ANALYSIS OF SAR WAVE MODE IMAGETTE TAKEN UNDER EXTREME WIND AND WAVE CONDITIONS

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ABSTRACT

Due to relatively small amount of in situ data available for the open oceans, particularly during extreme events, remote sensing techniques take an important role in the retrieval of geophysical information under such conditions. Up to now the only remote sensing system capable of providing two dimensional sea state information on a global and continuous scale is the Synthetic Aperture Radar (SAR). Is well known that ocean waves play an important role in the dynamics of extreme events like tropical or extratropical cyclones by conditioning the air/sea fluxes of momentum, heat and moisture.

In this study a data set of ERS-2 SAR images “imagette” is used to study extreme wind and wave conditions in hurricane cases.

SAR images of 10 by 5 km size are acquired in Wave Mode every 200 km along the orbit over all oceans providing about 1200 measurements daily. The data set has been reprocessed as single look complex images using the DLR BSAR processor.

A homogeneity test is applied to the imagettes to detect data takes which are affected by atmospheric features, e.g., rain cells. The imagettes are then calibrated using the I/Q channel standard deviation, as imagettes acquired in high wind conditions are particularly affected by power loss.

The retrieved radar cross section is used in combination with collocated ERS-2 Scatterometer data to derive wind speed and direction. Ocean wave parameters are computed for this dataset using the empirical CWAVE approach [1].

The work focuses on some illustrative case studies, e.g., Hurricanes Floyd and Gert in the North Atlantic in September 1999. Comparisons of the SAR retrieved parameters with parametric Holland type cyclone models are performed. Observed deviations between SAR measurements and model parameters are discussed. A strategy to apply the method on a statistical basis to improve parametric cyclone models is presented.

1 INTRODUCTION

The monitoring of extreme weather events over the ocean is a very important application of satellite sensors. Due to its capability to work independently of daylight and cloud coverage SAR measurements of ocean surface parameters taken during extreme events like tropical or extratropical cyclones are an efficient analysis instrument to better understand the dynamics of such storm.

Ocean waves, particularly in high wind and fetch limited conditions, can have an important role in the interaction between the ocean and the atmosphere, since they modulate the air/sea fluxes of momentum, heat and moisture. These parameters have been recognized as fundamental in the development of tropical and extratropical storms [2]. Several studies have demonstrated that SAR images of the ocean surface contain information on ocean waves [3]. Different techniques can be used to retrieve, the propagation direction of ocean waves, the surface wind speed and direction and to identify and analyze mesoscale surface features [4].

This study focuses on the analysis of ocean wave parameters, e.g., significant wave height, and retrieval of surface wind speed in extreme wind and wave conditions using a new data set of reprocessed ERS-2 SAR Wave Mode data. Some illustrative case studies of extreme storms, e.g., hurricane Floyd and Gert, are used for numerical experiments. The potential of wave mode data, which provide high spatial resolution and continuous sampling at the same time, to improve our understanding of storm dynamics is assessed.

The organization of this paper is as follow. In Section 2 the available datasets are introduced. In Section 3 the selection and radiometric calibration of the imagette are described. In Section 4 ocean wave analysis made using the CWAVE1 approach and the validation with numerical are presented. First results of wind speed retrieval using the CWAVE1 approach are shown. Some illustrative case studies of wind retrieval will be presented and discussed. Finally in Section 5 the conclusions and future steps are summarized.

2. DATA SOURCES

2.1 ERS-2 Wave Mode Data Set

In this study a unique data set of ERS-2 SAR Wave Mode images, also called “imagettes” is used to study extreme wind and wave conditions in hurricane situations. In SAR Wave Mode images of 10 x 5 Km with a nominal incidence angle of 23° and a spatial resolution of ~30 m in both dimensions are acquired every 200 Km along the orbit over all oceans. The SAR raw data were processed to obtain single look complex images using the German
Tab I: Number of imagettes acquired within 500 Km of the center of different hurricanes in the season 1999

<table>
<thead>
<tr>
<th>Hurricane track 1999</th>
<th>Num of pass</th>
<th>Num of Imagette</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bret</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Cindy</td>
<td>8</td>
<td>45</td>
</tr>
<tr>
<td>Dennis</td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>Floyd</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Gert</td>
<td>11</td>
<td>48</td>
</tr>
<tr>
<td>Irene</td>
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<td>19</td>
</tr>
<tr>
<td>Jose</td>
<td>6</td>
<td>31</td>
</tr>
<tr>
<td>Lenny</td>
<td>6</td>
<td>27</td>
</tr>
</tbody>
</table>

Fig 1.: Hurricane Floyd (Sep. 1999) imagette track with location of Wave Mode acquisition.

Fig.2. Scatterometer wind field (left) with collocated imagettes (center) and ocean 2D wave spectrum relative to the upper imagette (right) acquired over the hurricane Gert on Sep 19, 1999.

Aerospace Center processor BSAR in the framework of the WAVEATLAS project. More technical details about the reprocessing of the data can be found in [5]. In total more than 800000 imagette were processed, covering the period from January 1999 to December 2000.

The ERS-2 Wave Mode provides about 1200 global measurements each day. In particular the data set contains images acquired over all North Atlantic storms classified as hurricanes [6] in 1999. The number of overflights and the respective number of imagettes acquired in the vicinity of the hurricane (within 500 km from the hurricane center) are summarized in table 1. In Fig 1. the sampling of hurricane Floyd which occurred in September 1999 is shown; the diamonds represent the imagettes acquired within 500 Km from the hurricane center with the color coding referring to the power loss corrected Normalized Radar Cross Section (NRCS). The color of the hurricane path indicates the respective Saffir-Simpson storm intensity categories, as reported in [7].

2.2 Scatterometer data set

As the Wave Mode data is available at the same time and location within the larger ERS-2 SCAT swath, to every imagette a precisely collocated wind vector is associated. ERS Scatterometer wind fields processed at the French Processing and Archiving Facility(F-PAF) are available [6].

Scatterometer measurements of wind direction are used to retrieve wind fields, with higher resolution, from imagette, using the scatterometer algorithm. In Fig 2 a typical scatterometer frame is shown with the position of two
subsequent imagettes superimposed. Wind vectors are provided on a grid of 19 by 19 measurements with coverage of 500 by 500 kilometres and a spacing of 25 kilometres. The maximum distance to the respective Wave Mode imagette is thus 17.7 kilometres. The respective Wave Mode images are shown on the right of Fig. 2.

3. PREPROCESSING OF ERS-2 WAVE MODE DATA

3.1 Investigation of inhomogeneous image features.
To exclude imagettes that contain features that could have a negative effect on the subsequent processing a homogeneity test is applied. Inhomogeneous features found in the open ocean are mainly due to atmospheric phenomena, inhomogeneous wind field or surface slick [5]. The test used has been introduced in [5] and is based on statistical properties of periodograms, which are commonly used for spectral estimation. The homogeneity parameter $\zeta$ defined in [5] is close to one for homogeneous images. For inhomogeneous images it can exceed one significantly. A threshold of 1.05 is used to separate homogeneous and inhomogeneous cases. Most of the imagettes acquired near the hurricanes show homogeneous wave fields, which are suitable for subsequent wave parameter extraction. Only few imagette are inhomogeneous. Such imagette are located near the center of the hurricane showing structures of the eye wall or rain cells, as shown in Fig. 3 where the diamond representing the imagette are coloured according the inhomogeneity value $\zeta$. In total only 5% percent of the imagettes acquired near the hurricane were found to be inhomogeneous.

3.2 Radiometric calibration and power loss correction
Unlike the SAR Image Mode Wave Mode imagettes are not delivered as radiometrically calibrated data by ESA. In any case to use the imagette for the wave analysis and wind speed retrieval their mean intensity has to be accurately calibrated and translated into normalized radar cross section (NRCS) values. In this work a rough first calibration of the imagettes was performed using the calibration constant estimated by [8] using a data set acquired in September 1996. Before applying the calibration a cross check with the new data set described in Section 2 has been made to verify if there is a drift in the value of the constant. The imagette NRCS has been evaluated using the formula

$$\sigma_{\text{im}}^0 = A^\text{s} \cdot k \,, \quad (1)$$

**Fig.4a:** SCAT NRCS vs SAR NRCS before power loss correction.

**FIG. 4b:** SCAT NRCS vs SAR NRCS after power loss correction.
where $A$ is the amplitude and $k$ is the calibration constant. The evaluated NRCS has been then compared with the corresponding SCAT NRCS simulated using the geophysical model function CMOD-2FR [7]. Since the real ($I$) and imaginary ($Q$) data channel are quantized by the analog to digital converter (ADC) with a limited number of bits (4 bits for each channel in the case of the ERS-2 wave mode), NRCS measurement are affected by a saturation effect, particularly for high values of NRCS. In Fig.(4a) this effect is shown plotting the imagette NRCS versus the simulated SCAT NRCS.

The power loss correction used to correct the imagette NRCS [9] is given as function of the $I$ or $Q$ channel standard deviation which is computed as part of the processing from the raw data. Fig. (4b) shows the scatterplot of the imagette NRCS vs the SCAT NRCS after the power loss correction is applied. As one can see the power loss correction is significant for values above -4 dB. This level of NRCS values can be easily reached in hurricane conditions, for wind speed above 30 m/s (compare Fig.7).

4. OCEAN WAVES AND WIND SPEED ANALYSIS

In this section, two cases studies are considered. Referring to the hurricane Gert an analysis of the ocean wave spectrum and NRCS of the Wave Mode data is summarized. Referring to the hurricane Floyd a technique that is able to retrieve information on significant wave height and wind speed from Wave Mode data using the empirical CWAVE-1 algorithm [1] is showed.

4.1 Hurricane Gert

It has been demonstrated that SAR data can be used to estimate the 2D ocean Wave spectra [10]. An example of a 2D spectrum retrieved from a SAR image is shown in Fig.3 for the upper imagette. This spectrum shows two wave systems. The first one is a wind sea, with a wavelength of about 125 m, due to the local wind field and is aligned with wind direction. The second longer swell system has a wavelength of about 500 m. Analysis of the imaginary part of the cross spectrum [11] revealed that these waves are travelling in southerly direction. A possible explanation is that the swell was generated by the hurricane Floyd which in that period was located about 1000 kilometers to the north of hurricane Gert. After radiometric calibration and power loss correction, which is particularly significant in this case of high wind speed, the two imagette of Fig.3 have been used to estimate the wind speed using the geophysical model function CMOD-5 (Fig.7), and compared with the SCAT wind speed and the wind speed simulated using the analytical Holland model [12] (tab II). Fig 5 shows a wind speed profile generated using the Holland model with the position and the relative value of speed in correspondence of the two imagettes. The value of speed retrieved from the lower imagette is in agreement with the simulated speed and higher than the SCAT speed, while for the upper imagette the retrieved value and the SCAT value are comparable and both lower than the simulated wind speed. To check whether the spectral parameters are consistent with other wave observations made in hurricane conditions a comparison with a parametric model presented in [13] is carried out. In this model the peak wave period $T_p$ is expressed as a function of the dimensional radial distance

$$\overline{X}_r = X_r g / U^2$$

(2)

and wind speed $U$ as

$$T_p = \frac{1}{0.97} \overline{X}_r^{0.21}$$

(3)

where $X_r$ is the distance to the hurricane center. Using the above values for wind speed derived from CMOD5 and radial distance we get $T_p=10.0$ s for the imagette at the boundary and $T_p=17.2$ s for the imagette closer to the hurricane center (compare Tab. II). This is in reasonable agreement with the observed wavelength of 418 m and 125 m, which correspond to 16.4 s and 9.0 s respectively assuming deep water.

4.2 Hurricane Floyd

The algorithm used for wave and wind parameter extraction is based on an empirical SAR imaging model and has as only input the calibrated imagettes. Using a training data set of imagettes collocated with ocean wave spectra and wind speed computed with the numerical model WAM, run at the European Center for Medium-Range Weather Forecast (ECMWF), a linear model is fitted. It takes as input variable the NRCS, the image variance and a number of additional spectral parameters [1].

In this study the CWAVE-1 method has been used to retrieve the significant wave height $H_s$ from imagette acquired during hurricane conditions. As it is difficult to obtain in situ measurements of sea state parameter, we have used numerical simulations carried out at the University of Miami [14], [15] for validation purposes. Fig. 6 shows an
example of $H_s$ estimation for the hurricane Floyd on 12 Sep. 1999. The $H_s$ retrieved from the imagettes, represented by triangles and color coded according to the vertical right color-bar, is superimposed to the simulated $H_s$ field, with colours referring to the horizontal color-bar. The agreement between the retrieved and the simulated $H_s$ is reasonable.

In a second step the CWAVE-1 algorithm has been used to retrieve the wind speed in 10 m height from imagettes. On a global scale the agreement with ECMWF wind data is reasonable with an rms error of 1.76 m/s that is below the standard used to measure the scatterometer performances [7].

Fig. 8 shows a scatterometer wind field, as color coded background, and the wind speed retrieved from the imagettes as color coded triangles. Even in this particular case the agreement is reasonable and it has to be pointed out that in the wind speed retrieval using the CWAVE-1 algorithm no external information on wind direction was used.
5. CONCLUSION

An analysis of ERS-2 Wave Mode data taken under extreme wind and wave conditions has been presented. The analysis has shown a good coverage along Hurricanes offering the opportunity of a statistical study of storms dynamics. Spectral information provided by SAR contains valuable information about the ocean wave dynamics in storms. First comparison of SAR derived wave heights with numerical model data show good agreement. First result of the of wind speed retrieval with CWAVE are promising.

It is expected that the results of the present study will give contributions to the improvement of the retrieval of sea state parameters, in particular under extreme conditions, and so to improve forecast models, in the long run.

REFERENCES

7. Off line Wind Scatterometer ERS Product User Manual (V2.1), CERSAT-IFREMER, Jan 1999
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