ESTIMATION OF THE SIGNIFICANT WAVE HEIGHT WITH X-BAND NAUTICAL RADARS

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ABSTRACT

The measurement of ocean waves and surface currents with a nautical radar is based on the spatial and temporal structure analysis of radar images of the sea surface. These radar images are generated by the interaction of HH-polarized electromagnetic waves with the sea surface ripples at grazing incidence. In these radar images the sea surface is visible as sea clutter. The spatial and temporal variability of the sea clutter information is analyzed in order to extract the unambiguous directional wave spectrum, and further sea state parameters, such as peak periods, peak wave lengths, mean directions, angular spreading, etc. . A general description of the wave and surface current monitoring system WaMoS II based on a X-band radar is given.

Furthermore this work deals with a method to obtain the significant wave height from sequences of nautical radar images. The method is based on a technique developed for the determination of significant wave height information from synthetic aperture radar imagery (Alpers and Hasselmann, 1982).

Results of the significant wave height inferred by WaMoS II are presented for 3 different stations located in the northern and central North Sea and in the Gulf of Biscay. Comparisons between the WaMoS II and buoy data are presented.

1 INTRODUCTION

With growing need of sea state information, in the last decades different sensors have been developed. Special interest has been shown lately in the use of remote sensing techniques to measure waves and surface currents. One technique to remotely measure the sea state is based on a nautical X-Band radar used generally for traffic control and navigation purposes. The fundamental interaction between the radar and the sea surface is assumed to be Bragg scattering, hence the small ripples are responsible for the radar return (Valenzuela, 1978). The longer surface gravity waves become visible in the radar images by: hydrodynamic modulation, tilt modulation and shadowing (Alpers et al, 1981; Plant, 1990; Wetzel, 1990). In order to derive wave information from radar images the temporal and spatial evolution of the radar backscatter information of the sea surface is analyzed by means of a discrete Fourier analysis, where spatial and temporal homogeneity within the observed area is assumed (Young et al. 1985; Ziemer and Rosenthal, 1987). Various comparisons of different sea state parameter inferred from nautical radar and buoy measurements, have been proved the reliability of this technique in order to derive energy and unambiguous directional distribution of ocean waves and the surface current (Ziemer and Günther, 1994; Nieto, 1995; Dittmer, 1995; Ziemer, 1991; Nieto et al. 1998 a,b).

In contrast to in-situ sensors, which are measuring the temporal evolution of the surface elevation at a given location, absolute values of the wave heights cannot be determined directly from radar images. In 1982 Alpers and Hasselmann developed a method to derive the significant wave height from synthetic aperture radar (SAR) imagery obtained by ERS-1 over the ocean. The basic idea of this method is that the significant wave height is assumed to be linearly correlated to the root square of the signal-to-noise ratio of the radar image. The general possibility to use this method also for the determination of the significant wave height from nautical radar images has been shown for various installations (Ziemer and Günther, 1994; Nieto et al, 1998 a;b).

The paper is organized as follows: in section 2 a brief description of the WaMoS II data capture system and the data processing is given. The method to derive the significant wave height is discussed in section 3. In section 4, results of WaMoS II measurements from different installations are presented and compared with buoy data. Summary and conclusion are given in section 5.

2 THE WAMOS II SYSTEM

The WaMoS II „data capture system“ consists of an A/D converter that is connected to a marine X-Band radar (9.41 GHz) and a PC. Furthermore the WaMoS II contains a processing software designed to infer sea state information from the spatial and temporal radar backscatter measurements.

2.1 WAMOS II DATA CAPTURE SYSTEM

For wave and current monitoring purposes the radar requirements are:

(1) A minimum antenna rotation speed of 36 rpm (antenna rotation time: $RPT < 1.7$ s),

(2) a maximum radar pulse length of 80 nsec,

(3) a minimum antenna length of 2.44 m.

These requirements allow to obtain radar images with a range resolution of 8.5 m and an angular resolution of 0.9° every 1.7 s. The standard WaMoS II analysis uses a sequence of 32 radar images, so that waves in the range of 0.025 Hz to 0.2 Hz can be detected. This frequency range corresponds to wave periods from 5 s to 40 s. The operating range of WaMoS varies from 0.1 km to 5 km depending on the wind speed and on the installation height. The minimum wind speed required for operational measurements is 3 ms^{-1} (Nieto, 1997).

2.2 WAMOS II DATA PROCESSING

In order to infer wave and surface current information from sequences of radar images an inverse modeling technique is applied. This technique can be separated into the following steps:

1. **Image Transformation:** For the data analysis a subimage of 1 km × 2 km is extracted out of the full polar radar image and transformed into Cartesian coordinates.
2. **Discrete Fourier Transformation:** The sequence of radar subimages is transformed into a 3-D image spectrum by using a discrete Fourier Transform (Young et al, 1985).
3. **Surface current determination**: The surface current is obtained by minimizing the distance between the position where spectral energy is located in the measured 3-D image spectrum and its theoretical position given by the dispersions relation for linear surface gravity waves (Young et al, 1985; Senet et al, 1997).
4. **Filtering the 3-D image spectrum:** The energy associated with the ocean waves is separated from the background noise by applying the dispersion relation as a pass-band filter (Young et al., 1985).

5. **Determination of the 2-D image spectrum**: Integration of the 3-D image spectrum over the positive frequency domain in order to obtain a non-ambiguous directional 2-D image spectrum (Young et al, 1985; Atanassov et al, 1985).
6. **Determination of the 2-D wave spectrum:** Transformation of the 2-D image spectrum into a 2-D wave spectrum by using a Modulation Transfer Function (MTF) (Ziemer and Rosenthal, 1987).
7. **Computation of the directional wave spectrum**: Transformation of the 2-D wave spectrum from the wave number space into the frequency direction space.

From the 2-D wave spectrum all important sea state parameters can be derived in real time. Table 1 gives names and symbols of the major sea state parameters and the corresponding ranges and accuracies provided by then standard WaMoS II.

Table 1: Names, symbols, range and accuracies of wave parameters provided by standard WaMoS II.

Name	Symbol	Range	Accuracy
2-D wave number spectrum	$E^{(2)}(k_x,k_y)$	-	-
2-D frequency direction spectrum	$E^{(2)}(f,\theta)$	0.025-0.21 Hz, 0-360°	-
1-D frequency spectrum	$S(f)$	0.025-0.21 Hz	-
Mean period	T_{m02}	5 - 40 s	+/- 0.5 s
Peak period	T_p	5 - 40 s	+/- 0.5 s
Mean wave direction	$\theta(f)$	0 - 360°	+/- 2°
Peak direction	θ_p	0 - 360°	+/- 2°
Integrated wave spreading	Spr	0 - 90°	-
Peak wave length	λ_p	40 - 600 m	-
1st peak period 2)	T_{p1}	5-40s	+/- 0.5 s
1st peak wave length	λ_{p1}	40 - 600 m	-
1st Peak direction	θ_p	0-360°	+/- 2°
2nd peak period 2)	T_{p2}	5-40 s	+/- 0.5 s
2nd peak wave length	λ_{p2}	40-600 m	-
2nd peak direction	θ_p	0-360°	+/- 2°
Surface current velocity	U	0-20 ms^{-1}	+/- 0.2 m s^{-1}
Surface current direction	θ_U	0-360°	+/- 2°

1) With *a* and *b* being the directional Fourier coefficients, 2) 1st refers to the first and 2nd to the second energy maximum of the 2d frequency direction spectrum.

3 ESTIMATION OF THE SIGNIFICANT WAVE HEIGHT (H_S) FROM NAUTICAL RADAR IMAGES

Due to the non-linearity of the imaging mechanism of ocean waves, the significant wave height can not be determined directly from radar images. However a method to infer wave heights from synthetic aperture radar (SAR) images was developed by Alpers and Hasselmann (1982) and successfully applied

(Brüning et al., 1994; Plant and Zurk, 1997). The basic idea of this method is to relate the measured signal-to-noise ratio (*SNR*) linearly with the significant wave height of the observed wave field. Applying this relation to WaMoS II data H_s is given by:

$$H_s = A + B\sqrt{SNR}$$

where A and B are calibration constants which depend on each radar installations and each antenna impulse response. Theses calibration constants are determined within a calibration period by means of a least squares method.

The *SNR* proposed by Alpers and Hasselmann (1982) relates the SAR image spectrum with the sum of the clutter and thermal noise spectra. In contrast to this for WaMos II purposes the *SNR* is defined as:

$$SNR = \frac{SIG}{BGN},$$

where *SIG* is the energy of the wave spectrum and *BGN* the background noise. For *SIG* as well as for *BGN* different definitions have been used. The maximum correlation between the H_s inferred by WaMoS II and by a buoy has been found for deep water conditions for the following definitions for *SIG* and *BGN*:

$$SIG = \sum_{i_x=1}^{N_{kx}} \sum_{i_y=1}^{N_{ky}} E^{(2)}(i_x,i_y)\,\Delta k_x(i_x)\Delta k_y(i_y)$$

$$\begin{aligned} BGN = & \sum_{i_x=1}^{N_{kx}} \sum_{i_y=1}^{N_{ky}} \sum_{i_f=1}^{N_{kf}} F^{(3)}(i_x,i_y,i_f) \cdot \\ & \Delta f(i_f)\Delta k_y(i_x)\Delta k_x(i_y) - \\ & \sum_{i_x=1}^{N_{kx}} \sum_{i_y=1}^{N_{ky}} F^{(2)}(i_x,i_y)\,\Delta k_y(i_x)\Delta k_x(i_y) \end{aligned} \qquad (4)$$

where $E^{(2)}$ is the 2-D wave number spectrum and $F^{(3)}$ the 3-D and $F^{(2)}$ the 2-D image spectrum. The extension of the spectra is N_{kx}, N_{ky} and N_{kf} and Δk_x, Δk_y its wave number resolution and Δf its frequency resolution. The results presented in the following section refer to this *SNR* definition.

4 RESULTS

In this section comparisons of H_s data obtained by buoy and WaMoS II from 3 different stations:

1. FPSO[1] Norne, northern North Sea (Norway)
2. FPSO Curlew, central North Sea (Great Britain)
3. Lighthouse Cabo de Peñas, Gulf of Biscay (Spain).

are presented.

4.1 FPSO NORNE

This WaMoS station located in the northern North Sea with an average water depth of about 80 m. The presented data sets were obtained during a calibration phase from November 1997 till January 1998. The WaMoS II data are compared with buoy data gathered at the same location. During this calibration phase the WaMoS II measured every 3 hours over a period of 30 minutes continuously, while the buoy delivered data 10 minutes mean values. Figure 1 shows the scatter plot of the H_s obtained by WaMoS II and buoy. The correlation coefficient for this data set is $r = 0.89$. This value represents an accuracy of about 90% of the WaMoS(3)I assuming the buoy data as true. This correlation is in the order of accuracy two wave rider buoys can reach.

[1] Floating Production and Storage Offshore

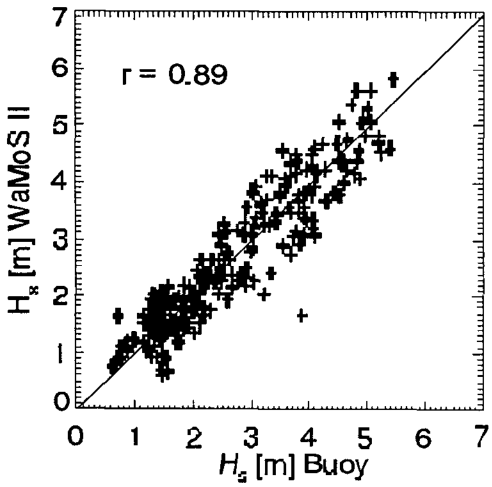

Fig. 1: Scatter plot of the significant wave height (H_S) obtained by the WaMoS II and the buoy both located at FPSO Norne in the northern North Sea. The correlation coefficient is r = 0.89. Data: *STATOIL.*

The corresponding time series of H_s as obtained by the buoy and WaMoS II measurements are shown in Figure 2. Both time series show a good agreement for low (< 2 m) as well as for high H_s (> 3 m). Also the variation of the H_s with strong increases or decreases of H_s exhibit similar evolution in both time series.

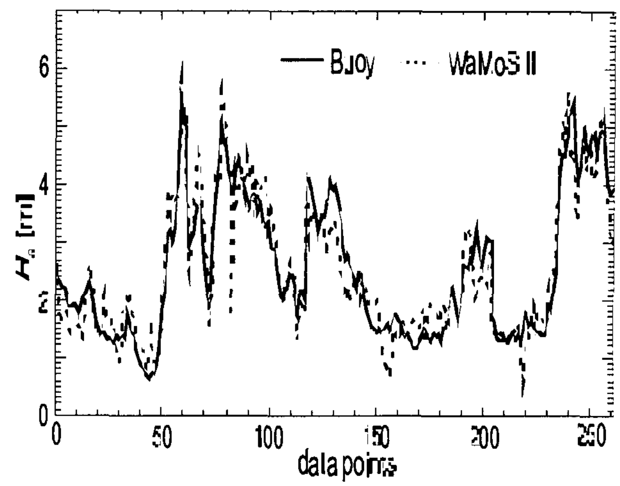

Fig. 2: Time series of the significant wave height (H_s) gained by a buoy (solid line) and by WaMoS II (dotted line) obtained at station Norne.

4.2 FPSO CURLEW

This WaMoS station is located in the central North Sea with an average water depth of about 92 m. The presented data sets were obtained during a calibration phase from May till June 1998. The WaMoS II data are compared with buoy data gathered at station Auk Alpha about 33 nm Southeast of Curlew, where the water depth is about 83.5 m. During the calibration phase the WaMoS II measured every full hour over a period of 30 minutes continuously, while the buoy delivered data 10 minutes mean values.

Figure 3. shows the scatter plot of the H_s obtained by the WaMoS II and the buoy. The correlation coefficient for this data set is r = 0.85.

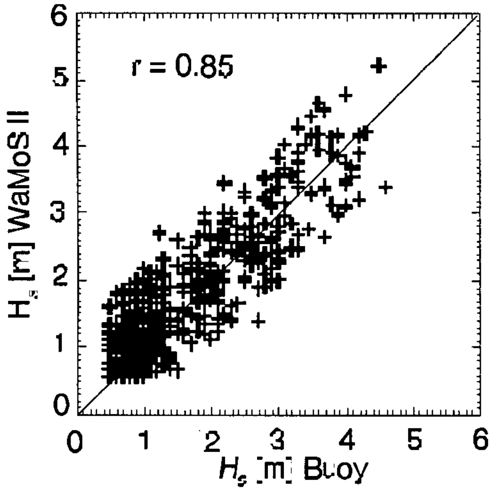

Fig. 3: Scatter plot of the significant wave height (H_S) obtained by the WaMoS II located at FPSO Curlew and a buoy operating at Auk Alpha 33 nm SE of Curlew. The correlation coefficient is r = 0.85. Data: *SHELL.*

The slightly lower correlation coefficient between the buoy and the WaMoS II can be explained by the distance between deployment position of the buoy and WaMoS II measuring area. Nevertheless it is in the same range of accuracy like at the Norne station.

The corresponding time series of the of H_s as obtained by the buoy and WaMoS II measurements are shown in Figure 4. Also these time series show a good agreement of H_s evolution.

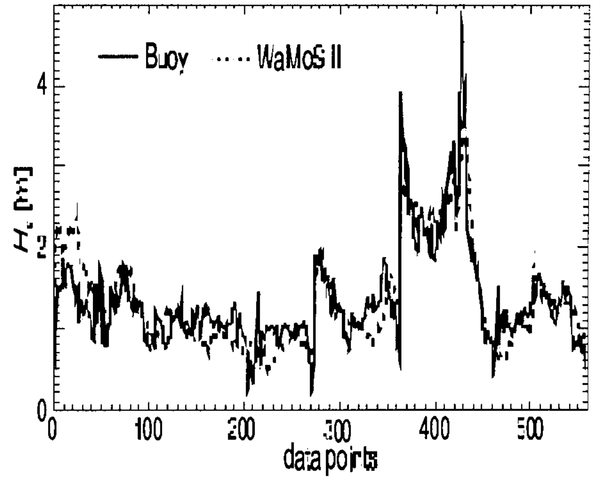

Fig. 4: Time series of the significant wave height (H_s) gained by a buoy (solid line) and by WaMoS II (dotted line) obtain for Curlew.

4.3 LIGHTHOUSE CABO DE PEÑAS

This WaMoS station is located on-shore in the Gulf of Biscay. The WaMoS II analysis area is located about 2 km off shore with an average water depth of about 45 m. The presented data sets were obtained from February till April 1998. The WaMoS II data are compared with buoy data gathered about 18 nm North of Cabo de Peñas, where the water depth is about 600 m. During this time the WaMoS II measured once every full hour over 3 minutes, while the buoy delivered every hour 30 minutes mean values.

Figure 5 shows the scatter plot of the H_s obtained by the WaMoS II and the buoy. The correlation coefficient for this data set is r = 0.71.

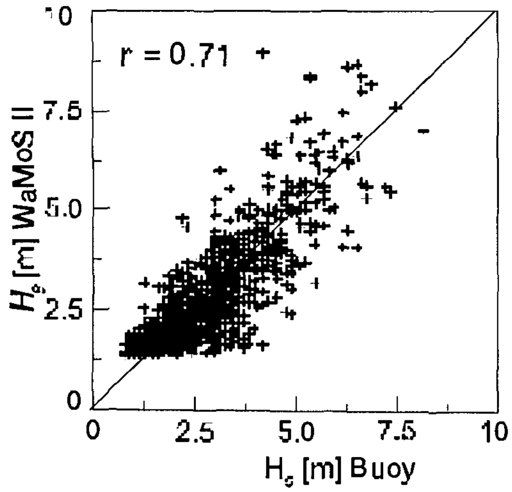

Fig. 5: Scatter plot of the significant wave height (H_S) obtained by the WaMoS II located at lighthouse Cabo Peñas and a buoy operating about 18 nm North of WaMoS II monitoring area. The correlation coefficient is $r = 0.71$. Data: *Clima Marítimo.*

The lower correlation of 0.71 between the two data sets can be related to two reasons. One reason is the fact of the different positions of two wave sensors. This fact becomes more relevant than in the case of the Curlew station as it is related here to a significant change in the bathymetry. Especially the long waves change their characteristic as they propagate from deep water (buoy position) to the coastal area, where the WaMoS II measurements were carried out. Another reason is the different averaging interval of the compared data, while the WaMoS II data represent 3 minutes averages the buoy delivers 30 minutes mean values.

The corresponding time series of the of H_s as obtained by the buoy and WaMoS II measurements are shown in Figure 6. Also this time series show a good agreement for H_s evolution. Even though the correlation between H_s derived by WaMoS II and the buoy is a little lower than for the previous stations FPSO Norne and FPSO Curlew, the general evolution of H_s is well observed by WaMoS II. The higher maxima of the H_s inferred by WaMoS II can be related to the shoaling of the waves while approaching the coast.

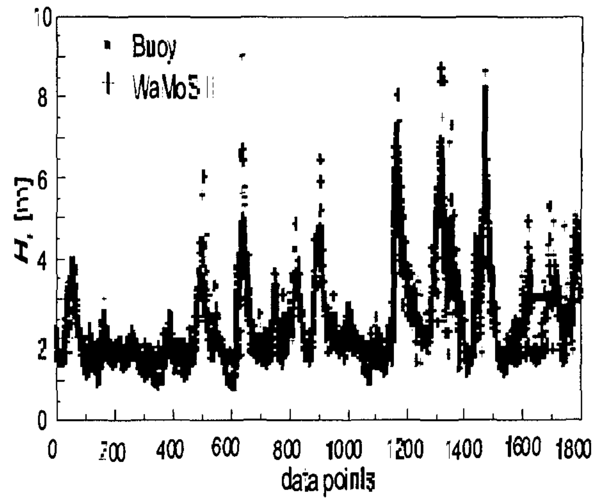

Fig. 6: Time series of the significant wave height (H_s) gained by a buoy (solid line) and by WaMoS II (dotted line) obtain for Cabo Peñas.

5 SUMMARY AND CONCLUSIONS

WaMoS II a remote sensing technique for real time measurements of the sea state and surface current based on a nautical X- band radar has been presented. By analyzing time series of radar images of the sea surface this system allows to obtain information of the spatial and temporal evolution of sea state parameters and surface currents. Applying a method to infer significant wave height information from SAR images (Alpers and Hasselmann, 1982), it is also possible to derive this information from sequences of nautical radar images.

Results of the significant wave height obtained by WaMoS II using this method have been compared with corresponding buoy data for 3 different stations namely: FPSO Norne, FPSO Curlew and lighthouse Cabo Peñas. For the first two deep water stations located in the open sea the correlation of H_s exceeds similar values as one would obtain for two different buoys. Only for the coastal station Cabo Peñas the correlation is a little lower, which can be explained by the different location where the WaMoS II and buoy measurements were carried out and by the different sampling time. In general it can be concluded that it is possible to obtain reliable data of the significant wave height with WaMoS II.

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