Article

RESULTS OF OPERATIONAL SEA-WAVE MONITORING WITH RADAR GAUGES

By Sebastian RÜTTEN, Stephan MAI, Jens WILHELMI, Theodor ZENZ, Hartmut HEIN and Ulrich BARJENBRUCH
(German Federal Institute of Hydrology (BfG))

Abstract

The German Federal Institute of Hydrology *(BfG)* developed a low-cost, non-contact sea-wave monitoring system based on a single radar sensor. A short description of the measuring system and the analysis of wave parameters is given. Furthermore, long-term wave measurements with this system, in combination with wind-measurements and statistics, are used to analyse possible future changes in wave heights. The results are in good agreement with those of other methods. Due to the good results achieved with the single radar sensor, an extension of the system which will be capable of recording directional information, is now under development. First results are presented in this study.

Résumé

L'Institut fédéral allemand d'hydrologie (BfG) a élaboré un système peu onéreux de surveillance à distance des vagues à partir d'un unique sondeur radar. Une brève description du système de mesure ainsi que l'analyse des paramètres des vagues est donnée. De plus, les mesures à long-terme des vagues avec ce système, combinées avec les mesures du vent et les statistiques sont utilisées pour analyser les changements futurs possibles des hauteurs de vagues. Les résultats concordent avec ceux établis au moyen d'autres méthodes. Du fait des bons résultats de l'unique sondeur radar, une extension du système qui pourrait enregistrer des informations relatives à la direction, est actuellement en cours de développement. Les premiers résultats sont présentés dans cette étude

Resumen

El Instituto Federal Alemán de Hidrología *(BfG)* ha desarrollado un sistema de seguimiento de bajo coste, que no tiene contacto con la ola, basado en un sensor con un único radar. Se proporciona en el presente artículo una breve descripción del sistema de medición y del análisis de los parámetros de las olas. Además, las mediciones de olas por periodos largos efectuadas con este sistema, en combinación con las medidas del viento y las estadísticas, se utilizan para analizar los posibles cambios futuros en las alturas de las olas. Los resultados concuerdan con aquellos obtenidos mediante otros métodos. Debido a los buenos resultados obtenidos con el sensor de radar único, una extensión del sistema, que está ahora en fase de desarrollo, podrá registrar la información direccional. En este estudio se presentan los primeros resultados.

1. Introduction

New construction projects off the German coasts such as offshore wind farms, require the operational monitoring of waves nearby such offshore structures. While much research on the consequences of climate change has been carried out with respect to the change of the sea level, only a few studies analyse its impact on waves. This may relate to the fact that no long-term records of wave parameters are available. Accordingly, several authors (Mai, 2008), emphasized the need for reliable, continuous wave measurements. Therefore, the German Federal Institute of Hydrology *(BfG)* (in cooperation with the German Federal Waterways and Shipping Administration *(WSV*) developed a monitoring system based on a radar liquid-level sensor.

To date, four systems have proven their functionality and robustness at different locations, covering a wide range of sea-state conditions. The first test assembly has been in operation at the gauge "Borkum Südstrand" close to the North-Sea island of Borkum since 2002. In 2006 an additional monitoring system was mounted at the gauge "Lighthouse Alte Weser" in the estuary of the rivers Jade and Weser (see Figure 1). To further analyse the functionality under offshore wave conditions, another system was installed in 2008 at the research platform "FINO 1" (http://www.fino1.de), which is approx. 45 km off the island of Borkum. In an international context, it is used in conjunction with the flood-defence project "Mose" in the lagoon of Venice, Italy (Wilhelmi and Barjenbruch, 2008).

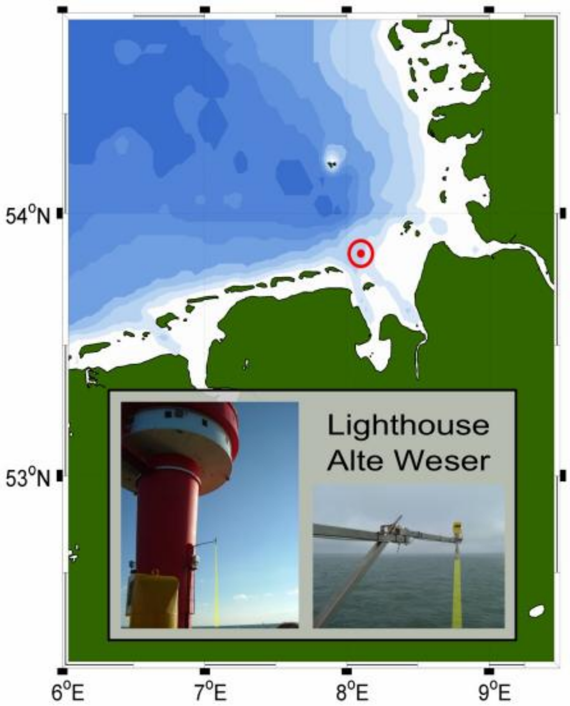

Figure 1*: The operational sea-wave monitoring system at the gauge "Lighthouse Alte Weser".*

Measurements of the radar monitoring system at the "Lighthouse Alte Weser" are considered within this study to analyse possible future changes in wave heights. The estimation of future changes includes the following steps:

a) Analysis of current and future wind statistics from results of a global climate model (see Section 3)

b) Derivation of a transfer function of wind speed to wave height (see Section 4)

c) Applying the transfer function to map the changes of the wind statistics to the changes in wave heights (see Section 5)

A description of the monitoring system at the "Lighthouse Alte Weser", data acquisition and processing is discussed in the next Section, while the extension towards an array of four radar sensors is described in Section 6.

2. Data and Methods

The data used as a basis for this study consists of wave and wind measurements recorded in the period from May 2006 until August 2011. Furthermore, wind data that were generated by the climate model" ECHAM5" were assessed for the years 1970-2090.

2.1 Wave measurements

Many of the sensors that are commonly used to monitor the water-surface elevations (e.g. wave-rider buoys or pressure gauges) have to be installed directly in the water. This requires much maintenance as those systems are permanently exposed to harsh environmental sea conditions such as wave attack and corrosion. For long-term measuring campaigns, sensors that are not directly in contact with the water are much more easily operated and maintained. The described monitoring system, developed by 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)* meets this criterion.

The measuring setup consists of a commercial radar liquid-level sensor, which is fixed to the end of a joist that is attached to a coastal or offshore structure (as illustrated with the "Lighthouse Alte Weser" in ***Figure 1***). The radar sensor emits electromagnetic pulses at a frequency of 26 GHz twice a 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 distance between the radar and the water surface is proportional to the travelling time of each pulse. This allows the measure of water-level oscillation and, in turn, to derive wave parameters such as the significant wave height. For further information see *Mai, S. and Zimmermann, C. (2000).*

In order to optimise the results, a very important first step is to detect outliers and replace them by interpolated values. This is particularly important because the commercial radar sensors were originally designed for level measuring in processing industries. The outliers are located by using physical criteria, by evaluating the possible maxima of velocity and acceleration of the water surface, as well as a statistical outlier test procedure. The removed data points are then replaced by applying a hermite polynomial which does not add artificial extremes (Wilhelmi and Barjenbruch, 2008). The sea -state parameters can then be calculated adopting the Wave Analysis for Fatigue and Oceanography (WAFO) Matlab toolbox for the analysis of random waves and loads, developed by the University Lund/ Sweden (WAFO, 2005). One example of long-term recordings of the significant wave height is illustrated in ***Figure 2 (c).***

The precision of this system was tested under laboratory conditions as well as in the field (*Wilhelmi and Barjenbruch, 2008*). The results of the wave-flume experiments reveal an accuracy of less than 0.5 cm for 95% (σ = 0.017 cm) of the recorded significant wave heights. Other field tests were also run on the offshore platform "FINO 1" in the North Sea. There, the radar gauge is mounted close to the pillars of the platform. For reference, a wave-rider buoy is anchored at a distance of 100 meters. The comparison of the calculated significant wave heights shows only slight deviations without a significant trend. Thus, interactions of the sea with the structure that might affect the wave-height measurements seem unlikely.

2.2 Wind measurements

The monitoring programme at the "Lighthouse Alte Weser" also includes wind parameters. A meteorological station of the Deutscher Wetter Dienst (*DWD* – German national meteorological service) records wind speed (***Figure 2 b***) and direction (***Figure 2 a***) every minute at a height of 30m above the mean sea level. For pre-processing, the data are converted to local Cartesian coordinates (U=zonal wind component, V=meridional wind component) with respect to a reference level of 10m above the mean sea level, following *Kleemann und Meliss (1993).*

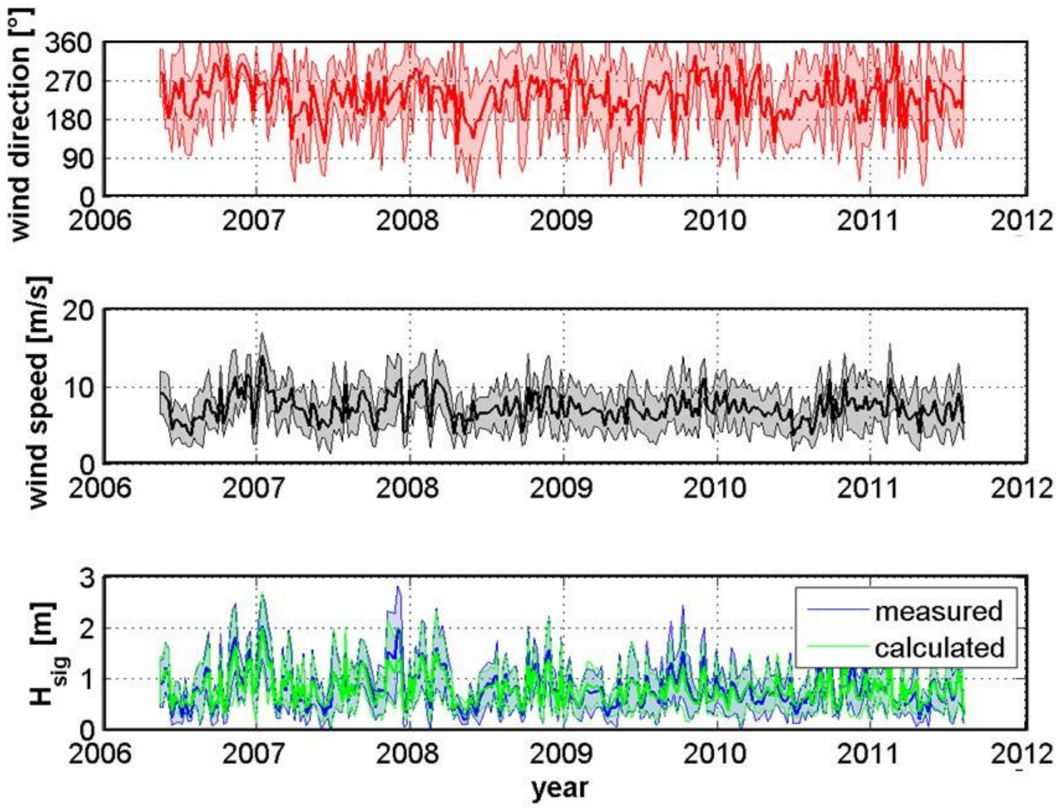

***Figure 2**: Illustration of the mean (bin size 1 week) wind direction **(a)**, wind speed **(b)**, and significant wave height **(c)** during the considered period. The shaded patches indicate the standard deviation.*

2.3 Climate data

To predict future changes in significant wave heights, additional wind-data of the Global Climate Model "Echam5" are used. This comprehensive general circulation model of the atmosphere was developed by the Max Planck Institute for Meteorology (Roekner et al., 2003). The data are given on a rotated pole grid with hourly resolution. As the "Lighthouse Alte Weser" is not located directly on a grid point of the model, the data needed to be interpolated linearly to the exact position. Analyses of the interpolation methods indicate only slight differences (average deviation of 0.1 m/s for U and V) when choosing the nearest-neighbour method instead of linear interpolation. The average variation of the wind speed is calculated with regard to its directionality to include directional changes. This is of particular importance, as the wave height at the "Lighthouse Alte Weser" strongly depends on the wind direction.

3. Transfer function

Besides wind speed and direction (or more precisely: wind stress and fetch), various additional factors influence the wave generation at the "Lighthouse Alte Weser". Amongst them, wind duration and water depth are commonly assumed to be the dominant parameters. However, at this particular observation site, some additional aspects may also play an important role. As the structure is located within the estuary of the River Weser, wind-current interactions could be relevant. Moreover, the water depth at the site (about 11m) is strongly tide-dependent. Due to the complexity of the processes involved, a deterministic calculation of the significant wave heights is almost impossible.
Assuming that all time-dependent differences will average out due to the long time period of the recorded parameters, this study presents a simple transfer function for the location at "Lighthouse Alte Weser", which depends only on the zonal (U in m/s) and meridional (V in m/s) wind components:

$$H_{sig}[cm] = f(U,V) = 34{,}1 + 4{,}51U - 1{,}18V + 0{,}62U^2 + 0{,}63V^2 \quad (1)$$

One possible interpretation of this function is that the wind stress, which is proportional to the square of the wind speed, is the fundamental impulse, whereas the linear correction terms include directional dependencies. The constant offset is partly caused by a lower measuring threshold of the radar gauge. A comparison of the calculated and measured significant wave heights is shown in ***Figure 3***, resulting in a correlation coefficient c=0.84 with an R^2 goodness of fit of 0.71. Besides the expected scatter, there are only few wider deviations. A comparison of the times series (Figure 2 c) shows an overall good agreement as well. For a wind speed of 16 m/s at 240°, a significant wave height of H_{sig} =2.06m is estimated by the transfer function (1). This is in good agreement with the results given by Mai (2008), who derived a significant wave height between 1.80m and 2.20m by adopting the phase-averaged wave model SWAN. Assuming that the transfer function will continue to hold under the possible future climate as projected by the model, the variability of the exceedance probability of the significant wave height and the wind speed can be predicted.

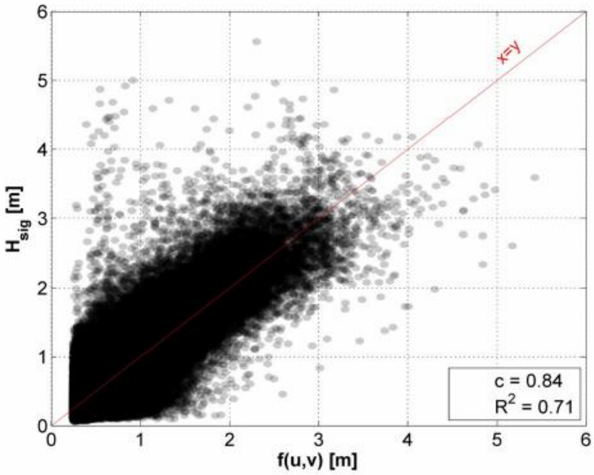

Figure 3*: Scatter plot of the comparison of significant wave heights.*

4. Prediction of wave-height changes

As a first step, a quantile-mapping-based bias correction for the considered location was made for the wind statistics of the global climate model. Thereupon, exceedance probabilities of wind speed and, by applying the transfer function, wave heights were calculated.

A general increase of the wind speed along with an increase of the significant wave height within the next coming years is suggested by the model (see ***Figure 4***). For the period from 2006 to 2045, an average increase of the 99% quantile of the significant wave height by 0.33 cm/year is indicated. In the subsequent 30 years, the model predicts an average increase that is slightly lower (0.17 cm/year). On the average of the period from 2006 to 2075, the derived change of the significant wave height at the "Lighthouse Alte Weser" suggests an increase of the 99% quantile by 0.26 cm/year.

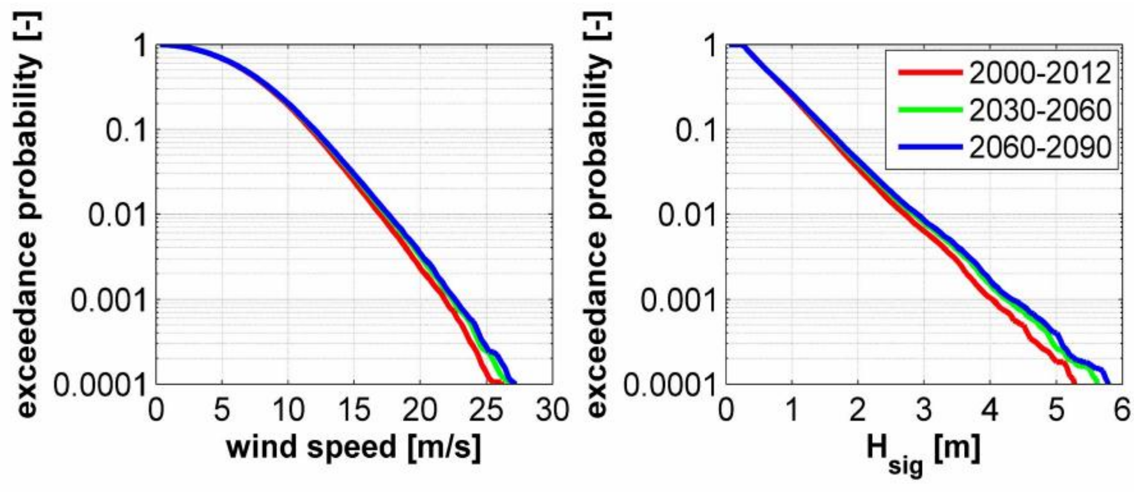

***Figure 4**: Exceedance probabilities of wind speed and significant wave heights at the "Lighthouse Alte Weser" within three time periods.*

The uncertainty of the predicted wind speed distribution can lead to wide discrepancies in the results. Mai and Zimmermann (2004) examined a climate scenario for the year 2050 near Solthörn, which is approximately 50 km east of the observation site. They determined an increase of the 99% quantile of the significant wave height by 0.4cm/year, which is close to the results estimated in this study. The slight difference may be attributed to the fact that the water depth near Solthörn is less than at the "Lighthouse Alte Weser". Therefore, climate-change related rise of water level causes an increased change in wave height. In contrast to the aforementioned good agreement, Weisse et al. (2003) proposed a trend of 1.2cm/year increase for the years 1958-2001 as determined by wind wave hind casts. This spread in the estimates of changes in significant wave height emphasizes the need for more continuous monitoring of sea-state parameters, including not only significant wave height and wave period but also wave direction.

5. Extension of the existing monitoring system by measurements of directional information

Precise recordings of wave direction would improve, on the one hand, numerical modelling of sea states (Haver and Nyhus, 1986) and, on the other hand, the design of coastal and offshore structures. Bowers et al. (2000) underline that the maximum hawser tension at some structures may occur when wind and waves are at 60-90°. They point out that the simple assumption of an aligned wind and wave direction is often invalid. They monitored a difference up to 60° before the storm is fully developed. Even at the peak of a storm, differences of 10-30° are common.

Therefore the radar based wave-gauging stations, which monitor water surface elevation at one point and thus, sea state parameters, as wave heights and wave periods, is enlarged towards monitoring wave direction. This development of the German Federal Institute of Hydrology *(BfG)* makes use of an array of commercial radar sensors. The technique is based on simultaneous recordings of wave profiles at several fixed positions. Basically, the cross-covariance spectral densities between these records are used to estimate the directional spectrum. Further information is given in the literature, e.g. Benoit et al. (1997).

While designing such an array, the following relevant guidelines should be taken into account (Goda, 1985) - to fully exploit the information of all sensor locations, the duplication of vector distances should be avoided. Furthermore, the array size is limited, on the one hand, 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. On the other hand, 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 the offshore or coastal structure to which it is attached. For an operational use of radar arrays, the number of sensors should be limited to three or four in order to keep it as simple and cost-effective as possible.

5.1 Laboratory tests and PC based simulations

The applicability of an array of three commercial radar liquid-level sensors to measure the directional wave spectrum under the constraints mentioned above was tested by numerical simulations and laboratory experiments. Since the cross-covariance method (Goda, 1985) presumes simultaneous records of the water-surface elevation at all sensor locations, the impact of the uncertainty in the simultaneity of measurements within the used array-dimension was analysed under laboratory conditions.

The laboratory experiment is set up in such a way that all commercial radar sensors record a distance to a reflector, moving along a known track. Therefore, the difference in the measured distance can be assigned to a time lag. The resulting uncertainty of the measuring time of all sensors was found to be Gaussian-distributed with a standard deviation of σ =0.05s. In addition to the uncertainty in measuring time, a standard deviation of the distance measured by the radar sensors of 0.5 cm (see Section 3.1) was considered. With these uncertainties in measuring time and distance, the optimal design of the radar gauge array was derived using the following numerical methodology:

The starting point was a measured time series of water-level elevations ($\eta_1(t)$) at the location of one radar sensor within the array. This time series was then assigned to the other sensor locations within the array prescribing wave velocity (v) and the vectorial distance of each sensor location to the location of the first sensor (n_i) using:

$$\eta_i(t) = \eta_1\left(t - \frac{\left|\vec{n}_i\right|}{\frac{\vec{n}_i}{\left|\vec{n}_i\right|} \cdot \vec{v}}\right) \tag{2}$$

Afterwards, the time series of these simulated surface elevations of all sensor positions were digitized with a frequency of 2 Hz, including possible uncertainties in time and distance of the measurement. The resulting dataset was used to calculate the directional spectral density, 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 extended maximum entropy method (Hashimoto et al., 1993) was selected for data analysis. As the simulated wave field is unidirectional, only the dominant wave direction is evaluated for accuracy examination. For the analysis of directional resolution, the mean absolute deviation (e) of the estimated direction θ_{out} from the prescribed direction θ_{in} is regarded:

$$e = \frac{1}{N}\sum_{i=1}^{N}\left|\theta_{out} - \theta_{in}\right| \tag{3}$$

With each parameter setting, 100 simulation runs (N) were performed. Figure 5 illustrates the resolution of a delta array, consisting of three sensors at the apexes of an equilateral triangle, as proposed by Goda (1985), for different edge lengths. On the x-coordinate, the standard deviation σ of an assumed Gaussian-distributed uncertainty in time is shown.

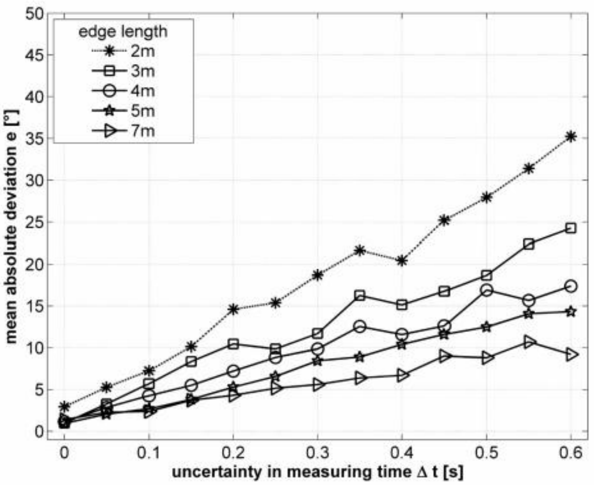

***Figure 5**: Resolving power of the radar gauge array, determined by adopting simulated computer data. The mean absolute deviation of the estimated direction is shown for Gaussian-distributed time lags with standard deviations up to 0.6 s. Additionally, the dependence on the edge length can be examined.*

The directional resolution of the simulated radar gauge array increases as the distance between the sensor locations increases or the time lag between all measuring devices becomes smaller. For a standard deviation of 0.05s a mean absolute deviation of e=5.2° was found for the smallest considered edge length of 2m. The resolution further improved to e=3.2° for a length of 3m and e=2.8° for an edge length of 4m. An expansion of the array size to 5m or 7m leads to a mean absolute deviation of e=2.0°. Despite the measuring time delay of the chosen radar liquid-level sensors, sufficiently accurate results will probably be achieved for edge lengths larger than 3m. On this basis, a triangular array design with edge lengths larger than 3m is recommended.

5.2 Onsite implementation of the radar array system

For a first field test of the radar array, an edge length of 3.5m was chosen. The prototype system was mounted at the gauge “Borkum Südstrand” in July, 2012. This location is particularly suitable as it is close to a revetment. Since information about directionality is necessary for revetment design, it is a potential operational site. Here, the wind blows predominantly from North-west. From this direction, the sea state is not influenced by obstacles like islands or shoals, while passing ships may generate waves there (Wilhelmi and Barjenbruch, 2008). The water depth at this site is approximately 8m (Mai et al., 2010).

The arrangement of the radar gauge array is illustrated in Figure 6. A star array (an extension of the delta shaped array with an additional sensor in the centre) was preferred for the first test assembly to further improve the directional resolution, since numerical results revealed that the error in wave direction, described in this study by the mean absolute deviation (e), further decreases by 59%.

***Figure 6**: First test assembly at the gauge "Borkum Südstrand". The specially developed triangular extension of the gauge is equipped with four radar liquid-level sensors.*

This choice is also supported by Mobarek (1965), who states that a four-detector array of wave gauges is sufficient to yield a good estimate of the two dimensional spectrum, provided the spacings between the probes were chosen carefully. In addition, a fourth sensor can be particularly advantageous in situations in which one sensor records erroneous data or even stops working.

5.3 First results of the extended monitoring system

First measurements of the extended monitoring system were analyzed for a time period of 30 minutes starting on 03.11.2012 at 11 pm. The recorded significant wave height is H-$_{sig}$ =0.76m with a mean wave period of T_m=3.57s. Figure 7 presents both the normalized spectral density, on the one hand, and, on the other hand, the direction as a function of frequency.

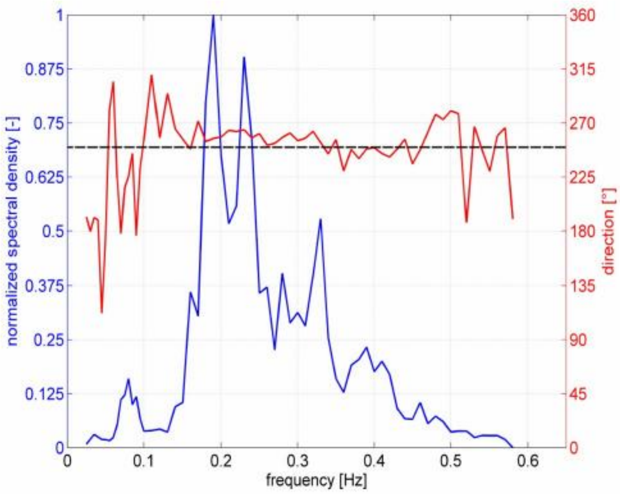

***Figure 7**: First results from the radar gauge array. The normalized spectral density (blue) and the direction of the waves (red) are illustrated as functions of frequency. The black dotted line denotes the mean wind direction.*

The dominant energy input is induced by wind-generated waves. The peak frequency is approx. 0.19Hz. Swell contributes only a small amount of energy to this sea state (small peak at approx. 0.07Hz). The directional information is estimated by applying the direct Fourier transformation method. For comparison, the mean wind direction θ_{ind}=250° at a mean wind speed of 12m/s is delineated in black. In the presented case, the wave direction coincides with the wind direction in the range of their mean intensities, since the wave approach is almost perpendicular to the beach and this is also the predominant wind direction at this particular site. Wider differences were found only in those frequency components of the wave spectrum that contain very little energy.

6. Conclusion

As demonstrated in this study, the monitoring system based on a radar liquid-level sensor, developed by the German Federal Institute of Hydrology *(BfG)* has proven its suitability for long-term measurements. In combination with wind statistics from a global climate model, this data was successfully used to examine possible future changes in sea-wave heights. Despite the simplicity of the presented transfer function from wind speed to wave heights, the results are in good agreement with that of other methods. The derived change in the significant wave height at the “Lighthouse Alte Weser” suggests an average increase of the 99% quantile by 0.26 cm/year until the year 2075. To detect long-term trends more accurately, continuous monitoring of sea-state parameters is indispensable.

Special emphasis shall be given to the fact that the system can be extended towards gathering directional information of the sea state, while the advantages (e.g. low costs and maintenance and high reliability) are retained. The first test assembly consisting of a star-shaped array of four radar sensors produced encouraging results.

7. Outlook

The comparison of the directions of the waves to that of the wind can only be considered as a first indication for the efficiency of the new developed directional measurement system, as significant deviations are often noted in the literature. To evaluate its accuracy more precisely, a Datawell Directional Waverider buoy MKIII will be deployed near to the gauge “Borkum Südstrand”. In addition, 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 offshore, where sea states conditions differ considerably from those at the gauge “Borkum Südstrand”. Moreover, there are hardly any obstacles such as islands in the vicinity of this site that might influence the sea state in any direction. Furthermore, larger waves and crossing seas are likely to occur at “FINO 1”.

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CONTACT DETAILS

Sebastian Rütten
Federal Institute of Hydrology *(BfG*)
Department of Hydrometry and Hydrological Survey
Am Mainzer Tor 1
56068 Koblenz
Germany
Tel.: +49 261 1306 5336
Email: ruetten@bafg.de

BIOGRAPHIES

Sebastian Rütten is a Physicist and since 2012 has been at the Federal Institute of Hydrology in Koblenz, Germany. He studied Physics at the University of Cologne, a Diploma thesis in Oceanography at the University of Bremen and during 2007 to 2009, was a student research assistant at the University of Cologne. From 2009 to 2011, Sebastian was engaged as a student research assistant at the University of Bremen and participated in two North Atlantic expeditions on the research vessel Meteor.
(Email: ruetten@bafg.de)

Dr.-Ing. Stephan Mai is a Physicist and Civil Engineer and since 2005 has been at the Federal Institute of Hydrology in Koblenz, Germany. He studied Physics at the University of Bremen and Civil Engineering at the University of Hannover in Germany. His Ph.D. thesis was in the field of coastal engineering. From 1989 to 1995, he was a student research assistant at the Alfred-Wegener Institute for Maritime and Polar Research. From 1990 to 1994 he was a student research assistant at the University of Bremen and between 1995 and 2004, Stephan was a research assistant at the Franzius-Institute for Waterways and Coastal Engineering.
(Email: mai@bafg.de)

Jens Wilhelmi is a Physics engineer and since 2000, has been employed at the German Federal Institute of Hydrology evaluating new measurement techniques and data transmission.
(Email: wilhelmi@bafg.de)

Ted Zenz is a Civil Engineer and electronic technician with studies in electronics and Civil Engineering at the University of Applied Science in Koblenz. He has been with the Federal Institute of Hydrology in Koblenz, Germany since 1989.
(Email: zenz@bafg.de)

Dr. Hartmut Hein is a Hydrographic Surveyor with studies in surveying at the University of Applied Science Hamburg. He has a Ph.D. with his thesis in the field of oceanography. In the period 2003 to 2009, he was a research assistant at the University of Hamburg. Since 2009, Hartmut has been at the Federal Institute of Hydrology in Koblenz, Germany.
(Email: hein@bafg.de)

Dr. Ulrich Barjenbruch is a Physicist with studies in Electrical Engineering and Physics at the University of Hannover. His Ph.D. thesis was in the field of solid state Physics. Ulrich has been the Chief of Department: Hydrometry and Hydrological Survey at the German Federal Institute of Hydrology since 2006.

His previous experience follows:

- 1984 to 1988: research associate at the Institute of solid-state physics, Technical University of Hannover
- 1989: research associate at the institute of physical and theoretical chemistry, University of Tübingen
- 1989 to 1995: research associate at the section of measurement and technology, University of Kassel
- 1995: state doctorate in "Electrical measurement technology", theme: "Highly sensitive measurement of magnetic fields"
- 1995: self-employed (engineering office), construction and application of highly sensitive magnetic field sensors

- 1995 to 1997: assistant professor at the University of Kassel (section of measurement and technology)

- 1997 to 2006: Chief of Department Physics, Instruments and Measurements at the German Federal Institute of Hydrology.
  (Email: barjenbruch@bafg.de)