APPENDIX

A Simple Method for Calibration of a Scatterometer over the Ocean*

Abstract. The absolute calibration of the backscatter signal of a scatterometer is essential for the retrieval of optimum quality geophysical products. The European Space Agency, ESA, targeted a specification of 0.2 dB for the accuracy of the European Remote-sensing Satellite, ERS, scatterometers. A radiometric error of this amount leads to a wind speed error of roughly 0.25 m s\(^{-1}\). An interbeam bias of the same amount may lead to notable wind direction effects. In this paper a method is discussed to obtain an accurate calibration of a scatterometer over the ocean using an accurate backscatter-to-wind transfer function and collocated winds from a numerical weather prediction model. The method is estimated to be accurate to a precision of 0.1 dB. It can be used for instrument monitoring and application of the calibration results has a demonstrable and beneficial impact on the wind inversion.

1. Introduction

It is not simple to obtain an accurate absolute calibration for a scatterometer. For the calibration of the European Remote-sensing Satellite (ERS) scatterometers [Attema, 1991] the European Space Agency, ESA, planned to perform the absolute calibration by a controlled radar return to the scatterometer from transponders when these are illuminated by one of the three scatterometer radar beams. In addition, an interbeam comparison was planned over the rain forest where the radar cross section is known to be very stable and rather time independent. Furthermore, the incidence angle response is known to be smooth over the rain forest. At first, the two techniques resulted in an inconsistent calibration. It was at this point that the ocean calibration method as described here in section 2 proved very useful. It helped detect an interpretation problem of the results obtained with the transponders. After solving the initial problems the three calibration methods are giving results that lie within the ESA specifications for the radiometric accuracy of the ERS scatterometers, which is 0.2 dB [Guignard et al., 1992, Stoffelen and Anderson, 1995, p. 8].

The ocean calibration method is still used for instrument monitoring purposes. The main advantage of the ocean calibration with respect to the other two methods is the much

* Based on:
shorter time period over which accurate results can be obtained. Within a period of 6 hours the method can detect sudden instrument anomalies, and consequently it could be decided to reject the data for real time use in for example a meteorological analysis. For instance, switching of instrument hardware modules may change the absolute calibration to a small amount. With the ocean calibration method these can be corrected for in the processing within a few weeks. So far, several cases of such anomalies have been found during the life time of ERS-1 and ERS-2. The timely detection of these is of the utmost importance to render the data useful for near real time application.

To perform an ocean calibration we divide the average of the measured backscatter measurements, denoted \( \sigma^0_M \), by the mean simulated backscatter \( \sigma^0_S \). For the computation of the latter, collocated wind data and a transfer function are needed. Stoffelen and Anderson [1997b; Chapter III] derived an accurate transfer function, denoted CMOD4, that has been adopted by ESA for operational use. Its formulation is

\[
z(\theta, V, \phi) = \frac{1}{B_0(\theta, V)} \left[ 1 + B_1(\theta, V) \cos(\phi) + B_2(\theta, V) \cos(2\phi) \right]
\]

where \( z = (\sigma^0)^{0.625} \), \( \phi \) is wind direction with respect to the pointing of the radar beam, \( V \) is wind speed, and \( \theta \) is the incidence angle of the radar beam at the earth’s surface. \( B_0 \) is usually referred to as the bias term and is by rough approximation proportional to \( V^{\gamma} \), where \( \gamma \) depends on incidence angle and varies between 0.35 and 1.0 for incidence angles between 18 and 57 degrees. \( B_1 \) and \( B_2 \) are respectively the upwind/downwind and upwind-crosswind amplitudes. From (1) it can be seen that wind direction modulates \( z \) through the \( B_1 \) and \( B_2 \) terms, and that the bias term is only dependent on wind speed and incidence angle. It is shown later that the computations to arrive at a calibration of sigma naught can best be done in \( z \) space rather than in \( \sigma^0 \) space.

The transfer function derived at the European Centre for Medium Range Weather Forecasts (ECMWF) was tuned using ERS data for the month of November 1991, which is before the last engineering calibration performed by ESA. By performing an ocean calibration for the months of March 1992, which is after the last engineering calibration, and November 1991, by taking the ratio of both months, and fitting this as a function of incidence angle, a beam independent multiplication factor to the transfer function had been derived such that it represents the mean backscatter values after the last engineering calibration. The evolving transfer function, which is CMOD4, has been implemented by ESA after comparing its performance against some other transfer function proposals [Offiler, 1994]. Furthermore, ECMWF kept a beam dependent sigma naught calibration in addition to CMOD4 in its scatterometer processing (called PRESCAT; Stoffelen and Anderson [1997a, b, c; Chapters II, III and V]), since this marginally improved the quality of
the retrieved winds. Although a beam independent transfer function is preferred, in this paper we denote, for convenience of notation, the combination of CMOD4 and March ‘92 ocean calibration as CMODEC. By using CMODEC, the “ocean” calibration procedure has for long been an integral part of the PRESCAT ERS scatterometer data processing. In the ESA processing CMOD4 is used, not CMODEC.

The calibration consists in a multiplication of the bias term with a beam and incidence angle dependent constant. The ERS scatterometer backscatter measurements are organized in 19 nodes across the swath. For each of these 19 nodes the triplet of incidence angles for the fore, mid and aft beam is more or less fixed along the track. We use for each node and beam the average value of the incidence angle. As such a calibration results in $19 \times 3 = 51$ calibration constants.

$V$ and $\phi$ need be available at any location where the scatterometer makes a measurement in order to obtain a quick procedure. Such a widely available wind data source is provided by a global Numerical Weather Prediction (NWP) model and we used the ECMWF model winds in our study. As such, changes in the mean ECMWF wind speed will change the mean sigma naught simulated using CMOD4 and ECMWF winds, since wind speed is the prime geophysical sensitivity of the backscatter signal over the ocean. Fortunately, forecast model wind error characteristics are monitored routinely by e.g. ECMWF and are also documented in special studies (e.g., Stoffelen [1998; Chapter IV]).

For each of the 19 nodes the triplet distribution of measurements from the fore, mid and aft beams can be plotted in a three dimensional measurement space, where each beam is represented by one axes. Stoffelen and Anderson [1997a; Chapter II] explored the coherence of the ERS triplet backscatter measurements by visualization of the 3D measurement space, and found that the data are generally distributed along a well-defined and conical (2D) surface. The two parameters describing the surface most likely express the mean amplitude and direction of the relevant gravity capillary waves at the water surface. Using this concept, the sigma naught calibration procedure should seek for a bias correction that moves the CMOD4 cone surface towards that surface in the measurement domain at which the density of measured ERS-1 (or ERS-2) scatterometer triplets is largest, in order to bring model and measurements as close together as possible, and thereby improve the wind inversion.

In section 2 the ocean calibration method is described in detail and both the effects of errors in the transfer function and the wind data are addressed. Section 3 presents the results of our method, whereas in section 4 a summary and conclusions are given. It is estimated that the method is accurate to a radiometric precision of 0.1 dB when the precise calibration of the transfer function and forecast model winds are given. It can be used for instrument
monitoring and application of the "ocean" calibration has a demonstrable and beneficial impact on the wind inversion.

2. Method

In this section the ocean calibration procedure is described. For the method to work accurately, the result should be independent of the geophysical conditions sampled by the collocation data set used for the calibration. Using Bayes theorem, for the joint probability density of the wind one may write

\[ p(V, \phi) = p(\phi | V) p(V) \] (2)

where \( p(V) \) and \( p(\phi | V) \) are the probability density function (pdf) of respectively wind speed and, at a given speed, wind direction. When combining (1) and (2) we see that for a uniform wind direction pdf, i.e., \( p(\phi | V) = (2\pi)^{-1} \), the harmonic terms disappear when integrated over \( \phi \). So, if we are able to achieve for the ocean calibration a collocation wind data set with uniform wind direction distribution, then our results are independent of errors in the harmonic terms of the transfer function, and insensitive to uncertainty in wind direction.

When we now also integrate over \( V \), the expected average backscatter becomes

\[ \langle z(\theta) \rangle = B_0(\theta, V) \] (3)

i.e., identical to the average value of the bias term. By computing the right-hand-side from CMOD4 and the collocated model winds we would have a reference to compare the mean measured backscatter against. As such, at each across-track node the application of Equation (3) for the three beams defines the center of gravity of the cone in \( z \) space. When this center of gravity matches for the measured and simulated triplets, then the inversion should work best [Stoffelen and Anderson, 1997a; Chapter II].

Computation in \( \sigma^0 = z^{1.6} \) (for Equation (1) we defined \( z = (\sigma^0)^{0.625} \)), using Taylor expansion, causes an additional term to be added to the mean backscatter [Stoffelen and Anderson, 1997a; Chapter II]

\[ \langle \sigma^0(\theta) \rangle = B_0^{1.6}(\theta, V) + 0.24B_0^{1.6}(\theta, V)B_2^2(\theta, V) + 0.25B_0^{1.6}(\theta, V)B_1^2(\theta, V) \] (4)

The right-most term is very small, since in this notation \( B_1 \leq 0.1 \). Since \( B_2 \leq 0.4 \), the mid term on the right-hand-side may contribute up to 4%, but dependent on wind speed. \( B_0 \) also depends on wind speed, and as such the term with \( B_2 \) may to a small extent interfere with systematic changes in mean \( B_0 \) due to changes in the wind speed level of the ECMWF model. It may be clear to the reader that the interference of the harmonic terms in the ocean
calibration is undesirable.

Stoffelen [1998; Chapter IV] finds the random wind component error of a forecast model to be normal distributed with a standard deviation of roughly 1 m s$^{-1}$. In case of unbiased component errors and a true wind component variance of 25 m$^2$ s$^{-2}$, he computed that model wind speeds would systematically overestimate the true wind speed by 2% (i.e., a pseudo bias would occur). The non-linear transformation of random wind component errors also causes a bias in the computation of the backscatter bias. For a wind speed sensitivity of $\gamma = 0.5$ in $B_0$ as defined in $z$ space, it follows that this may cause $B_0$ to be overestimated by roughly 1% or 0.04 dB, i.e. a very small amount. Although straightforward, we did not correct for this pseudo bias in the computations.

Figure 1. Example of the logarithm of the average transformed measured ERS-1 backscatter ($z$) versus incidence angle for the fore, mid and aft antennae in respectively solid, dashed and dotted for March 1996. The thin lines show the logarithm of the average transformed backscatter signal plus or minus one standard deviation (SD) of the transformed backscatter. One may note that the mean and SD do not exactly overlap for the three beams, suggesting an interbeam bias and thus a remaining calibration problem.
The scatter of measured triplets around the cone is roughly 5% and is assumed to have a normal distribution around the true $\sigma^0$ with zero mean. In $z$ space the distribution is therefore slightly skew and it is relevant to estimate the effect of this on the ocean calibration. Taylor expansion of $\sigma^0 [1 + \delta ]$ in $z$ space shows that

$$\langle z \rangle = (\sigma^0)^{0.625} [1 - 0.12 \delta^2 + O(\delta^4)] \quad (5)$$

Based on this result we conclude that the measurement noise is not a motivation for either computation in $z$ or $\sigma^0$ space, since for an expected standard deviation $\delta$ of 5% the $\delta$ terms between square brackets only amount to roughly 0.0003.

Polar satellites sample the trades and the westerlies in a systematic manner. This results in a modulation by more than a factor of two of $p(\phi | V)$ over the worlds oceans for medium and high wind speeds. For low wind speeds the modulation is much less, as is shown later. Freilich et al. [1998] assume $p(\phi | V)$ to be independent of wind speed, which to our experience is not valid. The wind direction distribution becomes increasingly uniform going from high to moderate, to low wind speed. The assumption of an invariant $p(\phi | V)$ for varying $V$, introduces additional uncertainty in the results. A way to remove the wind direction modulation for all wind speeds without this approximation, is to first determine $p(\phi | V)$ for a given data set, and subsequently in a second pass remove randomly a fraction of the data such that the resulting $p(\phi | V)$ becomes as uniform as possible. Then Equations (3) and (4) can be used for the ocean calibration, without unnecessary assumptions on $p(\phi | V)$ as in Freilich et al.

In Freilich et al. [1998] the wind direction distribution of the collocated winds is used to compute the mean contribution from the harmonic terms of the transfer function. However, this direction distribution is affected by the error in the wind direction of the collocated data, and thereby somewhat smoothed. As a consequence, the estimated contribution from the harmonic terms will be underestimated. We filtered wind directions by using collocated ECMWF winds. We assume here that a uniform ECMWF wind direction distribution corresponds to a uniform “true” wind direction distribution, and verify this later. After the filtering to a uniform $p(\phi | V)$ as proposed here, the contribution of the harmonic terms to the mean backscatter becomes negligible and its uncertainty unimportant.

After some testing, speeds were binned in 4 m s$^{-1}$ intervals, i.e. 0-4 m s$^{-1}$, 4-8 m s$^{-1}$, up to 36-40 m s$^{-1}$, and directions in 5 degree intervals. After the first pass over the data, for each speed interval the direction bin with the least points is searched for and in each bin the fraction to keep is computed as the ratio of this minimum and the actual number of points in the bin. In order to keep some points in the most data sparse areas of the wind domain, the minimum is bound to values higher than 5 in case of a month of data.
Some quality control is necessary on the backscatter data used. In particular, we found the calibration results to be very sensitive to ice contamination. We use Sea Surface Temperature (SST) fields, obtained from the National Center for Environmental Prediction, NCEP, and operationally used at ECMWF, with a temporal resolution of a few days and a spatial resolution of 100 km to reject potentially ice contaminated backscatter measurements. We found that in some cases a threshold as high as 279 K was only sufficient to exclude all ice areas. This threshold is used in this study. Furthermore, the big lakes in the US and Canada have been removed as target areas. For security, we also reject points where the forecast model wind is interpolated from one or more land points. We did not apply quality control in the wind domain.

Figure 2. As Figure 1, but now the modified backscatter is simulated from the ECMWF winds using CMOD4. For the three antennae, the average modified backscatter and the SD overlap to a large degree.
3. Results

3.1. Ocean Calibration

In this section we demonstrate the accuracy of the ocean calibration method. The ratio of measured and simulated backscatter was computed over periods of different length, from 6 hours to two months. Over a month, the wind direction filter rejects typically 50% of the collocation points, from about 25% at the lowest speeds up to over 60% at the highest speeds. No sensitivity was found to the sample of randomly selected points from the full data set. For different geographical areas and/or seasons the biases remain the same within the expected accuracy. In subsection 3.4 we check whether the ocean calibration is beneficial for the scatterometer wind inversion.

Figure 1 shows an example of the logarithm of the average measured backscatter versus incidence angle for the three antennae. After careful inspection, one may note that the mean does not exactly overlap for the three beams, suggesting an interbeam bias and thus a remaining calibration problem. We further analyze this here.

The thin lines show the logarithm of the average backscatter signal plus or minus one standard deviation. The standard deviation is computed as

\[ SD = \sqrt{\bar{z}^2 - \overline{z}^2} \tag{6} \]

and is determined by both the bias term and the harmonic terms, which means that the actual wind direction distribution affects \( SD \). However, a wrong calibration should affect the \( SD \) in the same way as it affects the mean of \( z \). Note that the wind direction distribution relative to north is similar for all nodes, but that the average and \( SD \) of the backscatter are determined by the “true” direction distribution relative to the respective beam pointing, which is different for each antenna. A similar value of \( SD \) for the three beams (after calibration) would thus indicate that the “true” wind direction distribution is indeed uniform.

Figure 2 is similar to Figure 1, but now the backscatter is simulated from the ECMWF winds using CMOD4. The average backscatter and the \( SD \) for the three antenna overlap to a large extent, as expected for simulated data and from a uniform input wind direction distribution. The \( SD \) of backscatter is similar to Figure 1, which indicates that the dynamic range of the transfer function, determined by \( B_0, B_2 \) and \( B_1 \), matches well the dynamic range of the measurements for each incidence angle. We further verified this, and the true wind direction uniformity, by plotting the ratio of the \( SD \)s as plotted in Figures 1 and 2 (not shown), which is generally smaller than 0.2 dB.

To further check the random wind direction filtering, wind direction can be retrieved
from each measured backscatter triplet. The distribution of retrieved winds is determined by the distribution of “true” wind directions and the wind direction retrieval error. We used PRESCAT to retrieve direction [Stoffelen and Anderson, 1997a, b, c; Chapters II, III and V], and it has been shown that its wind direction inversion has no large systematic error tendencies. Therefore, ideally one would expect that a data set with uniform “true” wind direction, would result in a uniform retrieved wind direction distribution.

We find that the retrieved wind direction distribution varies moderately with direction, with a standard deviation of less than 10% around the mean. If we assumed that this variation was equally caused by variations in the ECMWF and scatterometer direction error distributions then we may compute the error in the estimate of the calibration constant using (1). Ignoring the smaller $B_1$ and using the value of $B_2 = 0.4$ (which corresponds to its maximum [Stoffelen and Anderson, 1997a; Chapter II]), we find an uncertainty in the calibration of roughly 0.05 dB, which is very small indeed. Therefore, we conclude that

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**Figure 3.** The average difference between ascending and descending tracks of ERS-1 scatterometer (PRESCAT) minus ECMWF model wind speed versus latitude, for data from June 10 to July 1 1995. Each node is plotted with a different style and gray scale. The thin lines are the average differences plus or minus one SD of that difference. An eclipse effect does not appear.
after the wind direction filtering using ECMWF winds, the non-uniformity of the “true” wind is small and the error this introduces in the ocean calibration small.

3.2. Antenna Gain Variations

For ascending passes the antennae are moving from light to dark and dark to light again, whereas for descending passes they are always in sunlight. Temperature variations may deform the antenna and affect the antenna gain. Ascending and descending backscatter biases are marginally different, indicating the relative unimportance of antenna gain variations due to temperature changes.

A more detailed way of checking the effect of temperature on the antenna gain, is to plot the difference of the inverted scatterometer wind speed and the ECMWF wind speed versus latitude. The wind speed bias is particularly sensitive to simultaneous gain variations.
on the fore and aft antenna, and relatively insensitive to changes of the mid antenna gain [Stoffelen and Anderson, 1997a; Chapter II]. Geophysical changes at the earth surface associated with sunset or sunrise, that affect the 10m wind speed do occur not at the same latitude than where the antennae see sunrise or sunset. Furthermore, as a function of latitude the geophysical changes are expected to be smoother than the antenna gain effects.

For all data from 10-30 December 1995 and for all 19 nodes individually, the wind speed bias versus latitude was computed, separately for ascending and descending orbits. Subsequently, the difference of the bias at ascending and descending passes was computed in order to highlight the eclipse effect and eliminate latitude-dependent statistical and ECMWF model bias effects. The computations were repeated for the last 20 days of June 1995. It was found that the ascending minus descending wind speed bias difference versus latitude does not vary much (Figure 3). This confirms in more detail the relative unimportance of antenna gain variations along the orbit.

**Figure 5.** As Figure 4, but here the ECMWF wind speed was multiplied by a factor 0.93 before the backscatter simulation. Now the backscatter ratio varies around -0.04 dB, and is small everywhere.
3.3. Application

When PRESCAT was implemented at ECMWF, it was decided to implement the beam dependent ocean calibration (from March ‘92) as in CMODEC, because it resulted in a slightly better wind retrieval. However, the calibration coefficients were derived using Equation (4) rather than (3).

Figure 4 shows the bias in dB of ocean calibrated ERS-1 backscatter with respect to CMODEC for March ‘96, using Equation (3). It is clear that this bias is non-zero. No engineering changes have been detected from March ‘92 to March ‘96 in the backscatter data, but the mean ECMWF wind speed has been increased. The increased ECMWF wind speeds will give rise to increased backscatter as simulated by CMODEC. As a consequence, the ratio of the mean measured and simulated $\sigma^0$’s for March ‘96 will be smaller than for March ‘92 (zero) as verified in Figure 4. The thin solid curve gives the sensitivity of the backscatter (in $B_0$) to a 7% increase of wind speed at 8 m s$^{-1}$, which corresponds very well with the general trend observed in the calibration curves of the three beams.

The ECMWF model near surface wind speed is sensitive to the boundary layer parameterization scheme. Latter is subject to re-evaluation, for instance to solve problems with boundary layer humidity or cloud, and as such the level of ECMWF wind speed may change from one forecast model software cycle to the next. Stoffelen [1996] estimates the average speed level of ECMWF in 1996 to be roughly 10% larger than the average ERS scatterometer speed level. The 7% increase of the ECMWF wind speed between March ‘92 and March ‘96 is consistent with the scatterometer over model wind speed ratio of 1.10. It may be concluded that in March ‘92 the same ratio was roughly 1.03, which in retrospect verifies reasonably well with our experience (see, e.g., Stoffelen and Anderson [1997b; Chapter III], for departure statistics). Figure 5 is similar to Figure 4, but here the ECMWF wind speed was multiplied by a factor of 0.93 before the backscatter simulation. Now the backscatter ratio varies around -0.04 dB, and is small everywhere. Thus, for a proper use of ECMWF winds for the ocean calibration the wind speed has to be adjusted to the level of the ECMWF model in November (or March) 1992, to which CMOD4 had been tuned.

The (independent) problem of wind calibration of the scatterometer and ECMWF model to for example the buoy network is discussed by Stoffelen [1998; Chapter IV]. He compares NCEP model and scatterometer winds to in situ wind measurements. Latter are used to calibrate the two former wind data sources. A conclusion from the analysis is that scatterometer wind speeds are biased low by ~4% with respect to the buoys. It is found here that after the ocean calibration the node to node fluctuation of the wind speed bias is less than before (see at the end of this section). However, the effect is small and the backscatter calibration refinement suggested here has little impact on the overall wind calibration (and vice versa).
For verification purposes we computed the ratio as of Figure 5 also in $z$ space, and found the same curves, but shifted by +0.08 dB, probably showing the small interference of the term $B_0^{0.625}B_2^2$ in (4). Figure 6 shows the difference between ERS-1 and CMOD4 backscatter (after the 0.93 scaling of the ECMWF velocities) as computed in $z$ space. The bias varies with incidence angle and is different for the mid and fore/aft beams. To check stability, we repeated the computation for February ’96 and the ratios are within 0.01 dB of the ones computed for March ’96 for each beam and node, as shown in Figure 7. This is in line with our experience over the past years that the ocean calibration over a period of a month is rather independent of the geophysical conditions. In months with frequent tropical storms that are not well resolved by the ECMWF model (often in September) differences may amount to a tenth of a dB. However, these erroneous ECMWF wind cases may be rejected by a gross check on the ERS scatterometer minus ECMWF model speed difference. We did not carry this out.
The difference in Figure 6 is within the ERS scatterometer specifications for radiometric accuracy (0.2 dB), but it is still interesting to evaluate its effect on the wind retrieval. An improvement in the fit of the ERS-1 measurements with the CMOD4 cone should be particularly visible through a decreased average distance to the cone. Because the normalized distance to the cone [Stoffelen and Anderson, 1997a; Chapter II] is reasonably independent of wind speed, the average of it at each node is a good reflection of the overall fit of triplets to the cone. Table 1 shows the normalized distance to the cone after and before the backscatter bias correction. For all nodes the distance to the cone has decreased, even at the outer nodes where the correction is fairly small. On average the distance to the cone has decreased by 7%. As can be seen from Table 1, the correction has little effect on the backscatter triplet quality control, as the number of data is similar with or without bias correction.

A mid beam bias mostly affects the wind direction retrieval accuracy at low and moderate speeds and not so much the speed retrieval. Table 1 shows the $SD$ of the ECMWF minus retrieved scatterometer wind direction for all speeds. As expected, the largest improvement is found at the inner nodes where the mid beam bias is largest.

The fore and aft beam have very similar backscatter biases. This combination of fore and aft beam bias will mostly effect wind speed bias, and not so much wind direction. Indeed, the wind speed bias with respect to the ECMWF model winds is less variable from node to node after the bias correction than before.

4. Conclusions

The method of ocean calibration is briefly explained and it is motivated that application of the procedure in $z$ space rather than $\sigma^0$ space gives the most accurate estimate of the difference between the center of gravity of the transfer function cone and the center of gravity of the distribution of measured triplets. As a consequence, application of it in the processing of scatterometer data improves the geophysical product. The method is shown to be stable in time and may be applied for monitoring purposes, as has been done for more than 5 years now at ECMWF.

Land targets are also in use to determine the scatterometer calibration. The ESA rain forest calibration corresponds with the ocean calibration procedure to within the specified instrument precision of 0.2 dB. However, the stability of the land targets to an accuracy of 0.1 dB over all seasons is difficult to be assured of. Also, ESA employed transponders for absolute calibration. However, the relatively infrequent overpass over the transponders and the absolute accuracy of these, makes an absolute calibration on this basis only a tedious procedure. The consistent combination of several methods is probably the best guarantee for a good absolute scatterometer backscatter calibration.
In using the ocean calibration procedure we found that the ERS-1 scatterometer has been stable since March '92 until its switch-off in June 1996. Orbit maneuvers, however, occasionally caused temporary changes in the backscatter level due to a mispointing of the beams.

After the launch of the ERS-2 scatterometer, we have been able to compute the backscatter calibration coefficients within two weeks after the data had become routinely available. By measurement space visualization, Stoffelen and van Beukering [1997] verified that the calibrated triplets indeed lie closer to the CMOD4 cone surface than before the ocean calibration. As such, a quality assessment of the ERS-2 scatterometer winds could be made well before the engineering calibration was carried out, which provided the evidence that the ERS-2 scatterometer was functioning well.

A mid beam bias mainly causes problems in the wind direction retrieval, whereas a simultaneous and coherent bias in the fore and aft beams mainly causes a wind speed bias. Other bias types will cause combined speed and direction effects. The ocean calibration
reduces the average distance of the ERS backscatter triplets to the CMOD4 cone surface by 7% and proved effective in removing remaining backscatter biases.

The ECMWF model near surface wind speed is sensitive to the boundary layer parameterization scheme. Latter is subject to re-evaluation, for instance to solve problems with boundary layer humidity or cloud, and as such the level of ECMWF wind speed may change from one forecast model software cycle to the next. Using the ocean calibration method we found an increase of the ECMWF wind speed between March ‘92 and March
‘96 of 7 %. This is consistent with the results of dedicated wind calibration studies. After the ocean calibration the node to node fluctuation of the wind speed bias is less than before, and for some nodes the wind direction retrieval is improved. However, the backscatter calibration refinement suggested here has little impact on the overall wind calibration.

For the scatterometer processing we recommend correction of the backscatter biases between scatterometer measurements and CMOD4 for e.g. March ‘96 and thereafter a monitoring of the backscatter bias with respect to this. At the same time, checking of departure statistics of surface wind from one forecast model cycle to the next is necessary as an independent way to check speed level changes.

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