Measuring Programme Amelander Zeegat Storm Season 2003-2004

Measurement report on two northwesterly storms

RIKZ/OS/2004.129w

Measuring programme Amelander Zeegat Storm Season 2003-2004

Measurement report on two northwesterly storms

Colofon

Publisher: The Netherlands National Institute for Coastal and Marine Management *RIKZ*

Information:
Telephone: +31.(0)70.3114452
Fax: +31.(0)70.3114200

Author: Dennis Hordijk

Work document: RIKZ /OS/2004.129w
Status: Final report

Date: October 2004

Table of Contents

1 Introduction

1.1 Background

Primary water defences protect the Netherlands against flooding by the North Sea, the major rivers and inland seas *Markermeer* and *IJsselmeer*. The Dutch Water Defence Act [*Wet op de Waterkering*] stipulates that these water defences have to be tested every five years to determine if they guarantee the statutory safety level with respect to the applicable Hydraulic Boundary Conditions, which lay down normative water levels and waves.

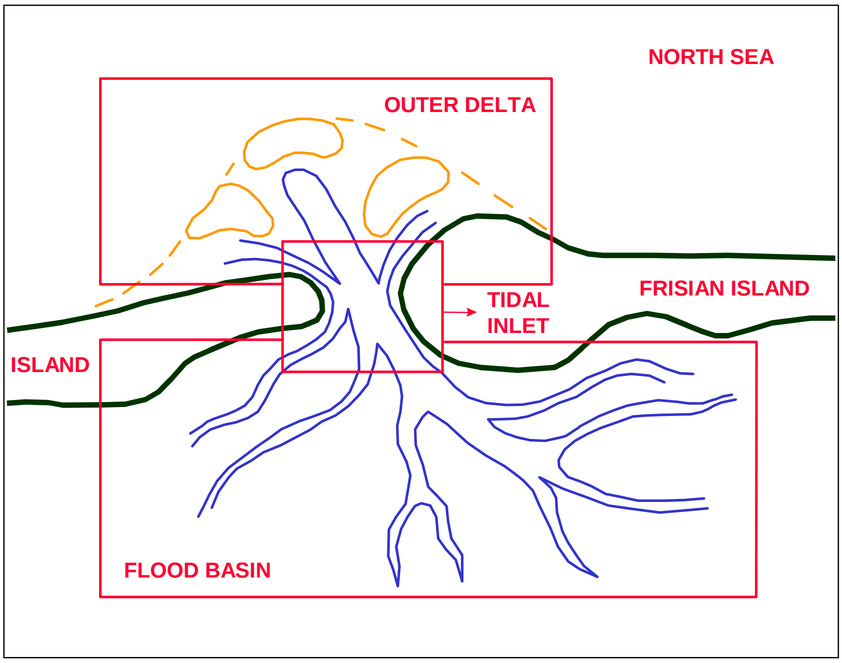
The normative wave conditions required for this testing are defined on the basis of wave measurements which have been carried out at five permanent stations in deep water over the past 25 years. Numerical wave model SWAN then translates deep water wave conditions into wave conditions applying to nearshore shallow water.

The definition of reliable wave boundary conditions obviously requires a reliable wave model, and verification of current wave modelling necessitates nearshore measurements

1.2 Wave measurements in a tidal inlet system

Wave measurements are carried out at various stations off the straight Dutch coastline near Petten and off Zeeland estuaries West Scheldt and East Scheldt, but as yet there are no relevant nearshore data available of the Wadden Sea. There are signs that waves penetrating from the North Sea via tidal inlet *Amelander Zeegat* (see figure 1.1) into the Wadden Sea, strongly affect the local wave pattern in the Wadden Sea if water levels are high, e.g. in the case of a storm surge. Measurements in a tidal inlet system during storms are therefore essential for understanding wave propagation into the Wadden Sea and for testing the reliability of present wave modelling. To this purpose, a measuring programme with directional waveriders was started at Amelander Zeegat at the end of 2003.

Figure 1.1 Diagram of the tidal inlet system



1.3 Objective

The objective of the measuring programme in tidal inlet Amelander Zeegat is to monitor wave propagation from the relatively deep North Sea via the tidal inlet into the Wadden Sea during storm conditions. The programme concentrates on penetration of long, northwesterly waves with periods of approx. 10 to 15 seconds, which can severely affect wave run-up and overtopping when penetrating up to the water defences along the Wadden Sea.

1.4 Storms measured

As a shallow outer delta shields the Amelander Zeegat, the degree of wave penetration strongly depends on the concurrent water levels: If water levels are high, there will be less wave breaking and consequently less energy dissipation at the outer delta than if water levels are low. Any North Sea wave penetration is therefore mainly expected to occur at higher water levels. A considerable water level increase at the Wadden Sea occurs in the case of spring tide combined with a long period of strong northerly to northwesterly wind. In these wind conditions, the increased fetch is furthermore expected to produce higher waves and longer wave periods. It is therefore essential to carry out measurements during northwesterly storms, to gain an understanding of the way in which North Sea waves affect the local wave pattern.

During the measuring period, which ran from 1 December 2003 to 30 April 2004, two northwesterly storms occurred which caused considerable increases in water levels. They were:
- 20-22 December 2003
- 7-9 February 2004

This measuring report discusses both storm periods.

1.5 Organisation

The measuring programme in Amelander Zeegat is part of the broad *Rijks-waterstaat* Project "Strength of and Stress on Water Defences" [*Sterkte en Belasting Waterkeringen – SBW*]. Being the leader of subproject Field Measurements [*SBW-Veldmetingen*], the *RIKZ* functions as the party commissioning the wave measurements. Realisation, management, maintenance and data handling – i.e. data collection, processing and storage – of the Amelander Zeegat measuring programme are in the hands of the *Rijkswaterstaat* directorates North Sea (*DNZ*) and North Netherlands (*DNN*). The latter is also responsible for the coordination of these activities.

1.6 Report outline

Chapter 2 briefly describes the field site, and discusses station set-ups as well as data handling – i.e. data collection, processing and storage – and data applicability. Chapters 3 and 4 then discuss storm periods 20-22 December 2003 and 7-9 February 2004 respectively, in particular wind, water levels and wave conditions. Chapter 5 provides the report's conclusion.

2 Field Site Set-up

2.1 Stations and equipment

At the end of 2003, directional waveriders were placed at several stations along this stretch to enable monitoring of wave propagation from the North Sea via the tidal inlet into the Wadden Sea in storm conditions:

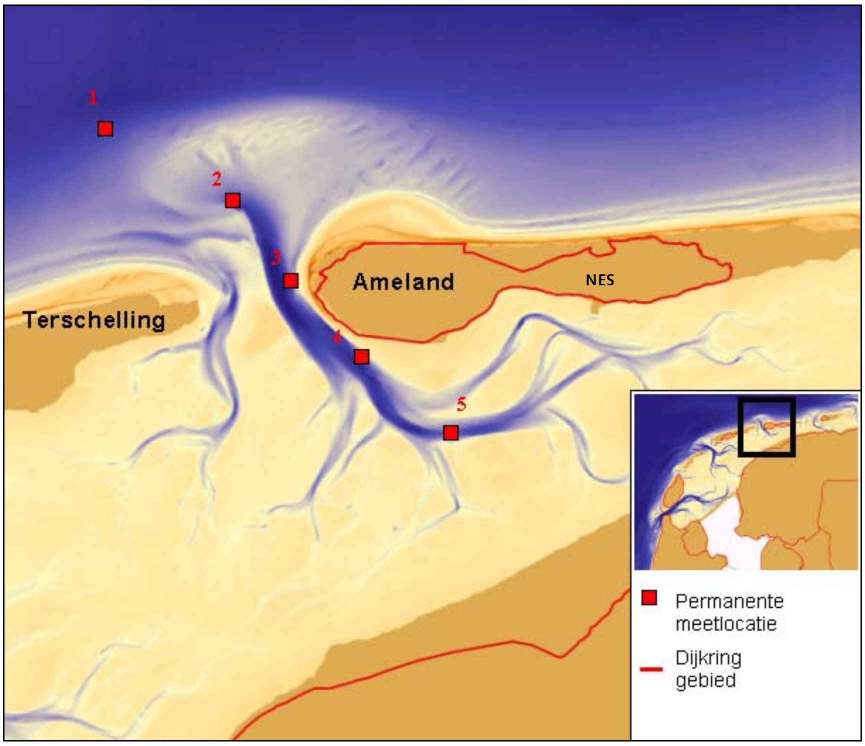
- Station 1 on the North Sea
- Station 2 on the Wadden Sea side of the outer delta
- Station 3 in the inlet throat, near the head of Ameland Island
- Stations 4 en 5 in the Wadden Sea flood basin

Figure 2.1 illustrates these stations. Factors included in selecting the stations, were mainly environmental restrictions – e.g. exclusion zones, shipping ways, suppletion activities and ship wrecks – and technical/equipment restrictions – e.g. sea bed slope with respect to anchorage and water depth.

Figure 2.1 Amelander Zeegat stations 2003-2004 (Bathymetry 1999)

Directional wave riders

Dike ring



Measurements at station 1 are essential for defining the boundary conditions to be used for model calculations. This station therefore also includes a back-up waverider to reduce the risk of data gaps, for example due to waverider failure at this station. The exact waverider locations and depths are listed in table 2.1 below.

Table 2.1 Amelander Zeegat stations 2003-2004

Station	Waverider Code	RD Coordinates [metres]		Depth [metres to Dutch reference level *NAP*]
		x	y	
1	AZB11	161,250	613,500	-19
	AZB12	161,450	613,500	-19
2	AZB21	167,400	610,140	-12
3	AZB31	169,380	607,200	-9
4	AZB41	171,930	603,900	-16
5	AZB51	175,700	600,760	-9

2.2 Data handling

The waverider signals are collected via the Ameland lighthouse. The light-house transfers the signals to a data collection station at Ferwerd, where the data are processed and stored by means of the RMI applications of the North Sea Measuring System. RMI processing is based on SWAP (Standard Wave Analysis Package), an analysis module which *Rijkswaterstaat* applies standard for processing wave sensor data [Hoekstra, 1994]. The first step in this analysis is automatic data checking for spikes and stagnations, followed by wave parameter and spectra calculations. The data are not only stored in the operational database of the North Sea Measuring System, but also in a duplicate database and in DONAR, the latter being the *Rijkswaterstaat* database for long-term data storage. *DNZ* then gives the data a visual check for mutual consistency before – seven days after collection – they are introduced into DONAR. Please refer to Appendix A for monthly diagrams of data availability in the databases.

A CD-ROM is enclosed, containing the spectra and parameters calculated for storm periods 20-22 December 2003 and 7-9 February 2004.

2.3 Data applicability

Directional waveriders generally collect data at a standard data collection frequency of 1.28 hertz, and so do the waveriders at Amelander Zeegat. Recent research into the effect of the data collection frequency onto wave parameter reliability has shown that this frequency is rather low for the Wadden Sea [Roskam, 2004]. The advice is therefore to apply waveriders with a data collection frequency of 2.56 hertz. Considering the fact that short waves generated locally at the Wadden Sea constitute a major part of the spectrum, a spectrum maximum of 1.0 hertz is recommended.

As a data collection frequency of 1.28 hertz and a spectrum maximum of 0.5 hertz were applied at Amelander Zeegat over the past storm season, a possibly considerable quantity of energy is not included in the spectra calculated. Depending on the station, the spectral wave parameters calculated are less reliable. An estimate of the maximum error rate with respect to storm conditions with minimum wave heights of 0.5 metre near stations 4 and 5, are listed in Table 2.2. Please note that the relative error rate will increase as the wave height decreases. In view of the objective of the measuring programme, this aspect is less relevant. It is clear that the error rate is more extensive for parameters which are sensitive to the high frequency part of the spectrum, such as period T_{m02}.

Table 2.2 Maximum error rate of calculated wave parameters due to low data collection frequency

Station	Estimated maximum error rate of wave parameters		
	H_{m0}	T_{m-10}	T_{m02}
1	Reliable	Reliable	Reliable
2	-5%	+5%	Unreliable
3	-5%	+5%	Unreliable
4	-30%	Unreliable	Unreliable
5	-30%	Unreliable	Unreliable

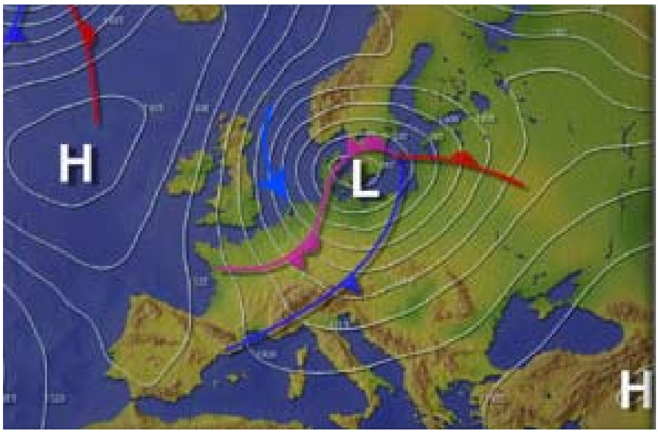
Based on the findings from the study into data collection frequencies, the conclusion was drawn that the measurements at station 1 during storms are reliable, and those for stations 2 and 3 reasonably reliable. As waves of < 2 seconds generated locally near stations 4 and 5 constitute a major part of the wave spectrum, the data collected at these stations at 1.28 hertz are likely to be less reliable. The data may nevertheless be applied to form a qualitative picture of North Sea wave penetration, although the data are less useful for a quantitative analysis of spectral wave parameters. The error rate of time domain parameters is considerably higher than those of the spectral wave parameters, so that it is recommended not to use the former.

3 Storm Period 20-22 December 2003

3.1 General

The first storm period which included a considerable increase in water levels, was from 20 to 22 December 2003. On 21 December a very active low pressure area travelled across the North Sea towards Denmark and caused gale force winds (see figure 3.1). During this period, save data were collected at stations 1, 2, 3, and 4. No measurements from station 5 are available, because its waverider was out of order from 17 to 31 December (see Appendix A).

Figure 3.1 Weather map



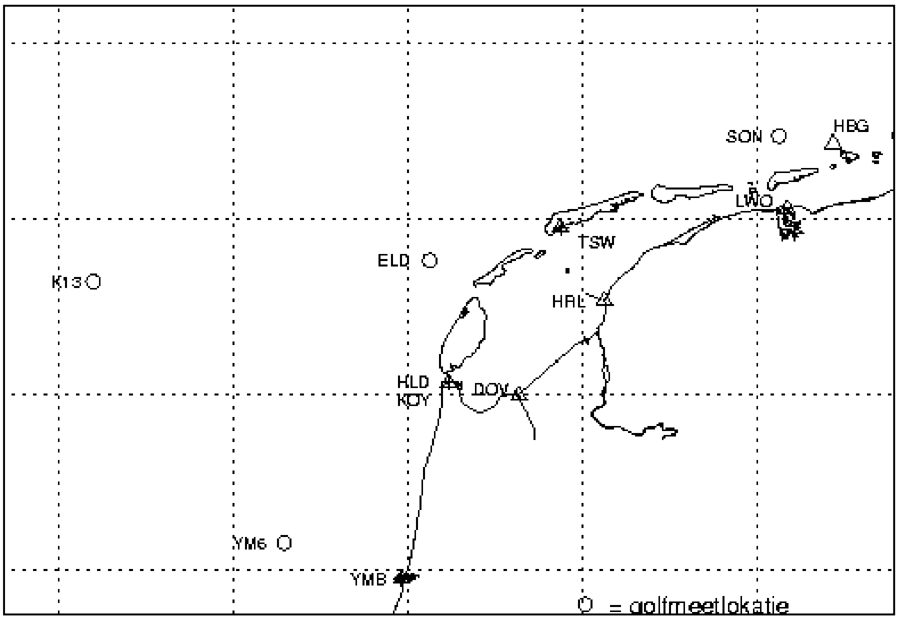
From: Royal Dutch Meteorological Institute KNMI

3.2 Wind measurements

Figure 3.3 below shows the wind conditions for the period of 20 to 22 December 2003, in particular the hour mean wind speeds and wind directions measured at station K13 – no other wind measurements in the immediate surroundings of Amelander Zeegat are available. This station is located at the North Sea, west of the Wadden Sea (see figure 3.2). Figure 3.3 shows that the wind veers from south to west in the second half of 20 December, and that it veers further to the northwest and north on 21 December. The maximum wind speed is in excess of 20 metres per second.

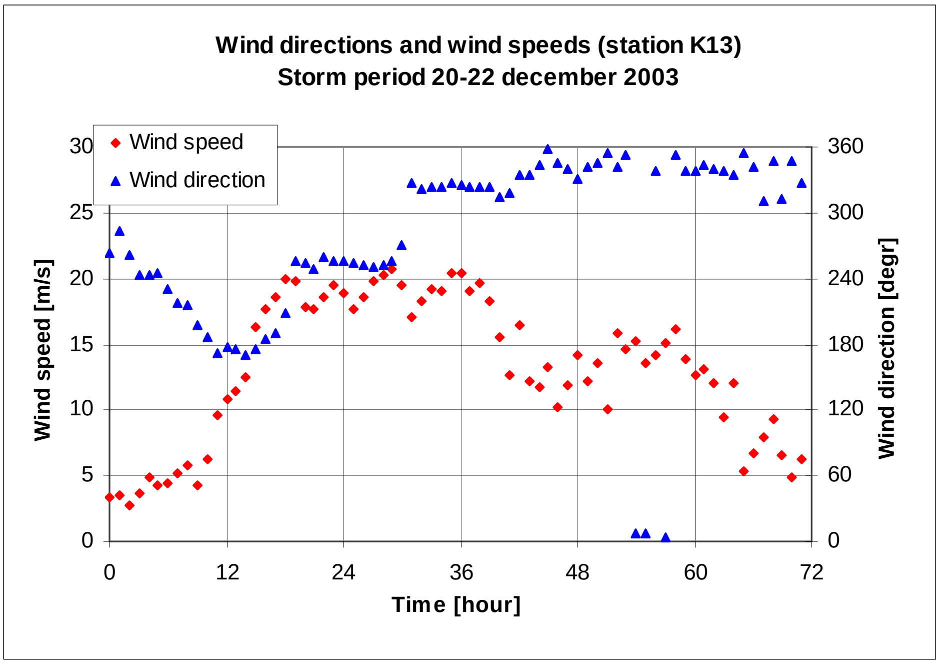
Figure 3.2 Map with stations referred to

o Wave measurement station



Note: Station Lauwersoog, as referred to in paragraph 4.2, is identified by' LW'.

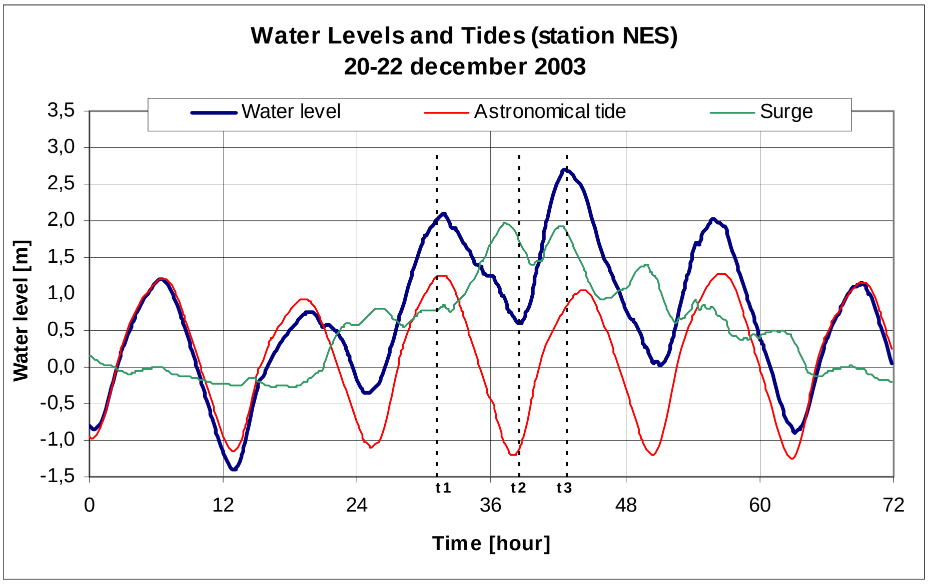
Figure 3.3 Wind speeds and wind directions at station K13



3.3 Water level measurements

Figure 3.4 gives the astronomical tides, water levels and wind set-ups measured at station NES, which is located at the Wadden Sea side of Ameland Island (see figure 2.1). It clearly shows that during the storm period the wind set-up gradually increases to a maximum of nearly two metres. The water level reaches its maximum level during the second high tide on 21 December, when it amounts *NAP* +2.67 metres.

Figure 3.4 Water levels, tides and set-ups at station NES



3.4 Wave measurements

For processing these measurements, wave density spectra and wave parameters were calculated over 20-minute blocks shifting every 10 minutes. This means that every block overlaps the preceding block by 10 minutes. The paragraphs below present a number of data.

3.4.1 Energy density spectra

Appendices B.1 to B.3 give the energy density spectra calculated for waveriders AZB11, AZB21, AZB31 and AZB41 at three points in time on 21 December, i.e. t1, t2 and t3 in figure 3.4. These points in time were selected on the basis of the water levels measured at NES:

- The first point in time is 07.00 hours, which is the time of the first increased high tide, measuring *NAP* +2.00 metres.
- The second point in time is 14.20 hours, when the following low tide concurs with the peak of the storm (*NAP* +0.50 metres).
- The third point in time is 18:40 hours, when the water level reaches its maximum of *NAP* +2.67 metres briefly after the peak of the storm.

Point in time 1 – first increased high tide:
Appendix B.1 shows that at this point in time, the sharp low frequency peak of the spectrum lies at 0.12 hertz, which corresponds with a peak period of well over 8 seconds. Wave breaking at the shallow outer delta of Amelander Zeegat, i.e. at approx. *NAP* -4 metres, results in major energy dissipation, which shows as a sharp drop in wave energy between two outer stations AZB11 and AZB21. In the area between second and third stations AZB21 and AZB31, the quantity of low frequency energy further drops, but at the third station a remainder of low frequency energy is measured. This remainder dissipates virtually entirely between third and fourth stations AZB31 and AZB41.

Hypothesis:
The hypothesis is that long waves at the tidal inlet refract towards the channel walls, after which they dissipate on the channel walls and the shallower areas behind the walls.

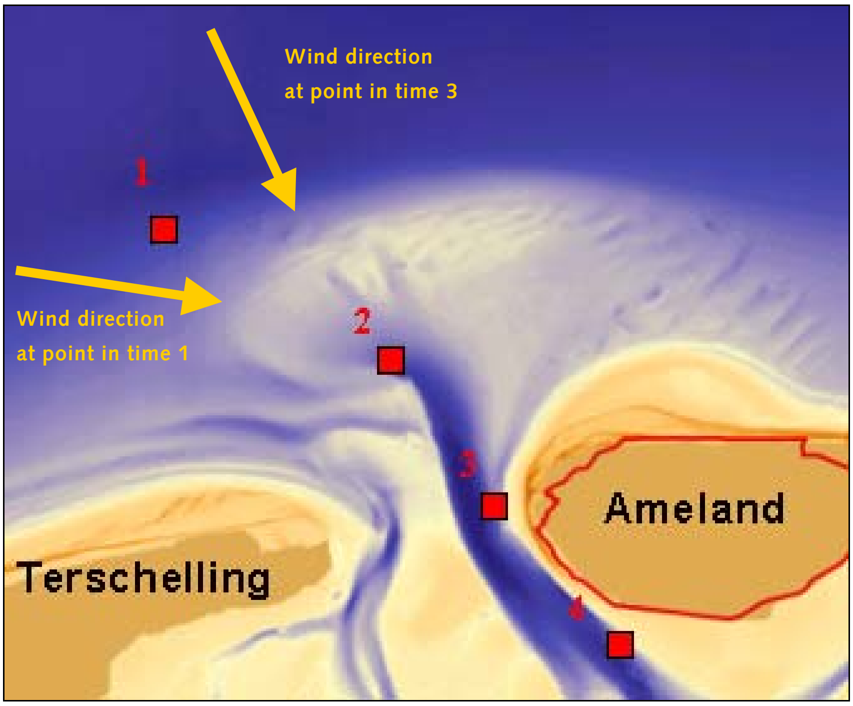
Point in time 2 – low tide:
Appendix B.2 illustrates that at this point in time, when the water level has dropped since the first point in time, the low frequency peak at first station AZB11 on the North Sea has shifted left in relation to the first point in time. The offshore peak period is then approx. 11 seconds. As a result of the low water level of *NAP* +0.5 metres, virtually all low frequency energy dissipates at the outer delta. This is clearly demonstrated by the spectra for the stations behind the outer delta, i.e. AZB21, AZB31 and AZB41. The spectrum for station 4, AZB41, contains a noticeable peak at 0.2 hertz.

Hypothesis:
The hypothesis is that this peak is caused by local generating and/or redistribution of wave energy.

Point in time 3 – second increased high tide:
At this point in time, the water level measures *NAP* +2.67 metres. Appendix B.3 shows that also at this water level most of the energy dissipates at the outer delta. In the area between second and third stations AZB21 and AZB31, the low frequency energy further dissipates. As appears from a comparison of the data at the first and third points in time (see Appendices B.1 and B.3), at the third point in time less wave energy penetrates both relatively and absolutely into the tidal inlet than at the first point in time, despite the slightly higher water level at the third point in time. The observation is made that the wind direction at the third point in time was more northerly than at the first point in time.

Hypothesis:
The hypothesis is that at this point in time the waves cross the shallower part or 'ebb shield' of the outer delta as a result of the veering wind, which causes an increase in wave breaking and consequently of energy dissipation (see figure 3.5).

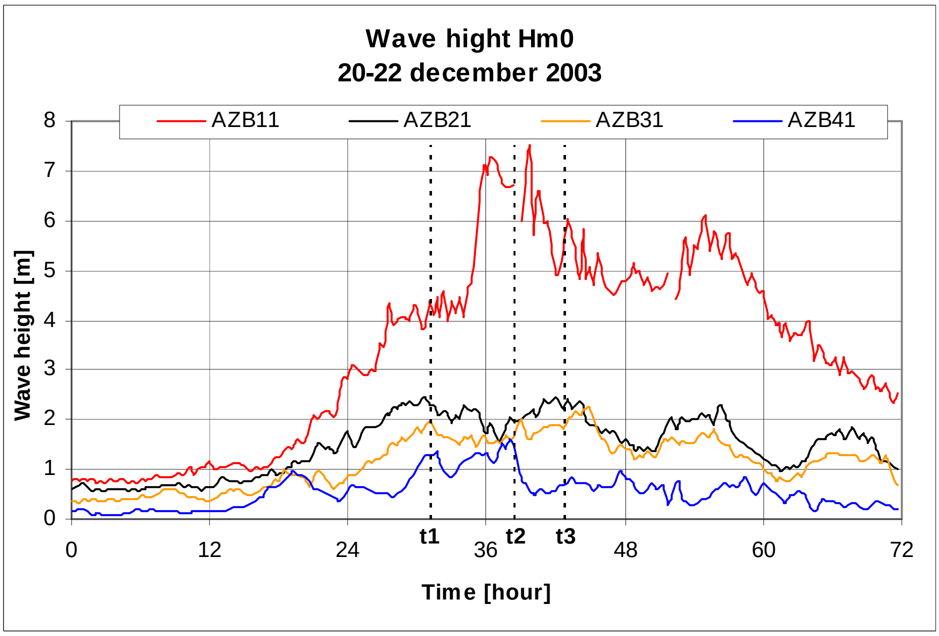
Figure 3.5 Wind directions at points in time 1 and 3 (Bathymetry 1999)

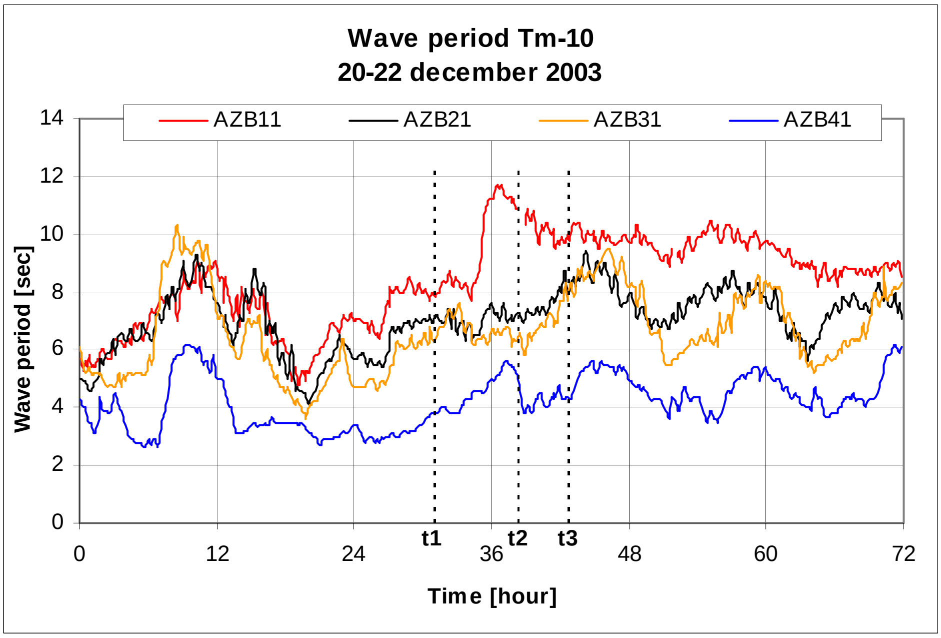


3.4.2 Wave parameters

As an illustration of the wave height and wave period variances during the storm period of 20 to 22 December 2003, figure 3.6 presents the curves of wave height H_{m0} and wave period T_{m-10} at the various stations. This figure shows that on 21 December, North Sea wave height H_{m0} at AZB11 increases over a short period of time from 4 to more than 7 metres, and that wave period T_{m-10} increases from 8 to 12 seconds. Wave breaking has a major adverse effect on the wave height at the shallow outer delta. Near stations 2 and 3, being AZB21 and AZB31, wave height H_{m0} reaches a maximum of 2 to 2.5 metres. The wave height curves for these stations also clearly show the high and low tides. Figure 3.6, finally, shows that the decreasing wave height along the measuring section combines with a decreasing wave period.

Figure 3.6 Wave height H_{m0} and wave period T_{m-10} curves



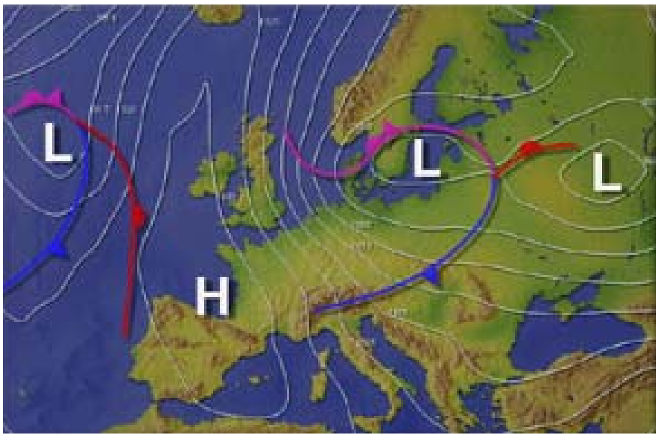


4 Storm Period 7-9 February 2004

4.1 General

The second storm period which included a considerable increase in water levels, occurred from 7 to 9 February 2004. A major difference in air pressure forming between a low pressure area travelling across the North Sea towards Denmark and a high pressure area quickly building up west of the British Isles, caused gale force winds (see figure 4.1). During this storm period, data were collected at all stations, this time also at station AZB51.

Figure 4.1 Weather map

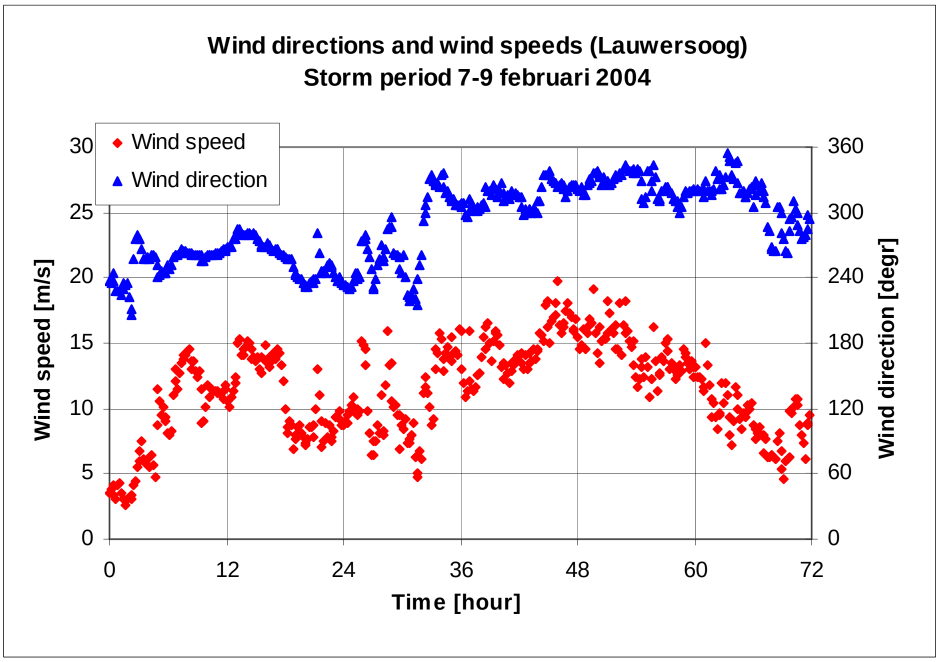


From: Royal Netherlands Meteorological Institute KNMI

4.2 Wind measurements

Figure 4.2 illustrates the wind conditions during the period of 7 to 9 February 2004, by means of the 10-minute mean wind speeds and wind directions measured at station Lauwersoog – please refer to figure 3.2 for the station's location. This figure furthermore shows that on 7 February the wind was westerly at wind speeds varying up to approx. 15 metres per second, which is equivalent to wind force 7. On 8 February the wind quickly veers to the northwest, while the wind speed at Lauwersoog increases to more the 18 metres per second, which is equivalent to wind force 8.

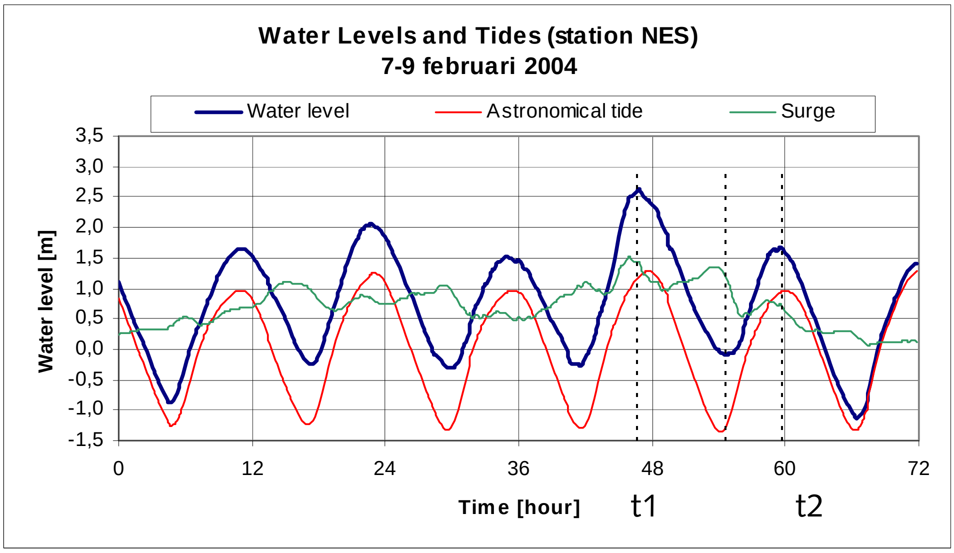
Figure 4.2 Wind speeds and wind directions at station Lauwersoog



4.3 Water level measurements

The astronomical tides, water levels and wind set-ups are given in figure 4.3 for station NES, which is located at the Wadden Sea side of Ameland Island. This figure clearly shows there was an increase in water level throughout the period of 7 to 9 February. The maximum water level occurs during the second high tide on 8 February, when it amounts *NAP* +2.57 metres.

Figure 4.3 Water levels, tides and set-ups at station NES



4.4 Wave measurements

As was described in chapter 3 on the earlier storm period, for the second storm period the energy density spectra and wave parameters were also calculated over 20-minute blocks shifting every 10 minutes. The paragraphs below present a number of data.

4.4.1 Energy density spectra

Appendices C.1 to C.3 give the energy density spectra calculated for three points in time, i.e. t1, t2 and t3, for waveriders AZB11, AZB21, AZB31, AZB41 and AZB51. The points in time were selected on the basis of the water levels measured at NES:

- The first point in time is 22.30 hours on 8 February, when the storm is at its peak and the high tide reaches its maximum level of *NAP* +2.57 metres.
- The second point in time is 06.30 hours on 9 February, when the only low tide during this storm period concurs with high North Sea waves of *NAP* –0.10 metre.
- The third point in time is 11.40 hours on 9 February, which is the time of the following high tide, amounting *NAP* +1.70 metres.

<u>Point in time1:</u>
Appendix C.1 illustrates that at this point in time the spectrum peak lies at 0.1 hertz, which corresponds with a peak period of 10 seconds. As described above about the December storm, here too wave breaking at the shallow outer delta causes a sharp drop in wave energy between two outer stations AZB11 and AZB21. It is clear from the Appendix that the quantity of low energy frequency at the tidal inlet further drops, and that near the third station a relatively substantial quantity of low frequency energy remains in the spectrum. Between third and fourth stations AZB31 and AZB41, however, this remainder virtually entirely dissipates. As referred to in the previous chapter, the hypothesis is that

long waves at the tidal inlet refract towards the channel walls, after which they dissipate on the channel walls and the shallower areas behind the walls.

Point in time 2:
Regarding this point in time, Appendix C.2 shows that at AZB11 on the North Sea the low frequency peak of the spectrum has shifted left in relation to the first point in time. The peak period is then approx. 11 seconds. As a result of the low water level of *NAP* –0.10 metre, virtually all wave energy dissipates at the outer delta. The minor quantity of low frequency energy remaining in the spectrum near second station AZB21, dissipates entirely in the area between second and fourth stations AZB21 and AZB41. The findings are comparable with those described in chapter 3 on the storm period in December 2003.

Point in time 3:
The spectral variances along the five stations at this point in time are comparable to those of the first point in time. Also at the third point in time, a remainder of low frequency energy is measured in the spectra at the second and third stations, after which it dissipates entirely between third and fourth stations AZB31 and AZB41. The top figure in Appendix C.3 shows generating of low frequency energy of approx. 0.05 to 0.07 hertz between the two outer stations. This generating may be caused by wave breaking over the ebb shield.

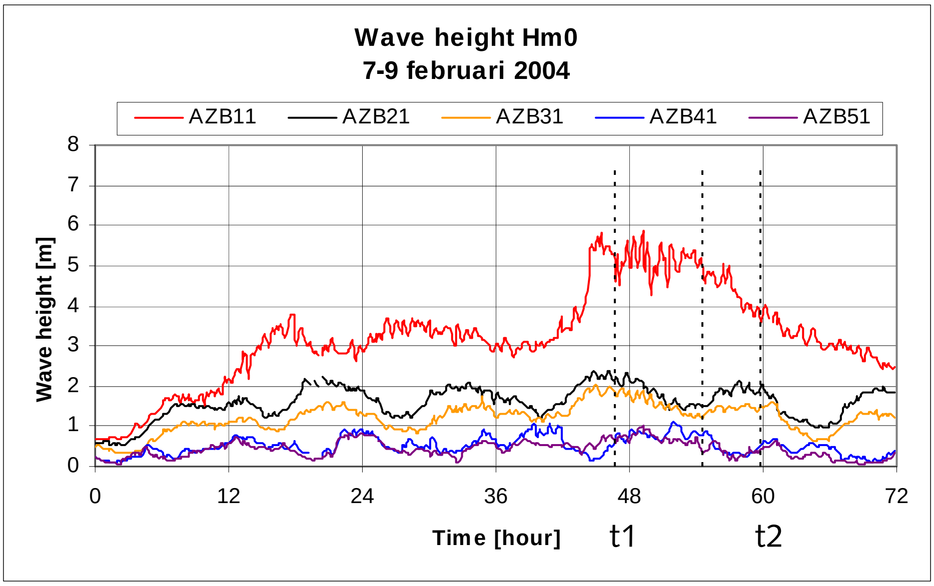
4.4.2 Wave parameters

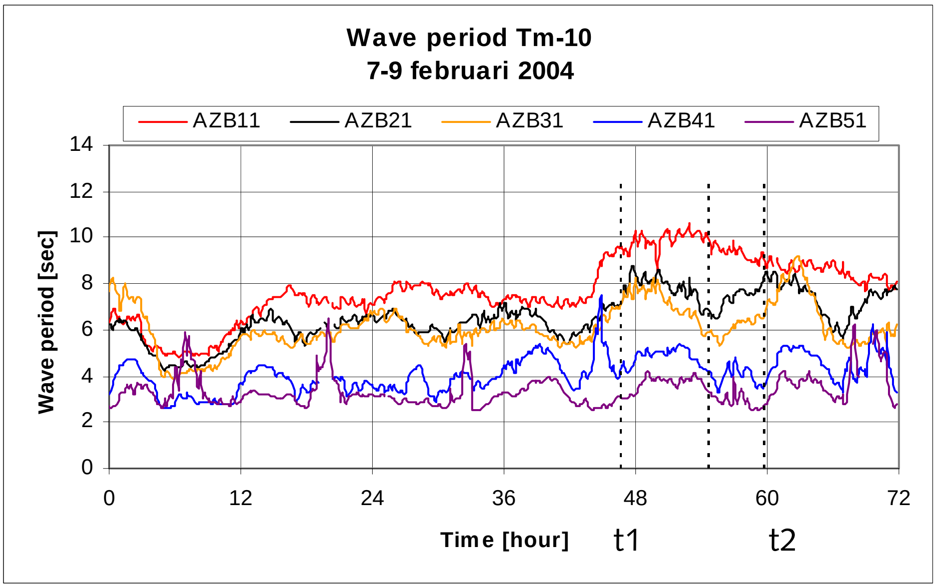
As a visualisation of the wave height and wave period variances during the period of 7 to 9 February, figure 4.4 presents the curves of wave height H_{m0} and wave period T_{m-10} at the various stations. This figure shows that North Sea wave height H_{m0} at AZB11 gradually increases to approx. 3.5 metres on 7 February. On 8 February, wave height H_{m0} increases further over a short period of time to nearly 6 metres, after which it gradually decreases on 9 February. The curve of North Sea wave period T_{m-10} is comparable.

As a result of wave breaking at the outer delta, wave height H_{m0} drops sharply between the two outer stations to approx. 2.3 metres near second station AZB21 at the peak of the storm. It is clear from figure 4.4 that not only between the second and third stations but also between the third and fourth stations, the wave height decreases further.

The same figure furthermore shows that the decreasing wave height along the measuring section concurs with a decreasing wave period. The observation is made that the curves of wave period T_{m-10} at waveriders AZB41 and AZB51 shows many spikes, at which time the wave heights are less than 0.30 metre. For these wave heights, the wave periods determined on the basis of the spectrum are unreliable.

Figure 4.4 Wave height H_{m0} and wave period T_{m-10} curves





5 Conclusions

During storm season 2003-2004, two storm periods occurred which caused a significant increase in Wadden Sea water levels. On the basis of the data, the conclusion can be drawn that the degree of North Sea wave penetration into Amelander Zeegat strongly depends on the concurrent water levels.

A comparison of the wave spectra measured during the storms, shows that the energy in the left part of the spectrum, i.e. < 0.25 hertz, virtually completely dissipates at the shallow outer delta when water levels are low.

A comparison of the spectra measured at high tides with considerably increased water levels, demonstrates that also in the case of increased water levels much of the low frequency energy dissipates at the shallow outer delta. When water levels are this high, part of the low frequency energy does penetrate into the tidal inlet, which results in clear spectral peaks at approx. 0.1 hertz at the first two stations at the Wadden Sea side of the outer delta. This low frequency energy has completely disappeared, however, in the spectra of the stations location at the flood basis. The hypothesis is that the North Sea waves penetrating into the tidal inlet, refract towards the channel walls during penetration through the channel, after which they dissipate on the channel edges and on the shallower areas behind them.

References

Hoekstra G.W.
Wiskundige beschrijving van het Standard Wave Analysis Package
Rijkswaterstaat, 682.83
6 September 1994

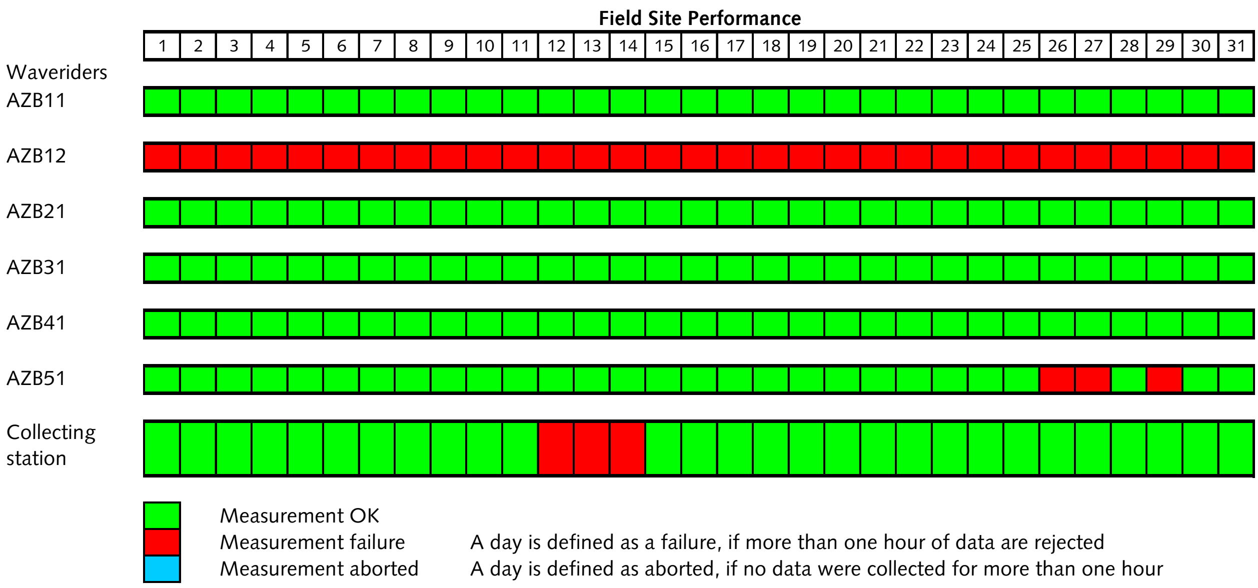
Roskam A.P.
Invloed inwinfrequentie op golfhoogten en golfperioden
RIKZ, work document RIKZ/OS/2004.128w
October 2004

Appendix A Data Availability

List of figures

Figure A.1 December 2003 Data Availability

Figure A.2 January 2004 data availability



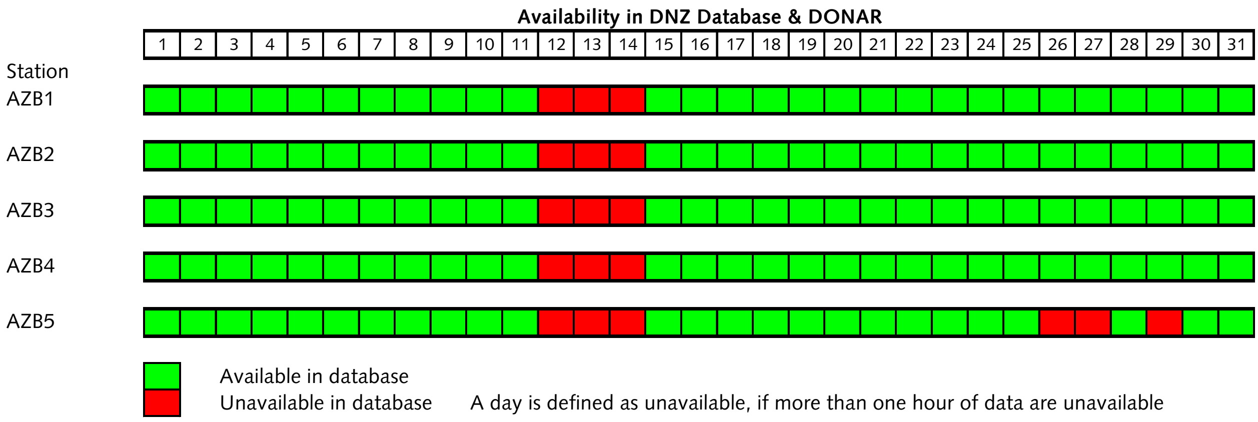
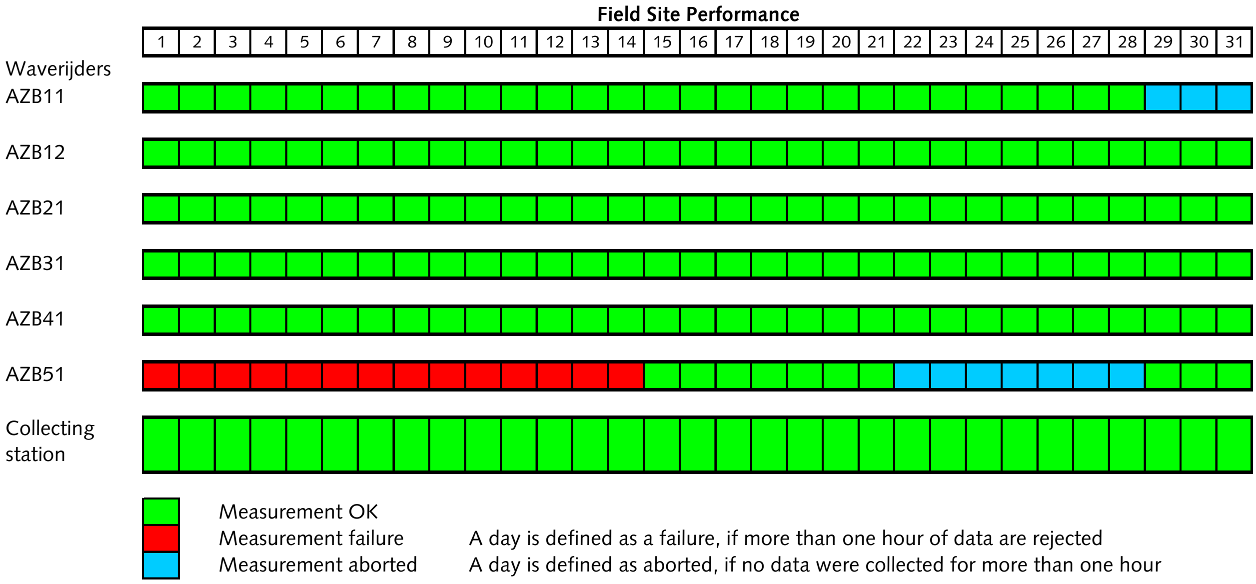


Figure A.3 February 2004 data availability

Figure A.4 March 2004 data availability



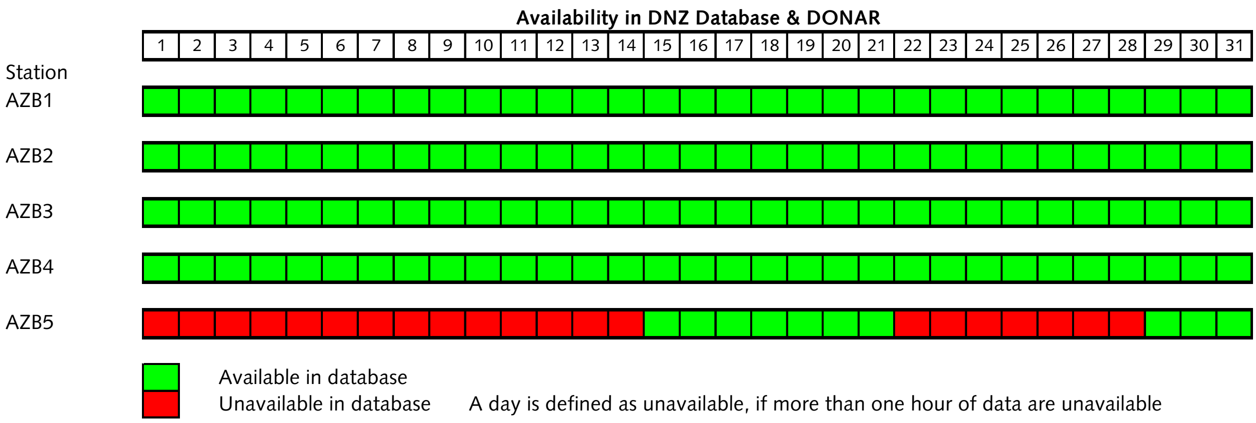
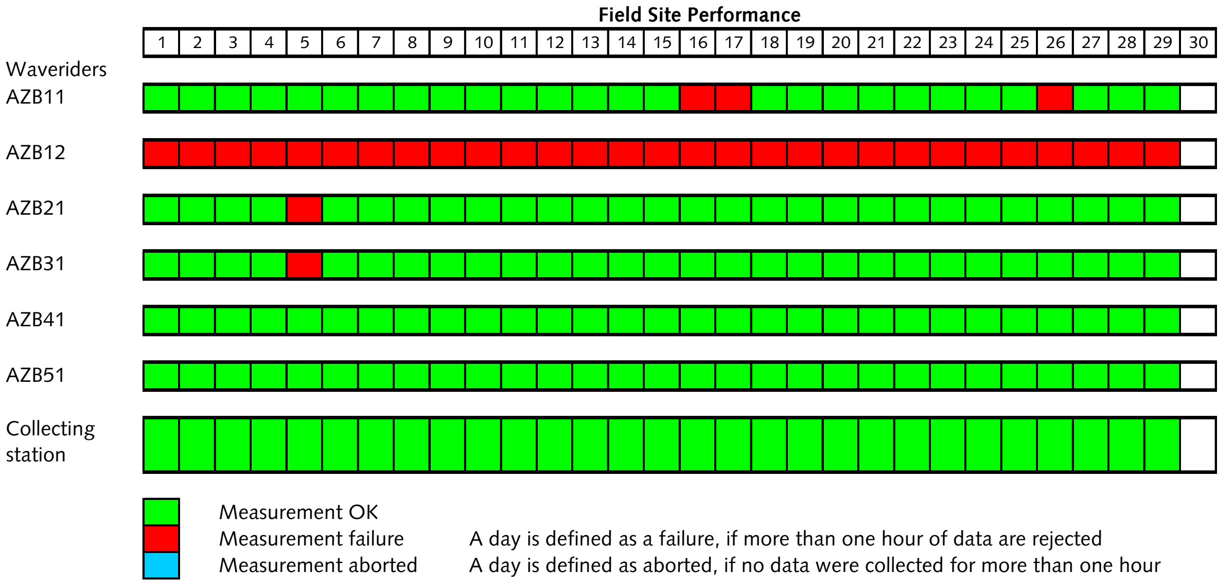
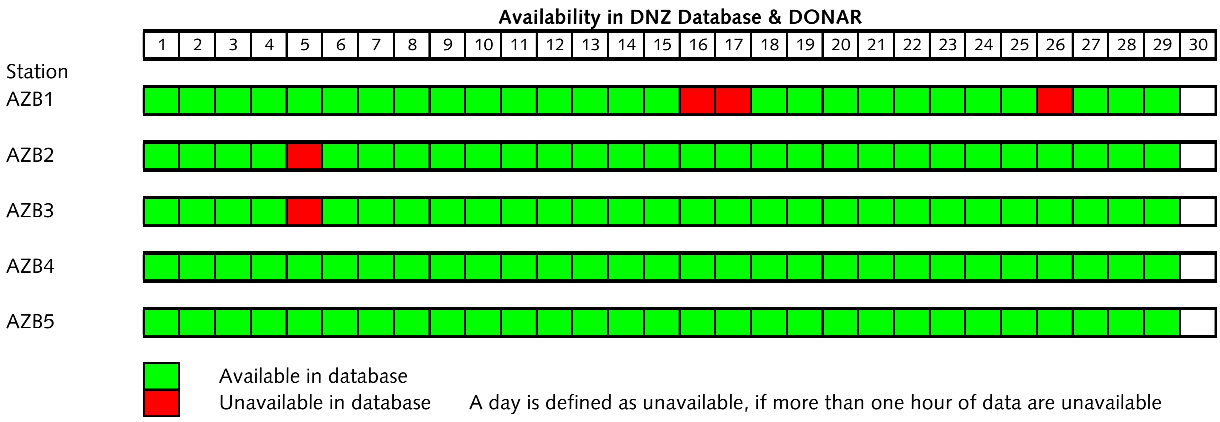


Figure A.5 April 2004 data availability

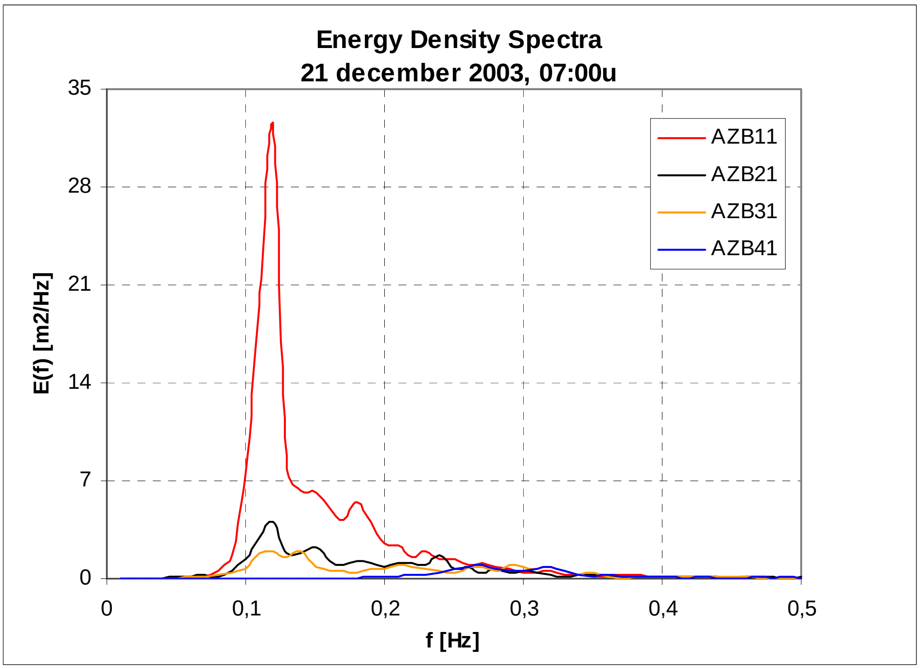


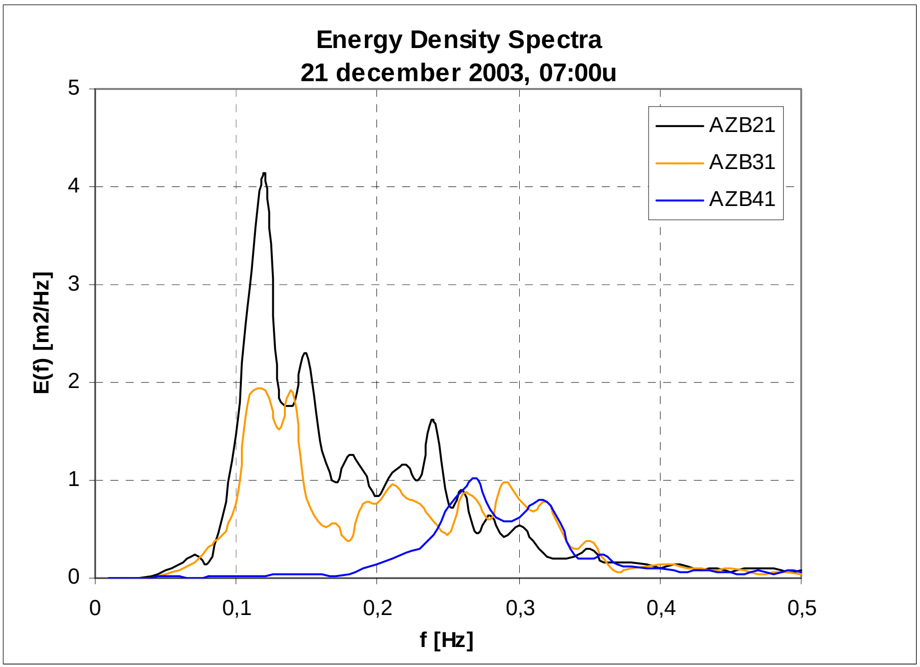


Appendix B Spectra for Storm Period 20-22 December 2003

List of figures

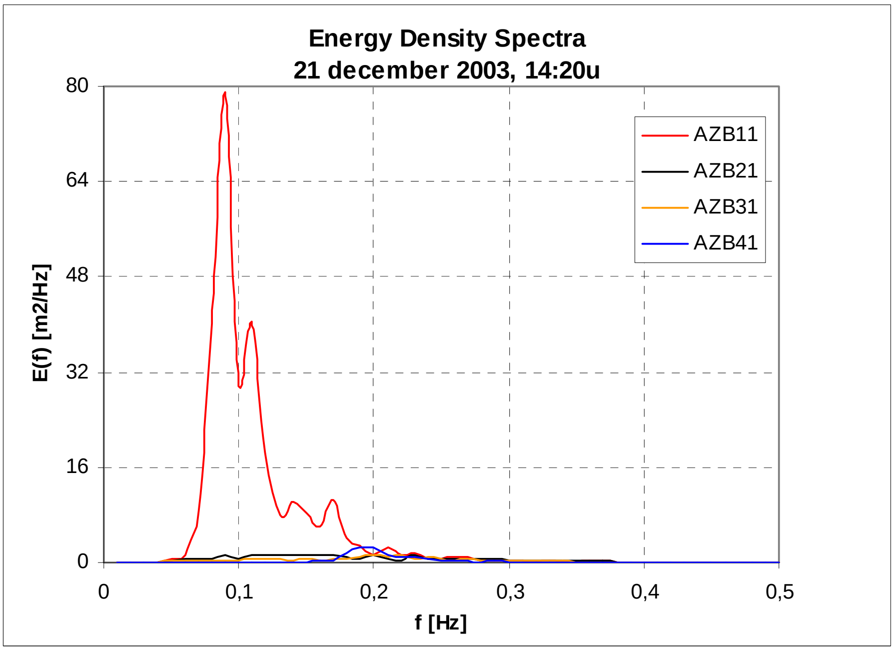
Figure B.1 Energy density spectra at point in time 1 – *NAP* +2.00 metres

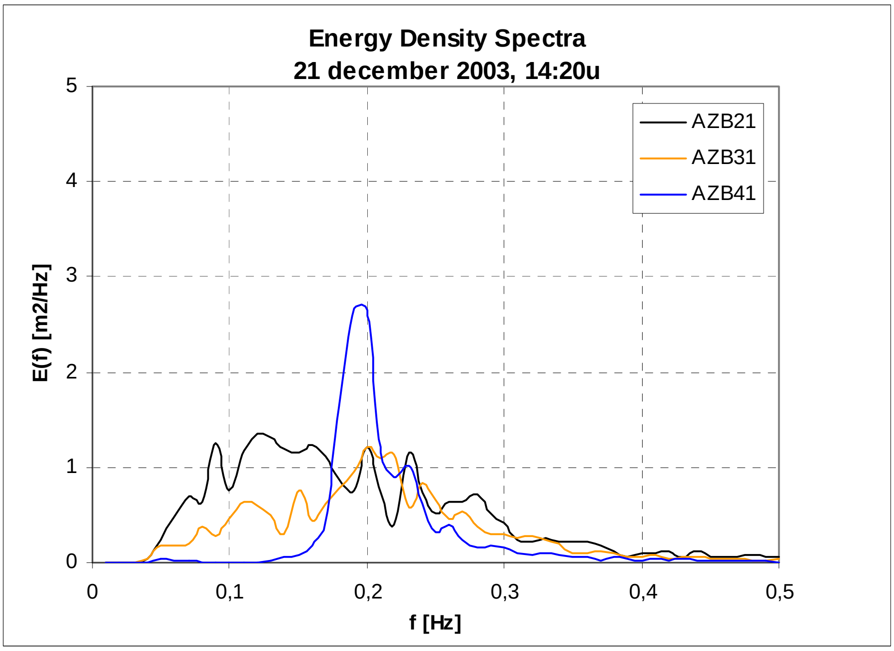




Station	H_{m0} [m]	T_{m-10} [sec]
AZB11	4.38	8.0
AZB21	2.29	6.9
AZB31	1.98	6.3
AZB41	1.28	3.8

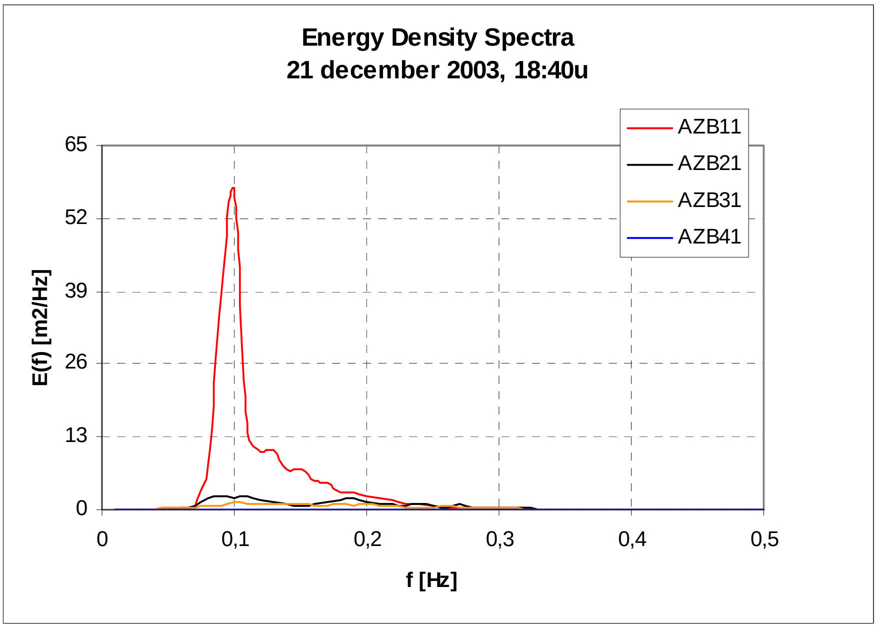
Figure B.2 Energy density spectra at point in time 2 – *NAP* +0.50 metre

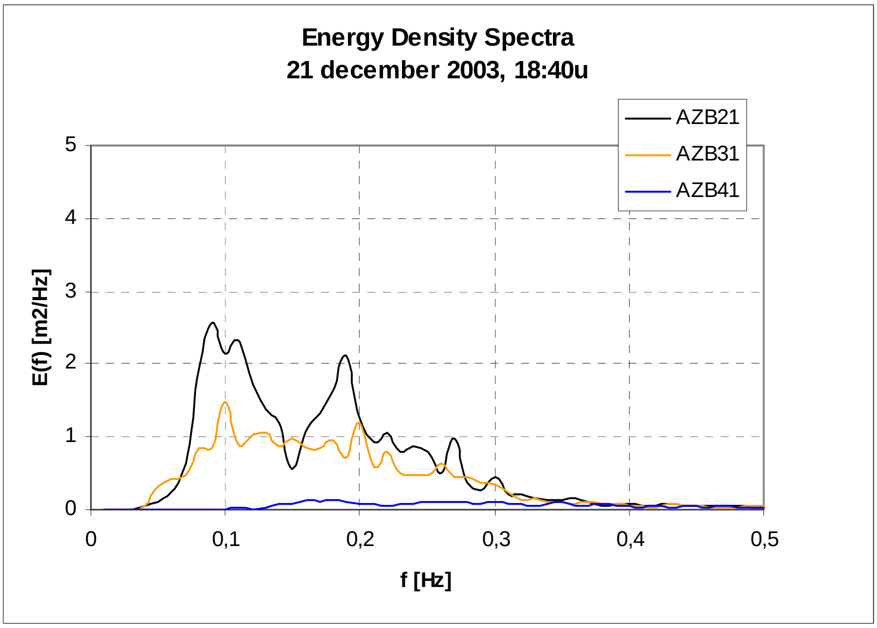




Station	H_{m0} [m]	T_{m-10} [sec]
AZB11	6.72	10.9
AZB21	1.98	7.3
AZB31	1.64	6.3
AZB41	1.49	5.1

Figure B.3 Energy density spectra at point in time 3 – *NAP* +2.67 metres



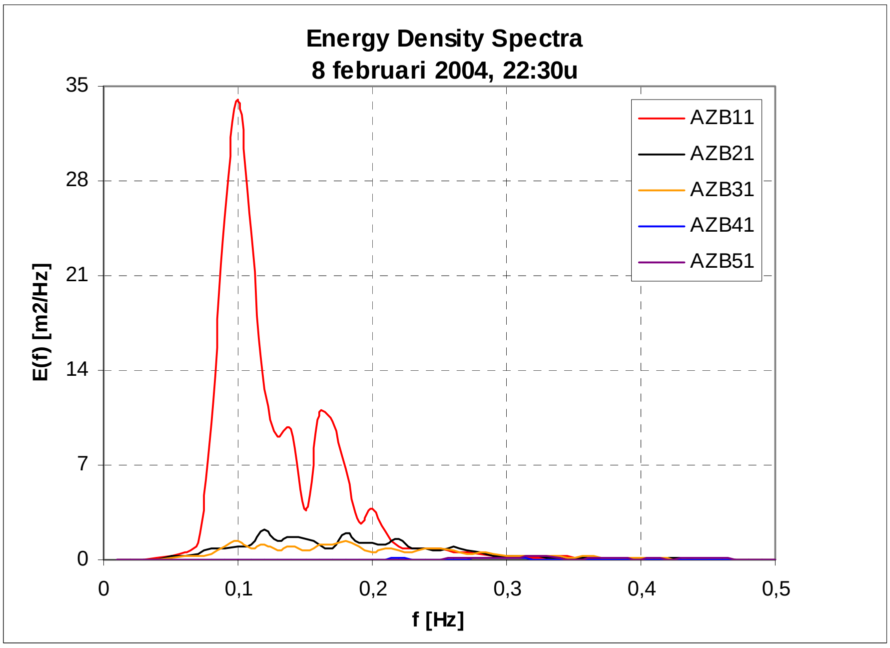


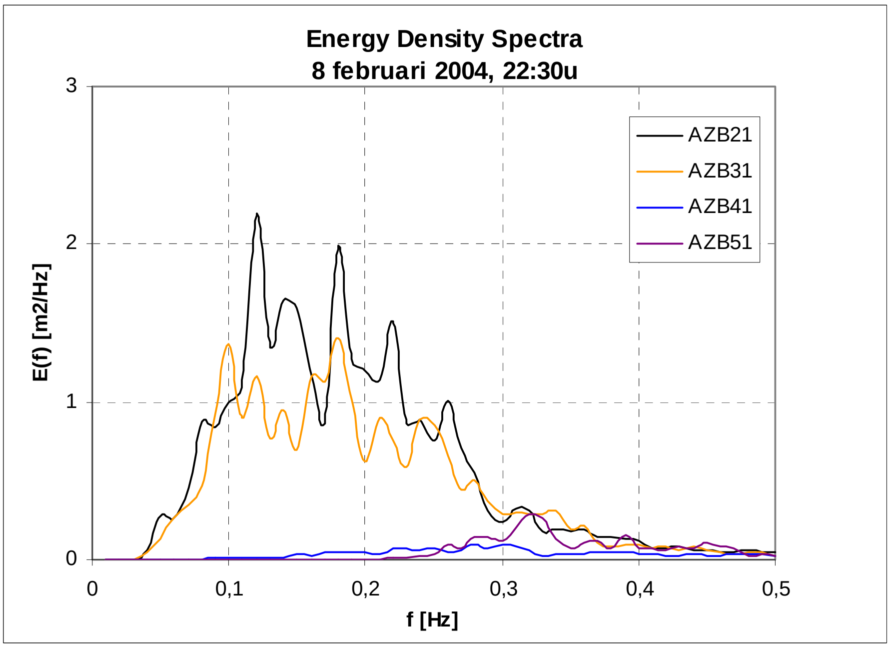
Station	H_{m0} [m]	T_{m-10} [sec]
AZB11	6.00	10.0
AZB21	2.34	7.9
AZB31	1.84	7.7
AZB41	0.51	4.4

Appendix C Spectra for Storm Period 7-9 February 2004

List of figures

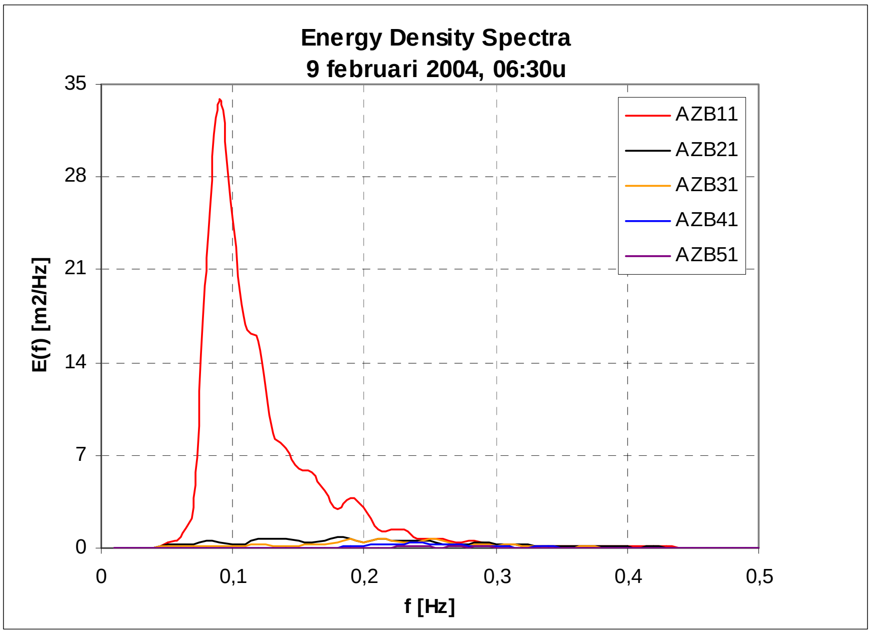
Figure C.1 Energy density spectra at point in time 1 – *NAP* +2.57 metres

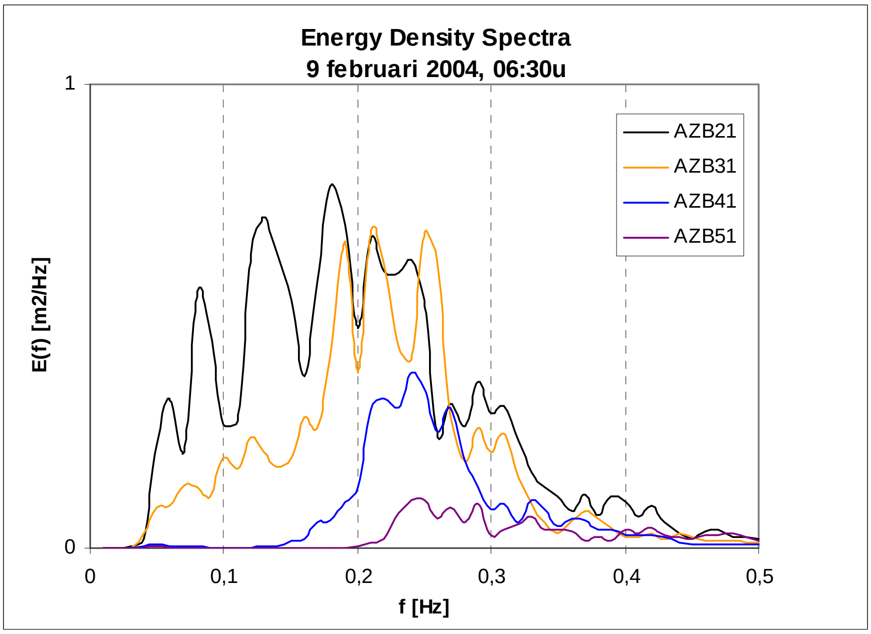




Station	H_{m0} [m]	T_{m-10} [sec]
AZB11	5.29	9.5
AZB21	2.14	7.0
AZB31	1.88	6.9
AZB41	0.54	4.0
AZB51	0.67	3.1

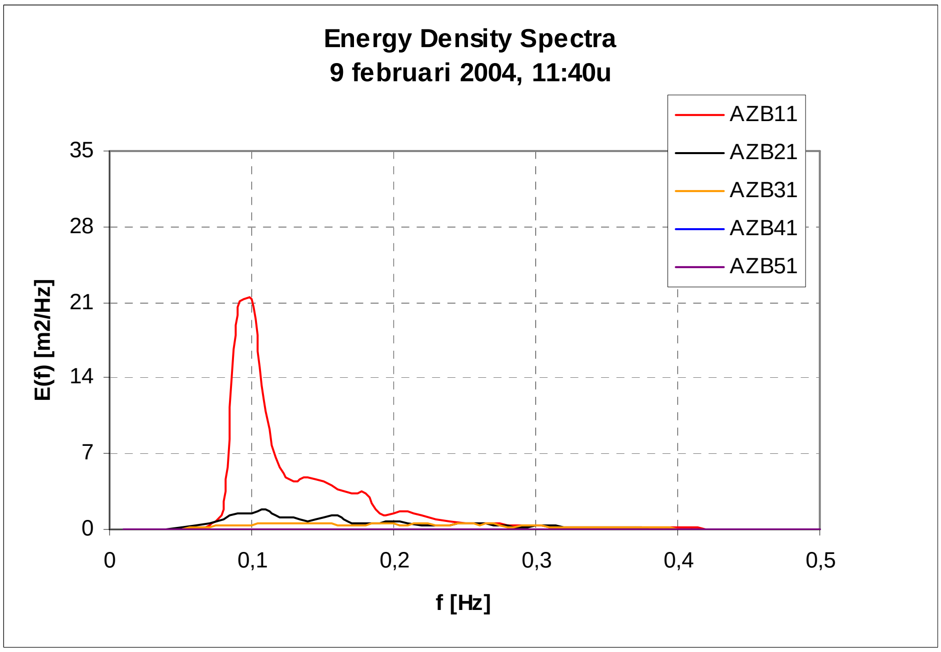
Figure C.2 Energy density spectra at point in time 2 – *NAP* -0.10 metre

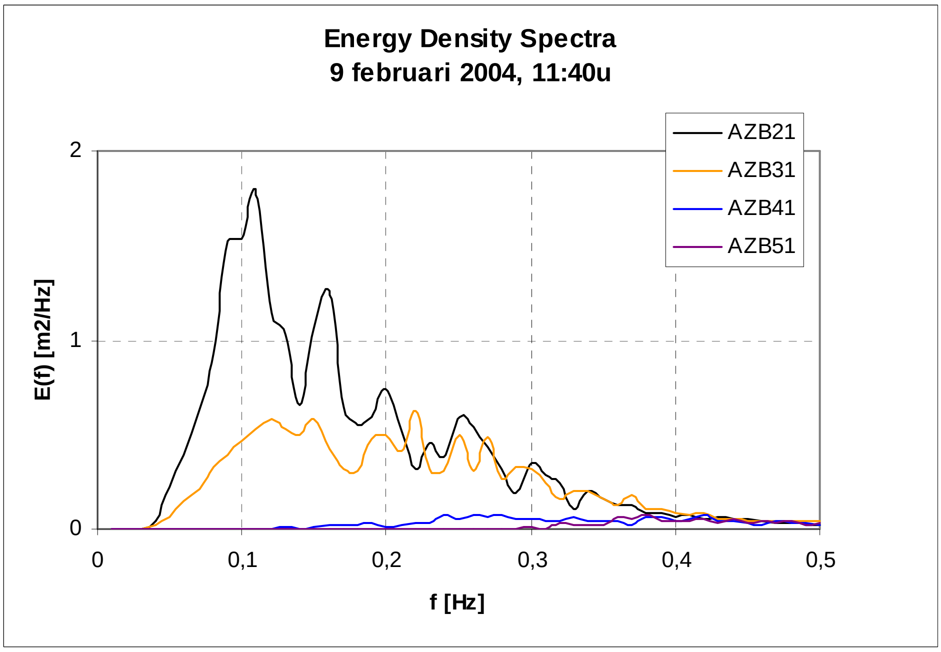




Station	H_{m0} [m]	T_{m-10} [sec]
AZB11	5.21	10.2
AZB21	1.50	6.9
AZB31	1.21	5.9
AZB41	0.78	4.2
AZB51	0.46	3.4

Figure C.3 Energy density spectra at point in time 3 – *NAP* +1.70 metres





Station	H_{m0} [m]	T_{m-10} [sec]
AZB11	3.95	9.4
AZB21	1.82	8.1
AZB31	1.40	6.5
AZB41	0.49	3.5
AZB51	0.36	2.6