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Validation of significant wave height product from Envisat ASAR using triple collocation

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Abstract. Nowadays, spaceborne Synthetic Aperture Radar (SAR) has become a powerful tool for providing significant wave height. Traditionally, validation of SAR derived ocean wave height has been carried out against buoy measurements or model outputs, which only yield an inter-comparison, but not an ‘absolute’ validation. In this study, the triple collocation error model has been introduced in the validation of Envisat ASAR level 2 data. Significant wave height data from ASAR were validated against in situ buoy data, and wave model hindcast results from WaveWatch III, covering a period of six years. The impact of the collocation distance on the error of ASAR wave height was discussed. From the triple collocation validation analysis, it is found that the error of Envisat ASAR significant wave height product is linear to the collocation distance, and decrease with the decreasing collocation distance. Using the linear regression fit method, the absolute error of Envisat ASAR wave height was obtained with zero collocation distance. The absolute Envisat ASAR wave height error of 0.49m is presented in deep and open ocean from this triple collocation validation work.

1. Introduction
Significant wave height (Hs) of ocean surface wave is one of the most important parameters for offshore engineering. Nowadays, spaceborne Synthetic Aperture Radar (SAR) has become a powerful tool for providing Hs, due to its high spatial resolution, wide spatial coverage and all-weather capability[1] [2].

Traditionally, the validation of SAR derived Hs has been carried out against buoy measurements[3] [4] [5] or ocean wave model outputs[4] [6]. In such type of validation works, the quality of the SAR Hs products is simply assessed through the direct comparison using the standard statistical methods (e.g. estimation of root mean square error), assuming no error in the observations nor model results. However, These methods only yield a inter-comparison, but not an ‘absolute’ validation.

Recently, triple collocation error model, in which the errors in all the collocated triple data set are taken into account, has been proposed [7] and now widely used in the validations of triple data set comparison, such as ocean wind and stress[8], soil moisture[9], and sea surface temperature[10]. Although Janssen P applied the triple collocation error model to carry out the error estimation from European Remote Sensing Satellite-2 (ERS-2) altimeter wave height data[11], this powerful error analysis method has not been used in the validation of significant wave height product from SAR data.
In this paper, the triple collocation error model is introduced in the validation of Envisat ASAR wave mode level 2 data, in order to estimate the root mean square error (RMSE) of significant wave height for ASAR data. The impact of the collocation distance on the error of ASAR wave height is also discussed.

2. Data sets

2.1. Envisat ASAR wave mode data
In wave mode, the Envisat ASAR collects data to form small SAR images (called imagettes) of 5 by 10 km every 100 km at incidence angle of 23°. The Envisat ASAR wave data used here were taken from 2003 to 2008, covering a period of six years. One example of Envisat ASAR imagette acquired at 19:16 UTC on 10 January 2009 over Pacific near Moresby Island of Canada is shown in figure 1. The products of Envisat ASAR used here are the Level 2 ocean wave spectra, as shown in figure 2.

![Envisat ASAR imagette](image1.png)

**Figure 1.** Envisat ASAR imagette acquired over Pacific near Moresby Island on 10 January 2009.

![Level 2 SAR ocean wave spectra](image2.png)

**Figure 2.** Level 2 SAR ocean wave spectra of the Envisat ASAR imagette.

2.2. Buoy data
Buoy wave height measurements are usually assumed to be of high quality and have been used in numerous studies for SAR wave height retrieval validation work. Significant wave height data have been collected from 152 buoys, which are freely available on the internet (http://www.ndbc.noaa.gov). The buoy data used here are obtained from three buoy networks: the National Oceanic and Atmospheric Administration’s (NOAA) National Data Buoy Centre (NDBC), the Coastal Data Information Program (CDIP), and the Environment Canada’s Marine Environmental Data Service (MEDS). The locations of the buoys used for this study are depicted in figure 3.

![Locations of the 152 collocated buoys](image3.png)

**Figure 3.** Locations of the 152 collocated buoys used in the validation.
2.3. Wavewatch III Hs hindcast

The third dataset used in this work are the wave height hindcast results from WaveWatchIII ocean wave model provided by IFREMER (Institut français de recherche pour l'exploitation de la mer). This dataset were downloaded via FTP from IFREMER. The globally hindcast results have a resolution of half by half degrees.

It should be noted here that, the wave height hindcast have not been assimilated with any observations (SAR or buoy) by now. Therefore, the triple datasets of Envisat ASAR, buoy, and model hindcast are independent. In this context, the errors of these independent triplets can be analyzed by the triple collocation error model, presented in the next section.

3. Triple collocation error model

Suppose three estimates $H_{\text{buoy}}$ (buoy wave height observation), $H_{\text{ASAR}}$ (Envisat ASAR wave height product) and $H_{\text{ww}3}$ (WaveWatchIII wave height hindcast), with their independent random errors ($e_{\text{buoy}}$, $e_{\text{ASAR}}$ and $e_{\text{ww}3}$), relate to the hypothetical true significant wave height $H$ linearly as shown below:

$$
H_{\text{buoy}} = \beta_{\text{buoy}} H + e_{\text{buoy}} \\
H_{\text{ASAR}} = \beta_{\text{ASAR}} H + e_{\text{ASAR}} \\
H_{\text{ww}3} = \beta_{\text{ww}3} H + e_{\text{ww}3} .
$$

(1)

The linear calibration constants $\beta_{\text{buoy}}$, $\beta_{\text{ASAR}}$ and $\beta_{\text{ww}3}$ in equation (1) can be eliminated by introduced new variables $H'_X = H_X / \beta_X$, $e'_X = e_X / \beta_X$ (with subscript X standing for buoy, ASAR, and ww3, respectively), and then eliminate the unknown truth $H$ utilizing the assumption of independent errors in order to obtain

$$
\{e_{\text{buoy}}^2\} = \left( \left( H_{\text{buoy}}' - H_{\text{ASAR}}' \right) \left( H_{\text{buoy}}' - H_{\text{ww}3}' \right) \right) \\
\{e_{\text{ASAR}}^2\} = \left( \left( H_{\text{ASAR}}' - H_{\text{buoy}}' \right) \left( H_{\text{ASAR}}' - H_{\text{ww}3}' \right) \right) \\
\{e_{\text{ww}3}^2\} = \left( \left( H_{\text{ww}3}' - H_{\text{buoy}}' \right) \left( H_{\text{ww}3}' - H_{\text{ASAR}}' \right) \right).
$$

(2)

The implementation of the error model using a iteration procedure described by Janssen [11] can be outlined as follows. First, the method starts with the initial guess of $\beta_{\text{ASAR}} = 1$, $\beta_{\text{ww}3} = 1$ and scales $H_{\text{ASAR}}$ and $H_{\text{ww}3}$ with $\beta_{\text{ASAR}}$ and $\beta_{\text{ww}3}$. In addition, first estimates for the errors and the calibration constants are determined using equation (2) and a neutral regression[12], respectively. In the next step, $H_{\text{ASAR}}$ and $H_{\text{ww}3}$ are scaled with the newly found estimates for $\beta_{\text{ASAR}}$ and $\beta_{\text{ww}3}$, then the errors and the calibration constants are determined again, until the convergence is achieved. Lastly, the RMSE of the Envisat ASAR significant wave height product can be obtained by $\text{RMSE}_{\text{ASAR}} = \{e_{\text{ASAR}}^2\}$.

4. Triple collocation and error analysis

4.1. Collocation criteria and collocated results

It is well known that the buoy and SAR measurements have little opportunity to be collocation exactly in space. Therefore, the collocation distance is an important issue in the validation work. In this context, the impact of collocation distance was analyzed using 6 years triple datasets.

In this study, different distances have been chosen as maximum distance of collocation criteria, from 200 km to 10 km, stepped by 10 km. Figure 4 shows how this collocation procedure works as an
example. As shown in figure 4, the distance between imagette acquired at 19:16 UTC on 10 January 2009 and the buoy in the west of Moresby Island (with NDBC buoy ID 46208) is 31 km.

The histogram in figure 5 shows the results of collocations through the match-up numbers of different distances. One can find that, the match-up numbers drop significantly with the decreasing collocation distance. For 200km, the number is above 17,000, and for 10 km, the match-up have only less than 100 for 6 years.

Furthermore, the collocations with deep and open ocean buoys, which were deployed at deeper than 200m water depth and 50 km offshore, have been selected from the total collocation results, with its histogram shown in figure 6.

**Figure 4.** Collocation example of Envisat ASAR and buoy.

**Figure 5.** Histogram of triple collocation numbers with the all buoys.

**Figure 6.** Histogram of triple collocation numbers with the deep and open ocean buoys.

4.2. *Error analysis on collocation distance*
Using the triple collocation error model presented above, the significant wave height errors for the Envisat ASAR wave mode data have been estimated. The estimation of the error for the Envisat ASAR with the dependence of the collocation distance is shown in figure 7. In the figure, the circles and lines refer the RMSE of Envisat ASAR Hs and the regression lines, respectively, while the blue and red symbols indicate the results from all buoys and deep-and-open-ocean buoys, respectively. It is shown that, the errors of Envisat ASAR are linear to the collocation distance, and decrease with the decreasing collocation distance.

Using the linear regression fit method, we obtained the error of Envisat ASAR for significant wave height with zero collocation distance. With this collocation distance, the buoy and satellite measurements were collocated exactly in space, which will be hardly achieved using the direct comparison of ASAR products and buoy observations. The RMSEs of 0.5551 m and 0.4899 m for the Envisat ASAR Hs are presented for the regions of all buoys and deep-and-open-ocean buoys, respectively.

5. Conclusions
The triple collocation error model technique is a promising method to estimate the error structures from remote sensing retrievals. In this study, we collocated significant wave height data from NDBC buoys, Envisat ASAR, and WaveWatchIII model within different spatial windows, for the duration of 6 years. First time, the triple collocation error model was introduced in order to estimate the RMSE of Envisat ASAR wave mode level 2 wave height data. The RMSEs of 0.5551 m and 0.4899 m for the Envisat ASAR Hs are presented for the regions of all buoys and buoys in deep and open ocean, respectively.
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