Tsch.Gesch.Gnk.Natuurw.Wisk.Techn.10(1987)4

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INSTRUMENTS AND EXPERIMENTS. THE CASE OF ATMOSPHERIC ELECTRICITY IN EIGHTEENTH-CENTURY HOLLAND

Introduction

Eighteenth-century atmospheric electricity is a good example of the intricate relationship that had by then evolved between electrical theory, scientific observations, and laboratory experiments, in which instruments played an essential part. This subject exhibits all the strengths and weaknesses of contemporary experimental science.[1] It was generally assumed in the eighteenth century that the earth was surrounded by an all-pervading electric fluid extending into the upper reaches of the atmosphere.[2] Natural phenomena such as lightning, Northern lights (the aurora borealis), whirlwinds, earthquakes, hail and rain storms were caused by local disturbances in atmospheric electricity. Since during this period only electrostatic phenomena were known in the laboratory, these natural 'electrical' phenomena were also seen in terms of the behaviour of static charges in the laboratory.

Most natural philosophers agreed so far — it was only in the explanatory details that disagreements occured. The cause was threefold: (1) conflicting observations, (2) conflicting experimental results, and (3) the use of model experiments when *natural* phenomena were recreated *artificially* in the laboratory. Observing and measuring the phenomena in nature, recreating and analysing the same phenomena in the laboratory, and making scale-model experiments were the three techniques applied to the study of atmospheric electricity. It is indisputable, that all three aspects contributed to the development of scientific instruments.

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1. This paper deals specifically with the interaction between experiments and the drive for new devices, and not with the philosophical implications. See note 32.

2. M. van Marum, "Antwoord op de vraag: Door proeven te toonen, welke luchtverhevelingen van de werking der natuurlijke electriciteit afhangen; hoe dezelven 'er door worden voortgebragt; en welke de bekwaamste middelen zijn om onze huizen, schepen en personen tegen de schadelijken invloed derzelven te beveiligen?", *Verhandelingen van het Bataafsch Genootschap der Proefondervindelyke Wysbegeerte* 6, pt.2 (1781) 18-23, and "Eerste vervolg der proefneemingen, gedaan met Teyler's electrizeer-machine", *Verhandelingen uitgegeeven door Teylers Tweede Genootschap* (*Verh. TTG*) 4 (1787) 219-225.

Instrumentation and the scientific method

In the 1620s Francis Bacon formalized the practices and attitudes of the early experimentalists into a coherent (if somewhat unrealistic) scientific method. His central theme was that nature should be interpreted through the senses, aided by experiments "fit and apposite."[3] His inductive method was translated into more realistic laboratory strategies by Robert Boyle, Robert Hooke, and ultimately by Isaac Newton in the second half of the seventeenth century. Indeed in Newton's *Principia* (1687) and *Opticks* (1704) were united the techniques of mathematical analysis (the scholarly tradition) and of experimentation (the craft tradition). The *Opticks* was cast in the rational mathematical mould of the *Principia*, but configurations of apparatus replaced the synthesis, and the 'proof' was the *experimentum crucis*.[4] To return to Robert Boyle, he continually stressed his indebtedness to the experience and practices of tradesmen, including the apothecaries, in their reliance upon observation and trial.[5]

These early instrumental techniques focused on the importance of the senses in observations — both in terms of philosophical debates about the nature of perception and the examination of the practical limitations of the senses. It led Hooke, for instance, to study the physiological mechanism of vision.[6]

Classical scientific instruments, those purely observational angle-measuring instruments used in astronomy, navigation, and surveying, had not extended the senses as the telescope and the microscope were to do in the early seventeenth century. These two devices had a remarkable impact on natural philosophy, for they revealed hitherto totally unsuspected phenomena. It took until the middle of the seventeenth century before they began to be used routinely, and before observations with them were generally accepted. They also had a great impact on the development of scientific instruments generally.

Hooke was a strong advocate for devising instruments for aiding the imperfect senses. As he enthused in his *Micrographia* (1667):

> "The next care to be taken, in respect to the Senses, is a supplying of their infirmities with Instruments, as it were, the adding of artificial Organs to the natural; this in one

3. F. Bacon, *Novum organum* (London 1620); see also J. Spedding et al. eds., *The works of Francis Bacon*, vol. VIII (Boston, 1861-1684) 61, 83.

4. For a brief discussion of Newton's problems with the *experimentum crucis*, see J.A. Lohne, "Experimentum Crucis", *Notes and records of the Royal Society* 23 (1968) 169-199. This topic has recently been drawing a great deal of renewed attention. My interest is in the relationship between the *experimentum crucis*, the scientific method as it evolved in the eighteenth century, and the development of experimental apparatus.

5. T. Birch ed., *The work of the honourable Robert Boyle* vol. III (new edn.; London, 1772) 396-399, 415, 442.

6. R. Waller, *The posthumous works of Robert Hooke* (London 1705) 98.

of them has been of late accomplished with prodigious benefit to all sorts of useful knowledge, by the invention of Optical glasses. By the means of the Telescope, there is nothing so far distant but may be represented to our view; and by the help of Microscopes, there is nothing so small, as to escape our inquiry; hence there is a new visible World discovered to the understanding. By this means the Heavens are open'd, and a vast number of new Stars, and new Motions, and new Productions appear in them, to which all the ancient Astronomers were utterly Strangers. By this the Earth it self, which lyes so near us, under our feet, shews quite a new thing to us, and in every little particle of matter we now behold almost as great a variety of Creatures as we were able to reckon up in the whole Universe it self."[7]

This argument was the impetus behind the development of ever more powerful (and complex) experimental apparatus with the expectation that these would make further discoveries possible. As Joseph Priestley expressed it in his *The history and present state of electricity* (1767), ever more powerful laboratory devices were capable, like larger microscopes and telescopes, of 'magnifying' natural phenomena.[8] The eighteenth-century air pump and electrostatic generator (electrical machine) were ideally suited for this kind of development; a trend of which the Haarlem natural philosopher Martinus van Marum, was a vociferous proponent. In March 1783 he charged the English instrument maker John Cuthbertson who had settled in Amsterdam, to construct the largest electrical machine then technically feasible. This monster — the eighteenth-century equivalent of our modern 'atom smashers' — can still be seen at the Teyler's Museum in Haarlem. Van Marum's aspirations were fully realized, for it produced 24 inch (70 cm) discharges, equivalent to about 300,000 volts, and with its large Leyden battery, had an energy output of about 600 joules, which made it the most powerful electrostatic generator constructed at that time, not to be surpassed for a century. Van Marum had truly brought lightning down from the heavens into his laboratory. His generator not only 'magnified' known electrical phenomena, but it also helped to place Holland on the scientific map as Van Marum was often asked to use his machine as a kind of instrumental Newtonian *experimentum crucis* to arbitrate between contending theories.[9]

7. R. Hooke, *Micrographia; or some physiological descriptions of minute bodies made by magnifying glasses* (London, 1667) "Preface".
8. J. Priestley, *The history and present state of electricity* (London, 1767) x, has his clearest statement about the importance of experimental apparatus. See also W.D. Hackmann, "The relationship between concept and instrument design in eighteenth-century experimental science", *Annals of science* 36 (1979) 205-224, esp. 218-219.
9. W.D. Hackmann, "Electrical researches" in: R.J. Forbes ed., *Martinus van Marum. Life and work*, vol. III (Haarlem, 1971) 329-378, and for a short account of the Dutch scientific method "Electricity in eighteenth-century Holland. A Newtonian legacy", paper delivered at the Nijmegen colloquium "Newton's philosophical and scientific legacy", 9-12 June 1987, in press.

'Passive' and 'active' instruments

The earliest scientific instruments were passive in their exploration of nature, but by the eighteenth century they had also become active — a distinction appreciated by Priestley.[10] Among the former are tools of measurement such as clocks, chemical balances, electrometers, galvanometers, and graduated astronomical angle-measuring instruments. Increasing their precision made scientific breakthroughs possible, but of course not inevitable. Tycho Brahe's new angular measurements were necessary for Kepler's work, and Flamsteed's for Newton.[11] The telescopes and microscopes were also passive in that they did not 'rearrange' nature in the laboratory. They revealed hitherto unsuspected phenomena and structures not observable with the naked eye. Discoveries, such as those made by Galileo, were usually not expected because they could not be related to past experience. There is, however, a key difference, between all these devices and the next generation of 'philosophical' instruments such as the air pump and the electrical machine. These not only 'aided' the senses as described by Hooke, but also made it possible to make experiments in a controlled laboratory environment (such as inside the bell jar of an air pump), that is, they actively interacted with nature. This distinction between passive (observational) and active (phenomena-interactive) instruments may help us to understand the basic features of experimental philosophy as reflected, for example, in the study of atmospheric electricity. It is also broadly in accord with the distinction made by the instrumentmaker's trade as it flourished in the eighteenth century, that is, between mathematical, philosophical, and optical instruments.

It was generally accepted that these devices reproduced 'real' natural processes. At the pragmatic level the debates were about the validity of the actual observations, and at the philosophical about the underlying theoretical framework to which the experimental results gave credence, such as the electrical nature of atmospheric phenomena, or at an even deeper level, the *microscopic* nature of the electric fluid. These considerations influenced both the design of the apparatus and the experiments. Furthermore, natural philosophers from Hooke to 's Gravesande and Van Musschenbroek stressed the importance of controlling the factors that might affect the experiments, including the design of the apparatus, in order to

10. See note 13.
11. A. Chapman, "The accuracy of angular measuring instruments used in astronomy between 1500 and 1850", *Journal for the history of astronomy* 14 (1983) 133-137. For details of other studies, see W.D. Hackmann, "Instrumentation in the theory and practice of science: scientific instruments as evidence and as an aid to discovery", *Annali dell'Istituto e Museo di Storia della Scienza di Firenze* (*Annali*) 10 (1985) 87-115.

ensure replicability — the standard by which new knowledge had to be judged. Yet complete replication was rarely achieved, not least because of the complexities of the phenomena under investigation. The striving for replicability was another important factor in the drive for standardizing apparatus and experiments.[12]

From prototypes to laboratory apparatus

Experimental apparatus, such as Otto von Guericke's air pump or Francis Hauksbee's 'chafing machine' (electrostatic generator), started their evolution towards standard laboratory devices as experimental prototypes. They only turned into non-controversial laboratory instruments after the debate about what was observed with them had been resolved, and the replications of these observations with similar instruments had been accepted by the scientific community. Experimental apparatus could next be adapted (or be devised specifically) for lecture-demonstrations. Early pioneers of didactic apparatus and the illustrative experiment for teaching purposes were Hauksbee and William Whiston. 's Gravesande was the first to write a comprehensive physics textbook based on this technique, his *Mathematical elements of natural philosophy, confirmed by experiments; or an introduction to Sir Isaac Newton's philosophy* (1720-1721). In the preface he makes unambiguously clear the Newtonian foundation of his intentions:

> "For Mathematicians think Experiment superfluous, where Mathematical Demonstrations will take Place: But as all Mathematical Demonstrations are abstracted, I do not question their becoming easier, when Experiments set forth the Conclusions before our Eyes; following therein the Example of the English, whose Way of teaching Natural Philosophy gave me Occasion to think of the Method I have followed in this Work. I shall always glory in treading in their Footsteps, who, with the Prince of Philosophers for their Guide, have first opened the Ways to the Discovery of Truth in Philosophical Matters."[13]

The first major experimental work modelled on the *Opticks* was Hauksbee's *Physico-mechanical experiments* (1709), on the nature of the luminescense produced by the mercurial barometer. This became the standard eighteenth-century pattern for laboratory (experimental) reports and pedagogic textbooks alike, in the manner in which experiments were used to ellucidate the properties of the natural phenomena under investigation. The same pattern was followed in the study of atmospheric electricity in the eigtheenth

12. H. Collins, "The seven sexes. A study in the sociology of a phenomenon, or the replication of experiments in physics", *Sociology* 9 (1975) 205-224, and S. Shapin and Simon Schaffer, *Leviathan and the air-pump* (Princeton, 1985) 225-282.

13. W.J. 's Gravesande, *Mathematical elements of natural philosophy, confirmed by experiments; or an introduction to Sir Isaac Newton's philosophy*, trans. from the latin by J.T. Desaguliers (London, 1731^4) "Preface", xviii.

century. This subject exhibited all the hallmarks of contemporary experimental science — the Newtonian system as interpreted by serious natural philosophers and popularizers of science alike. The impact of the latter on the development of experimental apparatus in the eighteenth century should not be underestimated.[14]

Atmospheric electricity and model experiments

Atmospheric electricity was an immensely popular subject in the eighteenth century, and was also one of the main preoccupations of the natural philosophers in Holland. The underlying theoretical framework was the behaviour of Franklin's single electric fluid. One of the most assiduous of mid-eighteenth-century Franklinian atmospheric electricians was the Italian Giovanni Battista Beccaria, who was very influential in Holland. Most atmospheric phenomena were thought to be caused by the restoration of imbalances in the amount of electric fluid in different regions of the atmosphere. It is instructive to examine how the various theories that were developed relate to experiments and the concomitant instruments. This also highlights a key aspect of eighteenth-century experimental science — the importance placed on model experiments in cases where the natural phenomena were too large or too complex to be studied in the laboratory directly.

Direct observations with instruments, and the analogous argument illustrated by conceptual models, yielded two basically different types of experiments. The first consisted of laboratory procedures isolating certain phenomena (say the electric spark) and determining their properties (the spark is hot); the second of laboratory models with which to imitate the natural phenomena as perceived — what Van Marum called 'imitative experiments' (*naabootsing*). Each led to the development of specific experimental apparatus. The technique of experimenting with scaled down laboratory models has been extremely fruitful in the history of science in general, and of electricity in particular, although it could also result in much triviality.[15] Model experiments were particularly popular in a subject like atmospheric electricity in which little direct experimental intervention could be made. It was not possible to experiment with real clouds (electrified or

14. Much has been written in recent years about the popularization of science and the importance of lecture-demonstrations in diffusing scientific knowledge, but in the eighteenth century there was also created a ready market for teaching science to juveniles, see J.A. Secord, "Newton in the nursery. Tom Telescope and the philosophy of tops and balls, 1761-1838", *History of science* 23 (1985) 127-151.

15. Van Marum, "Antwoord op de vraag". See also Hackmann, "The relationship between concept and instrument design", 220-223.

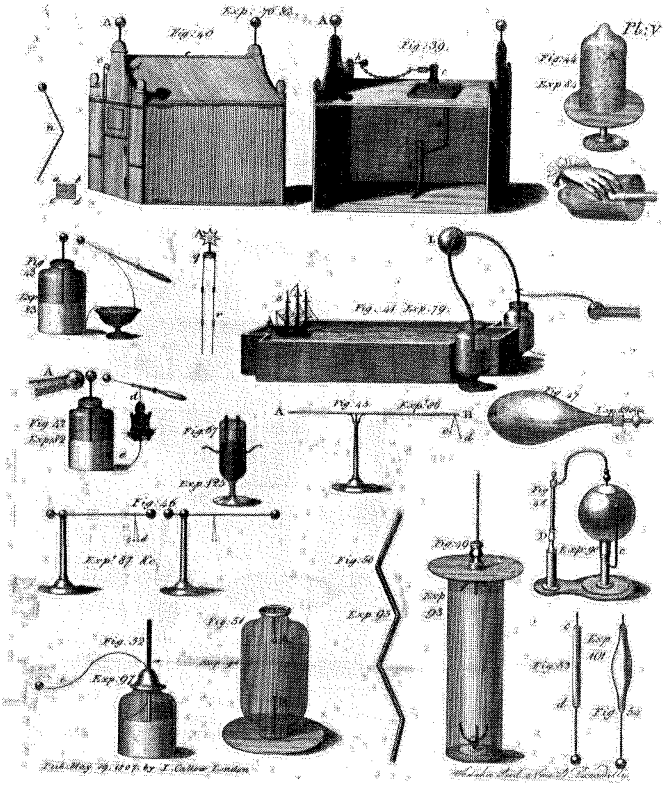

Plate 1.
Cuthbertson's model demonstrating the effects of lightning: figs. 39 and 40 are the thunderhouse of which the hinged walls will be blown outwards when the gunpowder in L is exploded by an electric spark; fig. 41 demonstrates the importance of the masts of ships being protected by lightning conductors. From his *Practical electricity* (London, 1807). The same models are depicted in his earlier Dutch books. (Copyright Bodleian Library, Oxford. Rigaud e. 108, pl. V.)

not), and George Wilhelm Richmann's attempt to draw lightning into his laboratory led to his death in St Petersburg in 1753. These large-scale phenomena had to be scaled down so that they could be coped with in the laboratory. A typical example is Franklin's suggestion (1750) by means of the analogous argument that artificially-produced electricity and lightning were essentially similar. He next recreated lightning in his laboratory with small scale models, and then 'proved' his analogous argument by means of the electric kite experiment. He found that the electricity obtained in this

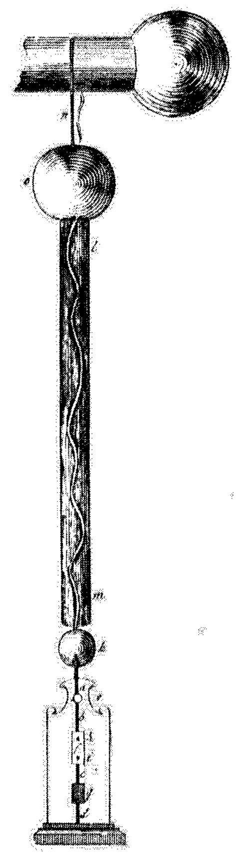

Plate 2.
Van Marum's scale model demonstrating the usefulness of a lightning conductor in conducting away the charge. The lightning flash is simulated by conducting the discharge by means of a glass tube (1 m) covered with a coating of bronze powder. He used a similar technique later on with his artificial clouds described in the text.

way had the same properties as the species of electricity generated by the electrical machine. Both, for instance, could charge a Leyden jar, produce sparks, and give shocks.

Kite experiments became all the rage. A French lawyer of Bordeaux, Jacques de Romas, flew a very large kite at a height of 1000 ft in a thunder storm and obtained discharges 10 feet long and 1 inch thick. It is surprising that more were not killed, especially since the significance of earthing this device was not fully realized. Electric kites became a standard item sold by

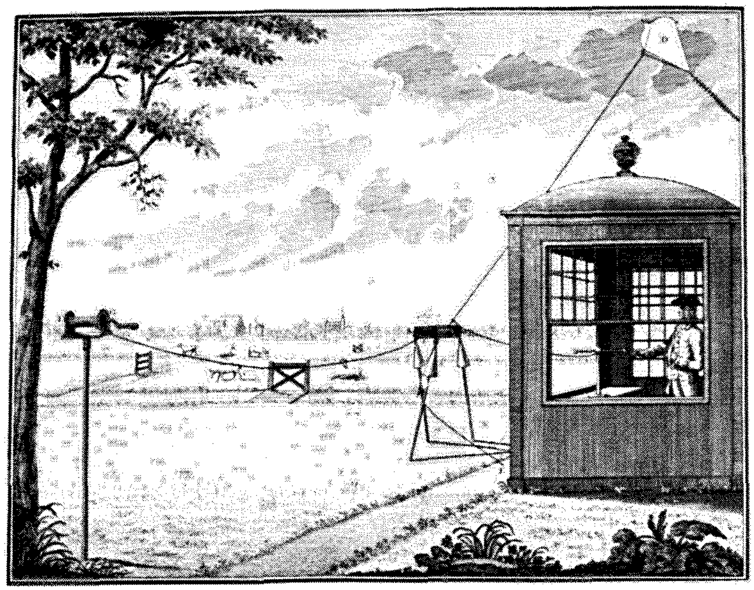

Plate 3.
Cuthbertson's electric kite and apparatus to test the electricity in a portable laboratory. From his *Algemeene eigenschappen van de electriciteit* (Amsterdam [1769]), plate VIII.

instrument makers as George Adams in London and John Cuthbertson in Amsterdam, as did the small scale models illustrating the properties of lightning, such as thunder houses and pyramids, and model ships with masts with miniature lightning conductors (plates 1 and 2). Also popular became the laboratory specially arranged for the observation of atmospheric electricity (plates 3 and 4).

The formation of clouds: electrical theories and models

One of the most important atmospheric phenomena which was thought to have a bearing on natural electrical phenomena was the formation of clouds. Laboratory experiments on the evaporation of water in 1742 led Desaguliers to conclude that the air was electrified positively, and that evaporation and the continuing vapour state of water in the atmosphere was due to water particles receiving 'electric virtue' from the air, causing these particles to repel each other. Any subsequent condensation was caused by the loss of electricity, allowing the fine water particles to conglomerate. This view was also held by Franklin, and in modified form by most natural philosophers,

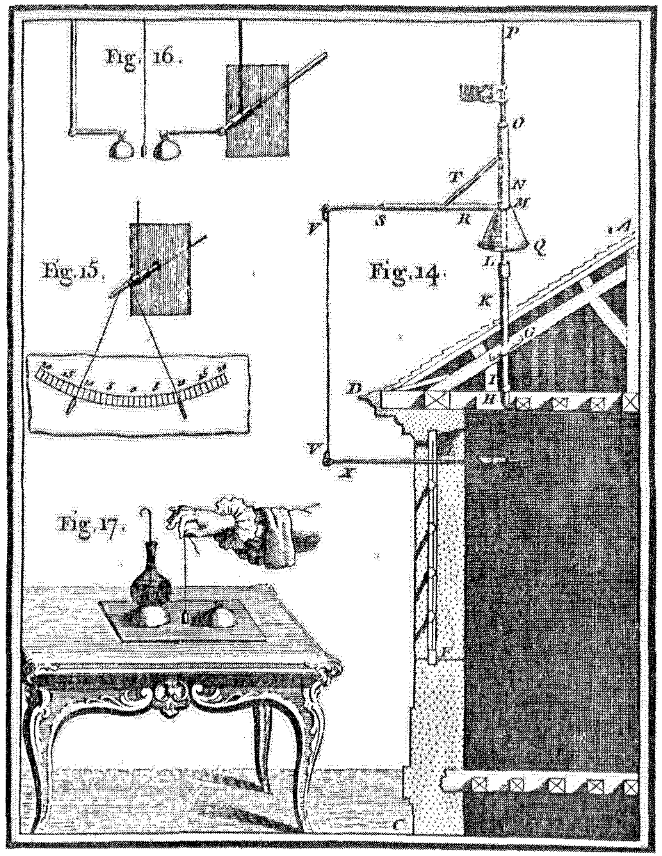

Plate 4.
Nollet's atmospheric electricity laboratory with apparatus, including his 'electrometer'. From his *Lettres sur électricité* (Paris, 1753), plate 4.

including Volta and Horace Bénédict de Saussure.[16] In 1753 Franklin determined that clouds were generally charged negatively, but sometimes also positively.[17] Thirty years later de Saussure discovered with his specially

16. J.T. Desaguliers, "Some conjectures concerning electricity, and the rise of vapour", *Philosophical transactions of the Royal Society* 42 (1742) 140-143; H.B. de Saussure, *Observations sur la physique* 25 (1784) 290-291 (a letter). Gilbert in *De magnete* (Dover publication, 1958) 91, had observed the attraction of water to rubbed amber.

17. Franklin's letter to Collinson in September, 1753; see his *Experiments and observations on electricity*, edited, with a critical and historical introduction by I.B. Cohen (Cambridge, 1941) 225-252; see also Cohen's *Franklin and Newton* (Philadelphia, 1956) 494-501.

designed atmospheric electrometers diurnal variations in the amount of electrcity in the atmosphere, even during fine weather. These where greater in winter than in summer. His instrumental observations agreed with Volta. In calm weather the atmosphere was positive, although during stormy weather it was negative. They concluded (in accordance with the hydrostatic model of electrical action) that clouds were normally electrified positively, and when highly charged gave up some of their excess electricity to the surrounding atmosphere. Both argued that a certain amount of electric fluid (positive charge) in addition to heat was necessary to change water into its vapour state. Thus, when clouds were formed by the heat of the sun, they obtained a certain quantity of electric fluid from the earth which was left negatively charged.[18]

During a period of fifteen years, Beccaria had never observed a serene atmosphere to be electrified negatively, except on four occasions, when his readings could have been affected by distant clouds.[19] This ran counter to the conclusion reached by Cornelis Rudolphus Theodorus (later Baron) van Krayenhoff in 1783, that clouds were usually charged negatively. His explanation was based on Franklin's 'insulated cup and chain experiment', a device which demonstrated the relationship between surface area (capacitance) and charge. According to this analogy he argued that when the globules of water broke down into smaller particles of vapour, the surface area of the cloud became larger thereby increasing its capacity to take up electricity. Conversely, the positive charge on a cloud was the result of a sudden decrease in its area caused by the condensation of the vapour back into water globules. Van Krayenhoff demonstrated this with the sponge analogy: when its area was decreased by squeezing it the superfluous water would run out. Thus rain, too, was an electrical phenomenon. Water vapour of clouds that lost charge would condense into rain.[20] The electric imbalances of clouds were caused by the heat of the sun which resulted in non-uniform rates of evaporation. This led to pockets of differing amounts of electricity in the atmosphere since air was a bad conductor, and the general circulation towards a state of electrical equilibrium in the atmosphere caused rain, hail, thunderstorms, and even (some thought) whirlwinds, waterspouts, and earthquakes.

These considerations prompted Volta to ask Van Marum to investigate

18. H. de Saussure, *Voyages dans les Alpes*, vol. II (Neuchâtel, 1786) 202-278.

19. A. Bennet, *New experiments on electricity (wherein the causes of thunder and lightning as well as the constant state positive or negative electricity in the air or clouds are explained...* (Derby, 1789) section VIII, 103.

20. C.R.T. van Krayenhoff, *Proef eener electrische natuurkunde in 't Fransch van den abt Jacquet* (Leiden, 1783) 155, 213.

atmospheric electricity with his huge electrical machine.[21] His experiments were on the whole negative. He could not increase the rate of evaporation of alcohol or water by electricity, did not find that electrified air held more water vapour, or that the atmosphere could be 'rarified' by electricity. His attempts to discover whether barometric pressure was affected by electricity were inconclusive. One of his most striking 'imitative' experiments was with 'artificial clouds' performed before the directors and members of the Teylers Society in 1787. It was typical of the mixture of theory and showmanship often found in this type of experiment. His two artificial clouds were made from large bladders filled with hydrogen gas. Both were charged by his electrical machine: one positively and the other negatively. This caused them to rise and also to approach each other slowly. When a short distance apart a spark jumped across the gap and both clouds immediately began their descent. Van Marum argued that this experiment demonstrated the observed behaviour of clouds before and during a thunderstorm. To make it more spectacular, he arranged for a third balloon filled with a mixture of hydrogen and air to be placed between the two clouds so that it exploded with a resounding bang when the spark occurred![22]

Another arrangement with which to demonstrate the same phenomenon was based on Aepinus' 'plate of air' condenser of 1759. He probably got the idea for this model experiment from Priestley.[23] Two large, smooth circular boards were suspended from the prime conductor of his generator. The top board had its lower face and side covered with tinfoil, while the bottom board had its upper face coated with varnish and bronze powder and its side with tinfoil. This board was connected to the earthed negative conductor of the electrical machine. At the centre of each board was a large copper sphere to act as a spark-gap between the condenser plates. When the electrical machine was set in motion, streams of sparks were observed to flow from the upper to the lower sphere, and from there along the bronzed surface "like numerous lightning bolts," to the earthed tinfoil side. Van Marum

21. J. Bosscha, *La correspondance de A. Volta et M. van Marum* (Leiden, 1905), especially Van Marum's letter of 31 August 1788 (letter IX) 36-42, and Volta's of 23 July 1789 and of 28 March 1792 (letters XI and XII) 46-63.

22. Van Marum, "Eerste vervolg der proefneemingen", 219-225. Similar artificial clouds were made by William Henley, see his report in *Philosophical transactions of the Royal Society* 64 (1774) 133-152. For a fuller discussion of Van Marum's experiments on atmospheric electricity and lightning conductors, see W.D. Hackmann, "The electrical researches of Martinus van Marum (1750-1837)" (Unpublished M.A. thesis, Queen's University, Belfast, 1970) 224-273.

23. J. Priestley, *The history and present state of electricity* (London, 1769^2) 232; Van Marum, "Eerste vervolg der proefneemingen", 229-231. A similar arrangement is described in T. Cavallo, *Volledige verhandeling over de electriciteit*, trans. by J.T. Rossijn (Utrecht, 1780) 223-224.

argued that there was much similarity between the bronzed surface of the board and a cloud, as either were only partial conductors of electricity. With this, and other model experiments, he also attempted to show that the lightning discharge was a more complex phenomenon than had been assumed by Franklin and Beccaria, and did not simply consist of a positively electrified cloud discharging its *excess* electricity onto a negative cloud or the earth. Electrical induction, the basis of Lord Mahon's 'return stroke' in lightning, was another important element in the mechanism of the lightning discharge. A similar explanation to Van Marum's was proposed by Van Krayenhoff in 1785.[24]

The lightning conductor and the 'rain pipe analogy'

The most dramatic aspect of atmospheric electricity was the thunderstorm. Its study led to the first practical benefit of electrostatics — the lightning conductor. In 1708 Dr Samuel Wall alluded to the similarity between lightning and the electric glow, and the, at that time, extremely small sparks that could be produced. The analogy between the two sets of phenomena became more and more obvious as the electrical laboratory apparatus increased in power. A dramatic breakthrough occurred with the invention of the Leyden jar in 1746. This device, connected to the new generation of electrical machines, produced sparks that had all the appearances of miniature lightning bolts, and on a small scale, even some of the destructive power. During the next twenty years the main development of the lightning conductor was based on model experiments in the laboratory.[25]
Dutch natural philosophers, too, were interested in this device. The best practical account was Van Marum's 1781 prize essay for the Bataafsch Genootschap. Lightning was described in the contemporary framework of the corpuscular, or fluid, theory, and the action of the lightning conductor in terms of what Sir Oliver Lodge called in 1892 the 'rain pipe analogy'. The conductor conveyed the electric fluid from the heavens to the earth, or *vice versa*. Thus, if the resistance could be kept at a minimum by using a highly conducting metal, and by efficient earthing, there would be little possibility for the 'side flashes' which caused most of the accidents and fires. As Lodge pointed out, this analogy would work perfectly well if lightning behaved as a

24. C.R.T. van Krayenhoff, "Onzijdige beproeving en verdedeging der metaalen blixem-afleideren", *Algemeen magazyn van wetenschap, konst en smaak* 1, pt. 2 (1785) 969-977, and *Voorschriften wegens het plaatsen van bliksemafleiders aan 's Ryks gebouwen* (Den Haag, 1819 and 1836).

25. Van Marum, too, demonstrated the effects of lightning conductors by means of his copy of James Ferguson's 'thunder façade' described in his "Antwoord op de vraag", pl. I, fig. 1, and with other models made by John Cuthbertson.

steady continuous current, but this is not the case. In reality, the lightning flash consisted of a series of surges, and these rapid oscillations caused conditions undreamt of until the late nineteenth century, and not shown up by the small laboratory scale models used by Van Marum and his contemporaries.[26]
Two questions dominated the development of the lightning conductor in the second half of the eighteenth century: (1) Does the conductor neutralize or attract and conduct away to earth the electric fluid of the thunder cloud? (2) Should the conductor terminate in a knob or in a sharp point? Franklin was unsure as to the answer of the first question. In his laboratory experiments he observed a glow discharge emanating from the tip of his minature conductor when the charge of the model cloud was neutralized (lost its charge). He observed that with an insulated conductor, this process stopped after a few minutes but, on the other hand, would last for as long as the cloud was charged if the conductor was earthed. He also noticed that the glow discharge was enhanced when the model conductor ended in a sharp point. Hence, he advocated that the real conductor should be terminated likewise. As he wrote in 1753:

> "A house thus furnished [with a lightning rod] will not be damaged by lightning, *it being attracted by the points and passing through the metal* without hurting anybody..."

By 1767 he regarded the mechanism as being somewhat more complicated, but he still persisted with the hydrostatic or fluid analogy:

> "Thus the pointed rod *either prevents a stroke from the cloud, or if a stroke is made, conducts it to the earth with safety* to the buiding..."[27]

The main fear was whether the conductor would actually *attract* the lightning stroke, a prospect that filled people with dismay. This led to the second question which was taken very seriously, on whether the conductor should terminate in a point or ball. The most impressive model experiment to try and settle this matter was performed by Benjamin Wilson at the

26. In other words before the work of Kelvin and others on 'electrodynamic capacity' or 'self-induction' and 'electrical inertia' or 'impedance'. The 'rain pipe' analogy is described by Sir Oliver Lodge in his *Lightning conductors and lightning guards* (London, 1892) chapter XXVIII. This analogy was aptly demonstrated by Cuthbertson's statement that the electric fluid passed through a pointed conductor like water through a pipe, in vol. 2 of his *Algemeene eigenschappen van de electriciteit, onderrichting van de werktuigen en het neemen van proeven in dezelve* (Amsterdam, 1782) "Experiment LXXX", 165. The oscillatory nature of the discharge was unwittingly hinted at by Priestley without realizing its significance, see F.W. Gibbs, *Joseph Priestley* (London, 1965) 47.

27. These quotes from *Poor Richard's almanac* (1753) and *Experiments and observations on electricity, made at Philadelphia in America. To which are added letters and papers on philosophical subjects* (London, 1769) are discussed by B. Schonland, *The flight of thunderbolts* (Oxford, 1964) 25-26.

Pantheon in London, in the presence of George III. His electrical machine was of conventional size, but its conductor was extremely large, made of pasteboard tubes coated with tinfoil, 155 feet long and about 16 inches in diameter, and suspended by silk cords from the theatre's ceiling. The discharge could be augmented by a second conductor consisting of 3,900 yards of copper wire. This arrangement, although less efficient than a good-sized Leyden battery, had more dramatic appeal. It represented an electrified cloud, under which he placed a model house, representing the Purfleet gunpowder magazin, complete with lightning conductor. Wilson's aim was to demonstrate that the lightning conductor terminating in a ball was less dangerous than Franklin's design ending in a sharp point, as his model ball-shaped conductor did not attract the lightning discharge as readily from the artificial cloud as the pointed version. In fact, the demonstration was inconclusive, and most natural philosophers continued to advocate the pointed conductor, as did Van Marum and Van Krayenhoff. It makes, of course, little difference whether the lightning conductor terminates in a small ball or point. George III's acceptance of Wilson's demonstration had more to do with political considerations because of the American War of Independence which made Franklin's opinions (even his scientific ones) unpopular, rather than with Wilson's performance.[28]

A characteristic example of Van Marum's scientific work is his series of experiments in which he tried to determine the best metal for the lightning conductor. He was primarily a chemist and this is reflected in his approach to the study of electricity. One of his main concerns was to discover the *nature* of electricity, treating electricity as if it were a chemical substance. Thus, he first identified electricity with phlogiston, the chemist's material fire, but later with Lavoisier's caloric (warmtestof). However, here he came up against an unresolvable inconsistency, for in experiments performed with Cuthbertson and Van Swinden, he found little correlation between length of wire fused by the electric discharge and melting point, which seemed to indicate that electricity and fire did not have identical natures. He also developed with Cuthbertson the fusion of wire technique for measuring electric charge.[29] These experiments also indicated that copper was the best conductor of electricity and produced the least 'lateral' discharges of all the

28. B. Wilson, *An account of experiments made at the Pantheon on the nature and use of conductors* (London, 1778).

29. Hackmann, "Electrical researches", 332-334; Van Marum, "Beschryving eener ongemeen groote electrizeer-machine, geplaatst in Teyler's Museum te Haarlem, en van proefneemingen met dezelve in 't werk gesteld", *Verh. TTG* 3 (1785) 183-191, 193-205; and "Tweede vervolg...", *Verh. TTG* 9 (1795) 89-91; and on the fusion of wire and melting point, "Eerste vervolg...", 17-31.

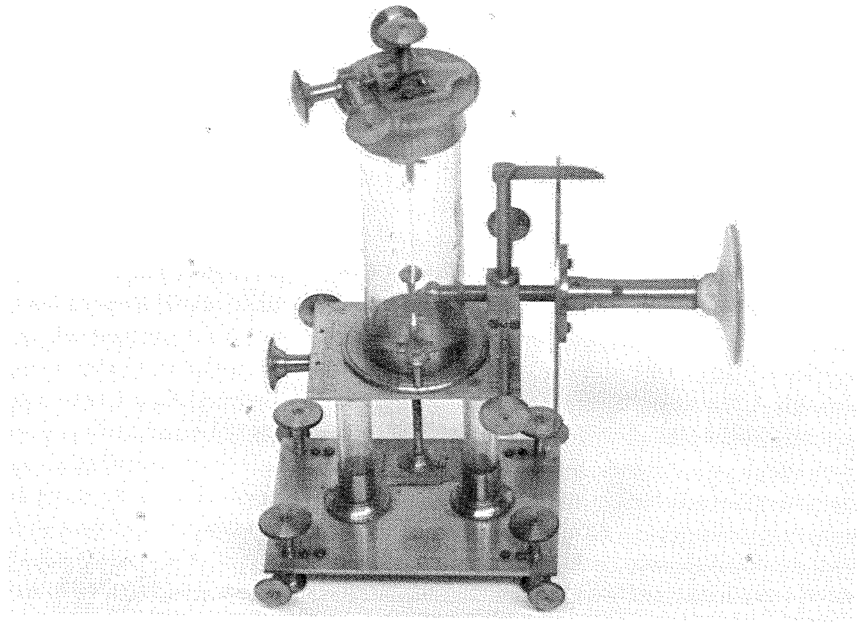

Plate 5.
Maréchaux's 'micro-electrometer' 1803-1805. Signed 'Maréchaux a Wesel N° 1'. Very sensitive single gold strip instrument with micrometer for the study of atmospheric electricity, contact potential of dissimilar metals and the intensity of the voltaic pile. This prototype was purchased by Van Marum from Maréchaux for 90 guilders in February 1805, and was one of a host of instruments developed for atmospheric electricity. In the collection of Teyler's Museum, inv.no.542. Overall height 24 cm.

metals tested. Thus, he concluded that copper offered the smallest resistance to electricity, and was, therefore, the most suitable for lightning conductors if costs were no object.[30]

By the 1780s the lightning conductor was well established, although it would take another hundred years before theory would make further advances. The study of lightning, the most extreme of the atmospheric electrical phenomena, resulted in several important eighteenth-century developments. On the theoretical side, it forced natural philosophers to investigate electrical induction (such as Mahon's concept of the 'return stroke'). On the instrumental side, it resulted in the development of new apparatus such as the air condenser which played an important part in the discovery of the

30. Van Marum, "Eerste vervolg...", 165-169.

voltaic pile. Another consequence was the improvement in electrometry. Sensitive instruments were devised specifically to measure the minute electric charges in the atmosphere, such as de Saussure's silver wire electrometer (1785), Bennett's goldleaf electroscope (1787), and the mechanical 'doublers' of William Nicholson (1790) and Tiberius Cavallo (1795), based on Volta's electrophorus and the forerunners of the nineteenth-century induction machines (plate 5).[31]

Conclusion

Dutch eighteenth-century atmospheric electricity, in common with contemporary experimental science, was made up of a mixture of observations based on instruments and conceptual models made of brass and wood. Logically, there was no reason why phenomena recreated in the laboratory should be the same as the ones in the real world — apart from the simple practical problem of difference in scale. Both for simple observations and for model experiments, the development of continually new and improved instruments were essential for progress. Sometimes new devices could lead to totally unexpected discoveries, as was the case with the Leyden jar — an instrument also important in experiments on atmospheric electricity.

Apparatus helped with discoveries in three ways: (1) they made it possible to change (or extend) the range of phenomena which could be investigated in the laboratory, (2) they helped with the formulation of new concepts, and (3) they led to the development of other instruments. Take the case of the Leyden jar. First, it was possible to analyse more powerful electrostatic phenomena. Second, it helped to formulate new concepts about electrostatic action on the phenomenological level, such as about the relationship between capacity (or surface area of coating charged), electrical intensity (or level of charge), and resistance (of the electrical circuit). Third, it opened the way for new apparatus such as Aepinus' 'plate of air', and Volta's electrophorus and parallel-plate condenser. These were essentially Leyden jars with moveable coatings. The same device gave Van Marum his 'artificial cloud' for his model experiments on atmospheric electricity. All these devices were consequences of Franklin's single fluid theory of the action of the Leyden jar, and in turn led to the discovery of 'adhesive' or 'contact' electricity, which in 1800 resulted in the discovery of the voltaic pile.

As an example of the interaction between instrumentation, theory, and discovery, the Leyden jar may seem rather atypical because it was so essential to the development of eighteenth-century electrical theory and of a

31. W.D. Hackmann, "Eighteenth-century electrostatic measuring devices", *Annali* 3 (1978) 3-58.

great variety of associated electrical devices. A similar case, however, can be made for other experimental apparatus, such as the air pump on vacuum theory and vacuum technology, and the discharge tube (Geissler, Crookes, etc.) on the elucidation of the various processes of radiation, progressing from cathode rays to X-rays, and eventually to radioactivity. But perhaps the influence of no other single instrument has been so all embracing as that of the Leyden jar. As we have seen with eighteenth-century atmospheric electricity, the interaction between instrumentation, scientific exploration and discovery flowed in both directions: advances in instruments resulted in new discoveries (or showed up specific properties of the phenomenon under investigation), and this in turn led to the design of new instruments — and so the process continued.[32]

SUMMARY

Instruments and experiments. The case of atmospheric electricity in eighteenth-century Holland

In this paper we examine the intricate relationship that exists between theory, scientific observations and laboratory experiments, using atmospheric electricity in eighteenth-century Holland as a case study. The three techniques applied to studying electrical processes in the atmosphere, and which also resulted in developing new instruments, were observing and measuring the phenomena in nature, recreating and analysing the same phenomena in the laboratory, and making scale-model experiments when direct intervention with the natural processes was not possible. In the course of this analysis we observe some of the strength and weaknesses of the eighteenth-century experimental method, and also the two-way interactions between advances in instrumentation, scientific exploration and discovery.

32. This paper concentrates on eighteenth-century experimentalism as the impetus for the development of new and better instruments. For a more detailed analysis, including a brief discussion of some of the contemporary philosophical implications (the analogous argument based on the concept of symmetry, and the problems with confusing explanations at the phenomenological *macro*-and the deeper abstract *micro-level*) see my "Scientific instruments. Models of brass and tangible signposts to the art of the possible", in D. Gooding et al. eds., *The uses of experiments. Studies of experimentation in the natural sciences*, in press.