Improved ASCAT wind retrieval using NWP

ocean calibration

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Abstract — **The Advanced Scatterometer (ASCAT) Wind Data Processor (AWDP) currently uses the so called *CMOD5n* Geophysical Model Function (GMF), which was originally derived for the ERS scatterometers. In order to deliver a high-quality ASCAT wind product, the operational AWDP uses backscatter measurement corrections that are estimated visually (VOC) for each wind vector cell (WVC). We propose an alternative and previously established method for estimating correction tables based on NWP ocean calibration residuals (NOC). It embodies a smooth incidence-angle dependent part that could serve as an appropriate ASCAT GMF correction, and a radar-beam dependent residual. The incidence-angle-dependent part of these correction tables is due to differences in calibration procedure of the ERS and ASCAT scatterometers. For the high ASCAT incidence angles for which the GMF has not been assessed by ERS data the modification is quite large, almost 1 dB. The incidence angle dependent part is derived by fitting the ocean calibration residuals of all beams obtained over one year of data. It is subsequently used to adapt the GMF (yielding CMOD5na). The remaining radar-beam dependent residual (NOCa) shows a wiggle pattern as function of incidence angle that is very persistent over time, apart from a seasonally varying offset. Both the effects of the GMF modification and the beam-dependent residual on the wind retrieval quality are investigated in this paper. Overall the performance of NOC is better than that obtained with the previously used VOC calibration method and the wind statistics show a much better symmetry of the left and right swath for NOC. The beam-dependent corrections improve the quality of the retrieved winds. NOC may thus be used for the intercalibration of the ERS and ASCAT scatterometers.**

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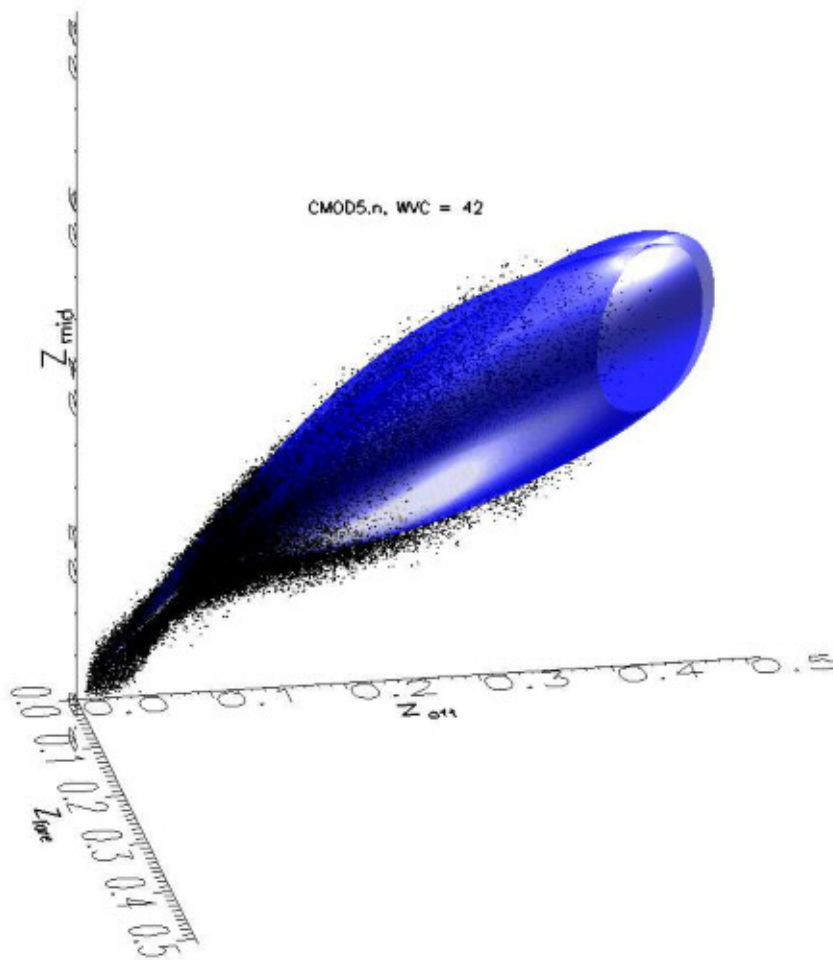(2) Unidad de Tecnología Marina (UTM - CSIC),

I. INTRODUCTION

THE METOP-A satellite was launched on October 19, 2006 and carries ASCAT. This instrument is a real-aperture C-band

vertically polarized radar with three fan beam antennas pointing to the left-hand side of the sub satellite track and three fan beam

antennas pointing to the right-hand side [1]. A measurement space is defined for each Wind Vector Cell (WVC) as the three-

dimensional or 3D (z_{fore}, z_{aft}, z_{mid}) space where $z = \sigma_0^{0.625}$, the transformed measured backscatter value of respectively the fore, aft

and mid beam [2]. The two-dimensional (2D) GMF manifold is a conical surface and the (fore, aft, mid) measurement triplets

generally lie in the proximity of this surface.

Fig. 1 shows a visualization of the measurement space. The backscatter triplets are shown as black points. Differences between

the cloud of triplets and the cone in each direction of the measurement space are, to a first approximation, caused by biases

between the ASCAT data and the ERS-based GMF. The blue double folded conical surface represents *CMOD5n*, the GMF that is

currently being used in the operational wind processing. *CMOD5n* is a modification of *CMOD5* that was used for ASCAT and

ERS wind processing in the past. Although the shape of the surface is the same for both *CMOD5* and *CMOD5n*, the latter relates

backscatter to equivalent neutral winds at 10-m rather than to real winds and is a better representation of the geophysical quantity

that is measured by the scatterometer (not depending on atmospheric stability). The GMF is introduced further in section II.

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Figure 1 – Visualization of CMOD5.n and the ASCAT triplets in 3D measurement space for the innermost WVC of the right swath (WVC 42, 12.5 km WVC spacing) for wind speeds up to 30 ms-1.

The AWDP uses corrections in order to achieve a high quality wind product. The currently used corrections are based on a Visual correction method for Ocean Calibration (VOC) [3]. In this method the Geophysical Model Function (GMF) is evaluated in the measurement space for its consistency with the distribution of measurement points. The VOC method scales each of the three axes of the measurement space, i.e., the fore, aft and mid beam σ_0, such that the distribution of measurement triplets is shifted towards the conical GMF surface as defined by *CMOD5n*. As a second correction, the axes are scaled simultaneously to compensate for a wind speed bias with respect to collocated ECMWF model winds. Thus instrumental or calibration errors as well as GMF defects can be accounted for.

Another method for Ocean Calibration (OC) resides in direct comparison of measured σ_0 data with simulated values from Numerical Weather Prediction (NWP) model winds using the GMF (see [2], [4]). This NWP-based OC (NOC) method, that was

also used for ERS scatterometers in the past, and for assimilation of ASCAT winds in the ECMWF model (see [6], section 4), is

explained in section II. Section III describes the derivation of the NOC backscatter correction factors. The NOC corrections are

furthermore split into an incidence angle dependent part, which is included in the GMF, and a remaining antenna-dependent part

(the NOCa corrections). In section IV, the impact of both VOC and NOCa antenna-dependent corrections on several wind-

inversion related parameters is assessed. Metrics based on the statistical distribution of several parameters will be discussed and

evaluated in section V. Section VI gives the summary and conclusions.

II.   NWP Ocean Calibration

The NOC method is based on the analysis of a large measurement dataset to estimate Fourier coefficients that can be directly

compared to those in the *CMOD5.n* GMF which may be written as ([5], [6], [7]):

$$\sigma_0(v,\theta,\phi) = B_0(v,\theta)[1 + B_1(v,\theta)\cos\phi + B_2(v,\theta)\cos(2\phi)]^{1.6} \quad \text{(eq. 1)}$$

where v is the wind speed, ϕ the wind azimuth direction relative to the radar beam look, and θ the radar incidence angle. The B-

coefficients are closely related to Fourier coefficients in z space ($z = \sigma_0^{0.625}$) such that Eq. 1 can be re-written as:

$$z(v,\theta,\phi) = \frac{1}{2}a_0(v,\theta) + a_1(v,\theta)\cos\phi + a_2(v,\theta)\cos(2\phi) \quad \text{(eq. 2)}$$

When the wind direction distribution is sampled uniformly for all wind speeds, then the mean $<(1/2)a_0>$ should be identical to the

mean $<z>$. This means that uncertainties in a_1 and a_2 do not contribute to the error in the estimated mean z.

In this paper only the ASCAT high resolution mode is used (12.5 km WVC spacing compared to the 25 km WVC spacing for the

nominal resolution). To arrange a uniform wind direction distribution, we split the collocated European Centre for Medium-range

Weather Forecasts (ECMWF) wind data into wind speed bins of size 1.0 ms^{-1} and azimuth angle bins of size 12^0. Our operational

product uses ECMWF winds (3-hourly 3-18 hour forecast winds) at spectral truncation T319 (corresponding to a grid with 160

points between pole and equator) interpolated to ASCAT wind locations and time. For the ocean calibration these ECMWF

forecast winds are used. Data from the global oceans between latitudes -55^0 and +65^0 are used. The latitudes are chosen such that

regions which possibly contain sea ice are conservatively excluded. The collocated ECMWF equivalent neutral 10-meter winds are converted to simulated z values using the *CMOD5.n* GMF (Eq. 2). The differences of measured and simulated <z> are averaged over all wind azimuth bins weighted in accordance with a uniform wind azimuth distribution. Next they are averaged over all wind speed bins weighted in accordance with the wind speed distribution. Thus, the NOC method needs only a few days of collocated ASCAT data and ECMWF winds to produce a reasonable estimate of difference in backscatter residuals, i.e., the difference between the two values of <z> as a function of incidence angle for each antenna. When these residuals are stable over time they may be used as correction factors for errors in the instrument, for monitoring instrument health or for GMF development. Stoffelen [8] notes that uncertainties in ECMWF wind speed and direction may cause small systematic biases in the residuals produced by the ocean calibration. Therefore, it is important to verify the effect of NOC in the scatterometer wind retrieval (see section IV) and other applications.

A time series of the ocean calibration is performed over the period of one year, from September 2008 to September 2009 for the ASCAT scatterometer in high-resolution mode (12.5 km WVC spacing). The one-year period is taken to average out the seasonal variations in the wind distribution that have an effect on the NOC residual. Successive periods of day 1-14 and day 15-last day of the month are taken as input for an ocean calibration run. The ASCAT backscatter data (level 1B product) is provided by EUMETSAT. Since the beginning of ASCAT operations, the calibration of level 1B data has been adjusted several times as additional transponder data was collected and calibration algorithms were refined. Corrections that account for differences in level 1B versions are applied to the backscatter data. These corrections have been able to transform the ASCAT backscatter measurements from each level 1B calibration cycle to the next cycle within a few hundredths of a dB (see [9] for details). Thus the results are made independent of the level 1B software version that is used. Level 1B software version 7.02 based on the 3-transponder calibrated data [10], [11] is taken as the reference by NOC.

Fig. 2 shows a typical example the ocean calibration residuals from the right-fore antenna as a function of incidence angle. Each line corresponds to a time period of half a month. The figure shows a good stability over time. The vertical fluctuations between lines are in the order of ~ 0.1 dB, corresponding approximately to ~0.1 m/s in the wind speed domain. These fluctuations are apparent for the whole incidence angle range. Seasonal variations in NWP wind distribution over the year may introduce a small varying bias in OC residuals and are the main cause of these fluctuations in the vertical axis direction [8]. The pattern within one line as a function of incidence angle shows distinct peaks and troughs. These are difficult to explain from the NWP comparison

procedure [2], [8] since the GMF terms are rather smooth as a function of incidence angle and subsequent WVCs see almost

identical NWP wind distributions. Moreover, variations in wind distribution are not expected to be fixed with respect to WVC

from one month to the next. The small wiggles are presumably ASCAT instrument calibration artifacts. Also for the other

antennas a peculiar incidence-angle-dependent pattern exists that is stable over time, with a very similar vertical shift over time

(see also Anderson et al [12]).
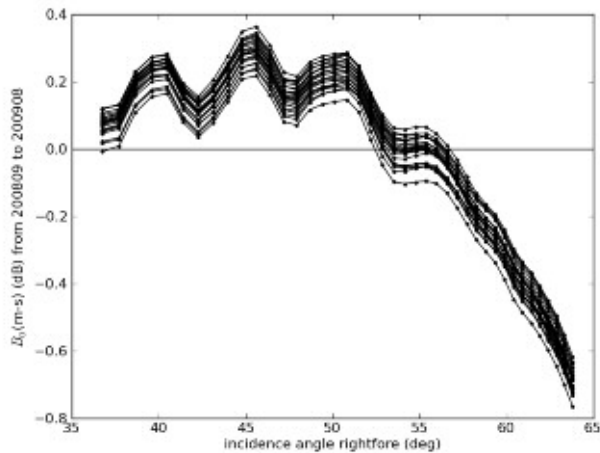
Figure 2 – Stability over time of the right-fore antenna NWP ocean calibration residual as a function of incidence angle (values

converted to dB) for the 12.5-km product.

III.   DERIVATION OF THE NOCa CORRECTION FACTORS

From a physical point of view the backscatter is a smooth and slowly varying function of incidence angle and no wiggles with

period ~ 5 degree as appear in Fig. 2 are to be expected. Similar wiggles also appear in independent rain forest study [12] and in

averaged backscatter from the scatterometer alone without using the collocated ECMWF winds. The wiggles could be caused by

level 1B calibration inaccuracies, but could also be introduced in the calculation of the level 1B σ_0 value out of the level 0 radar

data product, e.g. by inaccuracies in the antenna pointing or footprint area calculation. The NOC corrections are split into a main

smooth incidence-angle dependent part $B_0^{corr}(\theta)$ that is attributed to the wind GMF and a relatively small remaining beam-

dependent part (NOCa) that is attributed to instrument or level 1B calibration deficiencies. The latter corrections could be used as

correction factors for other geophysical products as well, e.g. soil moisture [13] and sea ice [14].

Fig. 3(a) shows the average of the NOC residuals over a time series of one year that define the NOC correction factors. The thick line is a fit function $B_0^{corr}(\theta)$ through the NOC correction factors for all six antennas. It is a third order polynomial in the incidence angle θ over the total range from 27.5° to 63.6°. Especially for the high incidence angles for which the GMF has not been assessed by ERS data the fit function has a quite large value, in the order of 1 dB lower than for the mid range incidence angles. The correction function $B_0^{corr}(\theta)$ is incorporated into the ASCAT GMF to yield CMOD5na:

$$CMOD5na = CMOD5n + B_0^{corr}(\theta)$$
$$B_0^{corr}(\theta) = a_0 + a_1\theta + a_2\theta^2 + a_3\theta^3$$

(eq. 3)

with polynomial coefficients $a_0 = 5.7236425879$, $a_1 = -0.4226930560$, $a_2 = 0.0105605079$, $a_3 = -0.0000864832$.

Fig. 3(b) shows the zoomed-in differences between NOC factors and the fit function. Clearly, remaining instrument calibration wiggles can be depicted in the range of -0.15 dB to +0.15 dB. These remaining factors are antenna dependent and therefore cannot be incorporated in the GMF. They will be referred to as NOCa corrections.
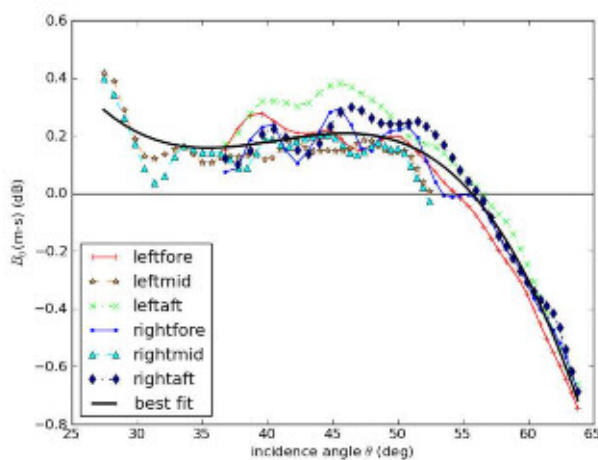
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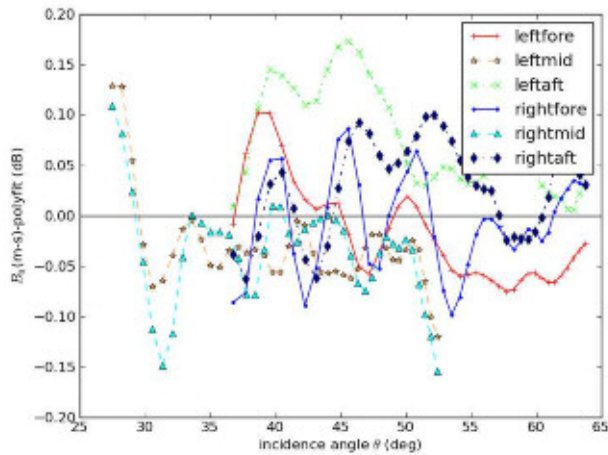
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Figure 3 –

a) Average of the ocean calibration residuals over one year (NOC correction factors). A polynomial fit through the NOC

calibration corrections is also shown.

b) NOCa corrections. Difference between NOC corrections and polynomial fit. i.e., residual corrections for *CMOD5na*.

All the computed 12.5-km product residual values are converted from linear space to dBs.

In this paper only the high resolution mode is used (12.5 km WVC spacing) [15]. The NOCa residuals for high resolution reveal

more detail than the residuals for nominal resolution (25 km WVC spacing). Using nominal mode corrections that are derived

from the high resolution mode corrections would lead to insufficient accuracy at the swath edges. NOCa corrections are also

calculated for the nominal resolution mode, yielding separate correction tables for high and nominal resolution.

IV.   COMPARISON OF THE WIND STATISTICS WITH NOCa AND VOC CORRECTIONS

In this section we compare ASCAT wind statistics from reprocessed wind products (first week of February 2009) by AWDP

using CMOD5na and NOCa corrections with the operational values where CMOD5.n with VOC corrections were applied.

Fig. 4(a) shows the wind speed bias as a function of WVC from CMOD5na+NOCa, CMOD5na and CMOD5n+VOC corrected

data with respect to the NWP winds from ECMWF. The VOC corrected bias is generally further away from zero. Moreover, it

shows an asymmetric pattern for the left and right swath. The NOCa corrected bias is generally closer to zero and it shows a

symmetrical pattern for the left and right swath as expected. The impact of the NOCa corrections can be seen by comparing

CMOD5na+NOCa with CMOD5na. The overall pattern is the same, but the NOCa corrections have clearly removed the

irregularities that can be seen for the CMOD5na case. Fig. 4(b) shows the u and v wind component Standard Deviation (SD) of

the difference between ASCAT winds and collocated NWP winds as a function of WVC. The patterns are comparable for the

NOCa and the VOC correction case, but are systematically lower for the NOCa case, denoting improved wind retrieval for

NOCa. Table 1 summarises the wind statistics in terms of bias and standard deviation for the two cases with respect to NWP

winds. The NOCa case has better statistics than the operational case (VOC). Biases are comparable, but SD values for wind

speed V, wind direction ϕ and wind components u and v are all slightly lower for NOCa.

Validation of ASCAT winds with an independent source is performed via triple collocation studies in which ASCAT winds are

compared with e.g. ECMWF winds and buoy winds. In [16], the ASCAT operational wind product (VOC) from one year of data

is used in such a triple collocation study. In the context of this paper, triple collocation studies have been performed for both

NOCa and VOC ASCAT winds from February 2009 with ECMWF and buoy winds. The resulting wind statistics from NOCa and

VOC data are alike, with almost identical SDs for the u and v wind components (not shown). Thus the results from [16] for VOC

ASCAT winds are applicable for NOCa as well.
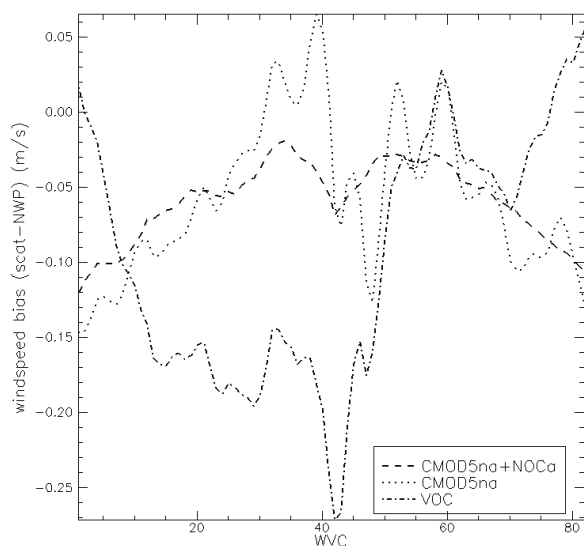
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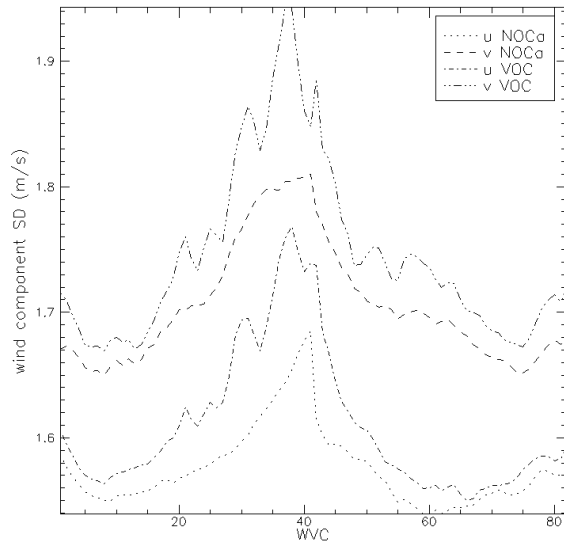
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Figure 4 –

a) Wind speed bias (V_{scat}-V_{nwp}) as a function of WVC. ASCAT data from the first week of February 2009 was processed using

CMOD5na in combination with NOCa, and *CMOD5n* in combination with VOC corrections.

b) Standard deviation of the wind component difference SD(u_{scat}-u_{nwp}) and SD(v_{scat}-v_{nwp}) as a function of WVC.

Table 1 – Wind statistics for NOCa and VOC correction (ASCAT data from the first week of February 2009)

	Bias NOCa	Bias VOC	SD NOCa	SD VOC
V	-0.06	-0.10	1.31	1.32
ϕ	0.49	0.74	16.38	16.98
u	-0.11	-0.09	1.58	1.61
v	-0.05	-0.05	1.71	1.75

The Maximum Likelihood Estimate (MLE) is the distance from a measurement triplet to the point on the wind cone in 3D measurement space that corresponds to the retrieved wind (see fig. 1). It is a measure of how well the measurements and GMF fit to each other. Due to instrument and geophysical characteristics of the scatterometer, the expectation value <MLE> is varying as a function of incidence angle or WVC. For the ease of monitoring and quality control (QC) the MLE is normalised using a WVC dependent factor, yielding an expectation value of <MLE>=1 for each WVC. In cases where a measurement triplet does not

represent the wind well, e.g. due to ice contamination, the MLE will have a large value. When the MLE surpasses a certain

threshold value, it is flagged by quality control (GMF_distance flag is set) [17].

NOCa and VOC use different MLE normalization and QC threshold tables and therefore a direct comparison of the MLE

average/SD values is not fair. In order to make a fair comparison between NOCa and VOC, the ASCAT wind product is

reprocessed using no MLE normalisation factors and the same QC threshold values in both cases. The resulting (non-normalised)

MLE average/SD value is shown in fig. 5. Without normalisation the MLE distribution shows variations as a function of WVC

that can be related to GMF errors, backscatter calibration errors, and the exact 3D shape of the GMF cone in 3D measurement

space. In the NOCa corrected case any WVC dependency caused by small interbeam biases is already corrected out by the NOCa

corrections itself. As such, the MLE is a smooth and symmetrical function. On the other hand, the VOC case shows asymmetry

and irregularities. Also, from fig. 5 it can be concluded that both the mean MLE value and its SD are smaller everywhere for

NOCa, which shows that the NOCa corrected data better fit the GMF cone.
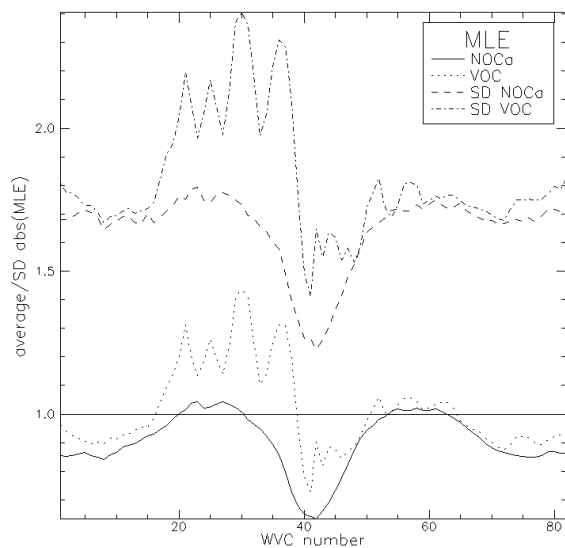
Figure 5 – Average/SD of the absolute value of the MLE per WVC. NOCa and VOC case are shown. ASCAT data from the first

week of February 2009 was processed without using MLE normalisation factors, and with the same QC thresholds applied for

both cases.

During wind retrieval (level 2) processing QC flags may be set to indicate special or anomalous conditions [18], [19]. The GMF_distance flag is set when the measured triplet has an anomalously large distance to the GMF cone, while the var_qc flag is set during 2DVAR ambiguity removal when a wind vector is spatially inconsistent with its neighbours [20]. The KNMI QC flag is an overall level 2 QC flag incorporating several other flags [21].

The occurrence of some important level 2 quality flags and their WVC dependency is shown in fig. 6 for the NOCa case. Backscatter calibration causes (small) changes to the cone location in measurement space and thus requires new MLE normalisation. MLE normalisation and QC threshold tables were recomputed using NOC corrections (see annex of [9]). The difference with the VOC case (not shown) is small but again favourable for NOCa with a smoother curve for the KNMI QC flag and GMF_distance flag and less points rejected by the 2DVAR spatial inconsistency flag (var_qc).
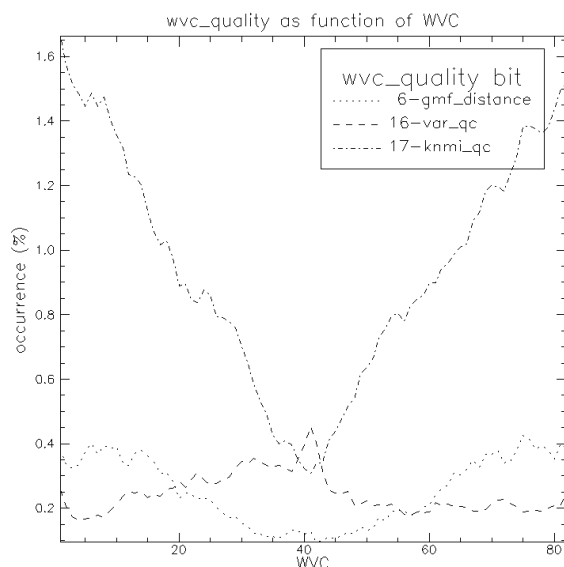

Figure 6 – Relative occurrence of some KNMI quality flags as a function of WVC. Data corrected with NOCa.

V. SUMMARY AND CONCLUSIONS

In many aspects the NOCa provides results that are comparable with, or better than the VOC method:

- The two-weekly OC residuals for data processed with CMOD5n and without applied corrections are varying within a small range of ~0.1 dB from period to period over the full observed timeframe of one year (see fig.2). This shows the consistency in the approach for applying NOCa corrections;

- The AWDP wind speed bias against ECMWF is small, but becoming symmetric for the left and right swath when the NOCa corrections are applied (see fig. 4a);

- The AWDP minus ECMWF wind speed, direction and component SDs are reduced for NOCa as compared to the VOC-correction processed winds (see fig. 4b);

- The MLE is reduced by up to 40% in certain WVCs when NOCa corrections are used as compared to the MLEs produced by AWDP with VOC corrections. Moreover, following expectation the MLE is becoming symmetric for the left and right swath when the MLE normalization factors are omitted (see fig. 5);

- The reduction in level 2 QC flag occurrences for NOCa-corrected AWDP compared to the VOC case is about 10% for the 2D-VAR spatial consistency check (see fig. 6);.

The symmetrical and beam-independent part of the NOC correction is put into a new version of the GMF, *CMOD5na*. ASCAT data processed with *CMOD5na* form a good basis for further GMF improvements using MLE residual analyses as a function of incidence angle, wind speed and wind direction.

The VOC WVC- and beam-dependent correction method makes use of a visual correction, judged by eye, and an integral multiplication factor to correct the mean wind speed to ECMWF. With hindsight, the VOC method was not focused on the modal winds and too much tuned towards the more extreme winds occurring at the different WVCs.

The remaining small beam-dependent part (NOCa) can be ascribed to instrument or level1B calibration deficiencies. It compensates for any remaining beam-dependent error. Most notably it removes the WVC-dependency of wind and MLE statistics. The NOCa-corrected backscatter triplets indeed visually better fit the GMF cone in measurement space at the modal wind speeds (not shown). The NOCa corrections may be used as correction factors for other geophysical products as well, e.g., soil moisture and sea ice. Since ASCAT is thought to have a superior calibration to ERS, the incidence-angle dependent part can be used to correct CMOD5n. The corrected CMOD5n would in turn be useful to determine an improved objective ERS calibration, i.e., to perform intercalibration of the ERS and ASCAT instruments.

Implementation of CMOD5na and NOCa corrections together with new MLE normalization factors is useful and leads to slightly better ASCAT winds, QC and MLE statistics where the asymmetry between left and right swath is diminished. The MLE normalisation results in appropriate QC thresholds and monitoring flag settings for the NOCa implementation.

Reprocessing the ASCAT wind product using the CMOD5na and NOCa corrections, as well as the newly derived MLE normalization and QC threshold tables, yields good-quality wind and MLE statistics, slighty better than with the VOC method. Moreover, the distributions are more symmetric for left and right swath.

Also in the experimental ultra-high resolution mode (6.25 km) CMOD5na and appropriate NOCa corrections are expected to result in better winds and improved statistics.

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