WAVE HEIGHT MEASUREMENTS WITH NAVIGATION RADAR

Jur Vogelzang[*], Kees Boogaard[*], Konstanze Reichert[**], and Katrin Hessner[**]
[*]Rijkswaterstaat, Delft, Netherlands
Survey Department
j.vogelzang@mdi.rws.minvenw.nl; c.boogaard@mdi.rws.minvenw.nl
[**]Ocean SenseWare, Geesthacht, Germany
reichert@gkss.de; hessner@gkss.de

KEY WORDS: Navigation radar, Wave spectrum, Significant wave height, Wave direction.

ABSTRACT

Images generated by a common ship's navigation radar contain wave information. Digital techniques allow rapid acquisition and processing of such data. Since the radar is looking at extreme grazing angles, effects like diffraction and shadowing dominate the backscatter mechanism. As a consequence, no reliable backscatter model is available that allows inversion to retrieve wave heights. In the Wave Monitoring System (WaMoS II), commercially made available by Ocean SenseWare, this problem is solved by fitting an empirical model to wave data measured by traditional means. The system has been tested at the Dutch coast near Petten, where every year an extensive wave measurement campaign is held. The radar data were collected using the mobile radar system of Rijkswaterstaat. The significant wave height is retrieved with an accuracy of 30 cm (20%) compared to buoy measurements. The wave direction is accurate within 9°. The system has also been tested for a short period at the IJsselmeer, a large lake, and was able to measure wave information at low wind conditions using improved analysis techniques. WaMoS II proves to be well suited for wave monitoring in shallow coastal area's and large lakes.

1 INTRODUCTION

Wave information is important for various purposes ranging from guidance and safety of shipping traffic, establishment of design criteria for coastal defences to morphological investigations. A number of wave measuring devices have been developed (e.g., pitch and roll buoys, step gauges, capacity wires, altimeters, pressure cells). Each instrument has its own advantages and disadvantages. All traditional instruments have in common that they collect wave information at one single point. Special interest has been shown lately in the use of remote sensing techniques to determine wave information as only these methods may give a synoptic view of wave fields at reasonable costs.

One system to remotely measure the sea state is based on a nautical X-Band radar used generally for traffic control and navigation purposes. Radar measurements of the sea state are based on the analysis of the temporal and spatial evolution of the radar backscatter information of the sea surface (sea clutter), received in the near range of the radar. For navigational purposes these sea clutter signals are considered as noise and are removed from the Plan Position Indicator (PPI) screen by applying a threshold to the radar echoes. Figure 1 shows a snap shot of the PPI screen, showing the Dutch coast and signatures of long surface waves approaching the coast. Significant wave length and wave direction can be derived by hand from such images. For operational retrieval of relevant sea state parameters, a series of such images is stored and analysed by means of a three dimensional Fourier transform. With the knowledge of the dispersion relation of linear surface waves it is possible to obtain unambiguous directional wave spectra and surface current in almost real time. From this wave spectrum all important sea state parameters can be derived (Ziemer and Günther, 1994; Nieto et al., 1998).

In contrast to in-situ sensors which measure directly the temporal evolution of the sea surface elevation at a given location, absolute values of the wave height cannot be determined directly from radar images. The reason lies in the observation geometry: the surface waves are imaged from extreme grazing angles. Effects like diffraction and shadowing are important and no rigorous radar backscatter model (i.e., a model derived from the Maxwell equations) exists to describe the relation between surface waves and radar echo.

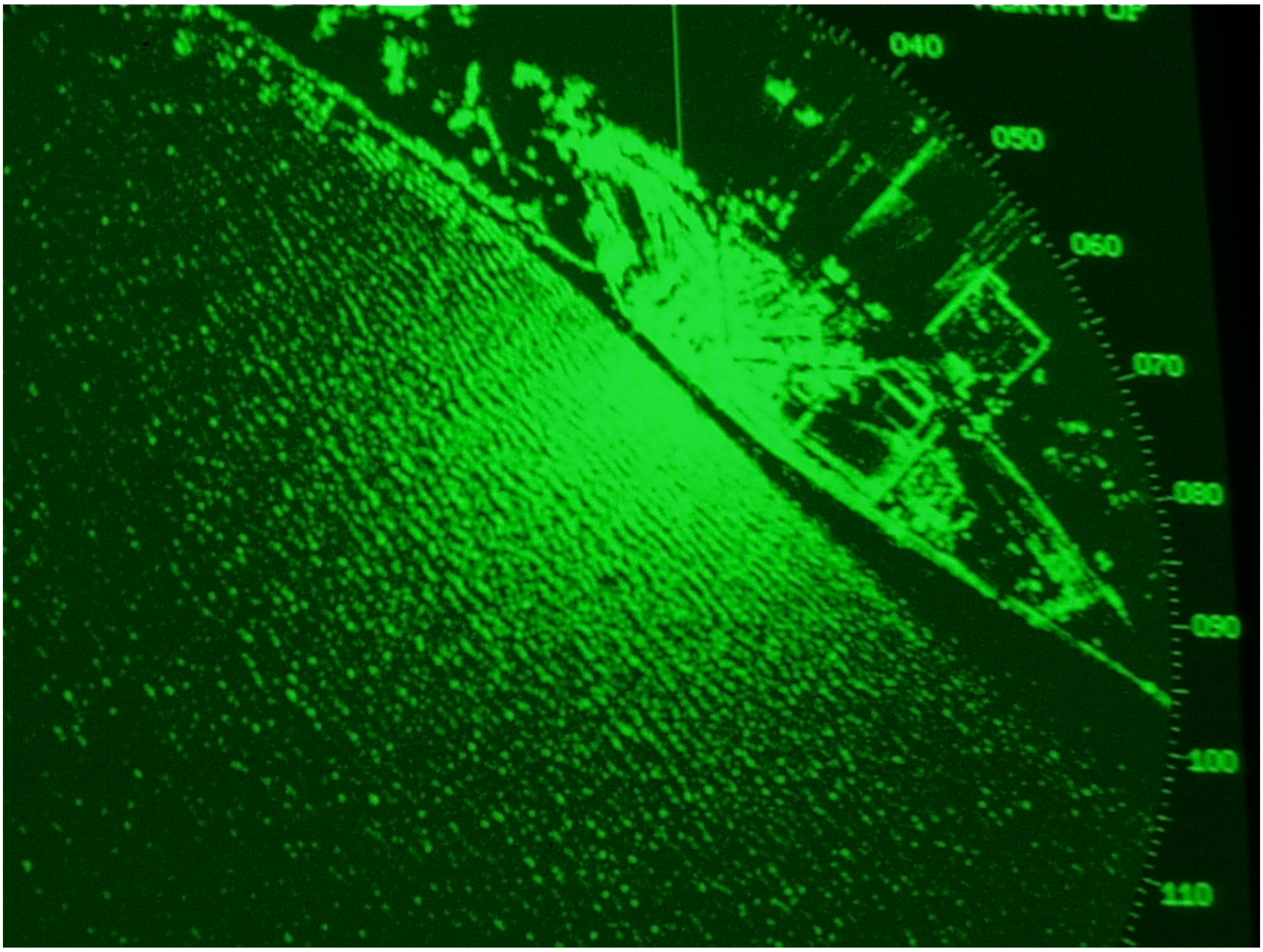

Figure 1. Part of a PPI image recorded at the Dutch coast near Petten, The coast line is from upper left to lower right. The direction scale at the edge of the PPI is partly visible. The wave pattern is clearly visible, and refraction may be seen near the shore. The image covers a few km.

However, an empirical relation between the height of a wave and the signal-to-noise ratio of the radar image exists. The general possibility to use this relation for determining the significant wave height from nautical radar images has been shown in a number of cases (Nieto et al., 1999a;b; Reichert et al., 1999; Hessner et al., 1999). The relation depends a.o. on the radar installation and in order to obtain reliable wave height information, each system must be calibrated once using independent wave height data, e.g., from a buoy. A typical calibration period takes a few days, but its length depends strongly on the range of meteorological conditions encountered. After calibration the system can be used as stand-alone wave measuring device. Note that the radar must stay at the same position during all measurements; calibration must be repeated when it is moved.

One wave monitoring system based on nautical radar measurement is the WaMoS II which has been developed at GKSS and that is now commercially made available by Ocean SenseWare. WaMoS II consists of a hardware and a software part. The hardware is an A/D converter that connects the nautical radar to a PC. The software controls the radar sampling, performs the data analysis, and allows to display the wave measurement results. The WaMoS system has been tested in a number of occasions. The system operates extremely well in rough weather conditions and can run automatically and unattended.

In this paper results are presented of wave measurements carried out by WaMoS II at the North Sea coast near the town of Petten in the Netherlands. The mobile radar of Rijkswaterstaat was used to acquire the radar data. The objective of this experiment was to determine the capability of WaMoS II for near shore wave measurements.

2 EXPERIMENT

The main experiment took place near the town of Petten at the Dutch coast. The dunes, which form the natural defence against flooding by the North Sea, are interrupted at this location and a dike has been built to protect the land. At this location, Rijkswaterstaat performs an extensive wave measuring campaign every winter in order to gather knowledge on the wave climate, which is used to establish criteria on coastal defences. A number of wave measuring devices is deployed in a linear array extending from the dike itself to about 10 km offshore. For the calibration of the WaMoS II significant wave height data of a Directional Waverider buoy located about 600 m offshore has been used.

The radar data were gathered using the mobile radar combination of Rijkswaterstaat, shown in Figure 2. It consists of two trucks, one carrying the radar and the other carrying a control cabin (left and right, respectively, in Figure 2). The trucks were parked behind the dike. The radar was built by Selesmar and operates at 9.375 GHz (X-band). It is a.o. used to determine whether or not a given location is suitable for a fixed radar post. The antenna is vertically (VV) polarised and was built by the Christiaan Huygens Laboratorium. It has an angular width of 0.39° and it is mounted on a hydraulic arm. During the experiment the antenna was lifted to its highest position, about 10 m above the ground, looking over the dike to the sea. The antenna repetition rate (rotation speed) was made adjustable for this experiment. During the experiment we used the maximum rate of one revolution every 1.5 seconds in order to achieve the best temporal resolution. The PPI and the computer with the WaMoS system were placed in the control cabin. The WaMoS II hardware digitised and stored the complete radar image on hard disk. For the wave analysis, an area of about 600 m × 600 m was selected (128 × 128 pixels, each pixel measuring 4.68 m × 4.68 m). The area was centred around the Directional Waverider buoy located 600 m offshore.

Figure 2. The mobile radar behind the dike at Petten. The photograph is taken from the landward face of the dike. The truck with the control cabin (right) partly blocks the sight of the truck with the antenna mount (left).

WaMoS was configured to capture a sequence of 64 consecutive radar images for each measurement. With an antenna repetition rate of 1.5 s, WaMoS can detect waves with frequency between 0.03 Hz to 0.34 Hz with a resolution of 0.005Hz. This frequency range corresponds to wave periods from about 3 s to 33 s. One single measurement thus takes about 2 minutes. The system measured continuously when the radar was switched on. However, it was not possible to operate the radar unsupervised due to the fact that the antenna repetition rate was increased beyond its original design. The radar was therefore only switched on if wind and wave conditions were interesting.

3 RESULTS

3.1 Comparison with buoy data

The campaign at Petten was held from October 20, 1999 to November 10, 1999. As an example, Figure 3 shows a two dimensional wave energy spectrum recorded at Petten using WaMoS on the mobile radar. The spectrum shows a distinguished wave system generated by local winds coming from West to Southwest. The obtained peak frequency of 0.14 Hz and peak direction of 80° corresponds to waves with a period of about 7 s and wave lengths of about 60 m propagating NE. This result is in good agreement with reference data. Also the current velocity and direction at the sea surface, averaged in the 600 m × 600 m measurement region, are indicated. The current velocity seems to be rather high, 2.9 m/s. A current meter was installed near the measurement region, but it was buried under sand during the radar measurements. It is therefore not possible to validate the current measurements.

The two dimensional wave spectrum offers the most complete description of the wave field as it allows to separate wave systems coming from different directions. All other sea state parameters like frequency spectrum, peak wave period, and peak wave direction can easily be determined from such spectra (see Table A in the Appendix). Figure 4 shows the main parameters characterising the sea state: significant wave height H_S, peak wave period T_P, and peak wave direction θ_P, for all periods the radar was switched on and the buoy delivered reliable data. As the buoy data represent 10 minutes mean values, the WaMoS II wave parameters were also average over 10 minutes. It is interesting to note that the buoy failed during the maximum of the storm on November 6, probably due to the heavy sea state, while WaMoS still produces wave heights that seem reliable.

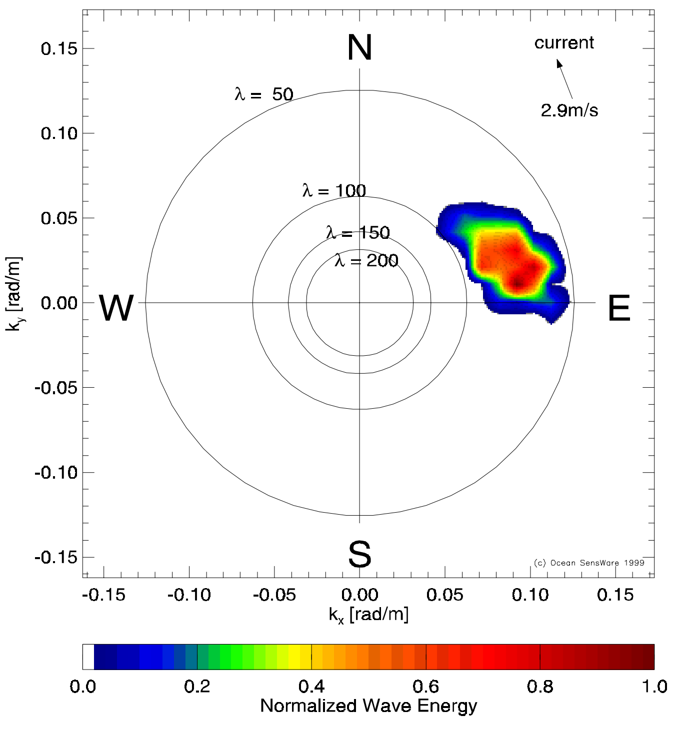

Figure 3. Two dimensional wave energy spectrum recorded with the mobile radar and WaMoS at Petten on October 31, 1999, 8:38 UTC. The spectrum has been normalised to one by the plotting software in order to cover the full colour scale.

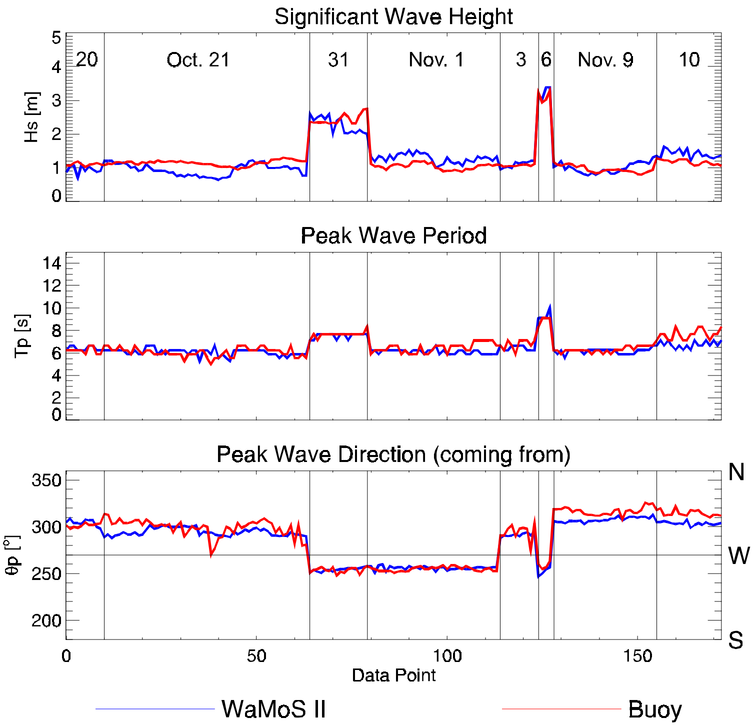

Figure 4. Significant wave height (upper panel), peak wave period (middle panel) and peak wave direction (lower panel) measured at Petten with WaMoS II (blue curves) and with a Directional Waverider (red curves). The figure covers only the periods during which the radar was switched on.

The time series of H_S (upper panel of Figure 4) shows that during the experiment most of the time the significant wave height was around 1 m, except for two storms on October 31, 1999 and November 6, 1999, respectively. During the storms the significant wave height increased to up to 3 m or more. The storms are also reflected in the peak wave period (middle panel of Figure 4), which rises from about 6 s to about 7 - 8 s in the storm periods. The peak wave direction was generally from western directions (between 250° and 300° true North). All three wave parameters show a good agreement between buoy and WaMoS II measurements. The small differences that occur may be due to local variations, since the buoy measures sea state at one position only, while WaMoS II data represent spatial mean values over an area of about 3600 m^2. Figure 5 shows a scatter plot of the buoy measurements versus the radar results. As expected from the previous results, this plot indicates good correlation between the buoy and radar measurements. The corresponding statistical parameters are given in Table 1. From this table it can be inferred that the significant wave height has a root-mean-squared error of 30 cm (20%) compared to the buoy measurements. The peak period is accurate within 0.6 s (10%), while the peak direction is reproduced within 9° (3%). Systematic deviations (bias) are small.

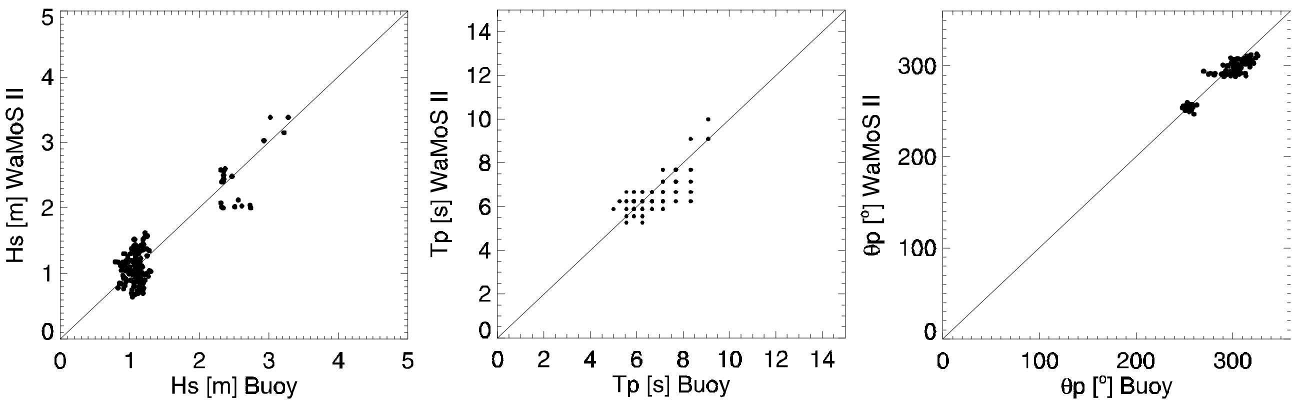

Figure 5. Scatter plots of buoy measurements versus radar results for significant wave height (left panel), peak wave period (centre panel), and peak wave direction (right panel).

	Significant wave height H_S	Peak period T_P	Peak direction θ_P
Correlation coefficient r	0.87	0.74	0.96
Root-mean-squared error σ	0.3 m (20%)	0.6 s (10%)	8.5° (3%)
Bias	0 m	-0.2 s	-3.9°

Table 1. Statistical parameters of the comparison.

3.2 Sensitivity analysis

As stated before, the standard WaMoS II wave analysis uses a part of the digitised radar image of 128 × 128 pixels (about 600 m × 600 m). The size of the window can be varied. Table 2 shows the results for various window sizes for October 31, 1999, 8:38 UTC. For each spatial window, the same number of 64 radar images was used in the analysis. Increase of the window to 256 × 128 pixels has little effect on the peak period and peak direction. Decrease of the window to 64 × 64 pixels shows deviations in these parameters.

	128 × 128	256 × 128	64 × 64
Peak period	7.3 s	7.3 s	7.9 s
Peak direction	254°	254°	252°

Table 2. Results for different sizes of the spatial window on October 31, 1999.

3.3 Deployment at IJsselmeer

On November 15 and 16, 1999, the mobile radar and WaMoS were located at the IJsselmeer, the largest lake of the Netherlands. The aim of this short deployment was to establish whether or not WaMoS can be used for lakes. There is a need for wave information along the IJsselmeer to assess safety of the coastal defences. However, the lake is too shallow to deploy buoys, so only equipment mounted on expensive measurement poles can be used. Moreover, the lake may freeze during cold winters, thereby damaging any wave measuring instrument that makes contact with the water surface. Ground based radar may provide a good alternative.

On November 15 there was almost no wind and hence not wave. On November 16, the wind increased a bit to about 3 - 4 Bft from the West and hence wave were generated. Visual observation showed waves with a period of about 3 s and a wave length of less than 20 m. This is at the resolution limit of standard WaMoS II. With a special analysis method, the WaMoS II obtained wave spectra in good agreement with the visual observations. As no reference wave data were available, these spectra can not be validated.

4 CONCLUSIONS

WaMoS II is a wave monitoring system based on a nautical radar. It allows to obtain unambiguous wave spectra and near surface current information in real time. The system was tested at two locations in the Netherlands. The radar data were collected by the mobile system of Rijkswaterstaat. At the Dutch coast near Petten, WaMoS was calibrated using data from a nearby buoy. The significant wave height is accurate to 30 cm (20%); the peak wave direction is reproduced within 9° (3%). WaMoS produces a wave spectrum every two minutes for an area of about 600 m × 600 m. It is not possible to decrease the spatial window significantly. The system functioned well under storm conditions during which the reference wave buoy failed. As the current meter in the area failed during the radar campaign, no validation of the current measurements is possible. Deployment at the IJsselmeer during light wind conditions indicated that the system may be very well suited to monitor waves also in large lakes.

ACKNOWLEDGEMENTS

The authors wish to thank the National Institute for Marine and Coastal Management/RIKZ and the North Holland Directorate, both of Rijkswaterstaat, for their assistance in the radar deployment and retrieval of the reference data.

APPENDIX

Name	Symbol	Range
2d wave number spectrum	$F^{(2)}(k_x,k_y)$	
2d frequency direction spectrum	$F^{(2)}(f,\theta)$	0.025 - 0.29Hz, 0 - 360°
1s frequency spectrum	$S(f)$	0.025 - 0.29Hz
Significant wave height	H_s	1 m - 20 m$^{*)}$
Mean period (Mean zero upcrossing period)	T_{m02}	3.5 - 55 s
Peak period	T_p	3.5 - 55 s
Mean wave direction	$\theta(f)$	0 - 360°
Peak direction	θ_p	0 - 360°
Integrated wave spreading	$J(f)$	0 - 90°
Peak wave length	λ_p	19 - 600 m $^{*)}$
1st peak period	T_{p1}	3.5 - 55 s
1st peak wave length	λ_{p1}	19 - 600m³ $^{*)}$
1st Peak direction	θ_p	0 - 360°
2nd peak period	T_{p2}	3.5 - 55 s
2nd peak wave length	λ_{p2}	19 - 600 m $^{*)}$
2nd peak direction	θ_{p2}	0 - 360°
surface current velocity	U	0 - 20ms^{-1}
surface current direction	θ_U	0 - 360°

$^{*)}$These values indicate the typical range, but they can be varied for individual installations.

Table A. Name, symbol, and range of the main sea state parameters as provided by standard WaMoS II.

REFERENCES

Hessner, K., K. Reichert, and J. Dittmer, 1999. Coastal application of a wave monitoring system based on a nautical radar. In: Proceedings IGARSS Conference, 28. June - 2. July 1999, Hamburg, Germany, Vol. 1, pp. 500-502.

Nieto, J.C., K. Reichert, J. Dittmer, and W. Rosenthal, 1998. WaMoS II: A wave and current monitoring system. In: Proceedings of the COST 714 conference on directional wave spectra, Paris, 1998.

Nieto Borge, J.C., K. Reichert, and J. Dittmer, 1999a. Use of nautical radar as a wave monitoring instrument. Coastal Engineering, (37), pp. 331-342.

Nieto Borge, J.C., K. Hessner, and K. Reichert, 1999b: Estimation of the significant wave height with X-band nautical radars. In: Proceedings OMAE Conference, 1999, (in press).

Reichert, K, K. Hessner, J.C. Nieto Borge, and J. Dittmer, 1999. WaMoS II: a radar based wave and current monitoring system. In: Proceedings ISOPE Conference, Brest, France, 1999.

Ziemer, F., and H. Günther, 1994. A system to monitor ocean wave fields. In: Proceedings 2nd. International Conference. On Air-Sea Interaction and Meteorology and Oceanography of the Coastal Zone, Lisbon, September 22-27, 1994.