## WP1 and 3

## DETECTION OF EXTREME SINGLE WAVES AND WAVE STATISTICS

W. Rosenthal, GKSS

H. Dankert, GKSS

J. Horstmann, GKSS

J.C. Nieto-Borge, DLR

H. Guenther, GKSS

A. Niedermeier, DLR

S.Lehner, DLR

J. Schulz-Stellenfleth, DLR

K. Reichert, OceanWaveS

K. Hessner, OceanWaveS

### ABSTRACT

Within the framework of the MaxWave project, new algorithms to detect extreme wave events from radar images have been developed. This work shows results obtained in the project concerning the detection of extreme waves, which produce serious damages to navigation and off shore industry, by using microwave remote sensing techniques. In addition, the paper contains a description of all the different sets of sea surface radar measurements acquired and processed for the MaxWave project. All these data cover different periods and different geographical areas, where different sea state conditions were presented.

### **INTRODUCTION**

Within the last years a considerable number of large ships, as well as off and onshore structures, has been lost or damaged. The causes of these accidents are in





Figure 2. Subimage of about 30km from ERS-2 SAR image mode taken in the vicinity of Cabo de Peñas (northern Spanish coast).

many cases reported as rogue waves. These are individual extreme waves of exceptional wave height and shape.

This paper deals with an overview of the results obtained in the Work Packages 1 and 3 of the MaxWave project. The main objective of the workpackages is the detection, investigation and explanation of rogue wave phenomena. In addition to conventional buoy data and standard spectral analysis, spatial radar data from marine radars and satellite imagery was used. The task included the detection of rogue waves, and extreme wave groups from the data, as well as the investigation on wave statistics with respect to those extreme wave events. As the acquisition of the new data sets and the derivation of new algorithm is best described jointly, the report about workpackage 1 and 3 is given together.

Two different radar concepts were used: Space borne Synthetic Aperture Radar (SAR) and Wave Monitoring System II (WaMoS II), a wave measuring device based on standard marine radar technology. These radar systems are described in more detail in subsequent sections of this paper.

Traditionally, rogue waves and wave groups have been studied by means of time series analysis of buoy records, which provide reliable information about the temporal variability of such phenomena at a fixed ocean position (e.g. the buoy deployment point). Radar systems instead provide spatial information of the sea surface at a given time and thus show a synoptic picture of the spatial structure of the ocean waves. Satellites observe the ocean surface continuously on a global scale thus showing extreme events during hurricanes or in the southern oceans, where most of the extreme events were found during this study. A new quality of observation comes from the fact that crossing seas can easily be observed.

In the case of nautical radar by every turn of the radar antenna, temporal information is acquired, too. In the frame of the project nautical radars were mounted on platforms to collect long term statistics, e.g. at oil platforms or on ships navigating through dangerous ocean areas like the Alghulas Current.

In recent years, it has been 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 suitable inversion algorithms. Although the information that the directional spectrum provides about sea state is very useful to determine expectation values of e.g. significant wave height and mean direction, the directional spectrum is not sufficient to describe properly the wave phenomena as extreme individual events, which are subject of the MaxWave project.

Therefore, it is necessary to extend the methods of analysis of radar images to the spatial domain in order to describe and identify properly individual waves and wave grouping variability in space. Figure 1 shows a scheme of conventional and the newly developed algorithms to analyze those extreme wave phenomena.

The following is structured as follows: The second section describes briefly the two radar sensors used. The third section deals with a description of the available data sets acquired from different measuring campaigns for the MaxWave project. The fourth section shows some results of the different algorithms developed within the project framework to detect individual wave height and wave grouping features. The fifth section shows the results of some of the described algorithms applied to a set of SAR images taken by the European satellite ERS-2. Global scale statistics of extreme wave phenomena are derived, a first step towards a Radar Hogben Atlas. Finally, the lasts section contains the conclusions and the outlook.

#### DESCRIPTION OF THE RADAR SYSTEMS USED

### Space borne Synthetic Aperture Radar

SAR sea surface images cover large areas of the ocean providing synoptic information about ocean waves. Space borne SAR systems can use several scanning modes to detect sea surface features on different scales (e.g. wave mode,  $10 \times 5 \text{ km}^2$ ; image mode,  $100 \times 100 \text{ km}^2$ ; or even larger in Scan SAR mode as provided by the recent European satellite ENVISAT, which can cover areas up to 500 x500 km<sup>2</sup>). Figure 2 illustrates an example of a SAR measurement taken by the European satellite ERS-2 in its image mode. The SAR image shows the long swell refraction due to the water depth changes in the vicinity of Cabo de Peñas (northern Spanish coast).

Beyond just showing a synoptic overview space borne SAR images have been successfully used to derive mean sea state parameters in the open ocean. An example of wave information extracted from SAR images can be seen in Figure 3, where an ERS-2 imagette is used to derive the wave spectrum. This wave spectrum has been obtained using the PARSA scheme (Partition Rescale and Shift Algorithm) [Schulz-Stellenfleth et al., 2003b]. The idea behing PARSA is to take the overall shape of the spectrum from numerical wave models like WAM using a spectral partitioning method (see Figure 2). Figure 4 shows globally distributed estimations of significant wave heights derived from the PARSA algorithm applied to the ERS-1 SAR imagettes acquired on September 5, 1996. In further sections of this report this images are used additionally to determine individual and thus maximum wave height.

Scan SAR images with a coverage of 400 x 400 km and a resolution of 100m do usually no longer show ocean waves, but can be used to determine severe weather systems on a synoptic scale. As an example the retrieval of surface winds from the analysis of the SAR image intensity is shown for a RADARSAT Scan SAR image taken near Greenland [Horstmann et al., ].



Figure 3. SAR intensity image (A) and the corresponding wave spectral estimation (B) by using the PARSA algorithm.



Figure 4. Significant wave heights estimated from a global data set of complex ERS-2 imagettes  $(10 \times 5 \text{ km}^2)$  acquired on September 5, 1996 using the PARSA retrieval scheme.

#### WaMoS II

WaMoS II (Wave Monitoring System) is an operational wave measuring sensor, which uses standard marine radars as a remote sensing device. Marine radars are used generally for ship traffic control and navigation purposes.

A WaMoS II measurement is a temporal sequence of consecutive radar sea surface images. Hence, the spatial and temporal variability of the sea surface is included in the WaMoS II data sets. WaMoS II is suitable to be mounted on coastal tower, as well as off shore platforms, providing sea state information in real time. Figure 5 shows the Ekofisk oil field in the central North Sea with a WaMoS II installation and an example radar data set. Three in-situ sensors, one wave rider buoy and two laser sensors are placed in this area. Recently, a new technique was developed extending the capabilities of nautical radar to determine environmental information. This new technique enables the measurement of high resolution ocean surface wind fields [Dankert et al., 2003b;c].

Figure 5. Exonsk on field in the central Porth Sea. A wave of system is installed on the platform (2/4k) in the background. A temporal sequence of sea surface images is shown. A wave rider buoy is placed near the oil field, and two laser sensors are mounted on the main complex.



Figure 6 shows the comparison of the significant wave height measurements taken from a WaMos II and a buoy. The data were collected in the vicinity of the Ekofisk oil platform (North Sea).



Figure 6. Comparison of significant wave height measurements obtained from buoy records (reference, red dots) and a WaMoS II (black records) installed in the Ekofisk oil platform (North Sea).

#### **RADAR DATA SETS ACQUIRED**

This section gives an overview of all the radar data, which were acquired, processed or made available to MaxWave project, as well as other radar data that were made available to the MaxWave project. Data from different WaMoS II installations on board moving ships (Grey Fox and Northern Pioneer), as well as from the oil off shore platform EKOFISK are available. Space borne SAR data were acquired from two satellites: ERS-1, ERS-2 and RADARSAT-1. The space borne SAR data available in the MaxWave project cover areas from 5 x 10 km<sup>2</sup> to up to 500 x 500 km<sup>2</sup> (ScanSAR). In addition, air borne Interferometric SAR (InSAR), which uses two SAR antennas operating simultaneously and enabling to obtain interferometric measurements of the ocean surface for wave height and current measurements [Schulz-Stellenfleth et al., 2001].

Table 1 summarizes the radar data available within the MaxWave project.

System	Platform	Time period	Location
WaMoS II	EKOFISK	Feb. 2-Sep. 13,	Central
	platform	2001	North Sea
WaMoS II	Grey Fox	Jun. 6-Aug. 6,	See Figure 8
		2001	
WaMoS II	Northen	Feb. 26-may 24,	See Figure 9
	Pioneer	2002	
InSAR	Aircomander	Nov. 9,	North coast
		2000	of Spain
SAR	ERS-1	Apr. 17-May 25,	Golf
		1992	Stream
SAR	ERS-2	Jul. 5-Jul. 8,	Agulhas
		2001	Current
SAR	ERS-2	Nov. 9,	North coast
		2000	of Spain
SAR	ERS-2	Aug. 21, 1996-	Globally
		Jun. 2, 1997	
ScanSAR	RADARSAT-1	Mar. 28-May 30,	South tip of
		2000	Greenland
ScanSAR	RADARSAT-1	1999 and 2002	Atlantic
			Ocean

Table 1. List of radar data available within the MaxWave project.

#### The cruise of Grey Fox

For the MaxWave project a WaMoS II system was installed temporarily on board of the Grey Fox (see Figure 7), which is operated by the Marine Carrier GmbH & Co (MACS). The Grey Fox is a multi-purpose container vessel sailing between Germany and Mozambique. The main purpose of the WaMoS II installation was to receive data from South Atlantic and Indian Ocean, especially from the area that is influenced by the Agulhas current along the east coast of South Africa, where the extreme wave events are observed frequently. This allows investigating wave conditions in ocean regions with strong wave-current interactions, which is believed to be one of the mechanisms for generating extreme waves. All radar data collected during 11 weeks cruise are stored on 34 DDS tapes.



Figure 7. The multipurpose container vessel Grey Fox (left) and the utilized X-band nautical radar antenna mounted on the front mast of the ship (right).

Figure 8 shows the positions of the WaMoS II measurements acquired during the cruise of Grey Fox. In addition to the nautical radar image sequences, space borne SAR data were acquired (see Table 1).



Figure 8. Map with the positions of WaMoS II measurements acquired on board the Grey Fox between June 6 and August 6, 2001.

#### The cruise of Northern Pioneer

In addition to the Grey Fox, another WaMoS II system was installed temporary aboard the container Northern Pioneer vessel (NSB, Niederelbe Schiffahrtsgesellschaft) on February 26, 2002 in Bremerhaven, Germany. The purpose of this installation was to receive data from the eastern North Atlantic, specially from the Gulf Stream area. This allows to investigate wave conditions in oceanic regions with strong fronts and strong currents, where extreme wave events are observed more frequently. WaMoS II sampled and stored data from February 26 to May 24, 2002. Figure 9 shows the positions where WaMoS II measurements were taken.



Figure 9. Map with the positions of WaMoS II measurements taken aboard the Northern Pioneer between February 26 and May 24 2002.

Figure 10 shows an example of a nautical radar image sampled by the WaMoS II system aboard Northern Pioneer. Different wave fronts approaching to the vessel can be seen. The yellow arrow in the Figure indicates the ship heading, and the white arrow indicates the wave propagation direction as determined by the WaMoS II system.



Figure 10. Nautical radar image as obtained by the WaMoS II system onboard Northern Pioneer on February 27, 2002 6:26 UTC. The color coding corresponds to the strength of the radar backscatter.

#### SAR data

As it is detailed in Table 1, different air and space borne data where acquired during the MaxWave project. Figure 11 shows a world map of some of the SAR data set: The 27 days of ERS-2 global distributed imagettes, which have been used to analyze extreme wave events in different areas of the ocean. This dataset based on 34000 imagettes was used to create a global atlas of extreme wave parameters taken during southern winter. Agreements were made with the European Space Agency to process more long term image data time series from the radar raw data in order to create a 'Radar Hogben Atlas'.



Figure 11. World map showing all the positions of 27 days of ERS-2 SAR imagettes processed. Each dot represents a SAR imagette color coded with red (over land), and blue (over water). The yellow color code represent the coverage of one day.

As an additional example of the acquired SAR data set for MaxWave project, Figure 12 shows a large area  $(500 \times 500 \text{ km}^2)$  scanned by the Canadian satellite RADARSAT-1 in its ScanSAR wide swath. The scene corresponds to the area around the southern tip of Greenland. These kinds of images are ideal to measure ocean surface winds in extreme weather situations [Lehner et al., 1998; Horstmann et al., 2000].



Figure 12. RADARSAT-1 ScanSAR images of the South tip of Greenland, acquired on April 1, 2000 at 20:30 UTC. Superimposed is the wind field retrieved from the Scan SAR data (blue arrows) and from the HIRLAM model (red arrows).

All these datasets are the basis for the results on individual wave statistics using the algorithms described in the next chapter.

# DESCRIPTION OF THE ALGORITHMS DEVELOPED

This section shows some results of the recently developed algorithm to determine individual wave parameters. Taking into account the goals of the project, two different kind of studies where carried out within the WP3 for the two different radar sensors (e.g. SAR and WaMoS II). The algorithms can be divided in two main groups: The first group of methods concern all of the techniques related to detect and identify individual waves. The second group deals with the algorithms developed to analyze wave groups from radar images. The description of these methods is detailed in the following sections

# Detection of individual waves from radar images and radar image sequences

The sea surface images, which radar system provide, are a function of many electromagnetic scattering mechanisms at the sea surface, influenced by currents, wave tilting, velocity of water particles, local wind, etc. All these phenomena, known as radar imaging effects yield the radar measurement of intensity. Hence radar images contain information about how the sea surface backscatters the radar fields rather than the wave elevation itself. Therefore, to detect individual waves, it is necessary to invert the radar imaging effects in order to obtain am estimation of the original sea surface scanned by the radar sensor. Figure 13 shows a scheme of the inversion technique. So the different known transfer functions and imaging mechanisms need to be numerically inverted in order to obtain wave elevation maps (for the case of SAR) or temporal sequences of wave elevation maps (for the case of WaMoS II). The inverted radar images or radar-image sequences are then used for the investigation of the behaviour of single wave, extreme waves and wave groups.



Fig. 13. Scheme showing the inversion method to derive wave elevation maps from radar images.

Figure 14 shows an example of a wave elevation map derived from the inversion scheme of an ERS-2 SAR imagette using the LISE method [Schulz-Stellenfleth et al., 2003a]. The square in the right part of the figure (the wave elevation map) locates the highest wave within the imagette area. The white line indicates a vertical transect, shown in Figure 15, where the highest wave can be more clearly seen.



Figure 14. SAR ocean wave retrieval in the spatial domain. The left image (A) shows a  $5x10 \text{ km}^2$  normalised ERS-2 wave mode imagette acquired at  $48.45^{\circ}$ S,  $10.33^{\circ}$ E on August 27, 19969, 22:44 UTC. On the right (B) the retrieved sea surface elevation field is shown.

Once the wave elevation map is obtained, the single wave detection can be carried out. Figure 15 shows a method to determine wave heights in the spatial domain. The methods locates each single local maximum and finds the closes local minimum around taking into account the direction given by the highest gradient between the maximum and the closer minima.



Figure 15. Vertical transect of the retrieved ocean wave field in range direction as indicated in Figure 14.



Figure 16. Detection of the individual wave heights from the wave elevation map shown in Figure 14 (right). Each local maximum is connected to the closest local minimum taking into account the direction given by the highest gradient between the maximum and the minima around.

As was mentioned above each radar (SAR or WaMoS II) has its own special features, which have to be taken into account to develop an inversion scheme, and from this to obtain a reliable estimation of the sea surface.

The main difference between SAR and WaMoS II data is not only the different imaging mechanisms, but the inclusion of the temporal dependence in the measurement. So the inversion scheme permits to derive temporal sequences of wave elevation maps [Nieto et al., 2003].

Figure 17 shows a WaMoS II image obtained at Ekofisk on June, 02, 2001, 22:15 (left). The inverted wave elevation map can be seen in Figure 16 (right). From the temporal sequences of wave elevation maps an inter comparison of the spatial and temporal evolution

of the maximum wave was carried out. The maximum in the elevation map presented in Figure 16, was traced through all radar images. By following all data points on the transect along wave travelling direction, the spatial evolution of the surface elevation was derived. Both time series displayed in Figure 17 yield about the same maximum wave height.



Figure 16. WaMoS II radar image as obtained on June, 02, 2001, 22:15 at Ekofisk. The grey scale corresponds to the radar backscatter strength (left). Corresponding sea surface elevation map (right). The sea surface elevation is color coded. The graph in the lower right corner of the map shows the section with the highest single wave of this measurement.



Figure 17. Temporal (upper panel) and spatial (lower panel) transect of the maximum wave height.

A recent algorithm to derive wave height from WAMOS data using tilt effects has been developed by [Dankert and Rosenthal, 2003d]. This method is as well applicable in the case when there are no in-situ measurements available to perform the nautical radar calibration. The method is based on the determination of the tilt angle at each pixel of the radar images.

# 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, because successive large single wave crests or deep troughs can cause severe damages due to their impact, or they can excite the resonant frequencies of the structures. For ships, an encounter with wave groups can sometimes cause capsize or severe damage. An extreme wave can develop from a large wave group due to interference of its harmonic components [Trulsen, 2001]. Therefore the detection of wave groups in space and time is of extreme importance for ocean engineers and scientists.

For SAR images two different algorithms have been developed. The first one is based on a wavelet decomposition technique to detect the borders between areas of different intensity within the SAR image. As this method works directly with the SAR intensity images, it does not need to apply any kind of previous inversion. Figure 18 shows an example of this method applied to an ERS-2 imagette.



Figure 18. Scheme of the wavelet-based wave grouping detection algorithm. This algorithm can as well be used to determine the crest length of the waves, which is of importance when calculating the impact waves can have on coastal structures.

The second method developed for SAR is based on the determination of the two dimensional wave envelope, the groups areas are there determined after thresholding the envelope. Figure 19 shows an example of the wave group detection by this method. The threshold height is the significant wave height.



Figure 19. Determination of the wave envelope in Figure 14 (up). Wave group detection (down). Each area is color coded depending on its mean wave height.

For WaMoS II image sequences, an algorithm has been developed for investigation of the properties of individual wave groups in space and time. Thereby the temporal envelope of the linear surface gravity waves, which are band-pass filtered, is determined for each point [Longuett-Higgins, 1986]. The filtering and determination of the complex envelope function are performed in the Fourier domain. The radar-image sequences are inverted to give the 2-D sea-surface elevation. The retrieved groups are investigated with regard to their area size and maximum amplitude. Radar-image sequences, collected with WaMoS II, allow the measurement of the spatial and temporal development of wave groups, their extension and velocities [Dankert et al., 2003a].

Figure 20 shows the results of two cases analyzed. On the left hand side a shallow water area with a water depth of 10 m (Helgoland), and beside in deep water (Ekofisk platform).Transparently superimposed are the wave envelopes of the dominant wave groups. All the areas that are retrieved by the method are counted and measured regarding their spatial size, with the result, that the total wave group area size for each inverted image is similar over the image sequence. The groups are not disintegrating in deep water due to dispersion. Fmal Selection - mage = 15 Thres = 2.50 m, H, = 3.00 m, Helgoland, 12-01-1999





Figure 20: Dominant wave groups from Helgoland (left hand side) and beside from Ekofisk. Transparently overlaid are the wave envelopes of the dominant wave groups with a chosen minimum area size.

On the left hand side of Figure 21 the center of energy of all selected wave groups for a given threshold level of 2.5 m is shown. The travel direction of all groups is varying, but agrees in average with the main travel direction of the single waves. One wave group path is shown in detail together with the travel direction, the group (solid contour) and its gravity center of every fifth time step. The crosses give the gravity center for the other time steps. The gravity centers are converging and diverging periodically over time, which could be a reason for parametric rolling of ships.



Figure 21: Left image: Center of energy of all selected wave groups of a Helgoland data set for a threshold of 2.5 m. One path is shown in detail. Right plot: Phase velocity  $C_0$  of the single waves and group velocity  $C_{\rm gr}$  with their mean values (top) for the highlighted wave group path. The line gives the velocity regarding linear wave theory.

The plot beside shows the phase velocity of the single waves  $C_0$ , the group velocity  $C_{gr}$  with their mean values  $C_{gr} = 8.35 \text{ ms}^{-1}$  and  $C_0 = 11.26 \text{ ms}^{-1}$  and the potential energy for the highlighted wave group path.

The line gives the velocities regarding the linear wave theory for shallow water, which are determined with the frequency and wave number at the spectral peak. Comparison of measured wave group velocities in shallow and deep water show good agreement of the average value with the group velocities resulting from linear wave theory. However, oscillations of the group velocities were observed in 2D. Overall, the application of the algorithm on nautical radar-image sequences shows the applicability of these data for detection and measuring of wave groups in spatial and temporal dimensions.

#### GLOBAL SCALE STATISTICS OF EXTREMA WAVE EVENTS

This section shows results of the application of the algorithms explained above for SAR images of the sea surface. The first example (Figure 22) shows a global map of  $H_{\text{max}}$  values estimated from the SAR data set, which was acquired during 27 days 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.



Figure 22. Map showing maximum single wave heights  $H_{\text{max}}$  derived from 3 weeks of ERS-2 SAR data acquired in August-September 1996. The rough areas in the southern hemisphere and the path of the hurricane *Fran* in the northern Atlantic are visible.



Figure 23. Histograms of ration:  $H_{max}/H_s$  different intervals of  $H_s$  in comparison to the distribution derived from Rayleigh distribution.

From this data set statistics of the ratio: maximum wave height/significant wave height can be carried out. Figure 23 shows the histograms computed for all the data set and separated for different ranges of significant wave height. It can be seen that when the significant wave height is higher the probability of finding a higher relative value of maximum wave height increases.

#### Swell tracking

Using the large amount of data, as the ERS-2 data set different kind of studies on global scale could be carried out. One of these studies is the swell tracking to determine the meteorological conditions responsible for extreme waves. A possible reason for forming of an extreme wave event can be a moving fetch. This situation occurs, when a wave or wave system travels with a storm system collecting energy from its high wind regions for several hours or even days. Within the project Maxwave it was possible for the first time to identify moving fetch as reason for an extreme wave.

The highest wave found in the 3 weeks of ERS-2 data from 1996 using the inversion scheme mentioned above, is an about 25 m wave in the central part of the southern Atlantic imaged on September 6, 00:44:40 UTC. Figures 24 to 26 show how it was tracked backwards in time. Coming from the Brazilian coast the group speed calculated from its wavelength is only slightly lower than the movement of a storm system as given by the ECMWF hindcast model wind fields.

The position of the backward tracking of the wave position stayed within the northern high wind region of the storm for several days as can be seen in Figures 24, 25 and 26. The storm itself turned clockwise on the southern hemisphere and moved eastward therefore hadving its highest wind speeds on its northern edge. Indeed the globally highest wind speeds on September 5 according to the six hourly hindcast model were in the northern part of this storm system.



Figure 25. First step of the 36 hour swell backtracking of most extreme wave found in southern Atlantic on top of the ECMWF hindcast wind field.



Figure 25. Second step of the 36 hour swell backtracking of most extreme wave found in southern Atlantic on top of the ECMWF hindcast wind field.



Figure 26. Third step of the 36 hour swell backtracking of most extreme wave found in southern Atlantic on top of the ECMWF hindcast wind field.

#### CONCLUSIONS AND OUTLOOK

Several different radar data sets were acquired in order to investigate the relationship of maximum to significant wave height. During ship cruises in the Atlantic Gulf Stream and the Alghulas region joint datasets of marine and space borne SAR data were acquired. Global imagette datasets yield the possibility to derive statistics and showed that there are more extreme waves on the oceans than was expected for this period of three weeks. Data acquired with airborne SARs are acquired only during a short time frame like a day, but yield the possibility to investigate into the possibilities of new planned space borne missions.

Within the framework of the MaxWave project, new algorithms were developed to derive 2D and 3D sea surface elevation fields from space borne complex synthetic aperture radar and nautical radar data respectively. In particular, these algorithms permit to investigate 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 domain. The application of these techniques to satellite SAR and WaMoS data permit to derive global distributed statistics 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 34,000 images distributed along 27 days, which correspond to three weeks of data, were available. For this data set, acquired during the southern winter a highest wave of about 25 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. The raw data of two years of ERS data are now in processing and the respective ENVISAT dataset is being collected.

#### REFERENCES

Dankert, H., Horstmann, J., and Rosenthal, 2002, W. Detection Of Extreme Waves in SAR images and Radar-image Sequences, in Proc. of 21st Int. Conf. on OMAE, Oslo, Norway.

Dankert H., J. Horstmann, S. Lehner and W. Rosenthal, 2003a, *Detection of Wave Groups in SAR images and Radar-Image Sequences*, IEEE Trans. Geosci. Remote Sens., Vol. 41, No. 6.

Dankert H., J. Horstmann, and W. Rosenthal, 2003b, *Ocean Wind Fields Retrieved from Radar-Image Sequences*, J. Geophys. Res., in press.

Dankert, H., Horstmann, J., Magnusson, A.K., Rosenthal, W., 2003c, *Ocean Wind Fields Retrieved from Radar-Image Sequences*, IEEE Transaction on Geoscience and Remote Sensing, to be submitted.

Dankert H., and W. Rosenthal, 2003d, *Ocean Surface Determination from X-Band Radar-Image Sequences*. Submitted to IEEE Trans. Geosci. Remote Sens.

Dysthe K.B., Refraction of gravity wave by weak current gradients, 2001, J. Fluid. Mech., Vol. 442, pp. 157-159.

Hoja, D., Schulz-Stellenfleth, J., Lehner, S., and König, T., 2002, *Global Analysis Of Ocean Wave Systems From SAR Wave Mode Data*, 3 Pages. IGARSS. Toronto, June 24rd-28th 2002, WEE, New York.

Horstmann, J., Lehner, S., Schiller, H. 2000, *Global Wind Retrieval From SAR Wave Mode Data*, Submitted To IEEE GRS.

Horstmann, J., Weinreich, I., Hauser, D., Lehner, S., and Koch, W.H, 2002a, *SAR Wind Measurements During The FETCH Experiment*, In Elsevier Oceanography Series *66*, *Pp. 445-453*.

Horstmann, J., Koch, W., Lehner, S., and Tonboe, R., 2002b, High *Resolution Wind Fields Retrieved from Spaceborne Synthetic Aperture Radar Images in*  Comparison to Numerical Models, in Proc. of 21s'Int. Conf. on OMAE, Oslo, Norway.

Horstmann, J., Koch, W., Lehner, S., Rosenthal, W., 2002c, *Mesoscale Wind Fields And Their Variation Retrieved From The Synthetic Aperture Radar Onboard ERS-1/2*, To Appear In M. GADE (Ed.): Surface Slicks *And Remote Sensing Of Air-Sea Interaction*, Kluwer Verlag.

Horstmann, J., Schiller, H., Schulz-Stellenfleth, J., and Lehner, S., 2003, *Global Wind Retrieval from SAR*, Submitted to IEEE Trans. Geosci. Remote Sensing.

Lehner, S., Schulz-Stellenifleth, Schättler, J.B. H. Breit, H., Horstmann, J., 2000, *Wind And Wave Measurements Using Complex ERS-2 Wave Mode Data*, IEEE GRS, Vol.3 8, No. 5, Pp. 2246-2257.

Lehner, S., Schulz-Stellenfleth, J., Horstmann, 2001, *Marine Parameters From Radar Satellite Data*, Archives Of Hydro-Engineering And Environmental Mechanics, Vol. 48, No. 2, Pp. 17-29.

Lehner, S. Schulz-Stellenfleth, J., Niedermeier, A., Horstmann, J., Rosenthal, W., 2002, *Detection Of Extreme Waves Using Synthetic Aperture Radar Images*, *3* Pages. IGARSS 2002, Toronto, June 24rd-28th 2002, WEE, New York.

Longuet-Higgins M.S., 1986, Wave group statistics, E.C. Monahan and G. Mac Nioceill (eds.), Oceanic Whitecaps, pp. 15-35.

Niedermeier, A., Romaneessen, E. Lehner, S., 2000, *Coastlines In SAR Images Using Edge Detection By Wavelet Methods*, IEEE GRS, Vol. 3 8, No. 5, Pp. 2270-228 1.

Niedermeler, A., Schulz-Stellenfleth, J., Lehner, S., Dankert, H., 2002, *Ocean Wave Groupiness From ERS-112 And ENVISAT Imagettes*, *3* Pages. IGARSS 2002, Toronto, June 24rd-28th 2002, WEE, New York.

Nieto-Borge, J.C, Niedermeier, A., Lehner, S., Rosenthal, W., 2003a, Determination of wave field properties in the spatial domain from space borne SAR. OMAE 2003 Int. Conf. Proc. Safety and Reliability. Cancun. Mexico.

Nieto-Borge, J.C., Rodriguez, G., Hessner, K., Izquierdo, P., 2003b, *Inversion Of Nautical Radar Images For Surface Wave Analysis*, Submitted To Journal Of Atmospheric And Oceanic Technology.

Nieto-Borge, J.C., Schulz-Stellenfleth, J., Niedermeier, A., Lehner, S., *Determination of Ocean Wave Groupiness from Spaceborne Synthetic Aperture Radar*, 2003c. To be submitted to Ocean Eng.

Schulz-Stellenfleth, J., Lehner, S., 2003a, Measurement Of Two-Dimensional Sea Surface Elevation fields Using Complex Synthetic Aperture Radar Data, Submitted to IEEE TGARS.

Schulz-Stellenfleth, J., Lehner, S. 2003b, A Parametric Scheme For Ocean Wave Spectra Retrieval From Complex Synthetic Aperture Radar Data Using Prior Information. To be submitted to J. Geophys. Res.