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National Report of Germany

Compiled by

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Within the federal system of Germany, responsibilities for waters are divided between national and federal authorities. Two federal agencies are dedicated to hydrological and environmental matters concerning the coastal waters. Both institutions are higher federal authorities.

The *Bundesamt für Seeschifffahrt und Hydrographie* – Federal Maritime and Hydrographic Agency of Germany (BSH) is the maritime partner for business, science, and environmental organisations. The BSH offers a wide range of services such as: prediction of tides, water levels, and storm surges, monitoring of the marine environment, prosecution of environmental offences, and improvement of the knowledge of the oceans. The *Bundesanstalt für Gewässerkunde* – German Federal Institute of Hydrology- (BfG) is responsible for the German waterways in federal ownership. In this position it has a central mediating and integrating function. The BfG advises federal ministries, such as the Federal Ministry of Transport, Building and Urban Affairs (BMVBS), and the Federal Waterways and Shipping Administration (WSV) in matters regarding the utilisation and management of the German federal waterways. In this context, the WSV operates a network of gauging stations both in coastal and inland waters. Additionally, the federal states and some harbour authorities operate their own tide gauges.

The report presents the recent activities of BSH and BfG in the field of water level measurements and prediction. The coastal tide-gauge (TG) network of the WSV on the North Sea and on the Baltic Sea is still in the state of the national report of 2011. The tide-gauge network is briefly described below. For a list of selected stations, meta data as well as data availability please refer to the report from 2011.

There are about 160 TGs along the coasts of Germany. About 100 of them are located on tidal rivers such as the Elbe, the Weser, and the Ems. Figure 1 gives an overview of all coastal TGs and GNSS (Global Navigation Satellite System) - stations.

The stations Sassnitz, Warnemünde, and Kiel Holtenau, that are located on the Baltic Sea and the tide gauges Hörnum, Helgoland-Binnenhafen, and Borkum-Fischerbalje on the North-Sea act as regional extension to GLOSS core network. Cuxhaven-Steubenhöft is the German contribution to the GLOSS core network. Additionally, a number of TGs in the North-Sea contribute to the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas (ICG/NEAMTWS). The BSH is the national Tsunami Warning Focal Point (TWFP) for the NEAMTWS in Germany.

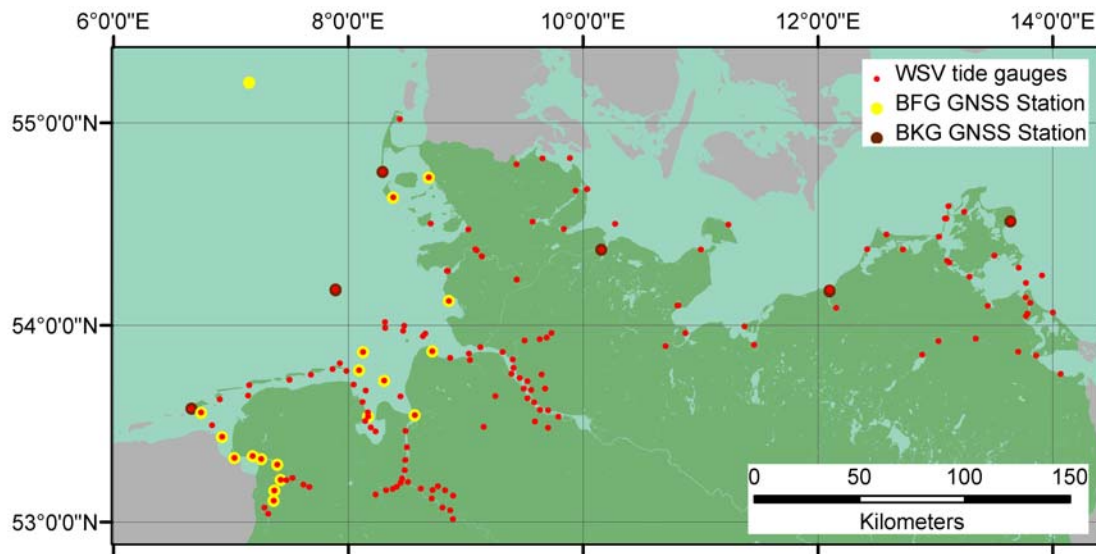


Figure 1: German coastline with tide gauges and GNSS-stations on federal waterways

The forecasting of water levels and storm surges is one of the major tasks of the BSH. During the last years advanced methods and tools for predicting water levels and storm surges have been developed intensively, leading to the availability of more information, both in the sampling rate of sea-level measurements and in the use of a variety of chains of numerical models. The measured time-series are provided in near real time by direct data telecommunication from the TGs. The applied models yield information about the atmosphere with forecasts of wind and air pressure on global and regional scales.

One of the central tools is the BSH-MOS (Model Output Statistics). Since 2011 in operational mode, it calculates quarter-hourly forecasts of wind pile-up at 32 tide gauges. To run this tool, information is required from the Global Forecast System (GFS) model from the National Oceanic Atmospheric Administration (NOAA) of the United States of America.

Additional inputs to BSH-MOS are results from the BSHcmo/BSHsmo, which is a water-level shelf-model that processes wind-speed and air-pressure provided by the German National Weather Service (DWD). Specific moisture and total coverage of clouds are other model input parameters that allow the calculation of heat-fluxes above the sea surface.

Tide predictions and online water-level data transmitted directly from the TGs are the third source of inputs to BSH-MOS. Both these inputs are needed to detect the crest of the tide automatically, calculate the wind pile-up and the curve progression.

The forecasts are disseminated to coastal authorities and relevant administration units, usually four times per day, but as often as needed in the event of a storm surge. This information is available via internet at <http://www.bsh.de>.

As mentioned before, the Federal Institute of Hydrology (BfG) is the scientific and technical consultant for the WSV. In this context the testing, improving and developing of new sea level measuring devices was one task some years ago. Besides the precise measurement of water level, there is an increasing demand on assessing waves in height and directions for different purposes like wave modelling and coastal engineering. The design of coastal structures like piles, breakwaters, and other offshore structures depend on the direction of the acting waves. To the present day, records on wave direction are scarce. The reason for this might be the high costs in purchasing and operation of these devices. There are mainly buoys, which also require regular maintenance. Therefore, the BfG developed a low-cost directional wave

monitoring system based on liquid-level radar sensors. These sensors work in the same way as the radar sea level devices with the great advantage of non-contact to the fluid. The newly developed device was tested on the TG ‘Borkum Südstrand’ which is located in the southern North Sea, off the island of Borkum (Figure 2). The main focus is the comparison of the results measured by the radar-based system and those of the *Datawell Directional Waverider buoy MK III*.

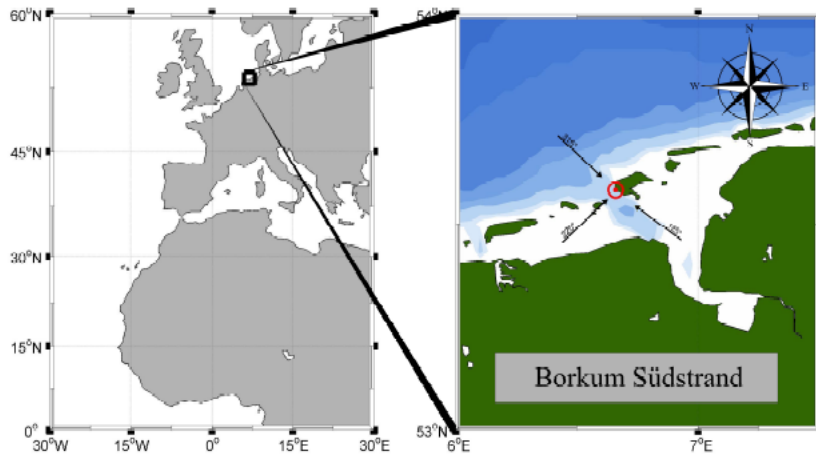


Figure 2: Location of the testing site at the tide gauge ‘Borkum Südstrand’, pointed out as red circle

The general condition at the testing site are good, waves propagate here in various directions, strongly influenced by the morphological conditions like shallow waters of the Wadden Seas and the island of Borkum. Furthermore, the significant wave height is in the range of above four meters, but it could be also seven meters. To determine and measure the direction of waves the device has to be able to assess it in two dimensions. Therefore, an array of radar sensors is required. The geometrical set-up with four radar sensors is shown on Figure 3.

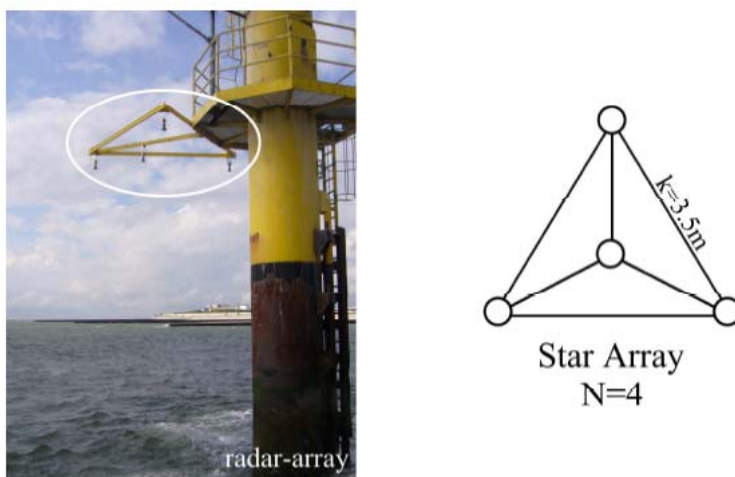


Figure 3: Radar array with four sensors at the TG ‘Borkum Südstrand’ on the left hand side and the general design of system on the right hand side

Radar sensors are widely used and well established in measuring water level. They operate by emitting a chain of electromagnetic pulses at a frequency of 26 GHz twice per second and, in return, detect the backscatter information from the water surface. As the travelling time of each pulse is proportional to the distance between water surface and sensor, the height of the

water surface can be easily calculated. To obtain the directional information of the sea state, all four radar sensors have to collect simultaneously the wave profiles at fixed points. Detailed information about the procedure is described in Benoit et al. (1997). In a distance of approximately 100 meters offshore from the TG Brokum Südstrand the above mentioned wave-rider buoy is moored. The water depth is about 20 meters.

The wave rider buoy works in a completely different way compared to the radar sensors. The wave height is calculated by the double integration of the measured vertical acceleration. By correlating the three-dimensional motion data, which are gained from the gravity-stabilized vertical and horizontal accelerometers, the directional wave spectrum can be yielded. More details on the device specification and the accuracy of this buoy can be found in the product data sheet (Datawell, 2006).

Data of both devices were investigated and analysed for the winter months November 2012 till mid of January 2013. The main focuses of this investigation are the comparison of the derived directional spectra and the dominant directions. Figure 4 shows the times series of dominant directions of both measuring devices, which are in a good agreement. Data of both devices are in good agreement even during rapid changes in the prevailing wave direction such as on the 25th of November on the 23rd of December.

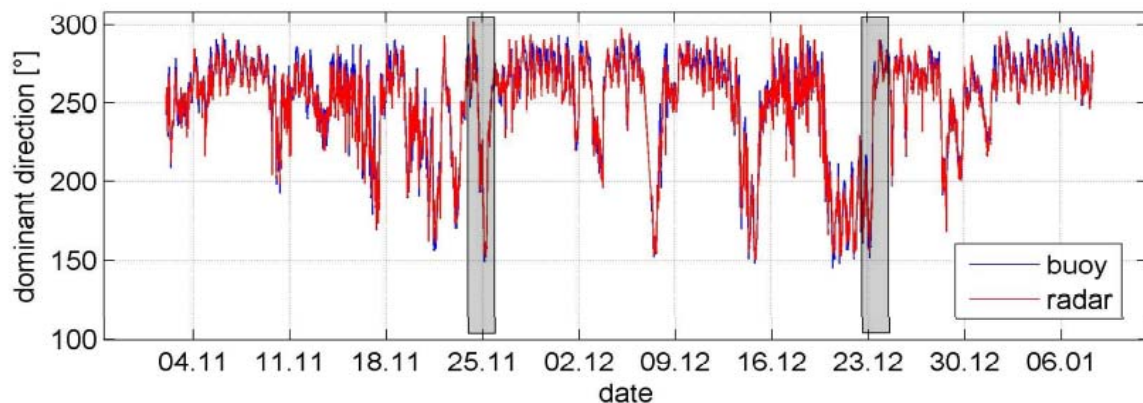


Figure 4: Time series of the dominant wave directions; Radar (red) and buoy (blue)

The graphical presentation shows also that the main wave direction is in the range of 150 to 300 degrees. This can be explained with the location of the testing site, which is close to the west coast of island of Borkum, where waves generated by easterly winds are not very common.

For more information on the whole project, please refer to Rütten et al. (2013) or contact Mr Stephan Mai (mai@bafg.de) at the Federal Institute of Hydrology.

As the main TGs of the German Coasts belong to the WSV, it is obviously that the data processing is their hands. On the other side the dissemination of sea level data in the broader context, as of GLOSS, are in the responsibilities of BSH and BfG. Different data streams to various institutes have thus been established.

The **raw sea-level data** are available at 1-minute intervals (the last 30 days only) and can be retrieved from: <http://www.pegelonline.wsv.de/>. Seven Tide gauges, which serve the national Tsunami Warning Focal Point (TWFP) for the ICG/NEAMTWS are available at the 'IOC Sea level data facility' <http://www.ioc-sealevelmonitoring.org/>. The raw data are also used by the BSH for the prediction of tides, water levels, storm surges, and currents.

Hydrological data processing is done by the local offices of the WSV who are also responsible for operating and maintaining the tide gauges. Thus, **high frequency delayed-mode data** is transmitted to GLOSS as soon as a batch has undergone quality control. Germany currently provides hourly data from seven stations but plans additionally to produce six minutes means in the near future.

High frequency fast-mode data for the station Cuxhaven is transferred on a monthly basis.

Mean sea level data from nine stations are transmitted to the PSMSL once per year.

Concerning **sea level data archaeology**, a number of efforts have been expanded at different institutions in the last years. Due to the federal structure archiving has not been uniformed.

At the WSV which responsible for coastal and inland waterways, the problem will be approached stepwise. A selected number of local authorities will test different methods to gain experience how the tasks are handled best and find a solution for the whole WSV. However, the task involves several steps, as searching the archive for old and historical charts and readings, order them chronologically and the preparation for scanning. The graphical files are the base for the conversation to numerical values. For the coastal area, one local authority has digitally archived all paper-based records from the tidal river Elbe and thus not suitable for investigation of sea level.

Besides the official data archaeology, there were activities in the context of the KLIWAS (*Impacts of climate change on waterways and navigation - Searching for options of adaptation*) research project within the BfG. In this context charts of four TGs (Bremerhaven Alter Leuchtturm (1965-1972), Mellumplate (1964-1990), Emden Neue Seeschleuse (1949-1982), Borkum Südstrand (1949-1985)) were digitalised.

Literature

Benoit, M., Frigaard, P. and H. A. Schaffer, 1997. Analyzing multidirectional wave spectra: A tentative classification of available methods. *Proc. Seminar on Multidirectional Waves and their Interaction with Structures*, San Francisco, CA, International Assembly of Hydraulic Research, 131–158.

Datawell, B. V. 2006. *Datawell Waverider Reference Manual*. Datawell BV, Zumerlustraart, 4, 2012

Rütten, S., S.Mai, J. Wilhelmi, T.Zenz, J. Winkelbauer, P. Fröhle and U. Barjenbruch, 2013. Comparison of directional spectra of sea waves estimated by an array of radar sensors and a directional wave rider buoy, *Proceedings of the 6th SCACR – International Short Course/Conference on Applied Coastal Research*, 4 – 6 June 2013, Lisbon, Portugal



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 newly developed, directional wave monitoring system is evaluated through comparison with a Datawell Directional Waverider buoy MK III, which is the most widely used device to measure the directional properties of surface 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 significant wave heights $h_{sig} > 0.6$ m), when local particularities of the test field are considered. In addition, the paper presents a detailed analysis of the alignment of wind and wave directions, separated in two frequency domains.

1. Introduction

For some years now, there has been increasing interest in the description of directional spectra of sea waves, because this information is very useful in various disciplines. Barstow et al. (2005) underline its fundamental importance for wave modeling and engineering applications. Forces acting on piles, breakwaters, and other offshore structures depend on the direction of the oncoming waves. Thus, the prediction of damage at coastal structures, for example, is sensitive on the directional characteristics of the attacking wave field (Suh et al., 2002). Furthermore, the knowledge of directional spectra of sea waves is essential for research purposes, such as diffraction and refraction studies (Panicker, 1975). Nevertheless, directional wave records are still rarely available. This might be due to the fact that the common measuring systems are expensive in acquisition and operation and require regular maintenance.

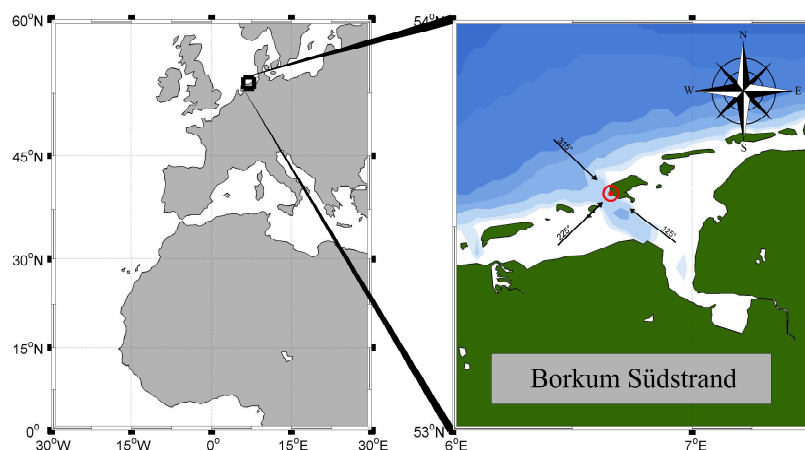


Figure 1. The observation site in the German North Sea on a large-scale map on the left. The right side depicts an enlarged section of the area around the gauging station “Borkum Südstrand” (red circle). The black arrows denote the directions parallel and perpendicular to the coastline.

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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. This study gives first a short description of the measuring principle. The main focus is then on the comparison of the results measured by the radar-based system and those of 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 here is in many directions 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, significant wave heights may exceed 4m, and maximum waves can be higher than 7m here (Mai, 2010).

2. Data and methodology

The newly developed directional wave monitoring system

Several measuring methods and analyzing procedures have been developed to gather wave directional information. Most of the systems are either in direct contact with the water and hence require a high capital and time investments for rugged design, repair and protection from corrosion or they are based on remote sensing and have 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 routine operational use.

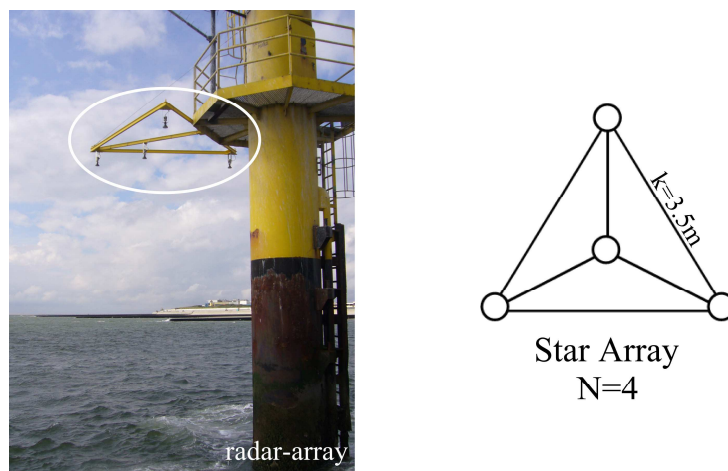


Figure 2. The radar-gauge array. The geometrical design, a star shaped array according to Goda (1985), is illustrated on the right side. The circles represent the sensor positions. The photo on the left depicts the first test assembly of the newly developed system at the gauge “Borkum Südstrand” (photo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

For several years now, the German Federal Institute of Hydrology has been using cost-efficient radar liquid-level sensors that were originally designed for industrial mass-applications, to monitor the water-level elevation at a single point. This particular radar sensor emits a series of 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 travelling 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 water-level oscillations and resultant wave parameters (for further information see Mai and Zimmermann, 2000). The results of wave-flume experiments revealed a measuring accuracy of less than 0.5 cm

for 95% ($\sigma=0.017$ cm) of the recorded significant wave heights (Wilhelmi and Barjenbruch, 2008). A detailed evaluation of the performance of microwave radar sensors under open ocean conditions is given in Boon et al. (2009). The high precision and reliability of this single-sensor monitoring system, is proven by the fact that such systems have 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 newly 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 derive the directional information of the sea state. More information can be found in the literature, e.g. in Benoit et al. (1997).

In designing of such an array several 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 size of the array and the number of sensors 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 distance between a pair of wave gauges must be less than one half of this wavelength). Furthermore, the duplication of vector distances should be avoided to fully exploit the information from 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 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 3.5 m was chosen for the first prototype (Figure 2, right). A first test assembly of this system was mounted at the gauging station “Borkum Südstrand”, in July 2012 (Figure 2, left).

The Datawell Directional Waverider buoy MK III

Besides the wave radar-gauge array, a Datawell Directional Waverider buoy MK III has recorded directional information of the sea states since November 2012. It is moored approximately 75~100m further offshore of the gauging station “Borkum Südstrand” where the water depth is approximately 20 m.



Figure 3. The location of the Datawell Directional Waverider buoy MK III in relation to the gauge “Borkum Südstrand” (photo 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 ($\sim 240^\circ$)

This buoy is equipped with gravity-stabilized vertical and horizontal accelerometers. The wave height is determined by integrating the measured vertical acceleration twice. The directional wave

spectrum is derived 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 then 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 the horizontal movement. Therefore, the buoy was moored with a standard Datawell rubber chord. Maintenance was carried out once a month.

Wind data

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

Data processing

In this study only overlapping wave records of both systems were used. This limits the study period to the time from 01 November 2012 until 16 January 2013, because the buoy had to be taken out of the water later in January 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, the records of 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 the results of the Diwasp analysis are compared with those of the Datawell software (Figure 4).

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

3. Results

Comparison of the derived directional spectra

A comparison of the directional wave spectra for 24 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 come from the south. 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

A more detailed analysis of this phenomenon considered the deviations of the high-energy range (normalized spectral density >0.5) of all time periods with significant wave heights exceeding 0.5 m. The directional deviation of both systems upon the direction determined by the buoy (bin size 20°) is illustrated in Figure 5.

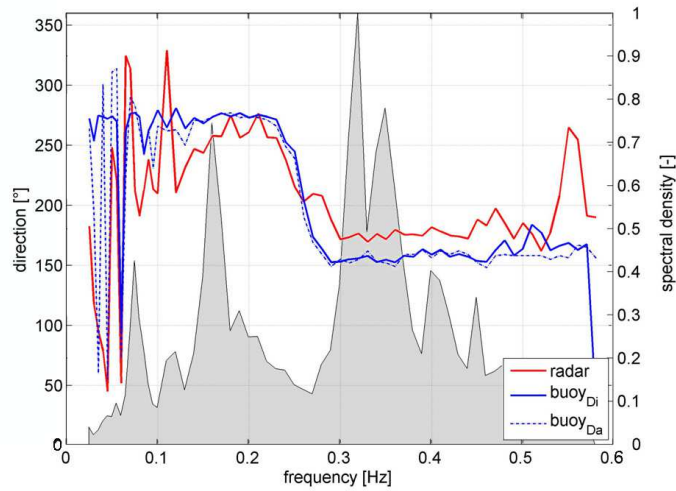


Figure 4. The directional wave spectrum derived for the 30-minute time span starting on the 24 November 2012 at 19:00 o'clock. The grey-shaded area illustrates the normalized spectral density. The red (radar) and blue (buoy) lines show the spectral directional distributions of both monitoring systems.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

The estimated directions agree best in the range of $\sim 200\text{-}240^\circ$. Within this range ($\sim 225^\circ$), waves travel perpendicular to the coastline (see Figure 1). The more the direction from where the waves come from turns north, the more does the northerly deviation of the direction determined by the buoy increase. As the same applies to southward changes, refraction might be the primary cause of the detected systematic deviations. This view is further emphasized by the large difference in water depth between the two monitoring locations ($d_{\text{buoy}} \sim 20\text{ m}$, $d_{\text{radar_gauge}} \sim 8\text{ m}$). The wave direction turns cross-shore (here $\sim 225^\circ$) when the water becomes shallower, since the propagation velocity of waves in shallow water reduces with decreasing water depth.

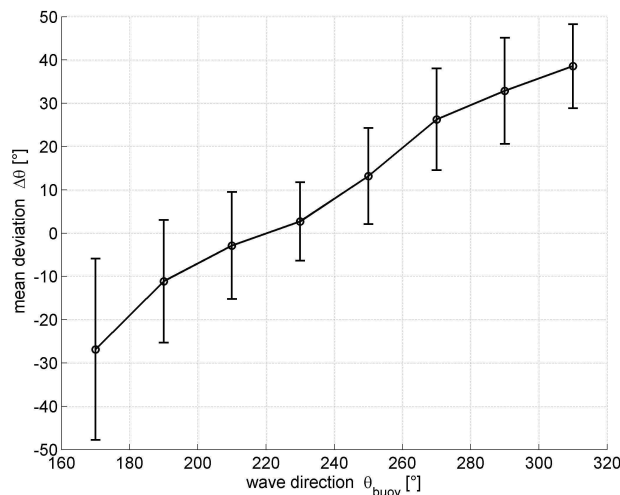


Figure 5. Indication of the strong influence of refraction. The mean deviation ($\Delta\theta = \theta_{\text{buoy}} - \theta_{\text{radar}}$) is plotted against the incoming wave direction, which is assumed to be aligned with the direction determined by the buoy.

However, the direct calculation of the refraction effect is impractical because of the varying water level, the diffraction due to surrounding islands, and the sparse information about the bathymetry at this site. Hence, in this study another, simple approach was 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 the frequency f :

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

The parameters $a=1.204$, $b=-273.5^\circ$ and $c=-0.6^\circ$ 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 (the wave-propagation velocity c is almost independent of the water depth d), they were excluded.

To improve comparability, the directions determined by the radar-gauge array were 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 are in good agreement. For example, both systems, are sensitive to sharp changes in the dominant wave direction (e.g. on 25 November 2012 or 23 December 2012). It is also interesting to see, that the dominant wave directions are limited in their directional ranges ($\sim 150^\circ$ - $\sim 300^\circ$). 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 there.

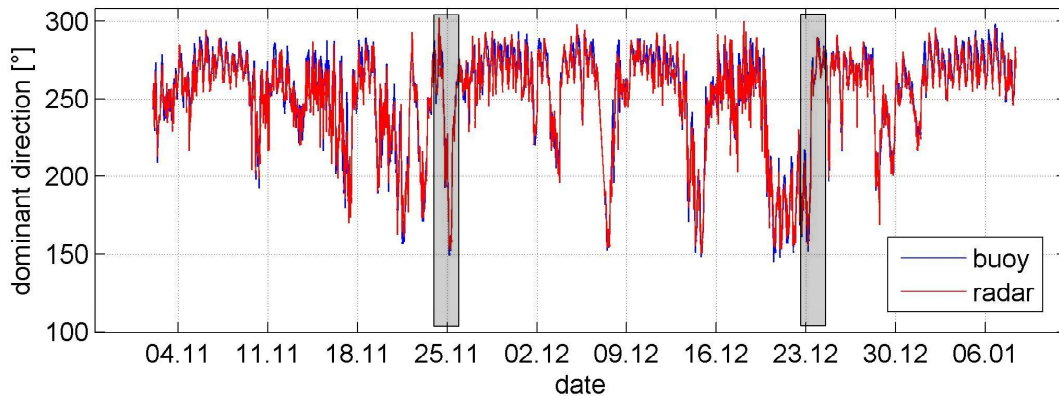


Figure 6. The dominant wave directions in the recorded time period, estimated by the buoy (blue) and the radar monitoring system (red).

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 of the sea states with a significant wave heights above 0.6 m is 3.4° . The expected better agreement of the estimated directions from there on towards higher waves cannot be observed.

On the one hand, this might be attributed to the sparse data set that is contributing to significant wave heights exceeding 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 (~2 m), for example, which can cause additional directional deviations, is neglected.

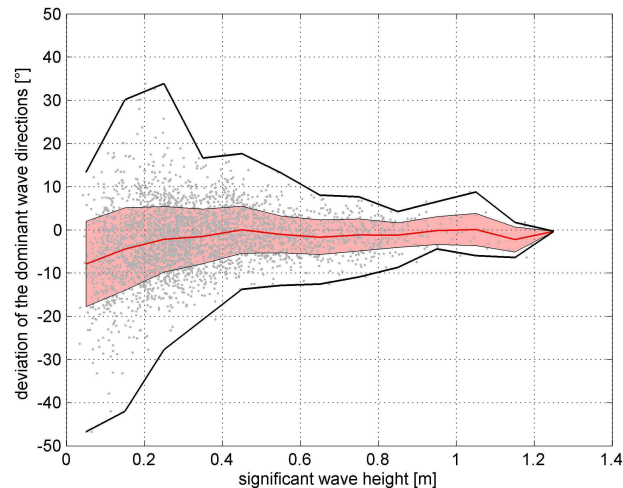


Figure 7. The dependence of the deviation of the dominant wave direction on the significant wave height. The grey dots mark the individual measurements, and the black line illustrates the maximum deviation, whereas the red line and the red-shaded patch show the mean and standard deviations.

A detailed analysis of the alignment of wind and wave directions

Particularly for offshore engineering applications it is important to gain also 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 5 November 2012 at 10:30-11:00 o’clock. This example shows a reasonable separation of the two domains with clearly distinguishable peaks. One has to keep in mind that there are cases, in which such an allocation is more difficult.

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 the maximum deviation, only sea states with a significant wave height exceeding 0.6 m were considered. On the whole, the results of the two measuring systems show only slight deviations in both domains, as well as over the whole frequency range. But the standard deviations of the estimated directions within the two domains are somewhat enlarged compared with the standard deviation of the overall dominant directions.

When comparing the wind directions and the wave directions, significant deviations are discovered in both domains.

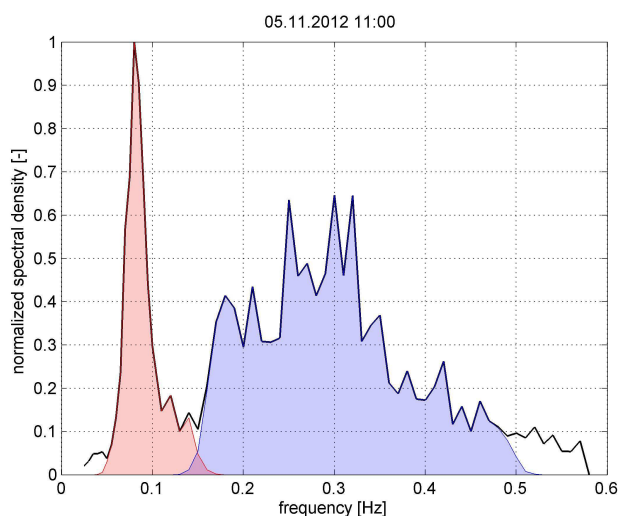


Figure 8. Illustration of the selected frequency domains. The red area symbolizes the part of the normalized spectral density corresponding to the low-frequency domain and the blue area those corresponding to wind-waves.

An example of the variation of wave directions (in the low-frequency domain and the 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), the wind direction changes by 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 explained by the low wind speed and the resulting small wave heights ($h_{sig} < 0.6$ m) during this time period. Besides, the energy input in the low-frequency domain is negligibly small.

From there onwards the wind speed and thus the wave heights increase until the peak of the storm ($\sim 14:30$ o'clock), while the wind and wave directions change only slightly towards west. During this time the directions in the high-frequency domain measured by the radar gauge array agree very well with those measured by the buoy, but again the 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 good agreement. At 16:00 o'clock, the direction of the low-frequency domain is $\sim 25^\circ$ further to the west of the direction of the high-frequency domain. The wind direction is $\sim 25^\circ$ to the south from the high-frequency domain.

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

Table 1. Comparison of the results of the two monitoring systems in both domains and in the entire dataset.

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

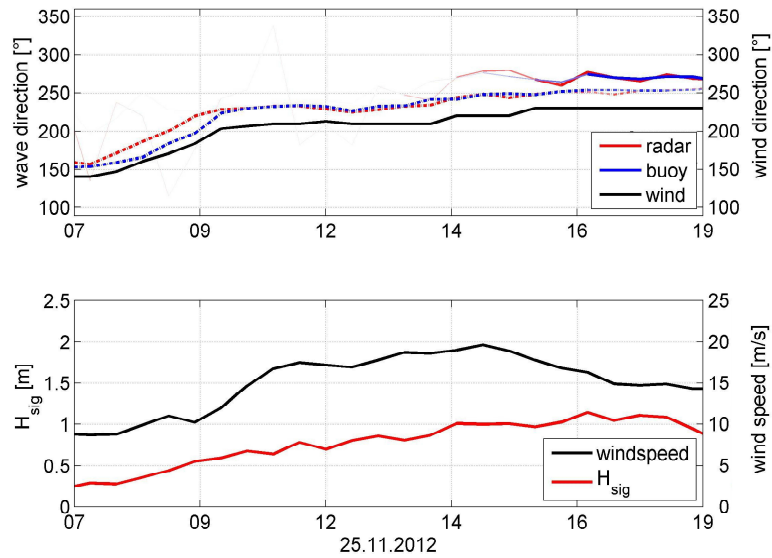


Figure 9. The upper panel depicts the development of the directions in the low-frequency domain (full line) and in the high-frequency domain (dotted line) domain. The color intensities and the line widths indicate the relative energy contribution of each frequency domain to the respective sea state.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

In general, both frequency domains reveal large discrepancies between the directions of waves and wind (Figure 9). The directions in the low-frequency domain are restricted to a narrow directional range, whereas the directions contributing to the high-frequency domain show a wider variability, that is more closely linked to the wind situation.

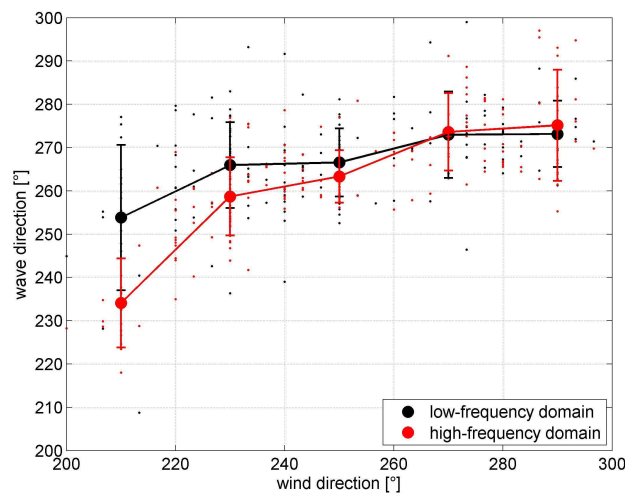


Figure 9. The dependence of wave direction (recorded by the radar gauge array) on wind direction at the gauging station “Borkum Südstrand” in different frequency domains.

4. Summary and discussion

Directional measurements of sea 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 by means of 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 significant wave heights exceeding 0.6 m.

Furthermore, the alignment of wind and wave directions, within two frequency domains, is examined for this particular observation site. As shown, neither the high-frequency nor the low frequency waves have a good correlation with the wind direction. This underlines the importance of directional wave measurements in addition to wind measurements, when estimating the loads acting on coastal structures.

To this date, an exact evaluation of the radar-gauge array was not possible due to the several 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 of land or the Wadden Sea are expected to be negligibly small.

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References

- Barstow, S.F., Bidlot J.R., Caires S., Donelan M.A., Drennan W.M., Dupuis H., Graber H.C., Green J.J., Gronlie O., Guérin C., Gurgel K.W., Günther H., Hauser D., Hayes K., Hessner K., Hoja D., Icard D., Kahma K.K., Keller W.C., Krogstad H.E., Lefevre J.M., Lehner S., Magnusson A.K., Monbaliu J., Borge J.C.N., Pettersson H., Plant W.J., Quentin C., Reichert K., Reistad M., Rosenthal W., Saetra O., Schulz-Stellenfleh J., Walsh E.J., Weill A., Wolf J., C. Wright C.W., Wyatt L.R., 2005. *Measuring and Analysing the Directional Spectrum of Ocean Waves*, COST Action 714 Collaboration(s), 3pp.
- Benoit, M., Frigaard, P. and H. A. Schaffer, 1997. Analyzing multidirectional wave spectra: A tentative classification of available methods. *Proc. Seminar on Multidirectional Waves and their Interaction with Structures*, San Francisco, CA, International Assembly of Hydraulic Research, 131–158.
- Boon, J. D., Heitsenrether, R. M., & Bushneil, M., 2009. Microwave-acoustic water level sensor comparisons: Sensor response to change in oceanographic and meteorological parameters. *OCEANS 2009, MTS/IEEE Biloxi-Marine Technology for Our Future: Global and Local Challenges*. IEEE. 1-10
- Datawell, B. V. 2006. *Datawell Waverider Reference Manual*. Datawell BV, Zumerlustra, 4, 2012.
- Goda, Y. 1985. *Random Seas and Design of Maritime Structures*. Univ. Tokyo Press.
- Johnson, D. 2002. DIWASP, a directional wave spectra toolbox for MATLAB®: User Manual. *Research Report WP-1601-DJ*, Centre for Water Research, University of Western Australia.
- Mai, S. and Zimmermann, C., 2000. Applicability of Radar Level Gauges in Wave Monitoring. *Proc. of the 2nd Int. Conf. Port Development & Coastal Environment*. Varna, Bulgaria
- Mai, S., Wilhelmi, J., Barjenbruch, U., 2010. Wave height distributions in shallow waters. *Proceedings of 32st International Conference on Coastal Engineering*, Shanghai, China
- Panicker, N.N., 1975. Review of techniques for directional wave spectra. *Proceedings of the International Symposium on Ocean Wave Measurement and Analysis*, New Orleans, 669-688
- Suh, K. D., Kweon, H. M., & Yoon, H. D., 2002. Reliability design of breakwater armor blocks considering wave direction in computation of wave transformation. *Coastal Engineering Journal*, 44(04), 321-341.
- Wilhelmi, J. and U. Barjenbruch. 2008. Application of radar gauges to measure the water level and the state of the sea. *Proceedings of 31st International Conference on Coastal Engineering*, Hamburg, Germany