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DIRECTIONAL WAVE SPECTRA MEASUREMENT BY AN ARRAY OF RADAR GAUGES

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Abstract

Up to now, measuring directional wave spectra has been costly and required intensive maintenance. Since the demand for such information has been constantly growing, the German Federal Institute of Hydrology – *BfG* began to develop a low-cost, non-contact directional wave monitoring system based on radar liquid-level sensors. Since July, 2012, a first test assembly has been mounted at the gauging station "Borkum Südstrand", which is located in the southern North Sea close to the island of Borkum. This study presents first records made by this new system during the winter season. To evaluate the accuracy, a Datawell Directional Waverider buoy MK III was deployed close to the gauging station. Besides the overall good agreement between the data of the two monitoring systems, systematic deviations suggest the occurrence of strong interactions of the wave field with the sea bed that will also be examined more closely in this study.

Key words: directional wave spectrum, wave gauge array, liquid-level radar sensor, Datawell Directional Waverider buoy, refraction, North Sea

1. Introduction

Along with the growth of European offshore industries, the demand for accurate and reliable monitoring of wave climates, in particular directional information, is steadily increasing. Several studies underline the importance of the knowledge of directional wave spectra for the design of coastal and offshore structures. Browers et al. (2000) for example emphasise, that the maximum tension at certain offshore structures occurs when wind and waves attack with an offset of 60°-90°. It should be noted that the assumption of aligned wave and wind direction is often inadequate although it is still widely upheld. Apart from various engineering applications, like design of moorings, offshore towers and piles, other disciplines, too, require a detailed knowledge of the directional wave spectrum (Panicker, 1975). Thus, marine researchers could be enabled to improve ocean wave theories as well as refraction and diffraction studies (Hashimoto, 1997). Moreover, uncertainties in numerical modelling of sea states, as used for climate research and coastal protection, could be further reduced (Haver and Nyhus, 1986).
Existing measuring systems, in particular those for the precise determination of local wave climates, are only used when they are indispensable, as they are expensive and require extensive maintenance.
The German Federal Institute of Hydrology – *BfG* is developing a low-cost, non-contact directional wave monitoring system based on an array of radar liquid-level sensors. A first prototype of this system has been mounted at the gauging station "Borkum Südstrand", since July, 2012 (Figure 1).

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Additionally, reference data are collected by means of a Datawell Directional Waverider buoy MK III, which is moored close to the gauging station (Figure 3).

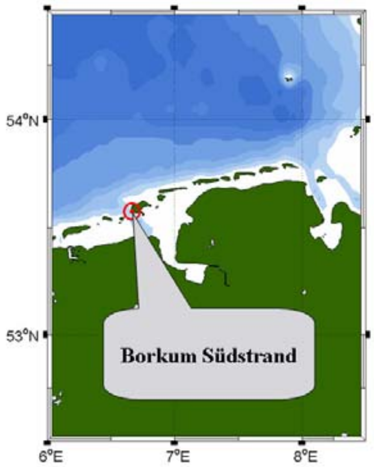

Figure 1. Location of the gauging station "Borkum Südstrand" in the southern North Sea (left) and photo (taken by S. Rütten, 17.06.2012) of the mounted radar-based system (right).

This paper presents first results of the field experiment gathered during the high wind season. In the interpretation of these measurements, the particularities of the local situation have to be taken into account. Therefore, a brief description of the observation site is given first. Then the paper gives some information about the measuring principles, as well as the data-processing procedure. A comparison of the results determined by the two measuring systems is discussed in the next Section, when special attention is given to the analysis of the influence of refraction, which is most probably the main reason for the detected systematic deviations. Moreover, the spectral analysis of the time series of directional (and significant wave height) data gives an indication of wave-tidal interactions.

2. Observation site

The gauging station "Borkum Südstrand" is located in the southern North Sea close to the island Borkum in the estuary of the River Ems (Figure 1). The water depth at the site is 8m.

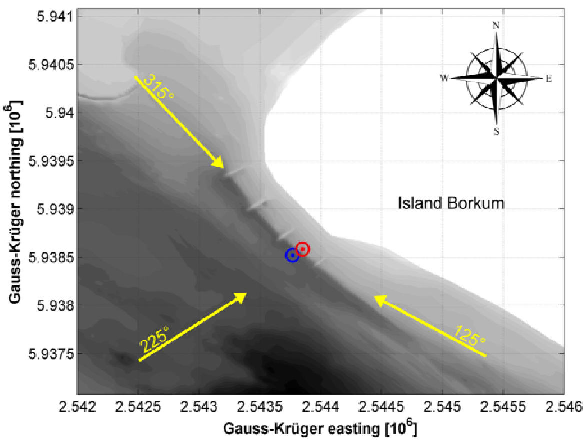

Figure 2. Illustration of the topography and the local particularities of the observation site. The red circle denotes the position of the radar array, attached to the gauging station, and the blue circle marks the position of the buoy. The yellow arrows demonstrate the directions perpendicular and parallel to the coastline.

The gauging station is especially suitable for a field test, as it has a reliable power supply and UMTS reception. This allows the convenient data transfer and remote surveillance of the system. Another advantage is the location of the gauging station close to a revetment, because directional wave information is also necessary for revetment design. The prevailing wind direction is North-West. Waves travelling along this direction (~270°-315°) are not influenced by islands or shallow waters, so that maximum wave heights may exceed 7m and significant wave heights exceeding 4m here (Mai, 2010).
Owing to the shadow zone of the island, wave generation is significantly hampered in the directional range of ~315°-125° (Figure 2). Waves coming from southerly directions might be affected by the widely varying water level of the Wadden Sea.
Besides, wave propagation is influenced here by a steep beach profile perpendicular to the fairway leading towards the port of Emden.

3. Methodology and data processing

3.1 *Wave gauge array*

Cost-efficient radar liquid-level sensors, originally designed for industrial mass-applications, are attracting more and more interest in hydrological surveying. Thus, the German Federal Institute of Hydrology - *BfG* in cooperation with the Federal Waterways and Shipping Administration - *WSV* and the German Federal Maritime and Hydrographic Agency - *BSH* developed a wave monitoring system, based on one of these sensors (Wilhelmi and Barjenbruch, 2008). Its main advantage is its non-contact measuring principle, which makes it robust and maintenance-free and hence particularly suitable for operational use:
This 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. The water surface elevation can be easily calculated, since the travelling time of each pulse is proportional to the distance between the radar sensor and the water surface. This principle allows to measure water-level oscillation and, in turn, to derive wave parameters such as the significant wave height (for further information see Mai and Zimmermann, 2000).
The precision of such a single-sensor monitoring system was tested under laboratory conditions as well as in the field (Wilhelmi and Barjenbruch, 2008). The results of the wave-flume experiments revealed a measuring accuracy of less than 0.5 cm for 95% (σ=0.017 cm) of the recorded significant wave heights. To date, four such systems have proven their functionality and robustness at different locations, covering a wide range of sea-state conditions ("Borkum Südstrand", since 2002; "Lighthouse Alte Weser", since 2006; lagoon of Venice (Italy), since 2007; research Platform "FINO 1", since 2008).
Based on the good experiences with this single-sensor monitoring system, the German Federal Institute of Hydrology - *BfG*, is developing an extension of the system that includes the measurement of directional wave information. To this end, an array of four radar sensors is used (Figure 1, right). The technique is based on simultaneous recordings of wave profiles at several fixed positions. Basically, the directional information is estimated by making use of the cross-covariance spectral densities between the records at all sensor locations. Further information is given in the literature, e.g. Benoit et al. (1997).
For the design of such an array, Goda (1985) highlights three guidelines:

1. To fully exploit the information of all sensor locations, the duplication of vector distances should be avoided.
2. The array size is limited by the smallest wavelength for which the directional analysis is to be made, because the minimum separation distance between a pair of wave gauges has to be less than one half of this wavelength.
3. The directional resolution of the array increases as the maximum distance between the wave gauges increases.

However, the maximum size of the array is often limited by the construction of its supporting offshore or coastal structure. 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 test design.

3.2 *Datawell Directional Waverider buoy*

To acquire additional reference data, a Datawell Directional Waverider buoy MK III was deployed in November, 2012 approximately 75~100m further offshore of the gauge Borkum Südstrand.

Figure 3. Photography of the location of the Datawell Directional Waverider buoy close to the gauging station (picture taken by S. Rütten, 31.10.2012).

The water depth at this location is approximately 20m. This surface following buoy is anchored to the sea bed by an elastic mooring. Due to this type of mooring, the actual position of the buoy is within an circle with a diameter of approximately 60 meter. The wave height is determined by integrating the vertical acceleration twice. For accurate heave measurements the accelerometer within the buoy is mounted on a gravity stabilized platform. Moreover, two perpendicular accelerometers record the horizontal motion. By correlating all three-dimensional motion data of the buoy, the directional wave spectrum can be estimated (Datawell, 2006).
According to the manufacturer's specifications, the accuracy in heave measurement is 0.01m, and the directional resolution is 1.5°.

3.3 *Data processing*

The radar-based monitoring system has been in operation since July, 2012. For this study however, only overlapping wave records of both systems were used, which limits the study period to the time from 01.11.2012 until 16.01.2013, because the buoy had to be taken out of the water on that date to avoid problems due to ice conditions. The data of both monitoring systems were processed in 30-minute intervals. For each of these time intervals the directional spectra were estimated, 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. The directions in this study are defined as the directions from which the waves are coming (by analogy with the wind directions).

4. Results

The directional wave spectra of the radar system and those of the Waverider buoy are shown by the example of the 24th November 2012, 19:00-19:30 o'clock in Figure 4. The normalized spectral density is illustrated as a grey graph in the lower panel with additional information about the significant wave height during this period. The upper panel depicts the corresponding spectral directional distribution of the radar-based system and of the Directional Waverider buoy. In this period, the sea state was dominated by two main directions, divided at a frequency of approximately 0.27 Hz.

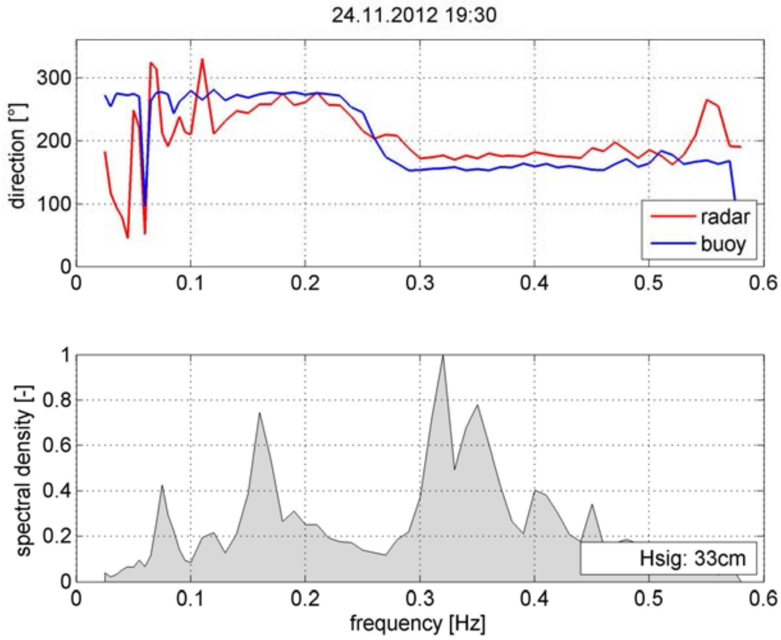

Figure 4. Comparison of the directional wave spectra of the two measuring systems shown for one time span. The upper pannel illustrates the spectral directional distribution and the lower one the normalized spectral density.

The mean wind direction in this period was south-east (120°). The upper frequency domain can be considered as wind sea, although it is not directly aligned with the wind direction. This deviation contributes to the fact that there is wind cover over the range of ~315°-125° (see Section 2). The superimposed direction of the lower frequency range (0.1-0.27 Hz) is not linked to the local wind situation. These waves can thus be classified as swell, which is not influenced by islands or shallow water (travelling along 270°, see Section 2).

Additionally, there is another minor peak in the spectral density at 0.07 Hz, contributing a third direction to the sea state. Its allocation to a defined direction is not appropriate, since the detected directions in this frequency range vary substantially.

On the whole, the estimated directional distributions of both measuring systems show a very similar pattern, especially in the sector with higher energy input (normalized spectral density >0.2). Lower relative energy input leads to fluctuations of the spectral directions that are estimated by the radar array.

Moreover, the results indicate systematic deviations between the two measuring systems. These will be analyzed in the following Section of this paper.

4.1 *Refraction analysis*

The directions, determined by the radar gauge array in the high-energy section, show less variability within the directional range, than the directions detected by the buoy in the equivalent section. They appear closer to a certain value around ~220°. To examine this phenomenon in more detail, 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.

Figure 5 shows the dependence of the mean directional deviation upon the direction estimated by the buoy. Obviously, the detected directions agree best in the range of ~200-240°. Within this range (~225°), waves travel perpendicular to the coastline (see Section 2). The more the wave direction turns north, the more increases the northerly deviation of the direction determined by the buoy compared with that of the radar-based system. The same applies to southward changes.

Figure 6 demonstrates how the directional deviation is connected to the frequency of the waves. The absolute difference in the detected directions is reduced as frequency increases. Above a certain threshold frequency (>0.3 Hz), there is no indication of a systematic directional deviation.

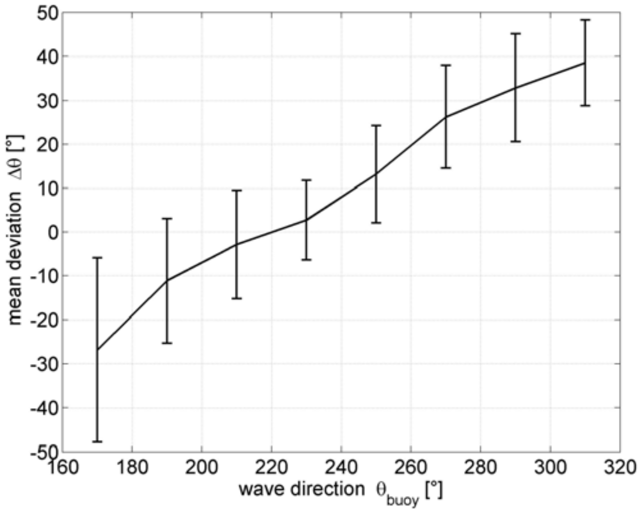

Figure 5. Refraction analysis. The mean deviation (theta buoy - theta radar) of the estimated directions is related to the wave direction measured by the buoy (bin size: 20°).

These two results indicate that refraction might be the primary cause of the detected differences. Since the propagation velocity of waves in shallow water reduces with decreasing water depth, the wave direction turns cross-shore when the water becomes more shallow. This is most likely the reason that constrains the wave motion at the gauging station towards the cross-shore direction (~225°).
However, the direct calculation of the refraction effect is impractical because of the varying water levels and sparse information about the beach profile. Hence, in this study a simple approach is preferred.

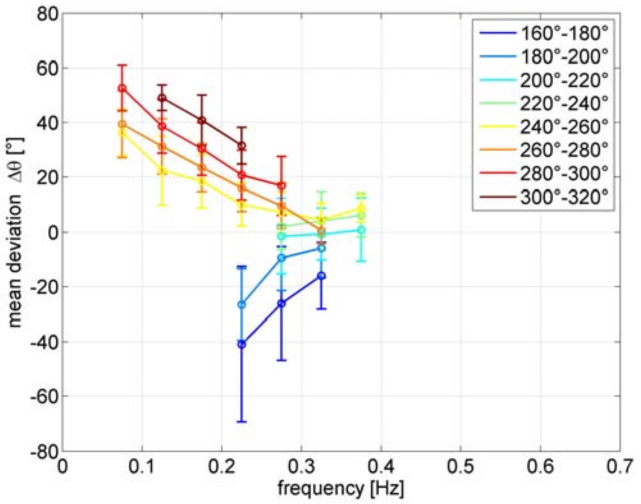

Figure 6. An illustration of the frequency dependence of the mean deviation (bin size: 0.05 Hz) for different wave directions (160°-320°).

Waves with a frequency larger than f=0.315 Hz satisfy the deep-water condition at this particular observation site (water depth d=8m):

$$d < \frac{L}{2} \quad \Rightarrow \quad c = \sqrt{\frac{g \cdot L}{2\pi}} = L \cdot f \tag{1}$$

with g denoting the acceleration due to gravity and L representing the wavelength.
These waves are assumed to be not affected by refraction, as the wave-propagation velocity c is almost independent of the water depth d. This is in good agreement with the threshold frequency resulting from the data analysis (see Figure 6).
To consider this refraction effect, the directions determined by the radar-gauge array θ_{radar} were adjusted by the equation:

$$\theta_{radar}(f, \theta_{in}) = \begin{cases} \theta_{radar} + [(a \cdot \theta_{in} + b) \cdot (\frac{-f}{0.315}) + (a \cdot \theta_{in} + b) + c] & \forall \quad f < 0.315Hz \\ \theta_{radar} & \forall \quad f >= 0.315Hz \end{cases} \tag{2}$$

where f denotes the frequency. The direction of the incoming waves θ_{in} is assumed to be the direction determined by the buoy, and the parameters a=1.204, b=-273.5° and c=-0.6° were calculated using a linear regression. One has to keep in mind that the varying water level of the Wadden Sea is not considered in this refraction analysis. For comparisons in further investigations, the directions determined by the radar-gauge array are adapted accordingly.

4.2 *Dominant wave direction and uncertainty estimation*

Figure 7 illustrates a comparison of the dominant wave directions as determined by the two monitoring systems. For the calculation the energy-weighted average is used.

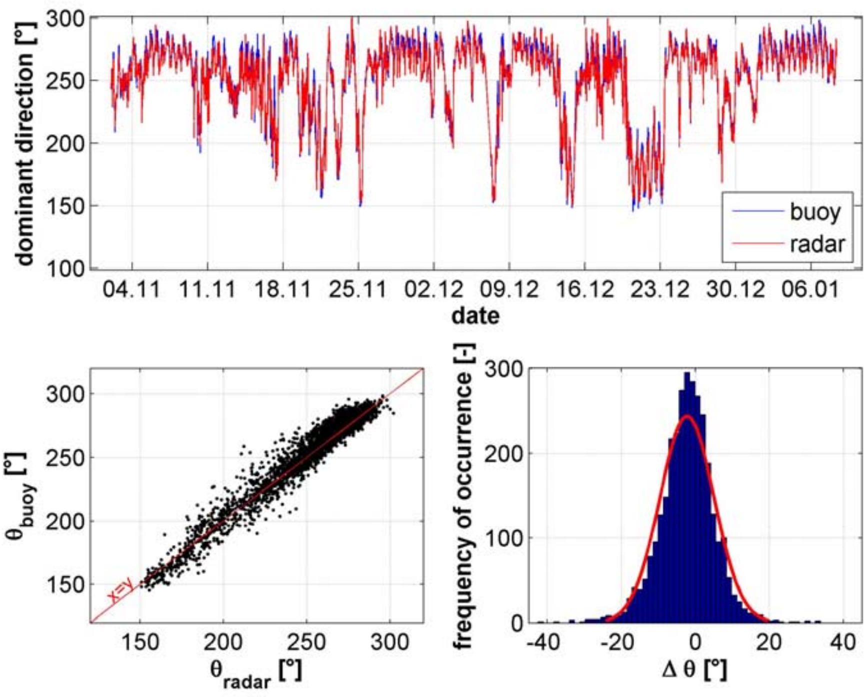

Figure 7. Illustration of the dominant wave direction calculated by both measuring systems. The upper panel shows their temporal variations, whereas the lower panel deals with their statistical characteristics.

The development of the dominant wave directions over time, which is displayed in the upper panel, shows a very similar pattern between both records. Directional changes can be observed with both monitoring systems at the same time.
It is noteworthy, that there is an upper limit (~300°) and a lower limit (~150°) limit in the detected wave directions. This result fits with the assumption, that beyond these directions wave generation is severely restricted by the island of Borkum (see Section 2).
The prevailing wave direction over the entire time period is oriented between 250°-300°. These findings correlate with the dominant wind direction (North-West) at this particular site (Wilhelmi and Barjenbruch, 2008). Southerly dominant wave directions are more rarely registered. Only during the three-day period from the 20th to the 23rd December 2012, were persistent southerly wave directions monitored. On the one hand, this is due to the less frequent occurrence of winds coming from the south, and on the other hand due to the interfering influence of the Wadden Sea. In its extensive tidal mud flats, no waves of high energy with long wavelengths can be generated. This effect can also be noted in Figure 6, as waves with larger wavelength, according to low frequencies (f<0.2 Hz), propagate only from the northern sector 240°-320°.
A closer look at the temporal variation of the dominant direction (Figure 8, upper panel) suggests an additional pattern, which appears to be a superimposed uniform oscillation. This pattern can also be observed in the records of the significant wave heights (Figure 8, lower panel), which are also roughly adapted to the local situation ($h_{m0\ radar\ corrected}=h_{m0\ radar}\cdot 1.1$). A deviation of 10 percent (with higher values measured by the buoy) might be due to shoaling ($K_{s\ radar} \sim 0.16$ and $K_{s\ buoy} \sim 0.4$ at a wavelength L_0=50m). It is noteworthy, that the oscillation influences both measuring systems, although in slightly different ways. In the rising parts of the curves the results of both systems agree quite well, whereas the values of the radar system in the descending part drop somewhat earlier. The temporal development of the detected oscillation is analyzed in more detail in Section 4.3 here below.

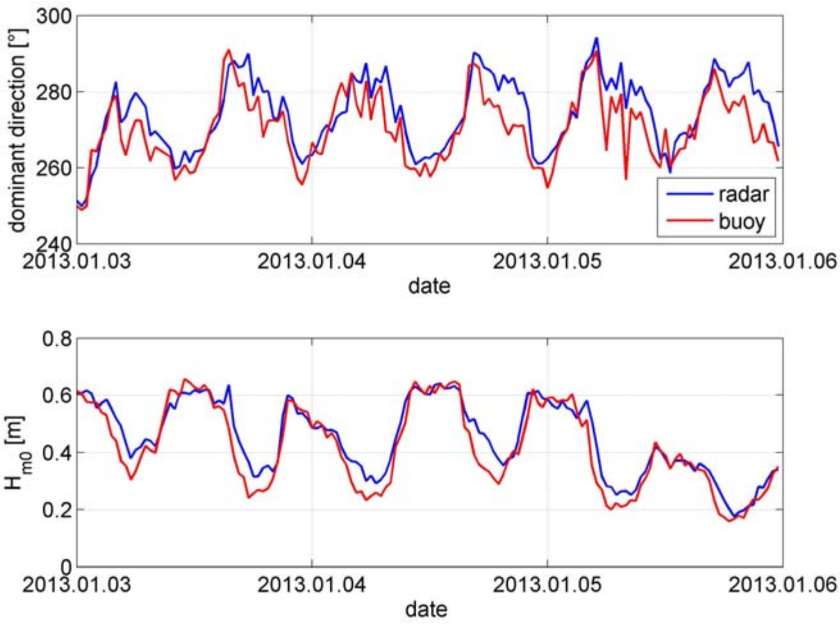

Figure 8. Extract form the time series of the dominant wave directions θ (upper panel) and the significant wave heights h_{m0} (lower panel).

The lower panel of the Figure 7 deals with the estimated uncertainty of the detected dominant directions. The scatter plot on the left side reveals a close correlation between the results of both monitoring systems. In addition, the consistency is underlined by the statistical evaluation on the right side. The comparison between the histogram, showing the frequency of deviations between the radar-gauge array and the buoy, and a Gaussian distribution (red line) indicates that there is no further systematic deviation in the detected dominant wave directions. The standard deviation of the Gaussian distribution is σ=7.3°.

4.3 *Detection of a tidal signal*

This oscillation can be detected not only in the directional data but also in the corresponding graph of the significant wave heights. For further examination, the data is analyzed applying the method of discrete Fourier transformation. The single-sided amplitude spectra are shown in Figure 9 for the wave-directional data as well as for the significant wave heights. In both panels a significant peak becomes apparent at $f_{p1}=2.237\cdot10^{-5}$Hz (which corresponds to a semidiurnal oscillation with a period of 12.41 hours).
The most likely explanation is that the M2 tide influences the dominant wave directions, as well as the significant wave heights. The derived tidal frequency is very close to the value given in the literature $f_{M2}=2.2365\cdot10^{-5}$Hz (e.g. Hicks and Szabados, 2006). An improvement towards better agreement is expected with a longer data set. This will become available from the gauging station "Borkum Südstrand" in the future.

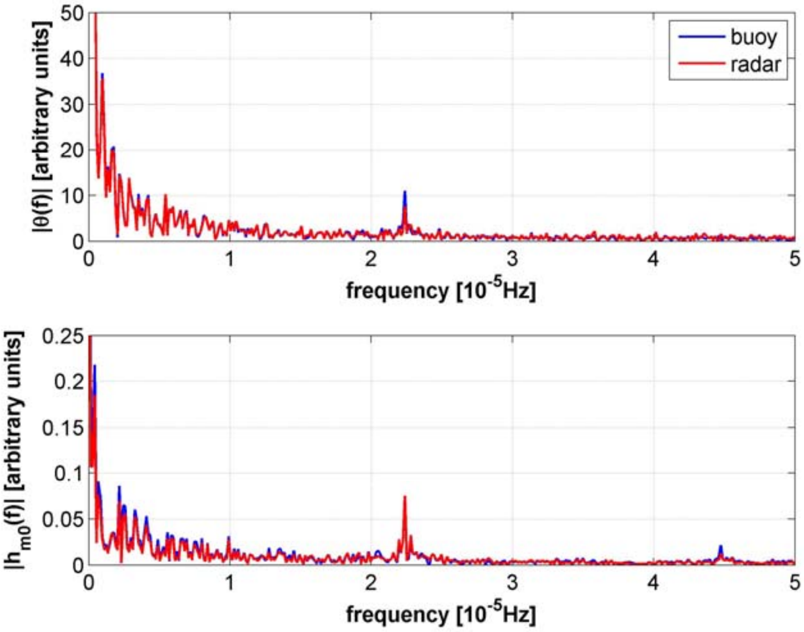

Figure 9. The single-sided amplitude spectrum of the dominant wave directions (upper panel) and of the significant wave heights (lower panel).

Furthermore, a second minor peak was determined in the amplitude spectrum of the significant wave heights at $f_{p2}=4.476\cdot10^{-5}$Hz, but not in the spectrum of the wave directions. This may be attributed to the shallow water overtide M4 with a frequency of $f_{M4}=4.4729\cdot10^{-5}$Hz (Dietrich, 144).
Unfortunately, the available dataset does not specify, whether the occurrence of the tidal signal is based on wave-current interactions, as proposed for example by Wolf and Prandl (1999) or on the varying water level (approximately 2m at the gauging station). Additional studies in this regard will be carried out.

5. Conclusions

A newly developed directional wave monitoring system, based on an array of four cost-efficient radar liquid-level sensors is presented in this study. First results of this system, recorded during the high-wind season, are promising. Very similar distributions of the directional wave spectra were found, when the measurements were compared with the values of a Datawell Directional Waverider buoy MK III. However, there are additional systematic deviations in the detected directions. This study points out some indications that allow to attribute these differences to the influence of refraction. This effect is given due consideration by adopting a linear adjustment equation. Although this is a simple approach that neglects, for example, the influence of varying water depth on refraction, it leads to a good agreement between the outputs of the two monitoring systems, which is reflected in the small standard deviation of the dominant wave directions (σ=7.3°). Moreover, the time series of the recorded wave directions reveal the existence of a certain tidal interference with the dominant directions as well as the significant wave heights. Further studies are required for a more detailed analysis of this effect.

6. Outlook

In order to avoid the need of correcting the influence of refraction, a second test assembly is planned to be installed at the research platform "FINO 1". This observation site is located close to the German offshore wind farm "Alpha Ventus", approximately 45 km off the coast in the North Sea. In the vicinity of this site, there are no obstacles, like islands, that might influence the sea state in any direction. Besides a Waverider buoy, additional directional measuring systems are installed at "FINO 1", such as an acoustic Doppler profiler (AWAC).

Another aspect in favour of this research platform is the larger variety of sea state conditions at this site that differ considerably from those at the gauging station "Borkum Südstrand". In general, larger waves and crossing seas are likely to occur at "FINO 1".

Acknowledgements

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