Retrieval of integral ocean wave parameters from SAR data using an empirical approach

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Abstract

Spaceborne Synthetic Aperture radar (SAR) is still the only instrument providing continuous two-dimensiona (2-D) ocean wave measurements on a global basis. For more than a decade the European satellites ERS-1 and ERS-2 have acquired SAR data over the open ocean operating in wave mode. The ERS acquisitions are currently continued by the ENVISAT ASAR wave mode. It is well known that the derivation of ocean wave parameters from SAR data is not straightforward and different approaches have been proposed. In this study we present a new technique, which is based on an empirical SAR imaging model. The method has the calibrated SAR image as the only input. A data set of 6000 globally distributed ERS-2 wave mode image spectra and collocated ocean wave spectra computed with the numerical model WAM are used to fit a linear model, which relates the SAR spectrum to integral wave parameters like, e.g., the significant wave height. This model is then used for ocean wave parameter retrieval. The radar cross section and the azimuthal cut-off wavelength estimated from the wave mode images are used as additional input variables. The method takes into account the coupling of the different parameters and is based on a least-square minimisation approach. The resulting coupled linear system of equations is solved using a singular value decomposition technique. Disjunct subsets of the collocated data set are used for fitting the model and retrieving ocean wave parameters. Scatterplots and global maps with the derived parameters are presented. It is shown that the standard deviation of the retrieved significant waveheight with respect to the WAM waveheight is in the order of 0.62 m. Other wave parameters, which are of practical relevance like mean wave periods are investigated as well.

1 Introduction

It is well known that synthetic aperture radar data contain information on ocean waves [1, 2]. There is still a lot of debate however about efficient techniques to estimate wave parameters from SAR data. If the objective is to estimate the two-dimensional (2-D) ocean wave spectrum there are basically two approaches. In the first approach the measurement is restricted to the long wave regime accepting the fact that some information on shorter waves is lost [3]. The second approach estimates the complete 2-D wave spectrum using some additional a priori information, e.g., taken from numerical ocean wave models [4, 5].

In this paper a different approach is investigated, which has the objective to estimate integral wave parameters like the significant wave height $H_s$, or the mean wave frequency from SAR data without explicit retrieval of the 2-D ocean wave spectrum. The idea is to fit a linear model which relates different key parameters of the SAR data, like the azimuthal cut-off wavelength, the normalized radar cross section (NRCS) or the image variance to the ocean wave parameter.

2 Data Set

To fit the model a colocated data set of 6000 ERS-2 wave mode cross spectra and corresponding 2-D ocean wave spectra from the ocean wave model WAM run at the European Centre for Medium-Range Weather Forecast (ECMWF) is used. The ERS-2 wave mode data set was processed at DLR and is described in more detail in [6]. The data are standard output from the operational WAM model runs performed at ECMWF at the four synoptical hours 00:00, 06:00, 12:00, and 18:00 UTC. The temporal gap between WAM and SAR measurement is thus less than 3 hours. The model is driven by $U_{10}$ wind fields computed with the atmospheric general circulation model (AGCM). The operational WAM model was run with a $1.5^\circ \times 1.5^\circ$ latitude-longitude grid. The collocation distance to the ERS-2 imagettes is thus less than 0.75 $^\circ$. The wave model data are given on a polar grid with 30$^\circ$ directional resolution and 25 frequencies.

3 General Approach

The derivation of a linear model for the parameter estimation is based on a least square minimisation. Let $S$ be a vector of SAR parameters with dimension $N_p$ and let $w$ be the corresponding ocean wave parameter. A model for the estimation
of \( w \) is fitted by minimising the following cost function

\[
J = \sum_{j=1}^{N} \left( w^{(j)} - a_0 - \sum_{i=1}^{N_p} a_i S^{(j)}_i \right)^2
\]

(1)

where \((w^{(1)}, S^{(1)}), \ldots, (w^{(N)}, S^{(N)})\) represent the available colocation pairs and the coefficients \(a_0, \ldots, a_{N_p}\) are to be determined.

Defining the matrix \( W \) of dimension \((N_p + 1) \times (N_p + 1)\) by

\[
W_{k,k'} := \sum_{i=1}^{N} \overline{S}_k^{(i)} \overline{S}_{k'}^{(i)}
\]

(2)

and the vector \( b \) of dimension \(N_p + 1\) by

\[
b_k = \sum_{i=1}^{N} w^{(i)} \overline{S}_k^{(i)}
\]

(3)

where we have defined \( \overline{S} = (S, 1) \), the solution for \( a \) follows from the system of linear equations

\[
b = W a,
\]

(4)

which was solved using a standard singular value decomposition technique in this study.

Once the model is fitted with the above approach the parameter \( w \) can be estimated from given SAR parameters \( S \) according to

\[
w \approx a_0 + \sum_{i=1}^{N_p} a_i S_i
\]

(5)

The fitting of the parameters \( a \) is done on a different data set then the subsequent tests of the model, which are shown as scatterplots in this paper. Both separate data sets contain about 2700 collocations each.

4 A three parameter model for \( H_s \)

In the first step a simple three parameter model was fitted for the estimation of the significant waveheight \( H_s \). The chosen parameters are given by

\[
S = (\rho_{1,2}, \lambda_{cut}, \sigma_0)
\]

(6)

where the components have the following meaning:
Figure 2: Global map with significant wave heights estimated with the empirical approach from 2700 ERS-2 SAR wave mode images acquired in early September 1996.

Figure 3: Difference between the SAR derived wave heights in Fig. 2 and colocated ECMWF WAM model wave heights.
Table 1: Parameters of linear model for the estimation of $H_s$ from three SAR parameters.

<table>
<thead>
<tr>
<th>$a_0$ [m]</th>
<th>$a_1$ [m]</th>
<th>$a_2$</th>
<th>$a_3$ [m/dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.17</td>
<td>13.49</td>
<td>5.53 10^{-4}</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Figure 4: Scatterplot of SAR derived mean frequency versus mean frequency provided by colocated WAM model data.

- $\sigma_0$: The normalized radar cross section (NRCS) estimated from the wave mode data as described in [7], i.e., the NRCS is the image intensity minus 44.96 dB.
- $\lambda_{cut}$: The azimuthal cut-off wavelength as defined in [8], i.e., $\lambda_{cut}$ is two times the 3dB width of the azimuthal look cross correlation function.
- $\rho_{I_1,I_2}$: The look cross covariance, which is in a good approximation equal to the SAR image variance minus 1 [6].

The first and second order statistics of these parameters as estimated from the fit data set is given by the mean

$$\mu_S = (0.08, 207 \text{ m}, -5.2 \text{ dB})$$

and the covariance matrix

$$\rho_S = \begin{pmatrix} 0.0026 & 1.28 \text{ m} & 0.02 \text{ dB} \\ 1.28 \text{ m} & 15696 \text{ m}^2 & 17 \text{ dB m} \\ 0.02 \text{ dB} & 17 \text{ dB m} & 2.7 \text{ dB}^2 \end{pmatrix}.$$  

Table 1 shows the estimated values for the coefficients $a$ derived from eq. 4 with

$$w = H_s$$

The application of the model to the test data set results in the scatterplot shown in Fig. 1. One can see that even with this simple model a good correlation of 0.84 with an rms of 0.62 m is achieved.

A global map with the SAR derived significant wave heights is shown in Fig. 2. One can see several storm areas in particular on the southern Hemisphere. Furthermore some higher waves can be found in the northern Atlantic, which are associated with the hurricane Fran, which hit the coast of Florida in early September 1996. The difference between the SAR derived wave height and the corresponding wave heights provided by the numerical model WAM run at the ECMWF is shown in Fig. 3. It can be seen that the overall agreement is good. The largest deviations seem to be associated with the strong storm events in the southern Atlantic and Pacific. We expect that the performance can be further improved by including nonlinear effects into the model. This is possible, but makes the cost function minimisation procedure more demanding.
In this section we extend the empirical linear approach described in the previous section for the estimation of the mean frequency

\[ \mathcal{T} = \left( \int F_{f,\varphi} \, d\varphi \, df \right)^{-1} \int f \, F_{f,\varphi} \, d\varphi \, df \]

where \( F_{f,\varphi} \) is the directional frequency spectrum. This means

\[ w = \mathcal{T} \]

in eq. 1. It is quite clear that in this case it makes sense to use more detailed information from the SAR spectrum than just the three parameters used so far. To keep the problem feasible from the numerical point of view we use a coarsely gridded polar spectrum with 6 directions and 5 frequencies between 0.04177 Hz and 0.41 Hz with logarithmic spacing. As the modulus of the SAR cross spectrum, that we use for the estimation is symmetric, we have 15 spectral bins to take into account. In addition we use the three parameters introduced in the last section, i.e., the vector \( \mathbf{S} \) in eq. 1 has the dimension 18. To keep consistent with the definition of the mean frequency the cross spectrum energies are normalized by the total energy of the spectrum, i.e., denoting the cross spectrum with \( \Phi_{f,\varphi} \) we define

\[ S = \left( \alpha^{-1} |\Phi_{f_1,\varphi_1}|, \ldots, \alpha^{-1} |\Phi_{f_5,\varphi_5}|, \lambda_{cut}, \sigma_0, \rho_{f_1,f_2} \right) \]

where \( \alpha \) is given by

\[ \alpha = \int |\Phi_{f,\varphi}| \, df \, d\varphi \]

The resulting model was fitted with a singular value decomposition technique as described in the first section. The respective scatterplot generated from the test data set is shown in Fig. 4. One can see a reasonable correlation of 0.75 and a rms of 0.02 Hz. It is expected that these results can be further improved by introducing nonlinear relationships in the model.

The corresponding global maps with mean frequencies of the WAM model and the SAR measurement are given in Fig. 5 and Fig. 6 respectively. One can see that the overall global distribution of wave frequencies is very well captured by the linear approach.

6 Conclusion

A new empirical approach to estimate integral ocean wave parameters from SAR data has been presented. A linear model was fitted using a colocated data set of ERS-2 wave mode data and corresponding ECMWF wave model spectra.

It was shown that a good estimate of the significant wave height with an rms of 0.62 m derived from an independent data set can be achieved based on three parameters, namely the normalized radar cross section, the azimuthal cut-off wavenumber and the image variance.

An extended approach was presented for the estimation of the mean wave frequency. In this case use was made of more detailed information as provided by the SAR cross spectrum. Using a coarsely gridded polar grid a linear model with 19 parameters was set up. The comparison of the retrieved mean frequencies with the numerical model showed good agreement.
overall agreement with an rms of 0.02 Hz. The same approach was also applied for the retrieval of wind speeds. The comparison with ECMWF wind speeds indicated reasonable agreement with a saturation effect at higher wind speeds.

It is expected that the approach can be further developed and improved by including nonlinear features in the model. This is possible, however the minimisation of the cost function becomes more demanding.

The techniques described in this study are currently applied to a larger data set of two years of ERS-2 wave mode data, which are reprocessed at DLR from raw data provided by ESA in the framework of the ERS AO WaveAtlas.

Acknowledgment

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References