X-BAND RADAR AS A TOOL TO DETERMINE SPECTRAL
AND SINGLE WAVE PROPERTIES

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1 INTRODUCTION

Weather and sea state forecasts for the offshore industry are based on spectral sea state parameters which up to now give no information about the risk to encounter extremes. Therefore there is a need to identify additional wave parameters that point at an increased risk for extreme waves and/or dangerous seas.

In recent years X-Band radars have been used to image ocean surface waves. Based on standard marine X-Band radar the wave monitoring system WaMoS II has been proven to be a powerful tool to monitor spectral sea state parameters also from moving vessels.

Within the EU funded project MaxWave and the German project SinSee strong emphasis was put on the development of new analysis software that in addition to the standard spectral wave output (OMAE 2000) allows the determination of single wave events from X-Band radar images. Main topic of the MaxWave project was the investigation of extreme waves and their influence on ships and offshore structures. The ongoing German funded project SinSee is dealing with the relation between ship movements and particular wave events.

In both projects the approach was to look at WaMoS II sea surface elevation sequences to understand the spatial behaviour of single ocean surface waves. To retrieve sea surface elevation maps new algorithms had to be developed. Such maps contain the spatial and temporal description of single waves and hence enable the investigation of individual waves.

For this paper two case studies were performed. In the first study single waves were validated against data retrieved from the wave spectra. It was carried out with WaMoS II data acquired onboard the oil platform 2/4 k at Ekofisk for the storm event May 29, 2001.

The second case study aimed at an independent validation between individual wave parameters derived from radar images and individual waves measured by a buoy. The data used in the second case study was measured on board the offshore wind test platform FINO in the Southern North Sea. A storm event from January 13-15, 2004 was taken for this investigation.

This paper is organized as follows: First an overview of the Ekofisk data set is given. Then the statistical sea state parameters are described with respect to their evolution during a particular storm event. Next the directional wave finding algorithm (DWFA) is presented by means of inverted radar images. A validation approach with data from the FINO platform and a reference wave rider buoy is shown. The paper closes with some examples of individual wave heights and their further potential.

![Figure 1: Geographical situation of the Ekofisk and FINO platform in the North Sea.](image-url)
2 WAMOS II INSTALLATION EKOFISK

Since 1994 a WaMoS II is installed at the platform 2/4 K in the Ekofisk oil field (ConocoPhillips), central North Sea (56°33.9 N, 3°12.4 E). The platform is operating in an area with an average water depth of 70 m. The X-Band radar used for WaMoS II measurements is a Furuno FR1510. The radar receives every 2.55 s a new radar image which has an average spatial resolution of 8.4 m. Each image ranges from 240 m to 2160 m. For one standard WaMoS II measurement a sequence of 32 radar images is sampled.

Within the MaxWave project nautical radar raw image sequences between February 2nd and September 13th, 2001 were stored on tapes. These data sets were scanned in order to identify storm events. For a first case study the storm on May 29, 2001 was identified, as it is characterized by a fast increasing wave height and bimodal sea state.

3 STATISTICAL PARAMETERS

Significant wave height ($H_s$) and peak wave period ($T_P$) are the two most used parameters to describe the sea-state (WMO, 1998). These parameters can be determined directly from the WaMoS II directional wave spectra.

Figure 2 shows the time series of standard sea state parameters during the storm on May 29, 2001 as obtained by WaMoS II (marked black). The standard sea state parameters from a reference buoy are plotted comparative to WaMoS II data (marked blue).

During the storm event $H_s$ increased from 1.5 m to 4.7 m at the peak of the storm (about 10:10 UTC). During the same time $T_P$ increased from about 6 s to 10 s, while the direction $\theta_p$ varied slightly between west and northwest. The measurements of these two sensors show a good agreement.

![Figure 2: Sea state parameters as obtained by WaMoS II and a reference buoy at Ekofisk on May 29, 2001.](image)

The spectral sea state parameters describe the sea state conditions as average values. These parameters do not contain information about the spatial behaviour of individual ocean surface waves. Therefore the further investigations were carried out in order to determine the single waves and thus sea surface elevation maps.

4 DETERMINATION OF SINGLE WAVES

To retrieve single waves the WaMoS II radar image sequences were inverted into sea surface elevation maps. For the inversion a method proposed by Nieto et al. (2004) was used. This approach assumes shadowing as the main imaging mechanism of ocean waves in nautical radar images and is based on linear wave theory.

Figure 3 shows a nautical radar image obtained by WaMoS II with clearly visible sea clutter at Ekofisk on May, 29, 2001, 10:10 UTC which present the peak of the storm. The wave pattern appears in the radar image as areas of high (red) and low (white) image intensity. The lower right area of the image is blanked due to platform construction. The colour-coding corresponds to the image intensity which is related to the radar backscatter strength. The standard wave parameters as determined by WaMoS II are given. The grey arrow indicates the peak wave propagation direction ($\theta_p$).
In order to identify individual wave heights from sea surface elevation maps, a directional wave finding algorithm (DWFA) was developed. Wave crest and troughs are detected in wave propagation direction (± 20°) in a distance of 4.5 times the peak wave length (λp). Wave crests are defined as local maxima of the surface elevation above mean sea level (η = 0) and troughs are local minima of the surface below mean sea level. This spatial algorithm corresponds to the zero up-crossing method which is generally used for the wave height analysis of surface elevation time series.

The horizontal distance between two adjacent zero up-crossing points defines the wave period. The vertical distance between the highest and lowest points between two adjacent zero up-crossing points is defined as the zero up-crossing wave height (H). The distance between a crest and trough is half the wave length.

Figure 4 shows the sea surface elevation map corresponding to the radar image shown in Figure 3. In the sea surface elevation map the wave crests are visible as light areas while wave troughs are dark areas. The individual waves, wave crests and troughs as obtained by DWFA, are localized and indicated as lines with respect to the wave propagation. The white lines demonstrate crests and troughs in wave propagation direction (up crossing wave), black lines respectively against wave propagation (down crossing wave). The black box indicates the area where the highest wave was found. The colour-coding is related to the surface elevation.

In this example N0 = 706 individual waves were determined by DWFA. A maximum wave height of Hmax = 9.0 m was identified in this measurement. The wave height H1/3 represented by the mean of the upper third waves (N1/3 = 235) is 4.9 m. These values coincide very well with the spectral wave parameters, Hs = 4.7 m and λp = 145 m as measured by the standard WaMoS II software (see Figure 3).

Figure 5 shows a cut through the sea surface elevation map where the highest individual wave was detected (see Figure 4, black box).

Figure 5: Cut through the sea surface elevation map of the area where the highest individual wave was detected on May 29, 2001, 10:10 UTC at Ekofisk.
A first validation of the achieved results was carried out by comparing the spatial and temporal evolution of the maximum wave. The related spatial and temporal transects are shown in Figure 6.

The upper panel shows the temporal transect of the surface elevation at the position where the crest of the maximum wave was found. The lower panel shows the spatial transect along the propagation line at the time when the maximum wave occurred. Compared to the relative coarse temporal resolution ($\Delta t = 2.55$ s), the spatial transect exhibits a finer resolution ($\Delta x = 8.4$ m). Both transect show the same characteristic of the wave profile and yield about the same maximum wave height (8.9 m and 9.0 m). The distance between the highest crest and the adjacent troughs give the individual wave wave period $T_i = 10.2$ s and wave length $\lambda_i = 126.6$ m.

The obtained values are in the same range as the spectral wave parameters $T_p = 9.7$ s and $\lambda_p = 145$ m measured by the standard WaMoS II (see Figure 3). This comparison shows that the achieved results are consistent.

5 VALIDATION OF SINGLE WAVE DETECTION

For the validation of the single wave detection algorithms an attempt was made to compare the results with independent surface elevations records from a buoy. At the WaMoS II station Ekofisk the independent wave rider buoy is outside the radar range. This is the reason, why in the following, data measured on board the offshore wind test platform “FINO” in the Southern North Sea (54°0.86 N, 6°35.26 E) was investigated. The platform is operating in an area with an average water depth of 30 m. Since August 2003 the Federal Maritime and Hydrographic Agency (BSH) runs a WaMoS II and a wave rider buoy at the FINO platform.

The buoy is set up to store the data with a frequency of 2 Hz. From that the sea surface elevation and the wave spectra can be determined. The temporal resolution of the buoy measurement is $\Delta t = 0.78125$ s. The buoy is moored so close to the platform, that it sometimes can be seen in the WaMoS II radar images.

5.1 WaMoS II installation at the offshore wind test platform FINO

Since August 2003 a WaMoS II is installed to measure waves and currents, with the aim to derive statistics on the general wave climate as well as on the probability of occurring extremes.

The X-Band radar connected to WaMoS II is a Furuno FR 2125 B. One measurement consists of 32 subsequent images, containing the spatial and temporal information of the individual waves. One radar image consists of about 300,000 pixels. The spatial distance of each pixel is 7.5 m. That means that these images contain as much information, as 300,000 buoys moored within a distance of 7.5 m. One radar revolution corresponds to $\Delta t = 2.5$ s.

For the validation of the developed algorithm a storm event from January 13 to 15, 2004 was chosen. This storm was particularly suitable for the validation because of an almost constant peak wave direction of North/ North-West as well as a significant wave height which increased from 1.5 up to about 4.0 m.

Figure 7 shows a radar raw image captured on January 14, 2004, 00:15 UTC, which was measured at the peak of the storm. The antenna is located in the centre of the image. The range of the radar is about 2 km. The wave pattern which is clearly visible appears in the radar image as areas of high (red) and low (white) image intensity. The lower left area of the image is blanked due to platform constructions. The colour-coding corresponds to the intensity of the radar backscatter strength. Wave parameters as determined by the standard WaMoS II are given.
In order to investigate single waves in time and space, the nautical radar image sequences obtained by WaMoS II were inverted into a sea surface elevation map. The following figure shows the sea surface elevation map corresponding to the radar image recorded on January 14, 2004, 00:15 UTC. In this case the colour-coding corresponds to the sea surface elevation.

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**Figure 7:** Radar image at FINO obtained by WaMoS II on January 14, 2004, 00:15 UTC.

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**Figure 8:** Sea surface elevation map at FINO corresponding to the radar image on January 14, 2004, 00:15 UTC.

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5.2 *First step of the validation/
Determination of the exact buoy position*

For the validation, the time dependent sea surface elevation of the inverted radar images were compared with the according time series of the moored buoy. An initial difficulty was to determine the exact buoy position in the radar image and thus decide on the values chosen for the comparison. The position of the wave buoy is covering only 1 pixel in the radar image. But the position of the buoy can range in a radius of about 50 m, which corresponds to about 7 pixels, dependent of wind-, wave-, and current-direction.

If the sea state is calm the exact buoy position is visible in the WaMoS II radar images. The signature of the wave buoy can be detected by averaging several radar images. At sea conditions which are more turbulent no signatures of the buoy are visible in the radar images. This means for the validation that the buoy position which was determined during a calm sea state is assumed for all sea conditions.

In Figure 9 a sector of such a mean radar image at FINO obtained by WaMoS II is shown. It was recorded on January 13, 2004, 03:12 UTC. The significant wave height was measured with $H_s = 1.6$ m. In the figure the signature of the buoy is clearly visible as an area of high (red) image intensity. In this example the buoy is located 275 m off the radar antenna. The position of the buoy is marked with a cross. The second cross described with 'analysis’, represents the reference point in the WaMoS II image, 50 m away which is chosen for the further comparison. The grey scale corresponds to the intensity of the radar backscatter strength. The grey arrow indicates the peak wave propagation direction ($\theta_p$).
5.3 Second step of the validation /
Comparison of sea surface elevation in between the drift radius of the buoy

In the night from January 13 to 14, 2004 the exact buoy position was not known because of the strong sea state. In order to identify the differences due to different locations a first investigation was made by comparing the sea surface elevation at those two neighbouring WaMoS II measuring points, shown in Figure 9. Figure 10 shows the achieved comparison. The time series of one measuring cycle of 32 images is plotted. The black line represents the sea surface elevation at the determined buoy position, the dotted grey one at the position 50 m away. Both time series are shifted about half a wave length. The time shift is related to the wave propagation. The waves arrive first at the position further offshore (dotted grey line) and then at the determined buoy position (black line). Apart from this time shift the two curves of the sea surface elevation show, as expected, a good agreement.

5.4 Third step of the validation /
The adjustment of the different temporal resolutions

The buoy and the radar are sampling the raw data at different sampling rates. The buoy measurements, with a temporal resolution of $\Delta t = 0.78125$ s, were temporally averaged to fit the WaMoS II temporal resolution of $\Delta t = 2.5$ s. Subsequent to that validation step the two sensors and their sea surface elevation were compared.

Figure 11 shows the time series of the buoy sea surface elevations with the different temporal resolutions. The blue dotted line represents the buoy measurement with the original temporal resolution of $\Delta t = 0.78125$ s. The light-blue line depicts the buoy measurement with adjusted temporal resolution of $\Delta t = 2.5$ s. This plot indicates the expectations of the following WaMoS II / wave buoy comparisons.

In Figure 12 a comparison of the sea surface elevation obtained by WaMoS II and the wave buoy on January 14, 2004, 00:15 UTC is shown. The black line in the figure represents the sea surface elevation determined from the WaMoS II data, the blue line is related to the wave buoy data set adjusted to the WaMoS II resolution of 2.5 s. The general shape of
the two curves is rather similar. The periods compare very well, just the amplitudes show small differences. Two times the buoy values are higher and once lower than the WaMoS II measurements. A further more detailed analysis needs to be carried out to understand the quality of this first comparison. Nevertheless it shows, that the sea surface elevation measured with WaMoS II delivers data which is comparable to a moored buoy.

Figure 12: Comparison of the sea surface elevation of the WaMoS II and wave buoy measurement at FINO on January 14, 2004, 00:15 UTC.

6 INDIVIDUAL WAVES - $H_{\text{MAX}}/H_s$ RATIO

The determination of single waves and their validation showed quite good results. A possibility to use this data is to look at occurring extremes. One criterion for extreme waves that is often used in time series analysis is the ratio $H_{\text{MAX}}/H_s \geq 2$. This criterion cannot be applied to 2-dimensional data however it can give an interesting picture of the distributions during a storm situation.

The WaMoS II data from both stations Ekofisk and FINO were analysed under this aspect.

For the storm event on May 29, 2001, $H_{\text{MAX}}$ was determined from sea surface elevation maps for 64 data sets. $H_{\text{MAX}}$ is defined as the maximum wave height in the sea surface elevation map, independently of its location. In Figure 13 the time series of $H_{\text{MAX}}$ and the ratio $H_{\text{MAX}}/H_s$ during the storm is shown. In the upper panel the black dots refer to $H_s$ as obtained by WaMoS II, the red asterisks refer to $H_{\text{MAX}}$ obtained from the sea surface elevation maps. The vertical line gives the time where the maximum of $H_{\text{MAX}}$ appears.

In the lower panel the ratio $H_{\text{MAX}}/H_s$ is presented. The dotted line indicates $H_{\text{MAX}}/H_s > 2$. The vertical line points out where the maximum of $H_{\text{MAX}}/H_s$ is reached.

Figure 13: upper panel: $H_s$ and $H_{\text{MAX}}$ at Ekofisk as obtained on May 29, 2001. lower panel: ratio of $H_{\text{MAX}}/H_s$.

The maximum individual wave height $H_{\text{MAX}} = 10.2$ m was observed on May 29, 15:15 UTC. At that time $H_s$ was measured with $H_s = 4.0$ m, which yields to a ratio of $H_{\text{MAX}}/H_s = 2.55$. The maximum ratio of $H_{\text{MAX}}/H_s$ was detected around one hour later on May 29, 16:15 UTC with $H_{\text{MAX}}/H_s = 2.56$.

The same investigation was carried out for data from the FINO platform. $H_{\text{MAX}}$ was determined from sea surface elevation maps for 26 data sets. Figure 14 shows the time series of $H_{\text{MAX}}$ and the ratio $H_{\text{MAX}}/H_s$ during the storm event from January 13 till 14, 2004. The upper panel represents $H_s$ as obtained by WaMoS II data (marked as black dots) and $H_{\text{MAX}}$ obtained from the sea surface elevation maps (marked as red asterisks). The maximum individual wave height $H_{\text{MAX}} = 7.1$ m was observed on January 13, 23:02 UTC. At that time $H_s$ was measured with $H_s = 4.2$ m. This results in a ratio of $H_{\text{MAX}}/H_s = 1.69$.

In the lower panel the ratio $H_{\text{MAX}}/H_s$ is shown. The commonly used freak wave criterion is indicated with the horizontal dotted line. The vertical line represents the maximum of the $H_{\text{MAX}}/H_s$ ratio. The maximum ratio was detected on January 13, 14:01 UTC with $H_{\text{MAX}}/H_s = 2.8$. 
These two examples show that the common criterion $H_{\text{max}}/Hs \geq 2$ for freak waves can not be applied to spatial data. Especially in the second example of FINO the maximum ratio of $H_{\text{max}}/Hs$ was identified a couple of hours before the maximum of $Hs$ was reached.

A further more detailed analysis needs to be carried out to understand the quality of the extreme wave event criterion. Validation and use of statistics for 2-dimensional data must be included in further considerations and investigations.

7 SUMMARY AND CONCLUSION

A statistical analysis of a large X-Band radar data set was carried out with the aim to identify and validate individual wave events from nautical radar images. An algorithm was developed to invert the raw data into sea surface elevation maps. This new algorithm that identifies single waves in space and time was applied to WaMoS II radar data from the offshore platform Ekofisk and the offshore wind test platform FINO. The identification of the maximum wave height from spatial radar data sets is described. The difficulty to detect extremes in statistical data is discussed.

These preliminary findings were verified with data from an in-situ sensor. From the offshore wind test platform FINO suitable radar data sets and in-situ data were available. First comparisons of the sea surface elevation from WaMoS II maps and a wave buoy show a good agreement. The results of the individual wave detection were applied to the extreme wave event criterion: $H_{\text{max}}/Hs \geq 2$. This investigation pointed out that further validation and an extension of the extreme statistics for 2-dimensional data is needed. The aim of this further investigation is to receive a warning criterion for offshore platforms and navigation.

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9 REFERENCES


