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A Powerful Method of Measuring Sea Wave Spectra and their Direction

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ABSTRACT: Coast-lines and estuaries are often areas where dense population, industrial plants, housing and recreation facilities concentrate. More recently, offshore activities like oil-exploration platforms and wind schemes became established as well. Therefore, knowledge of the physical processes which interact on the coast and in coastal waters is very important. The physical processes are driven by several factors: tidal forces, wind forces, as well as hydrological and meteorological phenomena. The consequences of these processes, namely the variations of the water level and the movements of waves can be observed very easily. Water level is measured by gauging stations and the waves are recorded by special devices. Besides the need of precise measurements of sea levels there is an increasing demand for assessing waves in their height and direction for different purposes like sea-wave modelling and coastal engineering. The design of coastal structures such as piles, breakwaters, and offshore structures like wind farms must take account of the direction of the impacting waves. To date, records of wave directions are scarce. The reason for this might be the high costs of purchasing and operating such measuring devices. These are usually buoys, which require regular maintenance. Against this background, the German Federal Institute of Hydrology (*BfG*) developed a low-cost directional sea-wave monitoring system that is based on commercially available liquid-level radar sensors.

Keywords: Wave, Wave-height, Wave-direction, Sea state, Wind-force, Wind-direction, Directional wave spectrum, Datawell Directional Waverider buoy, North Sea

1 INTRODUCTION

Marine structures for shore protection and quay-walls of ports and harbours are well known examples of coastal engineering works. Nowadays, platforms and rigs for the exploitation of oil, gas as well as offshore wind-farms play a major role. All these structures are subjected to the hostile actions of winds, waves and tidal currents as well as many other influences like corrosion (Goda, 1985). In order to understand this physical environment, comprehensive investigations have to be made in order to design these structures so that they can sustain the rough forces of sea and coastal waters. Information about these dynamic loads from the sea on all these structures are required. Sea-level is one of the core variables in these processes. It is measured at tide-gauges (TG) with special devices. Nowadays, radar-sensors are widely used and well accepted (NOAA, 2009; Blasi & Barjenbruch, 2009 and Blasi, 2008). The main advantage of these devices is its non-contact measuring principle, which makes them robust and maintenance-free and hence particularly suitable for operational under unfriendly marine condition. It is worth to mentioned, that these systems have proven their functionality and robustness at different locations, covering a wide range of environmental conditions ("*Borkum Südstrand*" in the North Sea, since 2002; lagoon of Venice (Italy), since 2007; research Platform "FINO 1", since 2008). Detailed descriptions of radar-sensors are given in (Mai and Zimmermann, 2000) and (Wilhelmi and Barjenbruch, 2008) for more in-situ applications.

In addition to the measurement of sea-levels by radar sensors, it is possible to determine waves in their heights. In order to measure waves, which have a higher frequency, the measuring device has to work with higher frequency, too. Waves have been measured at "Lighthouse *Alte Weser*" since 2006 (Rütten, et.al. 2012). The installed sensor emits electro-magnetic 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 sea-level can then be calculated, because the distance between the radar sensor and the water surface is proportional to the travelling time of each pulse. Furthermore, it allows deriving wave parameters like the significant wave height. To get a better knowledge about waves in the open sea, waves are also measured at the research platform FINO 1, which approximately 45 km off the coast in the North Sea. FINO 1 is a research platform, where many other oceanographic and metrological parameters are measured to allow a full investigation of the open-sea environment.

As mentioned above, marine structures have to withstand the dynamic loads from the sea and coastal waters. Therefore knowledge about wave heights and their directions is an essential issue in planning and design of marine structures. Wave direction is an important parameter in the solution of many coastal engineering problems. With the use of an array of radar-sensors, a low-cost and nearly maintenance free wave-measuring devices can be created. Based on the good experiences with single-sensor devices, the German Federal Institute of Hydrology (*BfG*) established an array of radar-sensors to measure waves and their direction.

The newly developed device was tested on the TG 'Borkum Südstrand' which is located in the southern North Sea, off the island of Borkum and on the research platform FINO 1. The main focus is the comparison of the results measured by the radar-based system with those gained by the Datawell Directional Waverider buoy. This paper presents first results of the field experiment gathered during the high wind season and a storm surge.

2 OBSERVERSION SITES

The newly developed device was tested on the TG *Borkum Südstrand* and on the research platform FINO 1. *Borkum Südstrand* is located in the southern North Sea, off the island of Borkum (Figure 1). The main focus is the comparison of the results measured by the radar-based system with those of the Datawell Directional Waverider buoy MK I

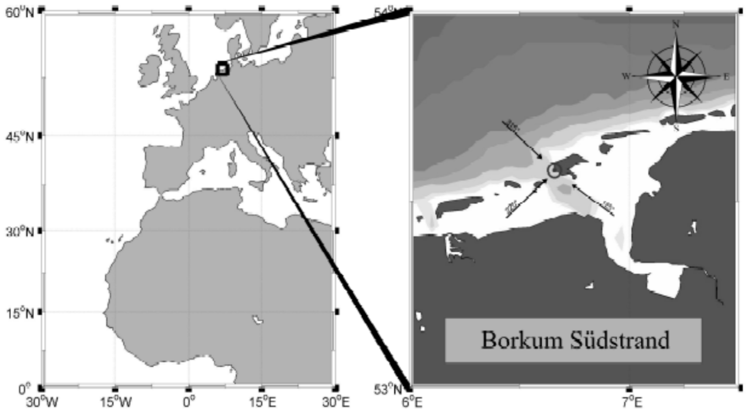

Figure 1. Location of the testing site at the tide gauge 'Borkum Südstrand', red circle.

The prevailing wind direction here is North-West. Waves travelling along this direction (~270°-315°) are not influenced by islands or shallow waters. The significant wave height is in the range of more than four meters, but it can reach even seven meters. Due to the shadow effect of the island, the wave generation is significantly obstructed in the range of ~315°-125° (Figure 1). Waves travelling from south might be affected by the sea-level of the Wadden Sea, which is also varying in time.

The second testing site is the research platform FINO 1, located approximately 45 km off the coast in the North Sea and where ideal condition of of an open-sea environment exist. The water depth is about 30 meters. The station is well equipped with various measuring devices. Of great advantage for this comparative study is the Waverider Buoy DWR (Datawell BV). A detailed description can be found in (Senet, et al, 2012). The Waverider Buoy is located 200 m westward and anchored on the sea-floor.

3 MODUS OPERANDI AND DATA ANALISYS

3.1 *Array of Radar Sensors*

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 array has the shape of a triangular star with radar sensors at the end points and one in the centre of the triangle. 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 the sensors, 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. This 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 recordings 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 the following guidelines:

- To fully exploit the information of all sensor locations, the duplication of vector distances should be avoided.
- 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.
- 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 approximately 75~100 m further offshore of the gauge *Borkum Südstrand* in November, 2012. The water depth at this location is approximately 20m. This surface-following buoy is anchored to the sea floor by an elastic mooring. Due to this type of mooring, the actual position of the buoy is within a 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°.

Data measured with both devices in the winter months November 2012 till mid of January 2013 were investigated and analysed. The main focuses of these investigations were the comparison of the derived directional spectra and the dominant directions. Figure 2 shows the times series of dominant directions of both measuring devices, which are in a good agreement even during rapid changes in the prevailing wave direction such as on the 25th of November on the 23rd of December.

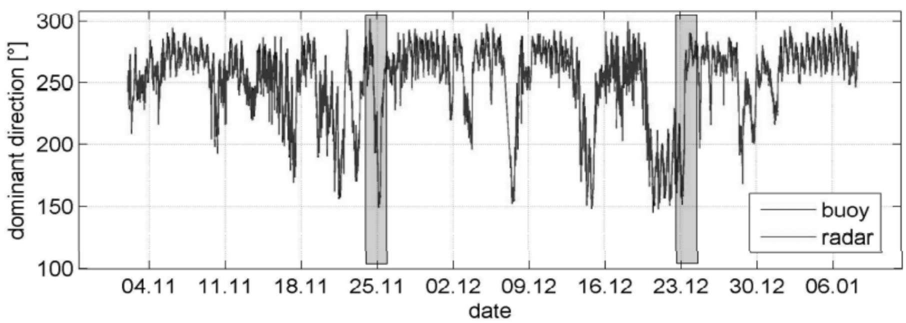

Figure 2. Time series of the dominant wave directions; radar and buoy.

3.3 *Field Data Analysis*

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. November 2012 until 16. January 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.

The directional spectra were estimated for each of these time intervals. The directions given in this study are defined as the directions from where the waves are coming (by analogy with the wind directions). The directional wave spectra of the radar system and those of the Waverider buoy are shown by the example of 24 November 2012, 19:00-19:30 o'clock in Figure 3. 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.

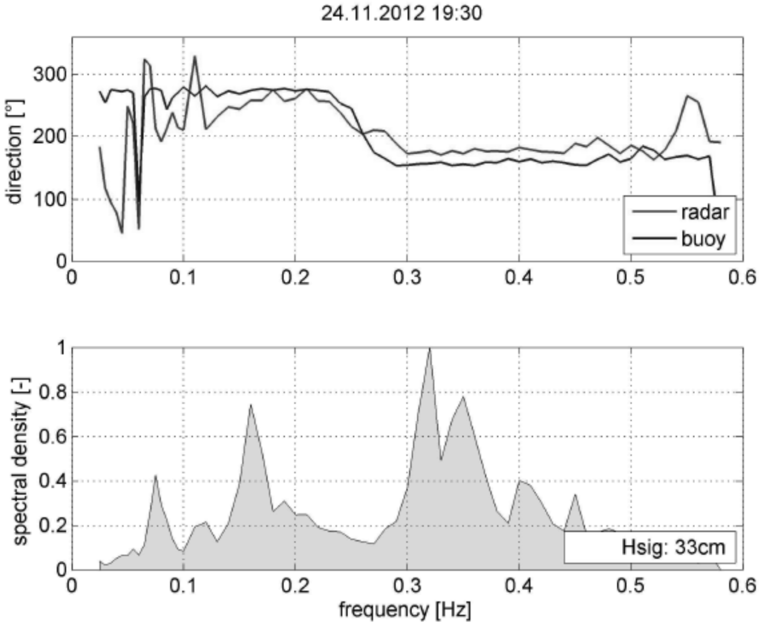

Figure 3. Comparison of the directional wave spectra of the two measuring systems for the same space of time. The upper part shows the spectral directional distribution and the lower one illustrates the normalized spectral density.

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°. 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 very similar patterns, 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.

3.4 *Dominant wave direction and uncertainty estimation*

The illustrated comparison of the dominant wave directions as determined by the two monitoring systems is given in Figure 4. For the calculation the energy-weighted average is used.

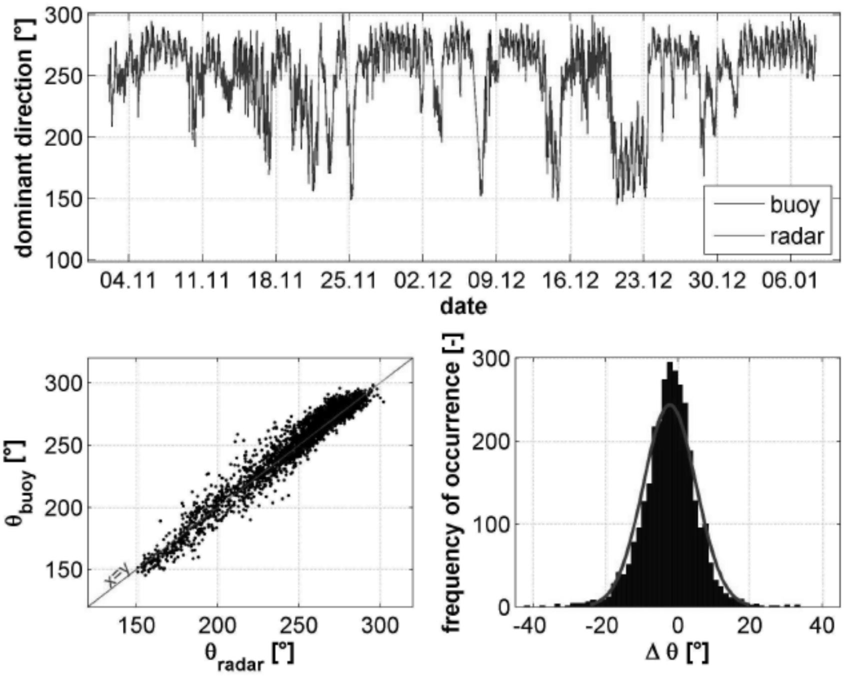

Figure 4. Illustration of the dominant wave direction calculated by both measuring systems. The upper panel shows their temporal variations, whereas the lower panel deals with their statistical characteristics.

The development of the dominant wave directions over time, which is displayed in the upper panel, shows a very similar pattern in 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°) 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*. 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 can also be observed in the records of the significant wave heights (Figure 5, lower panel), which are also roughly adapted to the local situation. A deviation of 10 percent (with higher values measured by the buoy) might be due to shoaling. 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 lower panel of the Figure 4 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-hand 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°.

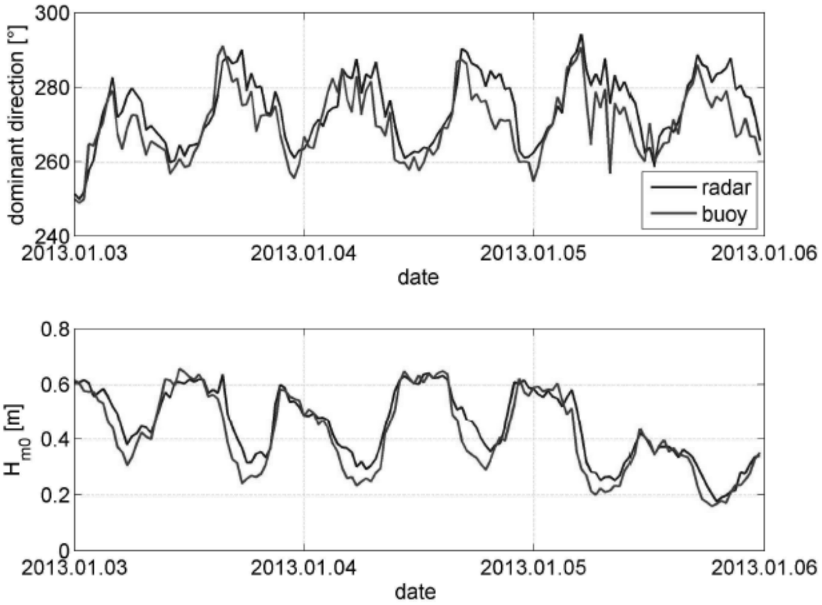

Figure 5. Extract form the time series of the dominant wave directions θ (upper panel) and the significant wave heights h_{m0} (lower panel).

3.5 *Field experience during extreme events*

The gained knowledge at the TG *Borkum Südstrand is* reasonably persuaded. As mentioned above, the same measuring system is installed at the research platform FINO 1, and works well. Hurricane *Xaver* hit the North Sea Coast with strong sea-state and extreme water level during the 5th and 6th of December 2013. The new developed device was able to measure the significant wave height (H_s), the mean wave-period (T_m), the mean wave direction (Dir_M) and the directional spread (spread) without any difficulties. These characteristic parameters have been measured all four sensors and the average for each was calculated.

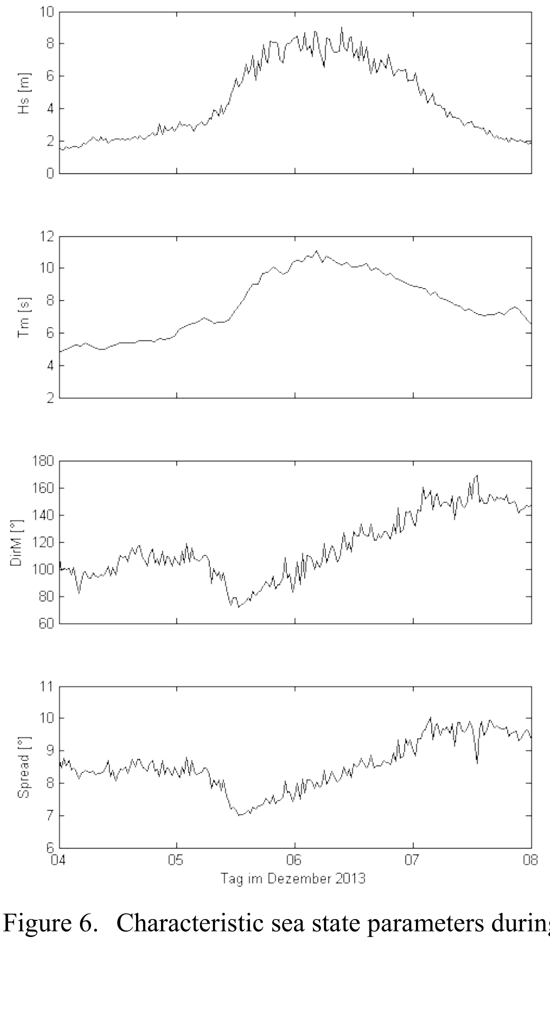

Figure 6. Characteristic sea state parameters during the hurricane *Xaver* from 5th and 6th December 2013

On the 6th of December the maximum of the significant wave height of 9.04 m was estimated (Figure 6). The maximum oft the mean wave-period was 11.1 sec. The mean wave direction was in the range of 100° to 150°. At the same time the wind direction was 250° to 300°. The mean velocity of the wind speed was 30 m/s.

Over the whole storm the highest wave height was 15.5 m. This value is the average of the four radar sensors and up to date the biggest measured wave height on the platform FINO 1 (Mai et al. 2010).

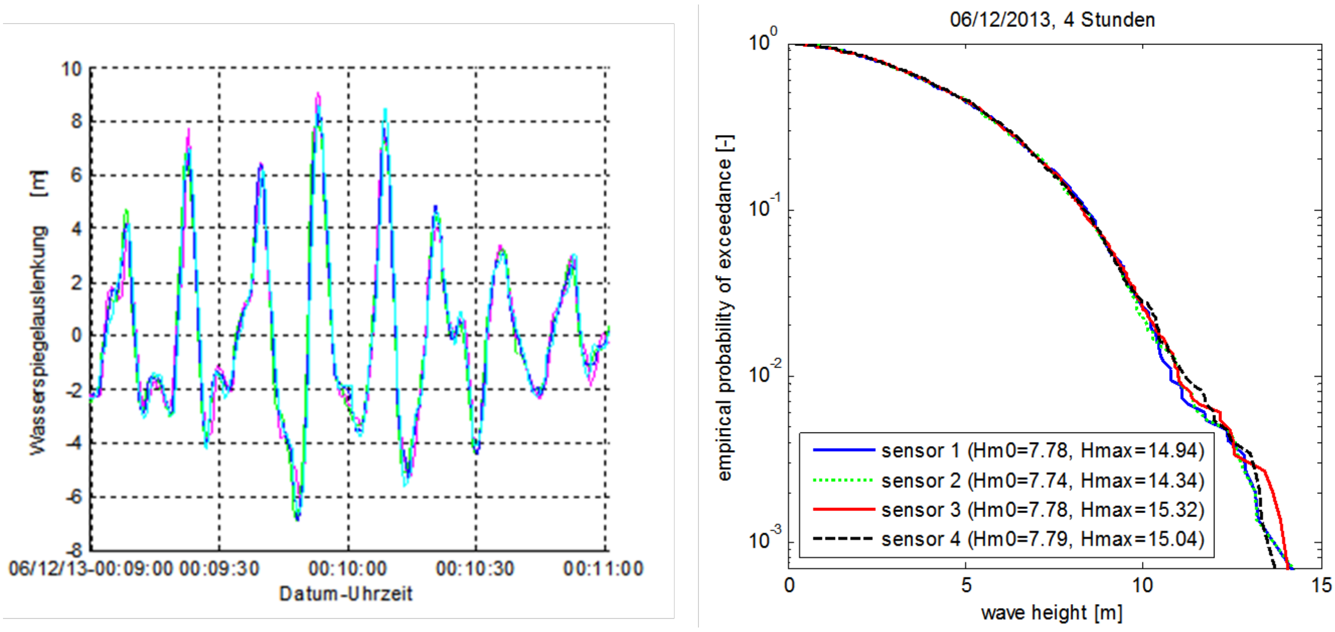

Figure 7. Relative change of sea-level (left), and cumulative distribution of the wave height (right) during the storm event.

Figure 7 illustrate the relative change of the water-level and cumulative distribution of the wave height. All four sensors of the array show a very good agreement of the wave height distribution. The diagram shows also that every hundredth wave reached the height of 10.9 m and even more at the beginning of the storm on the 6th of December. A wave height of 14.1 m and more was measured on every thousandth one.

It is worth to mention that for the first time it was possible with an array of four sensors to make statements to determine accuracy of the wave height distribution.

4 CONCLUSIONS

A new developed directional wave monitoring system, based on an array of four radar sensors was investigated 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, which need further investigation. But main advantages are the low cost of design and maintenance. The system has proven as a reliable tool during the hurricane event in December 2013. The gained and measured information a very unique and will by assist in design and planning of marine structures.

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