Analysis of Two-dimensional Sea Surface Elevation Fields Using Spaceborne and Ground-Based Remote Sensing Techniques

Wolfgang Rosenthal (1), Susanne Lehner (2), Andreas Niedermeier (2), José Carlos Nieto Borge (2), Johannes Schulz-Stellenfleth (2), Heiko Dankert (1), Jochen Horstmann (1)
(1) GKSS Research Center, Geesthacht, Germany
(2) Deutsches Zentrum für Luft und Raumfahrt, Wessling, Germany

ABSTRACT

This study, which is performed in the framework of the European Project MAXWAVE, deals with both theoretical aspects of extreme waves description as well as new techniques to observe these waves using different remote sensing techniques. The final goal is to improve the understanding of the physical processes responsible for the generation of extreme waves and to identify geophysical conditions in which such waves are most likely to occur.

Space borne Synthetic Aperture Radar (SAR) is capable to provide simultaneous high resolution measurements of ocean waves on a global scale. Due to their all weather capability SAR is still the only instrument providing directional information on waves on a continuous basis.

In the present study a reprocessed data set of complex SAR images acquired by the European Remote Sensing satellite ERS-2 is used to estimate different ocean wave parameters. A new method is presented to derive two dimensional sea surface elevation fields from complex SAR data. The method allows to analyse wave fields in more detail than conventional SAR wave measurement techniques, which only estimate the wave spectrum, i.e. second order moments of the wave field. The technique provides parameters like maximum to significant wave height ratios and wave steepness. Global maps and statistics of the new parameters are presented.

Complementing the SAR measurements a nautical radar operating at X-band near grazing incidence (WaMos II), which can be operated from both ships and ground based stations, is used to analyse the time-space structure of the wave field using temporal sequences of radar images. The data are, e.g. used to investigate the propagation of wave groups.

KEY WORDS: Ocean waves, groupiness, SAR, wavelets, edge detection, ENVISAT, Imagettes.

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. Investigations of the ship accidents is often difficult as they have to rely on eye observations of the ship personal.

Eye witnesses, reporting on individual extreme waves in deep water, mention either single high waves or several successive high waves, and very steep ‘walls of water’. In general it is mentioned in these reports that rogue waves deviate in shape or in height strongly from the average sea state, characterised by the common statistical parameters like significant wave height and peak period. 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. Some areas seem to be more exposed, such as the Gulf Stream (Holthuijsen, 1991), Agulhas Current (Gründlingh, 1999), Kuroshio Current, Nantucket Shoals, Cape Horn, and others. Primary generation mechanisms for these waves can include wave-current interaction, refraction around shoals, diffraction around islands and nonlinear coupling and phasing of different wave components.

Here, the global availability of the SAR imagettes (about 1000 images of 5x10 km globally distributed a day) is used to analyse 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.

Fig. 1 shows the 2D elevation field derived from the SAR images with the highest wave found in the whole data set of about 3 weeks duration. A data set of about 30,000 of such elevation fields is used for the:
- Analysis of individual waves, e.g. freak waves.
- Statistical analysis of maximum wave heights and resulting exceedence probabilities.
- Analysis of wave grouping.
- Estimation of statistical moments higher than second order.
- Detection of inhomogeneous wave features.

Statistics of individual wave height and wave groupiness for the one dimensional case is investigated; e.g., in the papers of Longuet-Higgins (1986), Phillips et al. (1993); Magnusson et al. (1999), and Prevosto et al. (2000).

We will use this global SAR data set to explain the generation mechanisms of extreme waves in respect to either linear superposition for special geophysical situations or due to nonlinear instabilities for the two dimensional wave spectrum.

Fig. 1. SAR ocean wave retrieval in the spatial domain. The left image (A) shows a 5x10 km normalised ERS-2 wave mode imagette acquired at 48.45°S, 10.33°E on Aug 27, 1996, 22:44 UTC. On the right (B) the retrieved sea surface elevation field is shown.

A GLOBAL DATA SET OF REPROCESSED ERS-2 WAVE MODE DATA

To take advantage of the full high resolution image information, ERS-2 wave mode raw data were processed to single look complex SAR imagettes. These data are not available as a standard ESA (European Space Agency) product. The original SAR raw data were processed with the SAR processor BSAR, which developed at the German Aerospace Center (DLR). In total 34,310 SAR imagettes were processed representing 27 days of data between August 21, 1996 and June 2, 1997. Studies on the use of ERS-1/2 wave mode data for wind and wave measurements have been published by Kerbaol et al. (1998), Lehner et al. (2000), Heimbach et al. (1998) and Hasselmann et al. (1996).

Fig. 1 shows an imagette from the reprocessed data set with ocean wave patterns. Details of the SAR processing and a first comparison with ocean wave model data provided by the European Centre for Medium-Range Weather Forecast (ECMWF) can be found in Lehner et al., 2000).

Having the full image information available the reprocessed data set allows to apply image analysis techniques for detection of individual waves and wave groups on a global scale.

Fig. 2. Significant wave heights estimated from a global data set of complex ERS-2 imagettes acquired on September 5, 1996 using the PARSA retrieval scheme.

SAR RETRIEVAL OF OCEAN WAVE PARAMETERS

SAR retrieval of two dimensional ocean wave spectra

Traditionally, SAR ocean wave measurements were carried out in the spectral domain using SAR image variance spectra to estimate two dimensional ocean wave spectra (Mastenbroek et al., 2000; Hasselmann et al., 1996; Krogstad et al. 1994). This approach was later extended to the cross spectra of two SAR looks, which made use of the SAR integration time (about one second for ERS-1/2 and ENVISAT), to retrieve wave propagation directions without ambiguity (Engen et al., 1995).

A scheme to estimate two dimensional ocean wave spectra from look cross spectra using additional prior information from wave models is, e.g. described by Schulz-Stellenfleth (2002). The idea of the scheme, which is called PARSA (Partition Rescale and Shift Algorithm) is to take the overall shape of the spectrum from numerical wave models such as WAM using a spectral partitioning method. The SAR measurement is then taken to estimate integral parameter, (such as wave height, wave length, wave propagation direction, and directional spreading) of different wind sea and swell systems. The main application of the method is global ocean wave model assimilation using the Advanced SAR (ASAR) wave mode data, on board the European satellite ENVISAT. A map with significant wave heights derived with PARSA for a global data set of reprocessed ERS-2 imagettes acquired on Sep 5, 1996 is shown in Figure 2.

SAR retrieval of two dimensional sea surface elevation fields

Although the spectral approach is appropriate in particular for applications like wave model assimilation (Breivik et al., 1998), detailed information on the two dimensional sea surface elevation field provided by SAR is disregarded. Instead of performing 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 by Schulz-Stellenfleth et al. (2002). Using a Fourier representation of the ocean wave field $\zeta$.
the corresponding normalised SAR intensity image at time \( t = 0 \) is given by:

\[
I(x) = \frac{1}{2} \text{Re} \left[ \sum_i \zeta_i \exp(-i(kx - \omega t)) \right]
\]  

Here, \( T_i \) is the SAR transfer function (Hasselmann et al., 1991), \( \omega \) is wave angular frequency, and \( \zeta_i \) are the complex Fourier coefficients.

A new transfer function taking is under investigation.

Fig. 3. Cut through the retrieved ocean wave field in range direction as indicated in Fig. 1.

Using the directional information contained in cross spectra (Engen et al. 1995) the mapping relation given by Eqs. 2, 3 can be inverted. 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 (Hasselmann et al. 1991) otherwise. For the extreme weather cases needed for the generation of rogue waves westerly winds were prevailing causing mainly range travelling waves.

Fig. 1 shows a retrieval of a sea surface elevation field (B) using a normalised ERS-2 SAR imagette (A). The image was acquired in the south Atlantic with about 10 m significant wave height according to the ocean wave model run at the ECMWF. Application of the inversion scheme described in (Schulz-Stellenfleth et al., 2001) using the ECMWF spectrum as prior knowledge gave a slightly higher \( H_s \) of 11.5 m.

DETECTION OF EXTREME INDIVIDUAL WAVES

Individual waves of exceptional height were detected in the derived ocean wave fields using a matched filter approach. The required model for an individual wave is based on a harmonic wave, which decays both in the propagation direction defined by the peak wave number vector \( k_p \) and in the across propagation direction.

\[
m(x) = \cos(k_p x) \cdot \exp(-\alpha(k_p x)^2 - \beta(k_p x)^2)
\]  

Here \( k_p \) is the peak wave number vector found in the retrieved wave spectrum and \( \alpha \) and \( \beta \) are parameters describing the rate of decay in \( k_p \) and \( k_p \perp \) direction. The box in Fig. 1 indicates the location of the highest individual wave found by searching for the maximum of the cross covariance function of ocean wave field and individual wave mode. Eq. 4. Fig. 3 shows the respective cut through the wave field. It can be seen that the detected individual wave has a height of about 30 m. With a corresponding significant wave height of 10 m this wave can be called a rogue wave according to the requirement \( H_{\text{max}} \geq 2H_s \), which is often used as a definition.

Fig. 4 shows a global map of \( H_{\text{max}} \) values estimated from the SAR data set, which was acquired during 3 weeks in the winter season of the southern hemisphere. It can be seen that the highest values occur in the southern Atlantic near Antarctica. In the northern Atlantic high individual waves are observed due to the passage of the hurricanes Fran and George.

Fig. 5 shows an overview of the wave grouping algorithm applied to an ERS-2 SAR imagette from October 7, 1996, 7:31:48 UTC (61°11' S, 22°47' E). This imagette was taken as an example as it shows swell travelling in low wind condition and is thus a good example for detector wavelet based techniques.
quasilinear theory. Wavelet edge detection, which consists of decomposition, thresholding and blocktracing are described by Niedermeier et al. (2000). The red lines in figure 5 are thus steep edges in the SAR image.

Groups of such edges are formed using a blocktracing algorithm and those above a certain threshold are selected. This yields the large blue groups visible on the SAR imagette.

Fig. 5. Scheme showing the wavelet-based grouping algorithm.

**Interpretation of the wavelet coefficients in terms of wave steepness**

From the digital elevation model wave steepness can be derived by gradient methods. Comparing the wave steepness and wave height to the values in the wavelet domain allows an interpretation of the wavelet coefficient in terms of these parameters. Both are correlated to the wavelet coefficient as shown in Table 1.

On the example shown in figure 5, the steepness is correlated to the wavelet coefficient with a value of 0.54. For all available imagettes the correlation is 0.63. The correlation between the wave height and the wavelet coefficient is 0.75. As the thresholding is carried out in the wavelet domain using a relative threshold calculated from the mean and standard deviation of the wavelet coefficients, the groups are detected as the regions of higher and/or steeper waves in comparison to the averaged wave condition in the image.

Table 1. Correlation of maximum wavelet coefficient to maximal wave height/steepness per imagette using all imagettes.

<table>
<thead>
<tr>
<th></th>
<th>All Imagettes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height</td>
<td>0.75</td>
</tr>
<tr>
<td>Steepness</td>
<td>0.63</td>
</tr>
</tbody>
</table>

**WAVE GROUPINESS DETECTION WITH NAUTICAL RADAR WAMOS**

WaMoS (Wave Monitoring System) is an operational sensor, which was originally developed by GKSS Research Center. WaMoS measures wave fields by using nautical radar technology. Nautical radar operate at 9.5 GHz (X-band) with horizontal polarisation near grazing incidence. It covers areas within a radius of about 3 km with a varying resolution in range and azimuth of about 10 m. The radar antenna rotates with 2-second period of revolution. An ordinary WaMoS data set consists of a temporal sequence of sea surface images. Because WaMoS measures in space and time it is a suitable instrument to measure the spatial and temporal behaviour of the sea surface. Fig. 6 shows an example of a sea surface time series scanned with a WaMoS system.

Fig. 6. Example of a temporal sequence of sea surface images scanned with a nautical radar. The measurement was taken by the onshore WaMoS station on Helgoland (North Sea).

Using a multidimensional Hilbert transform, the wave envelope in space and time is computed. The retrieved groups are distinguished according to their area size and maximum amplitude (Dankert et al., 2003). The statistics of the detected is investigating by taking into account several group parameters, such as maximum of the envelope, average group length, distribution of group length, and number of waves in a group. Fig. 7 shows and example of the wave groupiness features detected with a nautical radar station located in the German
island of Helgoland (North Sea). Using a time sequence of such images and the related groups it was possible to estimate the phase and group speed of the ocean waves.

![Image](image-url)

**Fig. 7.** Detection of wave groups approaching to the coast line. The data were recorded by the onshore WaMoS station of Helgoland (North Sea).

**CONCLUSIONS**

An algorithm was developed to derive 2D sea surface elevation fields from space borne complex synthetic aperture radar and nautical radar data. In particular, it is possible to investigate individual waves and wave grouping.

A new data set of complex ERS-2 imagettes was reprocessed with the DLR BSAR processor, which can be applied for a global and continuous basis.

The traditional analysis of one dimensional buoy time series is extended to two dimensional wave fields. Applying the techniques to satellite SAR and WaMoS data, statistics were derived on the occurrence of extreme waves and wave grouping.

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 they help to identify "hot spots" and thus to improve risk maps. With the restrictions mentioned above it is possible to investigate non-Gaussian features of ocean waves, which can, for example, be caused by rogue waves.

At this time only 30,000 images, which correspond to three weeks of data, were available. For this data set, acquired during the southern winter a highest wave of about 30 meters was found in the South Atlantic. The data set is still too small for final conclusions, e.g. on the ratio of maximum to significant wave height. 10 years of SAR raw data are available, which will be reprocessed in the future.

**ACKNOWLEDGEMENTS**

This work has been carried out in the frame of the MAXWAVE project, which is partially funded by the European Commission (contract no. EVK:3-2000-00544).

**REFERENCES**


