A comparative report on the DWR MkIII and DWR4 data

During the development of the DWR4, the successor of the DWR MkIII with higher sampling frequency and improved data processing, many long and short term buoy deployments were conducted off the shore at Ymuiden, The Netherlands. A test from November 29 to December 22, 2011, profited from a large variety of meteorological conditions and sea states. Periods of calm were interspersed with rough and ferocious storms. During the test period, the significant wave height actually varied between 1 and 5.5 m, which are extreme values in 15 m water depth. The data of this test buoy that included both MkIII functionality and DWR4 functionality is used to compare both processing schemes. The results of this comparison are presented and explained in this report. It is shown that both processing schemes perform well and the minor differences of the results can be attributed to the higher sample frequency.

Scheme differences

In the new DWR4 data processing, a number of changes have been introduced.

- Foremost is the doubling of the sampling frequency, from 1.28 Hz in the MkIII to 2.56 Hz in the DWR4. This sampling frequency is the rate at which the buoy outputs the displacement data, the socalled ‘external’ sample rate. The primordial acceleration is sampled at a higher rate, and this ‘internal’ sampling frequency is increased from 3.84 Hz in the MkIII to 5.12 Hz in the DWR4.
- Secondly, the resolution of the displacement data has been changed through the use of a arcsinh (inverse hyperbolic sine) representation of numbers. This representation resembles a floating point notation of 12 bits having a 3-bit exponent. Both have an essentially logarithmic value distribution. Thus millimetre resolution for small values is realised, rising to 4 cm resolution at the maximal displacement of 20 metres.
- For the spectral analysis, both the MkIII and the DWR4 rely on Welch’s method that estimates the power spectrum by calculating the periodogram over windowed data segments using the Fast Fourier Transform. The difference here is the use of the Hann window in the DWR4, opposite to a Tukey window with $\alpha = 0.25$ in the MkIII. Also, the data segments in the DWR4 overlap (50%), whereas in the MkIII they do not. As a result, the number of segments in a 30 minutes record increases from 8 in the MkIII, to 17 in the DWR4, and this increase results in a smaller variance of the DWR4 spectrum.
- The length of a data segment expressed in seconds is equal in both schemes. Expressed in number of datapoints, a DWR4 segment is twice as long as a MkIII segment. As a result, the frequency step in the spectrum remains the same, 0.005 Hz for MkIII and DWR4 alike, but the frequency interval increases, from 0.025 – 0.58 Hz in the MkIII to 0.025 – 1.00 Hz in the DWR4, virtually a doubling of the range.
- Until now the analysis of the wave data in terms of zero-upcross waves was not implemented in the buoy firmware, but was left for the post-processing. In the DWR4 however, some basic zero-upcross wave analysis is implemented, specifically the one-loop calculations that can be performed “on the fly” and do not require data storage or sorting. These include H_{max}, the maximal wave height, and an estimator of H_s, the significant wave height, based on the rms (root-mean-square) value of the upcross wave heights: $H_s = H_{rms}\sqrt{2}$. The latter parameter serves as an alternative for $H_{1/3}$.
- Finally, a rudimentary level of quality control is added in the DWR4 scheme. The rare events that pitch or roll angles exceed 89°, or that accelerations exceed 1 g (standard gravity), are flagged, and segments containing such exceptions are precautionarily excluded from the spectral calculations. It is emphasized here that the occurrence of a flag does not imply an error, nor does the absence of a flag warrant a correct measurement. A flag is merely indicative of a sensor having got near the limits of its range.

Spectral parameters

An easy, yet significant test is the comparison of the main spectral parameters: the significant wave height (H_{m0}), the mean period (T_1), the zero-upcross period (T_z) and the crest period (T_c). Because of the wider frequency interval for the DWR4, we expect the spectral parameters of the new buoy to have slightly lower values than their MkIII counterparts. The effect will be strongest in the crest period that depends on the 4th spectral moment, while hardly noticeable in the

Datawell BV
Zomerluststraat 4
2012 LM Haarlem
The Netherlands

T +31 23 531 60 53
F +31 23 531 19 86
E sales@datawell.nl
W www.datawell.nl

significant wave height depending on the 0th moment only. The spectral moments are integrals of the power spectral density on the full frequency interval. In principle the upper limit is infinity, in reality it is finite. Thus the values of the moments, and of the spectral parameters derived from them, depend on the upper frequency limit that has been increased from 0.58 Hz to 1.0 Hz.
In order to make a fair comparison between the schemes, we therefore introduce two sets of parameter values in the DWR4: one for the full range of 0.025 – 1.0 Hz and indicated by the abbreviation FR, and one for the mid range of 0.025 – 0.58 Hz, indicated by MR. We thus expect the MkIII numbers to be slightly greater than the DWR4 (FR) numbers, and much more close to the DWR4 (MR) numbers.

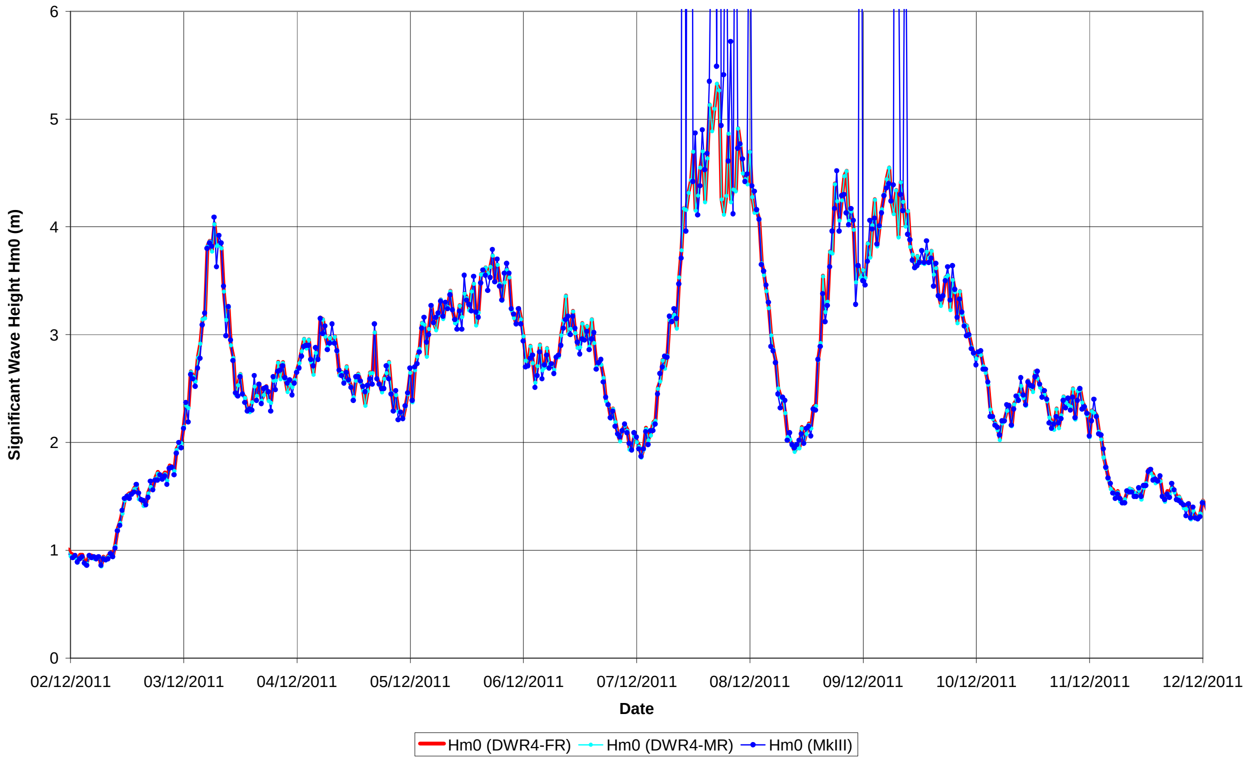

Fig 1. Comparison of the significant wave height H_{m0}

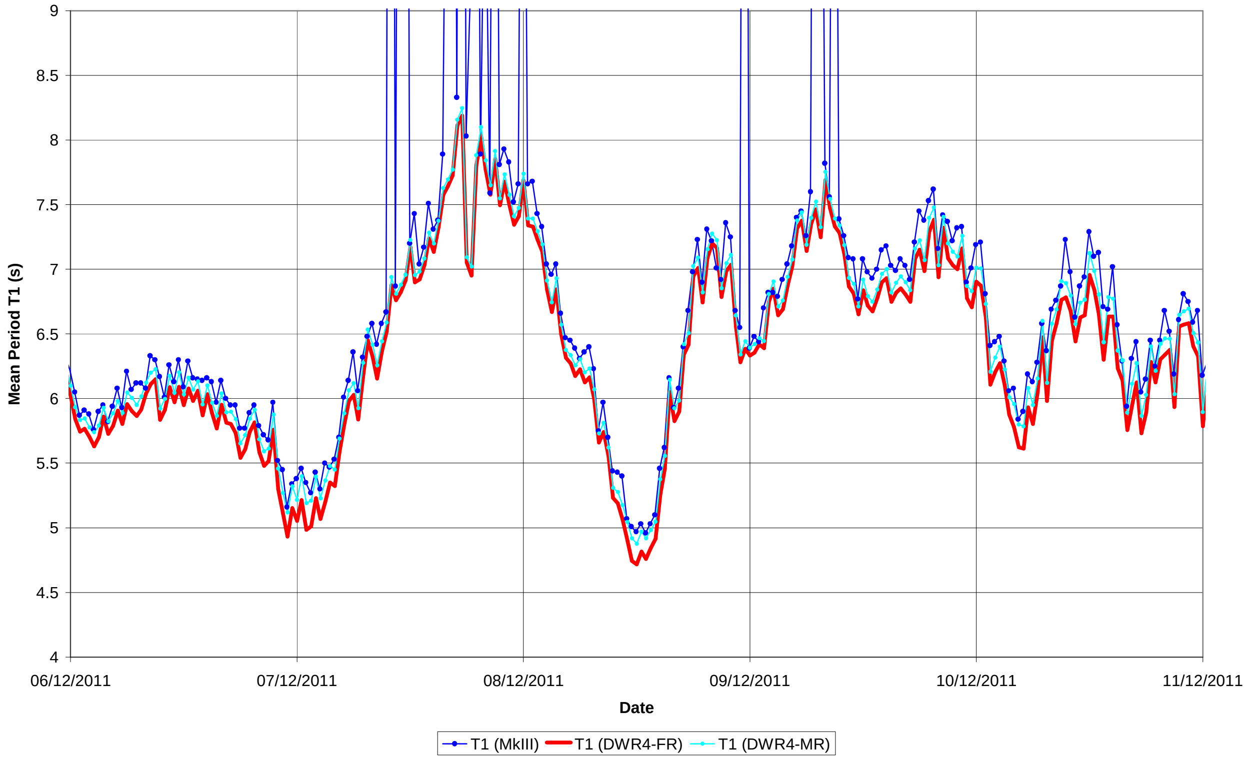

Fig 2. Comparison of the mean period T_1. Only five days are shown for better visualising of differences.

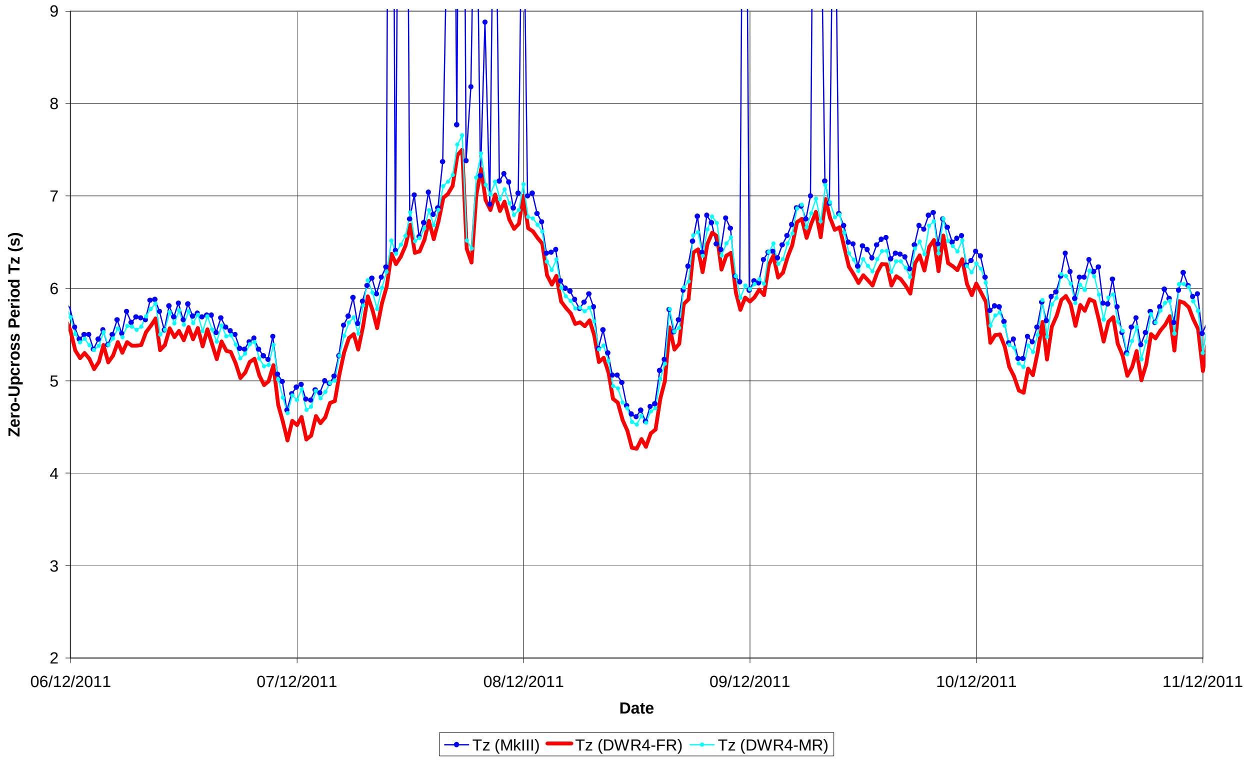

Fig 3. Comparison of the zero-upcross period T_z

Datawell BV
Zomerluststraat 4
2012 LM Haarlem
The Netherlands

T +31 23 531 60 53
F +31 23 531 19 86
E sales@datawell.nl
W www.datawell.nl

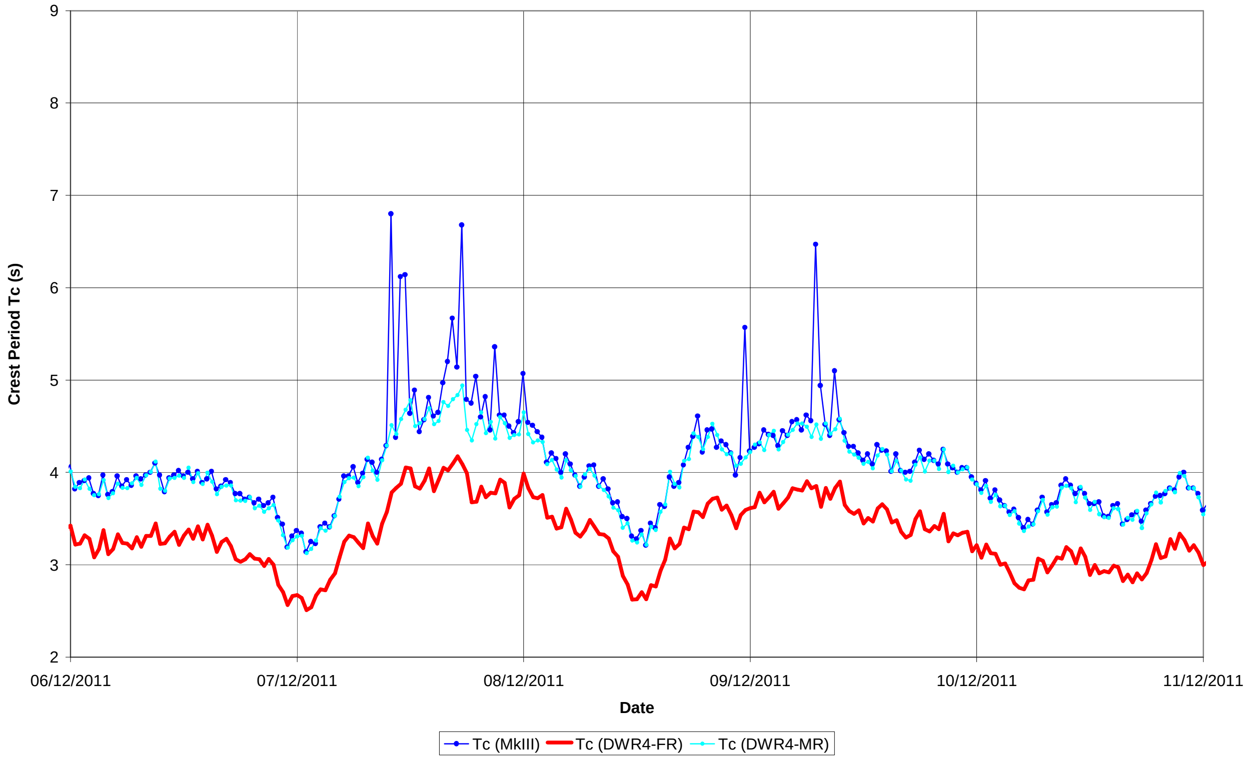

Fig 4. Comparison of the crest period T_c

In the figures above, the MkIII values are plotted as blue dots on a solid blue line. The DWR4 (FR) values are red, the DWR4 (MR) values are cyan. It is indeed seen that the impact of the upper frequency limit increases from Hm0 to Tc, and that the MkIII values agree well with the DWR4 (MR) values on the smaller frequency interval, both being consistently higher than the DWR4 (FR) values on the wider frequency interval.
A remark on the outliers in the plots is due here. These outliers all occurred during the two storms of 7 and 9 December, 2011, when the H_{m0} measured over 4 m, exceptional values in 15 m deep water. They do not signal malfunctioning of the buoy, nor any errors in the processing of the measurements. Rather these stray values show that during these storms the buoy experienced forces that did not result from normal orbital wave motion but were exerted by large breaking waves, probably of the plunging type. That both DWR4 curves - MR and FR - show no outliers is due to the quality control in this scheme that was described in the previous section.
It must be realised that this first test actually comprises most of the data processing: all heave information, the segmentation and windowing, the exact shape of the spectrum etc. This first comparison regarding the spectral parameters is hence a highly relevant test.
The conclusion must be that the new DWR4 scheme produces the same results as the MkIII if the traditional frequency interval is used. If the new, wider frequency interval is used, the parameter values are expectedly lower, an effect that is small in the H_{m0} and large in the T_c, in accordance with the theory.

Zero-upcross wave statistics

The DWR4 outputs some statistical parameters based on the analysis of zero-upcross waves. Only those parameters are output that can be calculated in one loop, "on the fly", without storage or sorting of intermediate results. These include the highest wave Hmax, and the period of the highest wave $T(H_{max})$, the longest wave T_{max}, and the height of the longest wave $H(T_{max})$, the average wave height H_{avg} and the average wave period T_{avg}, the number of upcross waves N_w, and the number of crests (maxima) N_c. In addition, the rms (root-mean-square) of the wave heights (H_{rms}) is used to obtain an estimator of the significant wave height $H_s = H_{rms}\sqrt{2}$.

The MkIII buoys do not output any statistical parameters. However some of the parameters are available in post-processing. Thus we can compare the two schemes with respect to H_{max} and $T(H_{max})$, H_{avg} and T_{avg}, N_w and N_c. Also, we can compare the above mentioned $H_{rms}\sqrt{2}$ to $H_{1/3}$, the average wave height of the highest one third of the waves, being the original definition of the significant wave height. It must be realised that this latter comparison is different in nature from the other. The two parameters, generated by to completely different algorithms, are only equal in value if the upcross waves obey a Rayleigh distribution. So strictly speaking, this comparison is a test of the "Rayleigh-ness" of the waves, rather than a comparison between the MkIII and the DWR4 results. Since however the Rayleigh assumption is so generally valid, agreement between $H_{1/3}$ and $H_{rms}\sqrt{2}$ is yet considered indirect proof of concordance of the two schemes.
A number of parameters stay outside the comparison: the MkIII parameters $H_{1/10}$ and $T(H_{1/10})$, the average wave height of the highest one tenth of the waves and the associated period, and also $T(H_{1/3})$, of obvious definition, have no DWR4 counterparts, since they cannot be calculated on the fly. On the other hand, the DWR4 parameters T_{max} and $H(T_{max})$ are new and without MkIII equivalents: these parameters are actually borrowed from the analysis method as implemented by one of our major customers. Their introduction is inspired by our wish to coordinate our methods of data analysis. Inclusion of these parameters in the plots below is merely illustrational.
In Figure 5, the upcross height parameters are plotted, the DWR4 values as solid lines, the MkIII values as dots. We find an excellent agreement for all three heights: H_{max}, H_{avg} and H_s (given by $H_{1/3}$ in the MkIII and by $H_{rms}\sqrt{2}$ in the DWR4). The time series of both H_{avg} and H_s show very smooth, and parallel, trends. In contrast, H_{max} is much more fluctuating in time, and the concordance of the DWR4 and the MkIII is all the more remarkable. Figure 5 comprises just five days to reveal the finer details of the time series. In Figure 6 the complete time series are plotted, spanning a full month. The agreement is perfect, except for the storm events on 7 and 9 December, where wave heights greater than six metres were measured. Here the drawback of the upcross wave analysis becomes clear: the usefulness of its results depends crucially on the strictness of the data quality control. This however is not different between the two schemes, and only shows that the expert's eye is indispensable for the correct assessment of wave-statistical results.
Figure 7 shows the wave periods, again for a short interval of five days, to not obscure the details. Good agreement is seen for the $T(H_{max})$, the wave period of the highest wave. For the average wave period we see concurrent trends, where the DWR4 values are systematically lower than those of the MkIII by 0.1 or 0.2 seconds. Another way of putting this is that the DWR4 registers slightly more waves than the MkIII (since T_{avg} is simply the reciprocal of N_w).

Datawell BV
Zomerluststraat 4
2012 LM Haarlem
The Netherlands

T +31 23 531 60 53
F +31 23 531 19 86
E sales@datawell.nl
W www.datawell.nl

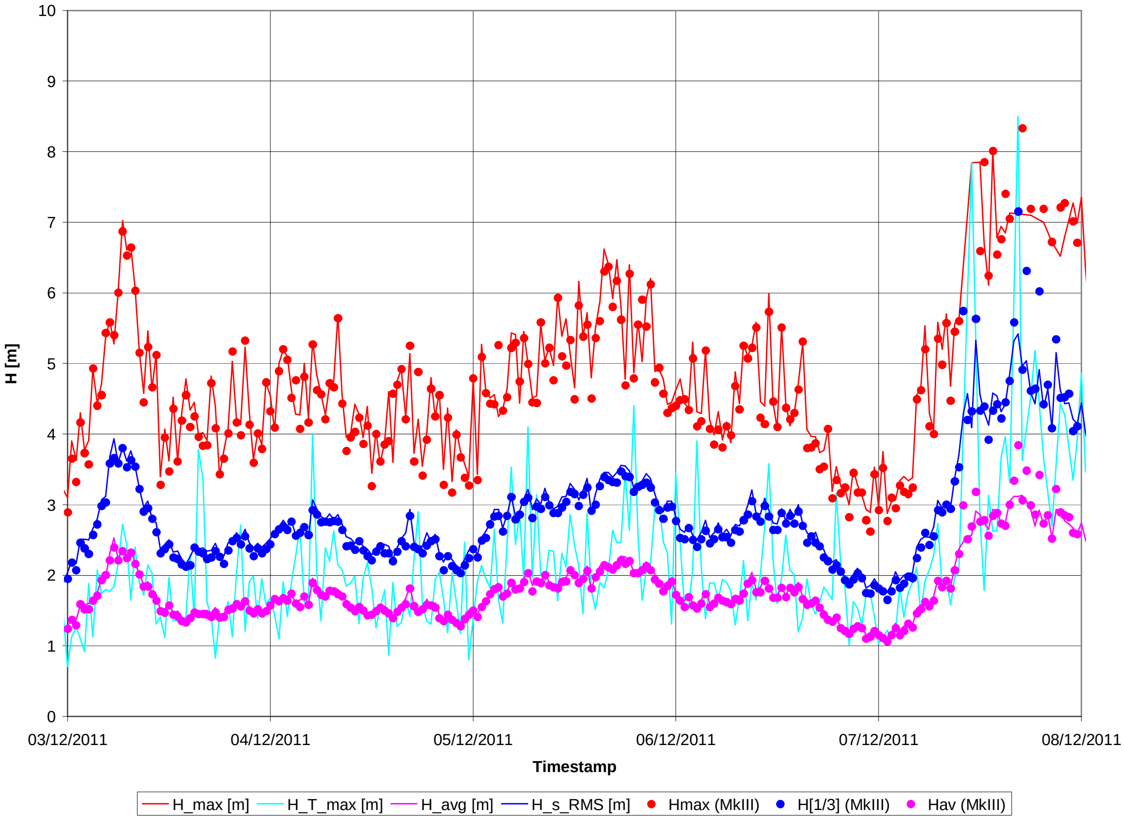

Fig 5. Wave height parameters in the zero-upcross wave analysis (detail)

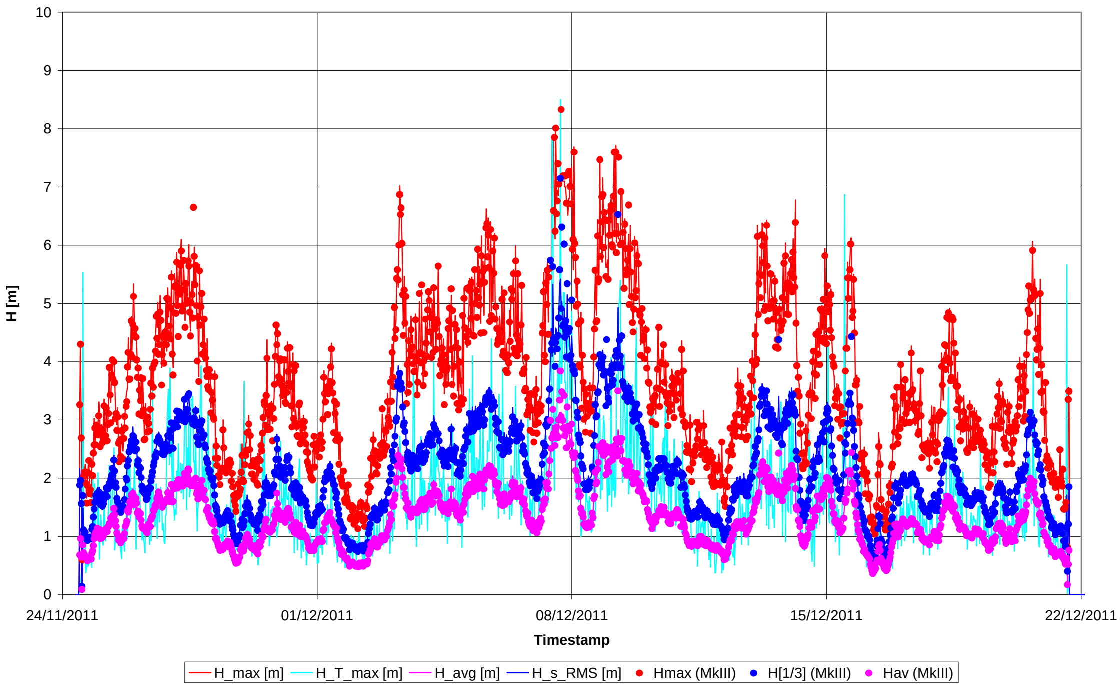

Fig 6. Wave height parameters in the zero-upcross wave analysis

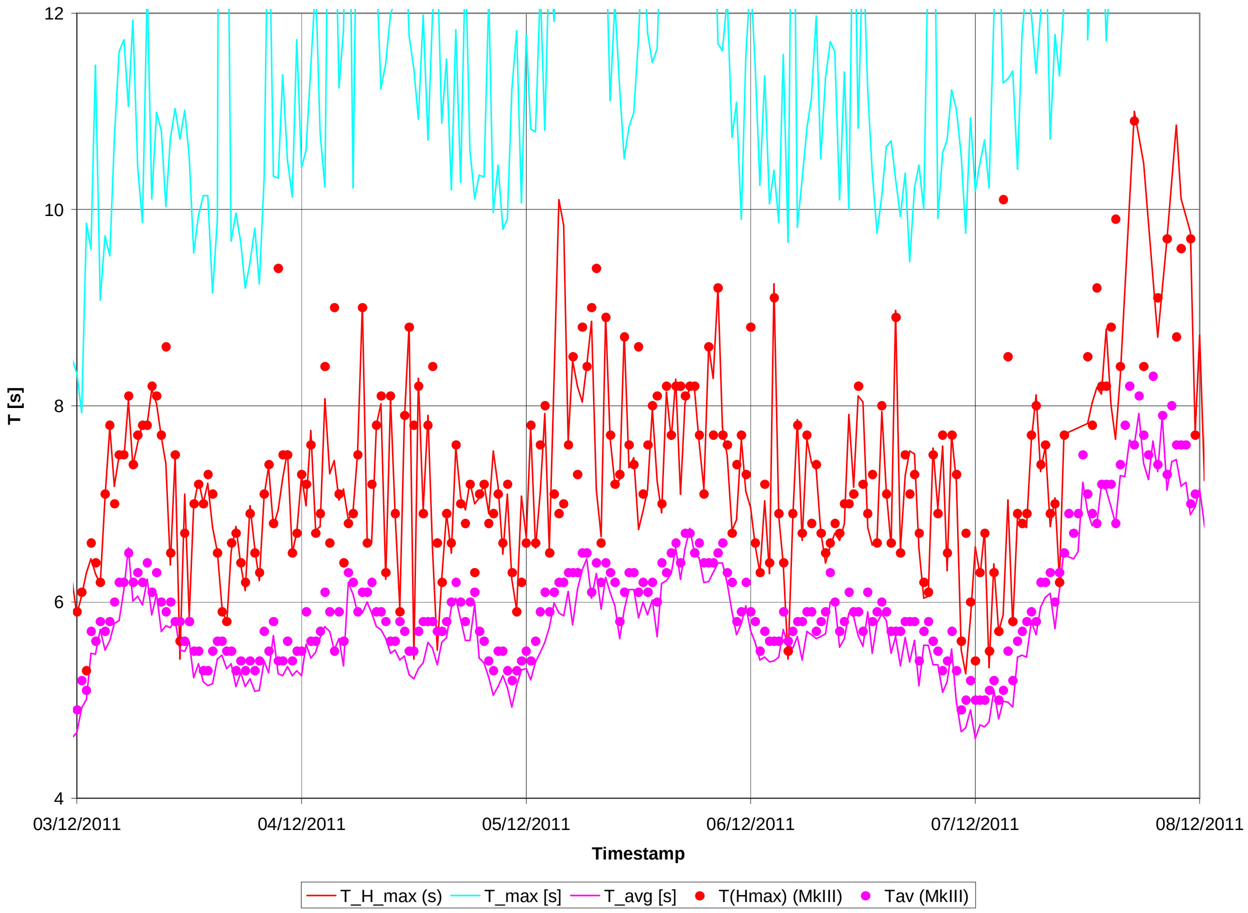

Fig 7. Wave period parameters in the zero-upcross wave analysis

From the higher sample rate and the higher resolution in the DWR4, this is actually not surprising. Near the mean sea level, the DWR4 has twice the number of datapoints, at ten times the resolution of the MkIII: where one scheme finds a zero-upcrossing, the other may not. The former buoy will report two short waves, the latter buoy a single long wave. In Figure 7, this effect is seen in the $T(H_{max})$ curves: either the two schemes have virtually identical values, or they differ substantially: where they do, one of the schemes, almost always the DWR4, has an extra zero-upcrossing in the highest wave. But actually this is a surprisingly rare event, occurring two or three times a day. This low occurrence also explains why the difference in the average wave period (i.e. in the number of waves) between the schemes is so small.
We can investigate this phenomenon a little closer, by looking at the number of crests, N_c. Here the same effects of doubled sample rate and resolution play a role. However, the effects are much stronger here, as can be seen in Figure 8. The number of crests that the DWR4 finds is close on a hundred greater than the number of crests in the MkIII, an increase of circa 20%. As a result, the bandwidth parameter ε, derived from the quotient of the number of waves and the number of crests, displays a significant shift from around 0.65 to 0.8. The conclusion from this structural break must be that the bandwidth ε greatly depends on the sample rate and resolution, and that it is hence a poorly determined physical quantity. If the DWR4 heave data are filtered by a low-pass filter and rounded to centimetre resolution, the bandwidth parameter resumes its MkIII value. The difference in ε between the schemes is thus not related to any error in either of them, but to its dependence on the sample rate.

Datawell BV
Zomerluststraat 4
2012 LM Haarlem
The Netherlands

T +31 23 531 60 53
F +31 23 531 19 86
E sales@datawell.nl
W www.datawell.nl

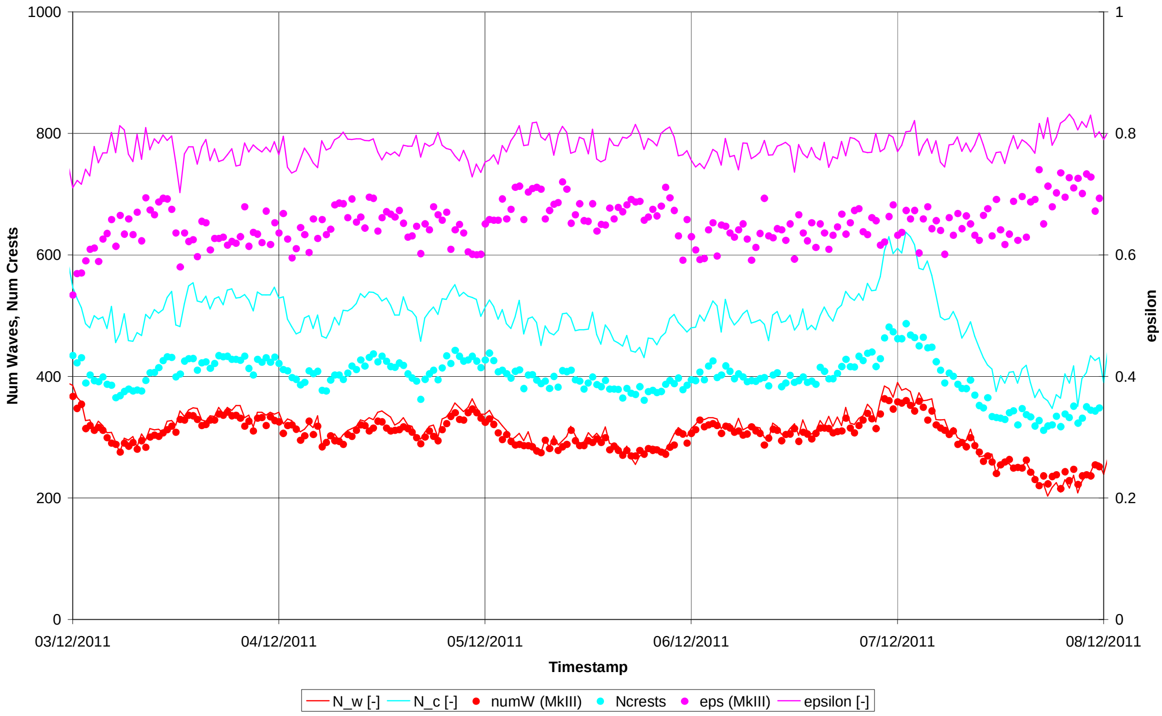

Fig 8. Number of waves N_w and Number of crests N_c (left axis) and bandwidth parameter ε (eps, epsilon, right axis) in the zero-upcross wave analysis

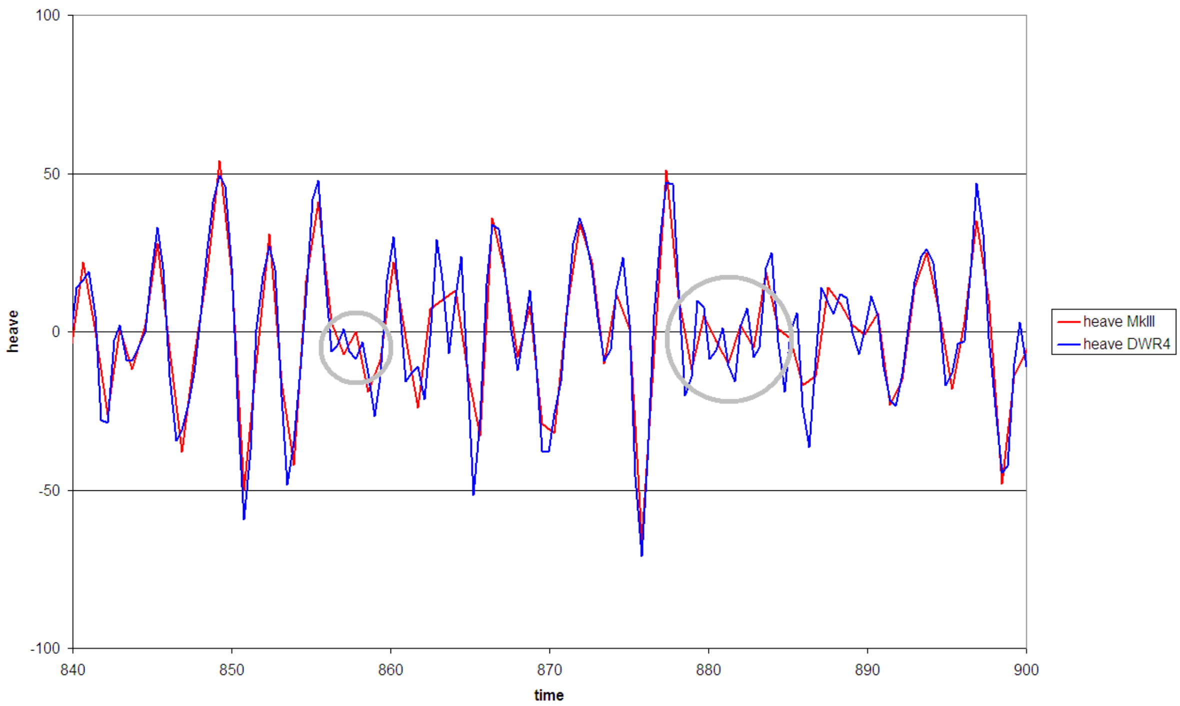

Fig 9. Detail of the heave time series of the MkIII (red solid line) and the DWR4 (blue solid line). The gray circles show regions where the DWR4 has extra crests (maxima).

An inspection of the heave time series of both buoy schemes in Figure 9 displays the same phenomenon in a direct way. In general, the series concur and the effect of the differences in sample rate and resolution remains invisible, apart from the DWR4 curve being somewhat smoother. At a few points in time, however, the extra information in the DWR4 yields an extra upcrossing or an extra crest. Two of these points are indicated by a gray circle. These minor differences lay at the basis of the trend break in the bandwidth parameter.

Please note that the spectral equivalent of ε, the spectral bandwidth parameter bearing the same name but determined from the crest period (T_c) and the zero-upcross period (T_z), suffers a similar problem. The fourth spectral moment, on which T_c and hence ε depend, is not finite for any current model spectrum (Pierson-Moskowitz, Bretschneider, JONSWAP), provided the integral is calculated on the full frequency interval from zero to infinity. In maths terms the integral is improper and divergent. Hence, theoretically T_c equals zero and ε is unity. In practice, the upper frequency will always be less than half the sampling frequency, and the now proper integral converges under all conditions. As a result, we do have nonzero crest periods and bandwidth values below unity. What we see in the zero-upcross bandwidth is the counterpart of this spectral phenomenon.
The conclusion from all this is that the bandwidth parameter, whether spectral or statistical, is not a good quantity to use in the scheme comparison. Its value depends crucially on measurement settings like the upper frequency limit, directly proportional to the sampling frequency, and the heave resolution. The inevitable structural break in this parameter is explainable and not indicative of any errors in either scheme.
In general, however, the conclusion from the wave-statistical results is no other than the conclusion from the spectral results: there is excellent concordance between both buoy schemes, even for parameters like the maximum wave height H_{max} and the corresponding wave period $T(H_{max})$. Again, this positive result for the high-level parameters is implicit evidence for an agreement on all the low-level measurements involved.

Individual heave spectra

Until now we investigated the high-level spectral and wave-statistical parameters, that summarize 30 minutes records into a single number. Let us now focus on individual, low-level results like the heave spectrum (in this section), and the directional spectrum (in the next section). More subtle differences or agreements not preserved by the global parameters may surface in the original 30 minutes records.
In Figure 10, a representative heave spectrum, pertaining to 1 December 2011, 22:30, is plotted. For the MkIII, the spectrum closest in time is that of 22:56, where this label refers to the time when the transmission from buoy to shore started. The heave data that it is based on dates from 22:26 to 22:53. The timestamps of the MkIII spectra are not synchronized to any real-world clock. In contrast, the timing of the DWR4 spectra is governed by the GPS clock in the buoy and matches the full and half hours of Coordinated Universal Time (UTC, without the leap seconds). Furthermore, the timestamps in the DWR4 refer to the start of the heave record that the spectrum is based on. Thus the heave data of the 22:30 spectrum is from 22:30 to 23:00, since the DWR4 spectrum spans the full 1800 seconds (and not just 1600 seconds as does the MkIII). The overlap between the two data sets is thus large, but not 100%.
The MkIII spectrum contains 64 frequency bins, between 0.025 and 0.58 Hz. The DWR4 spectrum has 100 frequency bins, between 0.025 and 1.0 Hz. In fact, the MkIII bins form a subset of the DWR4 bins, and by simply confining oneself to this subset, one can easily turn a DWR4 spectrum in a MkIII lookalike.
The extra bins of the DWR4 are not just at the high-frequency end of the spectrum. In the mid-range, 0.1 to 0.25 Hz, where the MkIII has a frequency spacing of 0.01 Hz, the DWR4 has a spacing of only 0.005 Hz, and this accounts for 15 additional bins. These extra mid-range bins are clearly discernible in Figure 10: the DWR4, in red, shows a few peaks and dips that the MkIII, in blue, does not, always at the frequencies where the DWR4 has a bin and the MkIII has not. Outside this interval, the match between the schemes' results is virtually perfect.
The gain at the high frequency end may not be immediately evident from the linear plot of the spectrum. The logarithmic plot of Figure 11 however shows a clear continuation of the f^{-4} decline up to 0.8 Hz. Beyond this frequency, the hydrodynamic response of the buoy, being 70 cm in diameter, falls off rapidly. It would take a buoy diameter as small as

Datawell BV
Zomerluststraat 4
2012 LM Haarlem
The Netherlands

T +31 23 531 60 53
F +31 23 531 19 86
E sales@datawell.nl
W www.datawell.nl

40 cm to utilize the full interval up to 1.0 Hz. This justifies the choice for 1.0 Hz as a frequency upper limit that serves the full range of Datawell buoy diameters.

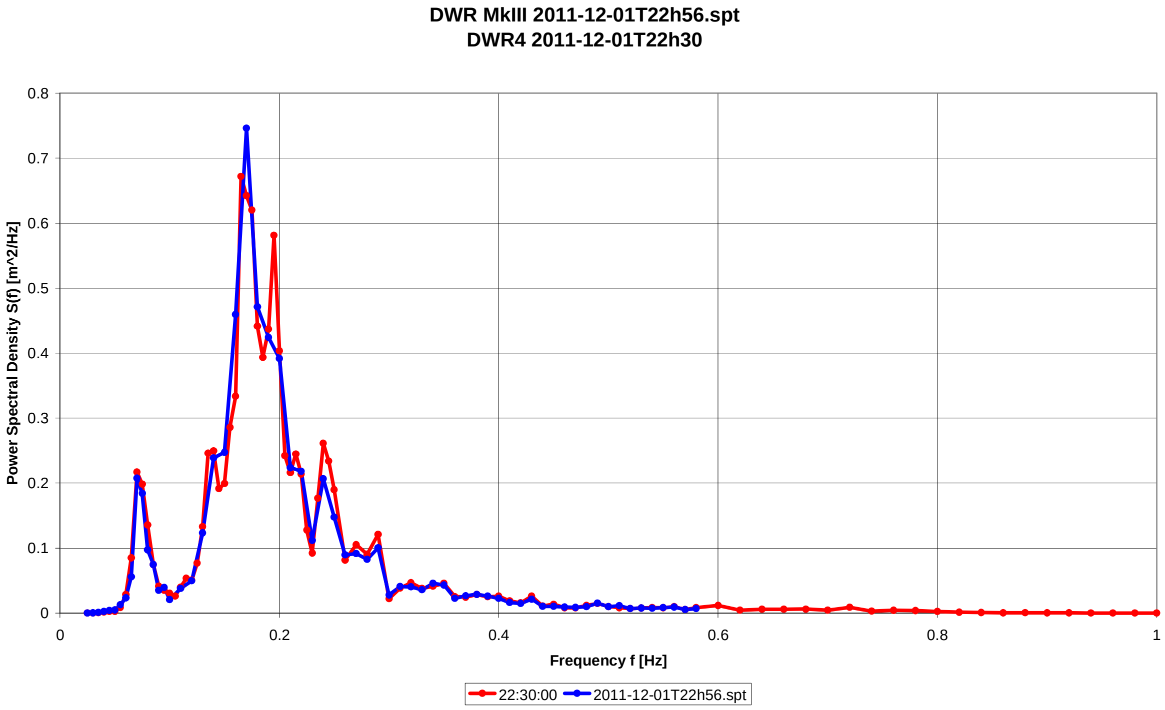

Fig 10. Heave spectrum of 1 December 2011, 22:30, for the DWR4 (red) and the MkIII (blue)

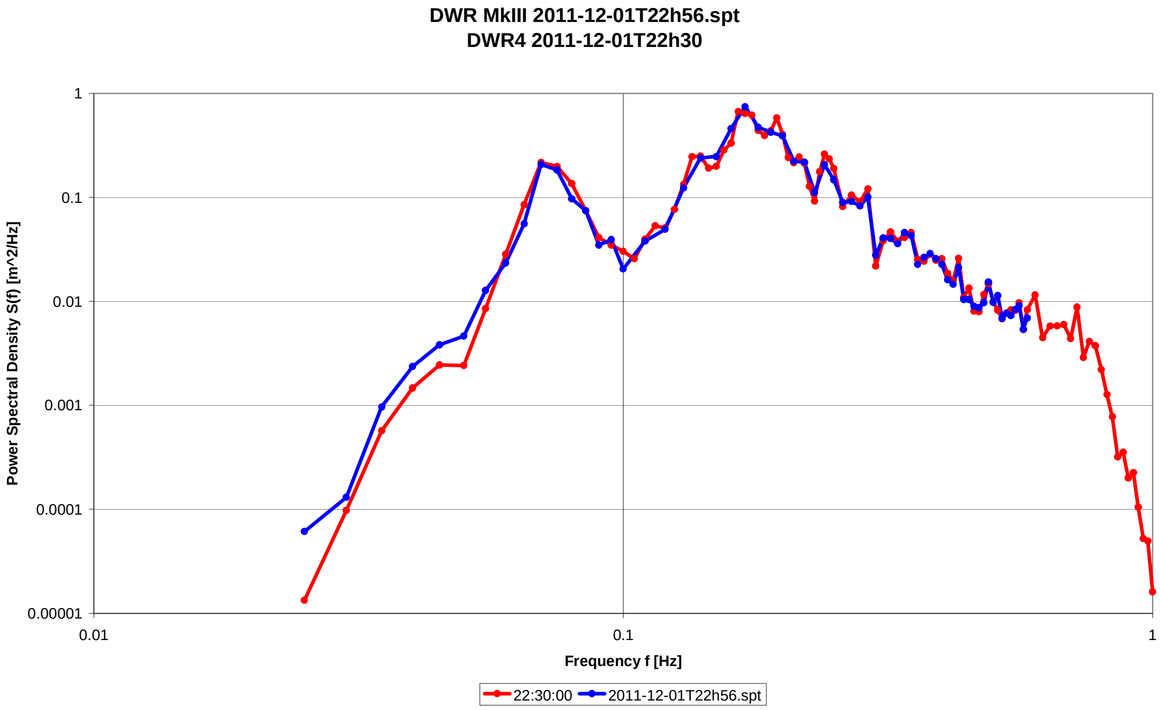

Fig 11. Logarithmic plot of the spectrum of Figure 10.

In conclusion, the heave spectra of both schemes display an excellent match, and they are much closer than any confidence interval guarantees. The extra mid-range bins in the DWR4 reveal some fine-structure of the spectrum, the high-frequency bins help determine the characteristics of the spectral fall-off here. The particular spectrum and the results discussed above are typical for all of the test period.

Individual directional spectra

For the displacement data of the previous section we have investigated the directional spectrum as well. The directional parameters that are compared are those proposed by Kuik, Van Vledder and Holthuijsen, J Phys Ocean 18, 1988, p.1020, viz. the mean direction, the directional spread, the skewness and the kurtosis. These parameters suit well directional distributions that are unimodal. If one wave field is dominant, unimodality is a valid assumption and the directional spread is then a measure of the single peak's width. When more than one wave field is present, the spread is a measure of the angular distance between the peaks, rather than of the width of any peak.
In the present spectrum, the wave fields are manifest at different frequencies. A swell is seen around 0.075 Hz, coming from NNW. See Figure 12. The wind sea from 0.14 Hz is westerly. The DWR4 nicely coincides with the MkIII, reproducing even small details at frequencies with low energy. The MkIII curve ends at a northerly direction, suggesting that the wind is turning from W to N. This suggestion is corroborated by the extra bins of the DWR4. Beyond 0.8 Hz however the directional data is no longer considered reliable, in the light of the large buoy diameter.
The directional spread at the peaks' frequencies is quite small, some 20° to 30°, indicative of separate wave fields and unimodal directional distributions. Again, the two schemes agree nicely on trend and details. The results bring out the excellent quality of both the MkIII and the DWR4, or actually of the heave and direction sensors whose measurements underlie both schemes.
In Figure 13, the skewness and the kurtosis of the directional distribution are plotted. These parameters are less known. They depend on the third and fourth statistical moment, respectively, which are less well determinable.
The skewness is a measure of the asymmetry of the distribution. Qualitatively, a positive skewness indicates that the tail on the right side is longer than the left side and the bulk of the values lie to the left of the mean. Vice versa for negative skewness. To know what left and right mean in a circular distribution, one must realize that wave direction is direction from where the waves arrive, and that +90° corresponds to East. A northerly swell is skew positive if the tail of the distribution is towards the east.
In the figure the skewness (the lower curves, left axis) is seen to vary mainly between -2 and +2. Below 0.17 Hz the skewness has a negative dip, whereas above this frequency the skewness is slightly positive on average. Both schemes agree on this general trend, but the agreement on the details is much poorer.

Datawell BV
Zomerluststraat 4
2012 LM Haarlem
The Netherlands

T +31 23 531 60 53
F +31 23 531 19 86
E sales@datawell.nl
W www.datawell.nl

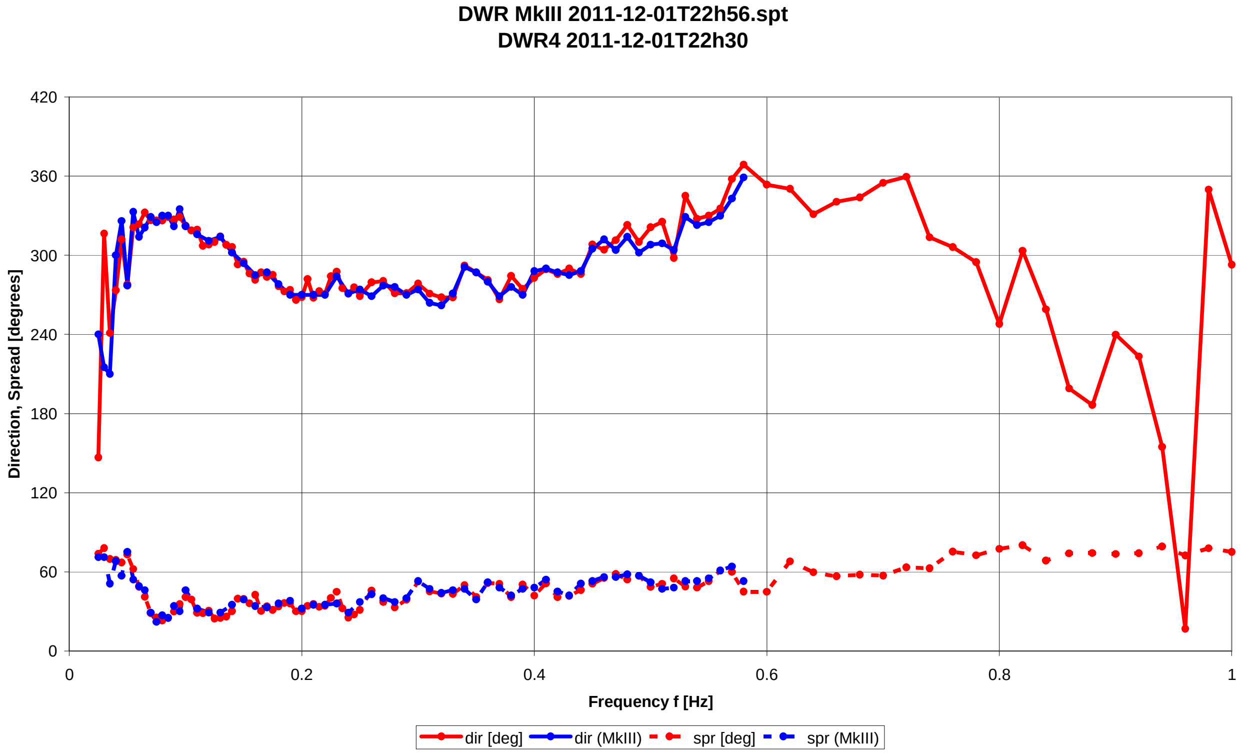

Fig 12. Mean direction and directional spread for the spectrum of Figure 10.

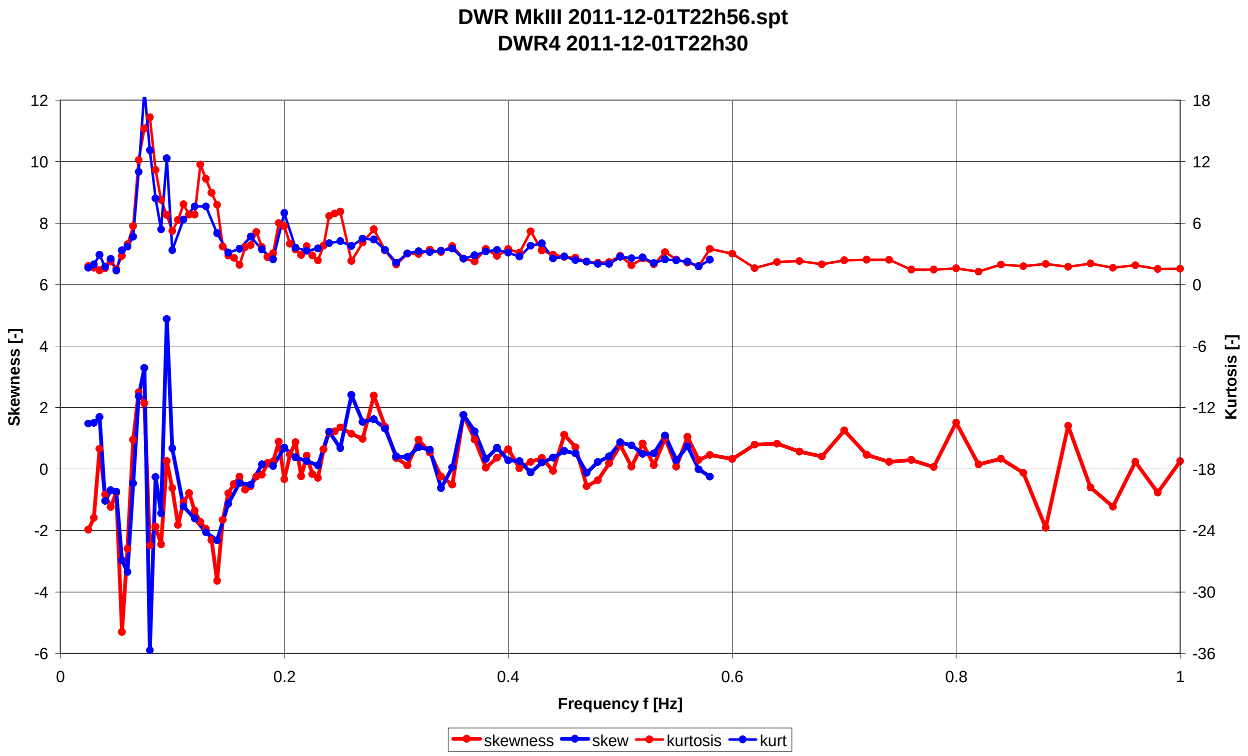

Fig 13. Skewness and Kurtosis for the spectrum of Figure 10.

Datawell BV
Zomerluststraat 4
2012 LM Haarlem
The Netherlands

T +31 23 531 60 53
F +31 23 531 19 86
E sales@datawell.nl
W www.datawell.nl

Similar remarks apply to the kurtosis (the upper curves in Figure 13, right axis), which is a measure of the peakedness of the distribution. A large kurtosis corresponds to a distribution having a sharp peak. Small values of the kurtosis indicate a “broad” shape. The normal distribution has a kurtosis of 3. We see that the low-frequency swell has a kurtosis of almost 18, which suggests that its peak is quite acute. At the high-frequency end the kurtosis values are Gaussian or sub-Gaussian. Here too, the MkIII and the DWR4 agree on the general trend, but display quite a few incongruities when it comes to the details. Because the skewness and the kurtosis are essentially normalized higher moments, their values also depend on the directional spread that is used for the normalization.
In conclusion, the mean direction and directional spread for the two buoy schemes are in excellent agreement. The skewness and the kurtosis for the MkIII and the DWR4 show more variation. This variation however seems to be related to the nature of these secondary parameters that are less well-determined than the primary direction and spread.

General conclusion

The introduction of the DWR4 has opened new possibilities in the analysis of wave data: higher sampling rate and improved resolution, more segments, better window functions yield more datapoints, more spectral bins, and a higher upper frequency limit. Excellent agreement on the main spectral and statistical parameters between the schemes prove that both the MkIII and the DWR4 are valid schemes of data analysis, and it corroborates the status of the Waverider as the golden standard in the field of wave measurement.
At the same time, comparison of the two buoy schemes elucidates the dependence of many wave parameters on the upper frequency limit / the sample frequency, a dependence that was implicit as long as the sample rate remained constant. Now, with a second scheme present having a different sample rate, this dependence becomes visible as a structural break in the bandwidth parameter ε.
The doubled sample frequency, now 2.56 Hz, accommodates all Datawell buoys – directional and non-directional –, and employs their full orbit-following capacity. Since now the hydrodynamic response is the limiting factor for buoys of any diameter – 40, 70 or 90 cm –, there is no need to increase the sample frequency any further.
From the individual spectra, it is seen that the heave spectrum, the mean direction and the directional spread are measured with great accuracy and rendered correctly in both schemes. The variability of the secondary parameters skewness and kurtosis is seen to be greater, and is understood to be cause of minor differences in these parameters between the schemes.
The advantages of the DWR4 in the field of computation and processing, besides its extensibility with new measurement options, will make it the obvious choice for measuring waves.

Datawell BV
Zomerluststraat 4
2012 LM Haarlem
The Netherlands

T +31 23 531 60 53
F +31 23 531 19 86
E sales@datawell.nl
W www.datawell.nl