Extreme wave statistics from radar data sets

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Abstract. This paper summarizes results from the Maxwave project on the detection of extreme ocean waves by microwave remote sensing techniques. This includes the detection of rogue waves and of extreme wave groups from spatial radar data. Two different radar concepts are used: Spaceborne Synthetic Aperture Radar (SAR) and Marine Radar (Wave Monitoring System II), a wave measuring device based on ordinary nautical radar technology, yielding a time series of radar images. The data were used to compile a census on wave statistics with respect to those of maximum wave height and to improve prediction of extreme events.

Introduction

Traditionally, rogue waves and wave groups have been studied by means of time series analysis of buoy records. This analysis provides information about the temporal variability of such phenomena at a fixed ocean position, e.g. the buoy deployment point. Radar systems, on the other hand, yield spatial information of the sea surface. In the case of nautical radar, temporal information is also acquired. In recent years, radar measurements have demonstrated that both sensors (SAR and nautical radar) are reliable tools to analyze sea state by determining the directional spectra from the radar images and respective inversion techniques. To extend the measurements from expectation values of, e.g., significant wave height and mean direction to individual wave properties like maximum wave height or groupiness, new algorithms to analyze the spatial radar data were developed.

The radar systems used

Spaceborne Synthetic Aperture Radar

Images of these sensors cover large areas of the ocean at a resolution high enough to provide measurements of ocean waves. Spaceborne SAR systems can be used in several scanning modes, e.g., wave mode. Every day approximately 1000-2000 images of 10 x 5 km^2 are acquired across the globe. Image mode renders 100 x 100 km^2 scenes, when the satellite is in line of sight of an antenna station. In ScanSAR mode, as available from the European satellite ENVISAT or the Canadian RADARSAT, areas up to 500 x 500 km^2 are covered. Figure 1 illustrates an example of a RADARSAT ScanSAR image of hurricane Ivan during landfall at Jamaica on September 10, 2004, at 23:13 UTC.

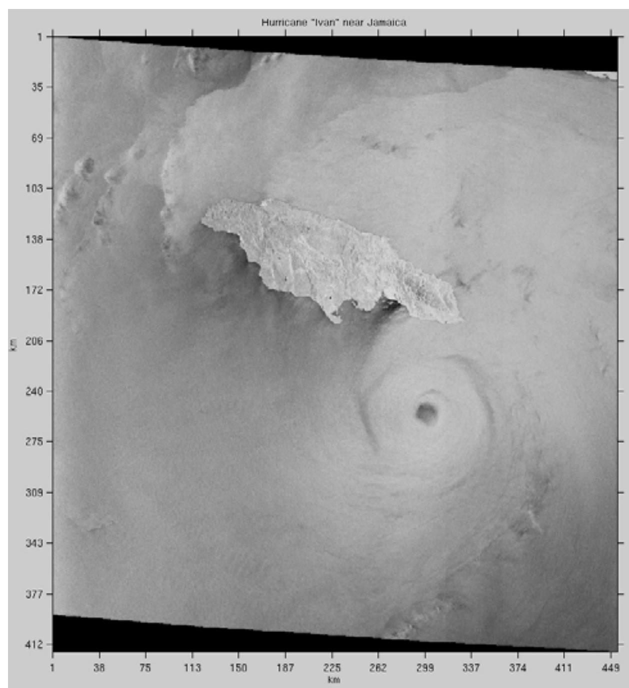

Figure 1. RADARSAT image of Hurricane Ivan (© RADARSAT) acquired on September 10, 2004, 23:13 UTC during landfall at Jamaica.

Even at that extent of coverage individual ocean wave properties can be resolved, the image shows a 250-m ocean wave system radiating out from the hurricane. Dispersion of the ocean waves and refraction around the island can be observed. Figure 2 shows a 10 x10 km^2 subscene of the hurricane eye.

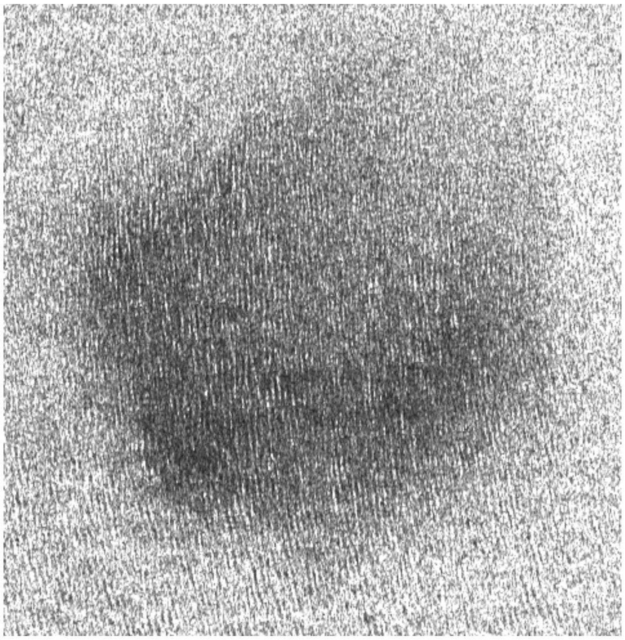

Figure 2. A 10 x 10 km subscene from Figure 1, zoom onto the eye of hurricane Ivan, taken on September 10.

For measurements of the global distribution of extreme waves, a dataset of 27 days consisting of 34,000 ERS SAR imagettes was reprocessed from wave mode radar raw data (*Lehner et a*l., 2000). These data have been used to analyse global wind fields (*Horstmann et al*., 2003), sea state (*Schulz-Stellenfleth et al*., 2005) and to create a global atlas of extreme wave events measured during southern winter (*Lehner et al*., 2002).

Marine radar

Using time series of marine radar images, the development of individual wave crests can be investigated. WaMoS II (Wave Monitoring System) is an operational wave measuring sensor that uses standard marine radars as a remote sensing device. Marine radars are generally used for ship traffic control and navigation purposes. A WaMoS II measurement is a temporal sequence of consecutive radar sea surface images, thus the spatial and temporal variability of the sea surface is measured. It is mounted on coastal towers, as well as offshore platforms, providing sea state information in real time. Figure 3 shows the Ekofisk oil field in the central North Sea with a WaMoS installation and an example radar dataset. Further, wave measuring sensors are placed in this area, i.e., lasers and a waverider. Recently, new techniques were developed extending the capabilities of nautical radar in order to measure high-resolution ocean surface wind fields and sea surface topography (*Dankert et al*., 2003; *Dankert and Rosenthal*, 2004).

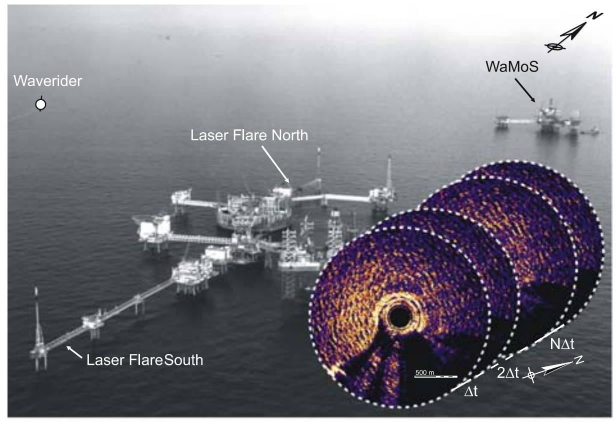

Figure 3. Marine radar measurements at Ekofisk.

Algorithms to derive sea surface topography

Radar images contain information on how the sea surface backscatters the electromagnetic waves rather than the wave elevation itself.

Therefore, to detect individual waves, it is necessary to invert the radar imaging effects in order to obtain an estimation of the original sea surface scanned by the radar sensor. Figures 4 and 5 are flow charts of the radar inversion schemes to derive two dimensional wave spectra and individual sea surface topography.

The PARSA algorithm (*Schulz-Stellenfleth et al*., 2005) is used to derive the two dimensional ocean wave spectrum from a single look SAR cross-spectrum using a wave model spectrum as a first guess. An example of a SAR intensity image and the derived ocean wave spectrum is given in Figure 6. Figure 7 shows a global map of one day of significant wave height derived by the PARSA scheme.

For the investigation of maximum wave height, sea surface topography is determined by numerically inverting the radar transfer functions in order to obtain wave elevation maps. The inverted radar images or radar image sequences are then used for the investigation of the behaviour of single waves, extreme waves and wave groups. Figure 7 depicts the employed LISE scheme (*Schulz-Stellenfleth and Lehner*, 2004).

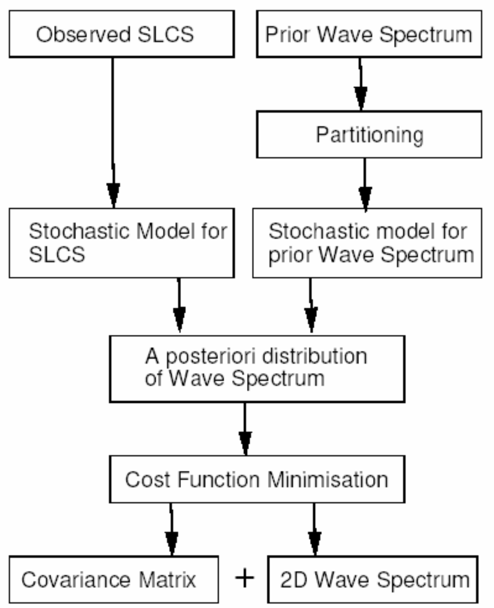

Figure 4. Scheme to invert an observed SAR single-look cross spectrum into a 2D wave spectrum using a prior spectrum, e.g., from a wave model, as a first guess.

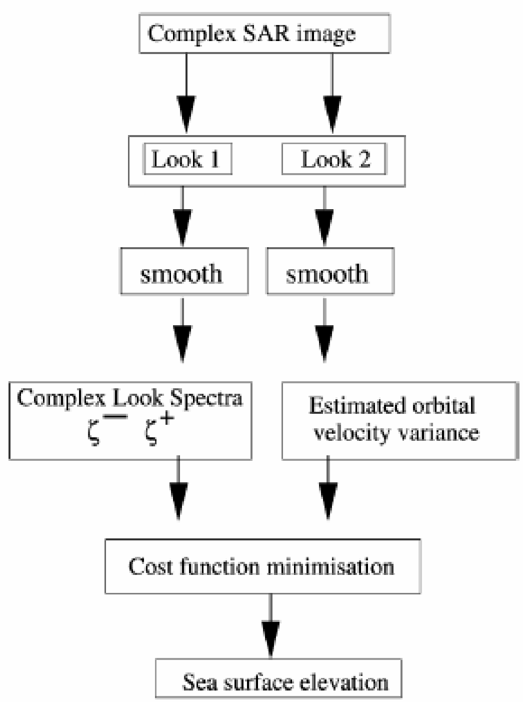

Figure 5. Significant wave heights estimated from a global data set of complex ERS-2 imagettes (10 x 5 km^2) acquired on September 5, 1996, using the PARSA retrieval scheme.

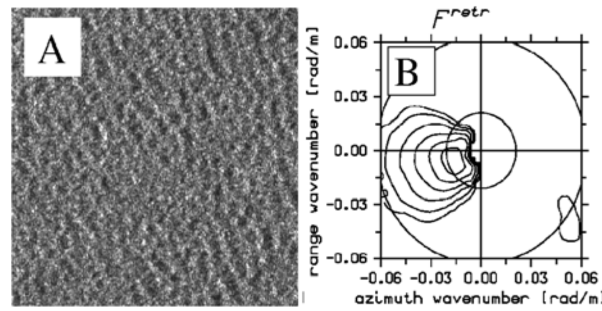

Figure 6. (A) SAR intensity image and (B) the corresponding spectral estimation using the PARSA algorithm.

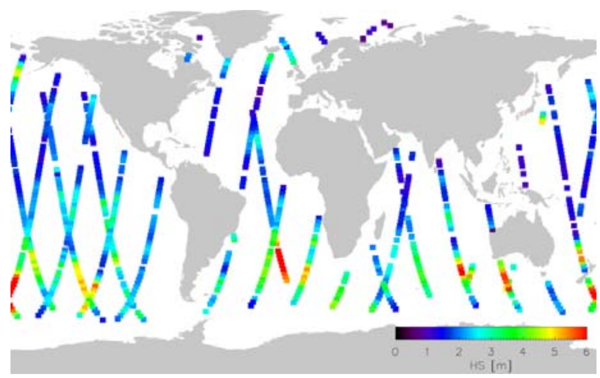

Figure 7. LISE scheme to invert a complex SAR image into a sea surface elevation.

Figure 8 gives an example of a wave elevation map derived from the inversion scheme of an ERS-2 SAR imagette using the LISE method. The square in Figure 8B (wave elevation map) locates the highest wave within the imagette area. The white line indicates a vertical transect, shown in Figure 9.

Once the wave elevation map is obtained, the single wave detection can be carried out. The method locates each single local maximum and finds the closest local minimum, taking into account the direction given by the highest gradient between the maximum and the closest minima.

A sequence of three weeks of imagette data was used in order to derive global statistics for individual wave heights.

The highest waves were found in the following typical situations: The waves were focused in a current, the ocean waves were generated in a moving fetch situation, in which the strongest wind field traveled with the group velocity of the waves. Ship accidents which were recorded as caused by extreme waves happened mainly in crossing seas or under fast changing weather conditions.

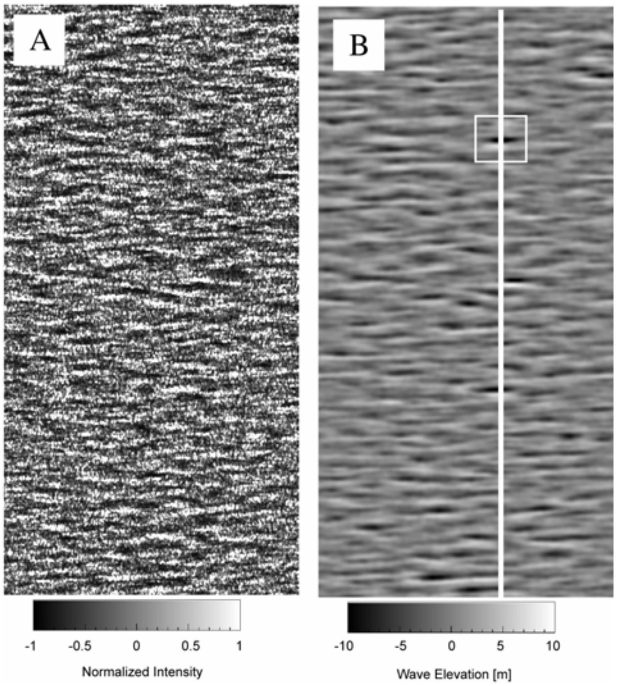

Figure 8. SAR ocean wave retrieval in the spatial domain. (A) A 5×10 km^2 normalized ERS-2 wave mode imagette acquired at 48.45°S, 10.33°E on August 27, 1996, 22:44 UTC. (B The retrieved sea surface elevation field.

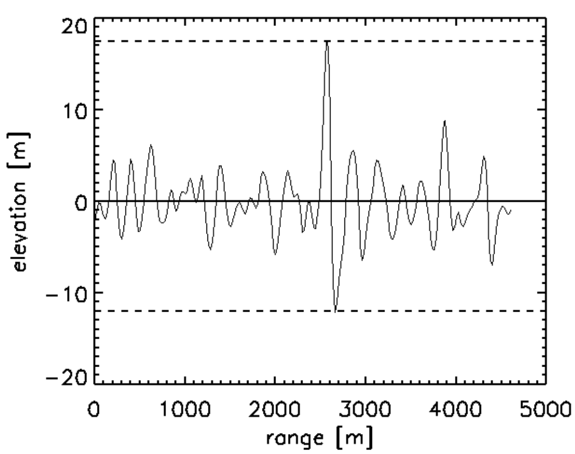

Figure 9. Vertical transect of the retrieved ocean wave field in range direction as indicated in Figure 8**.**

Wave group analysis from radar images and radar image sequences

Wave groups play an important role for the design and assessment of offshore platforms, breakwaters, or ships. Successive large single-wave crests or deep troughs can cause severe damages due to their impact, or may excite the resonant frequencies of the structures. An extreme wave can develop from a large wave group due to interference of its harmonic components. Figure 10 shows groups of high waves detected on marine radar images in shallow water near the North Sea island of Heligoland and at the Ekofisk oil platform. Details on the behavior of the groups in shallow and deep water are given in *Dankert et al*., 2003.

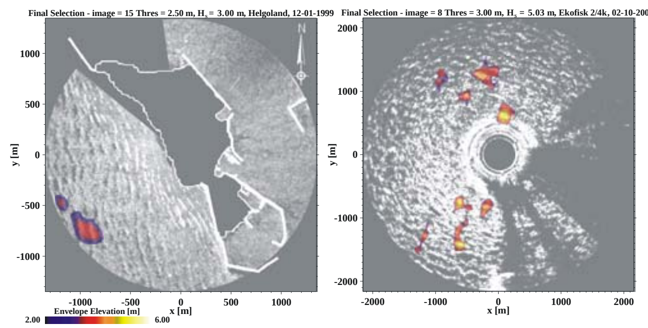

Figure 10. Dominant wave groups from Heligoland (left) and from Ekofisk (right). Transparently overlaid are the wave envelopes of the dominant wave groups with a chosen minimum area size.

For group detection in SAR images two different algorithms have been developed. The first is based on a wavelet decomposition technique to detect the edges between areas of different intensity within the SAR image (*Niedermeier et al*., 2005).

The second method developed for SAR, is based on the determination of the two-dimensional wave envelope, and the group areas are determined by thresholding the envelope (*Nieto Borge et al*., 2004). Figure 11 shows an example of the wave group detection using this method. The threshold height is the significant wave height.

Conclusions

Within the framework of the MaxWave project, new algorithms were developed to derive 2D and 3D sea surface elevation fields from spaceborne complex synthetic aperture radar and nautical radar data, respectively. In particular, these algorithms permit investigation of individual waves and wave grouping. Therefore, the traditional analysis of 1D buoy time series is extended to wave fields defined in the spatial domain and spatial plus temporal domains The application of these techniques to satellite SAR and WaMoS data permit us to derive global, distributed statistics on the occurrence of extreme waves and wave grouping.

Radar datasets were acquired in order to investigate

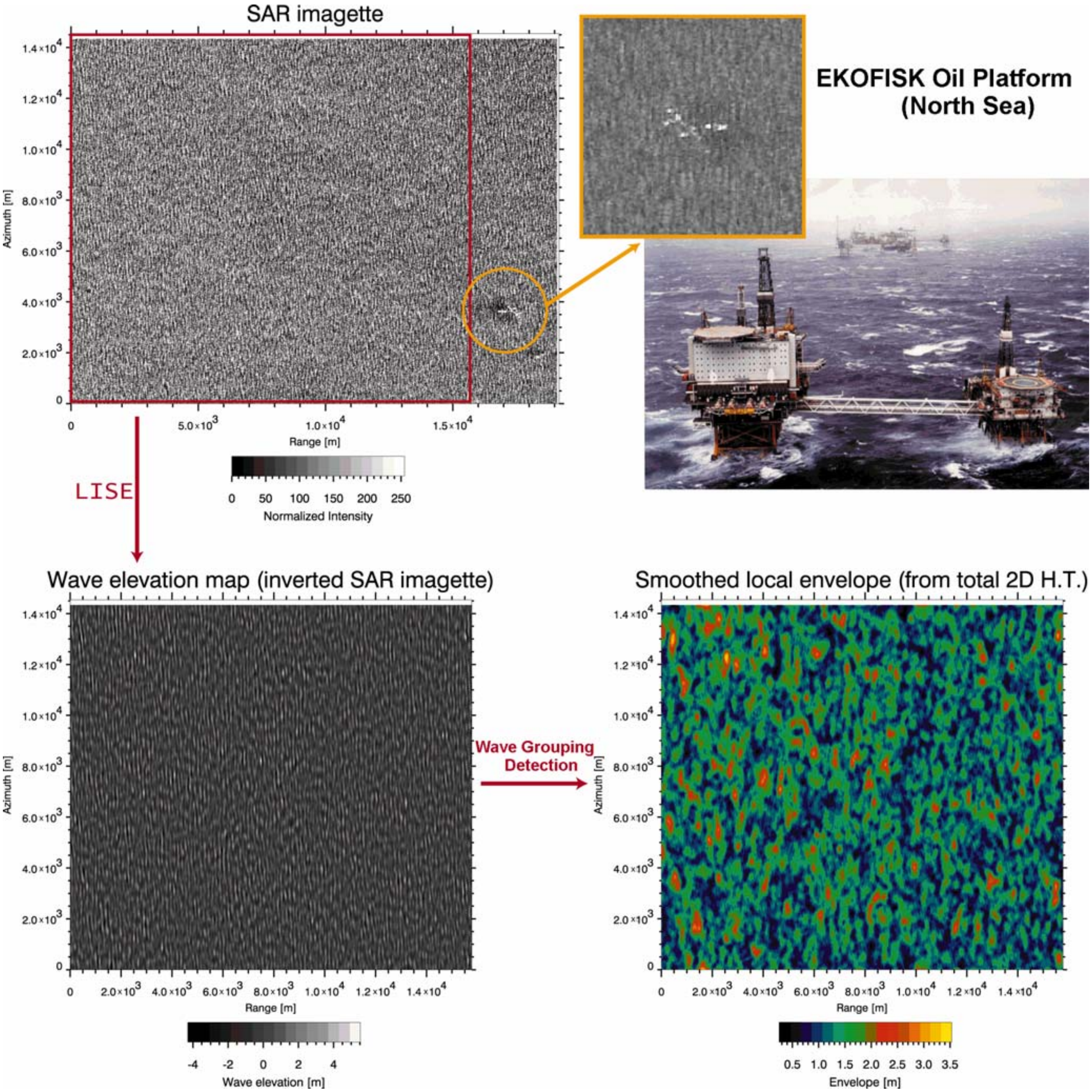

Figure 11. Wave groups measured at the oil platform Ekofisk.

the relationship of maximum to significant wave height. During ship cruises in the Atlantic Gulf Stream and the Algulhas region, joint datasets of marine and space-borne SAR data were acquired. Global imagette datasets yield the possibility to derive statistics and show that there were more extreme waves on the oceans than were expected for this relatively short period of three weeks.

For this study only 34,000 imagettes, which correspond to three weeks of data, were available. In this dataset, acquired during the southern winter, the highest wave of about 28 meters was found in the South Atlantic.

Global SAR raw data since November 1991 are available and will be reprocessed in the future.

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