WaMoS II: A WAVE AND CURRENT MONITORING SYSTEM

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Abstract

WaMoS II is an operational wave monitoring system that was developed at the German research center GKSS during the last 15 years. This now commercially available system uses any ordinary nautical radar working in X band as the sensor. The measurement principle is based on the backscatter of microwaves from the ocean surface, which is visible as a 'sea clutter' on the nautical radar screen. From that observable sea clutter an analysis is carried through to deduce the unambiguous directional wave spectrum and the surface currents. Sea state parameters as significant wave height, wave periods and wave lenghts, as well as wave propagation directions are provided in real time.

1. Introduction

For surveying the ocean wave field a common marine X-Band radar can be used. Mounted on a ship, oil rig or onshore it is a proven instrument that measures the wave energy its directions and heights, as well as the surface currents. In the near range of every nautical radar a noise signal, the so called sea clutter, is received. The Wave Monitoring System WaMoS II analysis exactly that signal, which is normally suppressed for navigational purposes, to describe the 3 dimensional spatial and temporal variability of sea surface (*Young et al., 1985*). WaMoS II needs a minimum wind speed of about 3m/s to provide the wave and current information. The system easily detects wave lengths from 40m - 600m and covers periods from 5s - 40 seconds.

This method that is based on a commercially available marine X-Band radar has been developed at the German GKSS research center during the last 15 years and is now commercialized.

2. Theoretical Background

The vertical displacements of the sea surface are commonly described by mean of the sea state. A sea state corresponds to those wave fields with invariant statistical properties along the position $\vec{r}=(x,y)$ and the time t. These wave fields are spatially homogeneous and stationary in their temporal evolution.

Sea states are usually described in the spectral domain by the three-dimensional power spectrum $F^{(3)}(\vec{k},\omega)$, where $\vec{k}=(k_x,k_y)$ is the two dimensional wave number vector and ω is the angular frequency. For linear wave fields there is a relationship between the temporal evolution and the spatial dependence. This relationship is known as dispersion relation

$$\omega=\sqrt{g \quad k\tanh(kd)}+\vec{k}\cdot\vec{U} \tag{1}$$

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where $\vec{U}=(U_x,U_y)$ is the two dimensional surface current, d is the water depth, and g is the acceleration due to gravity.

The wave spectral power density dependence holds for the dispersion relation (1) in the $(\vec{k},\omega)$-space (see Figure 1).

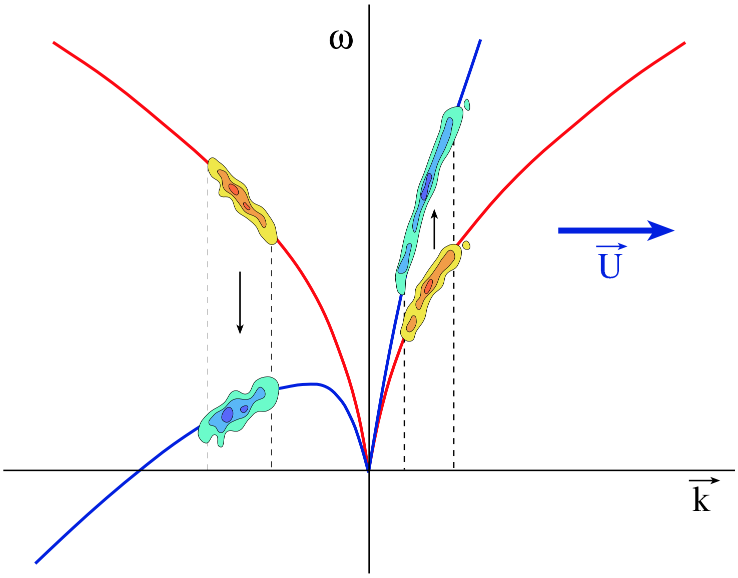

Fig. 1: Distribution of the wave energy in the spectral $(\vec{k},\omega)$-space. In presence of a two dimensional current $\vec{U}$, the frequency of encounter ω is shifted up for waves traveling in the same direction as $\vec{U}$, for the opposite directions ω is decreased.

Starting from the three dimensional spectrum $F^{(3)}(\vec{k},\omega)$ and the dispersion relation (1) other sea state spectral description can be obtained:

- Frequency spectrum: $S(\omega)=2\cdot\int_{\vec{k}} F^{(3)}(\vec{k},\omega)d^2k$, with $\omega>0$.
- Directional wave number spectrum: $F^{(2)}(\vec{k})=2\cdot\int_{\omega>0} F^{(3)}(\vec{k},\omega)d\omega$.
- Directional frequency spectrum: $E^{(2)}(\omega,\theta)=F^{(2)}(\vec{k}(\omega,\theta))k\dfrac{dk}{d\omega}$.

The one dimensional frequency spectrum $S(\omega)$ can be obtained from the function $E^{(2)}(\omega,\theta)$ integrating over all the wave propagation directions θ

$$S(\omega)=\int_{-\pi}^{\pi} E^{(2)}(\omega,\theta)d\theta \qquad (2)$$

In addition, the function $E^{(2)}(\omega,\theta)$ defines other common directional wave parameters, such as mean wave direction $\overline{\theta}(\omega)$, angular spreading $\overline{\sigma}(\omega)$, pitch and roll cross-spectra $C_{nm}(\omega)-i\cdot Q_{nm}(\omega)$, etc.

3. Analysis of Nautical Radar Data Sets with WaMoS II system

The Wave Monitoring System (WaMoS II) measures the spatial and temporal information of the sea state providing the full directional spectrum and current estimation in real time (*Ziemer and Günther, 1994; Dittmer, 1995*). This Wave Monitoring System is composed by an A/D converter plus a processing software to analyze the video signal from a conventional marine X-band radar and extract the information from the backscatter image of the sea surface, formally known as *sea clutter*. The system transfers the analog radar signal to a standard PC, where the data are stored and processed. The Figure 2 illustrates a scheme of a WaMoS II installation.

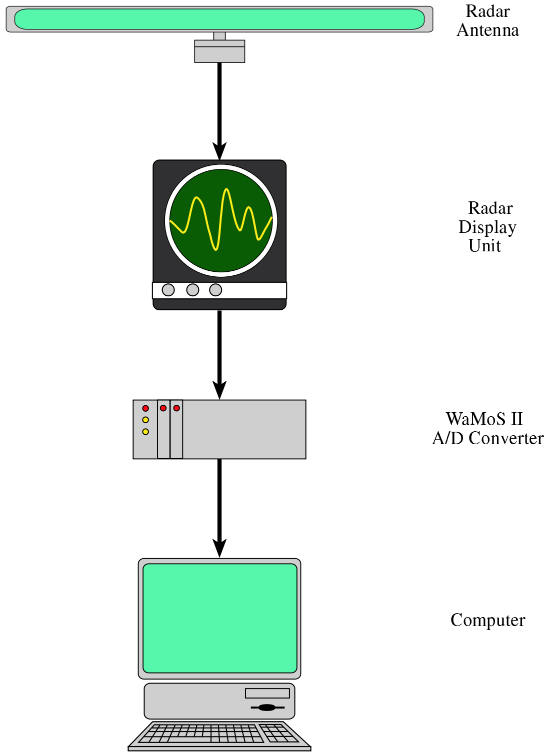

Fig. 2: Scheme of a WaMoS II installation.

To derive the sea state information from the WaMoS II device, a consecutive series of N_t images is taken (see Figure 3). The spatial and temporal resolution depends on each radar device. The temporal sampling interval is given by the antenna rotation time, which is approximately two seconds. The spatial resolution lies typically around 10 m. To analyze the data a rectangular subgrid with the size of 1 km x 2 km is cut out of the full radar image. This is to reduce the amount of data and the computation time. So, the results are delivered in real time.

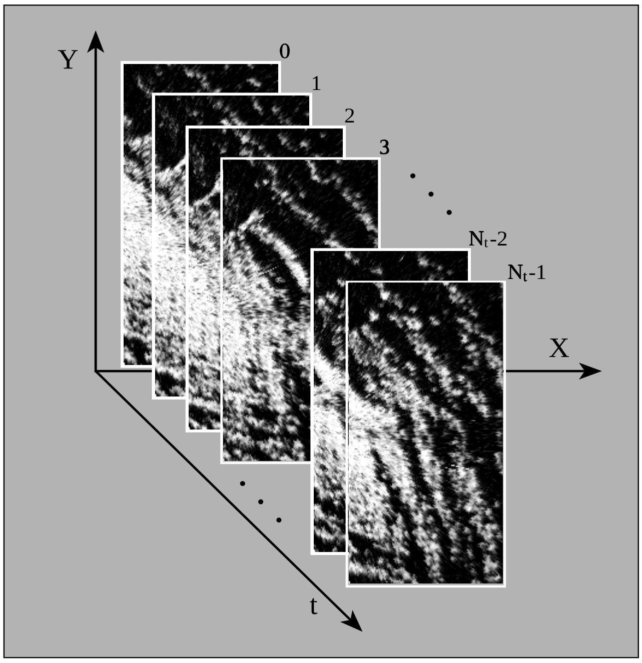

Fig. 3: Example of a temporal sequence of sea clutter images sampled by WaMoS II system.

The sampled data set is transformed into the spectral domain to obtain the three dimensional image spectrum estimation $I^{(3)}(\vec{k},\omega)$. There are three main contributions to the total spectral energy in the function $I^{(3)}(\vec{k},\omega)$

- Wave field components (*Young et al., 1984*)}.

- Higher harmonics of the wave components due to nonlinear radar imaging mechanisms (*Nieto, 1997*; *Seemann, 1997*).

- Background noise spectral energy due to the speckle noise (*Seemann, 1997*), which is connected with the scattering on the rough sea surface and the local wind field (*Hatten, 1997*).

The estimation of the wave spectrum $F^{(3)}(\vec{k},\omega)$ is obtained by applying an inverse modeling technique. The wave spectrum inversion method involves the following steps:

- Calculation of the surface current $\vec{U}$:This parameter is obtained by minimizing a cost function which depends on the square distance of the wave components $(\vec{k},\omega)$ of the image spectrum $I^{(3)}(\vec{k},\omega)$ to the dispersion shell (3) (*Senet, 1997*). In a similar way than the current fit is carried out, recent studies have shown that the mean water depth d can be derived (*Outzen, 1997*).

- Filtering of the image spectrum: The purpose of this step is to remove all the $(\vec{k},\omega)$ components of $I^{(3)}(\vec{k},\omega)$ which do not belong to the wave field (e.g. background noise components, higher harmonics, etc.). Therefore, once the surface current is estimated, the dispersion relation (1) is applied as a pass-band filter in the three dimensional spectral space. Hence, an estimation of the wave field three dimensional spectral density is obtained (*Young et al., 1984*).

- Estimation of the significant wave height: The filtered spectral density obtained is related to the scale of the sampled gray levels provided by the WaMoS II system. The filtered spectrum is scaled using a similar technique than for SAR system (*Alpers and Hasselmann, 1982*). This method is based on the computation of the signal-noise ratio SNR, where the signal is the energy of the filtered spectrum and the noise is the total energy of the background noise components. The parameter SNR is closely related to the wave field energy m_0 and the significant wave height $H_s = 4 \cdot \sqrt{m_0}$ (*Nieto, 1998*).

Once the three dimensional wave spectrum $F^{(3)}(\vec{k}, \omega)$ is estimated, it is possible to obtain other sea state spectral densities, such as $F^{(2)}(\vec{k})$, $E^{(2)}(\omega,\theta)$ or $S(\omega)$ and their related integrated parameters. Table 1 shows an example of these integrated parameters provided by the system in real time.

Hs	Significant wave height	**MDIR**	Integrated mean direction
$\mathbf{T_P}$	Peak period	**Spr**	Integrated wave spreading
$\mathbf{Tm_{02}}$	Spectral mean period	$\theta_{\mathbf{P}}$	Peak direction
$\mathbf{T_{P1}}$	1st peak period of multi-modal spectrum	$\theta_{\mathbf{P1}}$	1st peak direction of multi-modal spectrum
$\mathbf{T_{P2}}$	2nd peak period of multi-modal spectrum	$\theta_{\mathbf{P2}}$	2nd peak direction of multi-modal spectrum
$\lambda_{\mathbf{P}}$	Peak wave length		
$\lambda_{\mathbf{P1}}$	1st peak wave length of multi-modal spectrum	**u**	Surface current speed
$\lambda_{\mathbf{P2}}$	2nd peak wave length of multi-modal spectrum	$\theta_{\mathbf{u}}$	Surface current direction

Table 1: Sea state parameters provided by WaMoS II in real time.

4. Results

In this section some intercomparisons between nautical radar results and in-situ sensor data are discussed. The shown results were taken from three different locations (e.g. two sites in the Bay of Biscay and a site in the North Sea).

The first shown results (figures 4 to 7) come from an oceanographic campaign (*EXBAYA 95*) carried out close to the Spanish city of Bilbao in February 1995. The purpose of this experiment was to analyze the capabilities of nautical radars for studying sea states. For that purpose, a directional pitch-roll buoy moored at 600 meters depth was used. During this experiment several cases of swell coming from North-west were measured. This is the typical sea state situation in the Bay of Biscay. These incoming wave fields are generated by storms in Northern Atlantic approaching the North of the Iberian Peninsula as very grouped long waves.

The results from the second location (figure 8) were obtained from February to April 1998 using an on-shore WaMoS II station, installed at the Northern coast of Spain (close of the city of Gijón), and a horizontal displacement directional buoy deployed at 200 m depth.

Finally, some additional data (figure 9) have been used from a WaMoS II station installed in the FPSO *Norne* (operated by *STATOIL*, Norway) and from a scalar heave buoy. These data were measured at Northern North Sea from November 1997 to January 1998.

To estimate the directional spectrum at a fixed location of the ocean it is necessary to know the geometrical properties of the wave field (e.g. heave, slopes, curvatures, etc.). A buoy delivers the temporal information about a limited number of sea state properties, such us pitch and roll, horizontal wave displacements, etc. Therefore the directional spectrum $E^{(2)}(\omega,\theta)$ can only be obtained by applying different families of interpolation methods. Hence, the final result depends on each used method. The estimation of the directional spectrum from spatial measurements is better defined, especially for multi-modal sea states composed by the superposition of single wave fields with different propagation directions (*Nieto, 1993*).

Figure 4 illustrates directional spectrum estimations from a pitch-roll buoy and a nautical radar mounted on a ship, showing a swell system approaching from North-West. The first three directional spectra were obtained from the same buoy record by using different interpolation techniques (Figures 4a to 4c). The last one (Figure 4d) was derived from the nautical radar measurement. The directional spectrum in figure 4a was obtained by the *Extended Maximum Likelihood Method* (EMLM) (*Isobe et al., 1984*). Figure 4b corresponds to the *Maximum Entropy* (AR(2)) estimation (*Lygre and Krogstad, 1986*). The Figure 4c contains the directional spectrum estimation by the *Gaussian Instantaneous Direction Method* (GIDM) (*Egozcue and Arribas, 1991*). It can be seen that EMLM provides the largest directional dispersion for the wave field. AR(2), instead, presents the narrowest spectrum. GIDM provides an intermediate solution. All of these different estimations belong to the same buoy record. In this case, the nautical radar result (Figure 4d) delivers a similar result than GIDM.

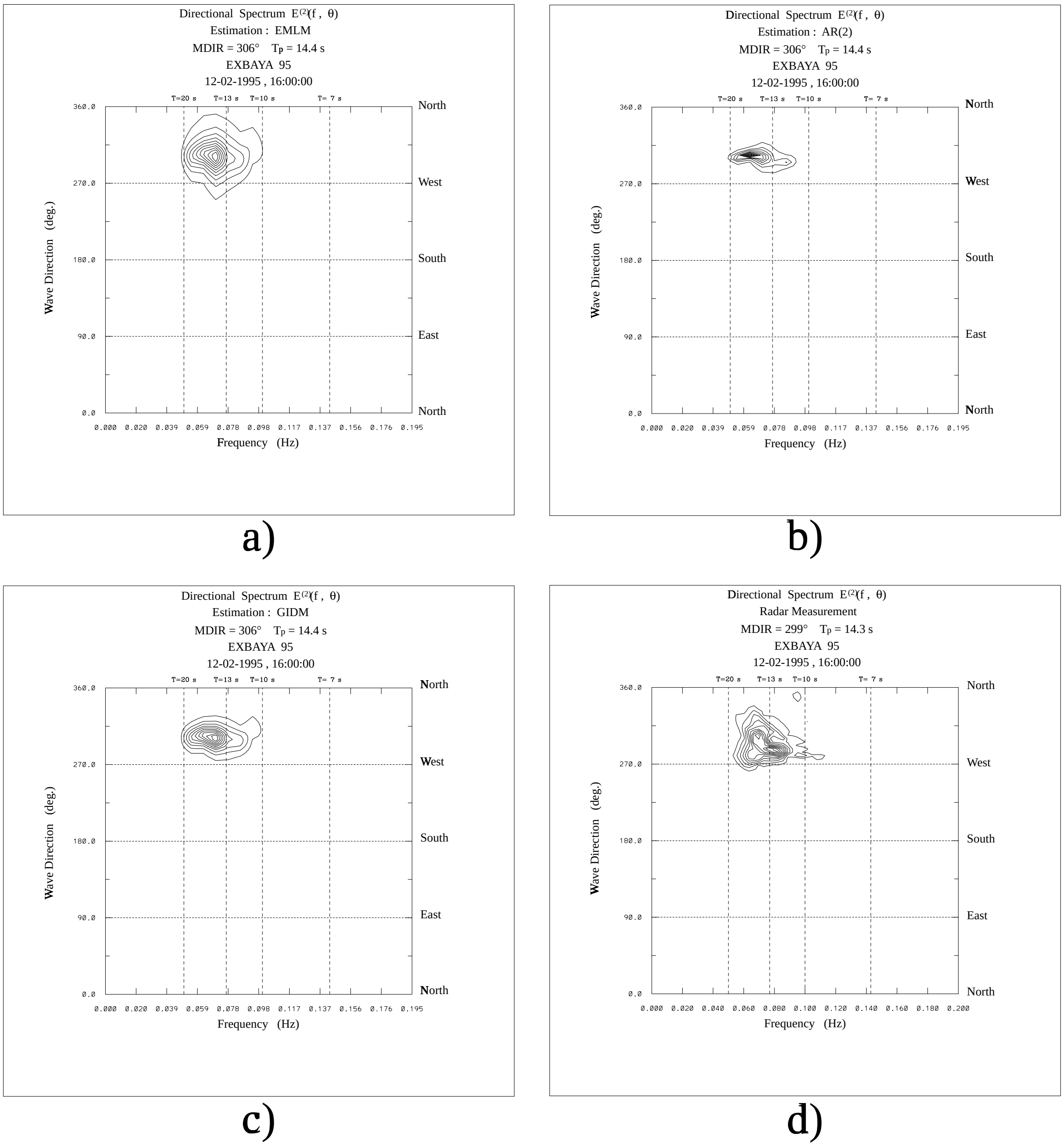

Fig. 4: Directional spectrum estimations from a pitch-roll buoy record and a radar measurement: *Extended Maximum Likelihood Method* (a), *Maximum Entropy* (b), *Gaussian Instantaneous Direction Method* (c) and nautical radar estimation (d). Measurement taken during the *EXBAYA 95* campaign.

The comparisons between the pitch-roll buoy and nautical radar estimation of the one dimensional frequency spectrum can be seen in Fig. 5. The shape of both functions are very close together. Similar results appear in the comparison of the mean direction depending on the frequency (Fig. 6) and the angular spreading (Fig. 7).

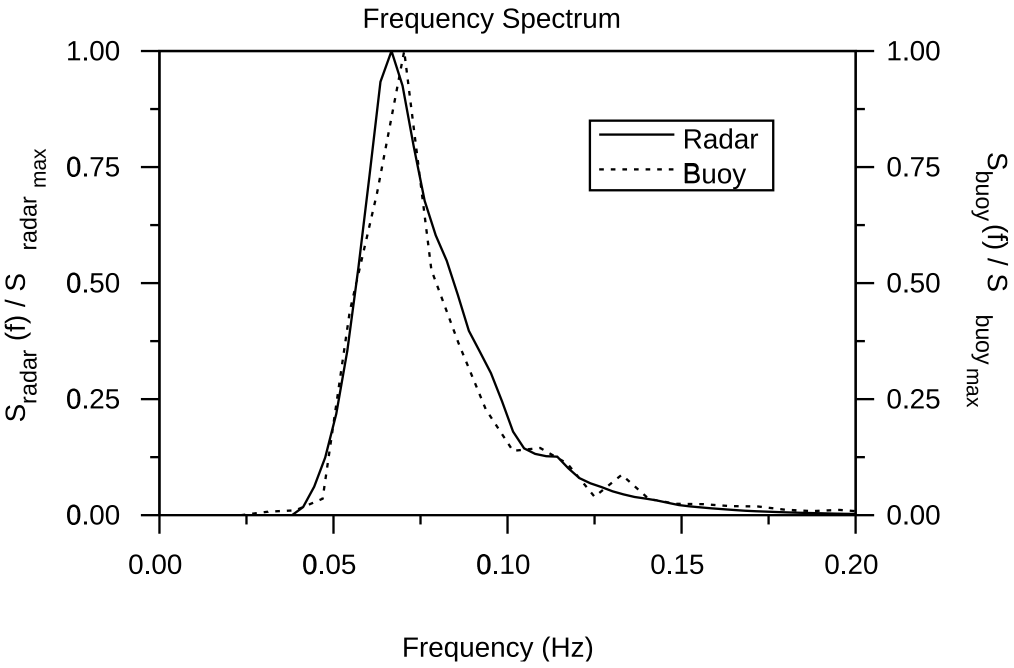

Fig. 5: One dimensional spectrum comparisons between the pitch-roll buoy estimation and the nautical radar result. Measurement taken during the *EXBAYA 95* campaign.

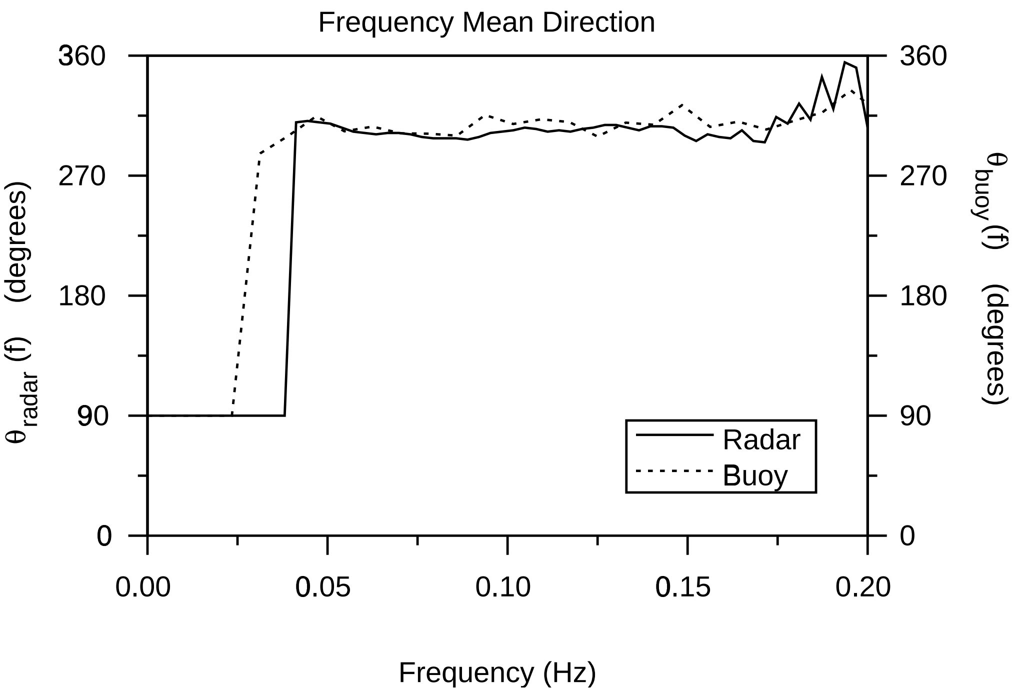

Fig. 6: Mean direction comparisons between the pitch-roll buoy estimation and the nautical radar result. Measurement taken during the *EXBAYA 95* campaign.

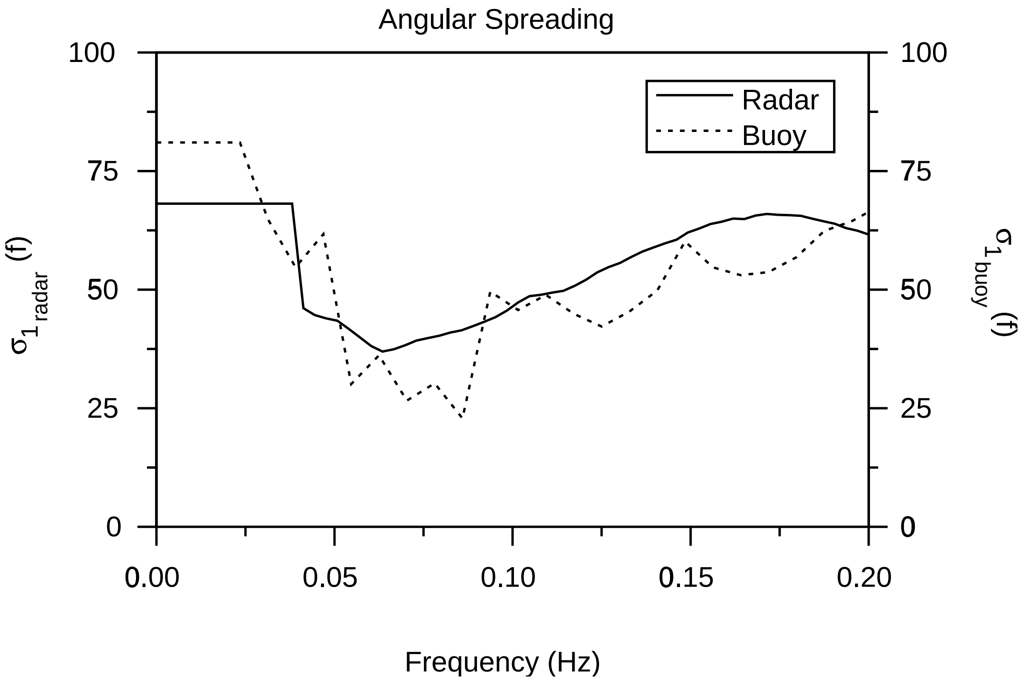

Fig. 7: Angular spreading comparisons between the pitch-roll buoy estimation and the nautical radar result. Measurement taken during the *EXBAYA 95* campaign.

The Figure 8 shows the temporal evolution of the peak direction obtained from a WaMoS II station and a horizontal displacement buoy moored in the Bay of Biscay. Both data sets have a similar behavior in their evolution. The directions close to the North are swell dominated sea states and the easterly directions correspond to wind sea wave fields.

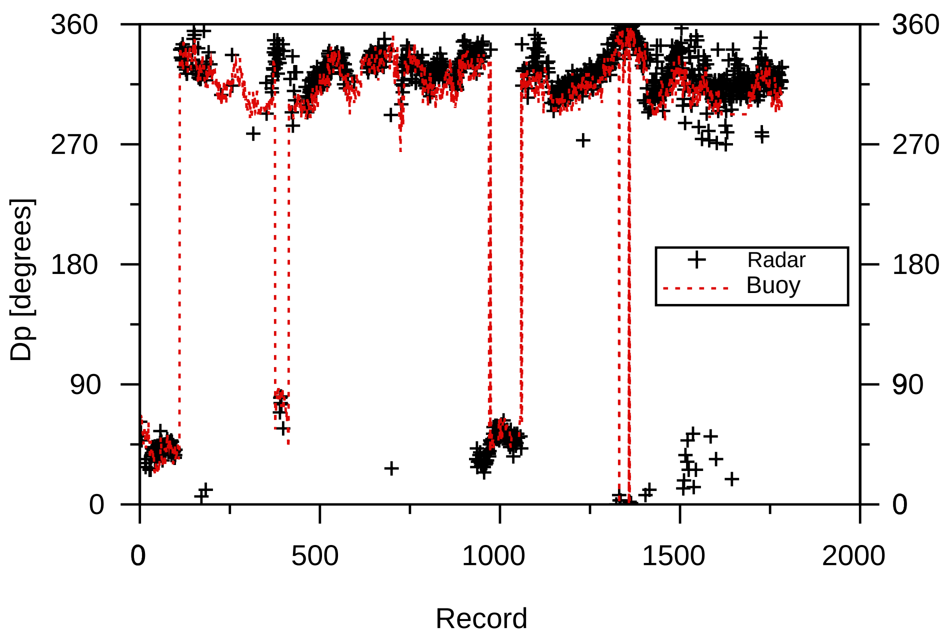

Fig. 8: Temporal evolution of the peak direction obtained from a WaMoS II station and a moored horizontal displacement buoy.

As it was mentioned above, WaMoS II leads to the significant wave height due to the estimation of the signal-noise ratio. Figure 9 shows time series of this sea state parameter and the comparison with the obtained results from a scalar buoy. These data were measured in Northern North Sea in the FPSO *Norne* (*STATOIL*).

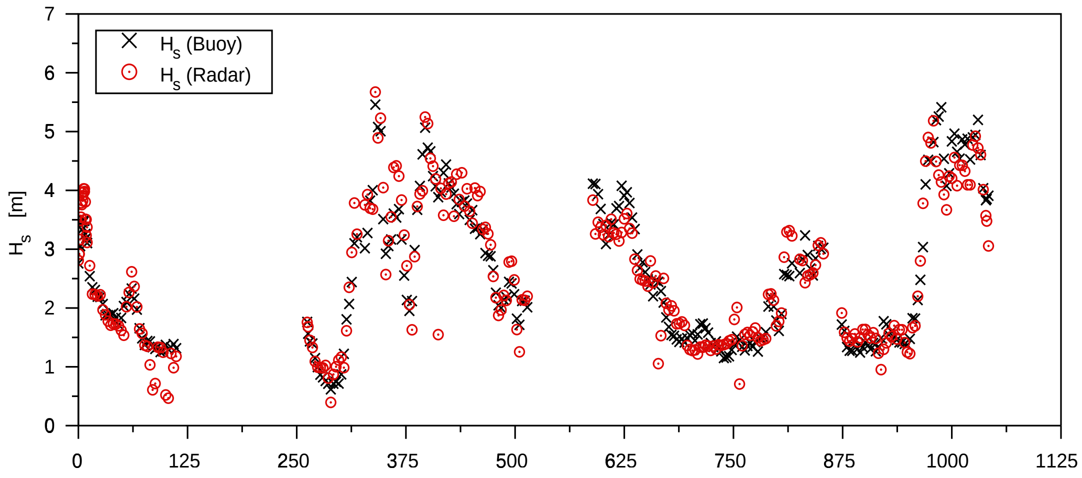

Fig. 9: Time series of significant wave height estimated by WaMoS II and by a scalar buoy.

5. Conclusions

WaMoS II is a remote sensing instrument based on a nautical X-band radar. This system is able to measure time series of sea surface images. Hence, the temporal and spatial dependence of wave fields is analysed. This spatial sea state information is required to estimate the directional surface motions of the wave fields and their directional wave spectra. From those estimated directional wave spectra the sea state parameters are delivered in real time, such as wave periods, propagation directions and significant wave heights.

Good estimations of the directional spectra are especially important to observe multi-modal sea states that occur due to the superposition of two or more wave fields generated by different meteorological situations.

Acknowledgement: The authors thank *STATOIL* and *RC Symek* (Norway) for the provision of some of the data.

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