Analysis of two dimensional sea surface elevation fields using spaceborne SAR

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Abstract**—Space borne Synthetic aperture radar are able to provide high resolution measurements of ocean waves on a global scale.**

The present study uses a reprocessed data set of complex SAR images acquired by the European Remote Sensing satellite ERS-2 to estimate different wave parameters relevant for ship security. In addition, a new method is presented to derive two dimensional sea surface elevation fields from complex SAR data.

The method permits to analyze wave fields in more detail than conventional SAR wave measurement techniques, which only estimate the wave spectrum. The technique provides parameters like maximum to significant wave height ratios, wave steepness, or the probability of wave breaking. Global maps and statistics of the new parameters are presented

Keywords-sea surface, sea state, rogue waves.

I. Introduction

Within the past 20 years at least 200 supercarriers, each more than 200 meters long, have been lost. In many cases the cause of the accident is believed to be 'rogue waves', i.e. individual waves of exceptional wave height or abnormal shape. The study of the ship accidents is often difficult as they have to rely on eye observations of the ship personal. In general it is mentioned in these reports that rogue waves deviate in shape or in height strongly from the average sea state. Such individual waves are transient phenomena on the ocean surface. And neither the occurrence of these waves nor their physical structure is well explained by standard wave models.

The global availability of the SAR imagettes (about 1000 images of 5x10 km^2 globally distributed a day) is used to analyze the occurrence and the shape of extreme wave events.

The standard information derived from SAR comes from a two dimensional spatial Fourier transform, in contrast to the usual buoy derived frequency spectra from time series of local sea surface elevation. Inversion techniques then yield spectral properties of the ocean wave spectrum like significant wave height and mean wave length and direction. Obviously it is difficult to observe and measure extreme waves on a quantitative and regular basis.

The objective of this paper is to present a technique, which provides estimates of the 2D sea surface elevation field from the SAR data. and can thus be understood as complementary to traditional retrieval schemes which provide estimates of the respective second order statistical moment given by the wave spectrum. Figure 1 shows an example of the 2D elevation field derived from a ERS-2 SAR image [1].

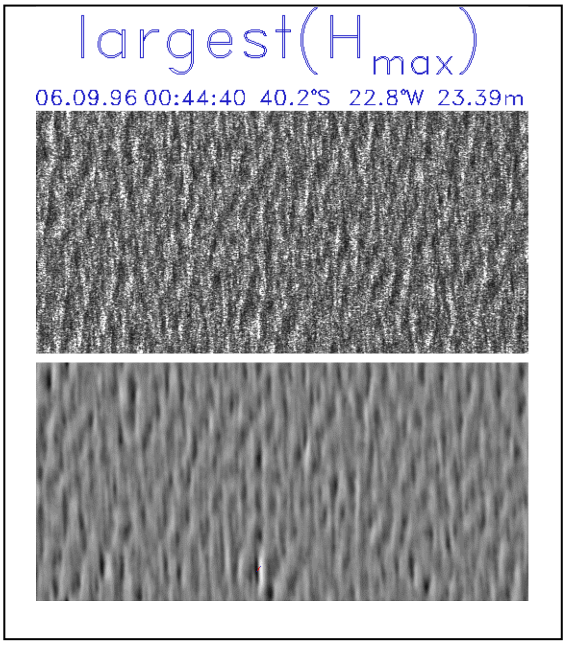

Figure 1. Example of a ERS-2 SAR image and its derived wave elevation field derived from an inversion scheme.

II. Determination of Sea State Parameters from SAR

Traditionally, SAR ocean wave measurements were carried out in the spectral domain using SAR image variance spectra to estimate two dimensional ocean wave spectra [2],[3],[4],[5], [6]. This approach was later extended to SAR look cross spectra, which make use of the SAR integration time in the order of seconds, to retrieve wave propagation directions without ambiguity [6].

A scheme to estimate two dimensional ocean wave spectra from look cross spectra using additional prior information from wave models is, e.g. described in [7].

The idea of the scheme, which is called PARSA (**Par**tition **R**escale and **S**hift **A**lgorithm) is to take the overall shape of the spectrum from numerical wave models like WAM using a spectral partitioning method (see Figure 2).

The SAR measurement is then taken to adjust integral parameters of the different wind sea and swell systems like wave height, wave length, wave propagation direction, and directional spreading.

The main application of the method is global ocean wave model assimilation using ENVISAT ASAR wave mode data.

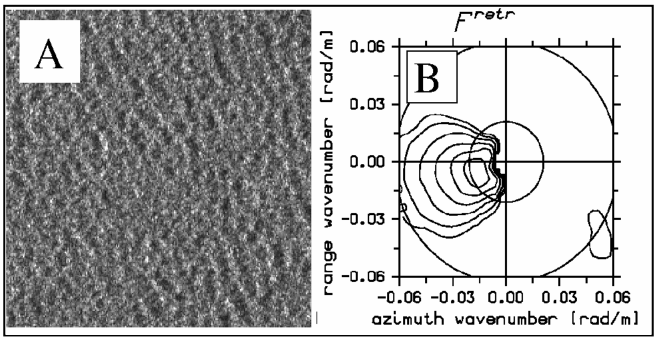

Figure 2. SAR intensity image (A) and the corresponding wave spectral estimation (B) by using the PARSA algorithm.

III. Estimation of Eave Elevation Fields from SAR Images

Although the spectral approach is appropriate in particular for applications like wave model assimilation, detailed information on the two dimensional sea surface elevation field provided by SAR is disregarded.

Instead of doing the SAR ocean wave retrieval in the spectral domain ocean wave fields can be derived by inversion of the complex SAR image itself. Details of this technique are given in [1]. Using a Fourier representation of the ocean wave field ζ

$$\varsigma(\mathbf{x},t) = 2\,\mathrm{Re}\left[\sum_k \varsigma_k \exp(-i(\mathbf{kx}-\omega t))\right] \tag{1}$$

the corresponding normalized SAR intensity image at time $t = 0$ is given by:

$$\frac{I(\mathbf{x}) - \langle I \rangle}{\langle I \rangle} = 2\,\mathrm{Re}\left[\sum_k \varsigma_k T_k^S \exp(-i\mathbf{kx})\right] \tag{2}$$

Here, T^s is the SAR transfer function [2], ω is wave frequency, and ζ_k are the complex Fourier coefficients.

Using the directional information contained in cross spectra [5] the mapping relation given by e.g. 1, 2 can be inverted to obtain an estimation of the sea surface elevation. Note that this quasilinear inversion technique is in general only feasible in cases where the dominant wave system is travelling in the approximate across flight (range) direction, as too much spectral energy is lost due to the azimuthal cut-off mechanism [2] otherwise. Fig. 1 shows a retrieval of a sea surface elevation field using a normalized ERS-2 SAR imagette (5x10 km^2).

IV. Extreme Individual Wave Detection

Taking into account the retrieved wave elevation fields from the SAR imagettes, a further study to detect individual waves can be carried out. Locating each local wave elevation maximum, the closest local sea surface minimum can be detected in order to determine each individual wave heights, and wave steepness. Using this algorithm, the wave height statistics in the spatial domain can be achieve for each imagette.

By using a data set of 34,000 globally distributed ERS-2 imagettes, analysis on a global scale can be carried out.

The extreme waves, much higher than the sea state average, were identified in the data set of 34,000 ERS-2 imagettes by using the criterion that H_{max}/H_s ratio was higher than 2 ($H_{max} > 2\ H_s$).

Fig. 3 shows a global map containing the number of found values in the used ERS-2 data set where $H_{max} > 2\ H_{s,}$ for a funded maximum height higher than 10 m. It can be seen that all the values are located in the southern hemisphere where the winter season was at this time.

The wave heights were found higher than expected before the analysis were carried out, but only two extreme sea states could be found with a maximum wave height higher than 20 m in the analyzed data set.

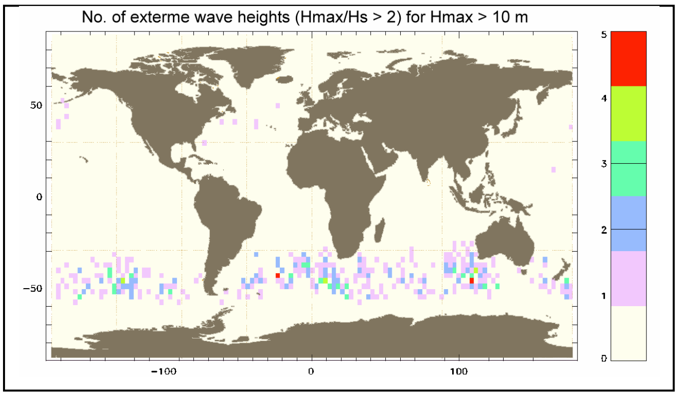

Figure 3. Number of found extreme sea states (Hmax > 2 Hs) during three weeks during three weeks between August-September 1996.

V. Conclusions and Outlook

An algorithm was introduced to estimate 2D sea surface elevation fields from space borne complex synthetic aperture radar data. In particular, it is possible to investigate wave field features in the spatial domain as individual waves.

A new data set of complex ERS-2 imagettes was reprocessed with the DLR BSAR processor, which allows to apply this technique on a global and continuous basis.

An analytical tools has been introduced extending the traditional analysis of one dimensional buoy time series to two dimensional wave fields. Applying the techniques to satellite SAR data, statistics were derived on the occurrence of extreme waves.

The remote sensing techniques described in this study help to find empirical relationships between mean sea state characteristics and probabilities of extreme wave events.

Furthermore, these techniques help to identify "hot spots" and thus to improve risk maps for navigation and installation of off shore structures. With the restrictions mentioned above, it is possible to investigate non-Gaussian features of ocean waves, which can e.g. be caused by rogue waves.

All this results have been obtained by using a data set of 34,000 ERS-2 imagettes, which correspond to three weeks of continuous data between August and September 1996. This amount of information is not enough to carry out a seasonal study of rogue waves and the identification of dangerous areas, were the occurrence of these extreme wave events is more probable. For that purpose, it is necessary to extend the period of analysis, specially taking into account that 10 years of SAR raw data are available. This amount of information will be processed in the future.

Acknowledgment

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