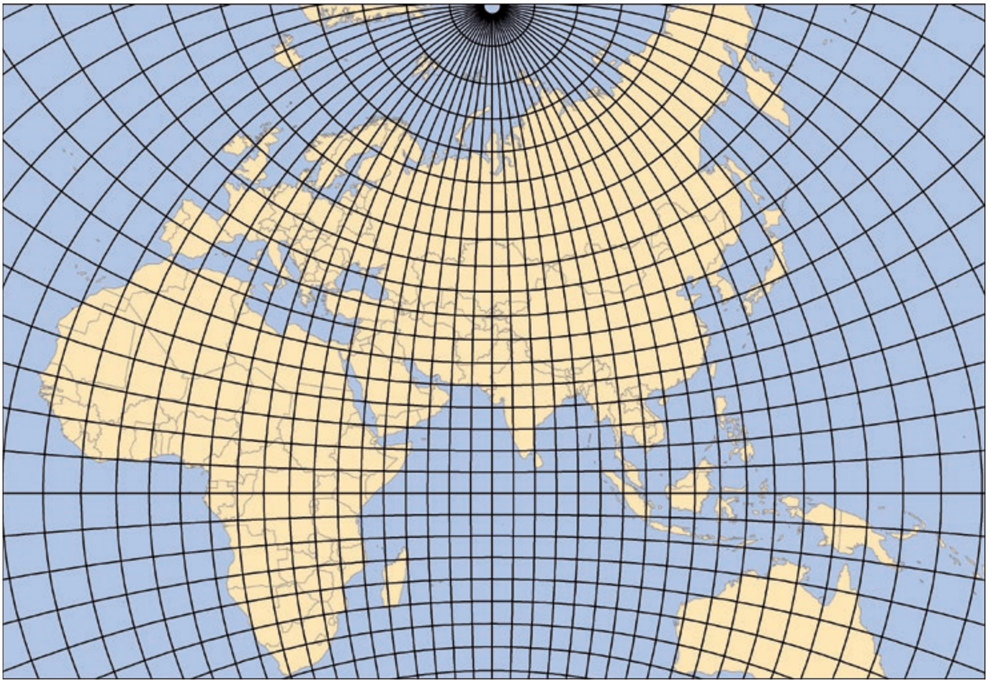

Figure 10.2 *- Modern map on Equatorial Stereographic projection, covering approximately the same area as Ibn Fadl'allah's map in east-west extent (180° of longitude).*

did. The link that Sezgin postulates between the Mamun geography and portolan charts is therefore very implausible. Moreover, despite Sezgin's repeated assertions, the meridians on Ibn Fadl'allah's map copy do not correspond with the Stereographic projection. On Ibn Fadl'allah's map the meridians intersect the equator at what are clearly intended to be equidistant intervals, which is consistent with the Globular projection. In the equatorial (or transverse) Stereographic projection the spacing of the meridians increases away from the central meridian. Figure 10.1 shows a tracing of the main characteristics of Ibn Fadl'allah's map copy, including, in red, the graticule with five degrees intervals and the effects of the fold in the paper in the middle.

Figure 10.2 shows approximately the same area in the equatorial Stereographic projection, albeit truncated in the south, on a modern map. In summary, the graticule on Ibn Fadl'allah's map copy is that of a simple Globular projection, which has nothing to do with the Stereographic projection.

10.3 Progress in astro-geodetic position determination

After having expressed his views on Ibn Fadl'allah's world map, Sezgin describes a process of progressive improvement in Arabic-Islamic astronomic geodesy, with increasing accuracies in the determination of longitude differences by means of the lunar eclipse method[646] to about 3° to 4° in the ninth and tenth centuries. In the eleventh century al-Biruni introduced a method of improving longitude difference determination using a new method, spherical trigonometry. Sezgin concludes from al-Biruni's citations of Ptolemy's *Geography* that al-Biruni was conscious of the fundamental weakness in Ptolemy's work: his reliance on itineraries and writes that al-Biruni "measured" the distances between cities.[647] However, this is also incorrect, as al-Biruni extracted his distances from itineraries, just as Ptolemy did and he reduced these distances for "windings in the road" by one sixth or one tenth, as also Ptolemy did before him.[648] According to Sezgin,

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[646] Determination of the longitude difference between two locations consists in essence of time difference measurement: the difference in local time at each locations is (more or less) a direct function of the longitude difference between the two locations. However, that difference in local times could only be measured if the 'local clocks' could be read at exactly the same moment in both locations. The occurrence of a lunar eclipse is a phenomenon that is observed at the same time everywhere on earth and in principle solved this need for synchronization of local time determination in both places. This method is not very accurate, but it was extensively applied in Arabic-Islamic astronomical geodesy.

[647] Sezgin I 2000,155. This is not what al-Biruni says. He states that in the past (Ptolemy's days) communications between cities were risky and people of different creeds tended to do harm to one another: "the divergence of their systems of belief adopted by those citizens was the main hindrance to travel", and distances were poorly known. But now that Islam has united all nations in one bond of love, travel had become easier and distances were more accurate and trustworthy. See Jamil Ali 1967, 190, 191.

[648] Raymond P. Mercier, "Geodesy", in *The History of Cartography, Volume 2, Book 1, Cartography in the Traditional Islamic and South Asian Societies,* ed. J.B. Harley and David Woodward, Chicago, University of Chicago Press: 1992, 186. See also al Biruni's own text in Ali 1967, 202, 206, 207, 257. Ptolemy reduced the distance from itineraries by one third to account for windings in the road and the tendency

al-Biruni's method was taken up widely and the lunar eclipse method was ever more rarely used after that. Tibbetts on the other hand relates that few of the improvements made by al-Biruni were picked up by his successors.[649] Sezgin describes that developments in astronomic geodesy after al-Biruni culminated in the thirteenth century in the methodological improvement described by Abu al-Hasan al-Marrakusi (1203-1260). This, according to Sezgin, entailed the simultaneous determination of altitude and azimuth of several stars (as well as local time by means of an astrolabe). Sezgin writes that, as a result of al-Marrakusi's improvement, locations in the Mahgreb "reached their true values" and adds the suggestive comment that "30 or 40 years later portolan charts appear".[650] However, it is unclear how al-Marrakusi's method worked, how revolutionary his method was and to what extent this method was picked up in the Arabic-Islamic world. Apart from Sezgin's description, not much can be found on al-Marrakusi's improvements in astronomical geodesy. The history of astronomical geodesy in the Arabic-Islamic world as Sezgin describes it may leave an impression with the reader of a steadily improving positional accuracy to the level of accuracy that portolan charts show. As Sezgin doesn't present clear numeric evidence that demonstrates this progressive development, the process may be described eloquently but is certainly not proven.

10.4 SEZGIN'S HYPOTHESIZED CONSTRUCTION METHOD OF PORTOLAN CHARTS

In Volume II of his work Sezgin continues to prepare the way for his hypothesis on the origin of portolan charts, arguing for "the most extensive presence of the Arabs in the Mediterranean world" and stating that the Arab conquests of the seventh to the ninth century AD demonstrate Muslim familiarity with the Mediterranean geography. He describes how the Muslims set up an extensive maritime trading network in the entire Mediterranean world and that all this maritime activity required exact knowledge of routes, distances between ports, circumferences of islands etc. In other words, Sezgin repeats the same arguments that other researchers have used to argue for a European origin, but then applied to the Muslim world: the assumption that repeated sailing of the same routes leads automatically to increasingly accurate knowledge of distances.

However, the extent of the Muslim trading network in the Mediterranean was limited. Although there was undoubtedly trade activity with notably the Byzantine Empire, Muslims traded mainly within the Islamic world itself. Moreover, from the end of eleventh century onward, Muslims lost their maritime dominance and were eclipsed by the Italian city states, beginning with Pisa.[651]

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of travellers to exaggerate the distance they travelled.

[649] Tibbetts *Later cartographic developments* 1992, 142.

[650] Sezgin I 2000, 168 – 172.

[651] See Chapter 1.1.2.

Sezgin doesn't explain how this presumed detailed and accurate knowledge of maritime distances (and possibly directions), acquired during the centuries of Muslim dominance, could have been so carefully preserved, while the geographic reform that had taken place under caliph al-Mamun was so quickly forgotten: al-Battani (d. 929) was unaware of that, as were al-Biruni, al-Idrisi and Ibn Said. The latter two, according to Sezgin, mistook whatever remained of the Mamun geography for Ptolemy's work.[652]

Sezgin hypothesizes that portolan charts are based on a framework of astronomically determined coordinates, supplemented by marine itineraries and "other topographical data".[653] Whereas this appears more plausible from a geodetic perspective than the European medieval origin hypothesis of a marine network of distances and directions only, Sezgin's hypothesis has some important flaws. He only expresses his hypothesis in general terms and steers clear of particularities such as the cities or points that constituted the presumed astro-geodetic framework. It is doubtful that there would have been enough of those points. Moreover, many of the points or cities for which astronomically determined positions were available were situated well inland. Sezgin does not attempt to explain how these points would have been tied into the presumed marine trilateration, unless the vague term "other topographical data" is supposed to cover that.

John Kirtland Wright used the geographical coordinates for 58 locations in the Marseilles Tables to construct a world map, shown in Figure 10.3, in which he sketched the coastlines only very roughly because no information is and was available that linked many of the points to the coast.[654]

Furthermore, Sezgin appears to be entirely unaware of accuracy issues around marine itineraries and the need for reconciliation of measurement errors and plane charting inconsistencies. Although al-Biruni calculated the mean longitude difference between Ghazna (near Kabul) and Baghdad from the two traverses, I have not been able to find any indication that the calculation of the arithmetic mean of series of measurements of the same variable was generally known and applied to distances determined in navigation in Arabic-Islamic culture. Sezgin merely uses the argument that marine distances (and directions?) became more and more accurately known in the course of time, an argument that is also used in the medieval origin hypothesis and which has been invalidated in this study. It is also unlikely that enough distances would have been observed to create a trilteration network of sufficient density to construct the coastlines, apart from the problems of collating all data, coordinating the cartographic effort and reconciling all data conflicts. Sezgin believes to find support in Gautier Dalché's conclusions regarding the *Liber de existencia riveriarum* of the end of the twelfth or beginning of the

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[652] Sezgin I 2000, 88, 97, 155.

[653] Sezgin II 2000, 14.

[654] John K. Wright, "Notes on the Knowledge of Latitude and Longitude in the Middle Ages." *Isis: International Review Devoted to the History of Science and Civilization*, Vol. V, Part I, 1923, 87.

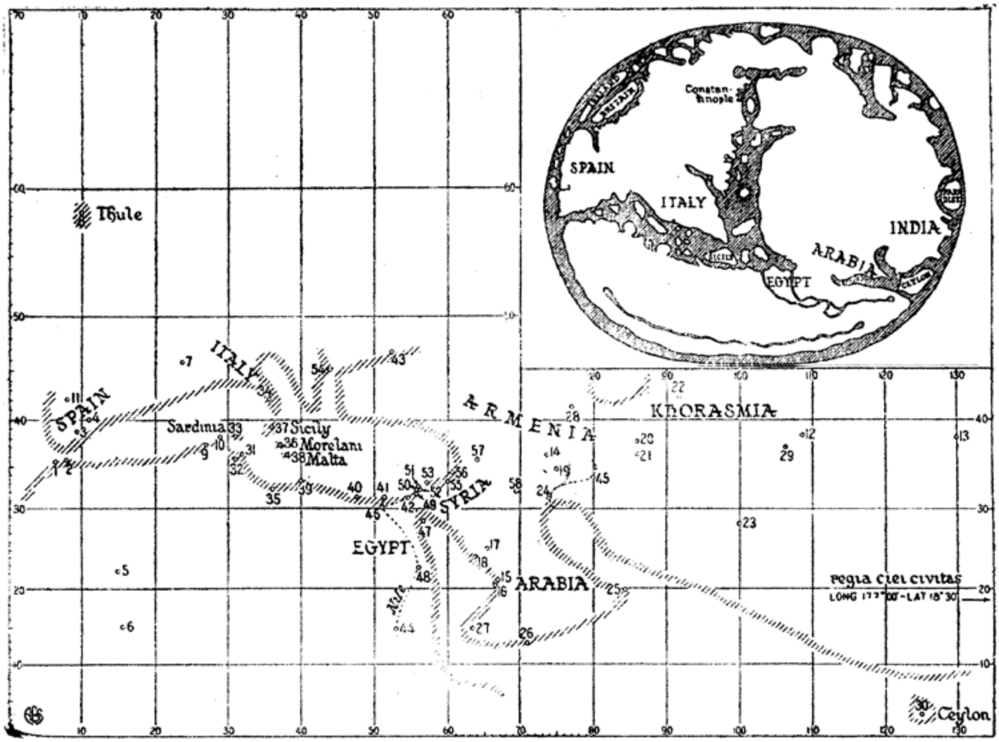

Figure 10.3 *- John Kirtland Wright's construction of a map of the Islamic world from the astro-geodetic coordinates in the Marseilles Tables (Gratefully reproduced from J.K. Wright, "Notes on the Knowledge of Latitude and Longitude in the Middle Ages", ISIS: International Review Devoted to the History of Science and Civilization, Vol. V, Part I, 1923, 87, Chicago: The University of Chicago Press).*

thirteenth century stating that enough distances and directions (sic) had by then been collected to allow the drawing of the first, almost perfect chart of the Mediterranean.[655] Sezgin is mostly vague regarding the availability of directional data and prefers to speak of "marine itineraries".

The one issue that a framework of astro-geodetic points would solve – at least in theory – is the problem of the map projection. Rendering the astro-geodetic data on an Equidistant Cylindrical projection would be easy, although there are, despite the wealth of astro-geodetic data in the Arabic-Islamic world, no examples available of that data being presented in the form of a map, let alone a map on this type of projection. However, in theory it would solve the map projection problem of portolan charts, were it not for the rotation angle of 10° that portolan charts exhibit, which is inexplicable if a framework of astro-geodetic points is postulated, and were it not for the regional scale differences in the charts. Sezgin omits to mention these issues.

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[655] Sezgin II 2000, 25.

For Sezgin's hypothesis to work would have required the latitudes and longitudes of *all* points of the astro-geodetic framework to be determined to a standard deviations of 7 and 6 arc minutes respectively in order to achieve the accuracy of portolan charts.[656] Al-Marrakusi's method resulted, as Sezgin relates, in a reduction of the error in the length of the main axis of the Mediterranean to 2°, which Sezgin calls "practically correct", but which is definitely not good enough to explain the accuracy of portolan charts, calculated in Chapter 7 of this study. Also a check of the available astro-geodetically or otherwise determined coordinates in the Islamic world, does not provide the slightest indication that such high accuracy was ever achieved and that enough points available to form an adequate geodetic framework.[657]

Summarising, Sezgin's evidence in support of an Arabic-Islamic origin for portolan charts so far is either faulty or non-existent. With the former qualification I refer to his attribution of the Stereographic map projection to portolan charts and to Ibn Fadl'allah's chart and with the latter to his use of qualitative and broad-brush arguments regarding the hypothesized construction method.

10.5 Further arguments presented by Sezgin for an Arabic-Islamic origin of portolan charts

Sezgin presents a number of additional arguments, intended to demonstrate the "high degree of development" of Arabic-Islamic mathematical geography. However, he provides no objective evidence at all for any of these arguments, but relies entirely on rhetoric. The most salient arguments referring to portolan charts are summarised below.

1. In his Preface, Sezgin sets the tone by some spectacular claims: "The two perfect renderings of Africa, which bear the names of Alberto Cantino and Nicolo de Caverio cannot be anything else but Portuguese or Italian versions of a predecessor/ example (*Vorlage*), originating in the Islamic world."[658]
2. The so-called Mahgreb chart is an undated portolan chart from the Islamic world, showing the Atlantic coasts and most of the Western Mediterranean. Based on the number of toponyms, which is smaller than for most other portolan charts, the Italian geographer G. Uzielli estimated in 1882 the chart to date from the thirteenth century, but a few years later Theobald Fischer revised that figure to the second half of the fourteenth century, based on the 'mature' representation of the European Atlantic, Great Britain and Ireland.[659] This was in the early years of portolan charts

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[656] In this case the single quote designates arc minutes.

[657] Edward S. Kennedy and Mary Helen Kennedy, *Geographical Coordinates of Localities from Islamic Sources,* Veröffentlichen des Institutes für Geschichte der Arabisch-Islamischen Wissenschaften, Reihe A: Texte und Studien, Band 2 (Frankfurt am Main: Institut für Geschichte der Arabisch-Islamischen Wissenschaften an der Johann Wolfgang Goethe-Universität, 1987).

[658] Sezgin I 2000, XIV.

[659] Fischer 1885, 220, 221

research and not much experience had been gained yet regarding the dating of portolan charts. Fischer concluded that the toponyms on the chart are mostly transcriptions of Italian names, except for the toponyms between Lisbon and Barcelona and those of North Africa, which are of Muslim origin and are much older than the names on Italian portolan charts.[660] Sezgin uses that argument to claim that also the relevant coastline section must be of Arabic origin and extends this to the entire coastline shown on a portolan chart.[661] Sezgin dates the Mahgreb chart, without providing any justification, to "about 1300" and states that, as far as he is concerned, the question which chart is older, the Mahgreb chart or the Carte Pisane[662], which is dated to the late thirteenth century, is still wide open.

After Uzielli's and Fisher's initial estimates, the Mahgreb chart was dated by Vernet to "somewhat earlier than that of Dulcert (1339)", based on the similarities in toponymy with the Luxoro Atlas, which had been dated to the early fourteenth century by Kretschmer in 1909.[663] However, the Luxoro Atlas has since been attributed to Francesco Cesanis, a Venetian cartographer, whose earliest extant chart dates from 1421.[664] Moreover, the Mahgreb chart exhibits roughly the same anti-clockwise rotation angles and scale difference between the Atlantic and the Mediterranean coasts as other portolan charts do. Both of these characteristics are incompatible with the supposed framework of astro-geodetic points. All this suggests the Mahgreb chart is most likely a product of the fifteenth century, as are the other two surviving Arabic portolan charts. It certainly seems unjustifiable to attribute such an early date to the Mahgreb chart as Sezgin does.

3. Sezgin squarely claims the wind rose on portolan charts to be of Arabic-Islamic origin and claims the names of the eight winds to be of Arabic origin too, which, he claims, was confirmed by E. G. R. Taylor. However, he clearly misquotes Taylor here, who only stated that the names *Garbino* and *Sirocco* have an Arabic origin, which is not disputed by anyone.[665] Furthermore he states that the eight-wind system that underlies the wind rose cannot be of Greek origin because the Greeks in antiquity used the twelve-wind system. However, he overlooks the many discussions in portolan chart literature that the Greeks used the eight-wind system too, the best testimony for this being the octagonal *Tower of the Winds* at the foot of the Acropolis in Athens.
4. Ibn Khaldun, writing around 1377, used the word *al-qunbas* or *qunabas* either to describe an entire portolan chart[666] or to describe the wind rose, which is Sezgin's interpretation. The word is clearly phonetically related to the medieval Italian word *compasso*. Sezgin states that "in the Arabic word *qunbas* we finally have the clue to the

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[660] Fischer 1885, 224.

[661] Seagin II 2000, 30, 31.

[662] Sezgin II 2000, 58.

[663] J. Vernet-Ginés, "The Maghreb Chart in the Biblioteca Ambrosiana", *Imago Mundi* Vol. 16 (1962), 4.

[664] Pujades 2007, 508.

[665] Sezgin II 2000, 56-58 and E.G.R. Taylor, "The 'De ventis' of Matthew Paris", *Imago Mundi* Vol. 2 (1937), 23.

[666] … according to Taylor, *The haven-finding Art* 1971, 117.

meaning of the word *compassum* in Ramon Llull's text", however without providing any evidence that the Arabic word is the source.[667]

5. Sezgin rejects a Sicilian origin for the wind rose, which has been suggested in literature, as "unfounded". He finds it "far more likely that that the wind rose system, together with portolan charts, reached Italy as one complete entity from Arabic Spain".[668] He doesn't voice the same concern for the absence of evidence regarding his own claim.
6. According to Sezgin one may assume "on good grounds" that plane charts reached Europe from the Islamic world during the thirteenth century, but omits to explain what those grounds are.[669]
7. Regarding Arabic navigation in the Indian Ocean Sezgin drops, without explanation, the strange statement that the word *khann*, which is an angular unit of 1/32 of a circle, or one *point* on the 32-point compass card, "appears to be the origin of the concept *rhumb line*"[670].
8. Sezgin claims that the two compass types that Petrus Peregrinus describes, a type of floating compass and a dry pivot compass, "originate, with high probability, from Arabic-Islamic culture." By way of evidence he refers to the letter Peregrinus wrote to Emperor Frederick II (sic) when the latter laid siege to the city of Lucera, "together with the Arabs". According to Sezgin: "For that reason one has suspected that Peregrinus took over some experiments from the Arabs".

   In the first place the letter Peregrinus wrote was addressed to Sygerus de Foucaucourt, a neighbour and friend in his native Picardy in northern France[671] and not to the Emperor Frederick II, who had been dead for nineteen years by then. It was Charles of Anjou who laid siege to Lucera.[672] Such details aside, Charles had indeed a group of Arab mercenaries in his army, but these were more likely battle-hardened soldiers rather than scientists. Peregrinus uses the word *pyxis* (buxus, box, bussola) to describe his compass. This name, Sezgin claims, derives from the Arabic *huqqa*, used in Indian Ocean navigation, which also means *box*, *tin* or *drum*. That this term occurs first in written form in the navigation manual of the sixteenth century Arab navigator Sulaiman al-Mahri doesn't bother Sezgin, who justifies this time-shift of two-and-a-half centuries by stating that the author was a "carrier of a discipline that had been practiced for generations".[673] Regarding the invention of the magnetic compass, Sezgin ends with some sweeping statements about his assertion that the compass was introduced by the Arabs in the Indian Ocean, although he does allow the "possibility that the original form of the float-

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[667] … according to Sezgin II 2000, 55.

[668] Sezgin II 2000, 58.

[669] Sezgin II 2000, 65.

[670] Sezgin II 2000, 234.

[671] Smith 1970, A13. Also:
Vincent Courtillot and Jean-Louis Le Mouël . "The study of Earth's magnetism (1269–1950): A foundation by Peregrinus and subsequent development of geomagnetism and paleomagnetism". *Review of Geophysics*, Vol. 45, RG3008, 3.

[672] See Sections 1.1.2-F and 5.7.4-B.

[673] Sezgin II 2000, 202, 224.

ing compass goes back to the Chinese". The compass reached, from the thirteenth century on, first locations in Spain, then Genoa, Venice, Sicily, Southern Italy and France.[674] I have not been able to find the slightest evidence, either in Sezgin's own works or in any other publication, of this postulated detailed migration path of the magnetic compass.

9. According to Sezgin, the *Toleta de Marteloio*, which I described in Section 5.3, is merely a "not-quite-understood copy of the Arabic *tiriffa* method", used in the Indian Ocean and described by the fifteenth century Omani navigator Ahmad Ibn Majid. This involves determining the length of a course leg oblique with the meridian by measuring the ship's course and the change in altitude of the Pole Star (or another star). The *tiriffa* is the distance that has been sailed when the height of the Pole Star has changed by one *isba'* (one finger width).[675]
   Let D be the length of an *isba'* of latitude that was assumed by these Arab navigators and A the course angle (azimuth) sailed, then the *tiriffa* T equals $T = D/\cos A$
   Although both the *Toleta de Marteloio* and the *tiriffa* method are based on trigonometric calculus, the *tiriffa* method is a different trigonometric calculation and solves a different problem. For comparison, see Table 5.2 for the formulas of the *Toleta de Marteloio*. Apart from the unexplained time gap between the descriptions of the two methods, one cannot possibly consider the *Toleta de Marteloio* to be a "not-quite-understood copy of the *tiriffa* method".

Although Fuat Sezgin describes a wealth of highly interesting material, his analysis can only be categorised as less than scholarly (or scientific). He makes extensive use of rhetoric rather than providing objective evidence, and takes unacceptable liberties in citing other authors, as well as liberties with uncertainties surrounding available historic material. His arguments regarding the Stereographic projection as a binding element between the Mamun geography and portolan charts are simply factually incorrect. He exhibits an unabashed bias towards Arabic-Islamic culture and does not grant even a shred of originality to other cultures, in particular Western European culture, but also Chinese.

Sezgin has not succeeded in invalidating the three standard arguments, presented in Section 10.1. The new arguments he presents in his attempts to demonstrate an Arabic-Islamic origin of portolan charts are either faulty or are presented without evidence.

The conclusion must therefore be as follows.

28. Despite the relatively advanced achievements of Arabic-Islamic culture in the area of geodesy, an Arabic-Islamic origin of portolan charts is highly unlikely.

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[674] Sezgin II 2000, 264, 265.

[675] Sezgin II 2000, 194. According to Sezgin two exact values were used for the *isba'*. Ibn Majid considered an *isba'* to be 1/224th of a circle, whereas the sixteenth century Sulaiman al-Mahri used a value of 1/210th of a circle.

11 CONCLUSIONS

11.1 OUTLINE OF THIS CHAPTER

The objective of the current chapter is to recap the conclusions drawn in the previous chapters (Section 11.2), in order to save the reader the effort of having to 'harvest' the results in this thesis in bits and pieces. Section 11.3 summarises and describes the four 'pillars' on which the medieval origin hypothesis is based and the consequences these conclusions have for the testing of the medieval origin hypothesis.

11.2 RECAP OF CONCLUSIONS BY CHAPTER

This section repeats the conclusions of each chapter and describes the end result of the test of the medieval origin hypothesis.

1. A point feature will be charted in different locations when different routes to that point are followed and plane charting techniques are applied.[676]

2. Plane charting of entire coastlines will not result in an exact plane chart or Equirectangular chart, i.e. a chart with a square or a rectangular graticule.

3. Errors due to plane charting affect longitude differences between points only, when the lines connecting origin and target points are rhumb lines.

4. The magnitude and sign of the longitude error due to plane charting are determined by the course bearing and the length of the line sailed.

5. Geographical and meteorological factors, combined with the limitations of sailing characteristics of medieval ships led to the strong preference of a trunk route for maritime trade along the northern Mediterranean coasts.[677]

6. The accuracy of medieval navigation, notably distance estimation, is generally grossly overestimated. A simulation model suggests a best achievable accuracy corresponding with a standard deviation of 16% of the distance sailed and a standard deviation of about 3 degrees in direction. However, this assumes a rigorous discipline to be applied to navigation, which is doubtful in the Middle Ages.[678]

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[676] For conclusions 1 – 4 see Section 3.5.4.

[677] Section 4.3.4. See also Pryor 1992. This is a confirmation of John H. Pryor's conclusion.

[678] For conclusions 6, 7 and 8 see Section 5.10.3.

7. The magnetic compass, as a single instrument suitable for the measurement of course direction, appears to have come into widespread use only during the first half of the fourteenth century, which would have been too late to have contributed significantly to the presumed body of navigation data, shared in Mediterranean maritime circles. It is therefore unlikely that the compass could have made a key contribution to the measurement data underlying the construction of the first portolan chart.

8. The calculation of the arithmetic mean, or other forms of averaging, of a series of measurements of the same variable (distance or direction), with the objective of improving the precision of the resulting estimate, was a technique not known and at any rate not practiced in medieval Europe, nor in the contemporary Arabic-Islamic world.[679]

9. The vellum sheets on which the portolan charts have been drawn were found to have retained their original shapes very well.[680]

10. Portolan charts are composites of smaller charts that have their own cartometric characteristics, such as scale and orientation. The division into coherent (first-level) sub-charts is reasonably consistent across the five investigated charts. The scale and orientation variations are statistically significant. Scale differences between sub-charts are about 25-30%, with the Atlantic coasts exhibiting the smallest scale and the Black Sea the largest. Orientations of sub-charts range on average from -7° to -11°, from the Western Mediterranean to the Black Sea, with the Atlantic coasts having a deviating rotation angle of -2° to -4°.

11. In some cases, smaller entities, such as the Alboran Sea and the Aegean Sea may be identified. The scale and orientation differences between such a second-level sub-chart and the first level sub-chart are smaller than the differences between the first-level sub-charts.

12. Sub-charts appear to have been fitted together based on overlapping stretches of coastline. This is notably evident on the Carte Pisane, the only chart on which a long stretch of Dalmatian coastline is shared by the Central and Eastern Mediterranean sub-chart and the only chart with a deviating orientation of the Adriatic Sea.

13. The joins between the sub-charts do not always coincide with the natural boundaries of sub-basins in the Mediterranean. Considerable overlaps may have existed between sub-charts. This is evident on the Carte Pisane (see conclusion 12) and in

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[679] Section 5.10.3 and Section 10.4.

[680] For conclusions 9 – 19 see Section 7.8.

a stretch of Tunisian-Algerian coastline on the RS-3, Dulcert 1339 and Roselli 1466 charts that fits well both in the Western and the Eastern Mediterranean datasets of each chart.

14. The scale bars in the charts show variations of several percent, both within a single chart and between charts. These variations are five to ten times smaller than the scale variations in the map image within a single portolan chart and there is no correlation between the two. This appears to indicate that the cartographer was not entirely sure of the scale of the charts and the scale variations within them. It also indicates that the charts were not built up from the scale bars.

15. The accuracy of the sub-charts, generally 10-12 km (one sigma), is very high for medieval charts of the approximate portolan chart scale of 1 : 5,500,000.

16. The accuracy of the Carte Pisane sub-charts is consistently worse than of those on the other charts. Also the other characteristics of the chart, such as the orientation of the Adriatic and Aegean Sea differ clearly from the other charts and appear to indicate that the Carte Pisane is an early chart, created before an approximate cartographic consensus emerged about the relative positions, orientations and scales of the component sub-charts.

17. Although the sub-charts exhibit to a greater extent the characteristics of the Mercator projection than of the Equidistant Cylindrical projection it is impossible to conclude with confidence that either of the two projections fits better to the charts than the other.

18. Considerable successive adjustments appear to have been made in the relative positions of the sub-charts. The islands of Corsica and Sardinia fit optimally with the Western Mediterranean sub-chart on one chart and with the Central Mediterranean sub-chart on another. Also the considerable changes in the Atlantic sub-charts indicate ad-hoc adjustments. Francesco Beccari, in his 1403 chart, was therefore not the first cartographer to attempt to optimise the charting of the Mediterranean.

19. Apart from its individual scale and orientation, each sub-chart also exhibits shear. This shear angle varies on the five portolan charts and appears to be an artefact of the cartometric analysis, indicating differential shifting of pieces of coastline on that sub-chart, introduced by the copying process from portolan chart to portolan chart.

20. The bearing and distance data in the *Compasso de Navegare* and, by implication, in other extant medieval Mediterranean portolans, have been scaled from one or more

existing charts. On the basis of our current knowledge, this can only have been done from portolan charts. No other candidate cartographic documents have come to light.[681]

21. The accuracy of both the distances and the bearings in the *Compasso de Navegare* is very poor. It is much worse than one would expect for scaled off data and even for observed data. Although the peleio have a considerably higher accuracy than the per starea course data, both regarding the bearings and the distances, to speak of "superior accuracy" of the peleio, as Lanman does, is unjustified, even if it only describes the accuracy relative to the per starea data.

22. The portolan mile used in the *Compasso de Navegare* appears to be the same unit of measure as shown in the scale bars of portolan charts. This is the logical consequence of the conclusion no. 20 and it is confirmed by the calculations of its length for the *Compasso* data. The portolan mile of the *Compasso* is somewhat shorter than the mile on the portolan charts, analysed in Chapter 7, with the exception of the Carte Pisane, with which it agrees reasonably well. However, the central Mediterranean distances in the *Compasso* deviate significantly.

23. Portolans of the Mediterranean and Black Sea were scaled from portolan charts. Therefore portolan charts must have existed before the extant portolans of the Mediterranean were compiled.

24. The constructional basis of portolan charts was *not* a plane charted geodetic network consisting of magnetic bearings and rhumb line distances.

25. The map projection found in portolan charts is *not* an artefact of the cartometric analysis process.[682]

26. The map projection must, in the absence of any other realistic explanations, be considered to have been designed into the charts intentionally.

27. The achievable navigational accuracy in the Middle Ages fell far short of being able to supply the base data from which a portolan chart could be constructed.

28. Despite the relatively advanced achievements of Arabic-Islamic culture in the area of geodesy, an Arabic-Islamic origin of portolan charts is highly unlikely.[683]

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[681] For conclusions 20 – 23 see Section 8.5.

[682] For conclusions 24 – 27 see Section 9.10.

[683] Section 10.5.

11.3 THE FOUR 'PILLARS' OF THE MEDIEVAL ORIGIN HYPOTHESIS

In the Introduction of this thesis I described the medieval origin hypothesis as resting on the following four 'pillars', which are interdependent in the sense that if one is rejected, the entire medieval origin hypothesis would need to be rejected. In other words, the acceptance of all four is a prerequisite for the medieval origin hypothesis to be accepted. The medieval origin hypothesis rests on the following assumptions.

A. It is assumed that sailors in the medieval Mediterranean practiced a disciplined form of navigation, estimating with mathematical rigour distance sailed, and possibly course direction, during trading journeys (the role of the compass is disputed).

B. It is assumed that a body of data on distances and possibly directions between ports was available and shared in the marine community. It is further assumed that the accuracy of the shared estimate of any distance (and direction) between two coastal points was brought to the level as evidenced by the accuracy of portolan charts by averaging of multiple estimates on the same route. The only medium for sharing this presumed body of data would have been portolans.

C. It is assumed that the thus improved estimates of distances (and directions) between coastal points were used to create the first portolan chart(s) by means of *plane charting*.

D. It is assumed that the map projection which various researchers believe to have discovered to underlie the charts is an artefact, an artificial by-product, of any cartometric analysis process.

In chapters 4 to 9 evidence has been supplied that undermines the medieval origin hypothesis at every point. In the following short summary the most important arguments against these four 'pillars' are summarised.

11.3.1 THE MATHEMATICAL SEAMAN

It has been shown that the sailing characteristics of medieval sailing ships, in conjunction with prevailing winds and other geographical factors such as nearby sheltering and anchoring options and the easy availability of drinking water reinforced the use of a trunk route along the northern Mediterranean coasts. Cross-basin routes were undoubtedly sailed, but analysis by Pryor (see chapter 4) has shown that the vast majority of trading ships favoured the coastal routes and galleys were even *forced* to stay close to the coast. Sailing ships had no practical capability of making headway against an adverse wind and would typically wait to pick up a favourable stern wind. No support can be found for the assumption that medieval trading ships criss-crossed the Mediterranean in every direction.

Moreover, the scarce historical evidence suggests that the mariner's compass or the dry-pivot compass was not in general use until sometime in the first half of the fourteenth century. Ramon Pujades mentions that the first occurrence of the term *bussola* dates from 1349, indicating that around that time this name, which is presumed to refer to the compass as a single boxed unit, became customary in medieval Mediterranean society. A floating compass, consisting of a magnetised needle, stuck through a straw or piece of cork and made to float in a bowl of water, is unsuitable for measuring course angles with any degree of accuracy. However, the timing of the introduction of the boxed compass does not exclude the possibility that the compass, as a single unit or instrument, may have been available earlier in a smaller community. The time of introduction of the compass, as a useable instrument to measure course directions, is still uncertain, but it is highly unlikely that its introduction would have been in time for it to have played a role in the widespread collection of navigation data that is assumed to form the constructional basis of portolan charts.

Navigation techniques in the thirteenth and fourteenth centuries are essentially unknown. There have been various attempts to postulate the widespread practice of a disciplined, mathematical form of navigation. Taylor spoke of the “mathematical seaman” and Kelley refers to the “southern European navigation method”. These concepts are not supported by independent historical evidence. They are even in conflict with the, if not general, than at least widespread attitude to precision that in the European Middle Ages until the end of the thirteenth century which is characterised by Ramon Pujades with the phrase “… mathematical precision [is] something with which the medieval mind was entirely unconcerned”. Alfred Crosby and John Kirtland Wright wrote extensively of the lack of attention to precision in medieval times and the charts themselves contain evidence of lack of precision in the detail of coastal features and islands. However, even when one assumes that this method of navigation was used, achievable precision falls far short of what is required to construct a portolan chart. Nevertheless it must have been good enough to notice the (considerable) scale difference between Mediterranean and Atlantic coasts and even the incorrect position of Sardinia, as the famous text on Beccari’s 1403 chart demonstrates.

The first conclusion is that no evidence can be found that medieval seamen went about their navigation in a highly disciplined manner, measuring distance and direction with mathematical rigour. The concepts of “mathematical seaman” and “southern European navigation method” are most probably based on reverse engineering to explain the accuracy of portolan charts.

The second conclusion is that medieval ships would not have been capable of criss-crossing the Mediterranean in every direction, collecting a geographically diverse and rich set of distances (and directions). The poor sailing capabilities of the ships, the patterns of prevailing summer winds and the geographic characteristics of the Mediterranean coasts would have led to a severely misbalanced set of measurement data, rich along the northern coasts and sparse along the southern. No evidence of this misbalance is visible in portolan charts.

11.3.2 SHARED BODY OF NAVIGATION DATA – PORTOLANS

The existence of a shared body of navigational knowledge in the medieval Mediterranean, from which the first portolan chart was constructed, is commonly assumed, without specifying what exactly is meant by 'body of navigation data'. Some medium for sharing, communicating and improving estimates of distances and possibly directions between ports and other coastal locations would have to have existed. Portolans are the only realistic medium that may be imagined, even though an increasing number of scholars avoid committing themselves to a statement that portolan charts derive from portolans. The latter may be wise, but it merely evades the crucial question how such navigation data would have been shared and improved.

A critical evaluation of the oldest surviving portolan, the *Compasso de Navegare*, in this thesis, demonstrates that its data were almost certainly scaled from, what would have to be, one or more pre-existing portolan charts. The data in the *Compasso* is of such a poor quality, that the scaling off can only have been done in a very sloppy way.

It is often postulated that the accuracy of the presumed shared *body of navigation data* had been improved in accuracy "through the cumulative experience of centuries". However, this is clearly an example of *presentist* thinking. There can be no question of any advanced treatment of series of the same measurement variable with the objective of improving its accuracy, neither in European nor in Arabic-Islamic culture. The calculation of the arithmetic mean of a series of measurements of the same observable became customary in scientific circles in Europe only in the middle of the eighteenth century. The existence of such a body of accurate knowledge would also fail to explain why medieval sailors would have discarded that data and instead use such evidently poor data as contained in the *Compasso de Navegare*.

Although it is very likely that geographic data was indeed shared in mariners circles, there are no indications that this concerned a detailed, rich and accurate collection of geometric data. The absence of an identifiable and justifiable set of base measurements therefore severely undermines the medieval origin hypothesis.

11.3.3 PLANE CHARTING OF NAVIGATION DATA – THE FIRST PORTOLAN CHART

In Chapter 7 it was demonstrated that portolan charts resemble a modern map of the Mediterranean and Black Sea areas and they do so with a remarkable degree of accuracy, which is, on average about 11 km at the one-sigma level for the on average 1:5.5 million scale charts investigated. The map projections of the modern maps used in the cartometric analysis were the Mercator projection and the Equidistant Cylindrical projection. These two map projections are very similar for an area with a limited latitude extent such as the Mediterranean and no firm conclusion can be drawn which of the two yields the best fit. Nevertheless the portolan charts investigated show more characteristics of the Mercator projection than of the Equidistant Cylindrical projection.

The cartometric analysis of the five charts in this thesis confirms the conclusion drawn by many earlier researchers, that portolan charts are composite charts, consisting of sub-charts, pasted together without correcting them to a single uniform scale and orientation.

In Chapter 9 it has been shown that a plane-charted geodetic network, which might have constituted the geometric framework for portolan charts, has a different shape from the coasts of the Mediterranean and Black Sea as rendered on a portolan chart. This difference is statistically significant.

The conclusion is that the portolan charts cannot have been constructed from a plane-charted network of distances and directions. Moreover, the accuracy of the nodes of such a geodetic network of navigation data falls far short of the 11 km accuracy mentioned in the first paragraph of this section, even when adopting a highly optimistic view regarding achievable navigation accuracy and regarding the capabilities of processing of the distances and directions that are assumed to have been measured.

11.3.4 THE MAP PROJECTION

The hypothesis that portolan charts were constructed from a plane-charted geodetic network was tested by considering the calculated positions of the coastal points of the plane-charted network to be the coastal outline of a ‘synthetic portolan chart’, which was then subjected to the same cartometric analysis as the five actual portolan charts. The result showed that the networks didn’t fit at all to the Mercator projection. This led to the conclusion mentioned in the previous section, that portolan charts cannot be based on a plane-charted network of directions and distances. However, this conclusion has the following important implication. The map projection found in portolan charts cannot be the unintentional result of a simple chart construction method or an accidental by-product of any cartometric analysis process. The follow-on conclusion is therefore that, in the absence of any convincing alternative explanation, the map projection is not accidental, but must have been intentionally designed into the charts as part of their construction.

11.4 KEY CONCLUSIONS FROM THIS STUDY

In the *Introduction* the research question was formulated as follows.

“The key question which this thesis seeks to answer is to what extent geodetic knowledge and geodetic analysis techniques may contribute to an understanding of the origin of portolan charts. This almost automatically leads to the intriguing and more specific question whether successful application of geodetic analysis techniques enables conclusions to be drawn on the origin of portolan charts and if so, which conclusions.”

The geodetic analysis technique that has been used with considerable success in this thesis is geodetic network analysis. This enabled the third and fourth 'pillars' of the medieval origin hypothesis to be unequivocally rejected. Aspects in which geodetic experience and knowledge have played an important role are the application of Least Squares Estimation and statistical testing in the cartometric analysis of the five portolan charts and the analysis of achievable navigation accuracy. Also the description of plane charting characteristics and the impact of the properties of map projections may be attributed to the geodetic domain. However, much of the statistical analysis of the *Compasso de Navegare* does not specifically require a geodesist.

An important conclusion to draw is therefore that geodetic expertise and geodetic analysis techniques can make an important contribution to research on portolan charts and have, as evidenced in this thesis, certainly contributed to an understanding of where the origin of portolan charts *cannot* be placed. Unfortunately no clues have been found that provide a positive indication of the elusive origin of these charts.

Another important conclusion is that that it is possible to extract far more information from portolan charts by means of quantitative techniques than has been done until now. This is not information that falls in the category 'useless detail', but information that that may play an important role in understanding the origin of these charts.

All four 'pillars' of the medieval origin hypothesis have to be rejected:

- The medieval seaman is unlikely to have navigated with mathematical precision; this concept runs counter to the widespread lack of attention to accuracy in the Middle Ages.
- The late introduction of the mariner's compass leaves only room for the distances as input for mapmaking, requiring a highly dense network of distances between points by trilateration.
- Medieval ships didn't criss-cross the Mediterranean at will; they mainly followed traditional trade routes along the northern coasts.
- The accuracy of distances between ports – the same holds for directions – could not have been improved "by cumulative experience" in any systematic manner, i.e. by calculating the average or arithmetic mean of a large number of measurements; this technique was not known and not practised in the European Middle Ages, nor in contemporary Arabic-Islamic culture.
- Portolan charts were not drawn by plane charting of a network of distances between ports and landmarks. The required density of distances could not have been achieved, the accuracy would fall far short of what is required and most importantly, plane charting of distances and directions that *would* have been accurate enough would have led to a significantly different charted shape of the Mediterranean.
- Portolan charts are based on a map projection that cannot have been created accidentally by any simple charting technique.

The geodetic basis of the charts, expressed in their accuracy and their map projection, is far beyond the capabilities of the European Middle Ages. Far from being primitive charts that are mildly anomalous in the Middle Ages, the charts are sophisticated cartographic products that can neither be explained in any way from medieval European, nor from Arabic-Islamic available geodetic-cartographic capabilities. The key conclusions from this study are therefore the following.

Portolan charts are sophisticated, accurate charts, intentionally constructed on the Mercator or the Equidistant Cylindrical map projection.

The geodetic and cartographic origin of portolan charts does not lie in medieval Europe.

An origin of the charts in Arabic-Islamic culture is highly unlikely.

12 SYNTHESIS

12.1 INTRODUCTION AND CHAPTER OUTLINE

It is unusual to add a chapter after the conclusions of a study have been drawn. However, the main conclusion from this study, that portolan charts are not original products of medieval Mediterranean culture, whether European or Arabic-Islamic, may yet leave a feeling of dissatisfaction and it probably generates more questions than it answers, although it does provide a satisfactory answer to all of the issues raised in Section 2.2: *Disputed, unclear and unsatisfactorily explained aspects of portolan charts*. Questions such as 'Where do they come from?' and 'How were they constructed and by whom?' have not and cannot been answered and are now more intriguing than ever.

The facile answer would be to conclude that they come from antiquity and that would indeed seem to be the obvious, if not the only possible conclusion. However, an antique origin cannot simply be assumed; it will have to be proposed as a hypothesis, requiring similar rigorous proof as has been presented in this study. This will have to be addressed in further research.

The more immediate questions how and where the source maps, underlying portolan charts, ended up in the Middle Ages cannot be answered with certainty either. An educated guess is possible, but this will, as is the nature of guesses, be speculative. Speculation certainly has a place in scholarly research, but only as the method to formulate a new hypothesis and the conjectures described in the next section must be seen of having the character of hypotheses.

Section 12.2 describes a hypothesis intended to answer how and when portolan charts ended up in the medieval world. A number of issues, such as the rotation angle of the chart, the length of the portolan mile, the wind rose and the scale bars on the charts, seen within the context of that hypothesis, are addressed in Section 12.3, as well as some unanswered questions.

The last section, 12.4, provides some recommendations for future research into portolan charts.

12.2 How did portolan charts arrive in medieval Italy?

12.2.1 Where from?

It appears to be the most likely scenario that Italian merchants acquired a body of ancient maps or charts through their trade with Constantinople. The maps/charts would have had overlapping coverage areas but different scales and I suspect the Italians attempted to bring these maps to a common scale using the overlaps between them. The cartometric analysis of Chapter 7 suggests that this process indeed happened in that way. The biggest scale differences exist for example for the Atlantic coasts and the Black Sea, where the overlap with the maps showing the Mediterranean may have been small. The merit of the Italian mariner-traders would have been that they saw the potential of these maps, while the Byzantines, who preserved the heritage of antiquity but did nothing with it, may not have been greatly interested them. It will have to be borne in mind that no person in the Middle Ages could have known how accurate these maps were.

12.2.2 When?

The acquisition of the maps/charts by the Italians and their initial usage is likely to have taken place earlier than the usually assumed time of appearance of the middle of the thirteenth century. Gautier Dalché's dating of the *Liber de Existencia* to the end of the twelfth century is not unrealistically early, as was argued by Pujades, if the medieval origin of the charts consists of the discovery of a body of ancient maps. A further indication that Gautier Dalché's early time estimate is not improbable is provided by John H. Pryor, who extensively investigated the logistics of Crusader transports.[684] Pryor notes that in the First Crusade all horses were brought to Palestine by land, but that a major revolution took place in transporting horses and troops by sea between 1096 and 1204. During this period horses were increasingly – *and* in increasing numbers – transported by ship. Furthermore, night sailing was developed by the Christians, which was unknown or at least not practiced by the Mediterranean Muslims. Pryor concludes that this maritime revolution was most probably introduced by improvements in navigation, rather than by e.g. developments in shipbuilding. Night sailing clearly requires knowledge of the waters ahead. Pryor also noticed that the average speed of transports increased by some 400%, suggesting that Crusader fleets were able to navigate with greater confidence, using more direct routes than before.[685]

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[684] John H. Pryor, *A Medieval Maritime Revolution: The Logistics of Crusading by Sea, 1097-1204;* presentation held at College Station (IN), USA, 2007. Not (yet) published; paper made available by the author.

[685] Pryor, 2007. The first recorded sea transport dates from 1123, when a Venetian fleet included 300 horses, but sailed along the coast, in short hops sailed in daytime only. They made an average speed of 0.85 knots only. By contrast, 1300 horses were transported by sea for the Third Crusade, the fleet following a direct route from Messina to Acre, which they completed in 21 days, making an average speed of 2.65 knots.

An intriguing and supporting explanation may be provided by the surface current patterns in the Eastern Mediterranean, where the currents generated by the gyres and eddies, described in Section 4.2.1 and shown in Figure 4.1, interfere positively to create a semi-permanent easterly surface current in the middle of the Eastern Mediterranean, known as the Mid-Mediterranean Jet, shown in Figure 12.1.[686] For the Third Crusade in 1189, the direct sea route from Messina to Palestine was used. In the presence of the Mid-Mediterranean Jet, the ships would have experienced a favourable easterly current of about a knot, as opposed to the persistent, up to one knot westerly current along the south Anatolian coast. With an average vessel speed of 4 knots, that would have made a significant difference in journey time. The 400% time reduction for the entire journey that John Pryor extracted from period documentation thus becomes

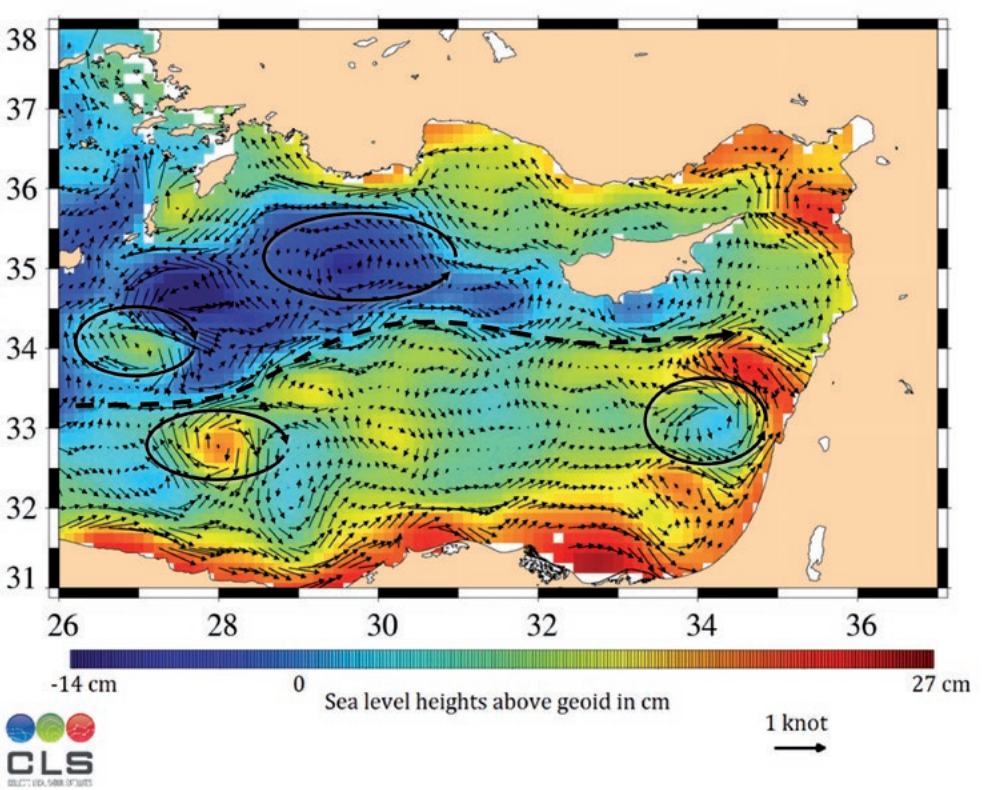

Figure 12.1 *- The Mid-Mediterranean Jet (dashed line), with, from left to right, the Iérapetra, the Marsa-Matruh, the Rhodes and the Shikmona gyres, drawn in by the author.*
(Colour image by courtesy of AVISO; The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes http://www.aviso.oceanobs.com/duacs/).

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[686] Claude Millot and R. Gerin, “The Mid-Mediterranean Jet Artefact”, *Geophysical Research Letters*, Vol. 37, Issue 12, June 2010.

understandable. Of course the key question, for which no certain answer can be given, is whether the availability of a chart for this sea, which would have shown that the route to the east was in principle unobstructed, enabled the Crusaders to use this direct route, or whether they would have done the same anyway without such a chart. However, given the step change, which Pryor describes as a maritime revolution, the conjecture that the Crusaders' access to these charts enabled this change appears to be plausible.

The indirect evidence provided by Pryor suggests that Gautier Dalché's estimate for the creation of the *Liber* cannot be far off the mark. Pryor's evidence even suggests that the first use of the conjectured body of charts took place in the middle of the twelfth century rather than towards the end.

It is unlikely that this body of charts was acquired by Venice; the earliest portolan charts appear to have been created along the Ligurian coast. Given the early date of the middle of the twelfth century, Pisa, which was at the peak of its power at that time, appears to be a more likely candidate than Genoa, which was at that time building up a power base in the Western Mediterranean, although it already had trading interests in the new Crusader States and Alexandria.[687]

12.3 Remaining issues

In the light of the conclusions of this thesis, some valid questions emerge regarding the geometric properties of the portolan charts:

1. Where does the portolan mile scale come from? Was this scale already present on the source charts or was it added in medieval times by the Italians?
2. How did the charts get their anticlockwise rotation angle?
3. Was the wind rose already on these charts or was it added in the Middle Ages?
4. How can the exaggeration of coastal features be explained?

The anticlockwise rotation angle of portolan charts is close to the value of magnetic declination in twelfth century Liguria, which makes it unlikely that their correspondence can be attributed to mere coincidence.[688] It appears that an effort was made to align these charts to magnetic north, possibly from a frequently sailed course leg or even using a visible landmark such as the peak of a mountain. Alternative explanations for this rotation angle, proposed in literature, have had to be rejected.[689] It is of course not known what orientation the conjectured source charts had; the earliest chart to exhibit the anticlockwise rotation angle is either the Carte Pisane or the Cortona chart, which-

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[687] See Sections 1.1.2-C and 1.1.2-D.

[688] See Figure 7.10.

[689] See Section 3.6.

ever is the oldest. The indications are that the mariner's compass and dry-pivot compass were not yet in widespread use, but they may nevertheless have been in existence.

The anticlockwise rotation angle does suggest that the wind rose was not merely copied form the source chart and may therefore indeed represent a medieval Italian invention. The wind rose on portolan charts has a geometric property that has not attracted much attention in portolan chart literature. This is the fact that thirty-two directions are derived from only sixteen points, regularly distributed on a hidden circle. The underlying geometric property is illustrated in Figure 12.2 with only eight points, but the principle also holds when the number of points on the outer circle is doubled to sixteen. This geometric property is nowadays secondary school material, but in the Middle Ages it would have required a person with mathematical skills, familiar with Euclid's *Elements* to design this, unless it is purely accidental. If it is accidental, the wind rose may have been invented anywhere, but if it was consciously designed, Pisa is far more likely place of origin than Genoa. The latter had a negative reputation regarding culture.[690]

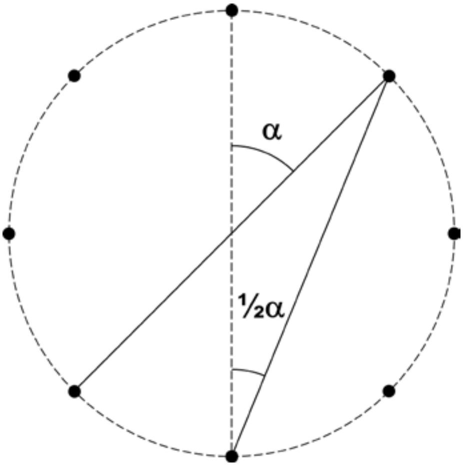

Figure 12.2 *- With 8 points on a circle 16 different angles can be constructed.*

Another element I wish to bring into this consideration is the Toleta de Marteloio. I have argued in Section 5.3 that the Toleta appears to be the creation of an accomplished mathematician and, unless the application of the geometric property shown in Figure 12.2 is accidental, the same may hold for the wind rose. The Toleta de Marteloio is probably the earliest application of trigonometric principles in the West. Trigonometry was developed in Arabic-Islamic culture. Together with a conjectured place of origin of the creation of medieval cartographic product in Pisa, the name of Leonardo of Pisa can hardly be avoided. There is no evidence to link him to the development of the portolan chart, but the mathematical complexity of both the wind rose and the Toleta de Marteloio suggests that more mathematical insight was contributed to their development that

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[690] See Section 1.1.2-D.

might be expected from even a reasonably gifted medieval cartographer-mariner. Not many alternatives appear to be available.

The scales of the source charts are evidently unknown. The body of extant portolan charts holds enough evidence that the Italian medieval cartographers had the skills to enlarge or reduce the scale of maps. However, even if the charts had the scale of around 1 : 5,500,000, dictated by the size of the available skins, this scale, as some authors have pointed out before, is too small for coastal navigation. If coastal navigation was a chiefly visual affair, it is indeed very likely that mariner-cartographers may have 'enhanced' the chart by exaggerating landmarks and other visibly verifiable geographic features such as the shape of small bays. This process explains the apparent contradiction and violation of Tobler's First Law of Geography, mentioned in Section 2.2.2.

The ultimate question concerns the origin of the source maps that underlie the portolan charts. Intriguing though his question is, it cannot be addressed in this thesis. The obvious hypothesis is that their origin lies in classical antiquity. However, as stated above, this must be treated as a hypothesis; an antique origin should not automatically be concluded from this study. It needs to be carefully evaluated and tested in the same rigorous manner as the medieval origin hypothesis has been tested in this study.

12.3.1 THE LENGTH OF THE PORTOLAN MILE REVISITED

Related to the first question in the previous section is the question what can be deduced about the elusive *portolan mile*. It is clear from the data that its length cannot be established with reasonable accuracy. There are two phenomena that cause this uncertainty:

1. The computed length of the portolan mile depends on the latitude for which it is evaluated. The medieval origin hypothesis held that the length of a portolan mile would be the same everywhere on the chart, because of the postulated plane charting construction. This has been demonstrated to be incorrect. The scale of the Mercator projection, to which portolan charts correspond closely, varies with latitude and the length of the portolan mile therefore varies correspondingly.
2. The scale differences on a single portolan chart are not reflected in corresponding lengths of the scale bars and therefore yield a different value for the portolan mile, depending on the sub-chart for which the calculation is performed.

The first issue indicates that, whatever length one calculates for the portolan mile, the calculation is valid only for a single parallel of latitude. In this thesis 39° 57' N has been chosen, which is the *true-to-scale parallel* of the Equidistant Cylindrical chart that best approximates the Mercator projection for the Western Mediterranean.[691] The second issue may be resolved by reducing all values to a chosen reference sub-chart. In this study

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[691] See Figure 6.28.

all regional variations in scale have been expressed as proportional to the scale of the Western Mediterranean on the same chart.

On portolan charts the length of the mile can be deduced from the scale bars provided, with the caveats mentioned above. For the *Compasso de Navegare*, for which I concluded it has been scaled from a portolan chart, the situation is different. The variation caused by issue 2 above could in principle be resolved, but issue 1 cannot.

The mile values derived from the portolan charts in Figure 12.3 have been normalised for the Western Mediterranean and for the latitude of 39° 57' N. If that wouldn't have been done, the scale differences of up to 30% would have to be compounded into the calculation as well. For the *Compasso de Navegare* the mean values per sub-basin, separated into estimates for the per starea and per peleio data, are shown. These mile length estimates cannot directly be compared with the portolan chart data, as their scaling off would have been affected by the coastal feature exaggeration (for the per starea distances), by the different scales of the sub-basin charts from which they were scaled off and by the evident sloppiness of the scaling off process. They do not apply to any particular latitude, but are simply the mean values of the available distances.

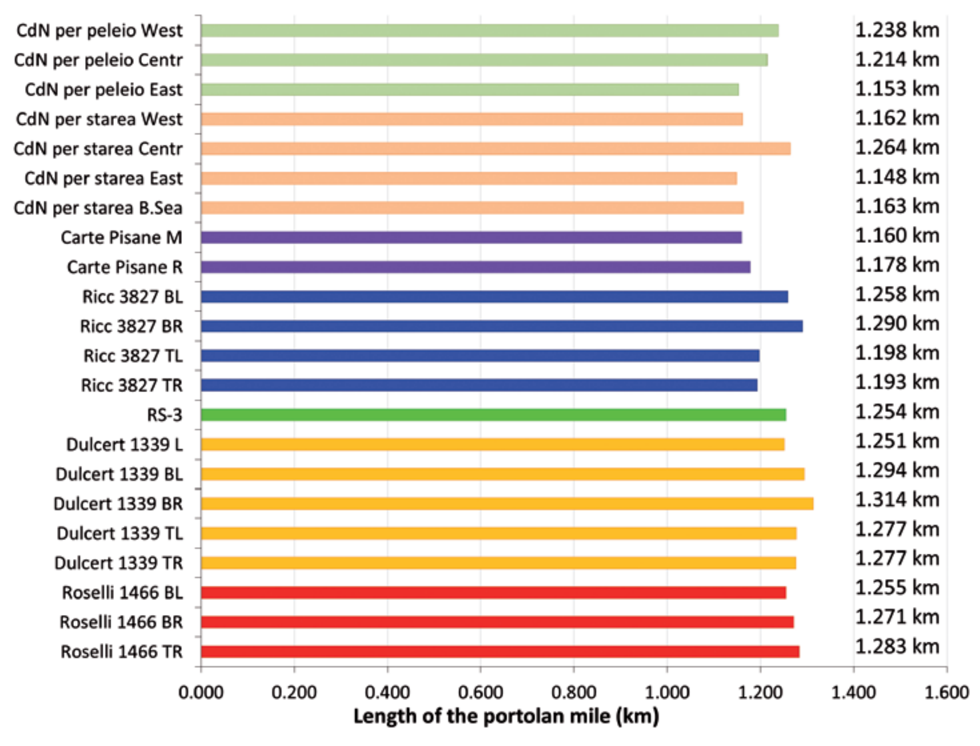

Figure 12.3 *- Portolan mile length for five portolan charts and the Compasso de Navegare.*

Given the conclusion that the scale of the source maps underlying portolan charts was not precisely known it is quite possible that the portolan mile was *not* an actual, separate distance unit, understood as such by medieval seamen and cartographers.

Many attempts have been made in the past to explain the mile used on portolan charts as an actual unit of measure, often involving extensive juggling with conversion factors. Wagner, for example, describes this presumed unit as the "Mediterranean mile"[692] and Kretschmer explains how Wagner came to consider the length of this mile as about 5/6 of the Roman mile. He refers to the work *Monosphaerium* (1526) by the French physician Jean Fernel, which, according to Kretschmer, mentions the *pes geometricus* as being exactly 246 mm.[693] Five of these make up a *passus geometricus* of 1.23 m, which translates into a *millia passuum* of 1230 m. The 'normal' Roman mile, was based on 1000 *passus vulgares* of 1.48 m, based on the *pes vulgarus* of 29.6 cm. Fernel, again as described by Wagner, refers to Campanus de Novara, a pupil of Leonardo of Pisa, as mentioning that one mile consists of 1200 *passus geometricus* or 1000 *passus vulgarus*. That would make the *millia geometricus* to be 1230 m, or about 5/6 of the standard Roman mile.[694]

However, the scale differences between the sub-charts of a portolan charts and the scale variations per chart suggest that the medieval cartographers did not know what the exact scales of these charts were. I find it more plausible that a baseline distance was used to establish the scale of the portolan charts, as well as their orientation with respect to magnetic north. This baseline would consist of two points, possibly or even probably along the Italian (Ligurian) coast and its distance may have been known in Roman miles (of ~1481 m), based on surviving milestones along an old coastal Roman road between those points. If the medieval cartographers were able to identify the two points at either end of their baseline on the portolan chart and used the distance in Roman miles as the basis to determine their scale, they would have overestimated the distance between the points on the portolan chart. If they would have drawn a scale bar on this basis on the chart, their rendering of the Roman mile on the portolan chart would be too small.

Figure 12.4 illustrates this with a hypothetical piece of coastline and an equally hypothetical Roman road along a coast; the distance between two locations A and B equals 100 Roman Miles, or 148 km. The road is assumed to contain some windings around bays and other topographical features, so that the shortest connecting line, 'as the crow

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[692] Wagner 1913, 397.

[693] How Kretschmer can say that Fernel established the *pes geometricus* as "exactly 246 mm" at a time when the millimetre (and the metre) had not yet been invented, is unclear. This must be translation or interpretation error. The metre was accepted by the French Academy of Sciences as the standard length unit in 1791 as one-ten-millionth of the meridional arc from equator to pole. Before that the *toise* was used in France as the standard unit of distance, of which only the approximate relationship with the metre is known.

[694] Kretschmer 1909, 53-57.

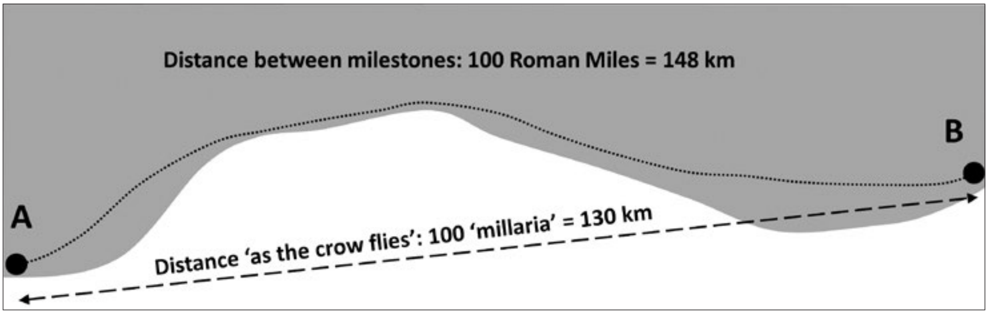

Figure 12.4 *- Conjectural origin of the length unit of portolan charts and portolans.*

flies', amounts to 130 km instead of 148 km. If this known distance of 100 *millaria* between A and B is used to add a scale to the chart, than any modern cartometric analysis will result in an estimate for the length of the mile of 1300 m. If this reasoning is correct – and I stress that it is entirely conjectural – than medieval cartographers and seamen alike must have assumed that portolan charts showed Roman miles.

I find this scenario explaining the scale of portolan charts more likely than the assumption that the *millia geometricum* of 1230 m was deliberately used. It would be impossible to explain this exactitude, bearing in mind that no-one could have been aware of the latitude dependence of the chart scale and the exact scale differences within a chart.

12.3.2 UNANSWERED QUESTIONS

The availability of detailed directional information on portolan charts and in portolans, at least in the *Compasso de Navegare*, decades before the compass, as a single boxed instrument, came into widespread use has always been one of the conundrums of portolan chart research. The question why this is so can still not be answered with certainty, but it seems likely that a dry-pivot compass at least was available to the originators of the portolan chart, who may have understood the potential of using a better compass in navigation. It will have to be borne in mind that the dry pivot compass had already described by Petrus Peregrinus in 1269. Portolan charts may have stimulated the development of the mariner's compass and its uptake in Mediterranean navigation, rather than the other way around, but I stress that this is entirely conjectural.

Looking at the coastal courses in the *Compasso de Navegare* one cannot but wonder about their purpose and the logic behind that. Were they meant to be used for the planning of a coastwise journey? Why does the *Compasso* not say something in the vein of: "From A to B: follow the coastline for so many miles; initially the course is north-east and this gradually changes to north towards B." Why this cutting off of pieces of land and inclusion of courses a ship cannot sail? Does it again reflect the medieval careless attitude to accuracy? Was the scaling off done by someone who had no experience in navigation?

Navigation along a coast would have been of an almost exclusively visual character. No medieval seaman in his right mind would have sailed along a coast, navigating on portolan data only, this quite apart from the abysmal quality of the data in the *Compasso* and other portolans. The journey would have ended on the rocks quickly! The question of the rationale behind the data is evidently something a modern person will ask; we cannot know what reasoning medieval men would have applied. It may have been for planning the length of a journey, or it may have been a help for those who had difficulty adjusting to the new format of representing space in the form of a map. Lanman felt that the *Compasso* had been mainly if not exclusively intended for long-distance navigation and he may be right, but even so, why are only 28% of the data peleio and the remaining 72% per starea course legs? Does this reflect an attempt to create a new use for the maps or charts? Were they indeed initially perceived as a solution, looking for a problem? That the *Compasso de Navegare* was intended to be a practical help in navigation seems indisputable, but what to think of the detailed directional specification well before the availability of the mariner's compass? Why create information that hardly anyone could use? These are all questions that will have to be addressed in further research.

Given the conclusion from this study that neither the European West, nor the Arabic-Islamic world could have been the culture from which portolan charts originated (in the sense of constructed from geodetic data), the question arises whether the Arabs had access to the portolan charts independently of the Italians. That question cannot be answered with any degree of confidence. The dates and cartometric characteristics of the extant Arabic portolan charts suggest that not to be the case, but that doesn't mean anything. Gautier Dalché found remarkable agreement between a number of distances in the *Liber de Existencia Riveriarum,* al-Idrisi's *Book of Roger* (1154) and Ibn Jubayr's *Rihla* (~ 1185).[695] Whether these distances were scaled from a portolan chart needs to be established by further analysis of the *Liber*. At any rate, if the Arabs had early access to the source charts, it appears they made not as good use of them as the Europeans did.

12.4 RECOMMENDATIONS FOR FURTHER RESEARCH

The most relevant work to be undertaken is in my opinion the investigation of the possibility of an antique origin. This will have to be placed in the context of contemporary cartography, or rather, what is known about that, the state of scientific knowledge, notably geodetic, and available survey practices. Now that the constraint of a marine network no longer applies, the option of a terrestrial geodetic network needs to be investigated. An interesting question to answer will be: if a terrestrial network is assumed, how can all the islands in the Mediterranean, not visible from the shore, have been positioned so accurately?

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[695] For a comparison of distances in these sources, see Gautier Dalché 1995, 62, 63.

A second, I believe necessary, study to be undertaken is a quantitative analysis of the *Liber de existencia riveriarum*. It would be highly interesting to undertake this evaluation in parallel with the reporting of a subset of more or less the same data by Arabic sources, such as Ibn Jubayr's *Rihla* and al-Idrisi, as Gautier Dalché has shown. I do not know whether that constitutes all available data, but if there is more, it would be very interesting to see both commonalities and differences.

A quantitative evaluation of more portolans, published in Kretschmer's *Die italienische Portolane des Mittelalters* would be very useful, notably with the intention to reveal any development in the data in the course of time.

Lastly, cartometric analysis of more portolan charts, using the method described in this thesis, will hopefully shed light on their development and use over the centuries. It would be especially interesting to find out whether the relative positions of the sub-charts eventually stabilize to a repeatable shape for the whole chart and what type of changes were made. This also holds for the Atlantic coasts: was the scale gradually increased; was the scale change an iterative process, converging to the right scale or was the process more erratic?

APPENDIX I
PLANE CHARTING EXAMPLES FROM CHAPTER 3

I.1 DIMENSIONS OF THE EARTH

1 degree latitude ≅ 60 NM
1 NM = 1852 m (NM = nautical mile)

The nautical mile is used in these examples because it is easier to relate values in degrees of latitude to linear units, as one degree of latitude equals approximately 60 NM. In these examples I assume the equality to be exact. The 6.5° latitude difference between Livorno and Dellys therefore calculates to 390 NM. Consequently Easting (E) and Northing (N) in the examples are also expressed in nautical miles.

Only in discussing the resulting charting errors will I revert back to kilometres, as this is a unit that makes the magnitude of the errors easier to grasp for most people than nautical miles.

I.2 THE 'SQUARE' SPANNED BY LIVORNO AND DELLYS

I.2-A INPUT DATA

	Latitude (φ)	**Longitude (λ)**	**Easting (E)**	**Northing (N)**
Livorno	43.4° N	10.4° E	624.000	2896.019
Dellys	36.9° N	3.9° E	234.000	2385.123

Table I.1 *– Coordinates of start end points.*

The **Mercator projection** is also known as the conformal cylindrical map projection. Easting and Northing have been computed using the spherical evaluation of the forward projection formulas:

$E = R \cdot \lambda$

$N = R \cdot \ln \tan \left({}^{\varphi}\!/_{2} + {}^{\pi}\!/_{4} \right)$

where R = 3,437,747 NM.

The Easting axis, i.e. the locus of points where N=0, is the equator and the Northing axis (E=0) is the Greenwich meridian, from which also the longitude λ is measured.

A **plane chart** is created by applying the Equidistant Cylindrical projection with the equator as the true-to-scale parallel. It is known under various names: *plane projection*, *square projection*, *plate carrée* in French and *kwadratische platkaart* in Dutch. A graticule with equal intervals in degrees of latitude and longitude consists of a pattern of squares. The forward projection formulas are:
$E = R \cdot \lambda$
$N = R \cdot \varphi$

A more generalised form is the Equirectangular projection with true-to-scale parallel at $\varphi_0 \neq 0$. This is normally the mean latitude of the area mapped. A graticule with equal intervals in degrees of latitude and longitude then consists of a pattern of rectangles. For that reason it is also known as the Equirectangular projection. The forward projection formulas are:
$E = R \cdot \cos \varphi_0 \cdot \lambda$
$N = R \cdot \varphi$

In the example below the parameter φ_0 has been set to 39.2°, which is the value that results from fitting the western Mediterranean subbasin on a portolan chart to the equirectangular projection. See Chapter 7: *Cartometric analysis of five charts*.

The denomination 'equidistant' of both the plane and Equirectangular projections refers to the property that all meridians are true to scale on the chart (in addition to the true-to-scale parallel). In this appendix the term Equidistant Cylindrical projection will be used for such projection when the true-to-scale parallel is different from the equator. An Equidistant Cylindrical projection in which the equator is the the true-to-scale projection will be designated by the term 'plane chart'. In the formulas above latitude (φ) and longitude (λ) are expressed in radians, π (pi) is the ratio of circumference and diameter of a circle.

I.2-B THE CALCULATION

For each of the three imaginary ships the exact (error-free) distances and courses will be calculated for the routes these ships have sailed. These values will be considered to have been 'measured' on board by the respective navigators and will be used in the Section C below to plot the location of Dellys on a plane chart and on an Equidistant Cylindrical chart.

SHIP #1

Ship #1 follows a direct course with constant azimuth to Dellys, which means it will sail along the rhumb line between Livorno and Dellys. What course should it follow and what distance does it have to log to arrive exactly at Dellys?

The course azimuth can be calculated from the Mercator coordinates of the two points, due to the following well-known properties of this projection.

- A rhumb line (on the sphere) projects as a straight line on the map.
- The bearing (or azimuth) of the projected rhumb line is equal to the azimuth of that rhumb line on the sphere.

The Mercator coordinates, Easting and Northing, are calculated using the formulas provided in Section I.2-A above. The bearing or azimuth of the rhumb line can then be calculated as follows, using plane trigonometry.

$$\alpha = \text{Azimuth}_{\text{Livorno-Dellys}} = \tan^{-1}\left[\frac{E_{\text{Dellys}} - E_{\text{Livorno}}}{N_{\text{Dellys}} - N_{\text{Livorno}}}\right] = 217.357°$$

Calculation of the length of a section of rhumb line between two points is simple when their latitudes are known, as is shown in Appendix II. The following relationship thus exists between this rhumb line length, the latitudes of Livorno and Dellys, the course bearing α and the radius of the earth R.

$$S = \left|\frac{R \cdot (\varphi_{\text{Dellys}} - \varphi_{\text{Livorno}})}{\cos\alpha}\right|$$

Substituting the latitude values provided in Table 1 above, the rhumb line length between Livorno and Dellys can thus be computed as S = **490.465 NM.**

The navigator can now solve the 'nautical triangle', i.e. work out the sides of the right-angled triangle shown in Figure I.1 below, using plane geometry and he would calculate the following values.

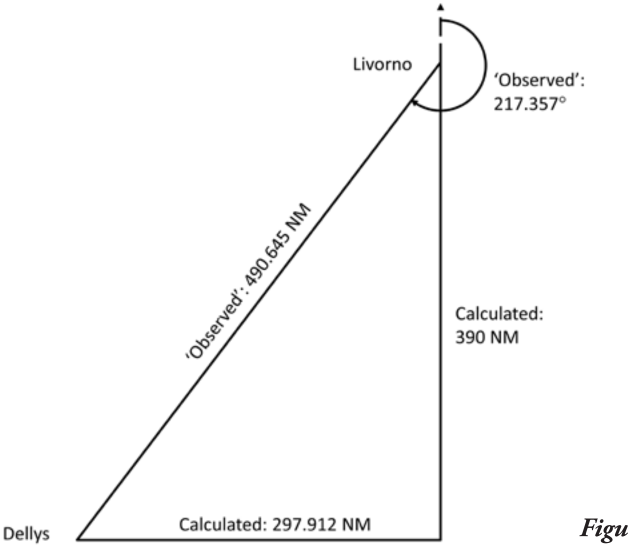

Figure I.1- *Solving the 'nautical triangle'.*

The north-south side of the triangle can be calculated as follows.

$\mathbf{d_{N\text{-}S}}$ = 490.465 · cos (217.357°) = **390 NM** (exact).

The base of the triangle, the east-west-side, is calculated as follows.

$\mathbf{d_{E\text{-}W}}$ = 490.465 · sin (217.357°) = **297.912 NM**

<u>Ship #2</u>

The route, followed by ship #2 consists of two legs: first the ship sails a course due west until it has reached the *longitude* of Dellys. It then sails due south until it reaches Dellys.

The ship therefore has to cover the 6.5 degrees longitude difference that separate Livorno and Dellys, sailing along the parallel of Livorno. One degree of longitude at the latitude of Livorno equals only 60 · cos φ_{Livorno} = 60 · cos (43.4°) NM.

The full 6.5 degrees west along the parallel of Livorno is therefore:

$\mathbf{d_{E\text{-}W}}$ **= 283.364 NM**.

The second leg of the journey is due south over 6.5 degrees *latitude*. Each degree of latitude constitutes 60 NM, so the total distance is:

$\mathbf{D_{N\text{-}S}}$ **= 390 NM.**

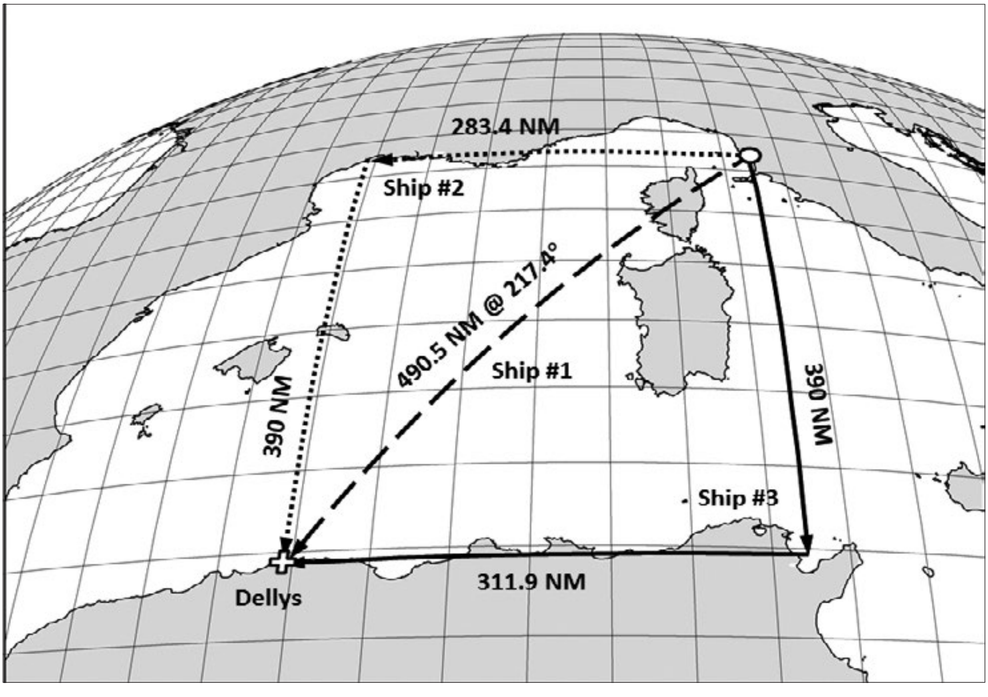

Figure I.2 *- Spherical distances and azimuths.*

Ship #3

Ship #3 begins by sailing 6.5 degrees of *latitude* due south, until it reaches the latitude of Dellys. The distance equals :

$\mathbf{d_{N\text{-}S} = 390\ NM.}$

Although both ship #2 and ship #3 have sailed a course due south, these courses are not parallel due to the diverging meridians. By the time ship #3 has completed its southerly course, it turns due west and needs to sail 6.5 degrees *longitude* along the parallel of Dellys, which equates to 60 · cos φ_{Dellys} = 60 · cos (36.9°) NM.
The full 6.5 degrees along the parallel of Dellys is therefore:

$\mathbf{d_{E\text{-}W} = 311.877\ NM}$.

The 'measured' courses and distances on the sphere are shown in Figure 2.

I.2-C Plotting the location of Dellys on a plane chart

On a plane chart the length of one degree of latitude is equal to the length of one degree of longitude everywhere on the chart. Consequently the length a degree of longitude is far too large on the chart (except on or near the equator) and all three navigators will therefore estimate the real longitude difference between Livorno and Dellys of 6.5° incorrectly. They will divide the number of nautical miles sailed by a number that is

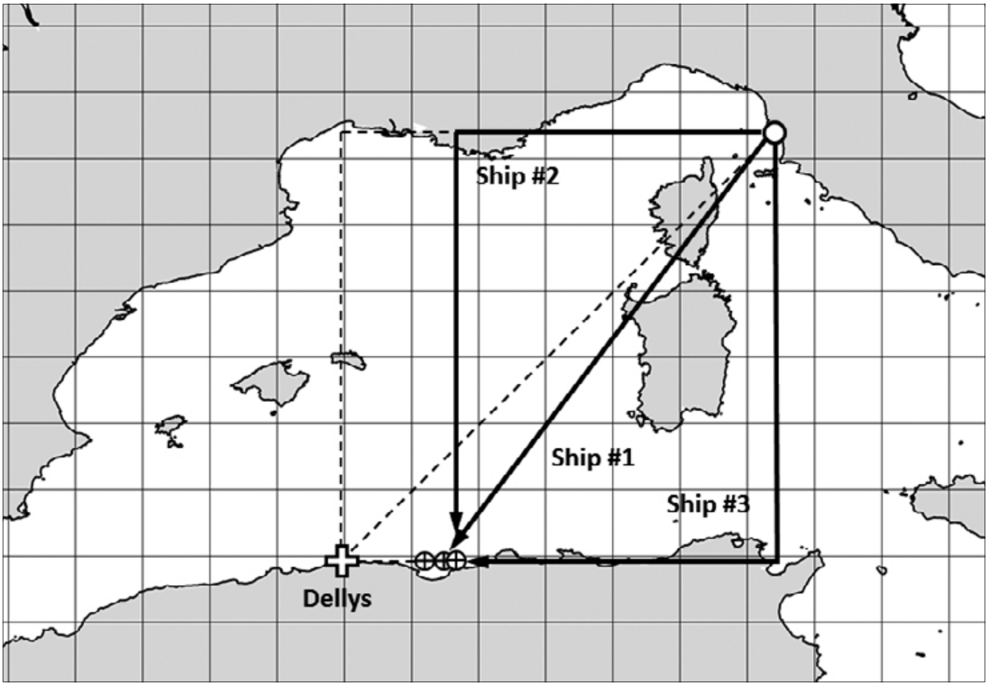

Figure I.3 *- Plotting the location of Dellys on a plane chart.*

too large, as they would use the plane chart figure for a degree of longitude of 60 NM. Hence they would calculate the longitude of Dellys as follows.

Ship #1: $\lambda_1 = \lambda_{\text{Livorno}} - 297.912 \div 60 = 10.4° - 4.962° = 5.438°$ E
Ship #2: $\lambda_2 = \lambda_{\text{Livorno}} - 283.364 \div 60 = 10.4° - 4.723° = 5.677°$ E
Ship #3: $\lambda_3 = \lambda_{\text{Livorno}} - 311.877 \div 60 = 10.4° - 5.198° = 5.202°$ E

The correct longitude of Dellys is 3.9° E.

One degree of longitude at the latitude of Dellys equals:
$60 \cdot \cos \varphi_{\text{Dellys}} = 47.981$ NM (= 88.861 km).
The longitude errors made by plane charting on a plane chart are thus:

Ship #1: $5.438° - 3.9° = 1.538° = 73.801$ NM (= 136.680 km)
Ship #2: $5.677° - 3.9° = 1.777° = 85.275$ NM (= 157.929 km)
Ship #3: $5.202° - 3.9° = 1.302° = 62.474$ NM (= 115.701 km)

I.2-D PLOTTING THE LOCATION OF DELLYS ON AN EQUIDISTANT CYLINDRICAL CHART (PORTOLAN CHART)

The natural question to ask is what would happen if the length of a degree of longitude were not to be overestimated that much, but would have a roughly correct mean value for the Western Mediterranean basin. This would lead to the adoption of a chart on Equidistant Cylindrical projection, or 'mid-latitude' chart instead of a plane chart.

The map projection of the western basin on a portolan chart corresponds closely to an Equidistant Cylindrical projection with true-to-scale parallel of about 39.2° N. This means one degree of longitude on a portolan chart corresponds, when converted to the real world, to about
$60 \cdot \cos \varphi_{\text{Livorno}} = 60 \cdot \cos (39.2°)$ NM = 46.497 NM = 86.112 km.

The longitude of Dellys would now be calculated much more accurately, as the number of nautical miles per degree longitude is now much more realistic. This leads to the following result for each ship:

Ship #1: $\lambda_1 = \lambda_{\text{Livorno}} - 297.912 \div 46.497 = 10.4° - 6.403° = 3.997°$ E
Ship #2: $\lambda_2 = \lambda_{\text{Livorno}} - 283.364 \div 46.497 = 10.4° - 6.094° = 4.306°$ E
Ship #3: $\lambda_3 = \lambda_{\text{Livorno}} - 311.877 \div 46.497 = 10.4° - 6.708° = 3.692°$ E

Using the value for the length of a longitude degree at the latitude of Dellys as calculated above, 47.981 NM (= 88.861 km), the following errors can be computed in the longitude determination of Dellys:

Ship #1: 3.997° – 3.9° = 0.097° = 4.660 NM (= 8.631 km)
Ship #2: 4.306° – 3.9° = 0.406° = 19.466 NM (= 36.052 km)
Ship #3: 3.692° – 3.9° = –0.208° = –9.957 NM (= –18.440 km)

These errors would be made in the charting of the location of Dellys if an Equidistant Cylindrical chart with similar characteristics as a portolan chart would be used for plane charting of new features, instead of a plane chart.

I.2-E Explanation of the differences

(1) No error in latitude determination

At first sight it appears surprising that all three navigators would determine the latitude of Dellys correctly. However, both the plane chart and the Equidistant Cylindrical projections have equidistant properties along the meridians, which means that all meridians are displayed true to scale on these charts and no latitude error is consequently made in the legs due south by ship #2 and ship #3 as long as the navigators would use the correct figure for the radius of the earth. The fact that ship #1 manages to sail exactly the right north-south distance even when following an oblique course is caused by a property of rhumb lines, of which the length only depends on their azimuth and the latitude difference of start and end point. This is a valid statement only when the rhumb line is not a parallel, as shown in Appendix II, formula (7). The north-south side of the nautical triangle is therefore exactly equal to the latitude difference between Livorno and Dellys.

(2) Errors in longitude determination

It is easiest to begin by explaining the longitude errors for the Equidistant Cylindrical chart. A true-to-scale parallel of 39.2° N has been assumed, which means the ratio of a degree of longitude and a degree of latitude on this projection is correct at that parallel.

The ship that sails the shortest linear distance west is ship #2, which does this along the parallel of Livorno, at 43.4° N. Although the ship does sail 6.5 degrees west until it has reached the longitude of Dellys, the navigator will divide the sailed number of miles by a figure for the length of a longitude degree that is too large, because that figure belongs to the parallel of 39.2° N, which is further to the south. This results in navigator #2 underestimating the longitude difference between Livorno and Dellys. Since this difference needs to be subtracted from the longitude of Livorno, this navigator will plot Dellys too far to the east.

The opposite happens to ship #3, which begins by sailing south, until it has reached the latitude of Dellys. From there it sails west along the parallel of Dellys of 36.9° N. This distance of 6.5 degrees it needs to cover to reach Dellys is considerably longer than the distance ship #2 sailed in westerly direction and it is also longer than 6.5 degrees along the parallel of 39.2° N, the true-to-scale parallel of the chart, at which the correct conversion value from miles to degrees exists. Navigator #3 converts the number of miles logged along the North African coast to a number of longitude degrees that is too large, therefore overestimates the longitude difference between Livorno and Dellys and plots Dellys too far to the west.

Ship #1 sails a direct course and suffers from the same effects as ship #2 in the first part of its journey, until its east-west navigation would be about correct at the parallel of 39.2° N, but it started to experience the effects of a proportionally too small mile-to-degree conversion as it sailed further south. The location plotted by the navigator #1 therefore falls between the two extremes created by navigators #2 and #3.

The relative differences between the plotted locations of Dellys by the three ships on a plane chart are in essence explained in the same way. However, with a value of 60 nautical miles to a degree of longitude, the mile-to-degree conversion factor is far too large for the Mediterranean. All three navigators use this factor. Navigators #2 and #3 should have used the conversion factor appropriate for the parallel along which they sailed west and, in a relative sense, navigator #3 makes the smaller error of the two, because the 60 miles-to-the-degree factor of the plane chart is closer to the value he should have used than it is for navigator #2, whose ship sailed along a more northerly parallel. All three ships plot Dellys too far to the east, but although the errors all three make are considerable, navigator #3 manages to plot Dellys closest to where it should be plotted. Navigator #2 makes the largest easterly error, as the mile-to-degrees conversion factor of the plane chart is far too large for the latitude where his ship sailed on a westerly course. As in the case of the Equidistant Cylindrical chart, navigator #1 should have used a varying conversion factor if he wanted to convert his sailed number of miles to a latitude and longitude values along the way and he therefore absorbs some of the error characteristics of ship #2's route and some of ship #3's route.

I.3 Four more arbitrary courses

The calculations for the four additional courses follow the same sequence of steps as the direct course the imaginary ship #1 followed in Section I.2 above:

1. Convert the latitudes and longitudes of all points to Mercator Easting and Northing and calculate the exact courses from Genoa to the four cities using these Mercator coordinates.
2. Calculate the length of the rhumb lines from Genoa to the four destination points indicated from the known latitude differences between the points and azimuths of the rhumbs calculated in the previous step.
3. Calculate the other sides of the nautical triangles for the four courses on the basis

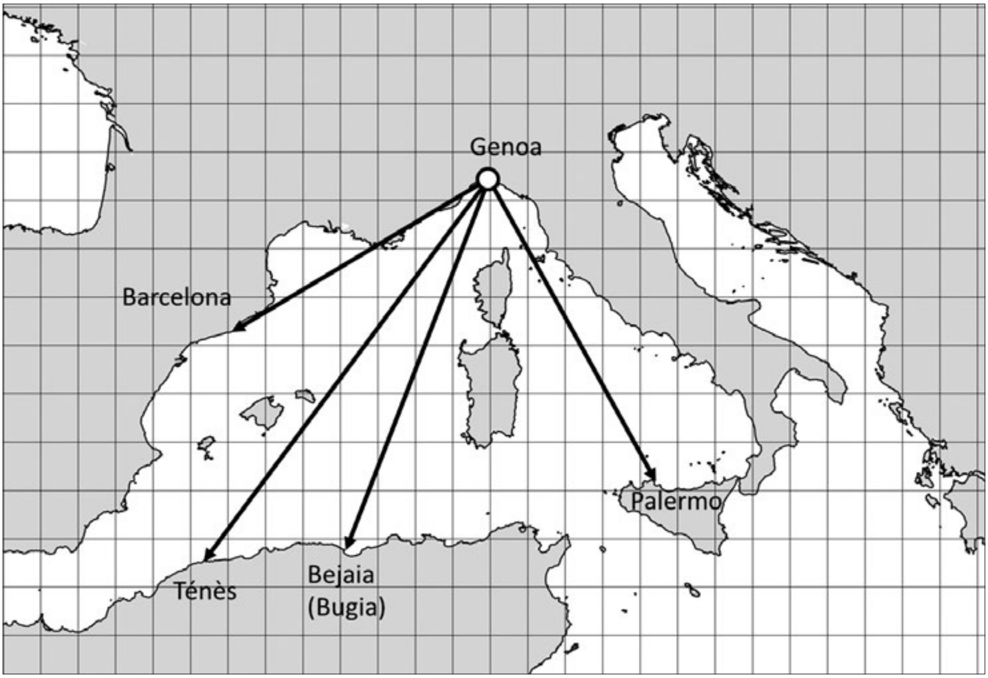

Figure I.4 *- Four more courses.*

of plane charting.

4. Calculate the longitude differences from the base of each triangle by dividing the length of the respective nautical triangle bases by the length of a degree at at the equator (i.e. 60 NM), i.e. the value for a true plane chart, and compare with the known longitude differences. The results are shown in Table I.B below.
5. Calculate the longitude differences again in the same way, but now with the parallel of 39.2° N (i.e. 46.5 NM), the value for an equirectangular (mid-latitude) chart and compare again with the known longitude differences. The results are shown in in Table I.2 below.

	Latitude error	**Plane chart Longitude error**	**Equirect. chart Longitude error**
Barcelona	0	151 km	31 km
Ténès	0	163 km	14 km
Bejaia (Bougie)	0	82 km	7 km
Palermo	0	-97 km	-12 km

Table I.2 *- Four more courses; longitude errors on plane and Equidistant Cylindrical charts.*

A number of curious things can be observed in this example: Barcelona, Ténès and Bejaia are plotted too far to the east on both the plane chart and the Equidistant Cylindrical chart, but Palermo is plotted too far to the west. The second thing to notice is that the *relative* differences between the errors of the four points are different for the plane chart and for the equirectangular chart. When plotting the locations on a plane chart Ténès has the largest error, but on an Equirectangular chart it is Barcelona that is furthest out.

The reason for the negative sign in the error of Palermo is the fact that the plane charting error depends on the azimuth of the rhumb line to the target point. The difference in the pattern of errors is not the same for the plane chart and the equirectangular chart is caused by the fact that, although the starting point, the length of the bases of the nautical triangles is the same, these numbers are divided by a different figure for the length of a longitude degree. After that division the pattern of longitude differences is still intact: the ratio between the pairs of figures in columns 3 and 4 is 0.78 (=46.5/60) in all cases, but when these longitude differences are subtracted from the true longitude values of the target points, differences emerge. The basis for this calculation is shown in Table I.3 below.

	Length of base of nautical triangle (NM)	Longitude diff. (deg) plane chart (1°=60 NM)	Longitude diff. (deg) equirect-angular chart (1°= 46.5 NM)	True longitude difference (deg)	Error on plane chart (deg)	Error on equirect. chart (deg)
Genoa - Barcelona	-296.9	-4.949	-6.386	-6.755	**+1.807**	**+0.369**
Genoa - Ténès	-344.6	-5.743	-7.411	-7.565	**+1.822**	**+0.154**
Genoa - Bejaia	-173.4	-2.889	-3.729	-3.812	**+0.922**	**+0.083**
Genoa - Palermo	+200.5	+3.342	+4.313	+4.452	**-1.110**	**-0.139**

Table I.3 *- Longitude errors in plane and Equidistant Cylindrical charts.*

The azimuth dependency can be visualised by extending the above example to a series of points regularly spaced in a fan from 0 to 360 degrees around Genoa:

The maximum errors do not occur exactly at azimuths of 90° and 270°. No error is made when the course runs due north or due south, but that had already been established.

The magnitude of the errors depends on the latitude of the departure point, in this case Genoa, and, needless to say, on the length of the section of rhumb line between departure point and target.
The examples provided in this appendix demonstrate that the errors due to plane charting are systematic and of a complex nature. The implication is that it is highly unlikely that they can be averaged out.

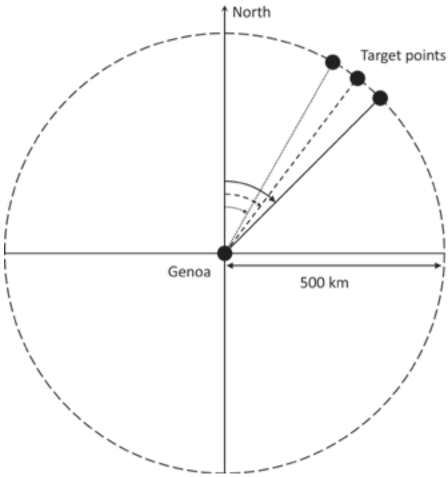

Figure I.5 - *A regularly spaced fan of points 500 km from Genoa.*

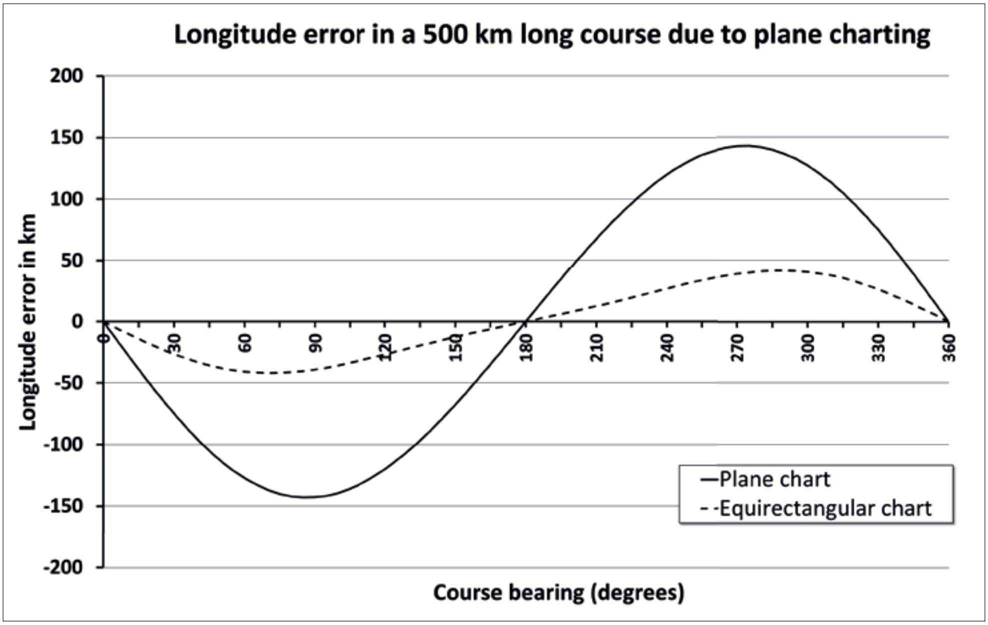

Figure I.6 - *Azimuth dependency of plane charting error.*

APPENDIX II
CALCULATION OF THE LENGTH OF A RHUMB LINE

II.1 An arbitrary line piece on a sphere

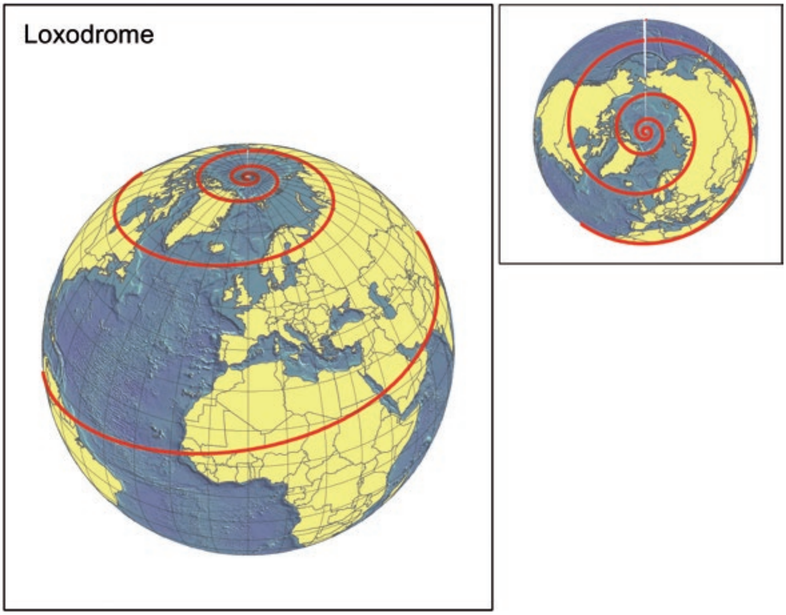

Figure II.1 - *Rhumb line or loxodrome in oblique and polar perspective projection.*

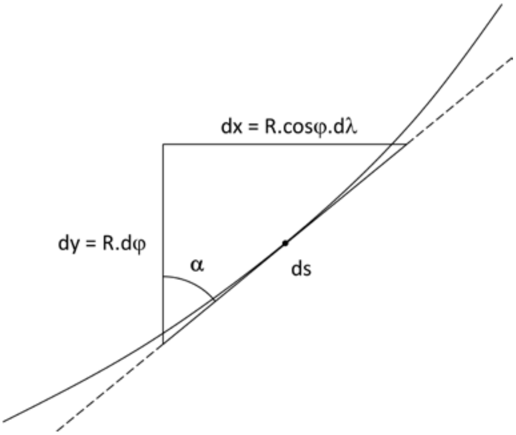

Figure II.2 - *Geometry of an infinitesimal section of a curve on a sphere.*

The length of an arbitrary, infinitesimal line piece *ds* on a sphere is:

$$ds^2 = dx^2 + dy^2 \tag{1}$$

where (dx, dy) are linear quantities defined in a local Cartesian coordinate system. Taking R as the radius of the sphere and considering ($d\varphi$, $d\lambda$) as differential latitude and longitude on this sphere, the following relationships hold:

$$dx = R \cdot \cos\varphi \cdot d\lambda \tag{2}$$

$$dy = R \cdot d\varphi \tag{3}$$

Substitution of equations (2) and (3) in (1) yields:

$$ds^2 = R^2 \cdot d\varphi^2 + R^2 \cdot \cos^2\varphi \cdot d\lambda^2 \tag{4}$$

II.2 A LINE PIECE IN A SPECIFIED DIRECTION ON A SPHERE

Let the azimuth of the line piece be α.
Then, with substitution of (2) and (3):

$$\tan\alpha = \frac{dy}{dx} = \frac{R \cdot \cos\varphi \cdot d\lambda}{R \cdot d\varphi} = \frac{d\lambda}{d\varphi} \cdot \cos\varphi$$

$$\cos\varphi \cdot d\lambda = \tan\alpha \cdot d\varphi \tag{5}$$

Substitute (5) in (4):

$$ds^2 = R^2\, d\varphi^2 + R^2 \tan^2\alpha \cdot d\varphi^2$$

$$ds^2 = (1 + \tan^2\alpha)\, R^2\, d\varphi^2$$

$$ds^2 = \frac{R^2}{\cos^2\alpha}\, d\varphi^2$$

$$ds = \left| \frac{R}{\cos\alpha}\, d\varphi \right| \tag{6}$$

Interestingly, this equation shows that, for rhumb lines sections that are not parallels, the length of a section of rhumb line depends on the azimuth of the rhumb line and the latitude difference of the start and end points only, when the radius of the earth is taken as a given.

The entire line length S of the rhumb line section between the points A and B is calculated by integration:

$$S = \int_{\varphi_A}^{\varphi_B} \left| \frac{R}{\cos\alpha} d\varphi \right| = \left| \frac{R(\varphi_B - \varphi_A)}{\cos\alpha} \right| \tag{7}$$

The values for latitude are in radians. The result of this formula is indeterminate when A and B lie on the same parallel, i.e. $\alpha = \pi/2$ or $\alpha = 3\pi/2$ (i.e. $\varphi_A = \varphi_B = \varphi$); in that case the length from A to B is calculated as follows:

$$S = R \cdot \cos\varphi \cdot (\lambda_B - \lambda_A) \tag{8}$$

II.3 MERCATOR SAILING – HOW TO PLOT SAILED DISTANCE IN A CHART?

The Renaissance sailor did not have this handy formula available and didn't solve his navigation problems algebraically anyway. Besides he also had to determine his longitude. He derived both by plotting the sailed distance in the chart at the compass bearing of the course he had followed. However he had to scale-correct the sailed distance because the Mercator chart magnifies features considerably for latitudes away from the equator. A plane chart does that too and distorts the course bearing as well, but nobody cared at the time. He would multiply his distance travelled by the secant of the mean latitude of his trajectory, but that is only an approximation, although it was quite adequate for Renaissance navigation.

The mathematically correct relationship for the mean scale factor along the rhumb line, not relevant for the Renaissance sailor, but certainly relevant for this study, is obtained as follows.

A rhumb line projects as a straight line in the Mercator projection and the bearing of this straight line is the same as the azimuth of the corresponding rhumb line on the sphere.

Let the desired length of the section of rhumb line from point A to point B in the Mercator chart be L. Since the relevant rhumb line section is a straight line in the map plane with bearing α, the following relationship holds, in which N indicates the Northing component of the Mercator map coordinates:

$$\cos \alpha = \frac{N_B - N_A}{L}$$

Substituting this relationship in equation (7) and rearranging the terms yields the following expression for the mean scale factor along a rhumb line:

$$\tilde{m} = \frac{L}{S} = \left| \frac{N_B - N_A}{R \cdot (\varphi_B - \varphi_A)} \right| = \left| \frac{\Delta N}{R \cdot \Delta\varphi} \right|$$

in which the Northing coordinate *N* is calculated as follows:

$$N = R \cdot \ln \tan \left({}^{\varphi}\!/_{2} + {}^{\pi}\!/_{4} \right)$$

The equations in this appendix are valid only for the spherical case, not on an ellipsoid. Both ellipsoidal and spherical formulas are provided by John P. Snyder.[696]

A more extensive derivation of the rhumb line equations, for the spherical case only, is provided by James Alexander.[697]

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[696] John P. Snyder, *Map Projections – A Working Manual*, US Geological Survey Professional Paper 1395 (Washington: United States Government Printing Office, 1987), 38-47.

[697] James Alexander, "Loxodromes: A Rhumb Way to Go", *Mathematics Magazine*, Vol. 77, No. 5 (December 2004).

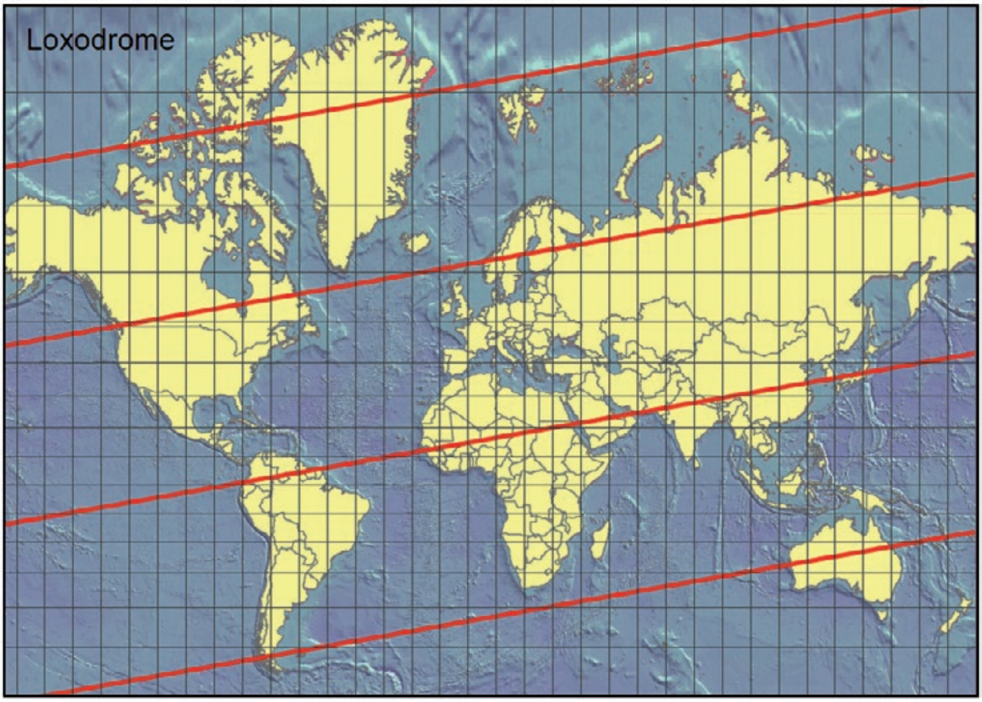

Figure II.3 *- The rhumb line from Figure II.1 on a Mercator chart.*

APPENDIX III
ACCURACY MODEL FOR MEDIEVAL NAVIGATION

III.1 INTRODUCTION

In Chapter 5: *Navigational practices in the twelfth and thirteenth centuries* an accuracy model for medieval navigation is described in qualitative terms. This appendix describes how the variances of the model components, described in Table 4.3 and Table 4.4, propagate into the position estimates of the medieval ship.

The basic equation for distance is the following.

$$d = v \cdot t \quad \text{......}(1)$$

The symbol d designates distance and v and t are speed and time respectively.
Linearisation of this equation results in the following relationship.

$$\Delta d = t_0 \cdot \Delta v + v_0 \cdot \Delta t \quad \text{......}(2)$$

Random variables are indicated by the Greek symbol Δ and the subscript $_0$ designates a constant.

The basis of the accuracy model is Kelley's assumption that a single value for speed and course bearing are recorded for the time interval, corresponding with one watch, i.e. about four hours. The model described in this appendix divides the problem into several independent components, represented by random variables. Another fundamental assumption is that the random variables in the accuracy model are unbiased estimators, i.e. they have zero expectations. Furthermore it is assumed that all random variables are normally distributed. It is stressed that the model aims to describe the measurement processes of medieval navigation and not just a physical reality divorced from those measurement processes.

The model distinguishes between model components that yield one outcome or realisation per four-hour watch interval and components that yield only one outcome for the entire journey and only acquire different values when multiple journeys and multiple ships are considered. An example of the first is the determination by the navigator of the ship's course during a watch interval. This process is repeated every four hours. An example of the second is the alignment of the compass on a particular ship on one journey. Before the invention of a weather-proof *binnacle*, the compass was normally placed inside a rear cabin on the ship to protect it against weather influences. The assumption is that it would be left there for the duration of the journey. The alignment angle is a random variable that will be different for different ships and for different journeys of the same ship (assuming the compass is removed after the journey), but for one journey it remains constant.

For the components of the model for which a new value is determined in every watch interval the total impact of the variable on the entire journey will be smaller than the impact of a variable that only acquires one realisation for the journey.

The assumption of zero expectation for all random variables in the model is key to the medieval origin hypothesis, which assumes that large-scale averaging[698] of observations was executed to increase the precision. The assumption that the calculation of an average will result in a smaller standard deviation (and variance) of the random variable is only valid if all random variables are unbiased over the population of all ships in the Mediterranean that contributed to the presumed build-up of a body of navigation data from which the first portolan chart was constructed.

Components of the model contributing to total along-course accuracy have been treated separately from the components contributing to cross-course accuracy. This is because the principal observables for these components are different, distance travelled and compass bearing respectively. The model assumes that none of the along-course variables correlates with any of the cross-course variables.

III.2 ALONG-COURSE ACCURACY

It is assumed that the ship is always running downwind with only a small drift angle. If the ship would begin to sail closer to the wind, from a dead run to a broad reach and then towards a close reach, the drift angle would increase progressively. The wood chip, the passage of which between two bulwark markers is the assumed basis of the measurement of distance at sea, would have to be dropped on the windward side. If it were to be dropped on the lee side it would end up too close to the hull, so close that it might not be visible from the deck anymore, whereas, if it would be cast into the water on the windward side, it would appear to drift away from the ship, in accordance to amount of leeway the ship is making. In both cases the ability to measure the ship's speed would be seriously compromised.

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[698] The terms 'average' and 'averaging' may refer to estimation of the mean, mode, median or any approximate central value of the probability density function of the relevant variable. The processes described in this navigation model imply that the determination of the arithmetic mean is meant.

In equation (2) Δv is a random variable. The scalar constant v_0 is the nominal constant speed assumed for the vessel. Analogously Δt will be considered to be the error in time measurement, while t_0 is the nominal time over which measurement takes place. This is the duration of the interval between speed measurements, nominally four hours.

The duration of the entire journey will be indicated by $T = n \cdot t_0$. The variable n is the number of four-hour intervals in the total journey.

Finally, the random variable used for the calculation of along-course accuracy will be designated by Δd_L, i.e. a subscript L having been added to distinguish this variable from the cross-course influences, which will also be expressed as a distance, Δd_X.

The random variable for along-course distance can be divided into two components, one a function of speed estimation, the other a function of time measurement with a sand glass.

$\Delta d_L = \Delta d_{speed} + \Delta d_{time}$ ....(3)

Both components Δd_{speed} and Δd_{time} have several constituents, as explained below:

$\Delta d_{speed} = \Delta d_{L,1} + \Delta d_{L,2} + \Delta d_{L,3} + \Delta d_{L,4}$ ....(4)

$\Delta d_{time} = \Delta d_{L,5} + \Delta d_{L,6}$ ....(5)

The objective of the following sections is to calculate the *variances* of these random variables.

A. CONTRIBUTION TO DISTANCE ACCURACY BY THE ACCURACY IN ESTIMATED VESSEL SPEED (Δd_{SPEED})

Measured vessel speed is a function of a number of component variables described in Section 4.5 of the main text.

$\Delta d_{L,1}$ = Random variable that quantifies the cumulative effect on the along-course distance estimate due to variations in *vessel speed* measurement from *interval to interval.*

$\Delta d_{L,2}$ = Random variable that quantifies the cumulative effect in the along-course distance estimate due to variations in *vessel speed* measurement *between different navigators*. I have allowed only one navigator per vessel, per journey, although in reality the task may have been divided over multiple navigators. That would make the results worse (i.e. a larger variance of this variable), so that my assumption of one navigator per journey represents the ‘optimum’ case.

$\Delta d_{L,3}$ = Random variable expressing the *sampling effect* in speed measurement.

$\Delta d_{L,4}$ = Random variable expressing the cumulative effect on the along-course distance estimate due to the (uncompensated) along-course component of *sea currents*.

B. CONTRIBUTION TO DISTANCE ACCURACY BY THE ACCURACY IN TIME MEASUREMENT (Δd_{TIME})

To obtain distance travelled, the measured speed of the ship needs to be multiplied with time lapsed, which is assumed to have been measured using a sand glass.

The following two distinct components contribute to the accuracy of this measurement.

$\Delta d_{L,5}$ = Random variable expressing the cumulative effect on the total distance estimate caused by variations in the measurement of the length of a watch interval of nominally four hours by means of a *sand glass*.

$\Delta d_{L,6}$ = Random variable that expresses the cumulative effect of *sand glass calibration*.

C. SYMBOLS USED

Furthermore the following symbols are used in the equations below.

t_0 = Length of the interval between observations, assumed to be nominally four hours.
n = Number of four-hour watch intervals in the journey
T = Total duration of the journey in hours ($T = n \cdot t_0$)
t_{obs} = Length of the period of one vessel speed measurement; nominally about ten seconds.
d^i = distance covered in watch interval i
d_0 = Nominal length of a watch interval at speed v_0 ($d_0 = v_0 \cdot t_0$)
D = Total distance covered in the journey, nominally $D = n \cdot d_0$
v_0 = Nominal speed of the vessel, assumed to be 4 knots
Δv_{sam} = Sampling variable in vessel speed
$v_{L,curr}$ = Speed of the along-course current component (not the total current speed!)
Δt_{int} = Random variable describing the deviation from the nominally 10 seconds long interval to measure vessel speed (expressed as a fraction of the nominal interval length)
Δt_{pers} = Random variable describing the navigators systematic (personal) error in timing in the nominally 10 seconds long interval to measure vessel speed; assumed constant for one journey, one ship.

$\Delta t_{\text{sand-int}}$ = Random variable quantifying variation of ‘sand clock time’ over a four-hour watch interval, but excluding calibration influences.

$\Delta t_{\text{sand-cal}}$ = Random variable of sand clock time resulting from the calibration of the sand clock; it is constant for the entire journey of one ship, but expressed in the equations over the period t_0.

σ^2 = Variance of any random variable.

D. CONTRIBUTION BY THE NAVIGATOR’S ESTIMATION OF VESSEL SPEED

There will be variation in the timing of the observer in chanting the ditty or pacing the deck in order to measure the speed with which a wood chip floats by between two markers in the bulwark of the ship. This is the measured time of the passage of the wood chip corrected for the nominal time interval of ten seconds. Since the navigator establishes the speed to be used for dead reckoning for the period of the watch, i.e. four hours, the influence of this variable affects the distance estimate for the entire watch period of four hours. This random variable acquires a new value or realisation at every four-hour watch interval. Also for this random variable the assumption is that its expectation equals zero. In other words, it is assumed that if a navigator will estimate this time interval correctly ‘on average’, the value will vary from interval to interval in accordance with the random properties of the variable.

The measurement of vessel speed will take some 10 seconds, with a distance between rail markers 20 m and a nominal vessel speed of four knots. Any percentage error in the timing of this 10 second interval will propagate as the same ratio into estimated vessel speed and into the estimated distance over the four-hour watch interval. Let the variance of the timing of the measurement interval, expressed as a ratio of the time interval be , then the variance of the distance sailed in the four-hour watch interval will be

$$\sigma^2_{\Delta d^i_{L,1}} = d_0^2 \cdot \sigma^2_{\Delta t_{int}}$$

Repeated *n* times for as many four-hour intervals, the variance of total distance due to the randomness in the estimation of ship’s speed, after substitution of $D = n \cdot d_0$ is:

$$\boxed{\sigma^2_{\Delta d^i_{L,1}} = \frac{D^2}{n}\sigma^2_{\Delta t_{int}} \quad \text{......} (6)}$$

The factor *n* in the denominator indicates that the effect of the randomness in vessel speed estimation, i.e. random in the sense that vessel speed takes on a new random value in each successive four-hour interval, has a tendency of partly cancelling out over the entire journey. The variance of this effect is *n* times smaller than it would be when only a single speed measurement would take place for the whole journey. Measuring vessel speed more often has a beneficial effect on the distance estimate of the entire journey.

E. PROPAGATION OF THE 'PERSONAL ERROR' OF THE NAVIGATOR

Each observer would have had his own procedure for executing the speed measurement process. It is inevitable that he would systematically overestimate or underestimate the vessel's speed. This systematic error in vessel speed measurement is taken to be constant for the duration of a journey. It is caused by the navigator consistently counting too fast or too slow, in other words, the navigator's 'personal error' in counting. It should be remembered that there was no technical aid at all in the Middle Ages that could help in calibrating the timing of such short intervals. Considered across the entire population of medieval navigators in the Mediterranean, this personal error may be treated as a normally distributed random variable with an expectation of zero, meaning that 'on average' the personal errors would cancel out. The calculation of its impact on the total distance of the journey proceeds along the same lines as the calculation in the previous section, except that no partial 'averaging out' effect takes place.

Each journey therefore supplies one realisation, one realised value, of this random variable, which, considered again as a percentage of the nominal observation interval of 10 seconds, propagates into the calculated distance for the whole journey at the same proportion as follows:

$$\boxed{\sigma^2_{\Delta d_{L,2}} = D^2 \cdot \sigma^2_{\Delta t_{pers}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)}$$

F. CONTRIBUTION BY THE SAMPLING EFFECT IN SPEED MEASUREMENT

The sampling error in vessel speed measurement is the difference between the average speed of the vessel during a four-hour interval and the instantaneous speed, measured at the beginning, middle or end of the four-hour watch and which is considered to be representative for the entire interval. Each four-hour interval has its own speed sampling error. The cumulative propagation of this sampling effect into the distance estimate of the journey is what is wanted. To avoid misinterpretation of the word 'error', this random variable will be termed 'sampling effect' instead.

The sampling effect may be treated as normally distance distributed random variable. The speed sampling effect over one four-hour interval *i* is defined as follows:

$\Delta v^i_{sam} = v^i_{measured} - v_0$

In this equation $v^i_{measured}$ is the vessel speed measured and v_0 is the true vessel speed, which, for convenience, I am assuming to be equal to the nominal speed of the vessel, four knots.

Distance sailed is obtained by multiplying by lapsed time t_0 of the watch interval. The variance of the cumulative sampling effect after n watch intervals, making use of $T = n \cdot t_0$, may be calculated as follows.

$$\sigma^2_{\Delta d_{L,3}} = \frac{T^2}{n} \cdot \sigma^2_{\Delta v_{sam}} \quad \text{.......................................} (8)$$

G. CONTRIBUTION OF RANDOM ALONG-COURSE CURRENTS

It will be assumed that the along-course current experienced by the ship has an expectation of zero and can be considered to be a normally distributed random variable. It is further assumed that the along-course current varies every four-hour interval, while its expectation remains zero. Because of the assumption of a zero expectation there is no need to introduce a random variable $\Delta v_{L,curr}$. The variable $v_{L,curr}$ can be directly used in the equation.

In behaviour this component is identical to the sampling effect. The variance of the cumulative effect of random on the total distance D of the journey may be expression by the following equation.

$$\sigma^2_{\Delta d_{L,4}} = \frac{T^2}{n} \cdot \sigma^2_{v_{L,curr}} \quad \text{.......................................} (9)$$

H. CONTRIBUTION BY THE ACCURACY OF THE ON-BOARD SAND CLOCK

Variations in the measurement of the length of a four-hour watch interval may be caused by changes in the humidity and variations in the granularity of the 'sand' and by ship motions. This variation is represented by a random variable that is assumed to have, again, an expectation of zero over the period of any four-hour watch.

In the evaluation of the impact this variable has on the estimation of distance, the nominal speed of the vessel will be used.

$$\Delta d^{i}_{L,5} = v_0 \cdot \Delta t_{sand\text{-}int}$$

Over the entire length of the journey the total distance error resulting from the random errors in the sand clock is shown below.

$$\sigma^2_{\Delta d_{L,5}} = n \cdot v_0^2 \cdot \sigma^2_{\Delta t_{sand\text{-}int}} \quad \text{.......................................} (10)$$

I. CONTRIBUTION BY THE CALIBRATION OF MARINE SAND CLOCKS

The impact on distance accuracy of variations in the calibration of multiple sand clocks is far worse than the variation in time intervals, experienced by any given sand clock. This was evaluated under Section III.2H above and that effect can be seen to 'average out' to some degree over the entire length of the journey because in one four-hour interval the sand clock may be slow, in other intervals fast. However, any variation in the calibration of a given sand clock, used on board during a given journey will remain constant during the journey. The variation in sand clock calibration can be modeled as a zero expectation, normally distributed random variable, implying the assumption that a population of *n* sand clocks will have a mean error that would tend toward zero.

The evaluation of the impact on distance is similar to that of the random sand clock error.

With $\Delta t_{\text{sand-cal}}$ defined as the effect of sand clock variation over a four-hour period, and because only a single realisation of the calibration variable influences the entire journey, the total sand clock calibration effect over the journey is *n* times as large. Multiplied by the nominal vessel speed v_0 its impact on estimated distance can be expressed by the following equation.

$$\Delta d_{L,6} = v_0 \cdot n \cdot \Delta t_{\text{sand-cal}}$$

The variance of the impact of sand clock calibration on the total distance of the journey can therefore be computed as follows.

$$\sigma^2_{\Delta d_{L,6}} = n^2 \cdot v_0^2 \cdot \sigma^2_{\Delta t_{\text{sand-cal}}} \quad \text{......} (11)$$

J. TOTAL ALONG-COURSE DISTANCE ACCURACY

In accordance with equations (3), (4) and (5) the variance of the total along-course distance measurement is the sum of the factors in equations (6) to (11).

$$\sigma^2_{\Delta d_L} = \sigma^2_{\Delta d_{\text{speed}}} + \sigma^2_{\Delta d_{\text{time}}}$$

$$\sigma^2_{\Delta d_{\text{speed}}} = \frac{D^2}{n}\left(\sigma^2_{\Delta t_{\text{int}}} + n \cdot \sigma^2_{\Delta t_{\text{pers}}}\right) + \frac{T^2}{n}\left(\sigma^2_{\Delta v_{\text{sam}}} + \sigma^2_{v_{L,\text{curr}}}\right)$$

$$\sigma^2_{\Delta d_{\text{time}}} = n^2 \cdot v_0^2 \left(\sigma^2_{\Delta t_{\text{sand-int}}} + \sigma^2_{\Delta t_{\text{sand-cal}}}\right)$$

III.3 CROSS-COURSE ACCURACY

Cross-course accuracy is simpler to estimate. The expectation, i.e. the theoretical cross-course distance, is assumed to be zero, as also here the assumption is that no bias, no systematic error is introduced in the measurement of course azimuth. That is not strictly true, as the magnetic declination along any course will affect all compass bearings in the same way, creating an average non-zero bias, even when the navigation results are considered of a large sample of ships that sailed that same course. However, the effects of magnetic declination are not stochastic (random) and magnetic declination therefore needs to be excluded from the estimates of the variances of the contributing phenomena. Magnetic declination will be taken into account in this study by using a palaeomagnetic model for the Mediterranean. This occurs in the analysis of the *Compasso de Navegare* in Chapter 8: *The Relationship between portolans and portolan charts* and in the analysis of the geodetic network in Chapter 9: *The map projection; artificial or intentional?*

Analogous with along-course accuracy and its components, cross-course accuracy will be treated as the sum of the effects of a number of phenomena that contribute to the positioning of the vessel perpendicular to the course. Only two of those phenomena are directly related to the compass. For that reason, and to facilitate comparison with the calculation for along-course accuracy, the effects of these phenomena will be compounded into a cross-course distance. The total cross-course accuracy, expressed as the variance of the distance cross-course, is designated by Δd_X and is subdivided into four components, the first two relating to the compass and other two to leeway and cross-course sea currents. Cross-course distance is modeled as a random variable, which is the sum of four component random variables, quantifying the phenomena described above.

A. Components of cross-course accuracy

$$\Delta d_X = \Delta d_{X,1} + \Delta d_{X,2} + \Delta d_{X,3} + \Delta d_{X,4} \quad \text{..........} \quad (12)$$

$\Delta d_{X,1}$ = Random variable, quantifying the effect of short-term *course variations*, caused by pitch, roll and yaw. This includes the effects on the measurement of course bearing caused by instability of the compass needle arising from the ship's motion.

$\Delta d_{X,2}$ = Random variable, quantifying the effect of *compass calibration*, mainly caused by the alignment of the compass with the ship's longitudinal axis. Compass construction errors also contribute to this variable.

$\Delta d_{X,3}$ = Random variable expressing the effect of *leeway* (drift) of the vessel.

$\Delta d_{X,4}$ = Random variable expressing the cumulative effect on the cross-course distance estimate due to the (uncompensated) cross-course component of *sea currents*.

B. Symbols used

The following symbols are used in the equations below in addition to those in the Section III.2.

ΔA_{int} = Random variable describing the compound effect of *azimuth* (bearing) *variations* over interval . Each four-hour watch interval will lead to a new realisation of this variable.

ΔA_{cal} = Random variable describing compass *calibration* and the effects of compass construction errors. This variable acquires only one realisation per journey per ship.

δ = Random variable that describes the vessel's *leeway* angle, assumed to lead to one realisation for each interval .

$v_{X,curr}$ = Random variable describing the speed of the cross-course *current* components (not the total current speed!). In the absence of more specific information it is assumed to be the same as the along-course component for current speed.

C. Contribution by course accuracy per watch interval

The random variable expressing the bearing or azimuth measured by the compass is assumed to have a single realisation over interval t_0, the watch period of nominally four hours. The random variable expressing cross-course as a distance from the nominal course after one four-hour interval *i* has the following simple relationship with the variation in course azimuth:

$$\Delta d^{i}_{X,1} = d^{i} \cdot \Delta A_{int}$$

in which ΔA_i is expressed in radians.[699]

Substituting $d^i = v_0 \cdot t_0$, extending the calculation to the entire journey of *n* watch intervals and substituting $D = v_0 \cdot T = v_0 \cdot (n \cdot t_0)$, the variance of this random variable is described in equation 13.

$$\boxed{\sigma^2_{\Delta d_{X,1}} = \frac{D^2}{n} \cdot \sigma^2_{\Delta t_{int}} \quad \dots\dots\dots (13)}$$

D. Contribution by compass alignment

Compass alignment, treated as a random variable over the population of all relevant medieval ships that sailed the Mediterranean, is assumed to have an expectation of zero. Construction errors in the compass are treated as a second element contributing to this variable. The effects of magnetic declination are excluded from this stochastic error model, as they cannot be captured in such a model.

The variance of the effect of a compass alignment on cross-course accuracy can be expressed analogously to the equation for the calibration of the sand clock in Section III.2I. This variable acquires a single realisation for any given journey of any ship.

$$\Delta d_{X,2} = D \cdot \Delta A_{cal}$$

$$\boxed{\boldsymbol{\sigma^2_{\Delta d_{X,2}} = D^2 \cdot \sigma^2_{\Delta A_{cal}}} \quad \dots\dots\dots (14)}$$

The units of ΔA_{cal} and $\sigma^2_{\Delta A_{cal}}$ are radians and radians squared respectively.

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[699] Formally this ought to be: $\Delta d^{i}_{X,1} = d^{i} \cdot \sin \Delta A_{int}$ but for small course variations the approximation shown by the equation in the text is adequate.

E. CONTRIBUTION BY VESSEL LEEWAY (DRIFT ANGLE)

It is assumed that medieval ships were mostly running downwind with only a small drift angle. Significant leeway might be made when a vessel would be attempting to sail closer to the wind. Large drift angles would incapacitate the windward steering oar in the turbulent wash of the drifting vessel and would make speed measurements next to impossible. For these reasons only small drift angles are assumed.

Although it is not realistic to assume that the wind direction would change after every watch, giving rise to a new realisation of the drift angle (as a random variable), it is nevertheless assumed that leeway is a random variable that is part of those contributing factors that affect the ship in each watch interval in a random manner. In other words, this random variable is assumed to have an expectation of zero and that leeway in any watch interval does not correlate with the leeway the vessel makes in the next.

$$\sigma^2_{\Delta d_{X,3}} = \frac{D^2}{n} \cdot \sigma^2_{\delta} \quad \text{...} \text{(15)}$$

F. CONTRIBUTION BY CROSS-CURRENTS

Analogous with the quantification of the impact of along-course currents, the assumption is that, whereas the regime of currents may be subject to considerable change during the journey, the consolidated effect of currents over a watch interval can be modeled as a normally distributed random variable with zero expectation. Its impact on cross-course distance accrued over interval *i* is as follows.

$\Delta d^{i}_{X,4} = v_{X,curr} \cdot t_0$

For the entire length D of the journey and substituting $T = n \cdot t_0$ its variance may be expressed by equation 16.

$$\sigma^2_{\Delta d^{i}_{X,4}} = \frac{T^2}{n} \cdot \sigma^2_{v_{curr}} \quad \text{...} \text{(15)}$$

G. TOTAL CROSS-COURSE ACCURACY

The total cross-course accuracy is thus as follows, in accordance with equation (12).

$$\sigma^2_{\Delta d_X} = \frac{D^2}{n} \left(\sigma^2_{\Delta A_{int}} + n \cdot \sigma^2_{\Delta A_{cal}} + \sigma^2_{\delta} + \frac{\sigma^2_{v_{X,curr}}}{v_0^2} \right) \quad \text{..} \text{(17)}$$

Alternatively total cross-course accuracy may be expressed as an angular value, in order to compare it directly with azimuth, yielding the following equation.

$$\sigma^2_{\Delta A} = \frac{1}{n} \left(\sigma^2_{\Delta A_{int}} + n \cdot \sigma^2_{\Delta A_{cal}} + \sigma^2_{\delta} + \frac{1}{v_0^2} \cdot \sigma^2_{v_{X,curr}} \right) \quad \text{......................................} \text{(18)}$$

APPENDIX IV
CARTOMETRIC ANALYSIS DETAILS

IV.1 Objective of this appendix

This appendix is intended to supply some additional details about the creation of identical points, the adjustment of the wind rose circles and describe the map projection formulas used in the cartometric analysis process described in Chapter 7. The selection process of the identical points is described in Section IV.2

IV.2 Coordinates of identical points

A total of nearly 4000 identical points have been created on the five portolan charts that have been analysed and the same number of corresponding points was established on the modern reference map, the VMAP digital dataset, described in Section 6.5.1. Additionally 119 points of the total of eight wind roses on the charts and 46 points belonging to scale bars were created on the portolan charts. All points were created using modern GIS (Geographical Information System) software, which allowed the points to be selected graphically, after which the coordinates were exported as a digital file for further processing.

A. Selection of identical points on the portolan charts

The selection process of the identical points began with the portolan charts; I selected points that were identifiable as a point feature both on the portolan chart and on the reference map. That included point features such as capes, promontories and the middle of river mouths (the width of rivers is usually exaggerated on portolan charts and therefore unusable in most cases). An example of this selection principle is shown in Figure IV.1.

The resolution of the scans is shown in Table IV.1, along with the approximate real dimensions of the charts. Because the dimensions in terms of pixels are greater than the ‘net’ size of the charts in centimetres, a different number of pixels per cm may be calculated for length and width. The smaller of the two numbers is provided in column 4. Column 5 shows one fifth of the figure in column 4 and represents a length of 11 km, expressed in pixels on the chart, assuming a nominal scale of all charts of 1 : 5.5 million. The resolution was in all cases significantly greater than the geographical features of which the best identifiable point was selected as identical point.

The GIS software allows zooming in the scale which allows the best visual identification of the points, of course with a lower limit determined by the resolution of the

chart	scan resolution (pixels)	real dimensions (cm x cm)	minimum pixels/cm	nr of pixels equivalent to 11 km
Carte Pisane	9128x5258	105x50	87	17
Ricc 3827	7942x4533	98x51	81	16
RS-3	5486x4009	57x48	84	17
Dulcert 1339	5886x4096	102x75	55	11
Roselli 1466	3674x2168	94x54	39	8

Table IV.1 *- Resolutions of chart scans used.*

scan. An identical point is created by hovering the cursor over the respective feature and creating a new point feature in the GIS software. The set of thus created points can be exported as a separate dataset, along with their (X,Y) coordinates in the internal GIS coordinate system. The resolution of the (X,Y) coordinates of the identical points is much higher than the pixel resolution. The reader is cautioned not to translate the pixel resolution into accuracy in a mechanical way, as the human brain allows greater resolution to be achieved when the selected point is part of e.g. a continuous line feature, such as in this case the coastline on the charts. Although the (X,Y) coordinates of point features on the digital scan of the charts are stochastic variables (the measurement, when repeated, will yield slightly different results), I have considered the impact of the finite accuracy of the coordinates on the cartometric analysis negligible.

Figure IV.1 *- Example of point feature selection versus scan resolution.*

B. Selection of identical points on the reference chart

Selecting the corresponding points on the reference map is slightly different because the reference map, or rather reference dataset, is a vector dataset, consisting of points, lines and areas, which allows the 'snapping' function of the software to be used.

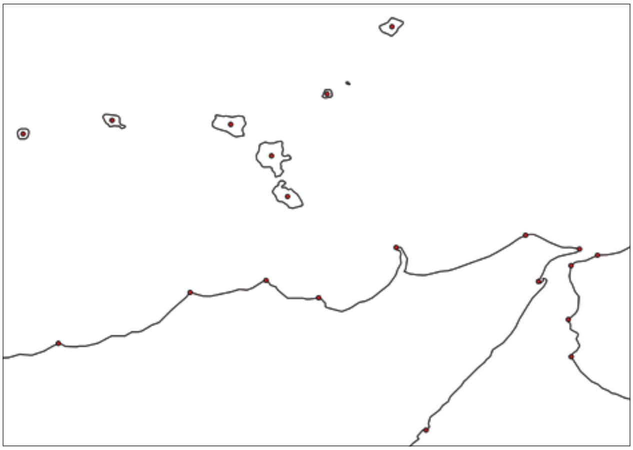

Figure IV.2 *- Identical points on the reference map in approximately the same area as Figure IV.1 (plane projection).*

Rather than creating the new identical point visually by manipulating the cursor to the optimum location, the GIS software is able to automatically create the point by coinciding it to the nearest point or line of the reference dataset. This process is therefore to a large extent repeatable. A small random 'personal error' will exist for e.g. points that are defined as the centre points of small islands, as demonstrated in Figure IV.1.

In Section 6.5.1. I estimated the accuracy of the reference dataset to be few hundred metres in the Mediterranean; assume a tentative figure of RMSE=0.2 km (MSE = 0.04 km^2). The Mean Squared Error of each sub-chart of a portolan chart, as reported in Chapter 7: *Cartometric analysis of five charts*, will thus contain a small contribution of the accuracy of the reference dataset. A nominal RMSE of 11 km (MSE = 121 km^2) for an arbitrary sub-chart might thus be corrected by subtracting the accuracy contribution of the reference dataset, yielding an MSE of 210.96 km^2. The corresponding square root yields a corrected accuracy for the sub-chart of RMSE = 10.998 km. This is well below the significance level of the 'raw' estimate of the cartometric analysis, which is why this effect can safely be ignored.

IV.3 PREPROCESSING – WIND ROSE ANALYSIS

It is assumed that the cartographer intended the wind roses on the charts to be perfect circles, divided into sixteen equal sectors of 22.5°. It is further assumed that the cartographer intended the vertical axis of the wind rose, connecting the winds *Tramontana* and *Mezzodi* to run exactly north-south.

The description below provides some more detail than the description in the main text, in Section 6.5.5.

I have used these features to analyse three characteristics of each physical portolan chart:

1. the deformation of the carrier material, notably shear and scale differences in the two main directions of the chart (length and width);
2. the misalignment of the portolan chart on the scanner.

The idea is that any deformation found in the wind rose(s) of each chart have occurred *after* the chart was drawn. Of course shear and differential scale between the two main chart directions are also determined in the main cartographic analysis of each chart, but by eliminating the shear and scale distortion found in the wind rose analysis and by eliminating chart/ scanner misalignment, the remaining rotation and shear angles, as well as scale differences will be compatible for the five charts analysed.

I have computed the deformation parameters by describing the effects of the assumed deformations in terms of the effects on the (X,Y) coordinates of the sixteen points on the circle perimeter of the wind rose. The deformation parameters have been computed by Least Squares Estimation. In order to do this in a way that yielded numerically stable results, a two- step process was required:

1. The (X,Y) coordinates of each point are transformed to a polar coordinate system, which yields polar coordinates (R,β) for each of the 16 points.

$$\begin{pmatrix} X_i - X_c \\ Y_i - Y_c \end{pmatrix} = \begin{pmatrix} R \cdot \sin\beta_i \\ R \cdot \cos\beta_i \end{pmatrix}$$

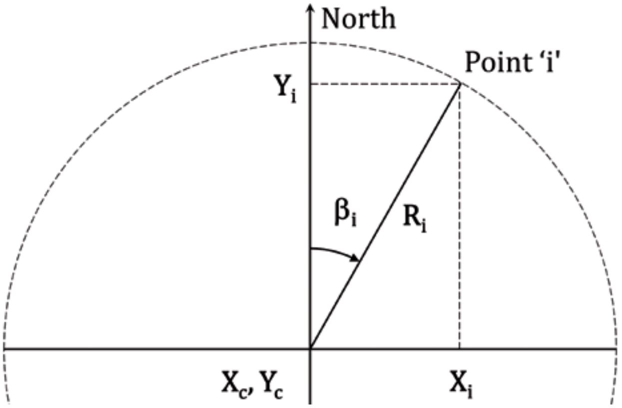

Figure IV.3 *- Polar and rectilinear coordinates of wind rose point 'i'.*

2. An affine transformation is applied with separate rotation angles for the X and Y axes and a single scale factor k, which operates on the X coordinates only. Affine transformation and polar transformation combined constitute the functional model

for the LSE process. This expresses the effects of the (affine) deformation on the (X,Y) coordinates.

$$\begin{pmatrix} X_i \\ Y_i \end{pmatrix} = \begin{pmatrix} X_c \\ Y_c \end{pmatrix} + \begin{pmatrix} \cos\gamma_X & \sin\gamma_Y \\ -\sin\gamma_X & \cos\gamma_Y \end{pmatrix} \cdot \begin{pmatrix} k \cdot R \cdot \sin\beta_i \\ R \cdot \cos\beta_i \end{pmatrix}$$

The measurements in the process are (X_i, Y_i) for i = 1 …16.
The parameters to be estimated are:

(X_i, Y_i) : the coordinates of the centre of the windrose. These are 'nuisance' parameters; they contain no useful information
R : The radius of the wind rose; nuisance parameter.
(γ_X, γ_Y) : The misalignments of the wind rose's X'-axis (east-west) and Y'-axis (north-south) respectively.
k : The ratio of X-axis scale over Y-axis scale.

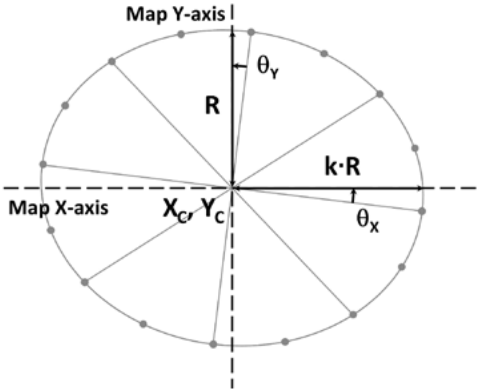

Figure IV.4 - *The estimated parameters from the wind rose adjustment.*

The results for the last three parameters are reported in Chapter 7: Cartometric analysis of five charts, in Table 7.1 to Table 7.5.

IV.4 MAIN CARTOMETRIC ANALYSIS

The main cartometric analysis performed on the five charts evaluates two map projections for all five charts, viz. the Mercator and Equidistant Cylindrical projections, and the Oblique Stereographic projection only for the Dulcert 1339 chart.

I have allowed for affine distortions in all cases, i.e. I have allowed the implicit parallels and meridians to intersect at an angle, different from 90°. Additionally I have allowed for an additional scale factor, which expresses stretch or shrink of one of the two main directions of the chart.

A. MERCATOR PROJECTION

The spherical projection formulas for the Mercator projection are as follows:

$$E = R \cdot \lambda$$
$$N = R \cdot \ln \tan \left(\frac{\varphi}{2} + \frac{\pi}{4}\right) = R \,.\, \overline{\varphi}$$

φ, λ :	latitude and longitude of the point (in radians);
$\overline{\varphi}$:	isometric latitude of the point
E, N :	Easting and Northing of the point;
R :	Radius of the earth

An affine transformation is imposed on Easting and Northing to yield the internal GIS coordinates that have been measured, as described in Section IV.1.

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix} + \begin{pmatrix} s_X & 0 \\ 0 & s_Y \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_X & \sin\theta_Y \\ -\sin\theta_X & \cos\theta_Y \end{pmatrix} \cdot \begin{pmatrix} E \\ N \end{pmatrix}$$

With $k_X = R \cdot s_X$ and $k_Y = R \cdot s_Y$ the combined equation yields the functional model for the LSE for the Mercator projection:

$$\boxed{\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix} + \begin{pmatrix} k_X & 0 \\ 0 & k_Y \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_X & \sin\theta_Y \\ -\sin\theta_X & \cos\theta_Y \end{pmatrix} \cdot \begin{pmatrix} \lambda \\ \overline{\varphi} \end{pmatrix}}$$

X and Y are measured for each identical point; the corresponding latitude and longitude from the reference map feature as constants for each point in the right-hand side of the equation.

The parameters, estimated by the Least Squares process are:

X_0, Y_0:	Origin shift of the internal GIS coordinate system. These parameters are nuisance parameters; they contain no useable information because the internal (X, Y) coordinate system of the GIS software is arbitrary.
θ_X, θ_Y :	Separate rotation angles, expressing the angle of the implicit parallels in the portolan chart and the X-axis of the internal (X, Y) coordinate system and the angle between the implicit meridians and the Y-axis. See also Figure 6.2.
k_x, k_y:	Separate scale factors for the X-axis and the Y-axis. Together these parameters determine the scale of the portolan chart relative to the internal (X, Y) coordinate system.

See also Section 6.5.6-A.

B. Equidistant Cylindrical projection

The Equidistant Cylindrical projection is simpler than the Mercator projection:

$$E = R \cdot \cos \varphi_0 \cdot \lambda$$
$$N = R \cdot \varphi$$

φ, λ : latitude and longitude of the point (in radians);
φ_0: latitude of true-to-scale parallel;
E, N: Easting and Northing of the point;
R : Radius of the earth

The same affine transformation is superimposed on this projection, yielding:

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix} + k \cdot \begin{pmatrix} \cos \theta_X & \sin \theta_Y \\ -\sin \theta_X & \cos \theta_Y \end{pmatrix} \cdot \begin{pmatrix} \lambda \cdot \cos \varphi_0 \\ \varphi \end{pmatrix}$$

The parameters to be resolved by Least Squares are the following:

X_0, Y_0: Origin shift of the internal GIS coordinate system. See previous section on the Mercator projection.
θ_X ,θ_Y : Rotation angles of implicit parallels and meridians in (X, Y) coordinate system. See previous section on the Mercator projection.
k: Scale of the portolan chart in the (X, Y) coordinate system. It is not possible to calculate separate scale factors for the Equidistant Cylindrical projection, as the scale factor along the Y-axis cannot be distinguished from the latitude of the true-to-scale parallel. See also Section 7.6.5-B. The radius of the earth cannot be separately determined, so a similar substitution as for the Mercator projection, $k = s \cdot R$, is here implied.
φ_0 : Latitude of the true-to-scale parallel.

C. Oblique Stereographic projection

This projection has been proposed as the underlying map projection of portolan charts by one author only, A.J. Duken. His analysis was discussed in Section 6.3.2.

The corresponding formulas are more involved than those of the Mercator and Equidistant Cylindrical projections. I only analysed the Dulcert 1339 chart for this projection, but used the same approach as I followed for the other two projections, superimposing an affine transformation on the (spherical) projection formulas.

The Oblique Stereographic projection formulas are the following:

$$E = R \cdot p \cdot \cos \varphi \cdot \sin(\lambda - \lambda_C)$$

$$N = R \cdot p \cdot \{\cos \varphi_C \cdot \sin \varphi - \sin \varphi_C \cdot \cos \varphi \cdot \cos(\lambda - \lambda_C)\}$$

$$p = 2\{1 + \sin \varphi_C \cdot \sin\varphi + \cos \varphi_C \cdot \cos \varphi \cdot \cos(\lambda - \lambda_C)\}^{-1}$$

The superimposed affine transformation is the same as for the Mercator projection, with two separate scale factors for X-axis and Y-axis:

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix} + \begin{pmatrix} s_X & 0 \\ 0 & s_Y \end{pmatrix} \cdot \begin{pmatrix} \cos \theta_X & \sin \theta_Y \\ -\sin \theta_X & \cos \theta_Y \end{pmatrix} \cdot \begin{pmatrix} E \\ N \end{pmatrix}$$

Substitution of the projection formulas, expressed in the first three equations in this section, into the affine transformation equation is required to obtain the complete functional model for the Least Squares calculation. Due to the complexity of the formula that has not been worked out here in this case. As with the other projections the scale of the chart and the radius of the earth cannot be separately resolved; hence an additional substitution of $k_X = R \cdot s_X$ and $k_Y = R \cdot s_Y$ is required.

The parameters, estimated in the LSE are in this case:

X_0, Y_0: Origin shift of the internal GIS coordinate system. See section on the Mercator projection.

θ_X ,θ_Y : Rotation angles of implicit parallels and meridians in (X, Y) coordinate system in the projection centre.

k_X , k_Y : Separate scale factors for the X-axis and the Y-axis. Together these parameters determine the scale of the portolan chart relative to the internal (X, Y) coordinate system.

φ_C , λ_C: Latitude and longitude of the projection centre of the projection, the point at which the map plane is tangent to the earth.

APPENDIX V
RELIABILITY OF THE CALS7K.2 ARCHAEOMAGNETIC MODEL

In order to quantify the accuracy of the CALS7k.2 global archaeomagnetic model, time series plots of magnetic declination have been made for a number of locations in the coverage area of portolan charts, shown in Figure V.1.

CALS7k.2 has been superseded by the global model CALS3k.4b. Both models provide smoothed calculations, using spherical harmonics, of the earth's magnetic field components. CALS3k.4b is based on much more data than CALS7k.2 and uses evaluations of spherical harmonics to a higher order and degree than CALS7k.2. As a result of that CALS3k.4b shows more detail in the behaviour of the magnetic field parameters, both spatially and temporally, than CALS7k.2.

Accuracy of both models depends greatly on the density of the data, which have been used as the input for the model's parameters, both in space and time. CALS3k.4b has the additional advantage that a confidence interval is calculated for the magnetic field parameters. For magnetic declination the 95% confidence level boundaries are provided, which equates to a band of twice the standard deviation about the calculated value. The graphs on the following pages have been generated using the online calculator provided with the GEOMAGIA database.[700]

Figure V.1 *- Locations of comparison calculation for magnetic declination.*

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[700] http://geomagia.ucsd.edu/geomagia/index.php
F. Donadini, K. Korhonen, P. Riisager, and L. Pesonen, "Database for Holocene geomagnetic intensity information", *EOS, Transactions, American Geophysical Union*, 87(14), 2006, 137.
K. Korhonen, F. Donadini, P. Riisager, and L. Pesonen, "GEOMAGIA50: an archeointensity database with PHP and MySQL", *Geochemistry, Geophysics, Geosystems*, 9, 2008. doi:10.1029/2007GC001,893.

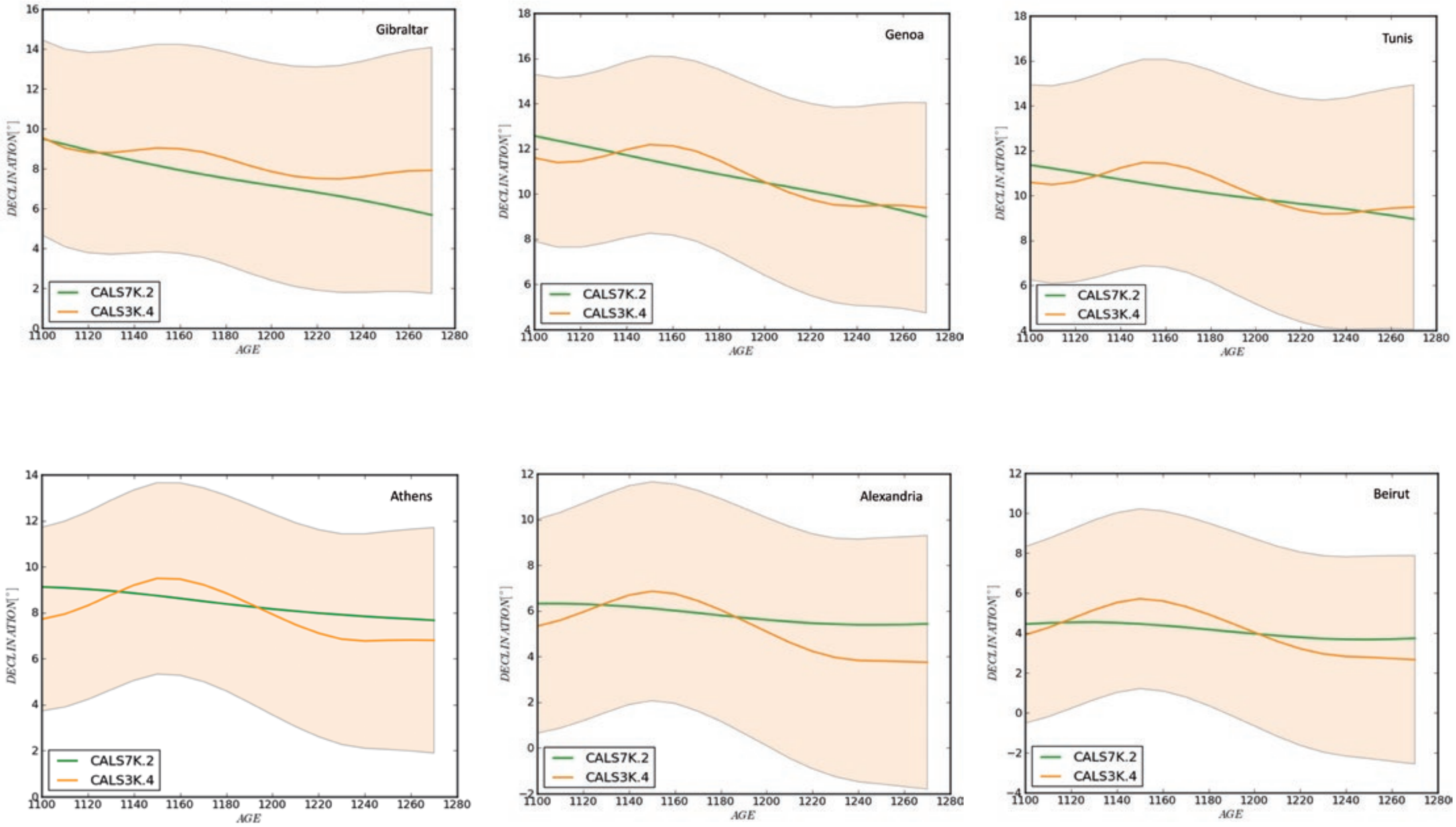

Figure V.2 - *Comparison calculations CALS7K.2 and CALS3K.4 for locations in the Mediterranean Sea.*

BLACK SEA

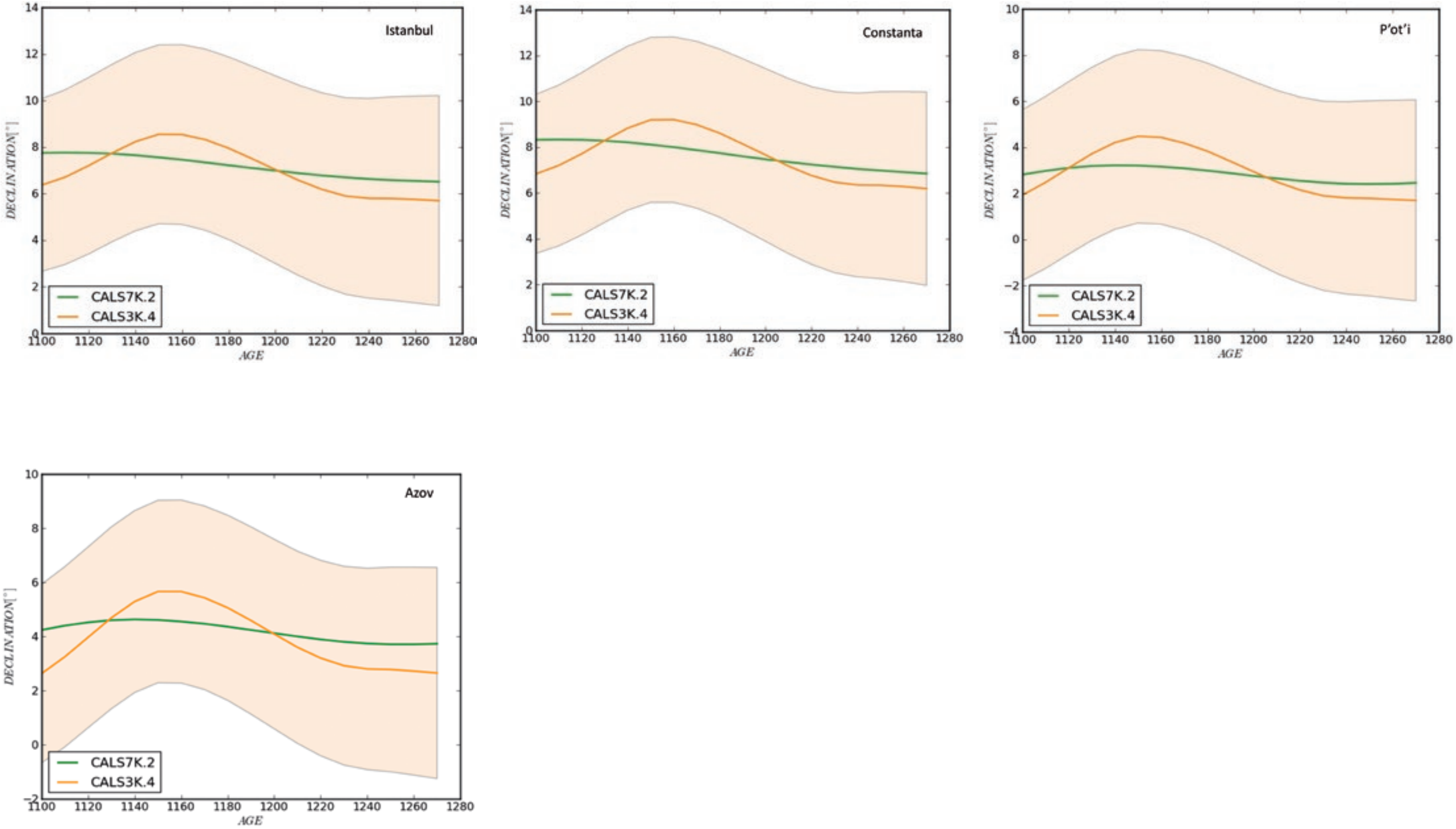

Figure V.3 *- Comparison calculations CALS7K.2 and CALS3K.4 for locations in the Black Sea .*

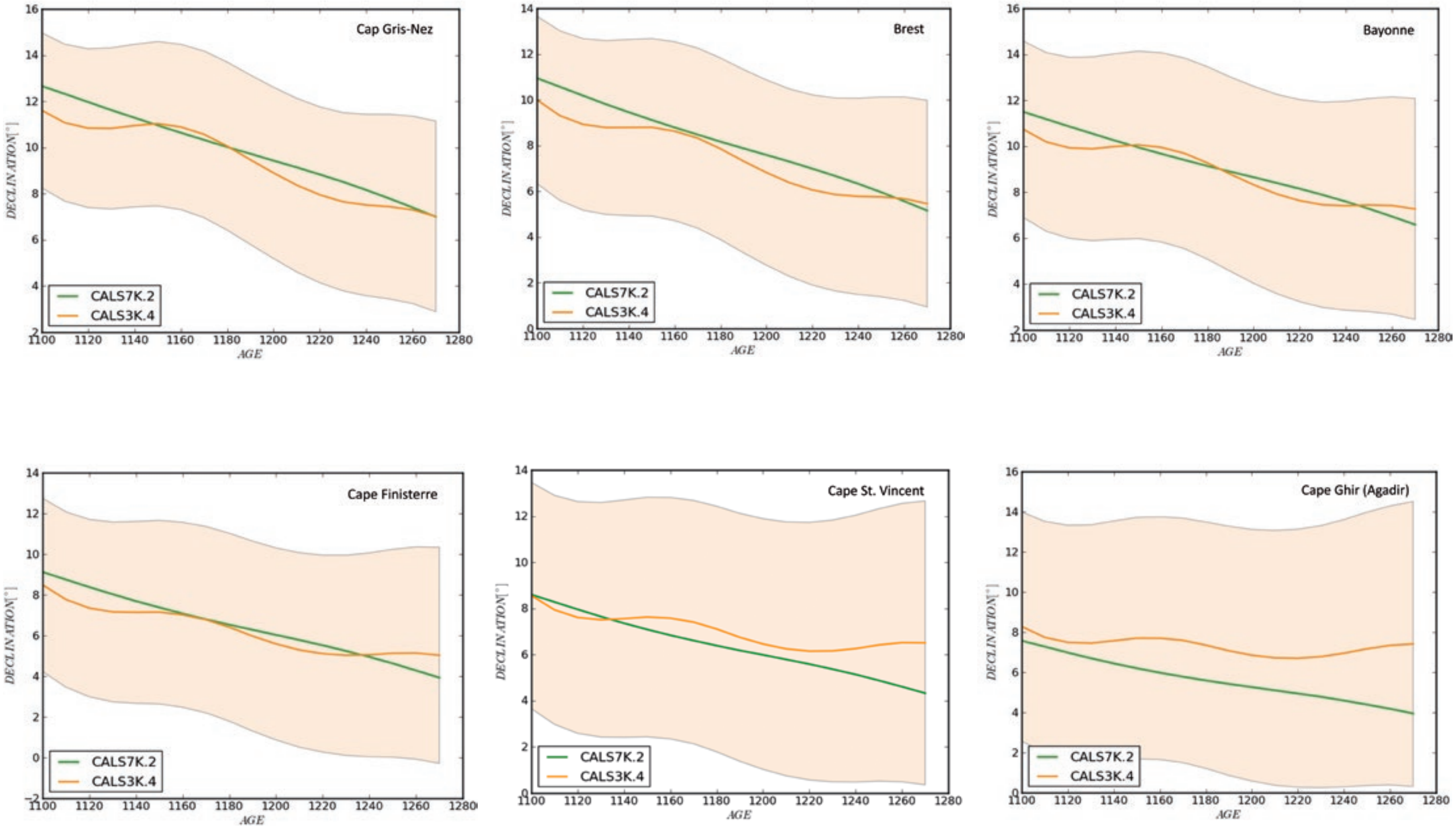

Figure V.4 - *Comparison calculations CALS7K.2 and CALS3K.4 for locations along the Atlantic Ocean coast.*

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CURRICULUM VITAE

Roelof (Roel) Nicolai was born in Achtkarspelen, The Netherlands on November 20th, 1953. After his secondary school education in Rotterdam and Assen, he studied Geodesy at Delft Technical University from 1971, graduating in May 1978 on the subject of Doppler satellite single point positioning. Until the end of 1979 he worked as a conscript junior officer at the Hydrographic Service of the Royal Netherlands Navy, establishing a unified coordinate system in the Dutch economic sector of the North Sea for use in oil and gas industry activities. He then joined the Survey Department of Rijkswaterstaat (Ministry of Public Works) as a project surveyor, providing consultancy and advice on marine survey equipment and developing geodetic software. In June 1984 he joined Shell, where he has worked since in a variety of roles and locations, beginning in the Sultanate of Oman, where he introduced the application of new hi-tech geodetic techniques (GPS and inertial surveying) and initiated and supervised the reprocessing of the geodetic control network of Oman. After three years he moved to Shell's offices in London, United Kingdom as team leader for offshore survey support. In 1992 he returned to Shell's head office in The Netherlands as geodetic advisor. He co-designed geodetic software for processing and quality control of 3D seismic surveys, using Kalman filtering techniques and, in a temporary assignment in Information technology, initiated and led the revision of the geodetic data model in the Open Geospatial Consortium, ratified later by ISO. Since 2006 he is Shell's Principal Technical Expert in geodesy, a global role, setting and maintaining geodetic standards and work practices in Shell's upstream business. In 2007 he was awarded honorary membership of the European Association of Geoscience Engineers for his contributions to the oil and gas industry in the field of geodesy. In 2003 he began to study portolan charts in his spare time, which culminated in the current thesis. His hobbies, apart from historic maps and charts, are sailing and listening to early Baroque music. Roel Nicolai is married and has three children.

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