Intercomparison of a WaveGuide radar and two Directional Waveriders

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Radar gauges are quite common for tank gauging and in the process industry and their star is rising in wave measurement. . They have excellent specifications, maintenance costs are low and they are easy to install. However the sea surface in wind force twelve differs from a liquid surface in a storage tank. The WaveGuide is based on one of those industrial radar gauges. During the winter of 2003/2004 the WaveGuide extensive measurements have been done at "Meetpost Noorwijk", the research facility of Rijkswaterstaat. Three WaveGuides and two Directional Waveriders were involved. In this report the differences in information from the two Directional Waveriders and the WaveGuide is discussed. Specially the aspect of data quality in difficult circumstances, like with spray or very smooth surfaces, is discussed. It is found that with respect to the wave parameters the WaveGuide and the Directional Waveriders perform equally well. Also it is found that during the 3 months period in all the occurred weather conditions no data had to be disapproved for longer than one second.

Introduction

Down-looking FMCW radars for wave measurements are in use already for 25 years. They have proved to be very robust and maintenance is hardly needed. Now the prices of FMCW radars came down they are being more widely applied for water level, tide, harbour oscillations and wave height at sea, lakes and rivers.

Radacs WaveGuide was introduced in 1998 based upon a commercial tank radar, first Enrafs Smartradar 873 and since 2000 with Smartradar 973. Enrafs Smartradar is designed for tank storage measurements and therefore approved by the authorities for weight and measures up to an accuracy of 1mm. So the instrument itself is very stable and accurate. However the sea surface in wind force 12 differs from a liquid surface in a storage tank. In this report the quality of WaveGuide information is described for sea states from twenty centimetres up to six metres.

In describing the quality of a wave sensor we have to realise that the sea is chaotic and its conditions are constantly changing. Even with very good instruments we will obtain different information if we are not measuring at exactly the same position and time.

WaveGuide information is extracted from the signal reflected by the water surface. Therefore the quality of information could depend on the conditions of the water surface. This raises questions about the quality of the information as function of the sea conditions. In this paper we will discuss the following questions:

- How do the wave height parameters derived with the WaveGuide compare with those derived with buoys in different sea states? The Directional Waverider is the de facto standard for wave measurements.
- Is data from bad quality or even lost in certain sea conditions e.g. due to spray or steep slopes?
- If data is being lost, does that happen in large sequences? Individual errors are mostly no problem for the processing but gaps longer than 1 or 2 seconds will cause problems.

During the winter of 2003/2004 an extensive measuring experiment was done at the Measuring Platform Noorwijk, the research facility of Rijkswaterstaat In this experiment very detailed information is being collected from three WaveGuides and two Directional Waveriders. This data is used for this study and will also be used for the development of new versions of the WaveGuide e.g. for the development of other processing schemes eg. for measuring high frequency waves or for wave direction.

Field experiment at Research Platform Noordwijk:

Research Platform Noordwijk is located 10 km offshore the Dutch coast in a water depth of ca 17m. At the suspension deck (15 m above mean sea level) three WaveGuides (973) were installed and in operation from 30th October 2003 till the summer of 2004. At distances of 500 and 1000m from the platform two directional waveriders were deployed (a 90cm and a 70cm version). Wind speed, wind direction, air pressure, air temperature and water temperature measured routinely at the platform are archived.

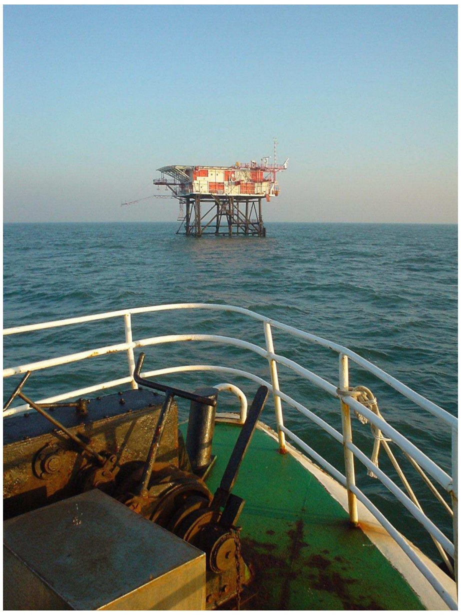

Fig. 1: Research platform Noordwijk.

Fig. 2: The suspension deck with the three WaveGuides

The WaveGuides were modified in a way that the raw beat signal itself (the mix of the transmitted and reflected signal) could be obtained and archived. From each individual measurement (50 ms duration) 1024 samples are taken of this beat signal.

The transmit signal consist of a 25ms upsweep (increasing frequency) and a 25ms downsweep (decreasing frequency). The interval between two measurements is 100 ms. The data were sent as network messages (udp) to two computers that store the data on their hard disks. Via the network connection to the platform the data could be examined on line during the experiment. Processing of the enormous amount of data (1,6 Gbyte/day/radar) had to wait until the computers returned in the office.

Fig. 3: The two Directional WaveGuides at 500 and 1000m distance.

Processing

The aim of this report is to compare the wave height information from the current WaveGuides and two Directional Waveriders. Therefore the raw samples were processed in the following way. The 1024 samples of the raw beat signal were split in 512 upsweep samples and 512 downsweep samples. Both parts were Fourier transformed (see Fig. 4). The low frequency part is due to internal reflections in the antenna. The first peak is from the water surface, the second and the third peak are from the signal bouncing between the water surface and the underside of the platform. The highest peak gives the distance to the water surface. By fitting a transfer function to the spectral points the exact peak position could be determined for both the upsweep and the downsweep spectrum. Due to the vertical velocity of the watersurface both peaks could be Doppler shifted. By averaging the peak positions this Doppler shift was eliminated. In this way time series of peak positions and signal strength for both the upsweep and the down sweep are obtained at a 10Hz rate.

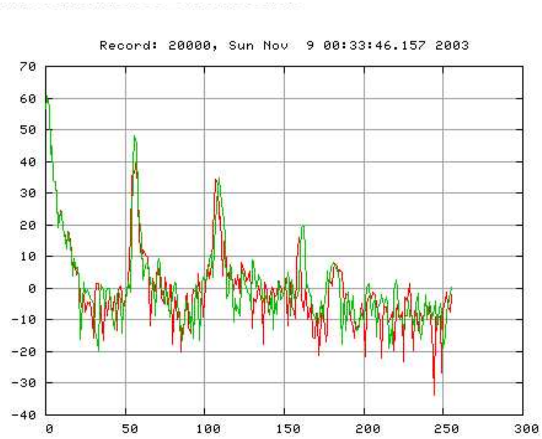

Fig. 4: The two reflection diagrams from the upsweep and downsweep beat signals of a single 50ms measurement.

These 10Hz sequences were used to investigate the quality of the individual measurements.
The standard wave processing program (SWAP) of Rijkswaterstaat is used to calculate the wave parameters from the WaveGuide and the two Directional Waveriders. This program needs a 2.56Hz sampling rate. This is derived by taking the nearest neighbour out of the 10Hz series. SWAP processes each 10 minutes a 20 minutes timehistory to energy density spectra and wave parameters. These data sets formed the basis for the intercomparison of WaveGuide and Directional Waveriders.

Conditions

Figure 5 indicates that waveheights from 25 cm to almost 600 cm occurred during the trial period.

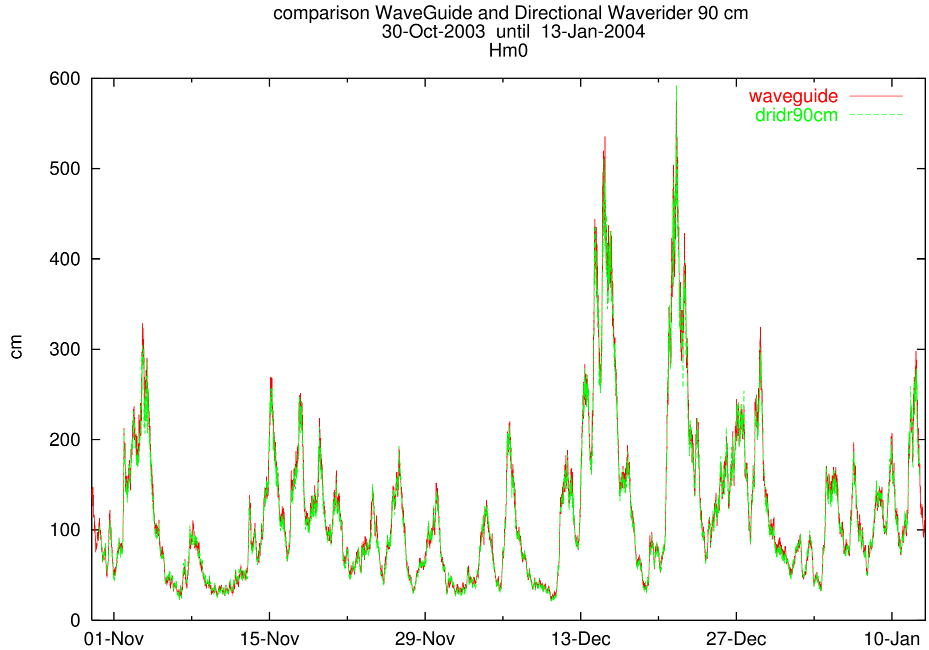

Fig. 5: The mean waveheight during the experiment.

How do the wave height parameters derived with the WaveGuide compare with those derived with buoys in different sea states?

In a random sea you never will obtain the same values for the same parameter measured at the same time by different instruments. Are these differences consistent with sampling variability, or are there significant deviations between the instruments?
A first step in data comparison is to produce per parameter timeseries and scatterplots, fit regression lines and calculate some statistics like bias, correlation coefficient. By these it is difficult to judge whether sensors differ from each other or not. For the parameters derived from the energy density spectra the variance of a parameter due to the randomness of the sea can be derived (see, e.g. Krogstad, 1999). As long as the parameters of the different sensors are within these confidence bands the conclusion can be drawn that the instruments do agree with each other.
We examined the following sea state parameters :.

HmO	Signicant waveheight	$4\sqrt{m0}$	f= 0 – 500 mHz
HTE1	Signicant waveheight	$4\sqrt{m0}$	f= 0 – 100 mHz
HTE2	Signicant waveheight	$4\sqrt{m0}$	f= 100 – 200 mHz
HTE3	Signicant waveheight	$4\sqrt{m0}$	f= 200 – 500 mHz
Tm02	Mean zero-crossing period	$\sqrt{m0/m2}$	f= 0 – 500 mHz

The waveheight parameters were classified in three classes, low, normal and heigh energy. The definitions of these classes are given within the result tables.
By this we examine the overall, low, middle and high frequency behaviour of the sensors in several waveheight conditions.

Hm0
Wave height in the overall frequency band 30-500 mHz.

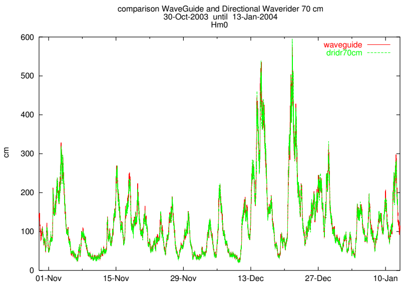

Fig. 6: The waveheight in the overall frequency band Hm0 (30-500mHz)

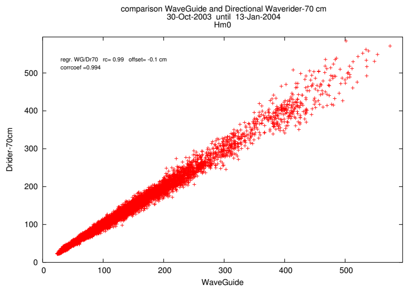

Fig. 7: scatter plot of WG and 70cm buoy.

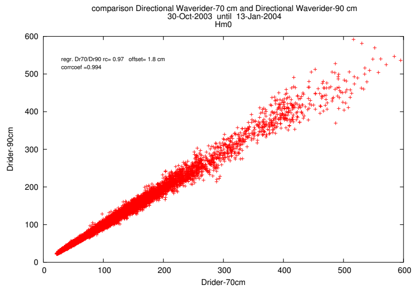

Fig. 8: scatter plot of the two buoys.

Compared to 70 cm buoy						
	WG	*90cm*	*theory*	*WG*	*90cm*	*theory*
Gradient of fit	0,99	0,97				
Offset of fit	-0.1 cm	1.8 cm				
Corr. Coeff.	0,99	0,99				
	Mean %			***Variance %***		
all	1,15	-0,74	0	6,2	5,49	8
0-50 cm	2,52	1,22	0	6,62	5,41	8
50–250 cm	0,92	-1,1	0	6,02	5,25	8
> 250 cm	-0,01	-2,23	0	6,35	6,77	8

HTE1

Waveheight in the heigh frequency band 200-500 mHz

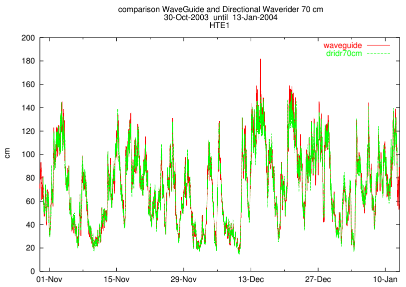

Fig. 11: Waveheight in de high frequency band HTE1(200-500mHz)..

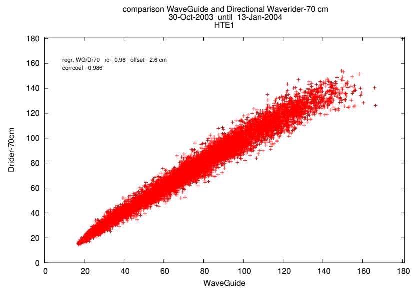

Fig. 10: scatterplot of WG and 70cm buoy.

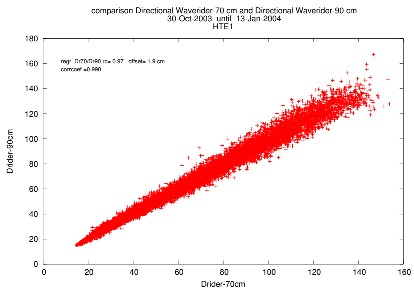

Fig. 9: scatterplot of the two buoys.

Compared to 70 cm buoy						
	WG	*90cm*	*theory*	*WG*	*90cm*	*theory*
Gradient of fit	0,96	0,97				
Offset of fit	2.6 cm	1.9 cm				
Corr. Coeff.	0,99	0,99				
		Mean %			***Variance %***	
all	0,38	-0.02	0	7,13	5,84	10
0-50 cm	0,66	1,82	0	8,02	6,15	10
50–100 cm	-0,15	-0,38	0	6,8	5,53	10
> 100 cm	1,23	-1,59	0	6,54	5,5	10

HTE2

Waveheight in the middle frequency band 100-200 mHz

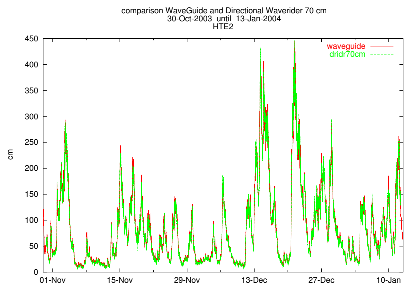

Fig. 12: Waveheight in the mid frequency band HTE2 (100 -200mHz).

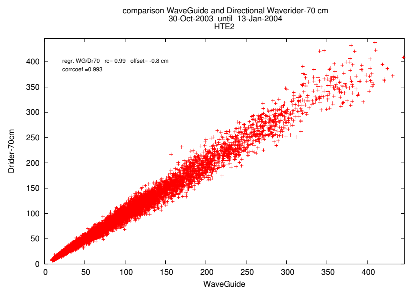

Fig. 13: scatterplot of WG and 70cm buoy.

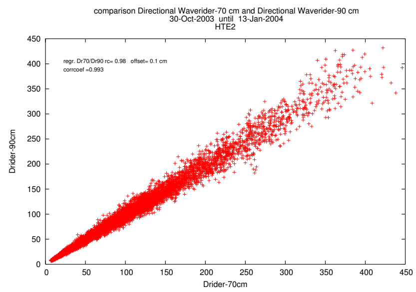

Fig. 14: scatterplot of the two buoys.

Compared to 70 cm buoy						
	WG	*90cm*	*theory*	*WG*	*90cm*	*theory*
Gradient of fit	0,99	0,98				
Offset of fit	-0.8 cm	0.1 cm				
Corr. Coeff.	0,99	0,99				
		Mean %			***Variance %***	
all	4,62	-1,72		10,16	8,05	12
0-50 cm	8,07	-1,8		10,78	7,94	12
50–250 cm	1,97	-1,64		8,75	8,11	12
> 250 cm	0,36	-1,8		7,67	8,31	12

HTE3

Waveheight in the low frequency band 30-100 mHz.

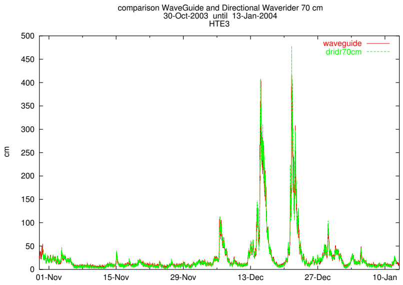

Fig. 15: Waveheight in the low frequency band HTE3 (30-100mHz)

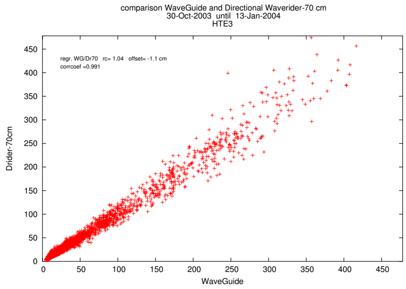

Fig. 16: scatterplot of WG and 70cm buoy.

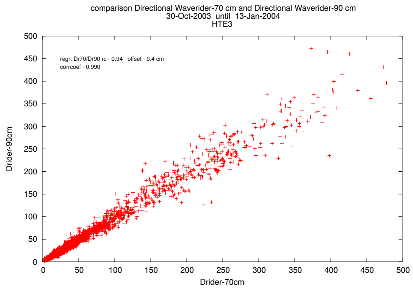

Fig. 17: scatterplot of the two buoys.

Compared to 70 cm buoy						
	WG	*90cm*	*theory*	*WG*	*90cm*	*theory*
Gradient of fit	1,04	0,94				
Offset of fit	-1.1 cm	0.4 cm				
Corr. Coeff.	0,99	0,99				
		Mean %			***Variance %***	
all	9,62	-3,21	0	20,25	12,31	14
0-20 cm	14,25	-2,95	0	20,99	12,48	14
20–100 cm	-1,33	-3,92	0	12,96	11,73	14
> 100 cm	-2,65	-3,41	0	11,03	12,52	14

Tm02

Waveperiod derived from the second en zero order moments.

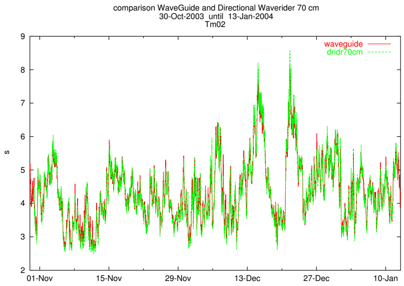

Fig. 18: wave period Tm02

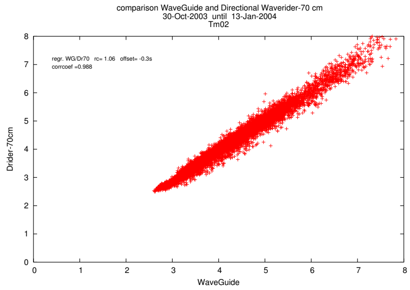

Fig. 19: scatterplot of WG and 70 cm buoy.

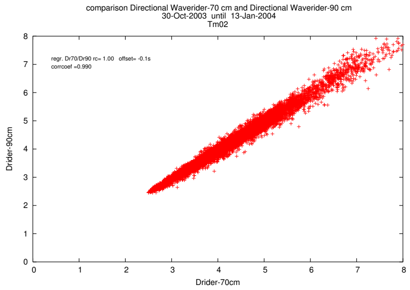

Fig. 20: scatterplot of the two buoys.

Compared to 70 cm buoy						
	WG	*90cm*	*theory*	*WG*	*90cm*	*theory*
Gradient of fit	1,06	1				
Offset of fit	-0.3 s	-0.15 s				
Corr. Coeff.	0,99	0,99				
		Mean %			***Variance %***	
all	2,87	1,57	0	4,56	3,05	6
0-20 cm						
20–100 cm						
> 100 cm						

Quality of individual measurements

The basic principle of a FMCW radar to measure distances is travel time measurement. The travel time is determined by the frequency difference between the transmitted signal and the signal reflected from the water surface. Therefore the transmi signal has to increase or decrease in frequency in a linear way.
The basis of processing is simple. The sampled beat signal (the low passed mix of transmit and receive signal) is fourier transformed and in the so calculated spectrum the position of the peak is determined. Figure21 gives an example of a typical beat signal spectrum (also called reflection diagram).

Fig. 21: The two reflection diagrams from the upsweep and downsweep beat signals of a single 50ms measurement.

This does not mean that there are no problems. The nature has some pitfalls in reserve and the processing has to cope with it.
First the stochastic character of the reflections on the sometimes very chaotic water surface causes very large fluctuations in the signal strength.
Secondly spurious peaks occur in the reflection diagram. They can come from from all kind off sources e.g. the multiple reflections between water surface and radar and reflections from objects within the side lobs of the radar beam. These results in more peaks in the refection diagram sometimes stronger than the one from the first reflection on the water surface.

In the reflection on the water surface two mechanisms dominate (de Loor 1982). First the specular refection where the water surface acts as a mirror. Secondly the diffuse scattering caused by the roughness of the water surface. Within an angle of 20 degrees the specular reflection is ca 10dB stronger than the diffuse scattering. For larger angles of inclination the diffuse scattering is dominant. Although the total opening angle of the antenna's main lobe is ca. 10 degrees, all kind off reflections can contribute to the reflection diagram.

For the quality of the information it is relevant to know when and how often situations occur where the data has to be disapproved. The following questions are being answered :

1. The most noticeable effect is the double reflection between radar and water surface. How often do they occur and are there special conditions where they occur more often ?
2. Weak reflections. How often they occur and do they occur in sequences due to slopes?
3. Noisy data. Do the large fluctuations in the signal strength cause uncertain measurements?

To answer these questions the whole dataset of 106 days with 10 measurements per second is split in 10 minutes blocks. Per block the following processing was performed;

- statistics of the measured distances (mean, standard deviation , number of measurements outside five times the standard deviation band).
- Statistics of the change in distance (mean, standard deviation, number of measurements outside the five times the standard deviation band).
- Statistics of the signal strength (mean, standard deviation, minimum, maximum and number of measurement with a signal strength below 25dB)

- Distribution of time intervals where the multiple reflection is stronger than the primary reflection. First the measurements where the multiple reflection is stronger than the primary reflection are marked. From this the number of consecutive occurrences are counted for sequences of 1,2,.. up to 10. So intervals from 0,1 up to 1 ms. Longer time intervals didn't occur at all.
- Distribution of time intervals where the results are maybe uncertain defined by the delta test. If the difference between two measurements is larger than five times the standard deviation of the differences this measurement is marked. From this the number of consecutive occurrences are counted for sequences of 1,2,.. up to 10. So intervals from 0,1 up to 1 ms. Longer time intervals didn't occur at all
- Distribution of time intervals where the signal strength is low. These are defined by an amplitude of the peak in the reflection diagram smaller than 25dB.

Results from the statistics.

Multiple reflections:

Already from the beginning of applying the FMCW radar for wave measurements it is noticed that the signal can bounce between the watersurface and antenna or bottomside of the platform. Sometimes can a multiple reflections be stronger than the first reflection. Figure .. gives their number in the 10 minutes blocks.

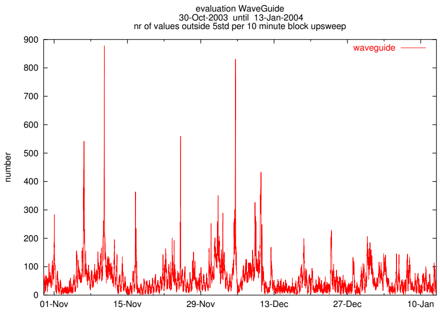

Fig. 22: number of spikes due to multiple reflections per 10 minutes block.

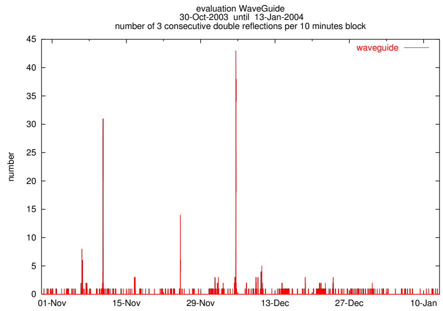

Fig. 23: Number of occurences of 0.3 s sequences of spikes per 10 minutes block.

In total they occur in ca 1% of the measurements with extremes of 14% in a 10 minutes period. They occur more often in lower seastates. From the analysis if the occur in longer time intervals it appears that 1% of them they occur in sequences of two (0,2 s). Only 82 intervals of 0,5s occurred in the total period. A sequence of 1s occurred ones.

Noisy data

Beside the effect of multiple reflection spikes in the data could occur by several reasons. The delta check gives the occurrences of these. Sequences longer than 0,2 s did not occur at all.

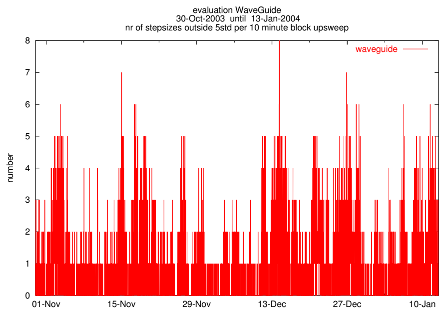

Fig. 24: number of individual spikes due to noise per 10 minutes block.

Signal strength

Weak reflections can cause erroneous data. Especially at steep slopes this is expected. If to large sequences occur this can result in disapproving the whole measuring period. Figures .... gives the mean , minimum and maximum values per 10 minutes block.

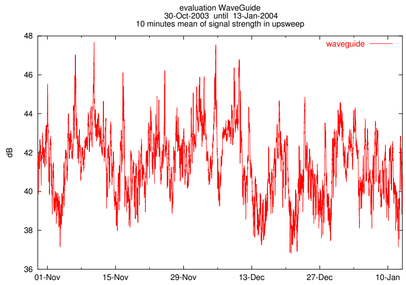

Fig. 25: mean signal strength per 10 minutes block.

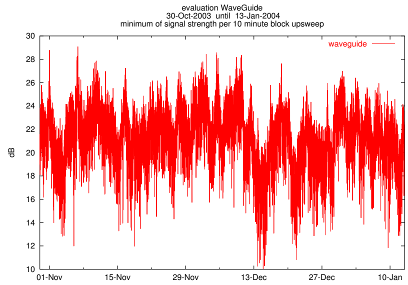

Fig. 26: minimum signal strength per 10 minutes block.

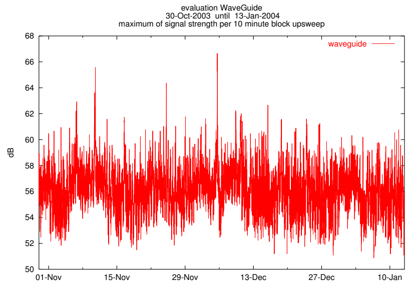

Fig. 27: Maximum signal strength per 10 minutes block.

Figures give insight in the possibility of sequences of weak signals. There the measurements with a signal strength lower than 25dB are marked. Later we will see that even at the period with lowest signal strength the results look very reliable.

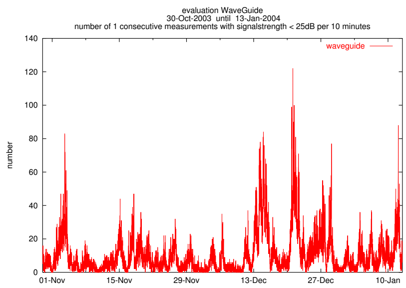

Fig. 28: number of individual measurements with a signal strength below 25db per 10 minutes block.

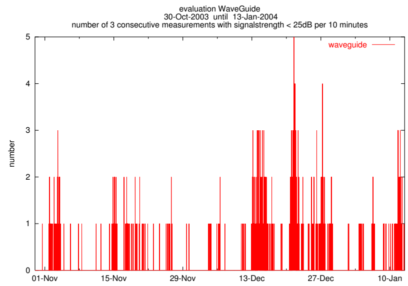

Fig. 29: number of occurrences of sequences of 0.3 s with a signal strength below 25dB per 10 minutes block.

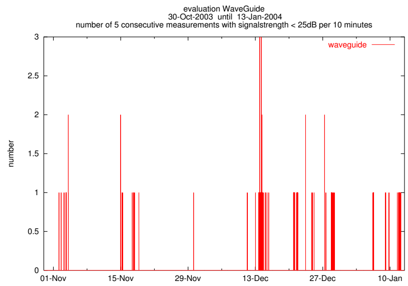

Fig. 30: number of occurences of sequences of 0.5 s with a signal strength below 25dB per 10 minutes block.

Conclusions

In the three months trial at research facility “Noordwijk” 10km offshore the Dutch coast a wide range of weather conditions occurred. In this conditions it is found that with respect to the wave parameters the waveguide and the Directional Waveriders perform equally well.
Also it is found that in all these weather conditions spray or smooth water surface no data had to be disapproved for longer than one second. These small gaps are no problem in wave processing.