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ESTIMATION OF SEA STATE DIRECTIONAL SPECTRA BY USING MARINE RADAR IMAGING OF SEA SURFACE

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ABSTRACT

Conventional marine radars are able to obtain images of the sea surface, commonly known as sea clutter, which contain information about the wave field. The present work shows how these marine radars are used as a remote sensing tool for monitoring sea states in real time. The full Wave Monitoring System is composed by an ordinary X-band navigation radar unit, an A/D converter to sample the analog radar video signal and a computer that deals with the processing of information and communication transference in real time.

Each marine radar measurement of the sea surface is a temporal sequence of images. Hence, these data sets contain information about the spatial and temporal dependence of the sea states. The data are transformed in the spectral domain (wave numbers and frequencies) in order to derive the sea state parameters, such as significant wave heights, wave periods, wave propagation directions, etc.

In the present work, the results obtained from the analysis of the nautical radar data sets are compared with data measured by conventional in-situ sensors, such as anchored wave buoys. These data were taken in different geographical locations: the Northern coast of Spain, where the swell is the dominant wave field, and several points in the North Sea, where the wind sea energy is commonly higher than the swell components.

INTRODUCTION

During the last two decades ordinary marine radars have been used to measure the directional distribution of the sea surface elevation by providing of the directional wave spectrum. In the near range of marine radars the sea surface *backscatter* is received. This sea signal is commonly called *sea clutter*, and it is considered as noise for navigation purposes. However, these data can be analyzed to determine sea state parameters, such as wave spectra, wave periods, propagation directions, significant wave heights, etc.

For this purpose, an operational measuring system, which is able to use and process the sea clutter signal, was developed at the German GKSS Research Center (Ziemer, 1991; Dittmer, 1995). This *Wave Monitoring System* (*WaMoS II*) consists of a conventional marine radar, an A/D converter (the system itself) to digitize the analog radar video signal, and a standard PC to store and process the data in real time.

Figure 1 shows an example of sea clutter image sampled with the *WaMoS II* system, at a radar station located in the German isle of Helgoland in the North Sea. The image shows wave fronts approaching the coast.

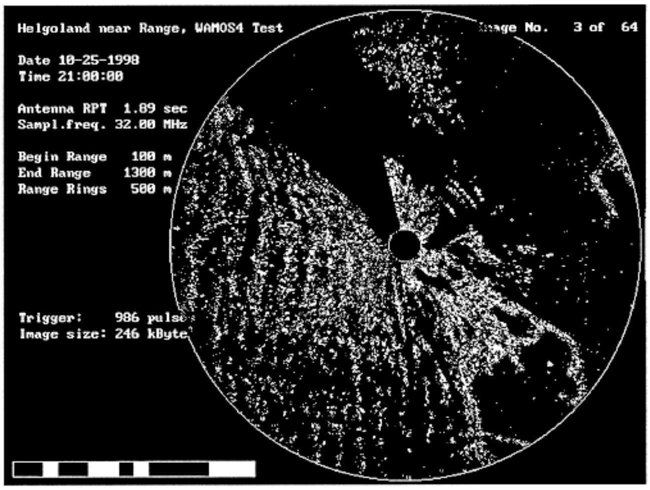

Figure 1: Example of sea clutter image.

Each measurement consists of a temporal sequence of radar images of the sea surface, which is a sea clutter time series. Hence the data contains information about the wave field dependence in space and time. The spatial and temporal sampling resolutions of these radar image time series depend on the technical features of the marine radar used.

Table 1 illustrates the minimum requirements of a nautical radar to measure sea state parameters. The right column shows how each technical parameter must be improved in order to improve the quality of the data. The antenna rotation speed affects to the sampling time of the radar image sequence, the radar pulse and the antenna lengths deal with the spatial resolution for each sea clutter image.

Technical Feature	Minimum Value	Improvement (Effect)
Antenna Rotation Speed	32 r.p.m.	Faster (Better Temporal resolution)
Radar Pulse Length	80 ns	Shorter (Better Range Resolution)
Radar Antenna Length	2.5 m	Longer (Better Azimuthal Resolution)

Table 1. Minimum nautical radar requirements for wave analysis purposes.

ANALYSIS OF MARINE RADAR IMAGES OF THE SEA SURFACE

To measure sea states using marine radars it is necessary to have a minimum amount of wind, typically higher than 3 m/s so as to produce ripples on the sea surface. These ripples interact with the electromagnetic fields emitted by the radar transmitter. Hence, what the radar receiver captures is the modulation of the backscatter pattern with the longer waves (wind sea or swell).

It is important to remark, that the final image in the radar screen is not a map of the wave field, but an image containing information about how the sea surface backscatters the electromagnetic fields. So, phenomena such as the wind speed, the wave tilts, and the wave heights affect the data.

To extract wave information from the radar imaging it is necessary to apply an inversion analysis technique in order to filter out the spectral components of the radar image spectrum and to estimate the wave spectral density, which leads to all sea state parameters.

Taking into account the actual microprocessor technology, the required computer time to process common marine radar data sets is about 2 minutes. Hence, nautical radars are suitable to be used as a real time sensor for sea state monitoring.

As mentioned above, a typical marine radar measurement is composed of a temporal sequence of sea clutter images $i(x, y; t)$. This data set contains information about several phenomena, such as the wave field spatial and temporal dependence, the wind speed, etc. The method of analysis takes into account the theoretical dependence of the spatial and the temporal evolution of linear waves. This method is composed of several steps, which are described below.

Image Spectrum Estimation

The first step of the method of analysis is to transform the spatial and temporal dependence into the spectral space, i.e. to the wave number $\vec{k} = (k_x, k_y)$ and wave frequency ω domains. For this purpose, a three dimensional *Discrete Fourier Transform* (denoted as *3D FFT* in figure 2) is applied to the measured data $i(x, y; t)$. Hence, the so-called *three-dimensional image spectrum* $I(\vec{k}, \omega)$ is computed. Three main contributions are present in the function $I(\vec{k}, \omega)$:

- Wave components (Young et al., 1985). These components represent the highest values of the image spectrum $I(\vec{k}, \omega)$.
- Speckle noise (Seemann, 1997). This contribution is highly correlated with the local wind (Hatten et al., 1998) and the significant wave height (Nieto et al., 1999).
- Higher modes of the wave components (Nieto, 1997; Seemann, 1997). This contribution appears in the image spectrum because of the non linear mechanisms of the radar imaging. The spectral energy of these components is small compared to the energies of the other contributions.

Two Dimensional Current Estimation

The estimation of the two-dimensional current $\vec{U} = (U_x, U_y)$ takes into account the wave components that are responsible for the highest values of the image spectrum. That means that most of the information in the sea clutter image is more due to the wave field than to the wind. This is true for normal waves (wind sea or swell), which size is much higher than the spatial and temporal resolution of the radar unit (Nieto, 1997).

To compute the surface current the linear wave theory is assumed. Hence, there is a dependence between the wave numbers and the frequencies, given by the dispersion relation

$$\omega = \sigma(\vec{k}; d, \vec{U}) = \sqrt{gk\,tanh(kd)} + \vec{k}\cdot\vec{U} \qquad (1)$$

where g is the acceleration of gravity, d is the water depth and the wave number $k = \sqrt{k_x^2 + k_y^2}$.

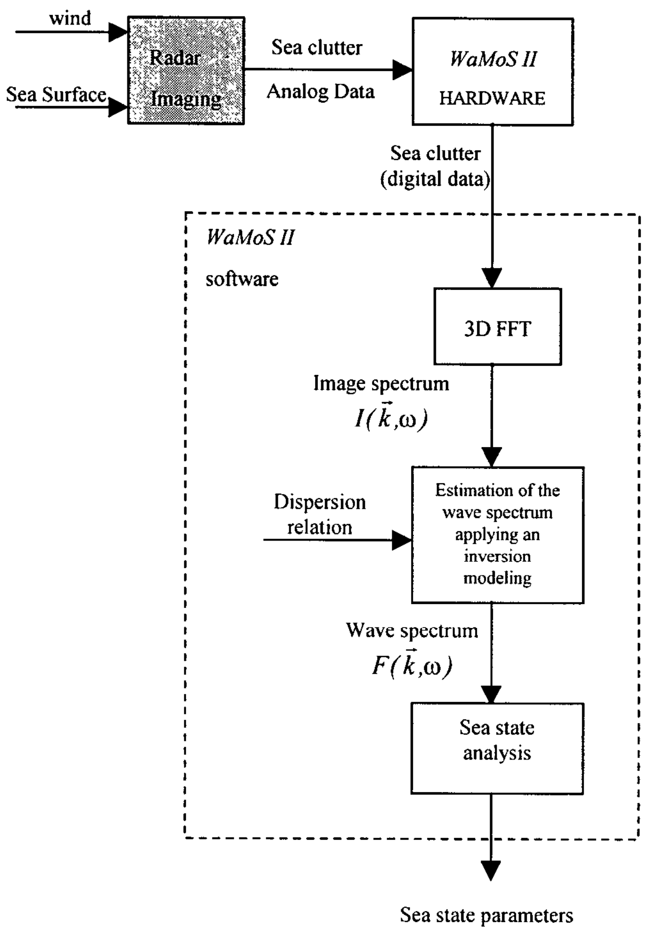

Figure 2: Scheme of the analysis of sea clutter time series

Assuming that expression (1) holds and taking all spectral points $(\vec{k},\omega)$, whose image spectrum value is higher than a previously defined threshold, which is usually 20% of the maximum of $I(\vec{k},\omega)$, the surface current velocity is computed by a linear regression (Young et al., 1985).

The current estimation is improved taking the spectral points of the higher modes (Senet, 1996). The higher mode dispersion relation is given by (Nieto, 1997; Seemann, 1997).

$$\omega = \sigma_p(\vec{k}; d, \vec{U}) = $$
$$= (p+1)\sqrt{g\frac{k}{p+1}tanh\left(\frac{kd}{p+1}\right)} + \vec{k}\cdot\vec{U}, \text{ where } p = 0, 1, \ldots \qquad (2)$$

The expression (1) is a particular case of (2) for $p = 0$.

Recent results have shown that the water depth d can be fitted following a similar scheme than the current estimation (Outzen, 1998).

Wave Spectrum Estimation

Once the two dimensional current is computed, the wave spectrum estimation is carried out removing all $(\vec{k},\omega)$ components, which do not belong to the wave field (Young et al., 1985). Those are the speckle noise and the higher modes. Hence the directional wave number spectrum is obtained

$$F(\vec{k}) = 2\int_{\omega>0} I(\vec{k},\omega)\,\delta(\omega - \sigma(\vec{k}))d\omega \qquad (3)$$

being $\delta(x)$ the Dirac's delta.

Due to the directional spectrum $F(\vec{k})$ has been measured using spatial and temporal information of the wave field, the full directional distribution of the sea state is known. This full directional description is the main advantage of marine radars comparing to in-situ sensors moored in a fixed point of the ocean, such a directional buoys, because it is well known that the point measurements are not able to describe all the statistical directional properties of sea states.

Frequency-Direction Spectrum

Once the wave number spectrum $F(\vec{k})$ is computed, other different spectral parameterizations are derived. The most used spectral density is the frequency-direction spectrum. That is defined as

$$E(\omega,\theta) = F(\vec{k})\frac{dk}{d\omega} \qquad (4)$$

The expression (4) has been obtained taking into account the dispersion relation (1).

The frequency-direction spectrum $E(\omega,\theta)$ leads to the most common sea state parameters, such as peak period, main direction, etc.

Significant Wave Height Calculation

The wave spectral estimations shown before, namely $F(\vec{k})$ and $E(\omega,\theta)$, are not property scaled. Hence, the total wave energy and the significant wave height cannot be computed from these spectral estimations. The reason is that the sea clutter image is codified in a relative grey level scale, which depends on each particular radar system.

A recent result (Nieto, 1998) has demonstrated that the spectral estimation given by (3) and (4) can be scaled. The scaling method follows a similar idea used for the Synthetic Aperture Radar (SAR) systems (Alpers et al., 1982). So, the significant wave height H_{mo} is computed by using a linear regression given by

$$H_{mo} = A + B\cdot\sqrt{SNR} \qquad (5)$$

where A and B are calibration constants, which depend on each radar installation. SNR is the ratio of the energy of the function $F(\vec{k})$ divided by the energy of the image spectrum

$I(\vec{k},\omega)$ excluding all points $(\vec{k},\omega)$ in which the dispersion relation (1) holds.

The wind speed is fitted in a similar way than the significant wave height (Hatten, 1998; Hatten et al. 1998).

RESULTS

This section deals with different results obtained from nautical radar measurements. The first part illustrates what the Wave Monitoring System delivers in real time. So, figure 3 shows the estimation of a directional wave number spectrum $F(\vec{k})$ of a bimodal sea state. This sea state was composed by two single wave field contributions. That is a long wave length swell propagating to the east with a high focused direction, and a wind sea propagating with a high angular spreading between north and west. In addition, figure 3 shows the estimated current, as well as the peak periods and peak wave lengths for each wave field contributions. This measurement was taken in the Northern North Sea in the FPSO Norne of STATOIL.

Figure 3. Example of directional wave number spectrum delivered in real time from a nautical radar measurement. The data were taken in the FPSO Norne.

The frequency-direction spectrum $E(\omega,\theta)$ of this bimodal sea state appears in figure 4. In a similar way than figure 3, the image of the figure 4 is a hard copy of the computer screen running the *WaMoS II* data analysis software in real time. The usual directional representation of $E(\omega,\theta)$, adopts the angles where the waves are coming from. So, there is a shift of 180° comparing to the directional representation in the function $F(\vec{k})$, where the propagation direction is considered. That is the direction where the waves are going to.

Once the $E(\omega,\theta)$ spectrum is obtained other sea state parameters are derived. Figure 5 is an example of the real time computation of the frequency spectrum $S(\omega)$, the main direction $\theta(\omega)$, and the angular spreading $\sigma(\omega)$. As in the case of figures 3 and 4, the example of figure 5 corresponds to the same bimodal sea state. Looking at the shape of the scalar spectrum $S(\omega)$, it is clear that the wind sea energy is higher than the swell energy for this case. So, the peak period (which takes into account the contribution of all the wave directions for each frequency) of the function $S(\omega)$ has a similar value of the primary peak period (which only takes into account the wind sea directions) of the wind sea.

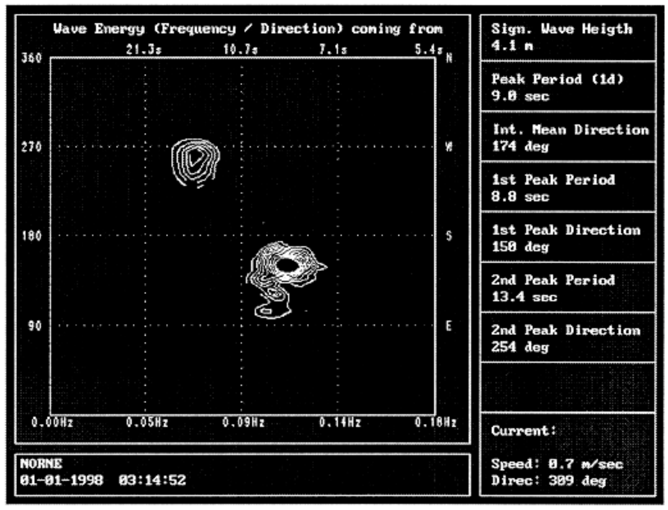

Figure 4. Example of directional frequency-direction spectrum delivered in real time from a nautical radar measurement. The data were taken in the FPSO Norne

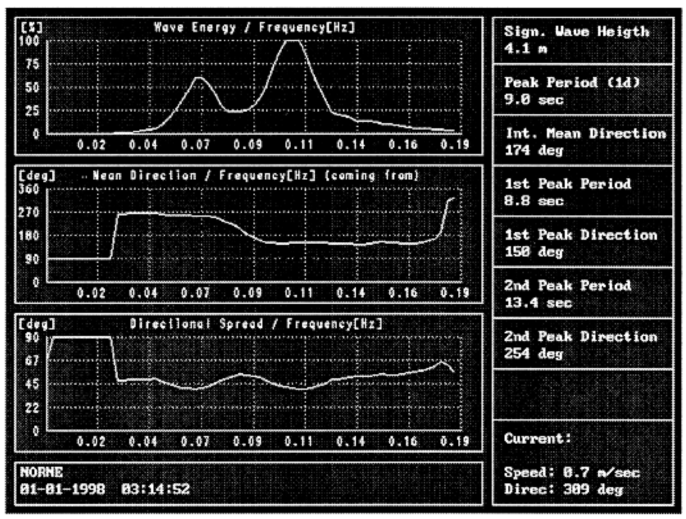

Figure 5. Example of frequency spectrum, mean direction and angular spreading delivered in real time from a nautical radar measurement.

The radar data collected at offshore platforms has been compared with buoy data in different calibration exercises.

Figure 6 shows two examples of the significant wave height obtained by a nautical radar and the corresponding buoy record. The first example (figure 6a) was taken in the FPSO Norne from November, 20th 1998 to January, 2nd 1999. The second example (figure 6b) has been measured in the North Sea platform of Ekofisk, from January 19th to 27th 1999, where the Norwegian Meteorological Office (DNMI) has installed a marine radar based sensor. Both data sets present a good agreement.

The frequency-dependent main direction of this swell case shown in figure 8, shows a high agreement between the two sensors, as in the case of the scalar spectrum. A similar result is obtained for the angular spreading (see figure 9).

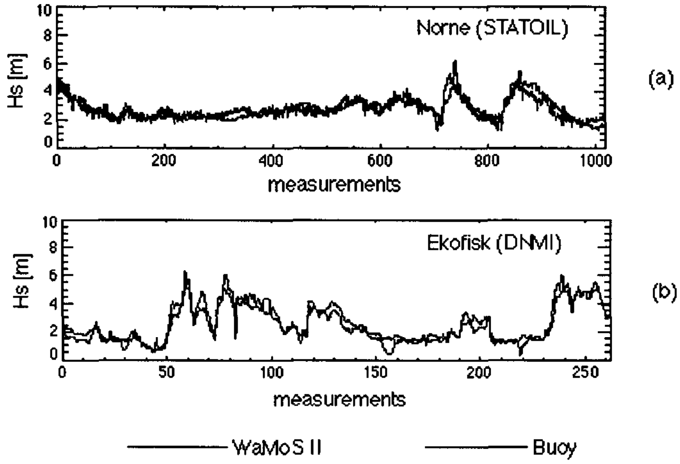

Figure 6. Comparison of radar and buoy data.

Figure 7 shows another the comparison of the $S(\omega)$ estimations obtained from a directional buoy and a radar system mounted, in this case, on an ocean going ship. This measurement was taken in the Bay of Biscay in deep waters (about 600-meter depth) close to the Northern coast of Spain. The measured sea state is an example of the typical swell wave field of this area, which comes from North-West and it is due storms originated in the North Atlantic Ocean. Both curves present a high coincidence.

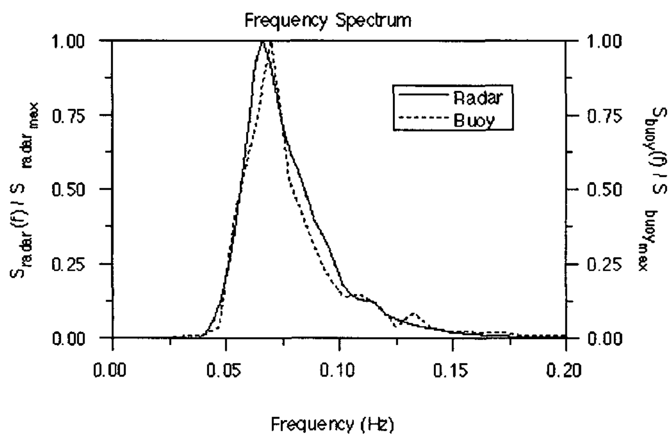

Figure 7. Comparison between the frequency spectrum obtained from the analysis of buoy records of wave elevation and the nautical radar estimation from a ship.

CONCLUSIONS

Common nautical radars can be used as a microwave remote sensing instrument to measure time series of sea surface images.

The spatial and temporal wave field dependence is required to measure the directional features of sea states. That is especially important to obtain information of multimodal sea states, which can be caused by complex meteorological situations. The result of the analysis of radar data delivers sea state parameters, such as mean and peak wave directions, wave periods and significant wave height.

The wave parameters derived from nautical radars are in good agreement with the available ground truth data.

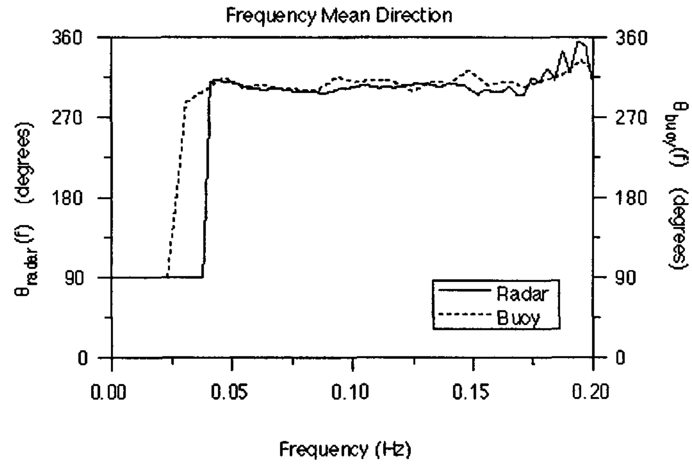

Figure 8. Comparison between the frequency-depending main direction obtained from the analysis of buoy records and the nautical radar estimation from a ship.

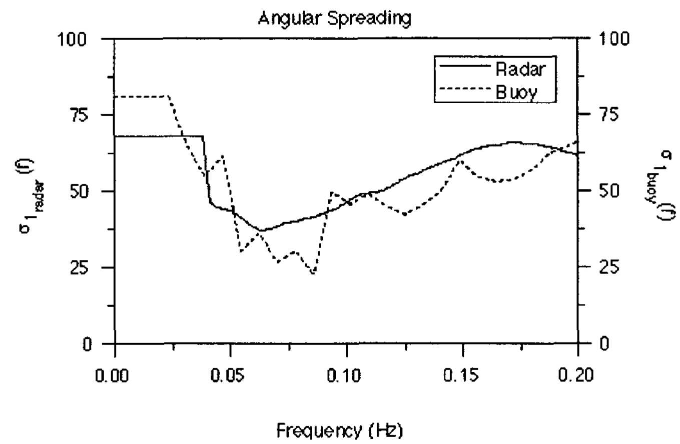

Figure 9. Comparison between the frequency-depending angular spreading obtained from the analysis of buoy records and the nautical radar estimation from a ship.

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