KU-BAND RADAR ALTIMETER SURFACE WIND SPEED ALGORITHM

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ABSTRACT

An algorithm for the retrieval of surface wind speed from Ku-band altimeter backscatter coefficient is proposed. The algorithm was derived using two-month worth of ENVISAT altimeter backscatter data collocated with ECMWF model and buoy wind speeds. The algorithm was extensively verified for ENVISAT, ERS-2 and Jason-1 altimeters. The algorithm performance is better than the “modified Chelton-Wentz” algorithm and the two-parameter algorithm implemented for Jason-1 altimeter. The algorithm was implemented for ENVISAT RA-2 on 24 October 2005. About a year of verifications afterwards showed better performance in terms of wind speed retrieval. The use of significant wave height as a second parameter for the altimeter wind retrieval algorithms is also discussed.

1. INTRODUCTION

Radar altimeter (RA) is one of the satellite-borne instruments which are able to measure surface wind speed over the ocean. The power of the reflected radar signal (the backscatter coefficient, $\sigma^0$) from the ocean surface can be translated into ocean surface wind (defined here as the wind speed at a height of 10 m above the mean sea surface, $U_{10}$). Several satellites carrying RA instruments were launched during the last few decades. The list includes, among others, GEOSAT, ERS-1, ERS-2, Jason-1, and ENVISAT. All those platforms carry at least a Ku-band altimeter. Some satellites like ENVISAT and Jason-1 carry a second altimeter operating with a different radar frequency (S-band for ENVISAT and C-band for Jason-1). Hereafter, only Ku-band altimeter is considered.

Although there are several satellite-borne instruments capable of measuring higher density wind vector fields across rather wide swaths (e.g. scatterometer), RA wind speed is still of great value for several applications like the correction of the altimeter estimate of mean sea surface height (e.g. the electromagnetic bias correction). RA wind speed data are very useful for monitoring the quality of model wind speeds. For example, at the European Centre for Medium-Range Weather Forecasts (ECMWF) the scatterometer wind speeds from both ERS-2 and QUIKSCAT, the buoy winds and the SSM/I (Special Sensor Microwave Imager) winds are assimilated in the atmospheric model. Therefore, these sources of data can not be used for independent verification of the model winds.

There are several empirical models for translating the Ku-band RA backscatter into ocean surface wind speed. The modified Chelton-Wentz (MCW) algorithm [1] is the mostly used in operational retrieval from Ku-band altimeters. It is the one adopted for several altimeters like the ones onboard ERS-1, ERS-2 and ENVISAT (until late October 2005). The algorithm, which was devised based on a limited number of GEOSAT altimeter-buoy collocations, consists of a look-up table relating $U_{10}$ to $\sigma^0$. Although this algorithm generally has a rather satisfactory performance, it was always felt that there was room for improvement. Some improvement attempts refined the existing one-parameter algorithm (e.g. [2]) while others tried to introduce a sea-state dependence by including measured $H_s$ as a second parameter (e.g. [3]) in retrieval algorithms. The sea-state dependence itself was the subject of several research efforts (e.g. [4]). The results of those studies show ranges of impacts from significant to no impact (e.g. [5]). Some related discussion will be provided in Section 6 concerning this issue. For the purpose of the current work, the sea-state dependence will not be taken into account. It will be shown that the use of significant wave height as a proxy for sea-state dependence may not be a good choice when $H_s$ is in excess of about 1.5-2.0 m.

2. MOTIVATIONS

More than two years of operational monitoring of the near-real time ENVISAT Radar Altimeter-2 (RA-2) surface wind speed product suggested that the implemented wind speed retrieval algorithm, namely the MCW, needs to be fine-tuned. Fig. 1 shows a whole year of global comparison between RA-2 and ECMWF model wind speeds as a density scatter plot. One can clearly identify the need of tuning at low wind speeds (below ~5 m/s) and at high wind speeds (above ~20 m/s). The latter shortcoming is due to the limitation of the MCW
look-up table that restricts the maximum wind speed value to around 20 m/s. A similar picture emerges when comparing the wind speeds from RA-2 and the buoy measurements (which are received through the Global Telecommunication System, GTS) as can be seen in Fig. 2 for slightly more than a year. It is worthwhile mentioning that the buoys are mainly located in the Northern Hemisphere (NH). Only buoys also reporting ocean wave data are used for the algorithm tuning and for the verification. The buoy wind speed observations were corrected based on the anemometer height. The procedure of [6] was adopted in this work. The RA-2 underestimated at low wind speed regime compared to buoys extends up to ~10 m/s. It is worthwhile mentioning that Jason-1 altimeter shows more or less the same picture (not shown). Keeping in mind that Jason-1 wind speed retrieval is based on the two-parameter algorithm, $\sigma^2 = f(U_{10}, H_s)$, of Gourrion et al. [3] one can question if $H_s$ is enough to represent the sea-state dependence. Of course, the possibility that the algorithm of Gourrion et al. [3] needs further tuning cannot be ruled out.

The need for improvement was also motivated by the comparison of the histograms of occurrence of wind speeds from the altimeters and the collocated model and buoy counterparts (not shown). The RA-2 histogram deviates from both model and buoy curves.

![Figure 1: Global comparison between ENVISAT RA-2 and ECMWF model analysis wind speed values during the period from 1 September 2004 to 31 August 2005.](image1)

![Figure 2: Global comparison between ENVISAT RA-2 and buoy wind speed values during the period from 1 January 2004 to 28 February 2005 (mainly in the NH).](image2)

### 3. Algorithm Tuning

Two months (January and February 2005) of global collocations between ENVISAT RA-2 backscatter coefficient, $\sigma^o$, and ECMWF model wind speed, $U_{10}$, were used for the algorithm tuning. While collocating various sources of data, it is important to ensure comparable scales (c.f. [7]). The ECMWF model at the time had a horizontal resolution of about 40 km (T511L). Horizontal diffusion in the atmospheric model reduces considerably activity at the short scales. This increases the effective model scale to be in the order of 70 km. On the other hand, the distributed ENVISAT RA-2 Fast Delivery Marine Abridged Records Product (FDMAR) consists of 1-Hz observations with a horizontal scale of about 7 km (the footprint corresponding to 1 Hz observations). For the purpose of the current study, it is found that a satellite “super-observation” represented by an average of 11 consecutive (1-Hz) RA-2 observations can be of a comparable scale as that of the model. After proper quality control (similar to the one used by [8] for ERS-2 RA), the total number of collocations used for the algorithm tuning is around 163,000.

While correlating the altimeter backscatter coefficient, $\sigma^o$, to the model wind speed, $U_{10}$, one needs to keep in mind that both quantities suffer from various kinds of errors. It would be incorrect to assume that any of them is free of error. Instrumental errors (e.g. instrument calibration) and errors due to ambient conditions are examples for the possible sources of errors in the altimeter backscatter measurements. On the other hand, imperfect model physics, parameterisation and numerics are responsible for errors in model winds. Assuming the errors are normally distributed around the truth, one can make use of averaging in a hope that enough volume of data leads to means closer to the truth.

The scatter plot between $\sigma^o$ and $U_{10}$ is highly scattered (not shown). The backscatter range was divided into bins of 0.1 dB. All collocated model $U_{10}$ values within each bin were averaged. The results are plotted as blue dots in Fig. 3 providing the number of collocations in the bin is more than 35. Similarly, the wind speed range was binned into 0.1 m/s bins and the collocated $\sigma^o$ values are averaged within each bin. The results are plotted as red crosses in Fig. 3 for bins with more than 35 collocations. A two segment function was fitted to the data in the form:

$$U_m = \begin{cases} \alpha - \beta \sigma^o & \text{if } \sigma^o \leq \sigma_b \\ \gamma \exp(-\delta \sigma^o) & \text{if } \sigma^o > \sigma_b \end{cases}$$

where $U_m$ is a first-guess estimation of $U_{10}$ while $\alpha$, $\beta$, $\gamma$, $\delta$ and $\sigma_b$ are parameters to be found by fitting. While fitting a two-segment function, one needs to consider the continuity of the function and, at least, its first derivative at the breaking point $\sigma_b$. Linear regression was done
for the linear segment. For the exponential segment, nonlinear curve fitting was used. A weighting function inversely proportional to (the sixth power of) $\sigma^6$ values was used to favour the densely populated middle part of the function. Neutral regression was used by fitting $U_m=f_1(\sigma^6)$ and $\sigma^6=f_2(U_m)$ and then the golden mean is considered. The following values were obtained:

$$\alpha = 46.5 \quad \beta = 3.6 \quad \gamma = 1690$$
$$\delta = 0.5 \quad \text{and} \quad \sigma_o = 10.917 \text{ dB}$$

(2)

Irrespective of the current accuracy of the ECMWF atmospheric model, one can still argue about the global validity of the model wind speed. Furthermore, it is desirable that the wind retrieval algorithm would perform satisfactorily against buoy wind measurements. To ensure that, the RA-2 collocations with available buoy wind measurements (as received through the Global Telecommunication System, GTS) were used to fine-tune the resulting algorithm during the same two months. The scale of the buoy observations is adjusted to RA-2 super-observation and model scales by averaging over five consecutive hourly measurements with the quality control procedure of [6]. The fine-tuning was done on a trial and error basis to find the optimal fit between the buoy winds and the RA-2 wind speeds as computed from Eqs. 1 and 2. It was found that the most optimal fit, can be reached by adjusting $U_m$ as follows:

$$U_{10} = U_m + 1.4 U_m^{0.096} \exp(-0.32 U_m^{1.096})$$

(3)

The proposed algorithm of Eqs. 1-3 is plotted in Fig. 3. Note that the final fit slightly deviates from the altimeter-model mean relation.

**Figure 3**: Relation between ECMWF model wind speed and ENVISAT RA-2 backscatter coefficient during the period from 1 January - 28 February 2005. Blue dots are mean wind speed for given bins of backscatter; red crosses are mean backscatter for given bins of wind speed. Green line is the proposed algorithm in Eqs. 1-3.

4. ALGORITHM VERIFICATION

Being an empirical model, the algorithm of Eqs. 1-3 needs extensive verification. The first set of verification is a reprocessing of two years (9 April 2003 - 9 April 2005) of ENVISAT RA-2 Ku-band $\sigma^0$ observations. Eqs. 1-3 were used to derive $U_{10}$. The resulting winds are collocated with the ECMWF model counterparts. The time-series of the global wind speed bias defined as the difference between the altimeter and the model wind speeds from the original product computed using the MCW algorithm and the proposed algorithm of Eqs. 1-3 are plotted in Fig. 4-a. The new algorithm produces wind speeds which are about 0.4 m/s higher than MCW. The proposed algorithm suggests that, on average the model underestimates surface wind speeds by about 0.25 m/s during that period. Verification of the ECMWF wind speeds against buoy observations (e.g. [6]) gives a similar signal. Fig. 4-b shows similar time-series for the NH Extra-Tropics (north of 20°N). It is clear that the same seasonal cycle exists in both time-series. However, the difference between the two biases suggests that the new algorithm is able to eliminate part of the seasonal variation. Fig. 5 shows the time-series of the global scatter index, SI, (defined as the standard deviation of the difference, SDD, between the two data sets normalised by the mean of the reference data set) between RA-2 and the model. It is clearly visible that the
new algorithm performs better than the MCW algorithm with a SI reduction of about 6% during the whole period. Most of the improvement is in the Tropics between latitudes 20°N and 20°S (not shown) where light to medium wind speeds are the norm.

The same algorithm, without any modifications, was also applied to five years (16 July 1998 - 23 June 2003) of ERS-2 RA observations. Similar results (not shown) to those of ENVISAT were obtained. The exception was the period from late January to early March each year since 2000 due to the “sun-blinding effect” (see [8]) experienced by the ERS-2 platform after the loss of its gyroscopes, resulting in σo values of poor quality.

The real challenge, however, was the implementation of the proposed algorithm to Jason-1 data. As mentioned earlier, the two-parameter algorithm of Gourrion et al. [3] is used to retrieve wind speed from Jason-1 backscatter coefficients and significant wave heights. Global monitoring of Jason-1 RA Operational Sensor Data Record (OSDR) products carried out routinely at ECMWF suggests that Jason Ku-band σo is about 0.4 dB higher than that of ENVISAT. Therefore, Jason-1 σo values were reduced by this amount before applying the algorithm of Eqs. 1-3. More than 18 months (1 November 2003 - 9 March 2005) of Jason-1 data were used and compared to the ECMWF model. The time-series of the global SI for the original OSDR product and as retrieved using algorithm of Eqs. 1-3 are shown in Fig. 6. The proposed algorithm (with σo values reduced by 0.4 dB) produced less error over the whole period. There are two possible explanations for this interesting result. The significant wave height may not be enough by itself to represent the sea-state dependence (see Section 6). The possibility that the algorithm of Gourrion et al. needs further tuning cannot be ruled out as well.

The ENVISAT RA-2 wind speeds in the collocation data set (altimeter - buoy collocations) plotted in Fig. 2 were recomputed using the algorithm of Eqs. 1-3. The resulted scatter plot is shown in Fig. 7. The improvement in wind speed regime below about 10 m/s is very clear in the plot. The few high wind speed observations are now aligned closer to the symmetric line. The bias is reduced by about 0.46 m/s and the scatter index reduced by about 0.5%. Similar results and plot emerged from ERS-2 comparison exercise (not shown). Although clear improvement was attained at low wind speeds, the overall improvement for Jason-1 data was less pronounced compared to the ENVISAT case. Summary of the improvements achieved by the proposed algorithm compared to the original algorithm with respect to buoy data is tabulated in Table 1.

5. IMPLEMENTATION TO ENVISAT RA-2

On 24 October 2005, the near real time RA-2 Level 1b and Level 2 Instrument Processing Facility (IPF) Version 5.02 processing chain was operationally implemented [9]. This processing chain introduced the algorithm of Eqs. 1-3 for the operational wind retrieval. Due

Figure 5: Time-series of the wind speed SI between ENVISAT RA-2 and ECMWF model from the original ESA product (blue) and as proposed by Eqs 1-3 (red) in the whole globe. The difference between the SI values of original and the proposed algorithms is plotted with a reference of the 0.12 value as the turquoise dashed line.

The ENVISAT RA-2 wind speeds in the collocation data set (altimeter - buoy collocations) plotted in Fig. 2 were recomputed using the algorithm of Eqs. 1-3. The resulted scatter plot is shown in Fig. 7. The improvement in wind speed regime below about 10 m/s is very clear in the plot. The few high wind speed observations are now aligned closer to the symmetric line. The bias is reduced by about 0.46 m/s and the scatter index reduced by about 0.5%. Similar results and plot emerged from ERS-2 comparison exercise (not shown). Although clear improvement was attained at low wind speeds, the overall improvement for Jason-1 data was less pronounced compared to the ENVISAT case. Summary of the improvements achieved by the proposed algorithm compared to the original algorithm with respect to buoy data is tabulated in Table 1.

Figure 6: Time-series of the wind speed SI between Jason altimeter and ECMWF model from the original Jason product (blue) and as proposed by Eqs 1-3 (red) in the whole globe. The difference between the SI values of original and the proposed algorithms is plotted with a reference of the 0.10 value as the turquoise dashed line.

Figure 7: As in Fig. 2 but ENVISAT RA-2 wind speed is computed from backscatter coefficients using Eqs. 1-3.
Table 1: Impact of proposed algorithm on altimeter-buoy comparison

<table>
<thead>
<tr>
<th>Altimeter</th>
<th>Period</th>
<th>Bias (m/s) Original Eqs 1-3</th>
<th>Scatter Index Original Eqs 1-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENVISAT</td>
<td>Jan. 2004 - Feb. 2005</td>
<td>-0.59 -0.13</td>
<td>0.1785 0.1696</td>
</tr>
<tr>
<td>ERS-2</td>
<td>Jan. 2000 - Feb. 2005</td>
<td>-0.44 +0.05</td>
<td>0.1991 0.1913</td>
</tr>
<tr>
<td>Jason-1</td>
<td>Oct. 2003 - Aug. 2005</td>
<td>-0.59 -0.40</td>
<td>0.1755 0.1741</td>
</tr>
</tbody>
</table>

to some practical limitations, the implementation was limited to $\sigma^o$ values between 7.0 and 19.6 dB. Beyond those limits wind speed is assumed constant and equals to the terminal tabulated values.

This implementation resulted in enhanced RA-2 wind speed characteristics. The comparisons against the model and the buoy observations show better agreement than before (similar to Figs. 7). The RA-2 wind speed histogram after the implementation of IPF Ver. 5.02 is in better agreement with the model and buoy histograms (see [10]) except for wind speeds below ~1 m/s where there are some doubts whether such very light winds are able to cause any wind wave generation (see [11]).

Fig. 8 shows the time-series of the global wind speed bias between the operational RA-2 and ECMWF model products over a period of 12 months since November 1, each year. While the bias from the period starting in 2003 and in 2004 show comparable negative values (around -0.15 m/s), the bias for the same period starting in 2005 (after the implementation of IPF Ver. 5.02) has a positive value of slightly less than 0.23 m/s. Similar time-series but for the standard deviation of the difference between RA-2 and the model are plotted in Fig. 9. It is clear that the standard deviation of the difference after the implementation of the IPF Ver. 5.02 is lower than the corresponding values in the last two years. The exception is about a month from the middle of December to the middle of January when the standard deviation of the difference from the recent period is comparable with that in the same period starting in 2003.

6. SIGNIFICANT WAVE HEIGHT DEPENDENCE

The sea-state dependence of the altimeter-derived surface wind was the subject of several research efforts (e.g. [2] and [4]). The results of those studies show ranges of impacts from significant to no impact (e.g. [5]). Reference [3] argued quite convincingly that earlier studies reported no sea-state dependency used a limited data set (GEOSAT - buoy collocations) and therefore were not able to detect such effect. Intuitively one would expect that sea state has an impact. The question however, would be: “is significant wave height, $H_s$, the proper parameter that can be related to this impact?” $H_s$ is an integrated parameter that includes both wind sea part (which is directly related to wind speed) and swell part (which may impact the altimeter wind retrieval). Therefore, unless there is a technique to separate those two different parts, it may not be possible to use the altimeter-derived $H_s$ in wind retrieval algorithms. Even Gourrion et al. [3], while introducing $H_s$ in their two-parameter algorithm, warned that $H_s$ may not be the best parameter to use.

ENVISAT RA-2 backscatter coefficients and significant wave heights (after quality control) were collocated with the ECMWF model surface wind speeds over a whole year of 2005. Average wave heights were computed for each bin with $\Delta \sigma^o = 0.1$ dB and $\Delta U_{10} = 0.1$ m/s. Bins of equal mean $H_s$ values were plotted in Fig. 10. Fig. 10 shows that for small wave heights (say $H_s < 2$ m), there is a correlation between wind speed and wave height for a given $\sigma^o$ value. On the other hand, for higher waves, the dependence of the wind speed on $H_s$ is very weak for any given $\sigma^o$ value. Furthermore, Fig. 10 shows that there is a saturation $\sigma^o$ value for each $H_s$ which can not be exceeded irrespective of the wind speed. In other words, there is a threshold $\sigma^o$ value for each $H_s$ so that the wave height dependence does not
hold anymore. Those threshold (or saturation) $\sigma^o$ values can be related to the wave height to the lowest order as:

$$\sigma^o_{\text{threshold}} = 12.62 - 0.77H_s$$  \hspace{1cm} (4)

![Graph showing the relationship between wind speed and backscatter coefficient.](image)

**Figure 10:** Same as Fig. 6 superposed with the dependence of wind speed-backscatter relationship on significant wave height. The relation is plotted for equal wave height values binned in a way similar to Fig. 6 but for the whole 2005.

### 7. CONCLUSIONS

The modified Chelton-Wentz (MCW) algorithm for the retrieval of altimeter surface wind speed from Ku-band altimeters was fine tuned using two-month worth of ENVISAT RA-2 - ECMWF model collocations. The algorithm was later adjusted using RA-2 - buoy collocations during the same period. The algorithm is given in Eqs. 1-3. The algorithm was extensively verified for the Ku-band altimeters of ENVISAT, ERS-2 and Jason-1 against ECMWF model and buoy observations. The algorithm increases altimeter wind speed by about 0.40 m/s compared to MCW algorithm. This is much in line with the expected correct global wind speeds. The proposed algorithm reduces the scatter index by about 5%. The algorithm performs even better than the two-parameter algorithm implemented on Jason-1. The proposed algorithm was implemented for ENVISAT RA-2 on 24 October 2005. Verifications over a year after the implementation showed better performance in terms of wind speed retrieval.

One year worth of data showed that the use of significant wave height as a second parameter for the altimeter wind retrieval algorithms may not be a proper choice for high sea-state conditions. It seems that there is a saturation backscatter coefficient value for each significant wave height which can not be exceeded irrespective of the wind speed. This issue needs further investigation.

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### REFERENCES


