COMPARISON OF DIRECTIONAL SPECTRA OF SEA WAVES ESTIMATED BY AN ARRAY OF RADAR SENSORS AND A DIRECTIONAL WAVERIDER BUOY

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Abstract

The performance of a new developed, directional wave monitoring system is evaluated through comparison to a Datawell Directional Waverider buoy MK III, which is most widely used to measure the directional properties of surfaces waves. The new system is based on an array of four radar-sensors, which makes it cost-efficient and almost free of maintenance. A standard deviation of 3.4° for the calculated dominant directions can be achieved (for sea states with h_{sig} >0.6 m), when local particularities of the test field are considered. In addition, a detailed analysis of the alignment of wind and wave directions, separated in two frequency domains, is performed within this study.

1. Introduction

For some years now, there has been an increasing interest in the description of directional spectra of sea waves, due to its manifold usage in various disciplines. Barstow et al. (2005) underline the fundamental importance for wave modeling and engineering applications. Forces on piles, breakwaters and offshore structures as well as their response to waves, for instance, depend on direction. Suh et al. (2002), for example, emphasize the sensitivity of damage predictions for coastal structures to the directional characteristics of the wave field. Furthermore, the knowledge of directional spectra of sea waves is essential for scientific purposes, such as diffraction and refraction studies (Panicker, 1975). Nevertheless, directional records are still rarely available. This might be due to the fact that the most common measuring systems are expensive and require extensive maintenance.

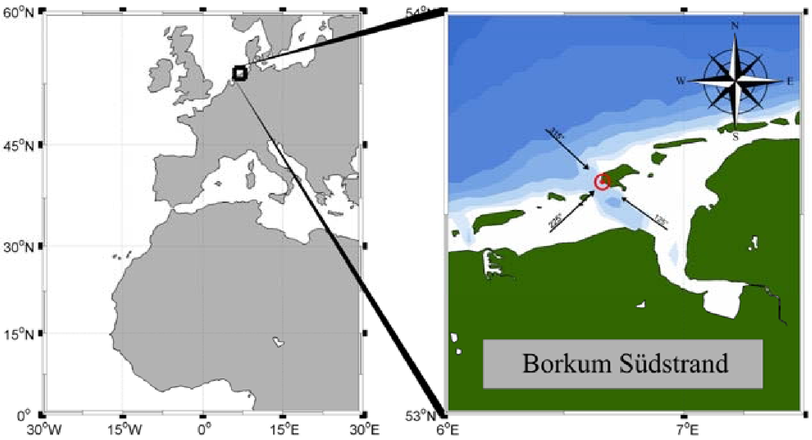

Figure 1. The observation site in the German North Sea. A large-scale map is shown on the left side. The right side depicts an enlarged section of the area surrounding the gauging station “Borkum Südstrand” (red circle). The black arrows denote the directions parallel and perpendicular to the coastline.

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Therefore, the German Federal Institute of Hydrology – *BfG* is developing a low-cost, non-contact directional wave monitoring system based on liquid-level radar sensors. In this study, a short description of the measuring principle is given. The main focus is on the comparison of the results estimated by the radar based system and the Datawell Directional Waverider buoy MK III at the gauge “Borkum Südstrand” (Figure 1). This test field is located in the southern North Sea off the island of Borkum. Although wave propagation along a large range of directions is strongly influenced either by islands or by shallow waters of the Wadden Sea, waves travelling along the prevailing wind direction (North-West) are not affected. Hence, maximum wave heights may exceed 7m and significant wave heights exceeding 4m here (Mai, 2010).

2. Data and methodology

The new developed directional wave monitoring system

Several measuring methods and analyzing procedures have been developed to monitor wave directional information. Most of the systems are either in direct contact with the water and hence require a high cost and time investment or are based on remote sensing, having a rather coarse spatial resolution. Thus, the German Federal Institute of Hydrology - *BfG* in cooperation with the Federal Waterways and Shipping Administration - *WSV* developed a directional wave monitoring system, based on radar technique. Its main advantage is its non-contact measuring principle, which makes it robust and maintenance-free and hence particularly suitable for operational use.

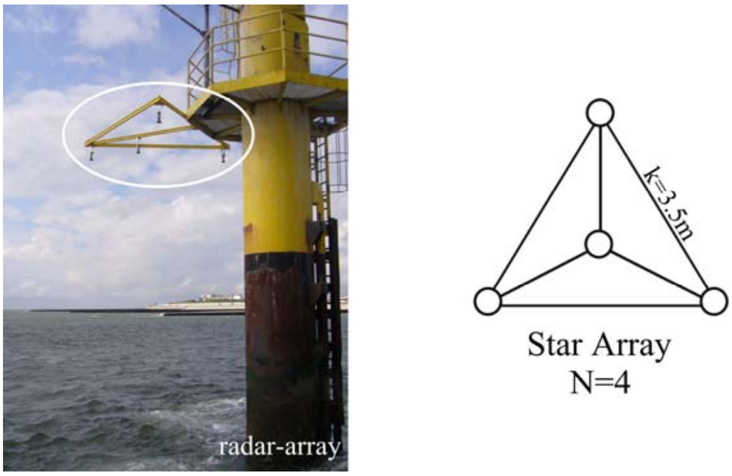

Figure 2. The radar-gauge array. The geometrical design, a star shaped array according to Goda (1985), is illustrated on the right side. The circles represent the sensor positions. The photograph on the left side depicts the first test assembly of the new developed system at the gauge “Borkum Südstrand” (picture taken by S. Rütten, 17.06.2012).

Since several years now, the German Federal Institute of Hydrology uses cost-efficient radar liquid-level sensors, originally designed for industrial mass-applications to monitor the water-level elevation at a single point. Therefore, the particular radar sensor emits electromagnetic pulses at a frequency of 26 GHz twice per second and, in turn, detects these pulses when they are backscattered at the water surface. Since the traveling time of each pulse is proportional to the distance between the radar sensor and the water surface, the water surface elevation can be easily calculated. This principle allows the accurate measurement of the water-level oscillation and resultant wave parameters (for further information see Mai and Zimmermann, 2000). The results of wave-flume experiments, for example, revealed a measuring accuracy of less than 0.5 cm for 95% (σ=0.017 cm) of the recorded significant wave heights (Wilhelmi and Barjenbruch, 2008).

Due to the high precision and reliability of this single sensor monitoring system, such a system has been in operation at various locations (“Borkum Südstrand”, since 2002; “Lighthouse Alte Weser”, since 2006; lagoon of Venice (Italy), since 2007; research Platform “FINO 1”, since 2008).

The new developed directional wave monitoring system is based on an array of four of those well-established radar-sensors (Figure 2). Simultaneous recordings of wave profiles at the fixed sensor positions are used to estimate the directional information of the sea state. Further information is given in the literature, e.g. Benoit et al. (1997).

For the design of such an array theoretical as well as practical aspects have to be taken into account. On the one hand, the resolution of the wave gauge array is limited by the array-size and number of sensors that are used. The directional resolution of the array increases as the maximum distance between the wave gauges increases, but the array size is limited by the smallest wavelength for which the directional analysis is to be made (the minimum separation distance between a pair of wave gauges has to be less than one half of this wavelength). Furthermore, the duplication of vector distances should be avoided, to fully exploit the information of all sensor locations (Goda, 1985).

On the other hand, the size of the array is often limited by the construction of its supporting offshore or coastal structure. Besides, for the operational use of radar arrays, the number of sensors should be limited to three or four, in order to keep them as simple and cost-effective as possible.

To meet these requirements, a star-shaped configuration (Goda, 1985) with an edge length of 3.5m was chosen for the first prototype (Figure 2, right). A first test assembly of this system has been mounted at the gauging station “Borkum Südstrand”, since July, 2012 (Figure 2, left).

The Datawell Directional Waverider buoy MK III

In addition to the wave gauge array, directional information of the sea states have been recorded by a Datawell Directional Waverider buoy MK III, since November, 2012. It is moored approximately 75~100m further offshore of the gauging station “Borkum Südstrand” at a depth of 20 m.

Figure 3. The location of the Datawell Directional Waverider buoy MK III in relation to the gauge “Borkum Südstrand” (pictures taken by S. Rütten, 31.10.2012). The direction of view in the left photograph is approximately 10°, whereas the angle of the right picture is almost cross-shore (~240°)

This surface following buoy is equipped with gravity stabilized vertical and horizontal accelerometers. The wave height is determined by integrating the vertical acceleration twice. The directional wave spectrum is estimated by correlating all three-dimensional motion data of the buoy (Datawell, 2006). The 3.48 Hz samples are first low-pass (cut off frequency of 1.5Hz) and high pass (cut off frequency of 0.033 Hz) filtered to reduce noise in the data. The data is than converted to a sample rate of 1.28 Hz. According to the manufacturer’s specifications, this leads to an accuracy in heave measurement of 0.01m, and a directional resolution of 1.5° (Datawell, 2006).

It has to be taken into account, that the directional resolution of the buoy is sensitive to the restriction of horizontal movement. Therefore, the buoy was moored with a standard Datawell rubber chord. In addition, maintenance was carried out once a month.

The wind data

Moreover, wind data was recorded by the German National Meteorological Service -DWD during the considered time period. The measuring station is located approximately 900m northeast of the gauge “Borkum Südstrand” on the island of Borkum. An ultrasonic anemometer, which is positioned 10 meter above ground measures wind speed and direction once a minute.

Data processing

For this study however, only overlapping wave records of both systems were used. This limits the study period to the time from 01.11.2012 until 16.01.2013, because in January the buoy had to be taken out of the water to avoid problems due to ice conditions. All data were processed in 30-minute intervals. Within these intervals, the arithmetically averaged means of wind speed and wind direction are assumed to represent the wind conditions. To achieve improved comparability of the directional wave spectra, both measuring systems were analyzed adopting the DIWASP Matlab toolbox, developed at the Coastal Oceanography Group, Centre for Water Research, at the University of Western Australia, Perth (Johnson, 2002). Within this toolbox, the Direct Fourier Transformation Method (DFTM) is selected for data analysis. This is acceptable, as there are only minor differences in the directional wave spectra (within the high-energy section) when comparing the results of the Diwasp analysis to those of the Datawell software (Figure 4).

The directions in this study are defined as the directions from which the waves are coming (by analogy with the wind directions).

3. Results

A comparison of the estimated directional spectra

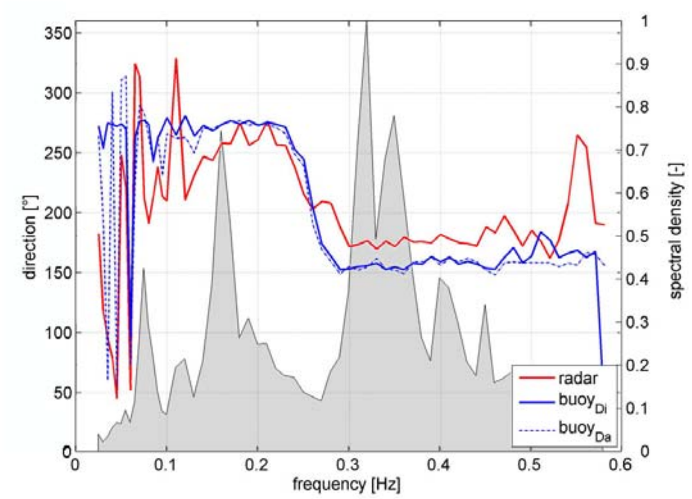

Figure 4. The directional wave spectrum estimated for the 30 minute time span starting on the 24th November 2012 at 19:00 o’clock. The gray shaded patch illustrates the normalized spectral density. The red (radar) and blue (buoy) lines show the spectral directional distributions of both monitoring systems. Furthermore, the blue dotted line depicts the spectral directional distribution of the buoy, as estimated by the Datawell software.

A Comparison of the directional wave spectra for the 24^{th} November 2012, 19:00-19:30 o'clock, as calculated by both measuring systems is given in Figure 4. Here the sea state is composed of two main components, having clearly distinguishable directions. Waves with frequencies up to ~ 0.27 Hz are coming from a westerly direction and those with higher frequencies propagate towards the north. Principally, the results of both measuring systems reveal this pattern in the section with a high spectral density (0.1-0.5 Hz), but there seems to be an additional systematic deviation.

Specific local characteristics

For a more detailed analysis of this phenomenon, the deviations of the high-energy range (normalized spectral density >0.5) of all time periods with significant wave heights exceeding 0.5m were regarded. The directional deviation upon the direction estimated by the buoy (bin size 20°) is illustrated in Figure 5. The estimated directions agree best in the range of ~200-240°. Within this range (~225°), waves travel perpendicular to the coastline (see Figure 1). The more the wave direction turns north, the more increases the northerly deviation of the direction determined by the buoy. As the same applies to southward changes, refraction might be the primary cause of detected systematic deviations. This view is further emphasized by the large change in depth between the two monitoring system locations (d_{buoy}~20m d_{radar_gauge}~8m). The wave direction turns cross-shore when the water becomes shallower, since the propagation velocity of waves in shallow water reduces with decreasing water depth. This is most likely the reason that constrains the wave motion at the gauging station towards the cross-shore direction (~225°).

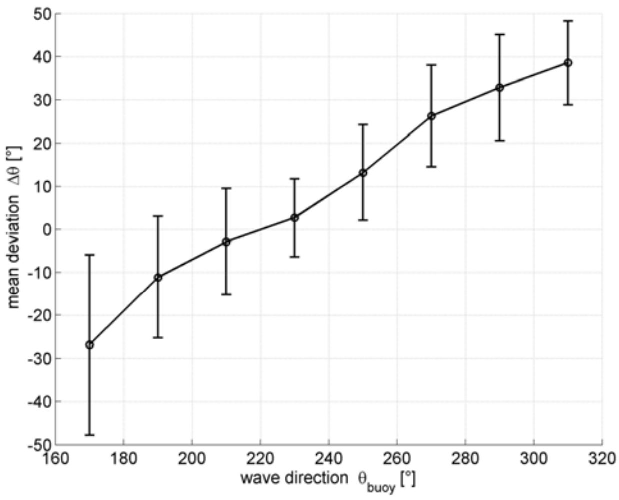

Figure 5. Indication of the strong influence of refraction. The mean deviation ($\Delta\theta=\theta_{buoy} - \theta_{radar}$) is plotted against the incoming wave direction, which is assumed to be aligned with the direction estimated by the buoy.

However, the direct calculation of the refraction effect is impractical because of the varying water levels, the diffraction due to surrounding islands and the sparse information about the bathymetry. Hence, in this study another, simple approach is preferred.

The directions calculated by the radar-gauge array θ_{radar} were adjusted by a transfer function, which depends linearly on the incoming wave direction θ_{in} (assumed to be aligned with the direction determined by the buoy) as well as on frequency f:

$$\theta_{radar}(f,\theta_{in}) = \begin{cases} \theta_{radar} + [(a\cdot\theta_{in} + b)\cdot(\frac{-f}{0.315}) + (a\cdot\theta_{in} + b) + c] & \forall \quad f < 0.315Hz \\ \theta_{radar} & \forall \quad f >= 0.315Hz \end{cases} \quad (1)$$

The parameters a=1.204, b=-273.5° and c=-0.6° were calculated using a linear regression. Waves with a frequency larger than f=0.315 Hz satisfy the deep-water condition at this particular observation site. As these waves are assumed not to be affected by refraction (wave-propagation velocity c is almost independent of the water depth d), they are excluded in the transfer function.

To improve comparability, the directions determined by the radar-gauge array are adapted by equation (1) in further investigations.

Comparison of dominant directions

The development of the dominant wave directions, that means the energy-weighted average of the respective sea state, is demonstrated for the considered time period in Figure 6. The results of both monitoring systems reveal a good agreement. Both systems, for example, are sensitive to sharp changes in the dominant wave direction (e.g. on 25th November 2012 or 23rd December 2012). It is also interesting, that the dominant wave directions are limited in their directional range (~150° - ~300°). As the test field is located close to the West coast of the island of Borkum (see Figure 1), wave generation due to winds with an easterly component is severely restricted.

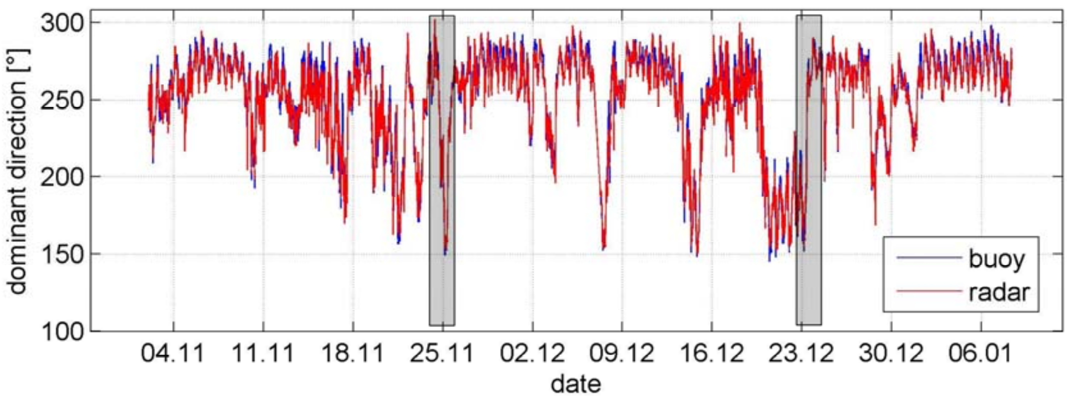

Figure 6. The dominant wave directions of the recorded time period, estimated by the buoy (blue) and the radar monitoring system.

A closer look at the results of both systems (Figure 7) reveals an improved consistency of the dominant wave directions with increasing wave heights. The standard deviation for sea states with a significant wave height higher than 0.6 m is 3.4°. The expected better agreement of the estimated directions from there on towards higher wave heights cannot be observed. On the on hand, this might be addressed to the sparse data set contributing to significant wave heights exceeding $h_{sig} > 1$ m. On the other hand one has to keep in mind that the correction, needed due to the influence of refraction, is a first order approximation. In this approach, the varying water level of the Wadden Sea (~2m), for example, is neglected, which can cause additional directional deviations.

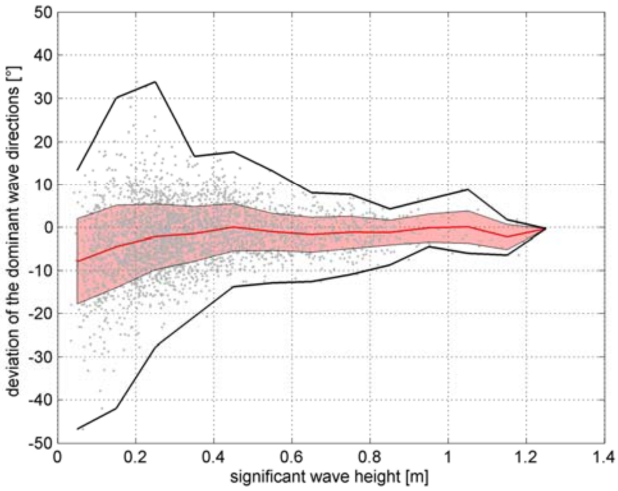

Figure 7. The dependence of the deviation of the dominant wave direction on the significant wave height. The gray dots mark the individual measurements and the black line illustrates the maximum deviation, whereas the red line and the red shaded patch show the mean and standard deviation.

A detailed analysis of the alignment of wind and wave directions

Particularly for offshore engineering applications it is also important to gain knowledge on the relative alignment of wave and wind loads. For a more detailed analysis of this correlation, the directional wave spectrum is first divided into two domains: the low-frequency domain (frequency range 0.05- 0.15) and the high-frequency domain (frequency range 0.15- 0.55). The cut-off frequencies are determined empirically for the gauging station "Borkum Südstrand". Figure 8, for example, illustrates the normalized spectral density of the sea state on 5th November 2012 at 10:30-11:00 o'clock. This example shows a reasonable separation of the two domains having clearly distinguishable peaks. One has to keep in mind that there are cases, for which such an allocation is more difficult.

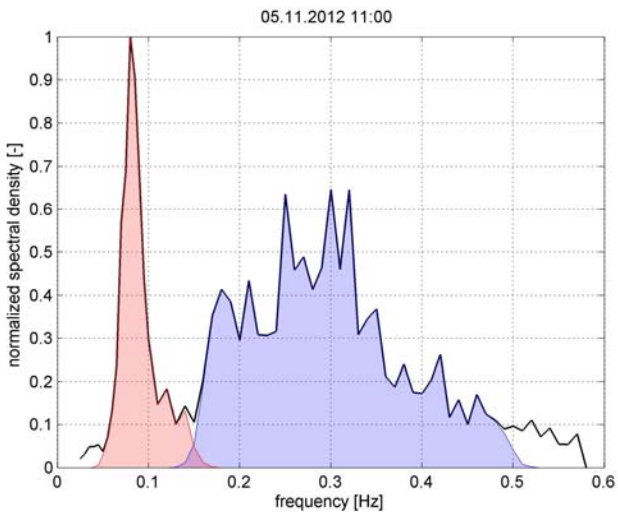

Figure 8. Illustration of the selected frequency domains. The red patch symbolizes the part of the normalized spectral density corresponding to the low-frequency domain and the blue area those corresponding to wind-waves.

These domains are separated for each sea state by making use of the Fourier-filter technique. For each domain, the direction is assumed to be represented by the energy-weighted average within its frequency range. A statistical comparison of the so estimated directions of both monitoring systems is given in Table 1. For the calculation of the standard deviation and maximum deviation, only sea states with a significant wave height exceeding 0.6 m were considered. Overall, the results of the two measuring systems show only slight deviations in both domains, as well for the whole frequency range. But the standard deviations of the estimated directions within the two domains are somewhat enlarged compared to the standard deviation of the overall dominant directions. This might be due to the fact that it is possible for each domain to contribute only a low energy input to the sea state, although the significant wave height is large.

Table 1. Comparison of the results of the two monitoring systems both domains, as well as for the entire dataset.

	low-frequency domain	high-frequency domain	All
$\sigma(\Delta\theta)$ [°]	13.9	3.8	3.4

When comparing the wind directions to the wave directions, significant deviations are discovered for both domains.

As an example of the development of wave (for the low-frequency domain and high-frequency domain) and wind directions for a storm surge is given in Figure 9. Within the first two hours (7:00- 9:00 o'clock), wind direction changes more than 50°. So does the direction of the waves contributing to the high-frequency domain, although they are not aligned with the wind direction. The deviation of the detected directions of both measuring systems can be addressed to the low wind speed and the resulting small wave heights ($h_{sig} < 0.6$ m) during this time period. Besides, the energy input of the low-frequency domain is negligibly small.

From there on the wind speed and thus the wave heights increase until the peak of the storm (~14:30 o'clock), while the wind and wave directions change only slightly towards West. During this time the directions of the high-frequency domain measured by the radar gauge array agree very well with those measured by the buoy, but again they waves are coming about 30° more from the West.

Approximately around the peak of the storm, the low-frequency domain starts to contribute an increasingly relevant part to the sea state, whereas the energy input of the high-frequency domain becomes smaller. Again, the estimated directions of the radar gauge array and the Directional Waverider buoy show a good agreement. At 16:00 o'clock, the direction of the low-frequency domain is ~25° further to the West of the direction of the high-frequency domain. The wind direction is ~25° to the south from the high-frequency domain

For a design analysis, three different loads acting on different parts of a coastal structure would have to be considered.

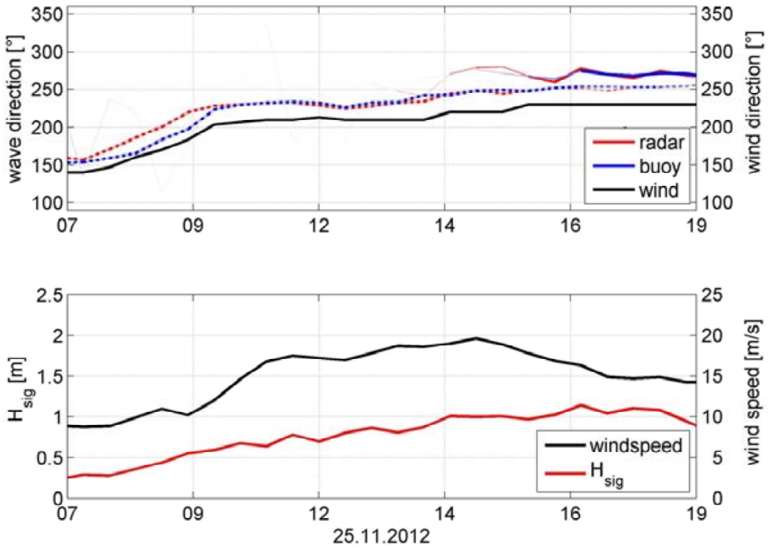

Figure 9. The upper panel depicts the development of the directions in the low-frequency domain (full line) and in the high-frequency domain (dotted line) domain. The color intensities and the line widths indicate the relative energy contribution of each frequency domain to the respective sea state. Additionally, the wind direction (black line) is illustrated. The lower panel shows the corresponding wind speed (black line) and the significant wave height (red line).

In general, both frequency domains reveal large discrepancies between the wave and wind direction (Figure 9). The directions of the low-frequency domain are restricted to a small directional range, whereas the directions contributing to the high-frequency domain show a larger variability, which is closer linked to the wind situation.

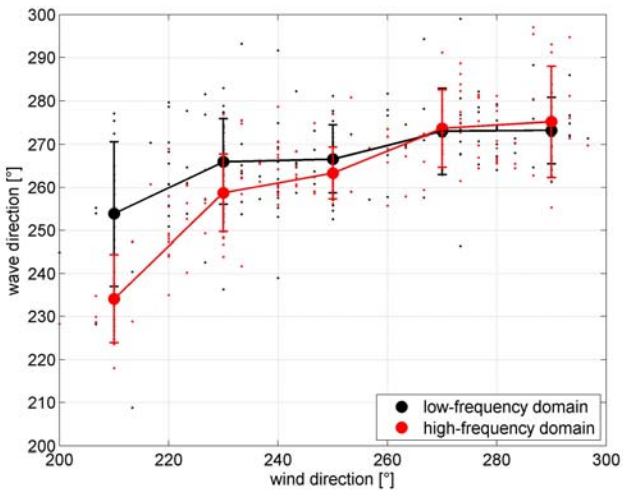

Figure 9. The dependence of wave direction (recorded by the radar gauge array) on wind direction at the gauging station “Borkum Südstrand” for different frequency domains.

4. Summary and discussion

Directional measurements of ocean waves, obtained by a radar gauge array and a Datawell Directional Waverider buoy MK III, are analyzed in this study. For comparison, the influence of refraction at the gauging station "Borkum Südstrand" is considered using a linear transfer function. Despite this simple approach, the dominant directions estimated by both systems reveal a standard deviation of 3.4° for sea states with a significant wave height exceeding 0.6 m.
Furthermore, the alignment of wind and wave direction, within two frequency domains, is examined for this particular observation site. As shown, there is neither a good correlation of the high-frequency, nor of the low-frequency waves with the wind direction. This underlines the importance of directional wave measurements in addition to wind measurements, when estimating the loads on coastal structures.
To this date, an exact accuracy evaluation of the radar gauge array is not possible due to the various particularities of the observation site that affect the wave propagation. To avoid the need for corrections a second test assembly is planned to be installed at the research platform "Fino 1" in April, 2013. This observation site is located ~ 45 km off the coast in the North Sea and thus disturbing influences are expected to be negligibly small.

Acknowledgements

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