Water Level Measurements with Radar Gauges at the German North Sea Coast

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1. Introduction

For more than a decade radar level gauges are being used in operational coastal hydrology in Germany (Kranz et al. 2001). Besides measuring water levels tests have been undertaken in order to acquire also the thickness of an ice cover (Barjenbruch et al., 2002) or the sea state (Wilhelmi and Barjenbruch, 2008). Four test sites for the use of radar level gauges are located in German coastal waters of the North Sea. Two of these test sites, one near the island Borkum and the other on the research platform FINO 1 about 45 km north of the island Borkum, are equipped with arrays of four radar level sensors given the opportunity to measure 2D wave spectra in addition to the water level (Rütten et al., 2013 and Blasi et al., 2014). The third test site, located at the lighthouse “Alte Weser”, is equipped with a single radar level sensor measuring 1D wave spectra (i.e. not wave direction) in addition to the water level. A fourth test site equipped with an array of five radar level sensors has just been installed at the research platform FINO 3 in July 2015. An overview over the test sites is given in Figure 1 (see also Mai et al. (2010)).

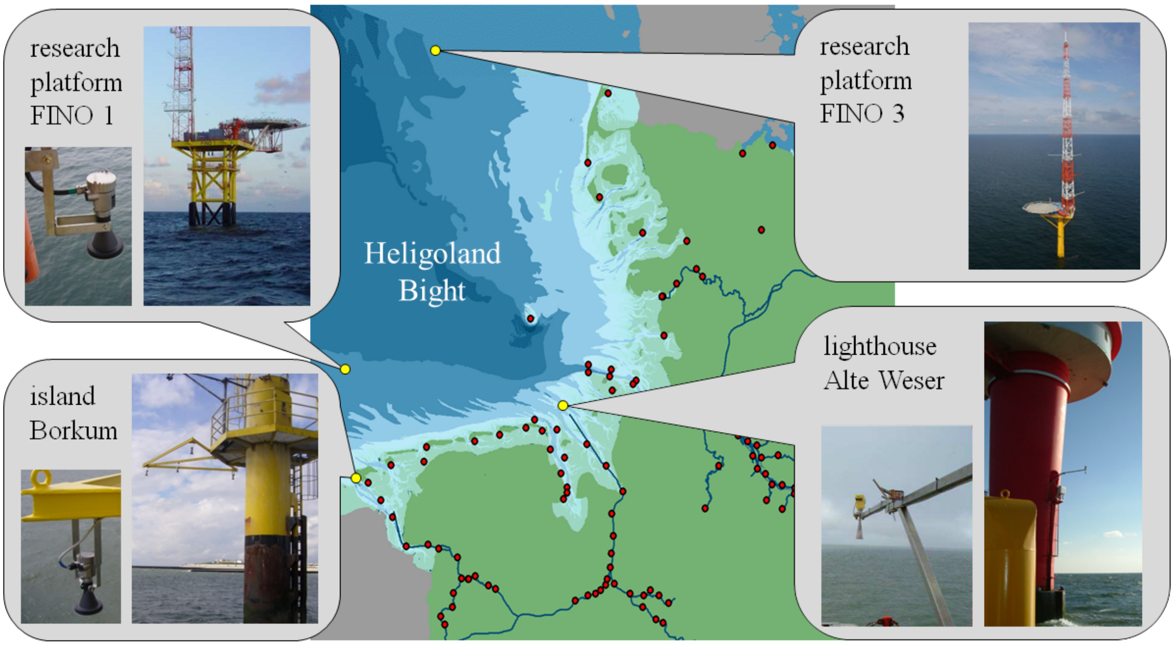

Figure 1: Test sites for the use of radar level gauges in German coastal waters of the North Sea

At all sites alternative devices for water level measurement are available for a comparison to the results of the radar measurement. E.g. a float with shaft encoder in a stilling well is permanently in operation near the island Borkum and at the lighthouse “Alte Weser”.

The use of radar level sensors for water level measurement is well documented by IOC (2006 and 2015). However there are remaining questions when discussing the accuracy of radar sensors, i.e. agreement of radar sensors and alternative (traditional) devices for measuring water level. It is reported that deviations in water level measurement derived from radar sensors and traditional devices may relate to the air gap between radar sensor and water surface (Fulford et al. (2010)) or to sea state conditions (Woodworth and Smith (2003), Martin Miguez et al. (2005), Heitsenrether et al. (2008). Therefore special focus is put on these questions in the following.

2. Description of the radar level sensor for monitoring of water level and 1D sea state

A radar gauge for monitoring the water level and 1D sea state is in operation at the lighthouse "Alte Weser" since 2006. This gauge consists of a single radar sensor (type: VegaPuls 42) and a ruggedized PC with embedded Linux. Real time calculations of water level and 1D sea state parameters, like mean wave period, significant and maximum wave height, are carried out by using the software Octave, which is in fact a freeware version of the software Matlab (Wilhelmi and Barjenbruch, 2008). Both water level and wave parameters are processed every minute. While each 1-minute value of water level relates to measurements within the last minute wave parameters are calculated every minute from measurements of sea surface elevation of the last 15 minutes. Water level and wave data are automatically transferred on-line to the operational hydrological data base of the waterways and shipping administration.

An example of a time-series of water level, significant/maximum wave height and mean wave period recorded at the lighthouse "Alte Weser" during the storm "Xaver" in December 2013 is given in figure 1.

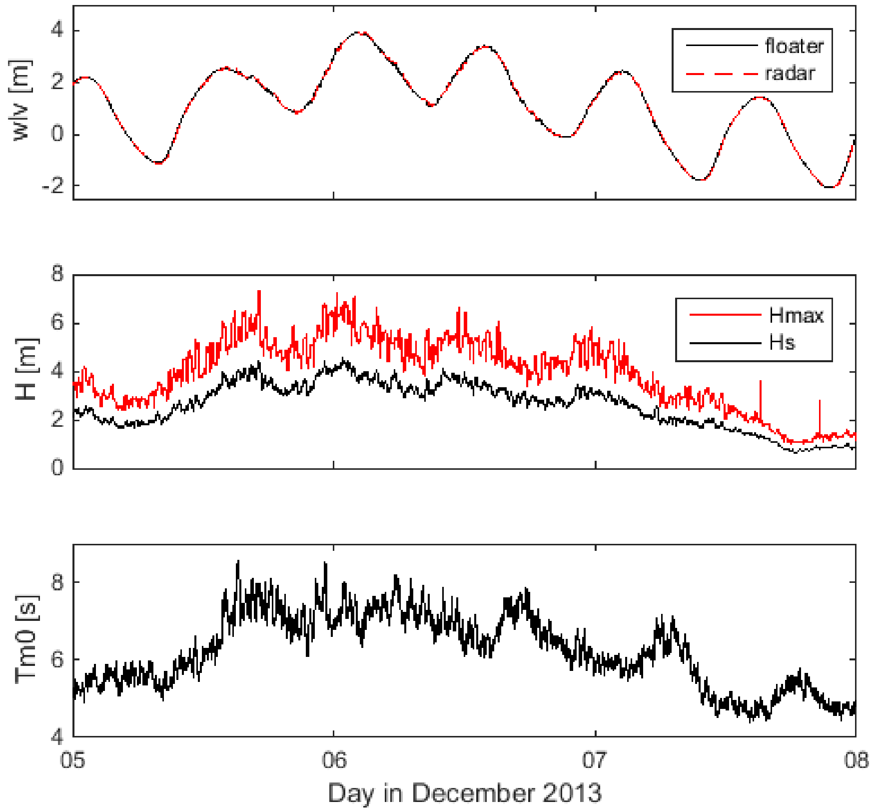

Figure 1: Water level (wlv), significant/maximum wave height (H) and mean wave period (Tm0) at the lighthouse "Alte Weser" during the storm "Xaver"

3. Description of an array of radar level sensors for monitoring of the water level and the 2D sea state

The array system for monitoring of the water level and the 2D sea state consists of at least of three radar level sensors similar to that being described in the previous chapter. Our system uses four sensors in a star configuration (figure 2) fulfilling the requirements with respect to the measurement of 2D sea state given by Goda (1985). The edge length of the star array varies from site to site depending on the geometry of the available offshore structure. The data acquisition and control of all sensors (type: VegaPuls 61) of each array is done by a ruggedized, remotely controlled PC with embedded Linux. The water level and the 1D sea state are independently calculated from time-series of each sensor. The directional information (2D sea state) is estimated by making use of the cross-covariance spectral densities between the recordings at all sensor locations. Further information is given by e.g. Benoit et al. (1997). At the site of FINO 3 the radar backscatter intensity is additionally recorded with an additional radar sensor in the center. The backscatter data may help to provide information on wave breaking and may help to explain varying accuracies of the radar level measurements in future.

An example of a time-series of water level, significant/maximum wave height, mean wave period and wave direction recorded near the island Borkum during the storm “Xaver” in December 2013 is given in figure 3.

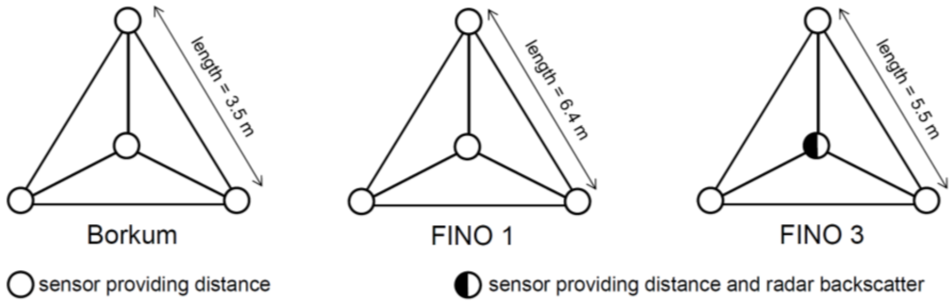

Figure 2: Star configuration of sensors within the radar arrays at Borkum, FINO 1 and FINO 3

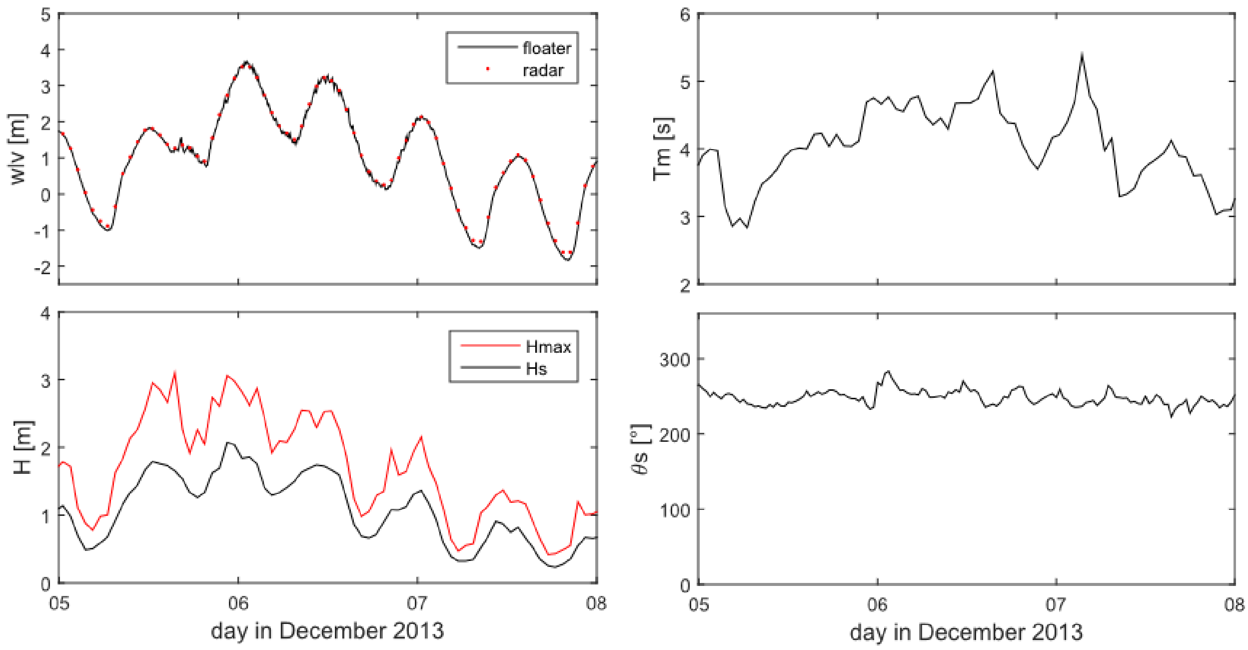

Figure 3: Water level (wlv), significant/maximum wave height (H), mean wave period (Tm) and wave direction (θs) at the gauge “Borkum” during the storm “Xaver”

4. Measurement uncertainty of the radar system in water level monitoring

The arrays used at the sites Borkum and FINO 1 allow the analysis of the intrinsic variance of water level measurements by radar sensors. For a time period from 1st of January 2015 to 28th of April 2015 water levels were calculated using each of the four radar sensors separately. 1-minute values of water levels were calculated from the original data sampled with 2 Hz without any filtering. The time-series of the average water level and of their deviation from the average is given in figure 4. The maximum deviation of a 1-minute value of a single sensor from the mean of the 1-min values of all sensors was 0.1 m. However only in 1 out of 10000 1-min values of water level the standard deviation between the data of the four sensors is larger than 0.045 m (figure 5(left)).

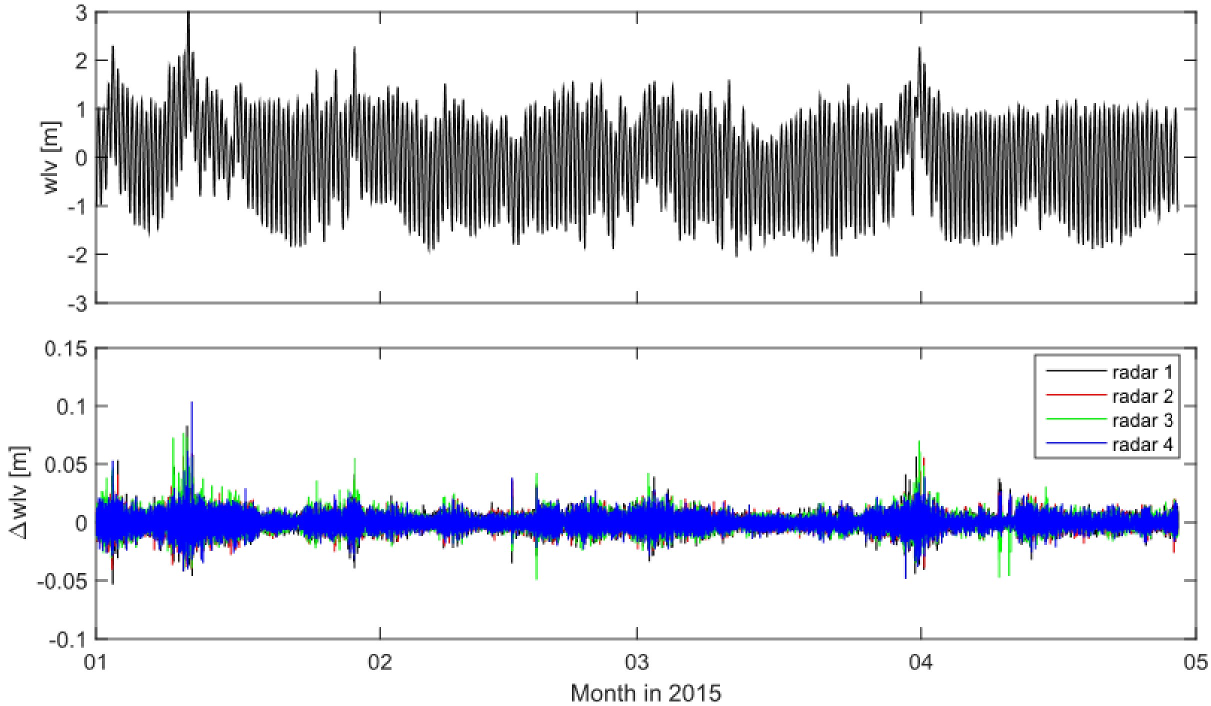

Figure 4: Averaged water level at Borkum and deviation of each sensor from the average

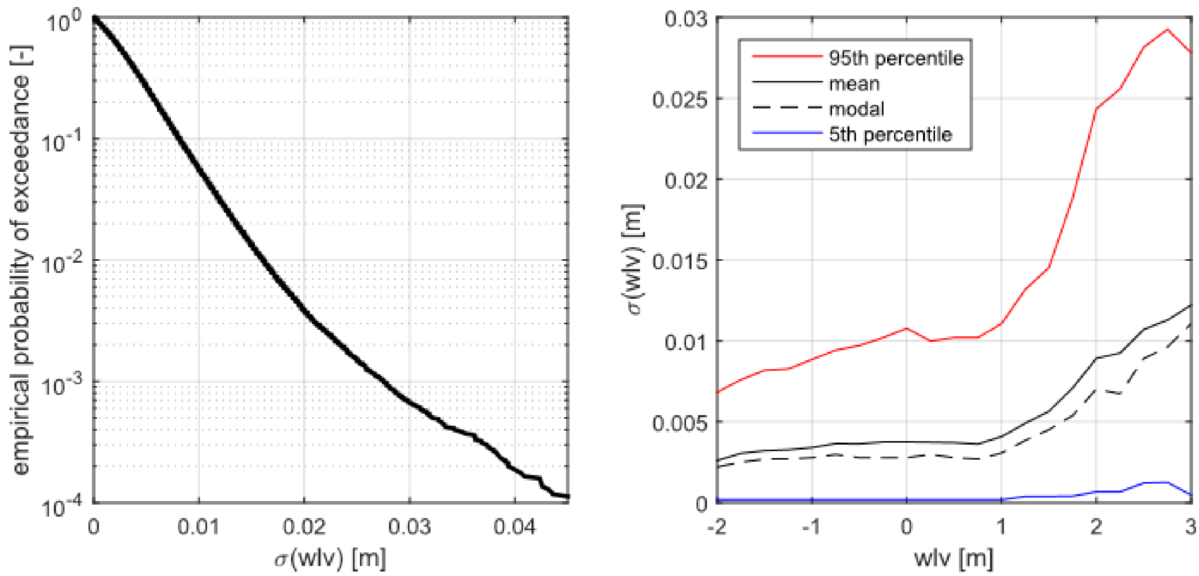

Figure 5: Standard deviation of water level measurements with 4 radars at Borkum: empirical probability of exceedance (left) and standard deviation versus water level (right)

As visible in the time series of the water level and of the deviation of the data of different sensors (figure 4) the standard deviation of the 1-min values of all sensors seems to increase under the condition of higher water levels. A quantification of this is given in figure 5. For the site near Borkum the mean of the standard deviation of the 1-min values of all sensors equals about 0.003 m for water levels below 1 m. For water levels of 3 m it increases to 0.012 m (on average). A change in sea state and not a change in air gap is probably the reason for the increase of standard deviation with increasing water level (i.e. decreasing air gap) since water levels above 2 m occur especially during westerly and northwesterly storms causing also higher sea state conditions.

Since the radar system also monitors sea state, it is possible to check for the influence of the sea state (calculated for 15 min periods) on the standard deviation of the 1 min water level values derived from all radar sensors. Figure 6 shows the effect of a change in significant wave height (Hs) on the standard deviation (right) and the effect of a change in mean wave period (Tm) (left). The significant wave height strongly influences the standard deviation of the measurements given by the different sensors while, on average, the wave period does not have a significant influence at Borkum. At Borkum the increase of the significant wave height from 1 m to 2 m leads to an increase in standard deviation from 0.006 m to 0.012 m. This is in good agreement with the microwave sensor error found by Boon et al. (2012) at Duck field research facility.

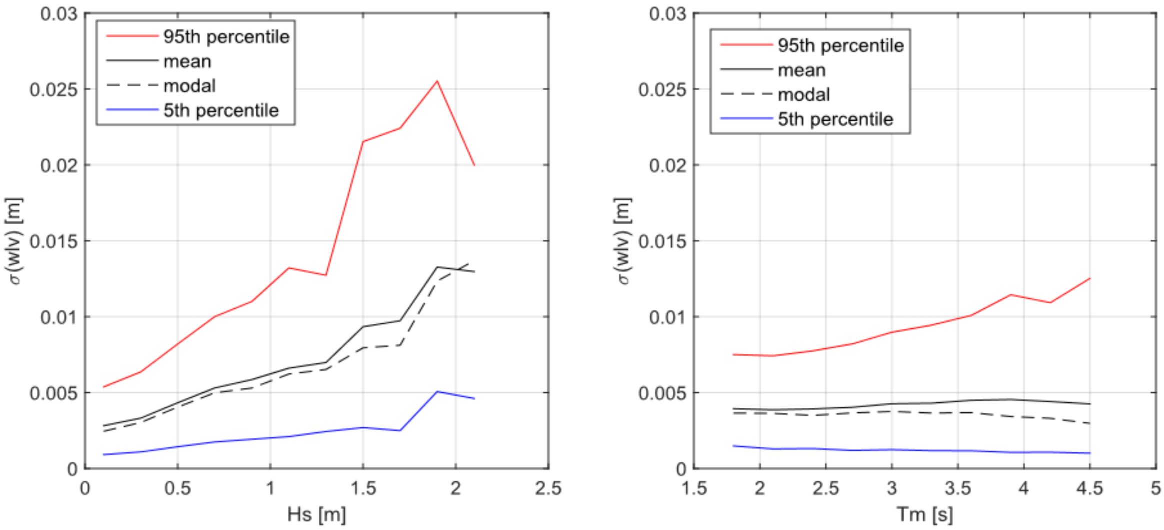

Figure 6: Influence of sea state on the standard deviation of water level measurements with 4 radars at Borkum: effect of significant wave height (left) and effect of mean wave period (right)

Similar results are found at the research platform FINO 1 in case of calm wave conditions (i.e. Hs < 2.5 m, Tm < 5.5 s) (see fig. 7). In case of more severe wave conditions the standard deviation of the 1 min water level values given by all radar sensors increases almost linearly with the significant wave height. A non-linear (quadratic) increase as expected by Boon et al. (2012) is not found at FINO 1. The average of the standard deviation equals 0.02 m in case of a significant wave height of 6 m. The increase of the standard deviation of 1 min values of water level with mean wave periods above approximately 5.9 s is probably related to an increase in wave height with increasing wave periods (see fig. 8). When analyzing wave events with Hs < 2 m only, no effect of the mean wave period on the standard deviation of 1 min values of water level is found.

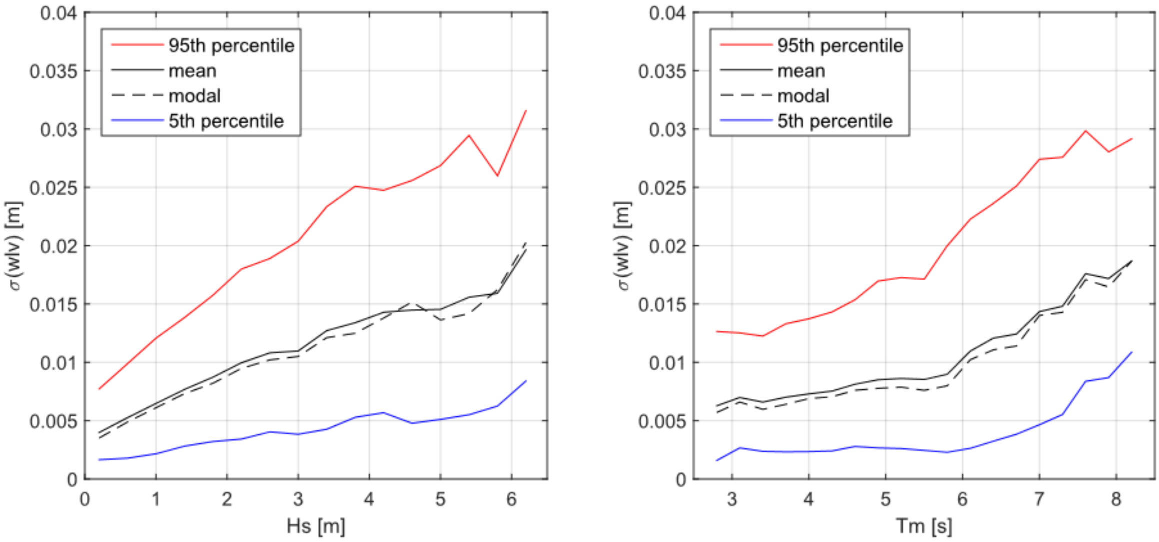

Figure 7: Influence of sea state on the standard deviation of water level measurements with 4 radars at FINO 1: effect of significant wave height (left) and effect of mean wave period (right)

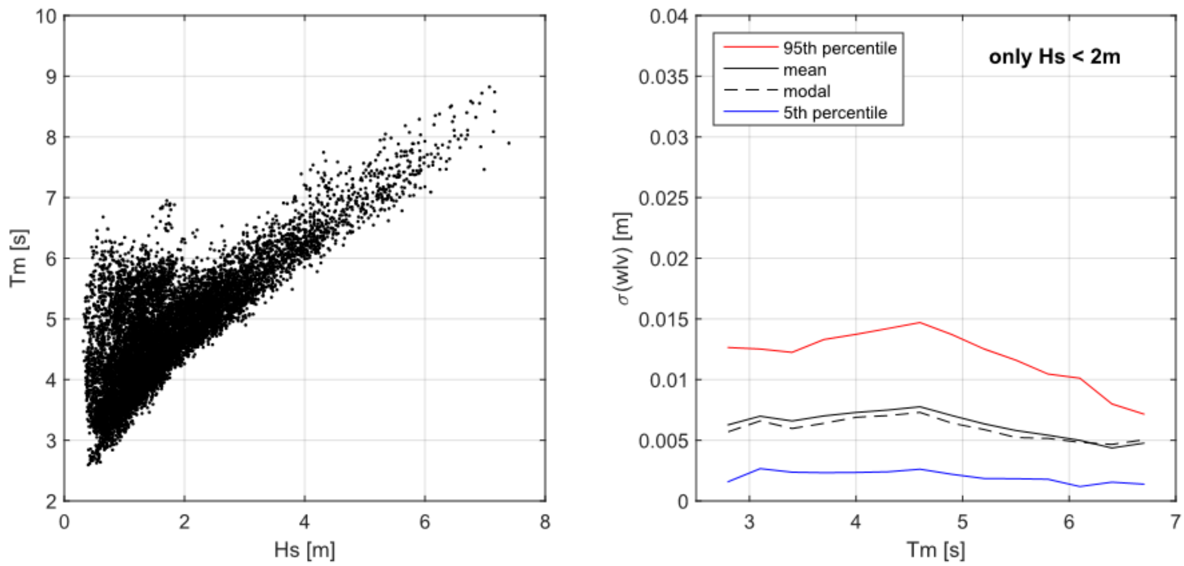

Figure 8: Correlation of significant wave height and mean wave period at FINO 1 (left), influence of mean wave period on the standard deviation of water level measurements with 4 radars for significant wave heights < 2 m (right)

The above given estimate of the intrinsic uncertainty of radar sensor measurements is the lower bound when comparing radar measurements with those by traditional devices, like floats with shaft encoders in stilling wells. For the site near Borkum a comparison of radar measurements with those of a float in a stilling well is given in the following. The analysis bases on the time-series as given in figure 4. A histogram of the deviation of the 1 min values of water level (one coming from the radar array (average of the four radar time-series), the other coming from the traditional system) is given in fig. 9 (left). The probability of exceeding a certain absolute deviation is given in fig. 9 (right). The distribution of these deviations is platykurtic (not normally distributed). The standard deviation of the distribution equals 0.04 m. The skewness is -0.48 and the kurtosis is 2.77 (excess kurtosis: -0.23). At the site near Borkum the deviation between the measurements of the radar array and of the float in a stilling well is larger than 0.07 m for about 10 percent and larger than 0.12 m for about 1 percent of the measured values (see fig. 9, right). This is about eight to ten-times the intrinsic uncertainty of the radar measurements (compare to fig. 5, left). During the 4 month of analysis the deviation between the measurements with the radar array (average of four radar sensors) and the float in a stilling well does not seem to depend on the sea state (significant wave height, mean wave period) at Borkum, as fig. 10 elucidates. However this may change under the condition of larger significant wave heights (larger than 2 m). Similar results are found when carrying out a comparison of the data sets acquired with a single radar sensor of the array and the traditional device.

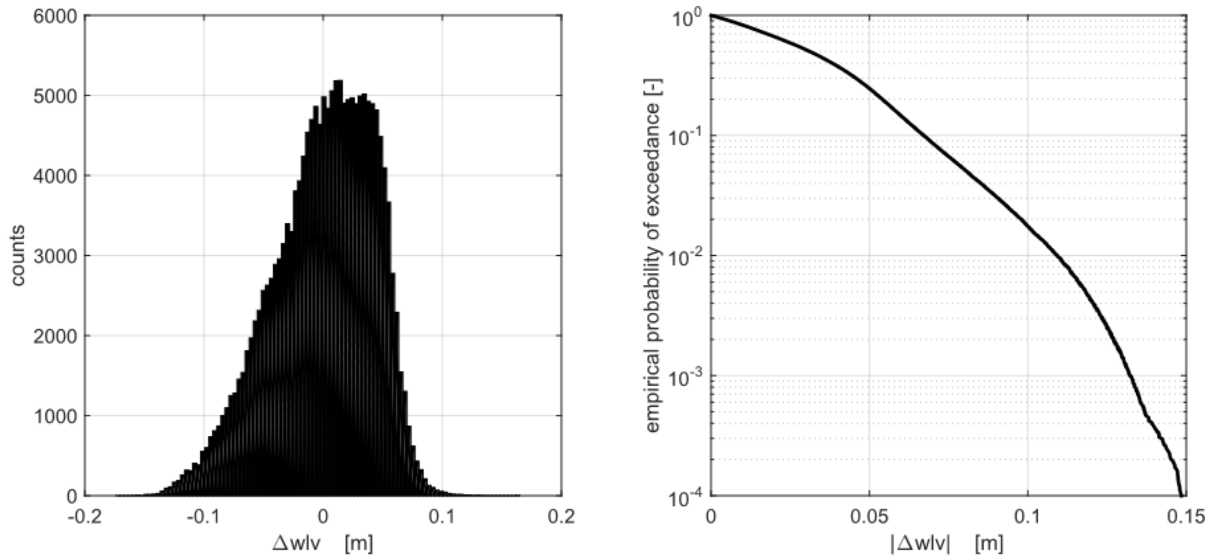

Figure 9: Histogram of deviations of 1 min values of water level measurements measured with radar array and float in a stilling well near Borkum (left) and empirical probability of exceedance of the absolute deviation (right)

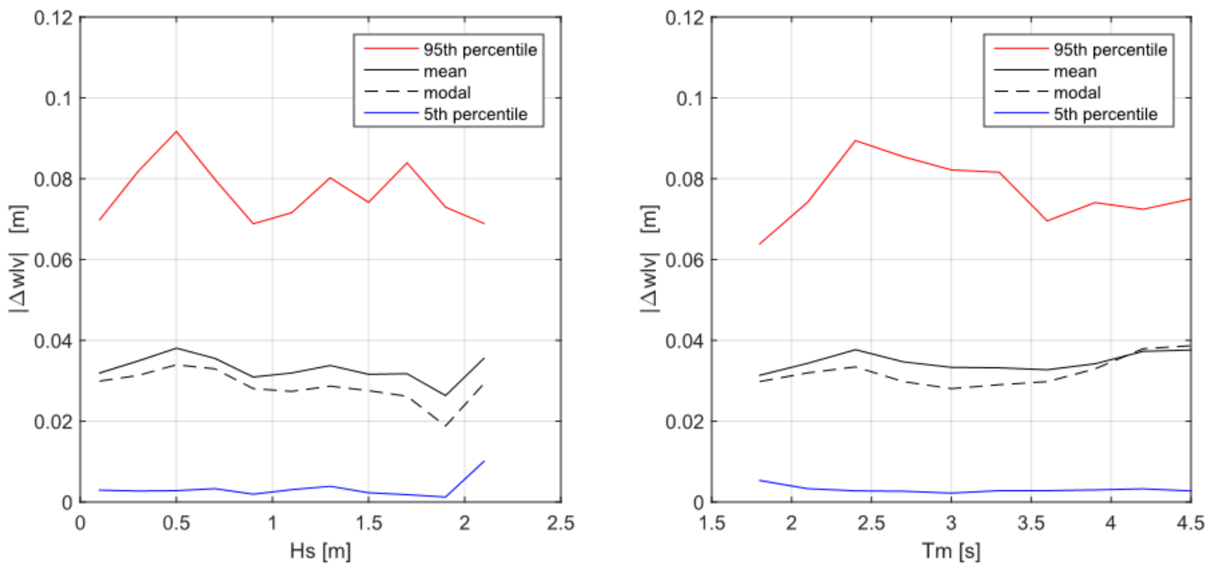

Figure 10: Influence of sea state near Borkum on the deviation between water level measurements with a radar array and a float in a stilling well: effect of significant wave height (left) and effect of mean wave period (right)

At the lighthouse "Alte Weser" the comparison of radar measurements with those of a float in a stilling well revealed less deviation (time of analysis: April 2009 to February 2010). A histogram of the deviation of the 1 min water level values (one coming from the single radar sensor, the other coming from the traditional system) is given in fig. 11 (left). The probability of exceeding a certain absolute deviation is given in fig. 11 (right). The histogram of deviations between measured 1 min water level values is leptokurtic (in contrast to the site near Borkum). The distribution shows a standard deviation of 0.03 m, .a skewness of -0.61 and a kurtosis of 4.56 (excess kurtosis: +1.56). At the lighthouse “Alte Weser” the deviation between the data of the radar sensor and the float in a stilling well is larger than 0.04 m for about 10 percent of the measured values and larger than 0.08 m for about 1 percent of the measured values (see fig. 11, right).

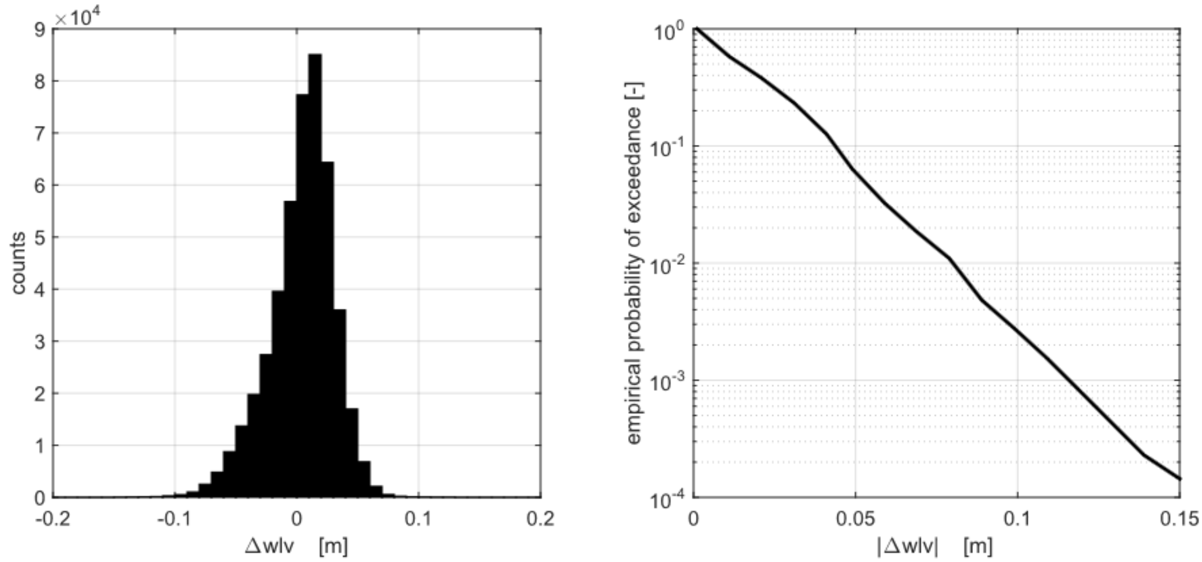

Figure 11: Histogram of deviations of 1 min values of water levels measured with a single radar sensor and a float in a stilling well at the lighthouse “Alte Weser” (left) and empirical probability of exceedance of the absolute deviation (right)

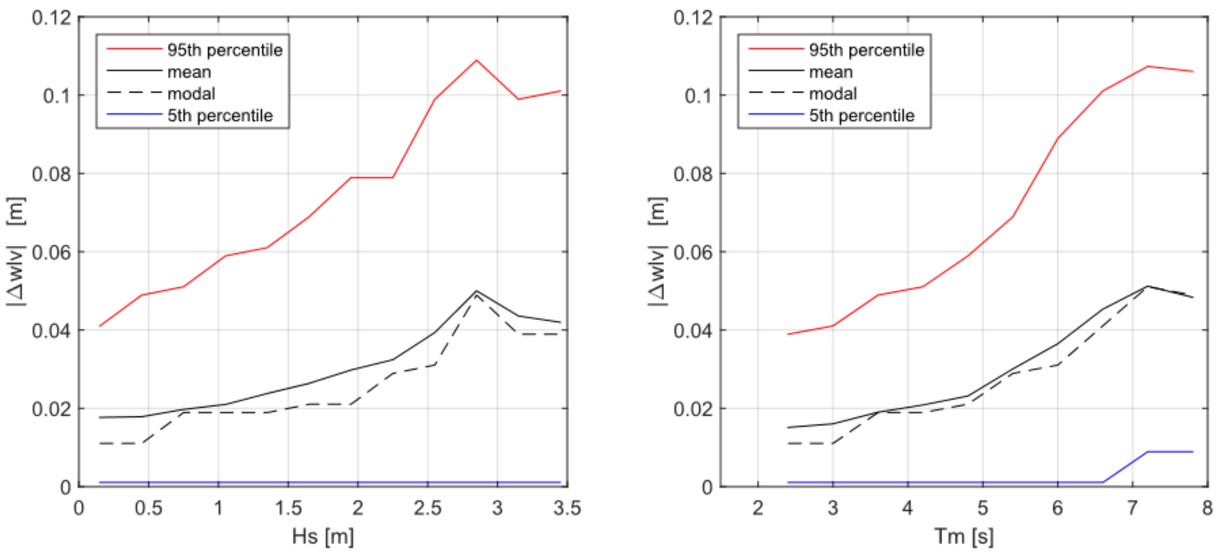

Figure 12: Influence of sea state at the lighthouse “Alte Weser” on the deviation between water level measurements with a single radar sensor and a float in a stilling well: effect of significant wave height (left) and effect of mean wave period (right)

In contrast to the site near Borkum a dependence of the deviation between the water level measurements with the radar sensor and the float in a stilling well on the sea state is found for the analysed 10 month period at the lighthouse “Alte Weser”, as shown in figure 12. An increase in wave height from 1.5 m to 3 m seems to double the mean deviation. As found for the standard deviation of the different sensors of the radar array at FINO 1 the increase of the deviation of 1 min water level values with mean wave periods at the lighthouse “Alte Weser” is also probably related to an increase in wave height in case of increasing wave periods (see fig. 13). When analyzing wave events with 0.3 m < Hs < 0.7 m only, no effect of the mean wave period on the deviation of 1 min values of water levels is found.

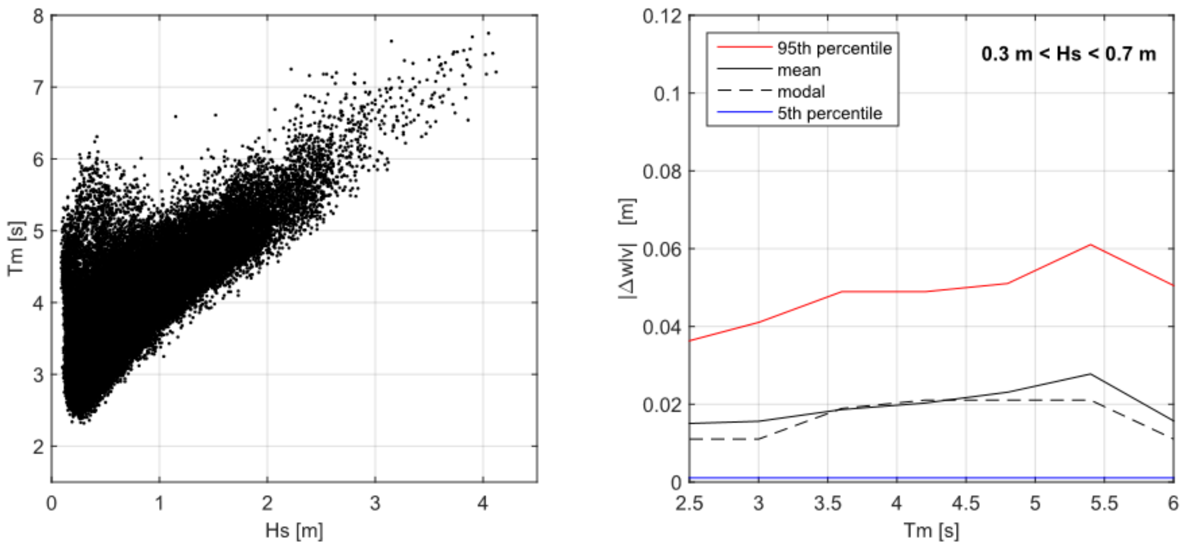

Figure 13: Correlation of significant wave height and mean wave period at lighthouse “Alte Weser” (left), influence of mean wave period on the standard deviation of water level measurements with 4 radars for significant wave heights with 0.3 m < Hs < 0.7 m (right)

5. Conclusion

The analysis of measurements with radar arrays in German coastal waters reveals that the intrinsic uncertainty of radar water level measurements increases linearly with the wave height (at least up to Hs < 6 m) and does not depend on wave period. Without waves the standard deviation equals approx. 0.003 m and with waves (Hs=2m) approx. 0.01 m (slightly depending on the site).

When comparing radar water level measurements with those undertaken with a float in a stilling well the accuracy is less good. For a long-term comparison an average standard deviation of 0.03 m (lighthouse “Alte Weser”) is found. The deviation of radar and float in a stilling well seems to increase with wave height as well and does not significantly depend on wave period. Without waves the average absolute deviation equals approx. 0.017 m and with waves (Hs=3m) approx. 0.04 m.

Future work at German test sites will focus on advanced filtering techniques for radar measurements as e.g. proposed by Boon (2014) and on using radar backscatter intensity as an indicator for the validity of a single radar distance measurement.

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