

# CLASH-EU

## Report on Field Measurements

### Petten Sea Defence

### Storm Season 2002-2003



July 2003



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### **Petten Sea Defence**

### **Storm Season 2002-2003**

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# 1 Introduction

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## 1.1 General

Wave and wave run-up measurements have been carried out at the Petten Sea Defence in the Netherlands since 1994. The *Rijkswaterstaat* Directorate North Holland (Information Service Water) carries out these measurements under the authority of the *Rijkswaterstaat* National Institute for Coastal and Marine Management (RIKZ). The Road & Hydraulic Engineering Division (*DWW*) is responsible for analysing the wave run-up measurements.

A range of equipment is used for various measurements during this measuring programme. The vertical water level deviations, for example, are measured by means of wave buoys, pressure sensors and radar equipment, while the wave run-up against the dike is measured by means of, among other instruments, a wave run-up staff and video cameras.

Although these wave and wave run-up measurements up to and including storm season 2000-2001 were filed, they were not documented. By the end of 2002, a beginning was made at an extensive analysis and description of the field measurements, which eventually resulted in the storm season report over 2001-2002 [Hordijk, 2003]. The intention is to describe the subsequent storm seasons in similar documents as well, so that the measurements carried out are efficiently documented and can be made available to interested parties.

The report on the field measurements carried out over storm season 2002-2003, has practically the same structure as that of storm season 2001-2002. The subsequent report, however, pays more attention to the analysis and description of long waves (generated locally) with periods exceeding 30 seconds.

## 1.2 Background

The Netherlands are protected against flooding by the North Sea, the major rivers, and the inland seas *IJsselmeer* and *Markermeer* thanks to primary water defences. The Water Defence Act (*Wet op de Waterkering*) stipulates that every five years these water defences are tested against the applicable standard of hydraulic boundary conditions. Boundary conditions are defined to this purpose as water levels and wave characteristics at a particular chance of occurrence, in relation to the applicable safety level. This information is included in the Hydraulic Boundary Conditions Manual [*Hydraulisch Randvoorwaardenboek*].

The *RIKZ* is responsible for the knowledge, the calculation equipment and the calculations used for defining the hydraulic boundary conditions for salt waters.

The availability and reliability of the hydraulic boundary conditions depend on the reliable, verified and generally accepted wave models, such as SWAN. Verification of these models requires wave measurements particularly in shallow water (near the dike).

### 1.3 Objectives

The main objectives of the Petten survey are to follow wave propagation from deep water through the surf zone to the dike, and to measure the wave run-up against the dike. This fieldwork knowledge is then used to quantify the reliability of a wave model (such as SWAN) and of wave run-up modelling with respect to the straight Dutch coastline.

The objective of writing this storm season report is to gain an understanding of the measurements carried out, and to describe the data so that they are transferable. This report therefore examines a number of general issues, such as the field site location, the equipment, data collection and data registration. It furthermore gives a description of the hydraulic conditions (wave climate, current conditions and water levels), wind conditions and bottom topography changes at the Petten Sea Defence during storm season 2002-2003.

### 1.4 Organisation

The measurements at the Petten field site are part of a joint research programme by the *RIKZ* and *DWW*. The primary objective of the *RIKZ* is "to provide applied recommendations on the basis of knowledge acquired". This knowledge is for the use of all departments of the Netherlands Ministry of Transport, Public Works and Water Management and – subject to the boundary conditions – that of relevant external partners. From an internal point of view, the *RIKZ* programme is part of the *HR-Meet/SBW5* project, which in turn is a subproject of "Strength and Stress on Water Defences" [*Sterkte en Belasting op Waterkeringen, SBW*] and aims to provide valid measurements for the improvement of scale models used to determine the hydraulic boundary conditions. The objective of project group *HR-Meet* is to measure, process and validate the wave data to meet the need of good measuring data required for determining hydraulic boundary conditions, for validating design and testing software, and for broadening the available knowledge of waves.

The *Rijkswaterstaat* Measurement Information Service Water of Directorate North Holland carries out the measurements at and maintenance of the field site.

### 1.5 Data Processing Method

Processing of measurement data used to be carried out by means of 'ad hoc' software (Fortran scripts). On the authority of the *RIKZ*, in 2002 the wave processing software programme Waves2002 was developed to streamline data processing and to improve processing maintenance. This programme was tested against data from storm season 2001-2002. The present version of Waves2002 allows processing of separate days only, which would make processing of the full storm season very time-consuming and inefficient. The batch version will be developed in the second half of 2003, which will enable processing of longer time spans without too much effort. The batch version shall eventually replace all ad hoc software that has been used so far.

The data processing method for storm season 2002-2003 was the same as that for previous storm seasons, ie by means of the ad hoc software. Waves2002 was used to generate a visual check of processing of, among other things, storm days. Several graphic results have been incorporated in this storm season report.

Validation was carried out on the raw measuring signal, where spikes, time errors and stagnations were cleared, and data gaps were completed. A validation at parameter level, which checks parameter reliability, was **not** carried out; the same applies to the storms! In other words, a general but no systematic validation was carried out.

As of next storm season, Measurement Information Service of Directorate North Holland is to carry out the measurement processing. At the time of writing this storm season report, the necessary preparations are being made to this purpose.

### 1.6 Report Outline

To begin with, Chapter 2 provides a detailed description of the field site. It starts by giving an outline of the field site set-up, followed by separate descriptions of the various instruments applied. It furthermore briefly discusses management and maintenance of the site and of data collection. Chapter 3 examines the availability of measurement data and storm data, as well as the reliability of the various types of measuring instruments. Chapter 4 describes the general characteristics and the morphological developments during measuring season 2001-2002. It also includes a brief analysis of the spectre's low frequency energy, ie the long waves, followed by the selection of a storm period which is interesting because of wind speeds and water levels. Chapter 4 discusses data processing by means of

Waves2002 and other software, as well as data storage. Chapter 5 gives a detailed description of the storm period selected in chapter 4, where a general description of the storm conditions is followed by, among other things, wind measurements, wave measurements and wave run-up measurements. To conclude, Chapter 6 provides the general conclusions and recommendations.

# 2 Description of Petten Field Site

## 2.1 Location

The field site is situated off the coast of the province of North Holland near the town of Petten, where the Petten Sea Defence (figure 2.1) gives local shelter to the coastline. Determination of the height of the sea dike was based on a safety level with a chance of exceedence of 1/10,000 per annum, and measures 12.75 metres above Dutch vertical reference level *NAP*. Over the years the adjacent dune areas have moved inland, so that in comparison with the coastline the Petten Sea Defence slightly extends out into sea.

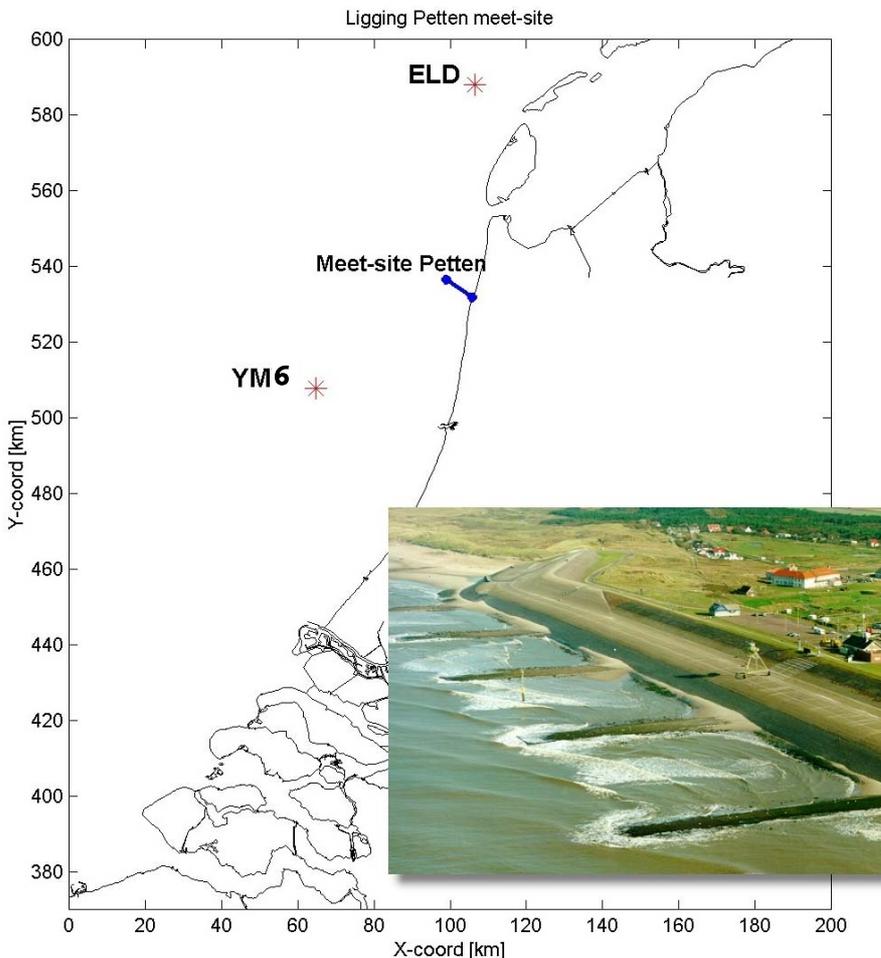
**Figure 2.1** Location of Petten field site

Location of  
Petten Field Site

Petten field site

Y coord. [km]

X coord. [km]



## **2.2 Equipment**

### **2.2.1 Field Site Set-up**

Measurements are taken at various locations to gain an understanding of wave behaviour off the Petten Sea Defence and the extent of wave run-up against this dike. These measuring points (MPs) are located on or near kilometre section 20,830 as referred to in the *Rijkswaterstaat* annual coastal sounding programme. The choice of measuring equipment depends on the particular location, the variables to be measured and the equipment available. The measuring points, variables to be measured and type of instrument are listed in tables 2.1 and 2.2.

**Table 2.1** Measuring points

| Meas. point | Sensor/Instrument  | Distance to ref. pt. <sup>1</sup> [m] | X coord. RD [m] | Y coord. RD [m] | Z [NAP m+]    | Location                         |
|-------------|--|---------------------------------------|-----------------|-----------------|---------------|----------------------------------|
| MP 13       | Anemometer (131)<br>Wind vane (132)                                  | -35                                   | 105798          | 531673          |               | <i>Dijk te Kijk</i> <sup>2</sup> |
| MP 22       | Barometer (221)  | -35                                   | 105798          | 531673          |               | <i>Dijk te Kijk</i>              |
| MP 14       | Video camera 1 (141)   | -0.2                                  | 105769          | 531693          | 17.3          | Crest of dike                    |
| MP 19       | Video camera 2, 3 (191, 192)   | 1.1                                   | 105759          | 531677          | 16.6          | Crest of dike                    |
| MP 12       | Pressure sensor (121)  | 12.7                                  | 105749          | 531683          | 9.28          | Dike's upper slope               |
| MP 11       | Pressure sensor (111)  | 18.2                                  | 105744          | 531685          | 7.16          | Dike's upper slope               |
| MP 9        | Wave run-up staff (091)  | 19.4 (centre)                         | 105743          | 531686          | 6.92 (centre) | Dike's upper slope               |
| MP 10       | Pressure sensor (101)  | 25.6                                  | 105738          | 531689          | 5.60          | Dike's lower slope               |
| MP 8        | Pressure sensor (081)  | 55.7                                  | 105720          | 531719          | 0.53          | Dike's lower slope               |
| MP 7        | Pressure sensors (071, 072)  | 75.4                                  | 105703          | 531730          | 0.11/<br>0.06 | Groyne section post              |
| MP 6        | Capacitance wire (061)   |                                       | 105661          | 531752          |               | }                                |
|             | Pressure sensor (062)  | 122.9                                 | 105662          | 531752          | -1.34         | }                                |
|             | Radar level meter (063)  | 122.7                                 | 105661          | 531753          | 8.98          | } Breaker                        |
|             | Anemometer (064)   | 122                                   | 105661          | 531751          |               | } bar post                       |
|             | Wind vane (065)  | 122                                   | 105661          | 531715          |               | }                                |
|             | ASM-IV (066)   | 122.7                                 | 105661          | 531715          | ?             | }                                |
| MP 18       | Pressure sensor (181)  | 170.5                                 | 105617          | 531771          |               | Sea bed                          |
| MP 17       | Pressure sensor (171, 175)<br>Current velocity meter (172, 173, 174) | 276.7                                 | 105522          | 531817          | -2.84         | Sea bed                          |
|             |  | 276.7                                 | 105522          | 531817          | -2.91         | Sea bed                          |
| MP 16       | Pressure sensor (161, 162, 163)                                      | 436.6                                 | 105377          | 531886          | -2.53         | Sea bed                          |
| MP 3        | Digital level meter (032)  | 609                                   | 105234          | 531985          |               | Post                             |
|             | Radar level meter (033)  | 609                                   | 105234          | 531985          |               | Post                             |
| MP 2        | Directional Waverider (021)  | 3526                                  | 102896          | 533802          |               | Petten <i>Polder</i>             |
| MP 1        | Directional Waverider (011)  | 7916                                  | 99003           | 535832          |               | NAP -20m                         |

<sup>1</sup> The distance to the reference point is defined in relation to section 20,830 with zero coordinates x= 105767, y = 531690 (corresponds approx. with crest of dike) and direction (nautical) 297.9 °

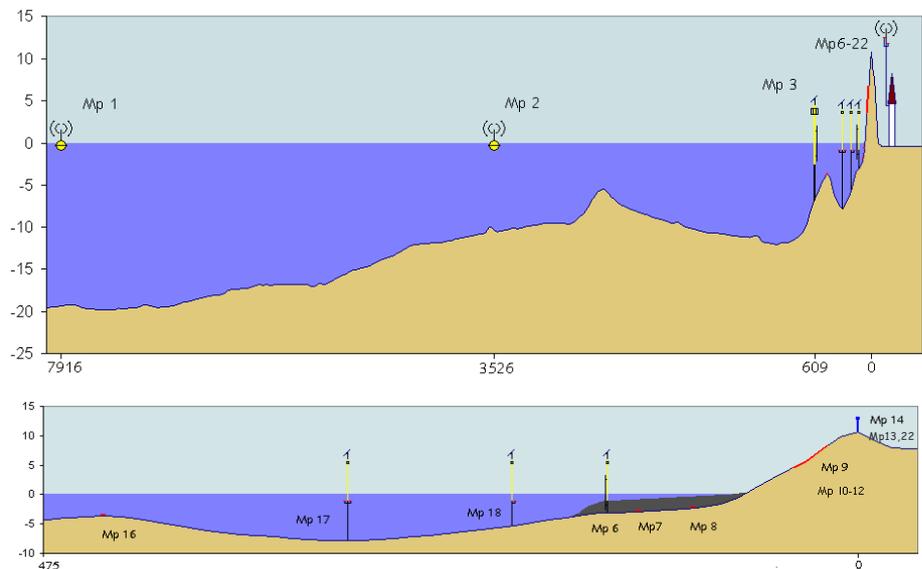
<sup>2</sup> Visitor Information Centre "*Dijk te Kijk*" (ie "Sea Dike on Show")

**Table 2.2** Equipment and measurement variables

| Measuring Point | Sensor/Instrument   | Measuring variables [unit]   | Data Collection Frequency (Hz)  |
|-----------------|---|--|---|
| MP 13           | Anemometer (131)<br>Wind vane (132)   | Wind direction [° ],<br>Wind speed [m/s]   | 1/60  |
| MP 22           | Barometer (221)   | Atmosph. pressure [mbar]   | 1/60  |
| MP 14           | Video camera 1 (141)  | Measuring section and surf zone  | 25 images/sec   |
| MP 19           | Video camera 2, 3 (191,192)   | Wave run-up (also in grid)   | 25 images/sec   |
| MP 12           | Pressure sensor (121)   | Water pressure [mbar]  | 4.00  |
| MP 11           | Pressure sensor (111)   | Water pressure [mbar]  | 4.00  |
| MP 9            | Wave run-up staff (091)   | Wave run-up [m]  | 10.00   |
| MP 10           | Pressure sensor (101)   | Water pressure [mbar]  | 4.00  |
| MP 8            | Pressure sensor (081)   | Water pressure [mbar]  | 4.00  |
| MP 7            | Pressure sensors (071, 072)   | Water pressure [mbar]  | 4.00  |
| MP 6            | Capacitance wire<br>Pressure sensor (062)<br>Radar level meter (063)<br>Anemometer (064)<br>Wind vane (065)<br>ASM-IV (066) | Surface deviation [m]<br>Water pressure [mbar]<br>Surface deviation [m]<br>Wind speed [m/s]<br>Wind direction [° ]<br>Bottom topography [NAPm] | 4.00<br>4.00<br>2.56<br>1 min. measured<br>1 min. measured<br>3 samples / 20 min (1/hr as of May) |
| MP 18           | Pressure sensor (181)   | Water pressure [mbar]  | 4.00  |
| MP 17           | Pressure sensor (171, 175),<br>Current velocity meter (172, 173, 174)   | Water pressure [mbar]<br>Current velocity [m/s]  | 4.00 / 1.00<br>1.00   |
| MP 16           | Pressure sensor (161, 162, 163)   | Water pressure [mbar]  | 4.00  |
| MP 3            | Digital level meter (032)<br>Radar level meter (033)  | Water level [NAPm]<br>Surface deviation [m]  | 0.10<br>2.56/10 min. measured   |
| MP 2            | Directional Waverider (021)   | Surface deviation [m] and wave direction [° ]  | 1.28  |
| MP 1            | Directional Waverider (011)   | Surface deviation [m] and wave direction [° ]  | 1.28  |

Figure 2.2 below gives the measuring point locations in the field site's (full) cross shore profile. To avoid confusion, an enlarged graph of the relevant area shows the positions just off the coast.

**Figure 2.2** Petten field site  
(distances and heights in metres)



### 2.2.2 Equipment Changes Compared with Previous Season

A number of equipment changes were made prior to and during storm season 2002-2003:

- Due to malfunctioning during the previous storm season, the water level staff at MP 3 was removed. In June 2003 a new Etrometa staff was mounted.
- Early November an ASMIV sea bed staff was placed next to MP 6 to gain an understanding of the sea bed changes near this measuring point during a storm.
- Prior to the storm season, two pressure sensors were added to MP 16.
- In addition to the radar level meter and pressure sensor, which seem less reliable, a capacitance wire was added to MP 6 as an 'objective' measuring technique.

### 2.2.3 Operation of Equipment

This subparagraph briefly describes the operation of the instruments used on the field site, in the following order:

- Directional waverider
- Digital level meter (DLM)
- Pressure sensor
- Radar level meter
- Current meter
- Wave run-up staff
- Video camera
- Wind speed and direction meter
- Barometer
- Capacitance wire
- ASMIV sea bed staff

Reference is made to appendix A, in which photographs illustrate all above-mentioned measuring instruments. Photograph 9 provides an overview of the measuring set-up near the dike.

*Directional Waverider (see photograph 1 in appendix A)*

The directional waverider is a buoy supplied by Datawell and has a diameter of 0.9 m. The instrument contains equipment for measuring vertical accelerations and horizontal positions, pitch, roll and heave. The buoy is furthermore equipped with two permanent accelerometers, a compass and a direction meter. The data collected are transmitted to shore by means of telemetric links. The directional waverider enables short wave registration including wave direction. MP 1 is set as the field site's offshore reference point (approx. 8 km seaward), while MP 2 is located at the height of a sand ridge on the Petten *polder* (figure 2.2).

*Digital Level Meter (DLM)*

The digital level meter consists of a vertical tube with an opening below the minimum water level. The opening's flow resistance functions as a high frequency filter. High frequencies (wind waves) do not penetrate into the tube. A float measures the water level within the tube, and is connected to a pulley by means of a metal wire. A counterbalance ensures continuous wire tension. The pulley's rotations then show the course of water level changes.

*Pressure Sensor (see photographs 2 and 6 in appendix A)*

The pressure sensor measures the total hydrostatic pressure (atmospheric pressure, upper water layer and any current pressure). The pressure sensors on the Petten field site are installed to define the wave spectrum (MPs 6, 7, 16, 17 en 18), and to read the layer thickness of the run-up waves against the dike (MPs 8, 10, 11 en 12). An additional number of pressure sensors (sensors 161, 171 and 062) were positioned at equal distances in the surf zone to enable measurements of long wave reflection.

*Radar Level Meter (see photograph 4 in appendix A)*

The radar level meters supplied by Enraf enable measurements of water levels and wave heights. On the Petten field site, *ITH* evaluates the usefulness of various types of this instrument in the surf zone (033 and 063). The first results of this evaluation should be available by the end of 2003.

*Current Meter (see photograph 5 in appendix A)*

The instantaneous current velocity and current direction are measured by an (Aquadopp) current meter (172-174) in a vertical direction, and in directions along and perpendicular to the coastline.

*Wave Run-Up Staff (see photograph 3 in appendix A)*

The wave run-up staff used for measuring wave run-up against the dike, was supplied by Etrometa. Operation of this instrument, which consists of a series of electrodes at 0.05 metre distance each, is based on the principle of electronic conductivity. The wave run-up staff,

measuring 12 metres in length, is placed in the dike revetment and registers the wave run-up height against the slope.

*Video Camera (see photographs 7 and 8 in appendix A)*

Whenever a wave run-up is expected to occur, a video is recorded (191 and 192) to get a two-dimensional picture of the wave conditions in between the two groynes and of wave run-up against the dike. A grid was placed onto the dike to enable three-dimensional wave run-up registration.

*Wind Speed and Wind Direction Meter*

Throughout the storm season, the wind speeds and relating wind directions are measured continuously at two locations, ie in the surf zone at approx. 10 metres above Dutch reference level NAP (064 and 065), and at the landward side of the dike also at a height of approx. 10 metres (131 and 132).

*Barometer*

A pressure sensor (221) located at the field site's Visitor Information Centre "Dijk te Kijk" ("Sea Dike on Show") measures the atmospheric pressure. This measurement is continuous throughout the storm season.

*Capacitance Wire (see photograph 10 in appendix A)*

The principle of the capacitance wire is that of measuring the capacity of two wires which are stretched closely along each other. An increase in water level along these wires results in a decrease in capacity, which allows charting of the water level deviations (for example as a result of water level changes and waves).

*ASMIV sea bed staff (see photographs 11 and 12 in appendix A)*

From November 2002 the bottom topography near MP 6 was measured by means of an ASMIV sea bed staff supplied by the German company Argus. This instrument consists of 192 optic sensors cast in a metal rod at equal distances of 1 centimetre. The measuring data show a clear distinction between the sea bed layer and the water layer above. The sea bed staff is a stand-alone sensor with 8 MB storage capacity and is programmed by using an infrared interface. The voltage is supplied by two 9 Volt batteries, which require replacement after 3 months (or 6 months). This year's use of the ASMIV is experimental. /TH shall evaluate this sensor and set up an indication for potential. If the

conclusion is that this instrument is very efficient at monitoring the sea bed during storms, the instrument shall be introduced at several Petten locations.

#### **2.2.4 Management and Maintenance**

The Information Service Water is responsible for keeping the field site operational, which entails preventive and corrective maintenance. Preventive maintenance means that the equipment is kept in such a condition that there is a mere slim chance of corrective maintenance. Corrective maintenance means that worn equipment is repaired or replaced.

Installation and maintenance of the instrument set-up at the *MSW*<sup>3</sup> post (MP 3) are carried out exclusively by the *MSW* technical management department. The MP 3 instrument set-up was therefore designed and installed by the *R/KZ* IT department. The *MSW* is responsible for operation of the DLM, but not for the operation of the radar level meter (and water level staff). These instruments are included in the maintenance programme of the *MSW* post.

#### **2.3 Data Collection**

In 2001 a system was developed on the basis of the Qinsy system, which allowed data transfer commands to be given from a different location. The measuring data are stored onto two PCs in a locked room at the Petten Visitor Information Centre "*Dijk te Kijk*". In 2002 a network link to Petten was set up for the purpose of daily sensor operation checks. The network is used for making daily copies of the measuring data. In IJmuiden they are burned onto CD, which in turn is sent to Den Oever for the first processing procedure. In Den Oever the (raw) data are then stored onto CD and approx. once every 7 days they are sent to the *R/KZ*. The *R/KZ* then carries out detailed processing (analysis and validation) of the measuring data.

---

<sup>3</sup> Monitoring System Water

## 3 Data Availability and Reliability

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This chapter describes the availability of measuring data concerning the full storm season 2002-2003, and for the storms (wind speed > 15 m/s) which occurred within that season. A brief discussion of the reliability of the available data is also included.

### 3.1 Data Availability

#### 3.1.1 Availability of Storm Season Data

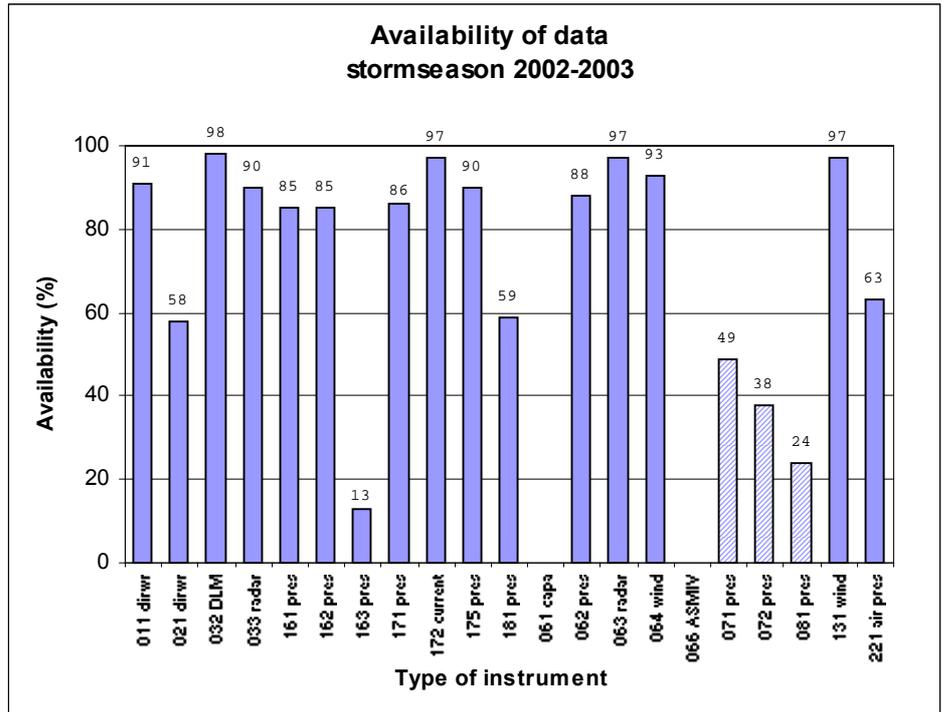
The degree of availability (ie existence) of the measuring data over storm season 2002-2003, is given in the bar graphs in appendix B. Key to the colours is:

- Green:** every day a minimum of 80% of the anticipated values is available after processing
- Yellow:** every day 50% to 80% of the anticipated values is available after processing
- Red:** every day less than 50% of the anticipated values is available after processing
- Black:** nil values available

Instrument numbers 091-121, 141 and 191 are positioned on the dike and do not generate any output unless there is sufficient wave run-up. They are therefore not included in the bar graphs. The ASMIV sea bed staff, which was introduced early November, is not included in the bar graph either. At the beginning of the storm season, it had not yet been decided whether or not a new water level staff was to be placed at MP 3, so that this water level staff was not removed from the bar graphs. As per storm season 2002-2003, the radar is used for collecting data at MP 3 at two different frequencies. This instrument is therefore included in the bar graphs for both frequencies.

The bar graph in figure 3.1 below shows the availability of measuring data for every instrument throughout the storm season. Figure 3.2 compares the data availability over storm season 2002-2003 with that over preceding storm season 2002-2002.

**Figure 3.1** Data Availability over Storm Season 2002-2003



**Figure 3.2** Comparison of Storm Data Availability 2002-2003 and 2001-2002

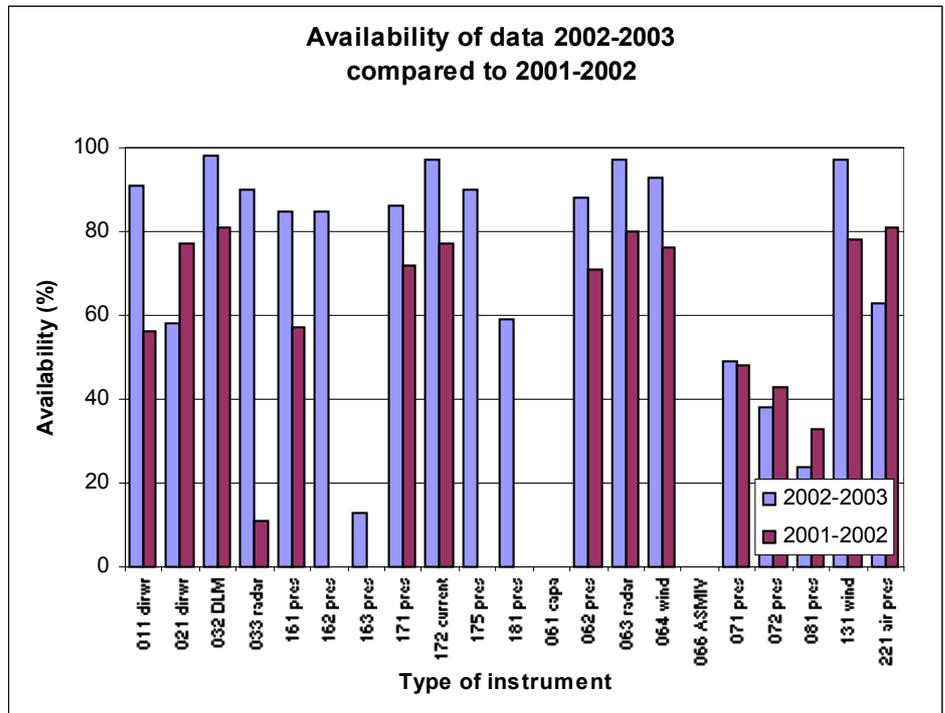


Figure 3.1 shows that data availability for the majority of instruments ranges from 85% to 98%. Several instruments however appear to have a relatively low availability percentage:

- 021 directional waverider (58%): The buoy broke loose on 27 October 2002 and consequently did not generate any output for nearly two months. After the buoy was repositioned, it operated well for several days, after which the signal increasingly faded away. Due to repairs the buoy then again did not function for a longer period of time.
- 163 pressure sensor (13%): This sensor was severely damaged during the storm at the end of October, after which it no longer generated any output.
- 181 pressure sensor (59%): Operation of this sensor was problematic throughout the season, and caused frequent breakdowns.
- 221 barometer (63%): Due to repairs abroad, this instrument did not generate any output for the first three months of the storm season.
- 071/072 pressure sensors (49%/38%): At low water the water level drops below the pressure sensors, which causes an interruption of data registration for over half of the storm season.
- 081 pressure sensor (24%): Over two thirds of the storm season the water level drops below the pressure sensor, which results in an interruption of data registration.

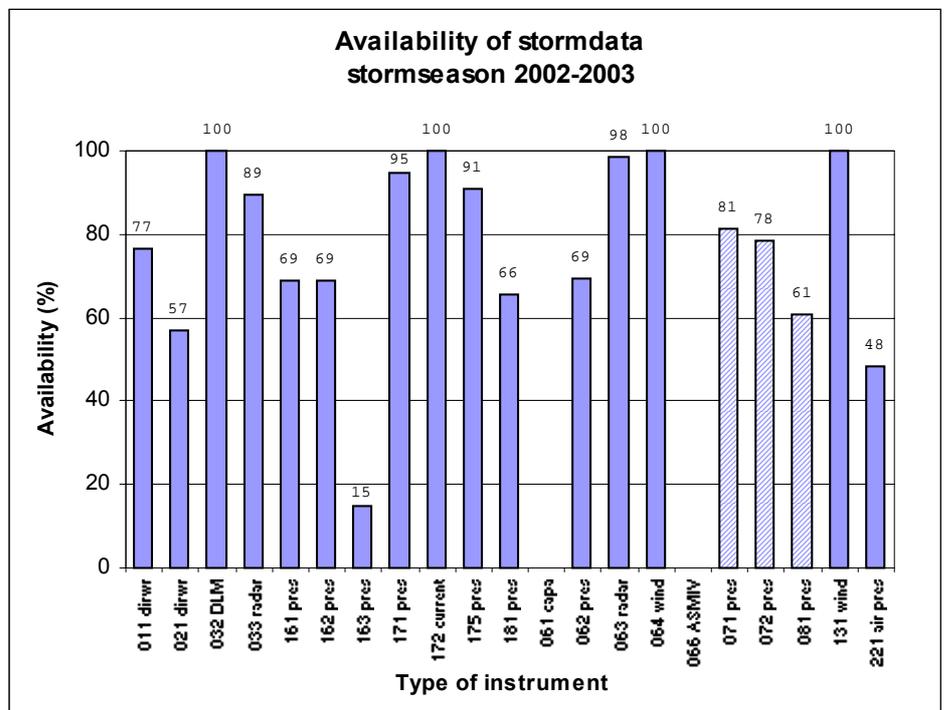
The availability of measuring values over the previous storm season turned out to be unacceptably low. Availability over storm season 2002-2003 required a considerable increase. The objective included in the project plan [Jacobse, 2002], was to obtain an average registration percentage of 80. Daily online checks of data collection (via the internet) and the availability of a back-up power unit, lead to a substantial increase in registration percentage. At an average of 80%, the objective was achieved. By decreasing the chance of instrument breakdowns, an even higher registration percentage is feasible for future projects. First of all an inventory needs to be made to this purpose of all possible breakdown mechanisms with their chance of occurring.

### 3.1.2 Storm Data Availability

One of the factors influencing the reliability of the hydraulic boundary conditions, is the reliability of the wave model used. Wave data of the storms which occurred, are essential for testing and where necessary improving the reliability of a wave model, such as the SWAN model. Furthermore good wave run-up data are of major importance for testing and designing dike heights.

Illustration of storm data availability over storm season 2002-2003, first required a selection of all storm hours within this season. A storm is defined to this purpose as the situation with wind speeds exceeding 15 m/s, which corresponds with approx. 7 to 8 Beaufort. The selection is based on the wind measurements (average per hour) carried out near IJmuiden (IJmuiden semaphore) for the Royal Dutch Meteorological Institute (*KNMI*). The total storm duration of this dataset is calculated at 66 hours. For the equipment used at the Petten field site, the storm data availability over these 66 hours is illustrated in the bar graph of figure 3.3 below. This graph shows the storm data availability for sensors 081, 071 and 072 as shaded bars. These instruments are located on the dike and stand clear at low water levels. This distorts the equipment's performance. As the capacitance wire and the ASMIV sea bed staff were not placed until halfway into the storm season, no storm data availability is given for these instruments.

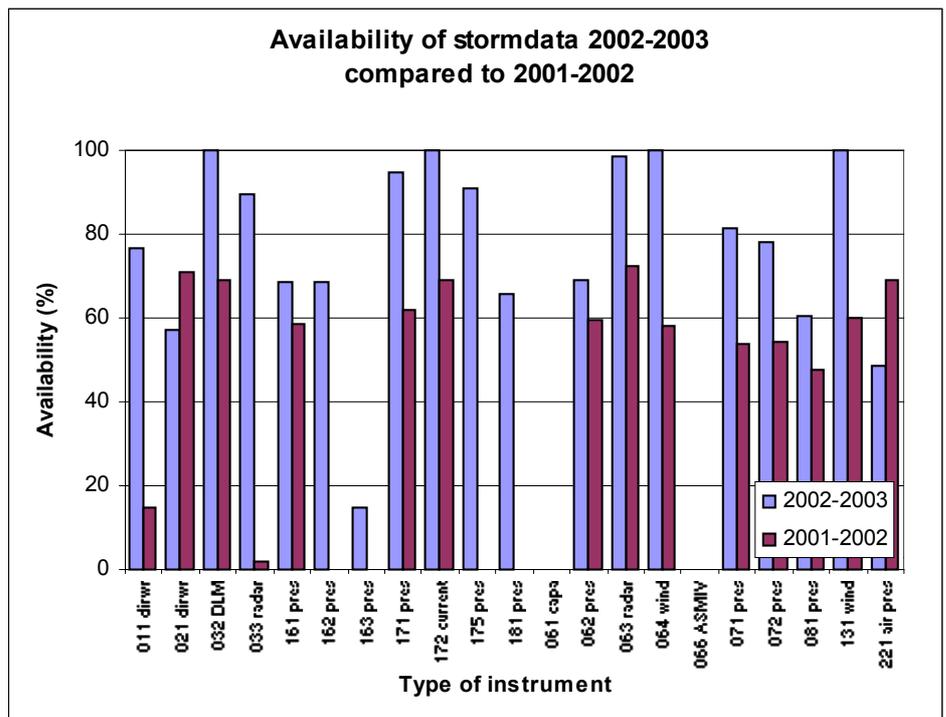
**Figure 3.3** Storm Data Availability over Storm Season 2002-2003



One of the conclusions which can be drawn from figure 3.3, is that nearly all equipment actually functioned during all 66 storm hours. Even pressure sensors 071, 072 and 081, which are positioned on the dike and stand clear at low water levels, still give a high output percentage. Other instruments show a relatively low availability of storm data. Due to a defect of pressure sensor 163, for example, this instrument was available for no more than 15% of the total storm duration. Given the fact that the barometer did not commence transmission until mid December, the storm data availability percentage for this instrument is relatively low as well.

In comparison with preceding storm season 2001-2002, the storm data availability has improved considerably (see figure 3.4 below). During this preceding storm season, the data collection equipment broke down quite frequently and for unnecessarily long periods of time. This problem had been solved for storm season 2002-2003, also thanks to the availability of a back-up power unit on site and the more alert response (online checks) to any malfunction and defects.

**Figure 3.4** Comparison of Storm Data Availability 2002-2003 and 2001-2002



### 3.2 Data Reliability

Where possible this paragraph indicates the data reliability of the various field site instruments. Reliability in this context is defined as the credibility of the measuring technique under field site circumstances. The main factors of reliability are the measuring circumstances (wave breaking, currents, etc.), which are briefly discussed below for every measuring instrument:

- *Directional Waverider*  
The directional waverider is a generally accepted instrument for wave measurements at deeper water. The criterion for using this buoy is the absence of wave breaking in the measuring area. As the Petten site meets this criterion (at MPs 1 and 2), it may be assumed that the measuring data generated by the directional waveriders installed, are reliable (with the exception of the wave direction and the directional distribution in the case of long waves, over 30 seconds/  $< 0,03$  Hz).
- *Digital Level Meter (DLM)*  
The DLM is a generally accepted instrument for measuring water levels and is applied on a large scale throughout the national water level network *MSW*. The standard deviation for the full set-up (ie DLM in a subdued water level tube) is 2.5 centimetres. The DLM positioned at MP 3 is part of the national measuring network (Petten South). These measuring data can be said to be very reliable.
- *Pressure Sensor*  
It may be said that the pressure sensors provide a virtually exact pressure measurement. There are doubts, however, about the accuracy of the process which translates the pressures measured into water level deviations, because it is not quite clear how for example the sensor distance to the water surface, the sensor distance to the sea bed, the water salinity, flow and sediment transport actually influence this process. The reliability of the final measurement results (water level deviations) generated by the pressure sensors has lately been a topic of discussion. Research into possible distorting influences such as flow, salinity and sediment transport is strongly recommended.  
Measurements in the past have shown that a number of sensors apparently offset long periods under water. As it turned out during the previous measuring season, this shifting offset occurs for pressure sensors which automatically compensate the atmospheric pressure. The pressure sensors which measure the hydrostatic pressure without this offset feature, seem to have a better performance.

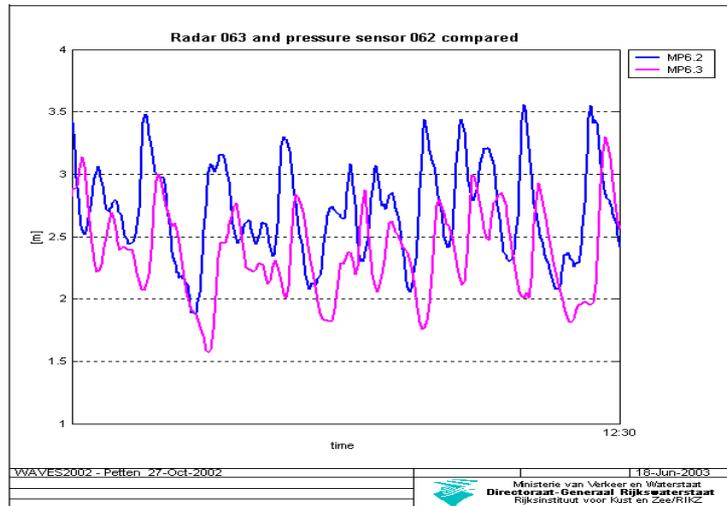
- Radar Level Meter

The radar level meter at MP 3 (033) is a new type of radar level meter which last year appeared to be having teething problems. This Enraf 973 radar level meter was therefore evaluated at Measuring Post *Noordwijk*. The objective of this project was to arrive at an improved instrument, with a clear indication of its measuring performance and areas of application. The final result is expected before the end of 2003. The result will enable a pronouncement on the data reliability of radar level meter 033 at MP 3.

The radar level meter at MP 6 is an old type: the Enraf 873. In principle, this type of radar level meter was approved for measuring waves at deep water (evaluation took place over 1997/1998 at Measuring Post *Noordwijk*). At the Petten field site, however, the sensor is applied differently, as MP 6 is positioned in the surf zone. As yet it is not suitable to apply the algorithm for determining surface deviations to wave breaking: It causes the sensor hardware to generate radar signals of long, high waves (approx. triple the average wave length) when it reads wave breaking. ITH estimates that it will take at least a year before a more reliable radar becomes available.

Figure 3.5 below compares the differences in signals generated by measuring instruments 062 (pressure sensor) and 063 (radar level meter). This figure clearly shows the differences in wave heights as measured by instruments 062 and 063, as well as a phase shift in measurements. A possible explanation of this phase shift of 2 seconds is the more shoreward position of the radar level meter (mounted on a distance keeper attached to the measuring post), which results in the radar level meter taking more shoreward and consequently later measurements than the pressure sensor. As referred to above, (part of) the explanation of the wave height differences measured by signals 062 and 063, could be for example the influence of current pressures on the pressure signal and that of spray on the radar signal. Research into the reliability of surf zone measurements shall include an analysis and assessment of both signals.

**Figure 3.5** Comparison of signals 062 and 063



- Current Velocity Meter*

The current velocity meter is positioned in the surf zone. It is not (yet) clear if the current data measured under turbulent circumstances are reliable.
- Anemometer/ Wind Vane*

The wind speeds measured at two different locations (MP 6 in front of the dike, and MP 3 behind the dike) are reasonably similar. The wind speeds however show a difference of 10-20°, which may result from different calibrations for both instruments. Contributing factor could be the changing wind directions due to the dike's geometry and (at MP 13) the building of the Visitor Information Centre. A comparison of both signals indicates that the deviation clearly depends on the wind direction. The sharpest deviations are found for southern winds.
- Barometer*

The reliability of the barometer measuring data depends on the instrument's set-up. Wind can for example distort the signal. Generally speaking, however, it can be said that the data provided by the barometer are reliable.
- ASMIV Sea Bed Staff*

The measuring principle of the ASMIV sea bed staff is that of optic measurement of water turbidity. The instrument's first results read, showed a clear distinction between water and sea bed. The results turned out to correspond closely with the simultaneous and accurate bottom height measurements. Considering the fact that this is a fairly simple measuring principle and that the measuring values closely correspond with the bottom height measurements, the conclusion was drawn that the ASMIV measuring data are very reliable. This summer a procedure will be started for this sensor to

be included in the National Equipment Stock (*L/B*). An indication for potential shall be drawn up in August, and an evaluation shall be carried out in consultation with the *Meetkundige Dienst*.

- *Capacitance Wire*

Considering the simplicity of the instrument's measuring principle, the water level variations measured are reliable provided the wire is sufficiently taut. The problem of a capacitance wire is that it slackens or even breaks in particular under storm conditions. It is essential that very regular checks (maintenance) are carried out to obtain reliable measurements. The bottom end of the wire is positioned at approx. 0.20 metre below Dutch reference level *NAP*, which means that measurements at low water are not accurate.



## 4 Processing of Measuring Season

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This chapter describes the characteristics of storm season 2002-2003. In a brief analysis, particular attention is paid to the low frequency energy measured, being the long waves. On the basis of the wind speeds and water levels measured, this chapter selects an interesting storm period, which is discussed in further detail in chapter 5. To conclude, this chapter describes data processing by means of Fortran software and Waves2000, as well as data storage.

### 4.1 Wind, Wave and Current Characteristics

#### 4.1.1 Wind Characteristics

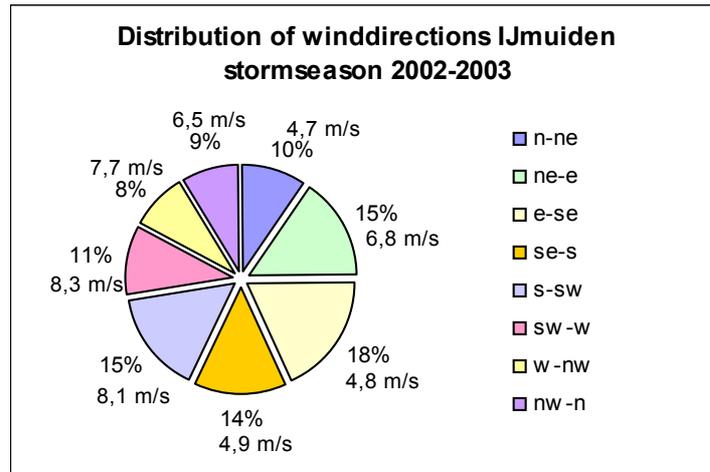
The wind directions and wind speeds are measured on the field site at MP 6 (in front of the dike) and MP 13 (behind the crest of the dike). A comparison of measuring values generated by these instruments shows that there is a slight difference in both wind speeds and wind directions measured. As indicated in chapter 3, an explanation of the differences in wind directions measured by MP 6 and MP 13, can be the different calibrations of both instruments. The dike's geometry also influences the wind direction to some extent, so that the direction at MP 13 (behind the crest of the dike) possibly somewhat differs from the wind direction at MP 6 (in front of the dike). An explanation for the sometimes fairly considerable differences in wind speed, can be the wind meter positions: at sea (MP 6) the wind speeds are generally higher than ashore (MP 13).

In view of the different measuring signals and the fact that the wind is not measured at the exact height of 10 metres (ie the standard height), the decision was made to describe the wind characteristics over storm season 2002-2003 on the basis of the data (average per hour) measured at IJmuiden on behalf of the Royal Dutch Meteorological Institute (KNMI)<sup>4</sup>. Measurement of these data was in fact carried out at the standard height of 10 metres. Distribution of the various wind directions over storm season 2002-2003 are summarized by the circle graph in figure 4.1 below, including the average wind speed per wind direction.

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<sup>4</sup> Data can be found on the internet: [www.knmi.nl/samenw/hydra](http://www.knmi.nl/samenw/hydra)

**Figure 4.1** Distribution of Wind Directions at IJmuiden over Storm Season 2002-2003



#### 4.1.2 Wave Characteristics

Directional waveriders (011 and 021), pressure sensors (062, 071, 072, 081, 161, 162, 163, 171, 175 and 181), radar level meters (033 and 063), and a capacitance wire (061) on the field site measure the vertical movement of the water level (wind set-up, waves) caused by the wind. Wave processing software was used to calculate wave parameters and spectra on the basis of the available 20-minute data blocks generated by the above-mentioned measuring instruments. This subparagraph gives the statistical characteristics of the 4 most important wave parameters, being:

- wave height  $H_{m0}$
- wave period  $T_{m-10}$  (0,03 – 0,50 Hz)
- wave period  $T_{m02}$
- peak period  $T_{pb}$ .

Mapping of the wave characteristics over storm season 2002-2003, required the mean value and exceedence frequencies to be calculated for these wave parameters. The results are listed in table 4.1 below. An illustration of the exceedence curves for wave height  $H_{m0}$  and wave period  $T_{m-10}$  is given in appendix C (figures C.1 and C.2). The fact that the exceedence curves represent a relatively short space of time (8 months), shows in small kinks in the curves. The dataset is in fact too small to allow statistical extrapolation. It should furthermore be noted that the distribution of  $T_{m-10}$  is not related to that of  $H_{m0}$ , so that the highest waves do not coincide with the highest periods. The higher periods are generally measured in the case of swell from the north, originating from an old storm field present in the wave field. These waves are characterized by a relatively small wave

height. Swell data need to be extracted to gain an understanding of the wind wave characteristics over season 2002-2003. An illustration is given in appendix C for pressure sensor 162 (figure C.3). The top figure in this appendix shows all 20-minute values of period  $T_{m-10}$  compared with the related  $H_{m0}$  values. The resulting scatter shows a clear distinction between swell (low  $H_{m0}$ , high  $T_{m-10}$ ) and wind waves (low  $H_{m0}$ , low  $T_{m-10}$ ). The bottom figure of this appendix gives the exceedence curves for the combination of wind waves including swell, and for wind waves after separating swell.

**Table 4.1** Wave Characteristics over Storm Season 2002-2003

| Parameter           |      | Measuring Instrument |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|---------------------|------|----------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                     |      | 011                  | 021  | 033  | 161  | 162  | 163  | 171  | 175  | 181  | 061  | 062  | 063  | 071  | 072  | 081  |
| $H_{m0}$<br>[m]     | gem  | 0.98                 | 0.78 | 0.99 | 0.61 | 0.67 | 0.87 | 0.54 | 0.60 | 0.60 | 0.52 | 0.59 | 0.42 | 0.54 | 0.58 | 0.48 |
|                     | 0.1% | 4.85                 | 4.65 | 4.84 | 2.91 | 3.21 | 3.54 | 2.03 | 2.48 | 2.75 | 1.68 | 2.30 | 1.71 | 2.02 | 2.07 | 1.65 |
|                     | 1%   | 3.48                 | 3.08 | 3.51 | 2.31 | 2.44 | 2.70 | 1.75 | 2.07 | 2.11 | 1.50 | 1.81 | 1.33 | 1.45 | 1.51 | 1.40 |
|                     | 5%   | 2.45                 | 2.13 | 2.37 | 1.60 | 1.77 | 1.90 | 1.31 | 1.56 | 1.57 | 1.24 | 1.47 | 1.00 | 1.10 | 1.16 | 1.02 |
|                     | 10%  | 1.93                 | 1.62 | 1.91 | 1.24 | 1.40 | 1.53 | 1.12 | 1.30 | 1.24 | 1.05 | 1.14 | 0.80 | 0.92 | 1.00 | 0.82 |
| $T_{m-10}$<br>[sec] | gem  | 5.4                  | 5.3  | 5.3  | 6.7  | 6.7  | 6.5  | 6.5  | 6.7  | 6.8  | 6.5  | 6.5  | 8.1  | 6.8  | 6.6  | 8.4  |
|                     | 0.1% | 11.2                 | 10.1 | 10.6 | 14.6 | 14.7 | 10.7 | 14.0 | 13.2 | 11.8 | 14.1 | 13.4 | 14.9 | 12.1 | 11.5 | 12.5 |
|                     | 1%   | 8.8                  | 8.5  | 8.7  | 11.9 | 12.0 | 9.5  | 11.3 | 11.0 | 10.1 | 11.6 | 11.4 | 13.0 | 10.7 | 10.2 | 11.6 |
|                     | 5%   | 7.6                  | 7.5  | 7.4  | 9.5  | 9.5  | 8.5  | 9.1  | 8.9  | 8.9  | 9.6  | 9.2  | 11.3 | 9.4  | 9.2  | 10.5 |
|                     | 10%  | 6.9                  | 6.9  | 6.8  | 8.7  | 8.7  | 7.8  | 8.4  | 8.3  | 8.3  | 8.6  | 8.3  | 10.4 | 8.7  | 8.5  | 9.8  |
| $T_{m02}$<br>[sec]  | gem  | 4.2                  | 4.1  | 4.1  | 5.4  | 5.4  | 5.4  | 5.5  | 5.5  | 5.3  | 4.6  | 4.6  | 5.6  | 4.8  | 4.7  | 5.7  |
|                     | 0.1% | 8.3                  | 7.4  | 7.4  | 9.8  | 9.9  | 9.1  | 9.2  | 8.0  | 8.0  | 7.9  | 7.9  | 9.7  | 7.8  | 7.5  | 8.0  |
|                     | 1%   | 6.8                  | 6.3  | 6.1  | 8.0  | 8.0  | 7.6  | 7.9  | 7.4  | 7.5  | 6.7  | 6.8  | 8.2  | 7.1  | 6.9  | 7.3  |
|                     | 5%   | 5.9                  | 5.6  | 5.3  | 7.0  | 7.0  | 6.8  | 7.0  | 6.8  | 6.8  | 6.0  | 6.0  | 7.3  | 6.2  | 6.1  | 6.8  |
|                     | 10%  | 5.5                  | 5.2  | 4.9  | 6.5  | 6.5  | 6.4  | 6.6  | 6.4  | 6.3  | 5.5  | 5.5  | 6.9  | 5.7  | 5.6  | 6.5  |
| $T_{pb}$<br>[sec]   | gem  | 6.0                  | 5.9  | 6.2  | 7.5  | 7.5  | 7.1  | 7.3  | 7.4  | 7.3  | 7.9  | 8.0  | 8.9  | 8.3  | 8.0  | 8.7  |
|                     | 0.1% | 19.6                 | 16.0 | 19.6 | 19.8 | 19.8 | 16.3 | 21.1 | 21.0 | 17.1 | 21.0 | 19.6 | 20.3 | 16.2 | 14.5 | 19.8 |
|                     | 1%   | 14.8                 | 14.2 | 14.2 | 16.5 | 16.5 | 12.6 | 16.2 | 16.3 | 14.4 | 17.4 | 16.5 | 17.4 | 14.0 | 13.2 | 15.6 |
|                     | 5%   | 10.0                 | 10.7 | 10.9 | 12.9 | 13.0 | 10.8 | 12.1 | 12.7 | 11.7 | 13.7 | 13.7 | 14.2 | 12.7 | 12.2 | 13.4 |
|                     | 10%  | 8.7                  | 9.4  | 9.7  | 11.0 | 11.1 | 9.9  | 10.7 | 10.9 | 10.9 | 11.8 | 11.9 | 12.9 | 12.0 | 11.6 | 12.1 |

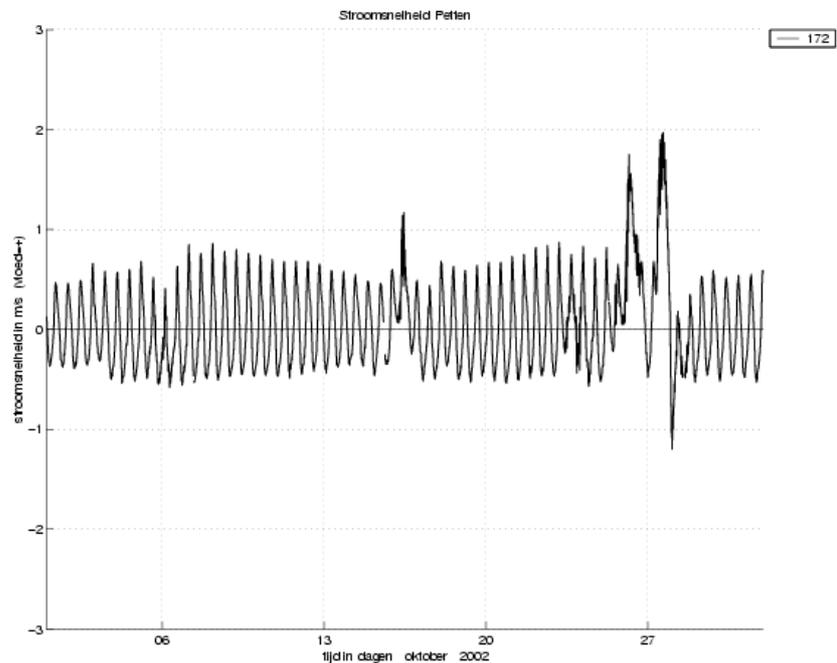
With reference to table 4.1, please note the following:

- The table clearly shows a decrease in wave height towards the coastline (in the table from left to right).
- For the peak period ( $T_{pb}$ ) it lists a number of very high and unrealistic values. This period measure is heavily influenced by the noise in the spectrum (random peaks), and contrary to  $T_{m-10}$  it is not a stable parameter.
- Period  $T_{m-10}$  does not decrease towards the dike, but actually increases! This increase is the result of long wave generating.
- $T_{m02}$  is much less sensitive to (the increase of) low frequency energy and is virtually constant towards the dike.
- During rough periods the buoy at MP 2 broke down quite frequently, and therefore on average measured waves with a relatively smaller height. This immediately shows in the exceedence curves for  $H_{m0}$ . Due to long-term failure, also pressure sensor 163 gives deviating values for its exceedence frequencies.
- As referred to in chapter 3 above, the radar picked up shorter wave lengths at MP 6 than the pressure sensor did. This clearly shows in the  $H_{m0}$  values. Radar 063 furthermore systematically and erroneously registers long waves, which results in higher  $T_{m-10}$  values.
- The pressure sensors 161 and 162 are similar, but sensor 163 produces deviating values and is most likely unreliable.

#### 4.1.3 Current Velocity Measurements

At MP 17 the current velocities were measured in 3 orthogonal directions by means of three instruments, being 172, 173 and 174. In theory the orbital motions can also be used to determine the propagation of long waves. Although the tidal current was determined, it was not included in the present processing (figure 4.2 below). This figure enables clear recognition of the current velocities ranging from approx.  $-0.5$  m/s and approx.  $0.8$  m/s under calm weather conditions. In the case of storm, the strong wind heavily influences the current velocities in shallow water (see figure 4.2 over 25-28 October 2002).

**Figure 4.2** Current Velocity  
Petten  
(Time in Days,  
October 2002)



## 4.2 Long Waves

### 4.2.1 General

At the Petten field site, long waves are measured mostly during storms, where a distinction can be made between two types of long waves: swell waves, which originate from a storm field elsewhere, and long waves generated locally. The cause of this local generating is the interaction between shorter waves and wave breaking in shallow water. Due to their very long periods, the waves do not run up against the dike, but cause reflection which in turn leads to a temporary water surface elevation. These elevations allow the shorter waves to run up higher against the dike. This paragraph gives an analysis of the low frequency energy (LFE) measured to gain an understanding of the relative share of the long waves, being the low frequency energy as part of the total energy in the wave spectrum.

### 4.2.2 Choice of Equipment

One way of measuring long waves is by means of pressure sensors and radar level meters. As mentioned in chapter 3, the reliability of the pressure sensors applied in particular (as well as the reliability of the radar level meters) has lately been a topic of discussion. First a (general) reliability check was carried out for the various pressure sensors and radar level meters, to decide whether or not the instruments' signals could be included in the LFE analysis. To begin with, every pressure sensor's wave signal

that was calculated on the basis of the pressure signal, was averaged into 10-minute blocks, which produced the variations of water level changes. The same averaging was carried out for the radar level meters. For every instrument the resulting 10-minute water levels of 27 October 2002 (storm day) were then compared with the water levels produced by the digital level meter at MP 3 (see appendix D.1). In the most reliable case, the trend line through this scatter would have a directional coefficient of 1. Please note that the directional coefficient, being dependent on the distance between the particular instrument and the digital level meter, can be somewhat influenced by wind driven set-up.

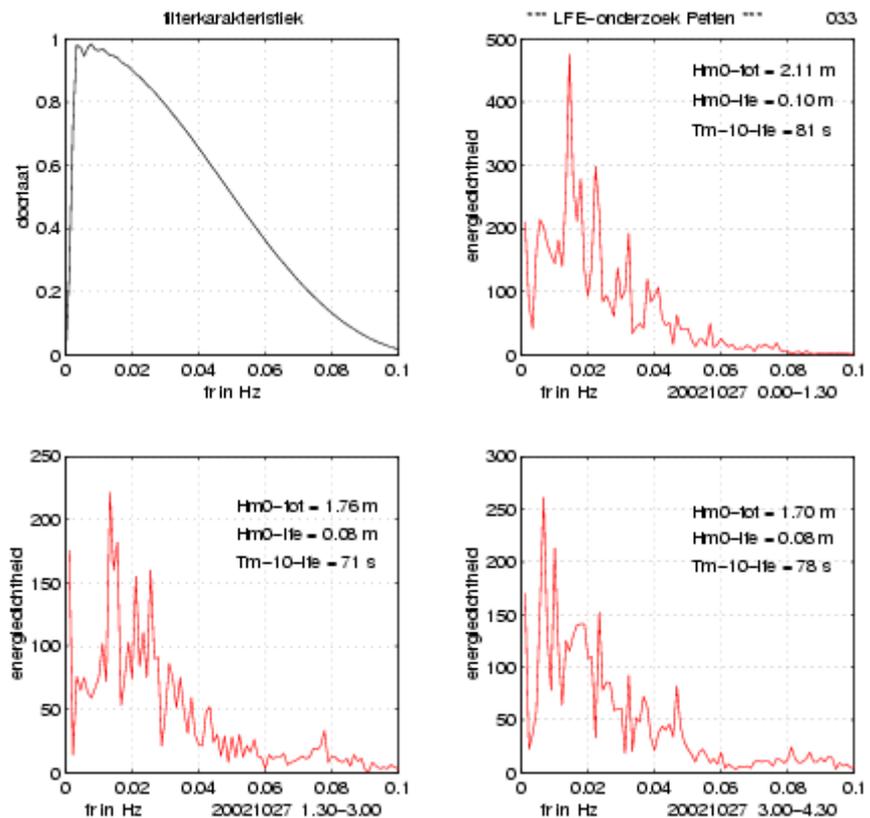
Based on the results in appendix D.1, a number of instruments was selected for the LFE analysis: radar 033 and pressure sensors 175, 181, 062 and 071. As the radar at MP 6 (063) systematically and wrongly generated long waves, this instrument is not further discussed. Pressure sensor 081 is positioned higher onto the dike and stands clear at low water (see kink in the scatter, appendix D.1), so that this instrument was also excluded from the LFE analysis.

#### 4.2.3 Definition of Low Frequency Energy

An analysis of the low frequency energy (LFE) first required the calculation of LFE wave spectra. The high frequency energy was therefore filtered out by twice calculating the running mean of the wave signal over 8.8 seconds. By twice calculating the running mean over 256 seconds, the very low frequencies (tide and seiches) were furthermore filtered out. The remaining data constitute the LFE spectrum, ie the long waves. The 15-minute spectra were averaged over 90-minute time blocks to arrive at a spectrum with fewer peaks. Figure 4.3 below gives an example of the spectra obtained after filtering out the high and very low frequencies, and shows the filter characteristic applied. Several characteristic wave parameters were then calculated by means of the LFE spectra:

- $H_{m0-TOT}$ : wave height  $H_{m0}$  of the total wave spectrum
- $H_{m0-LFE}$ : wave height  $H_{m0}$  of the filtered LFE spectrum
- $T_{m-10-LFE}$ : wave height  $T_{m-10}$  of the filtered LFE spectrum

**Figure 4.3** Example of LFE spectra and filter characteristic



#### 4.2.4 Low Frequency Energy Analysis

To gain an understanding of the relative share of LFE in the energy of the total spectrum (appendix D.2), an analysis was made of both a storm period (27-28 October 2002, see paragraph 4.4) and a very calm day with (seaward) eastern wind (13 October 2002). The variations of the above-mentioned wave parameters were plotted for space (from deeper water towards the dike) and time.

##### Developments through Time

Appendices D.3 and D.4 give graphs with the developments through time of parameters  $H_{m0-TOT}$ ,  $H_{m0-LFE}$  and  $T_{m-10-LFE}$  for three instruments: radar 033 and pressure sensors 175 and 062. This concerns the storm days 27-28 October 2002 as well as the calmer day of 13 October 2002. Apart from the figures illustrating wave heights and periods, the appendices include figures showing the ratio between wave heights  $H_{m0-LFE}$  and  $H_{m0-TOT}$ . This ratio is a measure for the relative share of long waves in the total wave height. The square of the wave length ratio is a measure for the relative share of long waves in the spectre's total wave energy. The above-mentioned appendices clearly indicate that on the Petten field site LFE is measured both on a stormy day such as 27 October 2002 and on a calm day such as 13 October 2002. On 13 October the  $H_{m0-LFE}$  is no more than 0.04 metre but this is a relative share of 10% to 20% in wave height, and of 1% to 4% in the

wave energy. It turns out that under storm conditions the low frequency wave height  $H_{m0-LFE}$  increases considerably (on 27 October to approx. 0.60 metre). Local generating of long waves causes this increase. On 27 October the relative share of long waves compared to the total spectrum is **approx. 10%**  
 $((H_{m0-LFE} / H_{m0-TOT})^2 = 0.30 * 0.30)$  .

#### Spatial Variations

Appendices D.5 and D.6 give the spatial variations of parameters  $H_{m0-TOT}$ ,  $H_{m0-LFE}$  and  $T_{m-10-LFE}$  for three different points in time (just before, at and after the peak of the storm). These points in time were selected on the basis of the figures giving the developments through time of the wave parameters in the above-mentioned appendices. Furthermore a random point in time on the calm day of 13 October 2002 was included in the appendix. These figures indicate that during the storm the wave height calculated from the total spectrum shows a sharp decrease towards the coastline, whereas the wave height calculated from the LFE spectrum is virtually constant towards the coastline. In addition a minor increase in wave period occurs between MPs 18 and 6, which is an indication of long wave generating, caused by wave breaking in the intermediate shallow area. As for 13 October, a minor increase occurs in wave height  $H_{m0-TOT}$ , from MP 18 towards the dike, which is caused by shoaling.

#### **4.2.5 Conclusions**

- At the Petten field site, long waves are measured under both calm and stormy conditions. On 13 October 2002, a calm day with a seaward wind and short waves at a height of approx. 0.40 metre at MP 3, the relative share of long waves in the total spectrum's energy amounts 1% to 4%. The wave height for the filtered low frequency part of the spectrum is approx. 0.04 m.
- Under storm conditions, the relative share of low frequency energy increases as a result of local generating of long waves. On 27 October, a storm day with waves up to approx. 5.5 metres at MP 3, values are measured up to approx. 0.60 metre for wave height  $H_{m0-LFE}$ . With their long periods ( $T_{m-10}$  is approx. 75 sec), these long waves do not run up against the dike, but result in a temporary water surface elevation of approx. 0.30 m. The relative share of long waves in the total spectrum's energy is approx. 10%.

### **4.3 Morphological Measurements**

Natural processes such as currents and waves lead to sediment transport which in turn results in constant changing of the cross shore profile at the Petten Sea Defence. As the cross shore profile has a direct influence on wave height, it is essential to monitor the bottom topography changes as part of wave measurements. During storm season 2002-2003, the sea bed was drawn up several times by means of sounding and groyne section measurements. It is important to know the maximum erosion depth during a storm, as this defines the maximum wave height. From the beginning of November 2002, the bottom topography is therefore measured continuously (3 times per 20 minutes) by means of an ASMIV sea bed staff near MP 6 in the surf zone to be able to define this maximum depth. No gales occurred since November, however, so that no interesting results could be collected and no further description of the ASMIV is given.

#### **4.3.1 Soundings**

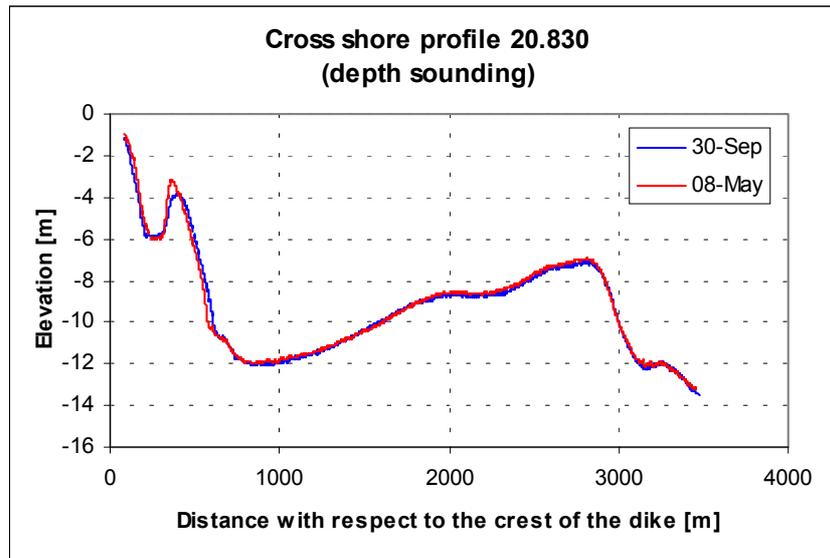
The soundings were carried out for 9 Jarkus sections over 5 groyne sections, being Jarkus section 20,830 (corresponding with the measuring section) as well as 4 sections north and 4 sections south of the measuring section.

The soundings were carried out on the following dates:

- 6 August 2002
- 30 September 2002
- 5 November 2002
- 18 December 2002
- 3 March 2003
- 8 May 2003
- 17 June 2003

Two soundings for Jarkus section 20,830 (corresponding with the measuring section) are given in figure 4.4 to illustrate the cross shore profile at the Petten Sea Defence. This figure shows that the cross shore profile at the Petten Sea Defence is subject to change in particular closer to the coastline. An account of all sounding results is digitally available in ASCII format (see paragraph 4.5.4).

**Figure 4.4** Soundings Jarkus section 20,830



#### 4.3.2 Groyne Section Measurements

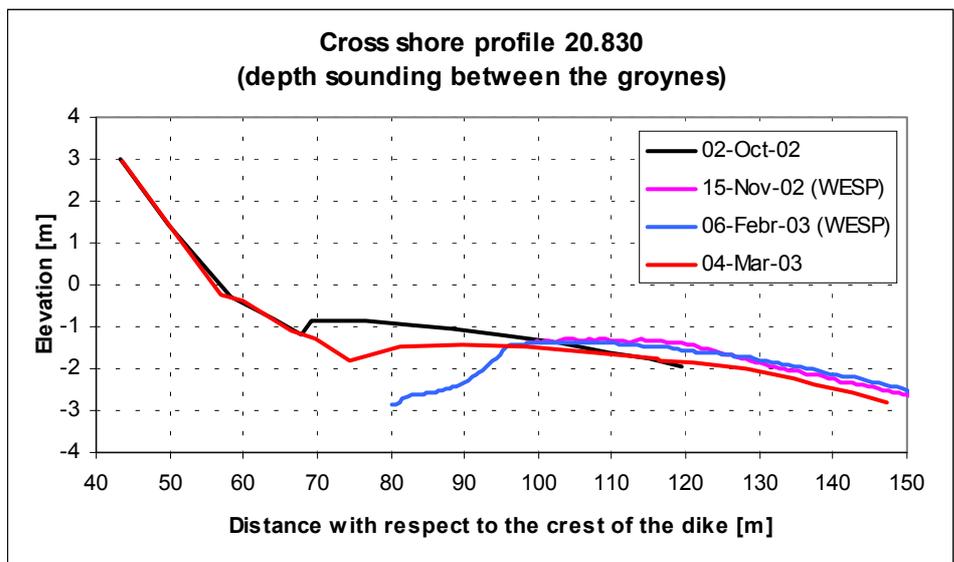
The groyne section measurements were carried out for 7 parallel sections in between the field site groynes, where the distance between the sections measured approx. 15 metres. A running measurement was taken of the sea bed level either by means of a 'Total Station' up to 100 to 150 metres from the crest of the dike, or it was measured further seaward by means of the 'WESP'.

The groyne section measurements were carried out on the following dates:

- 2 October 2002 (Total station)
- 15 November 2002 (WESP)
- 6 February 2003 (WESP)
- 4 March 2003 (Total station)

Figure 4.5 illustrates the results of the central section (section 20,830, corresponding with the measuring section). It clearly indicates that the bottom topography near the dike shows strong fluctuations during the storm season. The reading of 2 October gives a typical summer profile with a large quantity of sand at the toe of the dike. It follows from a comparison of the first three recordings that the sea bed near the dike was subject to severe erosion. This erosion was most likely caused during a gale at the end of October 2002 (see paragraph 4.4). During the calmer months early 2003, sand deposit was gradually transported into the profile, which raised the sea bed. The observation is made that figure 4.5 gives a mere random picture of a constantly changing process.

.....  
**Figure 4.5** Results of groyne section measurements Jarkus section 20,830



The bottom topography changes need to be considered not just in two dimensions (single section) but in three dimensions (interpolated over all 7 sections) to get a picture of – and to understand – the bottom topography changes within a groyne section.

The data required for 3D processing (results from sections 20,785, 20,800, 20,815, 20,830, 20,845, 20,860 and 20,875) are digitally available in ASCII format (X, Y, Z) (see paragraph 4.5.4).

#### 4.4 Storm Period Selection

##### 4.4.1 General

Storms measured are hind cast to enable quantification of the SWAN wave model reliability for storm conditions. The first criterion used for selecting periods which can produce interesting hind casts, is wind speed ( $> 15/s$ ). The related water levels which occurred, were included as well: storms at high water levels (from Dutch reference level *NAP* +1.80 m) can be very interesting for the analysis of the correlation between waves near the dike, wave run-up and wave overtopping. The combination of data availability, strong wind and high water provides interesting periods for, for example, hind casting by means of the SWAN wave model and for wave run-up analyses.

#### 4.4.2 Storms Occurred

The storms which occurred were selected on the basis of wind speeds measured. The selection of strong wind data, as described

in subparagraph 3.1.2, is based on the average wind speeds per hour measured at IJmuiden on behalf of the Royal Dutch Meteorological Institute (KNMI). Table 4.2 lists the periods with wind speeds exceeding 15 m/s for at least several hours. It furthermore includes the mean values for wind speed and wind direction which are derived from the 10-minute (field site) measuring results.

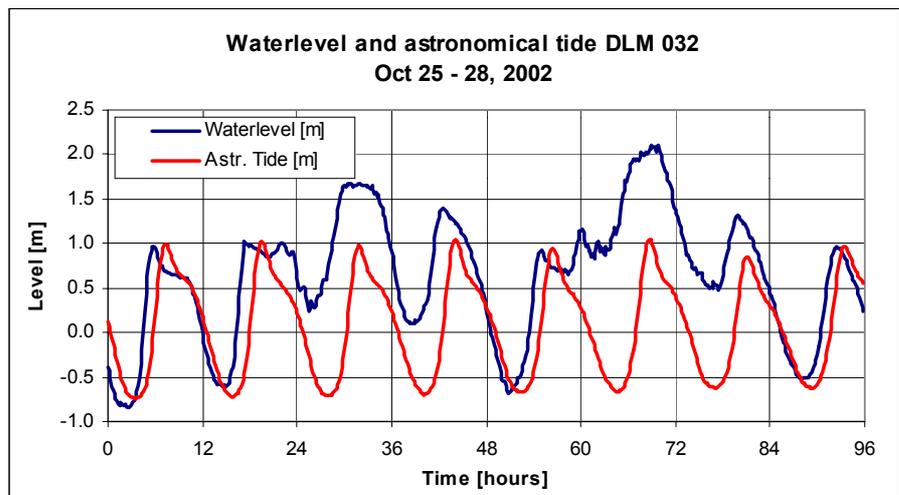
**Table 4.2** Storm periods during storm season 2002-2003

| Storm Period          | No. of Hours<br>Wind Speed<br>> 15m/s | Average Wind Speed<br>during Period u10<br>> 15m/s [m/s] |                    | Average Wind Direction<br>during Period u10<br>> 15 m/s [nautical degr.] |                    |
|-----------------------|---------------------------------------|--|--------------------|--|--------------------|
|                       |                                       | KNMI<br>IJmuiden   | Meas. Pt.<br>(064) | KNMI<br>IJmuiden   | Meas. Pt.<br>(064) |
| 26/10/02              | 12                                    | 16.7   | 18.3               | 259  | 255                |
| 27/10/02-<br>28/10/02 | 21                                    | 19.2   | 21.1               | 263  | 258                |
| 15/01/03              | 5                                     | 15.4   | 16.5               | 213  | 211                |
| 28/10/03              | 6                                     | 16.0   | 16.6               | 272  | 268                |
| 08/03/03              | 6                                     | 16.1   | 16.6               | 222  | 216                |
| 03/05/03              | 8                                     | 15.8   | 15.4               | 246  | 243                |

#### 4.4.3 Water Levels Measured

In addition to wind speed, wave height measured is another factor in determining to which extent a storm period is of interest. As the local water depth is a contributing factor in the maximum wave height, the highest waves are expected at higher water levels, which occur at a western to northwesterly storm during the high tide period. This type of storm can cause a significant wind driven set-up of the water level. The astronomical water levels and the actual water levels at Petten South (MP 3) taken from the Monitoring System Water (*MSW*) are both given in appendix E. This appendix shows that during one storm period only, ie **25-28 October 2002**, the water levels measured exceeded 1.80 metres (figure 4.6 below). A detailed description of this storm period is given in chapter 5.

**Figure 4.6** Water level and astronomical tide 25-28 October 2002



## 4.5 Data Processing & Storage

### 4.5.1 General

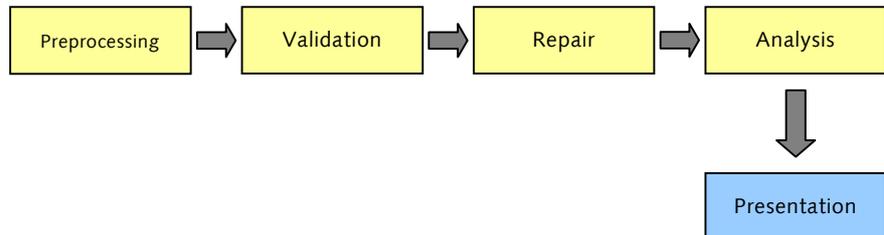
Wave data are generally collected in accordance with standard protocols and processed by a standard measuring system such as Measuring System North Sea of the Directorate North Sea, or measuring system ZEGE of Directorate Zeeland. These standard collection and processing procedures do not meet the processing levels required for specialized wave measurements such as those carried out near Petten. This type of measurements is usually processed by means of 'ad hoc' software. On the authority of the RIKZ, in 2002 the standard processing software programme Waves2002 was developed to streamline data processing and to improve the processing maintenance procedure. This programme was tested against measuring data from storm seasons 2001-2002 and 2002-2003. The present version of Waves2002 allows processing of separate days only, which would make processing of the full storm season very time-consuming and inefficient. The batch version will be developed in the second half of 2003, which will enable processing of longer periods of time without too much effort. The batch version shall eventually replace all ad hoc software used so far.

As this batch version was not yet available, data processing of storm season 2002-2003 was carried out using ad hoc software. The processing methods applied by this software are identical to those of Waves2002, so that a visual check could be generated of the results obtained. This check was for example carried out for storm period 25-28 October 2002.

#### 4.5.2 Data Processing

Processing and the eventual presentation of the measuring data in Waves2002, is done in 5 steps (figure 4.7). These steps enable the conversion of a raw measuring signal into a validated and if necessary repaired signal.

**Figure 4.7** Structure of Waves2002



##### *Pre-processing*

Pre-processing entails a general round of checks of the data read, which includes the deletion of for example major spikes and time errors (time data which are too fast or too slow) from the dataset. The signal is furthermore made equidistant in time, which means that the time differences between the measurements are given a constant value. The equidistant measuring data which have been checked and the processing reports are saved in various directories.

##### *Validation*

In the validation phase the signal is carefully checked after entry of the testing criteria (selected by the user), and any missing or rejected parts are automatically corrected. The signal is first checked for (smaller) spikes and then for stagnations in the signal. The validated signal, which can be used for wave analysis, and the processing reports are saved in various directories.

##### *Repair*

In the repair phase the user can, if required, manually repair or reject the validated signal. This type of data correction is very labour intensive and is therefore generally used for the analysis of very valuable storm periods only. This editing procedure is completed by saving the results in the designated directories, as is done for the previous phases.

##### *Analysis*

In the analysis phase, values are calculated with the validated (and if required repaired) measuring signals for a large number of characteristic descriptive parameters. A distinction is made to

this purpose between wave analysis (analysis of swell and wind waves) and low frequency analysis, ie the analysis of signals generated by complementary instruments such as barometer, DLM and anemometer. The low frequency analysis calculates 10-minute means of the relevant signals.

#### *Presentation*

This final phase enables the drawing of graphs and tables onto one or more sheets, depending on the output required. Reference is made to the Waves2002 user manual [Dekker et al, 2002] for a detailed description of the available options.

#### **4.5.3 Software Settings**

The possibility to select for example the test type and testing criteria (in the validation and consequent phases) leaves room for the final measuring signal, which is validated and if required repaired by means of Waves2002, to be influenced by the programme user's (subjective) judgement. This subparagraph therefore lists the settings as applied in the ad hoc software for data processing of storm season 2002-2003, in order to streamline data processing to some extent and to minimise the influence of (subjective) judgement on the final results. These settings shall in first instance also be applied in Waves2002 for processing of other storm seasons.

#### *Settings for Field Site, Instruments and Cross Shore Profile*

These settings depend on the field site set-up and can vary for every storm season and even within the storm season. No settings are consequently given.

#### *Validation Settings*

In the validation phase, any minor spikes of the data signal are deleted on the basis of the sigma/delta test with coefficient 4. For the stagnation criterion, a period of 6 seconds was set for wave signals and 12 seconds for current signals. No stagnation criterion was applied for slow signals such as atmospheric pressure, whereas a value of 2 seconds was set for the interpolation criterion. Reference is made to the Waves2002 user manual [Dekker et al, 2002] for further information on these criteria.

#### *Repair Phase Settings*

Processing of storm season 2002-2003 did not include repairs to signals. Any repairs of data gaps and the deletion of unreliable data for (future) processing of other storm season, are carried out on the basis of the Waves2002 user's common sense.

#### *Analysis Phase Settings*

In the ad hoc software, a minimum quality of 90% was set for all instruments with respect to determining spectra and parameters. The directional correction value was set at -2. These values shall in first instance also be applied in Waves2002 for processing of other storms

seasons. Reference is made to the Waves2002 user manual [Dekker et al, 2002] for background information on these settings. A value of 20 minutes was selected for the block length (ie the duration of the signal blocks to be analysed). This duration is long enough with respect to signal reliability, and short enough to be able to speak of a stationary signal within the block, which is generally the case for block lengths shorter than approx. 30 minutes. In the analysis the water level measured by the DLM (032) was used as a reference water level.

#### **4.5.4 Data Storage**

##### Central Data Storage

The (raw) measuring data produced by the Petten field site have so far been saved on CD-ROM. The data processed and the related processing reports are stored on a designated PC in room no. 8.12 at the *R/KZ* in The Hague, as well as on a network drive (Hrmeet\_sbw5). All present and future Petten measuring data which are processed (including the data for storm season 2002-2003), as well as the data for other future field sites which are part of the *HR-meet* project, shall be stored on this drive. In future all important data shall furthermore be stored on DONAR/WADI.

##### CD-ROM Data Storage

Various data have been stored onto the CD-ROM enclosed with this report to improve data access for further analyses (such as SWAN hind casts):

##### 1) Day Files (Validated at Signal Level):

- batch files (gm files, rr files, g2 files, tm files and hm files)
- gp files (parameters), gs files (spectra) en gd files (directional spectra)
- processing reports (results of general validation)

##### 2) Storm Data:

- raw data
- processed data

##### 3) Morphological Measurements:

- soundings (ASCII format (X, Y, Z))
- groyne section measurements (ASCII format (X, Y, Z))

A document giving a description of the structure of the various files mentioned above is also added.

The CD-ROM furthermore includes this storm season report in PDF format.

## 5 Report on Storm Period 25-28 October 2002

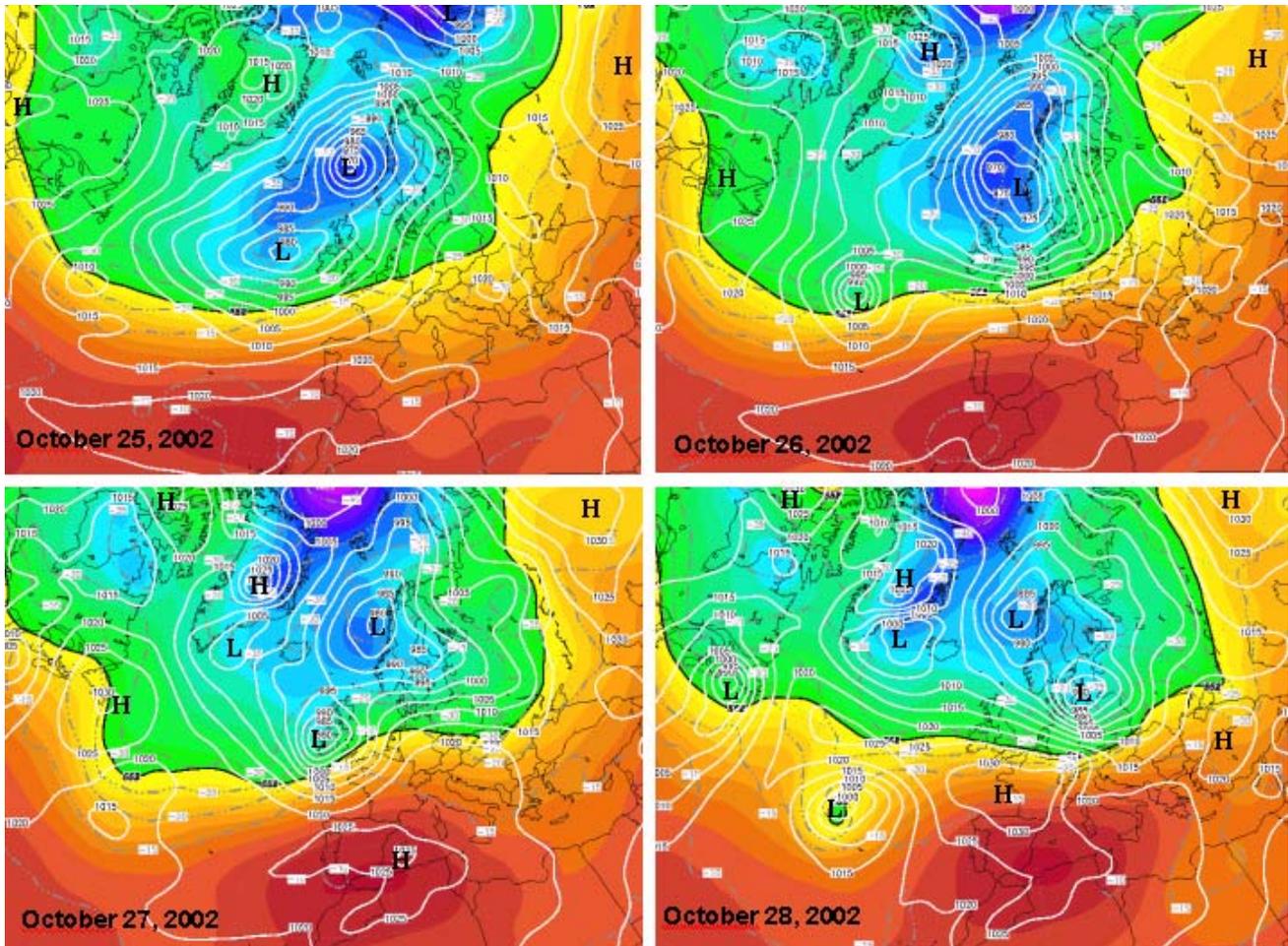
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In chapter 4 a very interesting storm period was selected on the basis of wind speeds and actual water levels: the period from 25 up to and including 28 October 2002. The present chapter discusses this storm period in detail, not only by giving a general description of the storm conditions but also by paying attention to both wind and wave conditions.

### 5.1 Storm Conditions

On Sunday 27 October 2002, a storm depression passed from Ireland via the North Sea and Denmark to the Baltic Sea (figure 5.1). The central pressure was at its minimum when the depression passed north of the Netherlands: 973 hPa around 13:00 hours local time. Between 10:00 and 21:00 hours, the average 10-minute wind reached maximum values of 10 Beaufort at several locations in the western and later on the northern provinces of the Netherlands. In the early hours of the afternoon, several measuring points in the western coastal provinces measured an average 10-minute wind force 11, which constituted a gale. The highest average per hour wind speed was 28 m/s at Flushing (province of Zeeland) and at IJmuiden. By midnight the storm near the eastern Wadden Sea had subsided to wind force 9. Along the west coast, the wind had by then subsided to wind force 7.

.....  
**Figure 5.1:** Atmospheric pressure 25 - 28 October 2002 [Source: Wetterzentrale Karlsruhe]



## 5.2 Wind Measurements

The wind directions and wind speeds were measured at MP 6 in front of the dike and at MP 13 behind the crest of the dike. Appendix F (figure F.1) gives the results (10-minutes means) as well as the values (averages per hour) measured on behalf of the Royal Dutch Meteorological Institute (KNMI). This appendix clearly shows that the wind directions measured near the field site are virtually identical to the IJmuiden values, whereas the wind speeds are slightly different. During the period 25-27 October, the wind direction varied between south and west. At 16:00 hours on 27 October the wind veered northwest, after which it stayed approx.  $300^\circ$ . There were strong wind speed fluctuations during the storm period. The maximum wind speed near the site was approx. 29 m/s, whereas IJmuiden registered a maximum wind speed of approx. 25 m/s.

### 5.3 Water Level Measurements

The water levels measured by the digital level meter at MP 3 (Petten South) and the astronomical tide are given in figure 4.6 above. This figure shows that during the period 25-28 October 2002 (0-96 hours in figure 4.6), the wind driven set-up increased by over one metre on 26 October. After a gradual decrease, the wind driven set-up increased once again to a maximum value of approx. two metres on 28 October. The highest water level was approx. Dutch reference level *NAP* +2.10m.

### 5.4 Wave Measurements

For a number of points in time, the absolute (20-minute) spectra for several instruments are given to illustrate the energy density spectrum changes through time (see appendix 7, figures F.3-F.7). This appendix also includes the standardised spectra to gain an understanding of the changes in spectrum form through space (landward). The points of time were selected on the basis of the wind speeds and water levels measured:

- 27 October 12:00 hours, several hours before the peak of the storm
- 27 October 16:00 hours, peak of the storm
- 27 October 20:00 hours, maximum water level and north-westerly wind
- 27 October 23:20 hours, several hours after the peak of the storm
- 28 October 06:00 hours, end of the storm (wind speed < 15 m/s)

A remarkable conclusion which can be drawn from appendix F, is that the peaks of the spectra measured are relatively wide, which can be explained by the wind being south to south-westerly for a relatively long period of time and not veering round to the northwest until the end of the storm. The appendix furthermore shows that in the case of wave propagation towards the dike, energy is redistributed over both higher and lower frequencies. The redistribution to higher frequencies is caused by wave breaking, while the redistribution to the lower frequencies is caused by long wave generating. This generating even results in the energy density spectrum shifting to the left (see spectra of MP 6).

To gain an understanding of the developments in wave height  $H_{m0}$  and wave period  $T_{m-10}$  during the storm period, appendix F (figure F.8) illustrates the variations of both parameters through time (per day). This concerns (in as far as possible) the same instruments as those for which spectra were constructed at an earlier stage (011, 021, 033, 161, 175 and 062). Figure F.8 shows that during the first two storm days, wave height reaches

a maximum of over 5 metres at MP 1 on 26 October. The wave period increases from approx. 6-7 seconds to approx. 8 seconds. After a sharp decrease in wave height on 26 October, the wave height shows a sharp increase on 27 October to more than 6 metres at MP 1, and approx. 3 metres at MP 6. The wave period then measures over 10 seconds. After midnight the wave height and wave period gradually decrease.

The observation is made with respect to figure F.8 that, contrary to the other instrument readings, wave period  $T_{m-10}$  measured by the radar at MP 6 (O63), shows strong fluctuations. It furthermore measures considerably higher periods. An explanation is that the radar at MP 6 continually measures (erroneously) long waves. As the low frequencies in particular are a major factor in the  $T_{m-10}$  period, this systematic radar error leads to the registration of excessively high periods.

Paragraph 3.2 above discusses the differences between the signals registered by the radar level meter and the pressure sensor at MP 6. This difference clearly substantiates the wave height differences in figure F.8

### 5.5 Wave Run-Up Measurements

Wave run-up against the dike is measured by means of a run-up staff which is placed in the dike revetment. The bottom of this staff, measuring 8 metres in length, is located at 5.70 metres above Dutch reference level *NAP*. The water layer thickness is measured along the run-up staff by means of pressure sensors 101, 111 and 121, which are placed in the slope of the dike. During storm period 25-28 October 2002, the run-up was measured between 06:00 hours and 10:00 hours on 26 October, and between 18:00 hours and 24:00 hours on 27 October. The run-up staff data were of reasonably good quality on the first day, but of poor quality on the second day due to many spikes and preferential values. Only the lowest of all sensors (sensor 101) measured the thickness of the run-up water layer. The other sensors are located higher onto the slope, and stood clear. On 26 October some 30 low run-ups to approx. 6.10 metres above Dutch reference level *NAP* were measured. On 27 October many more as well as much higher run-ups to approx. 7 to 8 metres above *NAP* are measured. The validated run-ups and water layer thicknesses at the staff bottom are given in appendix F (Figure F.2).

## 6 General Conclusions and Recommendations

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This chapter draws the general conclusions with respect to field site performance and data reliability. It furthermore suggests possible steps for improving the field site's shortcomings. Reference is made to *Projectplan veldmetingen Pettemer zeevering 2003* [Jacobse, 2003] for a more detailed plan with the necessary points for improvement and the actions planned.

- There was a sharp improvement on data availability in comparison with previous season. The minimum registration percentage of 80, which was an objective in the above-mentioned project plan, was achieved only just. An even higher registration percentage is feasible for the following seasons. In the short term, an inventory of the failing mechanisms and their chance of occurrence shall be given to this purpose. This inventory can be the basis for an efficient improvement of the field site's solidity.
- As it turned out, the results generated by the radar level meter and the pressure sensor at MP 6 in the surf zone, showed such differences that they are unacceptable. The strong recommendation is therefore made to research the reliability of the present measuring techniques in the surf zone. An inventory needs to be made of the influences for example of sediment, of salinity and current onto the pressure signal, and of spray and wave breaking (incapsulated air) onto the radar signal. The desired measuring accuracy (for example for model input) needs to be determined. Such research can be the first step to achieving a method for measuring wave breaking.
- The low frequency energy measured was analysed to gain an understanding of the relative share of long waves in the total amount of spectrum energy. This analysis shows that long waves are measured even under calm circumstances. On 13 October 2002, a calm day with seaward wind, the relative share of long waves in the total spectrum energy was 1% to 4%. During storms, the relative share of the low frequency energy strongly increases as a result of local generating of long waves. On storm day 27 October 2002 the relative share of long waves in the total spectrum energy was approx. 10%.

It is strongly recommended that that a more detailed analysis of the measuring data is made to gain an understanding of the occurrence of long waves and of the extent to which these waves reflect against the dike. This could be an analysis of the current velocity measurements at MP 17. Model research with models such as

Triton and Odiflocs is recommended to gain an understanding of the influence of long waves onto wave run-up and wave overtopping.

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## Appendix A Photographs of Instrument Set-Ups and Equipment

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### List of photographs

|                |                         |  |
|----------------|-------------------------|--|
| Photograph 1:  | MPs 1 and 2:            | directional waverider                                    |
| Photograph 2:  | MPs 6, 7 and 8:         | pressure sensors   |
| Photograph 3:  | MP 9:                   | wave run-up staff with pressure sensor MP 11 to its left |
| Photograph 4:  | MP 6:                   | radar level meter  |
| Photograph 5:  | MP 17:                  | Aquadopp current meter                                   |
| Photograph 6:  | MPs 10-12:              | pressure sensors   |
|                | MP 19:                  | video cameras  |
| Photograph 7:  | MP 19:                  | video cameras  |
| Photograph 8:  | MP 14:                  | video camera   |
| Photograph 9:  | MPs 6, 17, 16, 3 resp.: | set-ups near the dike                                    |
| Photograph 10: | MP 6:                   | capacitance wire mounted onto measuring post             |
| Photograph 11: | MP 6:                   | ASMIV sea bed staff                                      |
| Photograph 12: | MP 6:                   | ASMIV sea bed staff (sensors)                            |



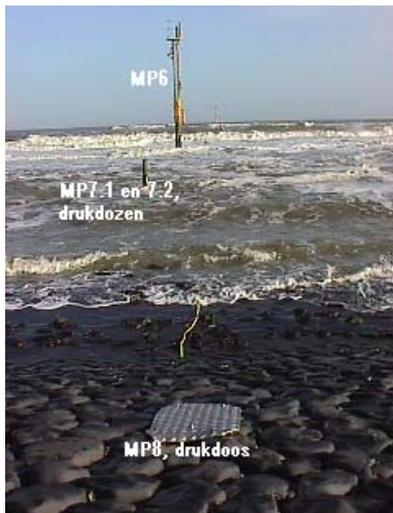
.....

Photograph MP1 and MP2  
**1** directional waverider



.....

Photograph MP6, MP7 en MP8  
**2** pressure sensors





.....  
Photograph Wave run-up staff  
**3** with pressure sensor  
MP 11 to its left

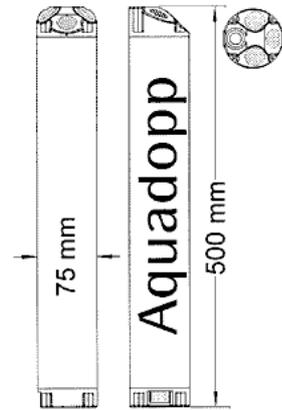


.....  
Photograph MP6 radar level  
**4** meter

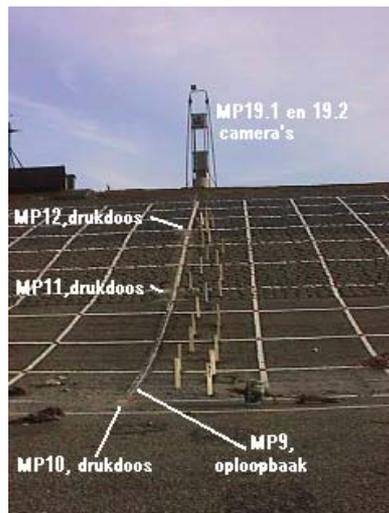




.....  
Photograph MP17 Aquadopp  
**5** current meter



.....  
Photograph MP10 t/m 12  
**6** pressure sensors,  
MP19 videocameras





.....  
Photograph MP19 videocameras  
**7**



.....  
Photograph MP14 videocamera  
**8**



.....  
Photograph MPs 6, 17, 16, 3  
**9** resp.: set-ups near  
the dike





.....  
Photograph 10 MP6 capacitance wire mounted onto measuring post



.....  
Photograph 11 MP6 ASMIV sea bed staff



.....  
Photograph 12 MP6 ASMIV sea bed staff





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Figure B.4 Data availability over December 2002

Figure B.5 Data availability over January 2003

Figure B.6 Data availability over February 2003

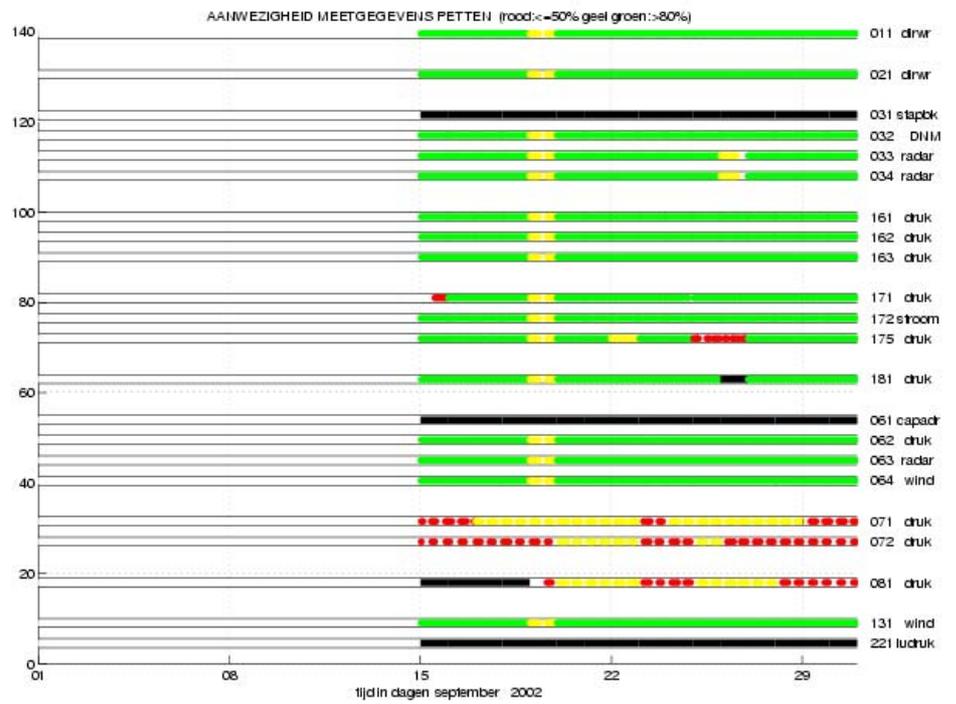
Figure B.7 Data availability over March 2003

Figure B.8 Data availability over April 2003

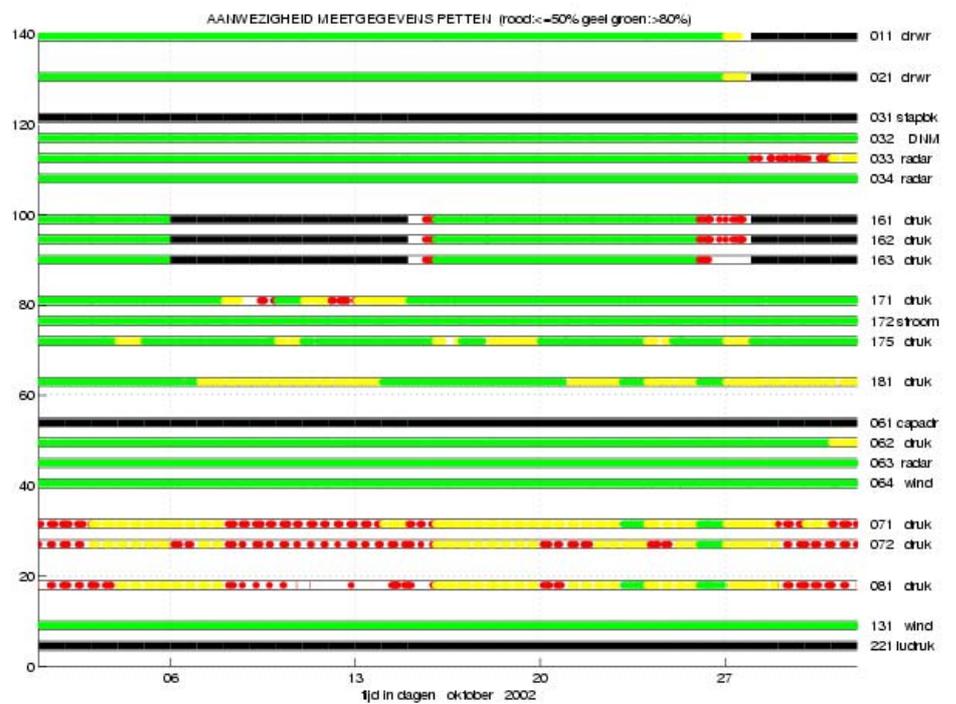
Figure B.9 Data availability over May 2003



**Figure B.1** Data availability over September 2002

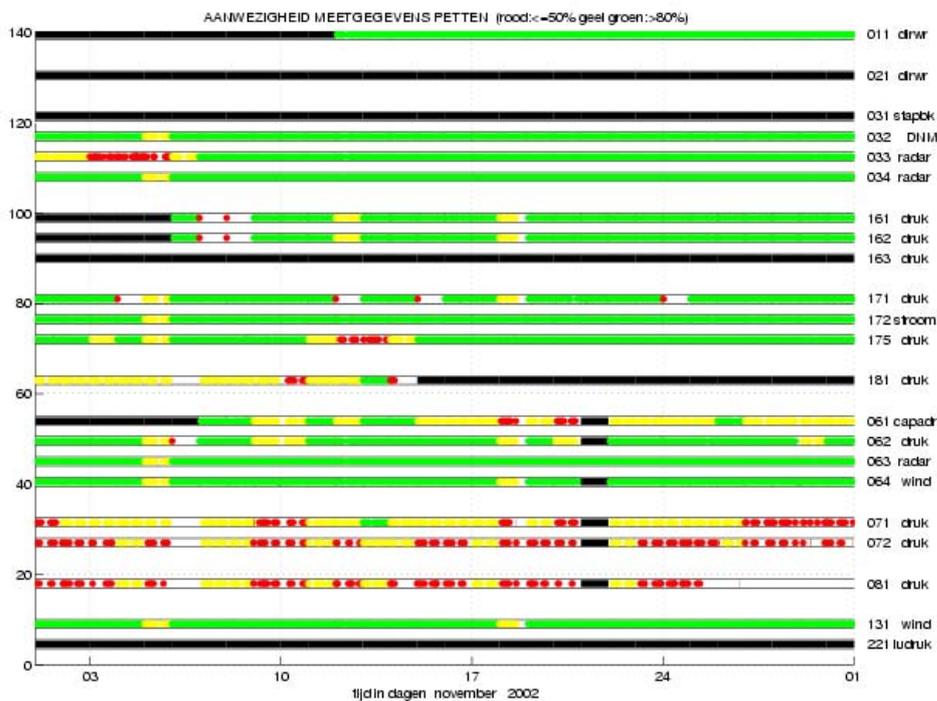


**Figure B.2** Data availability over October 2002

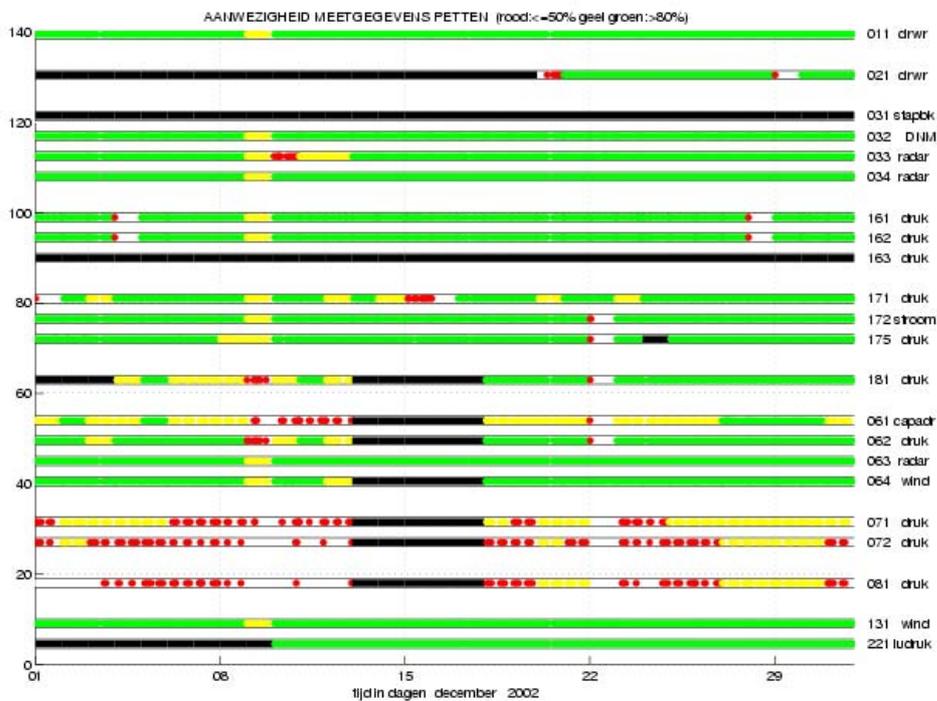




**Figure B.3** Data availability over November 2002

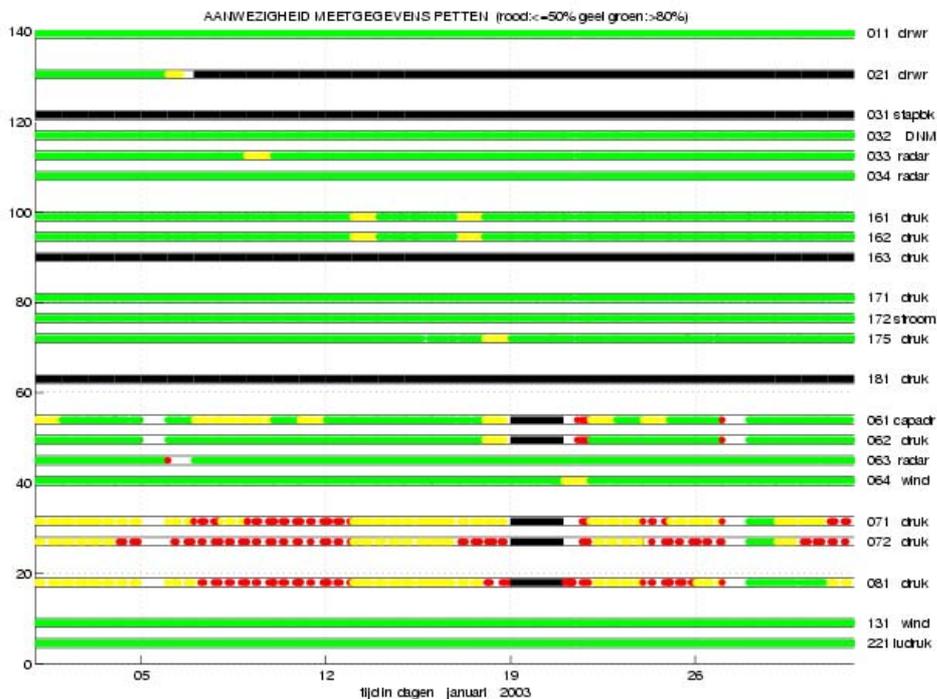


**Figure B.4** Data availability over December 2002

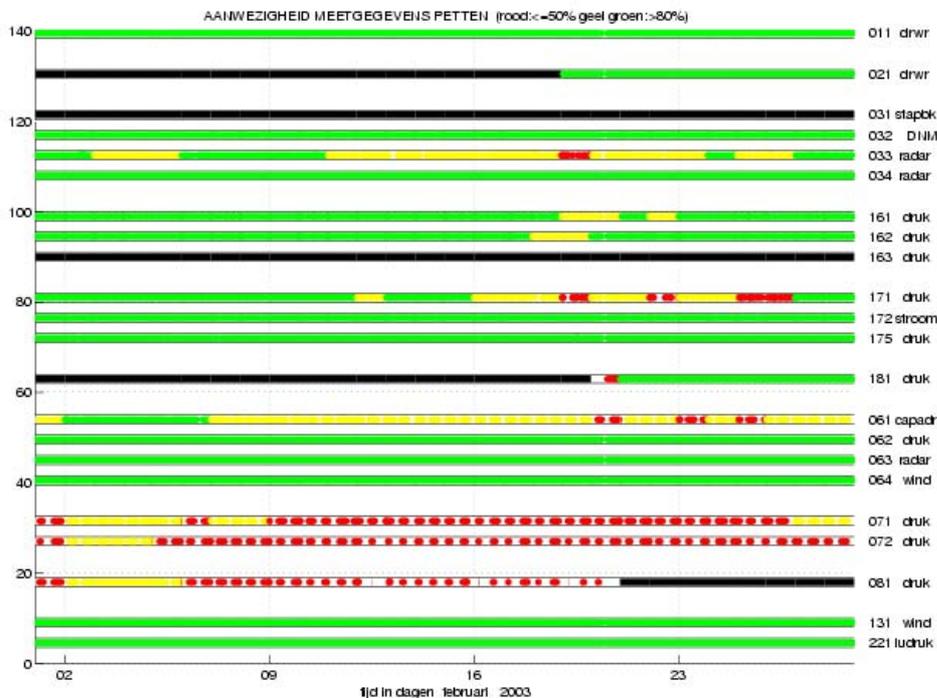




**Figure B.5** Data availability over January 2003

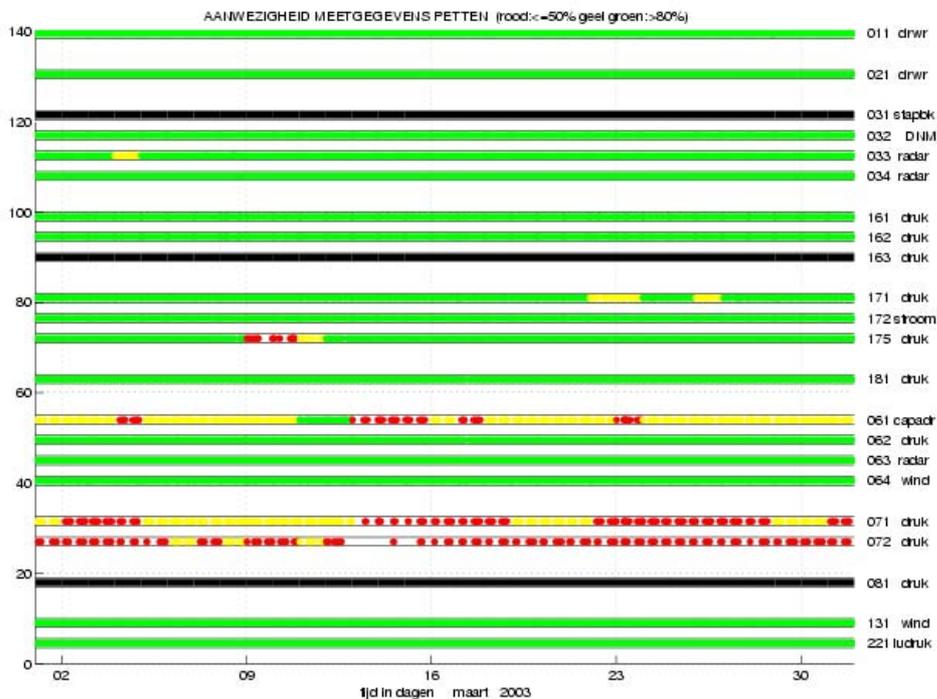


**Figure B.6** Data availability over February 2003

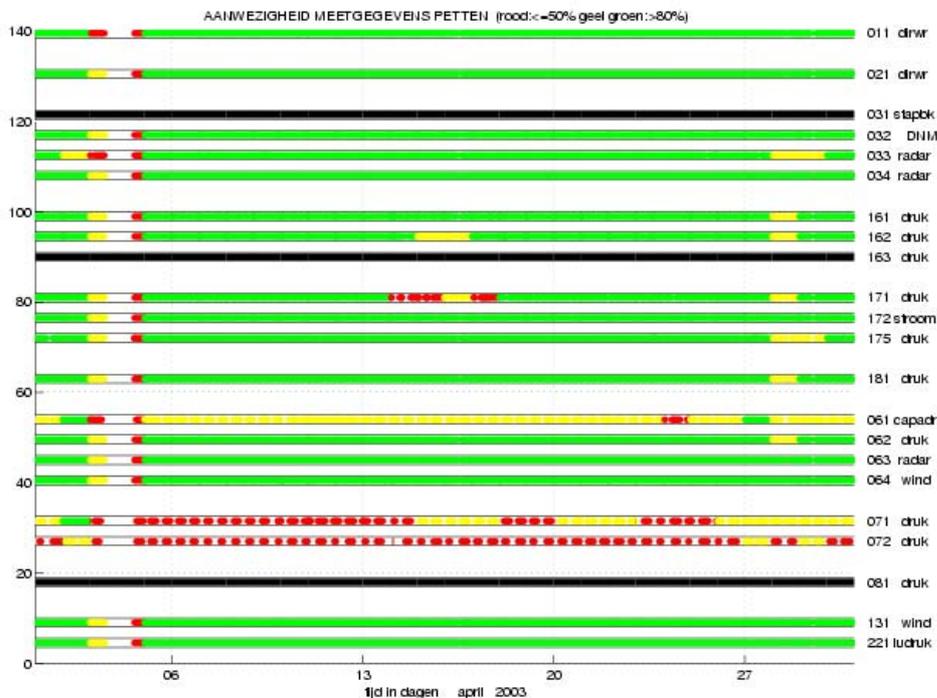




**Figure B.7** Data availability over March 2003

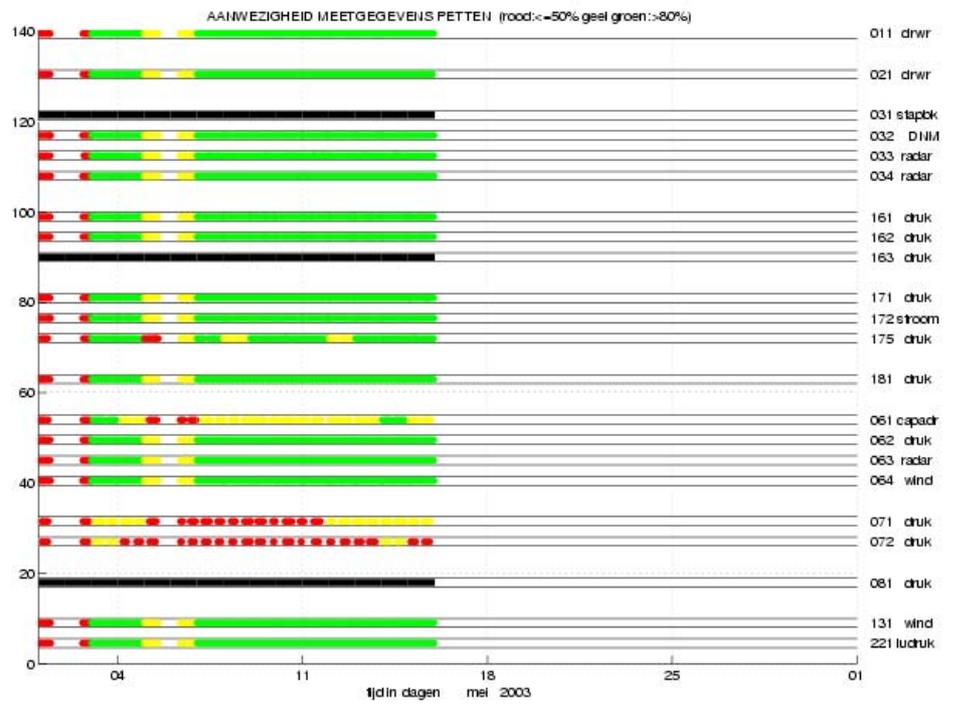


**Figure B.8** Data availability over April 2003





**Figure B.9** Data availability over May 2003





## Appendix C Exceedence Curves $H_{m0}$ en $T_{m-10}$ over Storm Season 2002-2003

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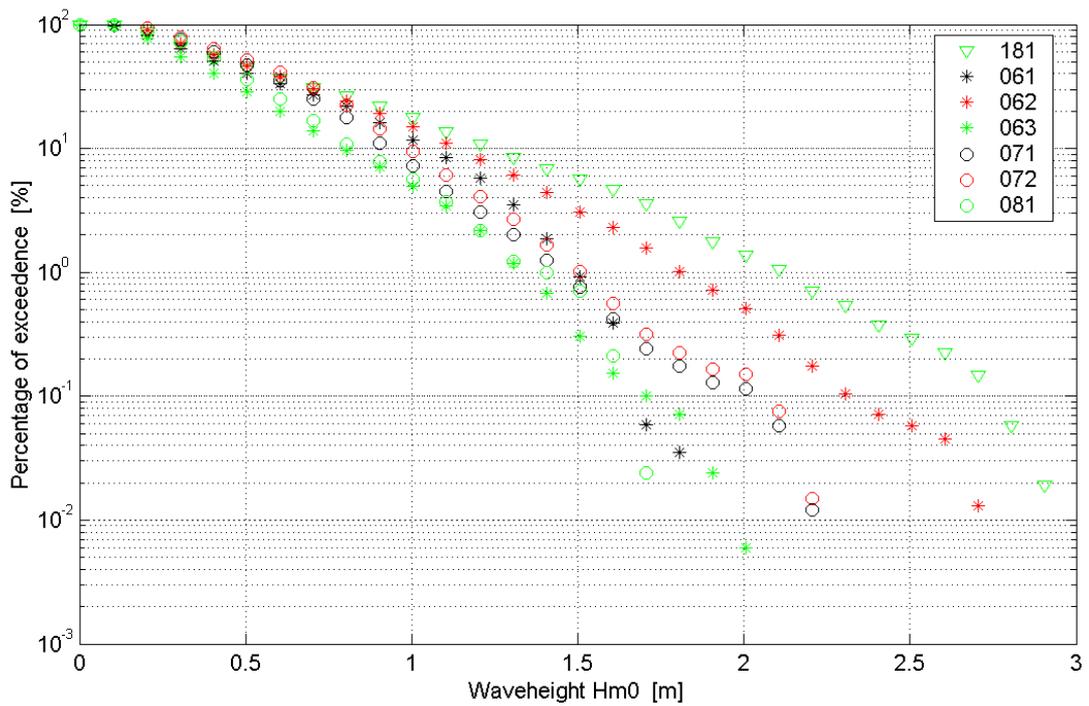
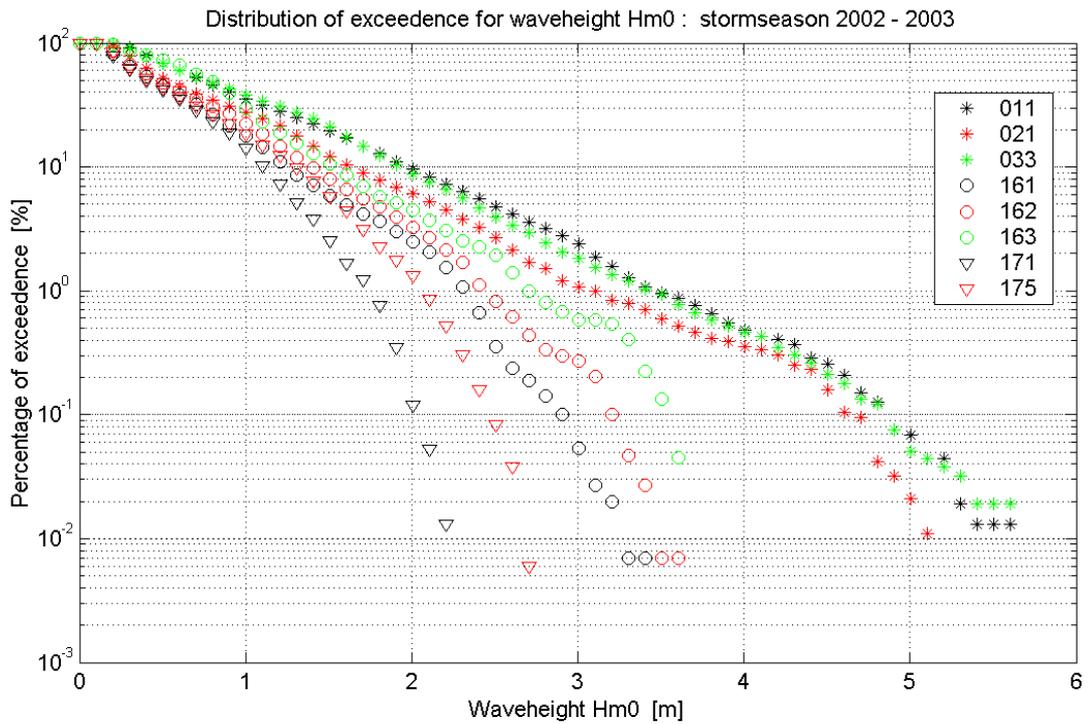
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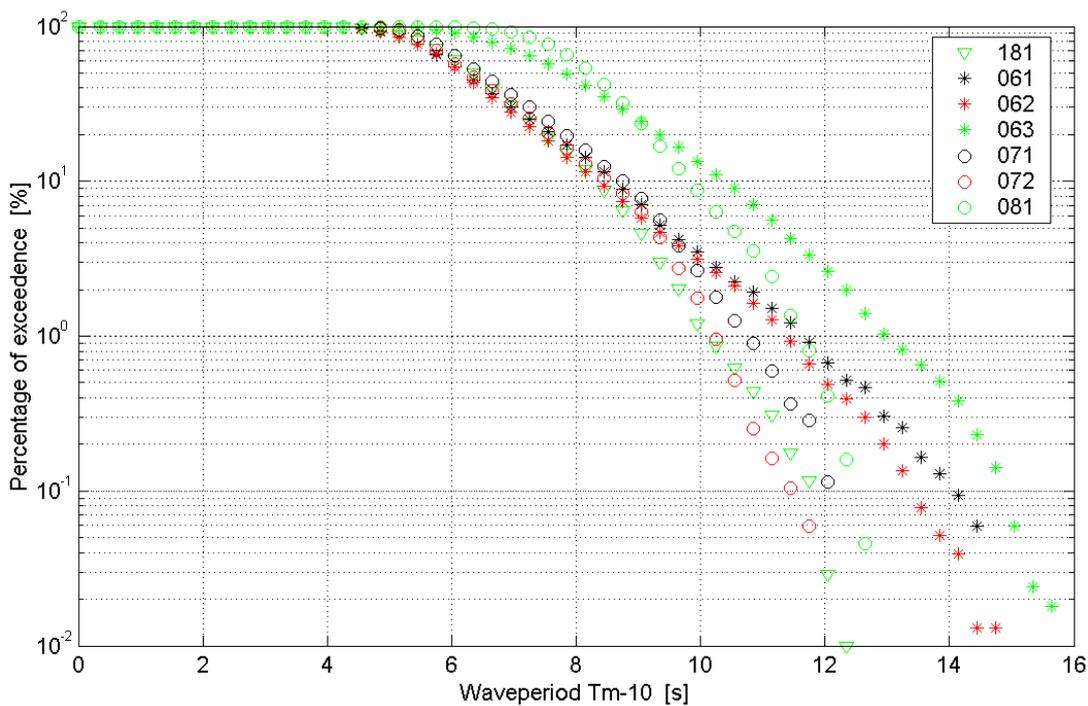
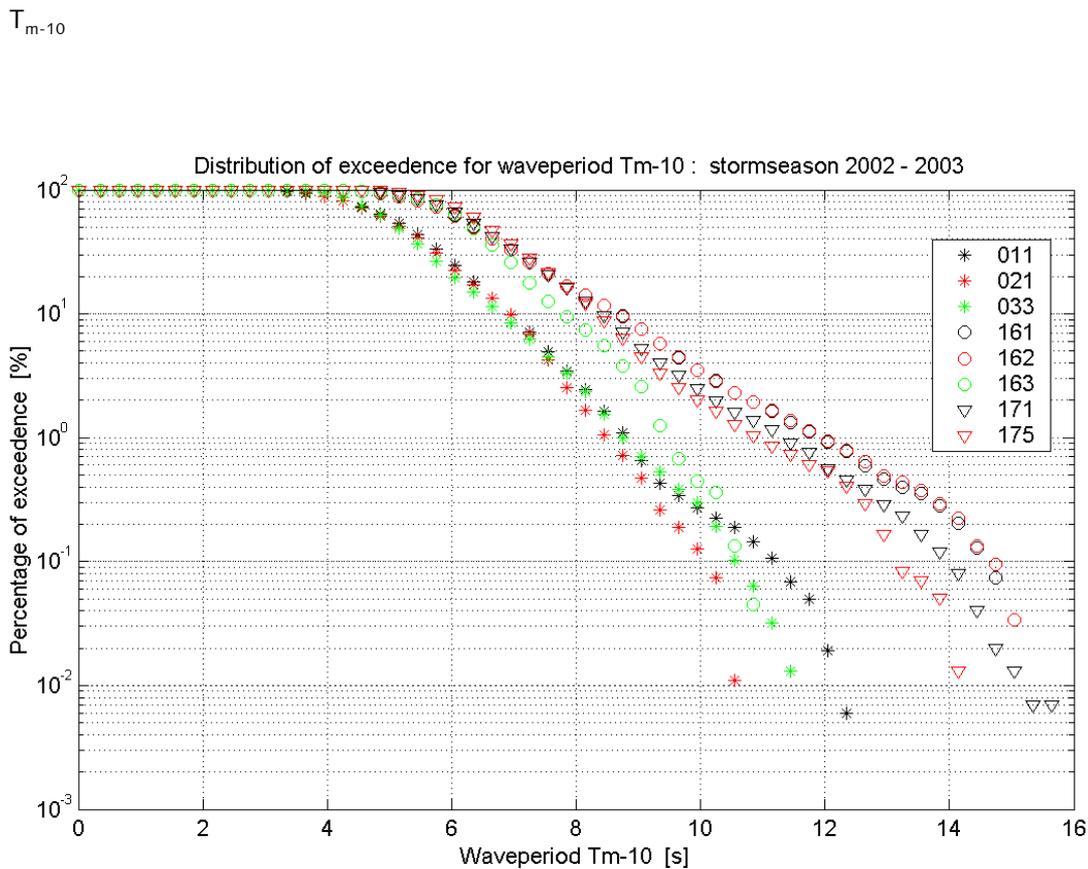
**Figure C.1** Exceedence Curves

$H_{m0}$



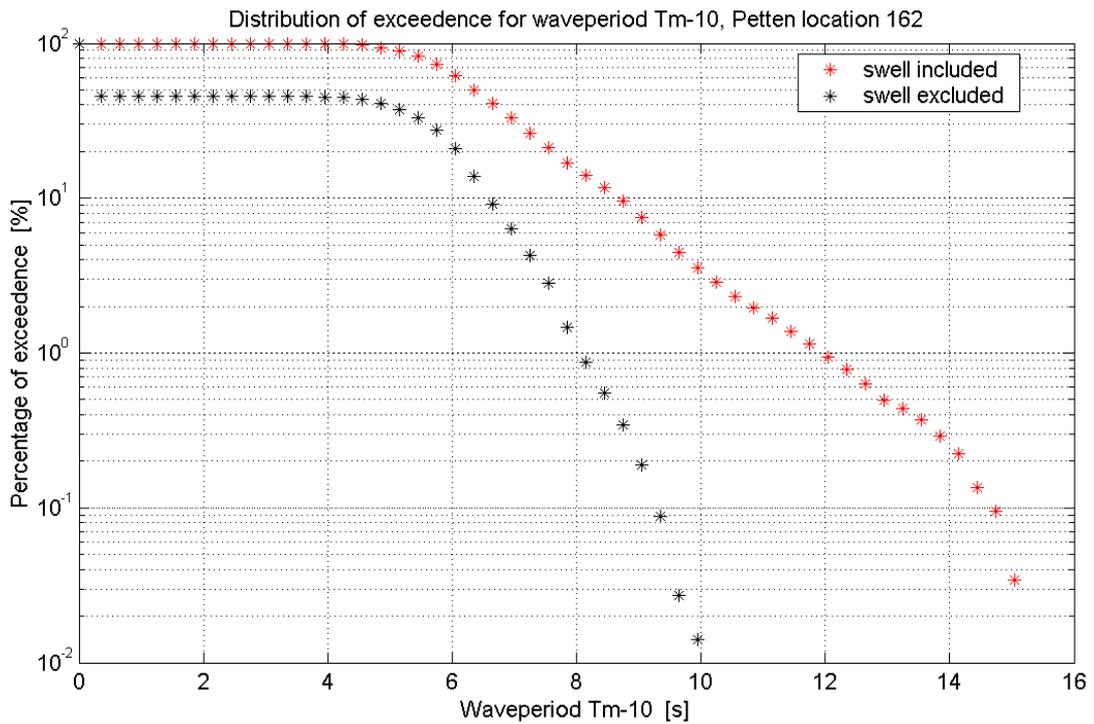
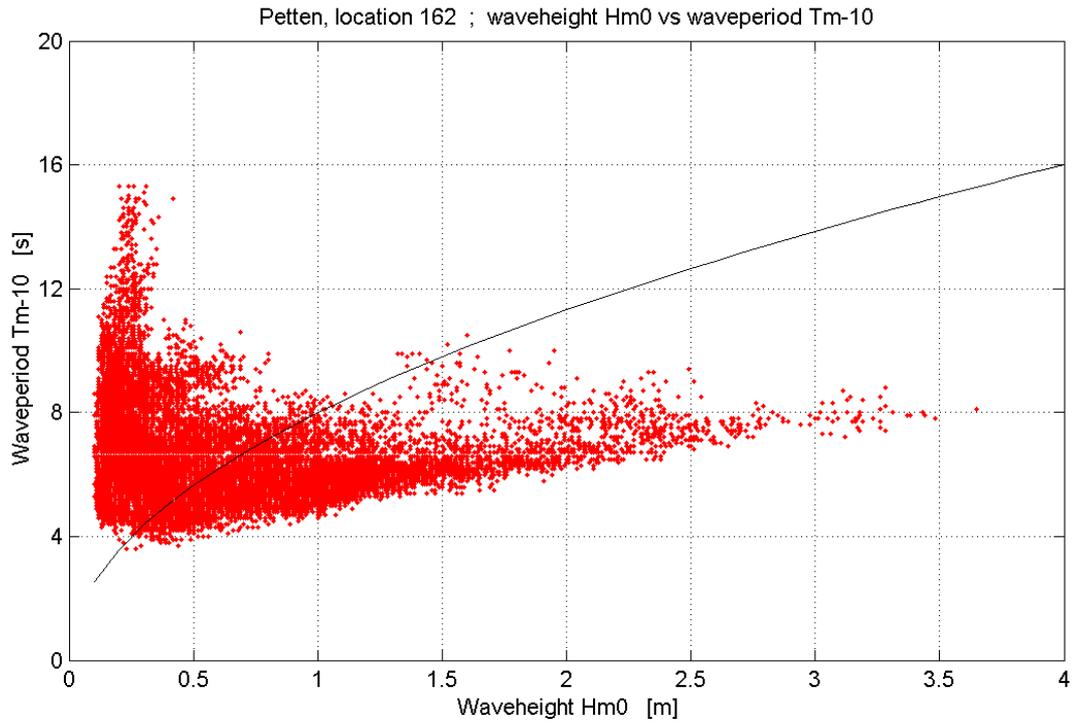


**Figure C.2** Exceedence Curves





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**Figure C.3** Swell for pressure sensor 162





## Appendix D Long Wave Analysis Results

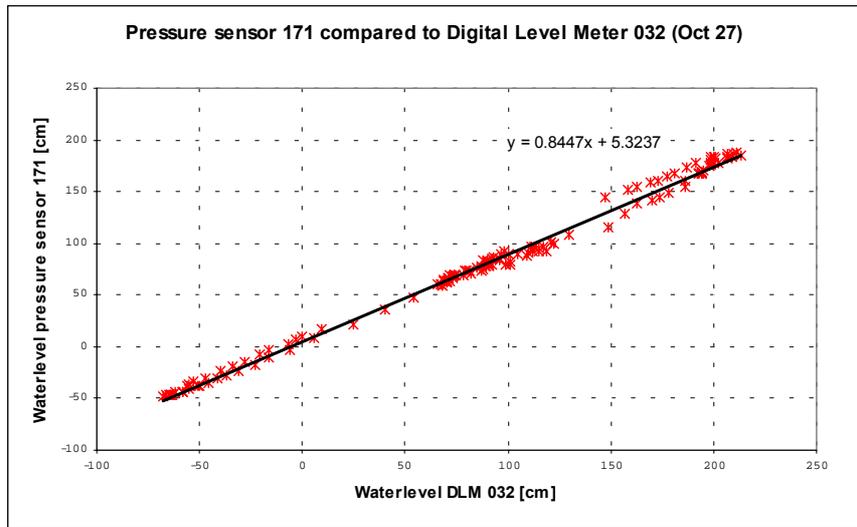
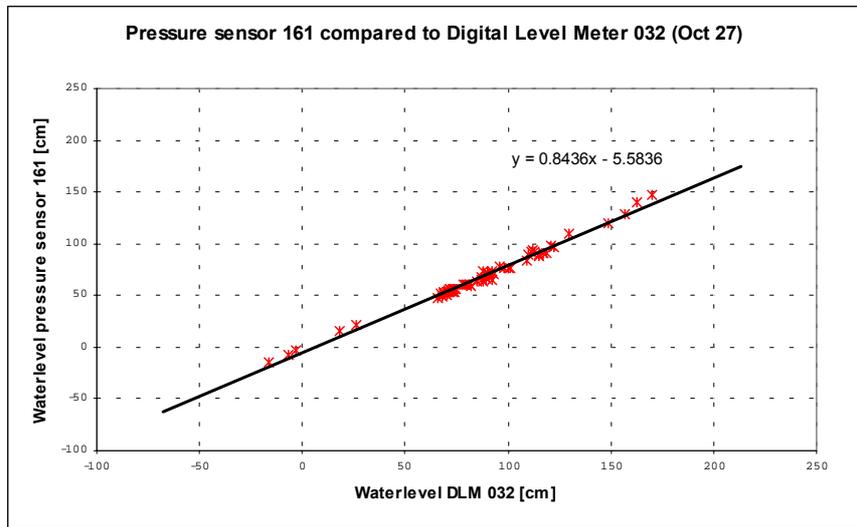
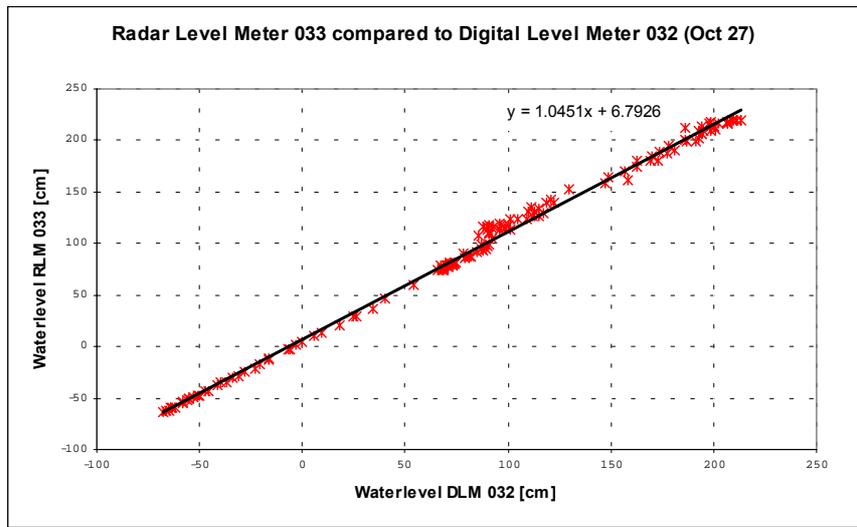
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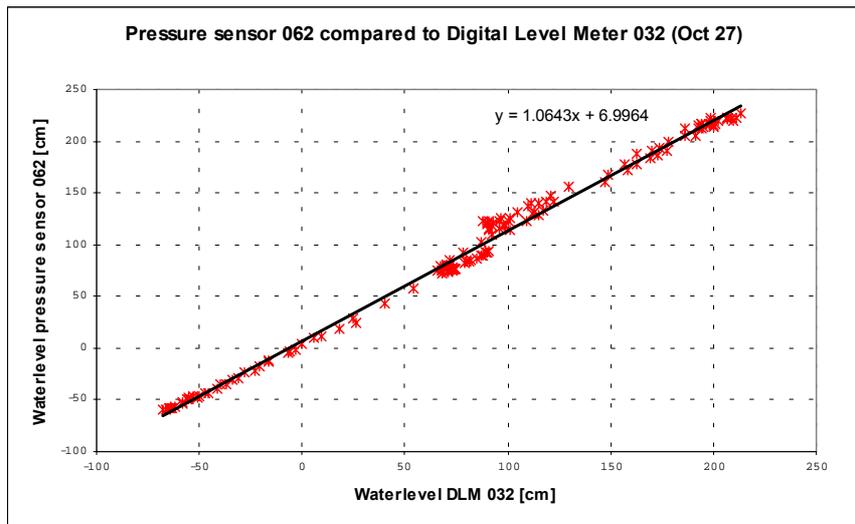
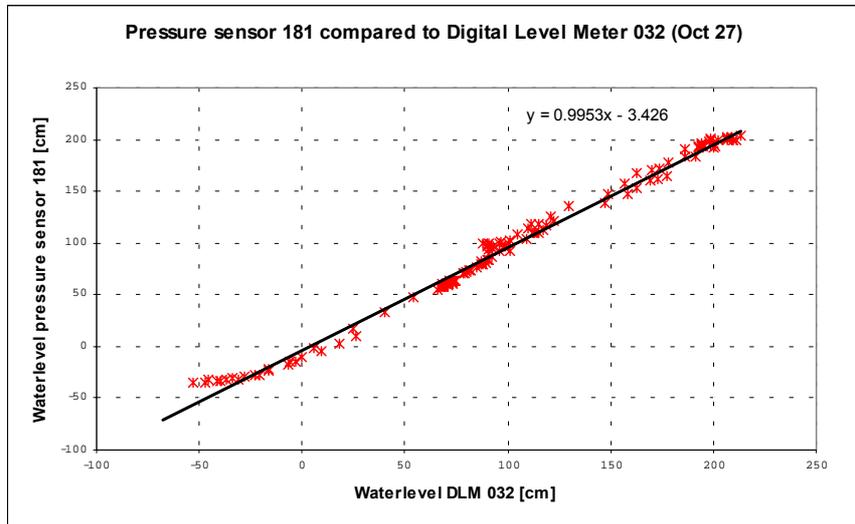
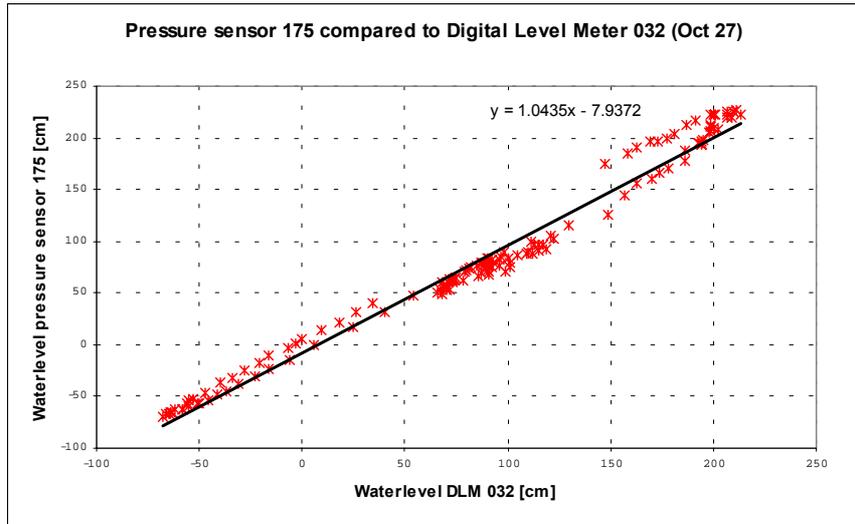
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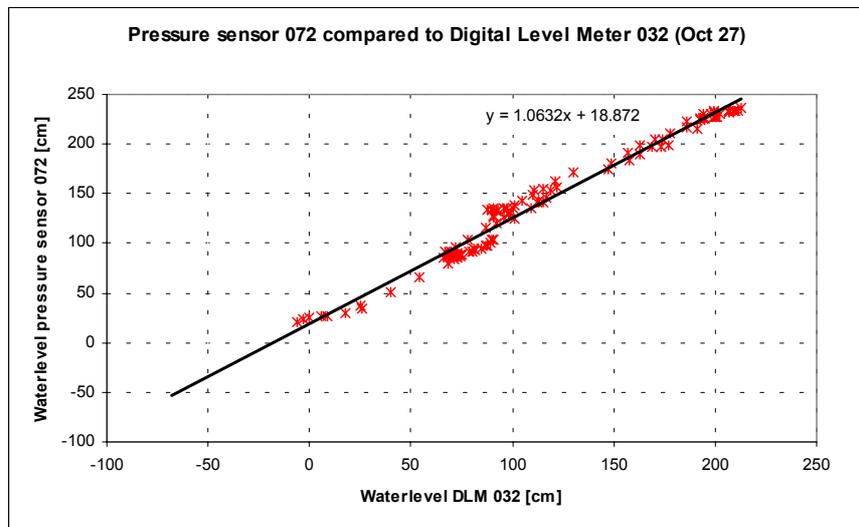
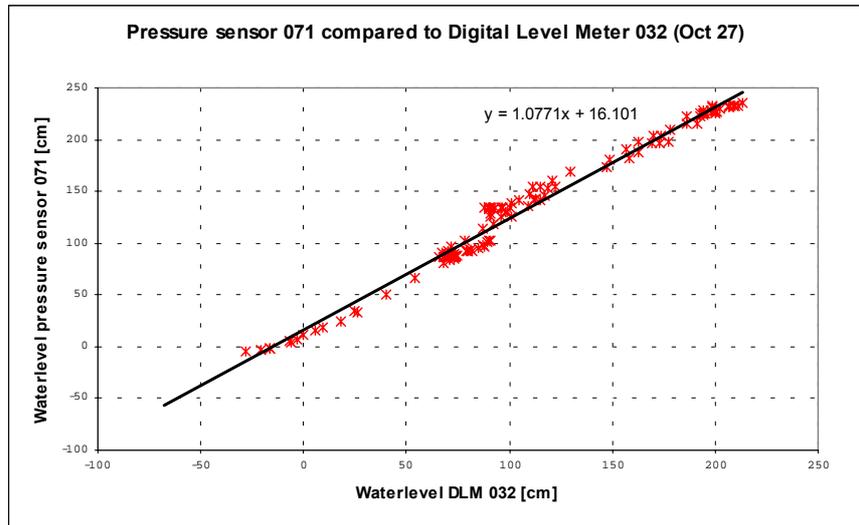
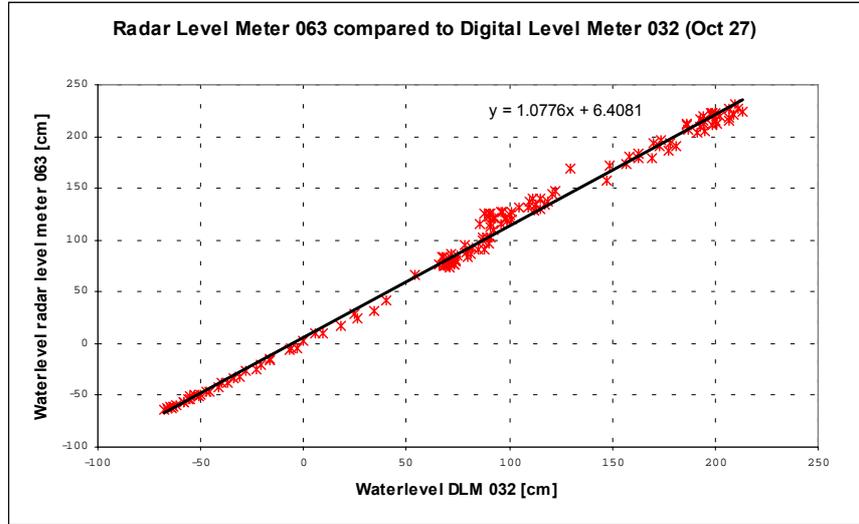
**Figure D.1** Water levels compared 27 October 2002



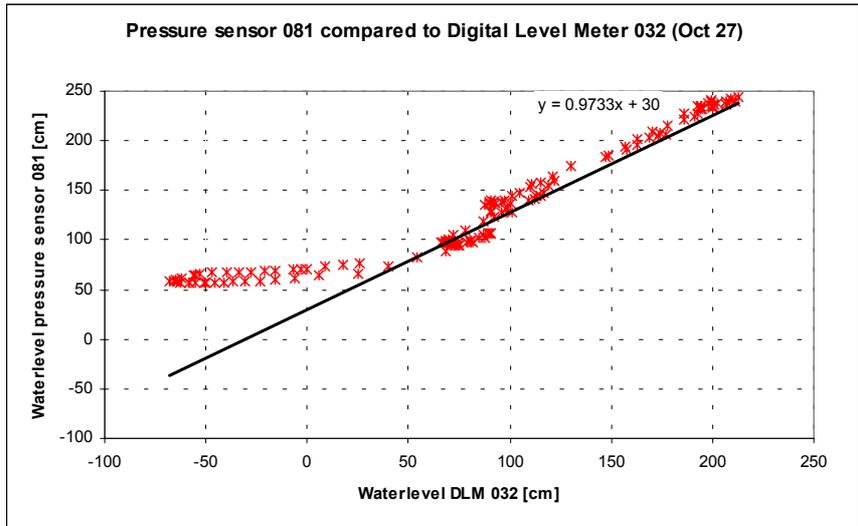






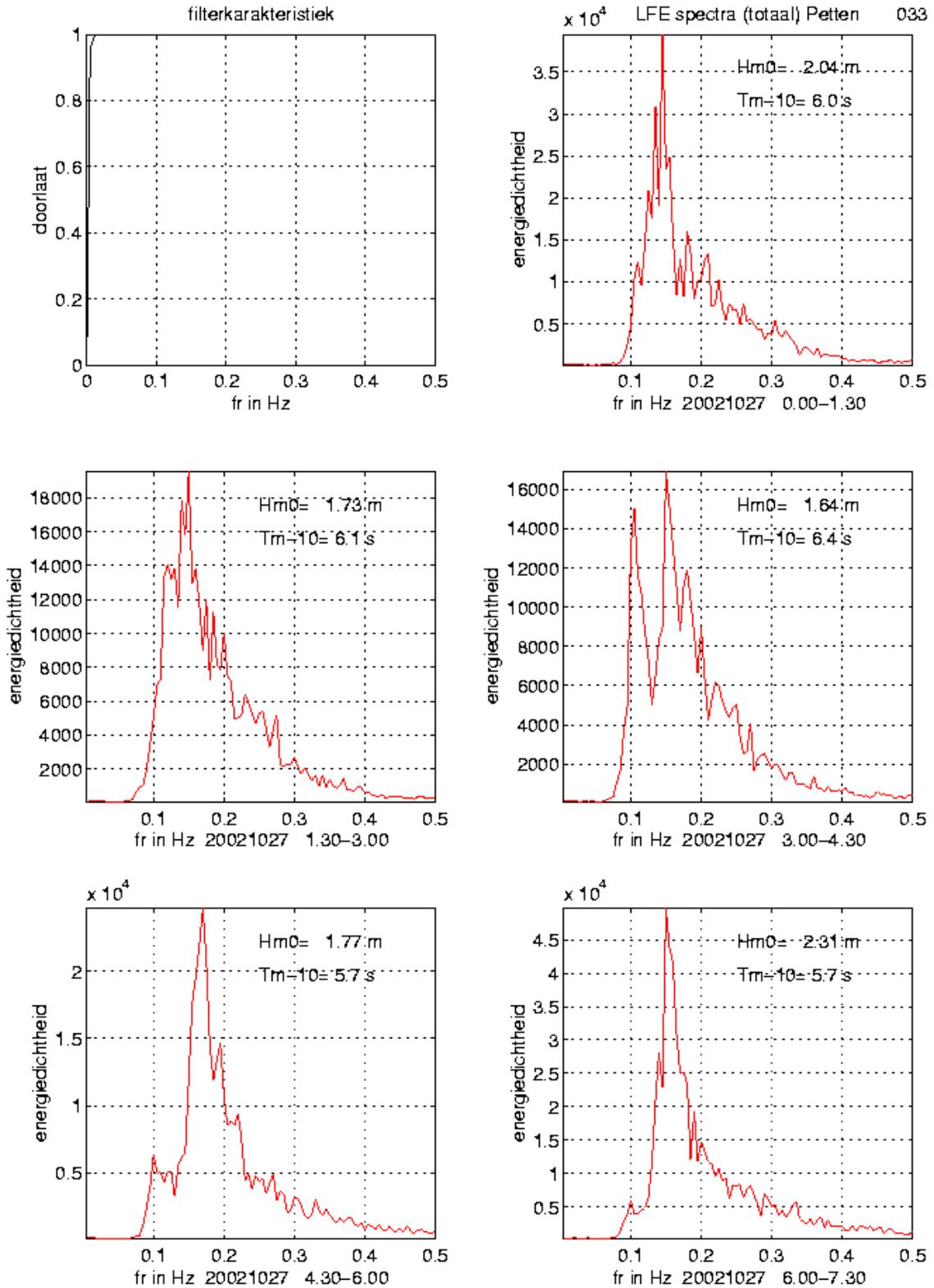




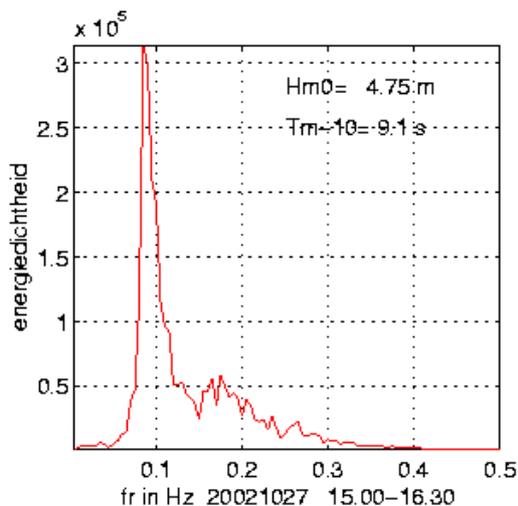
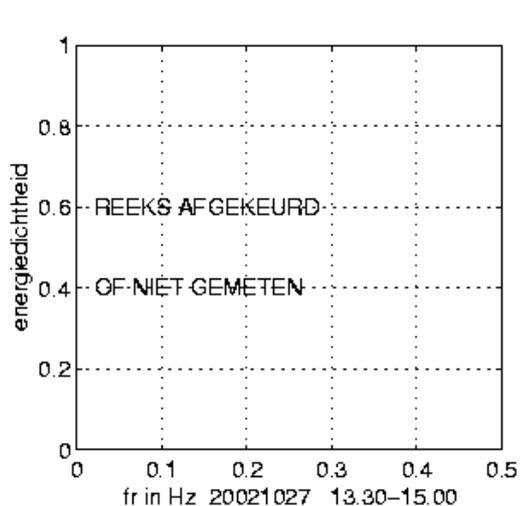
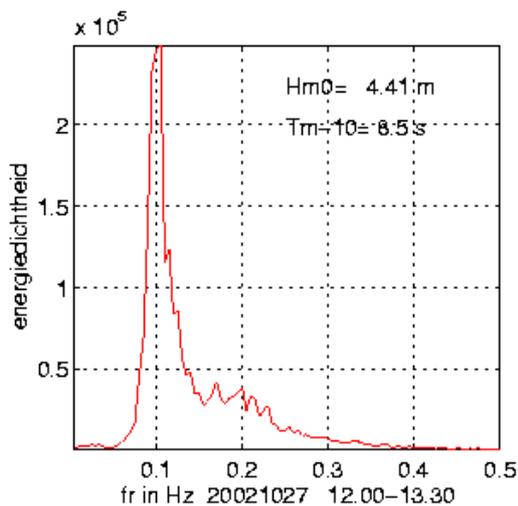
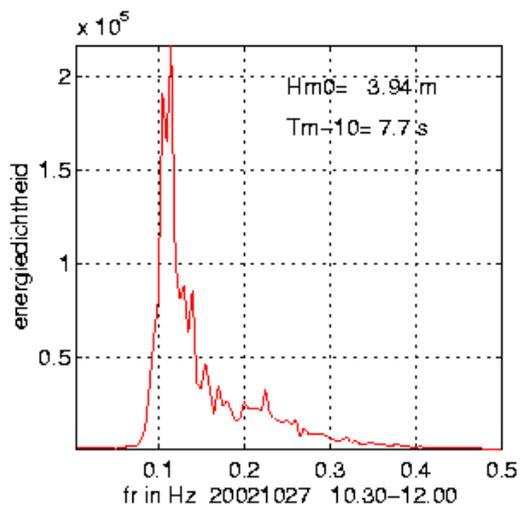
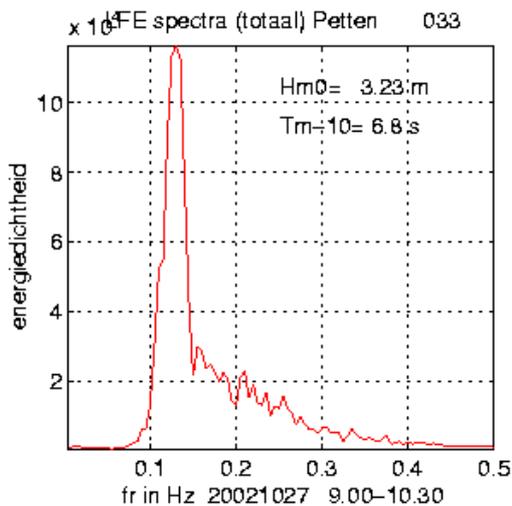
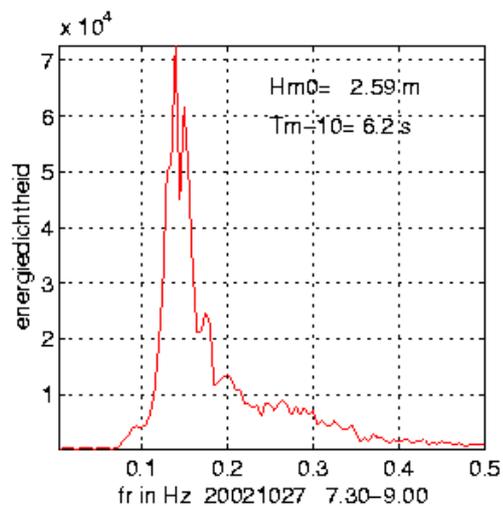




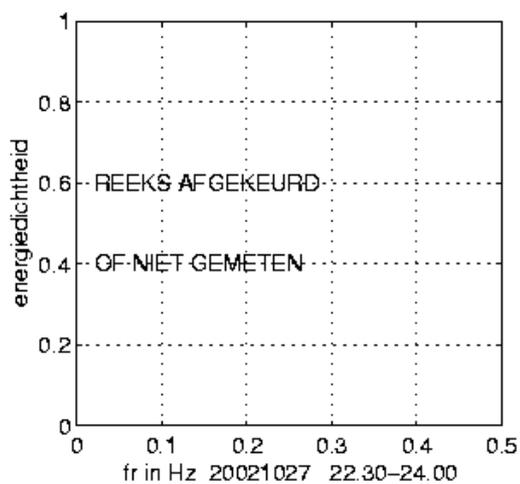
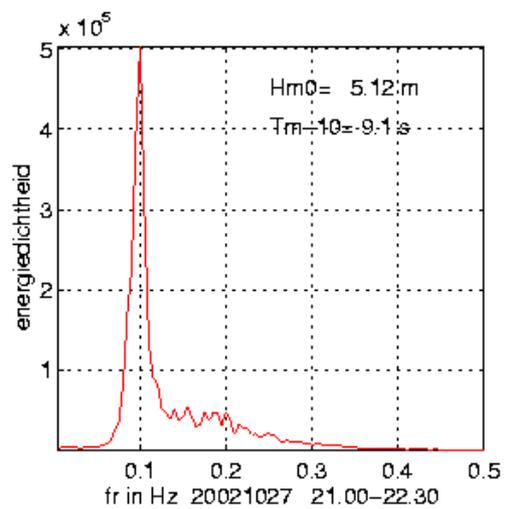
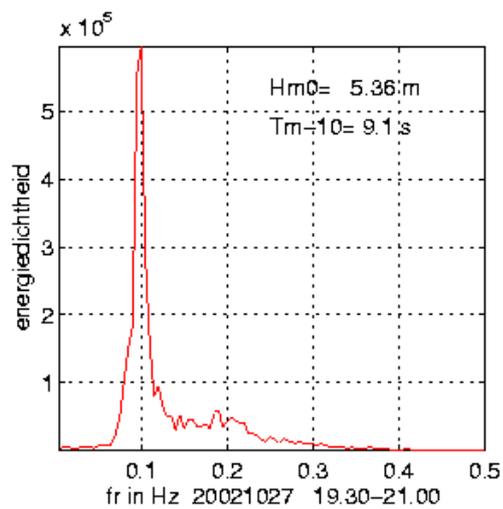
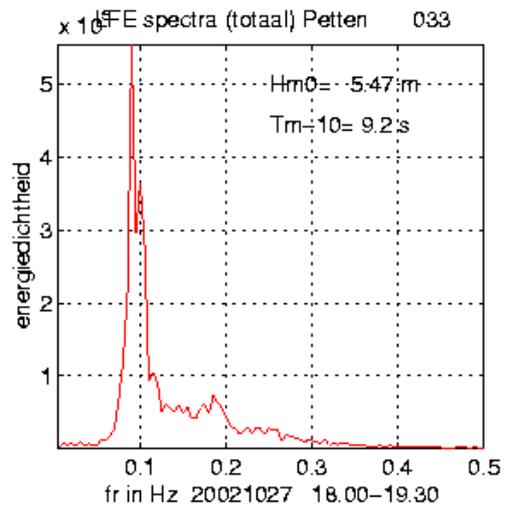
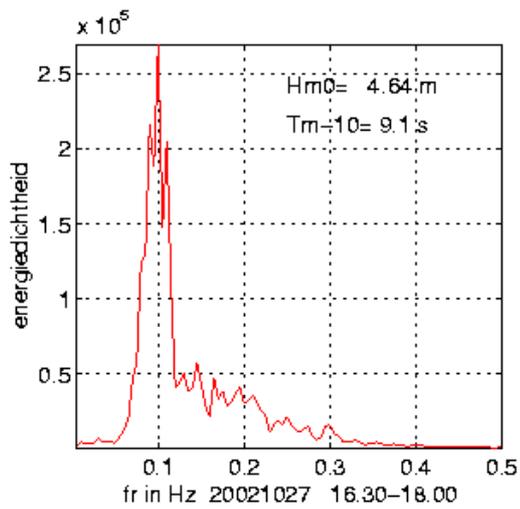
**Figure D.2** Total spectra  
27 October 2002



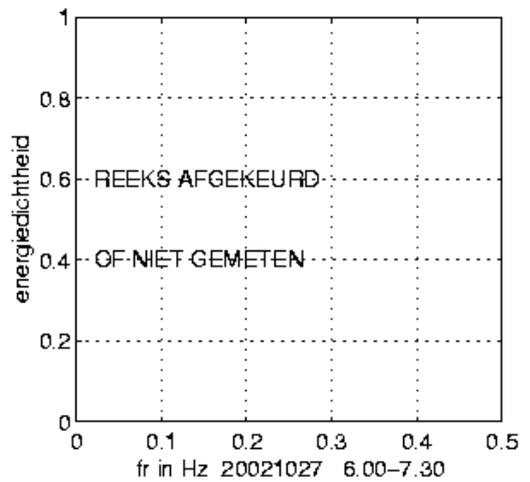
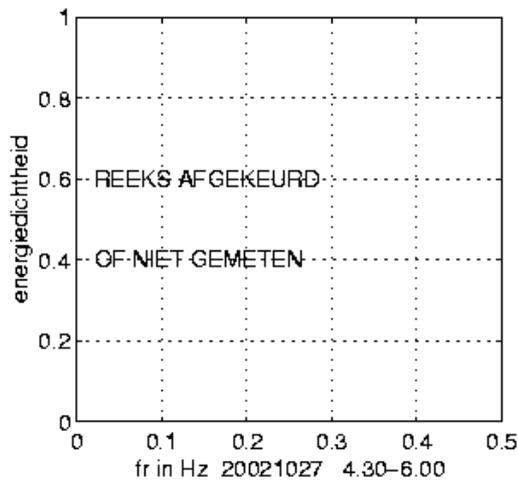
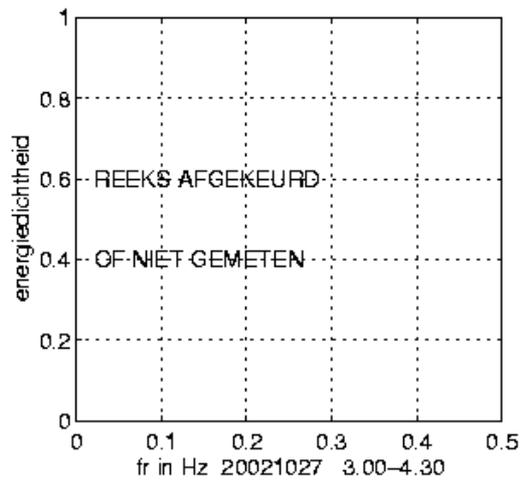
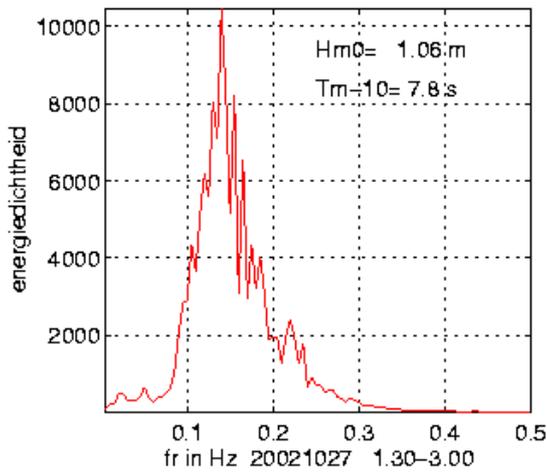
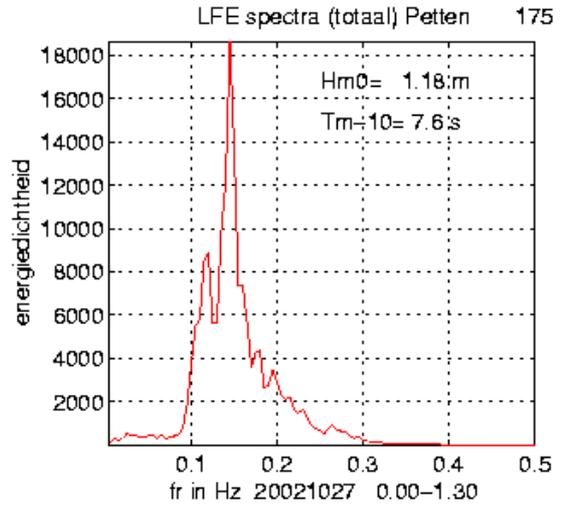
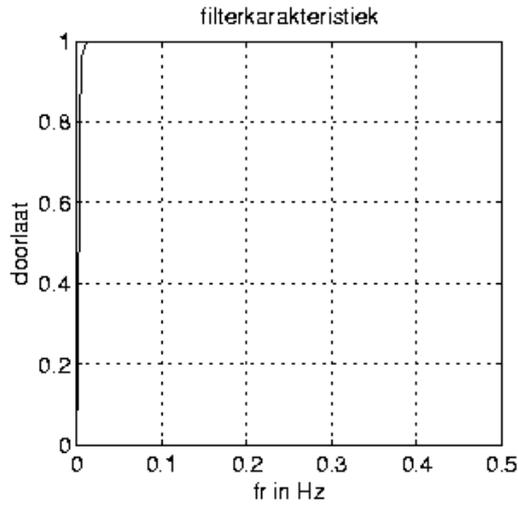




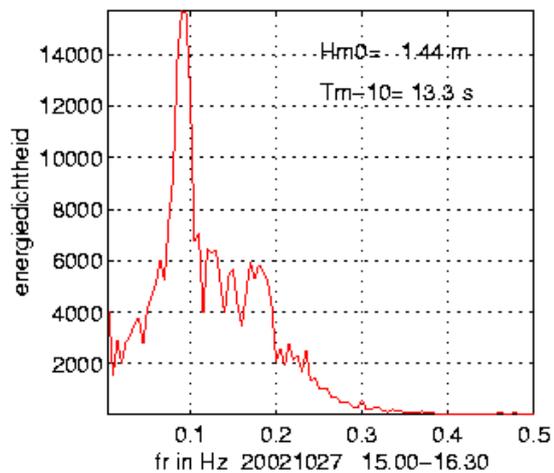
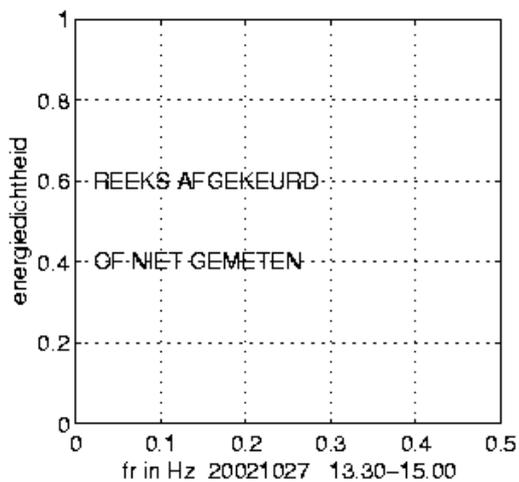
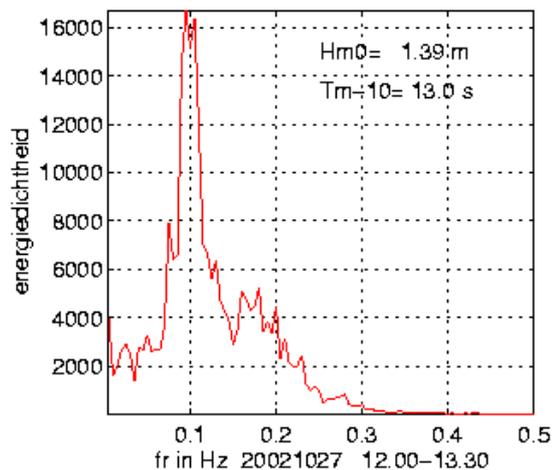
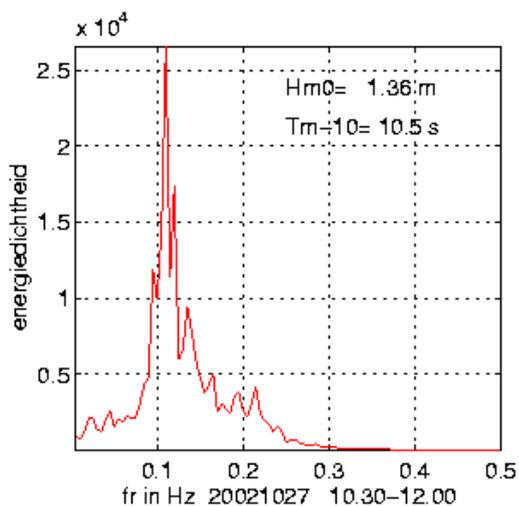
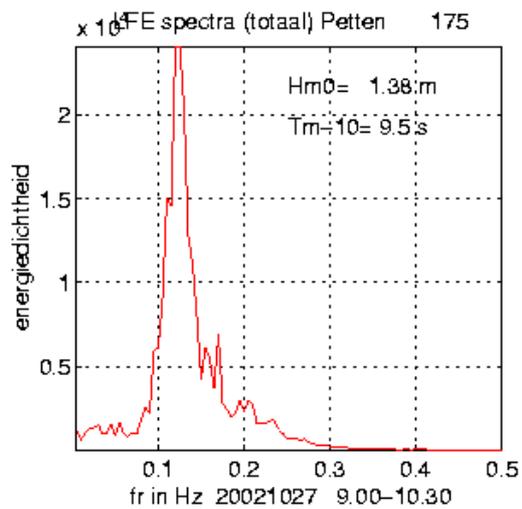
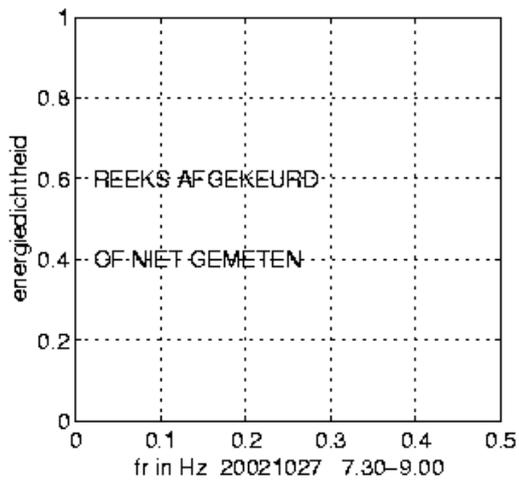




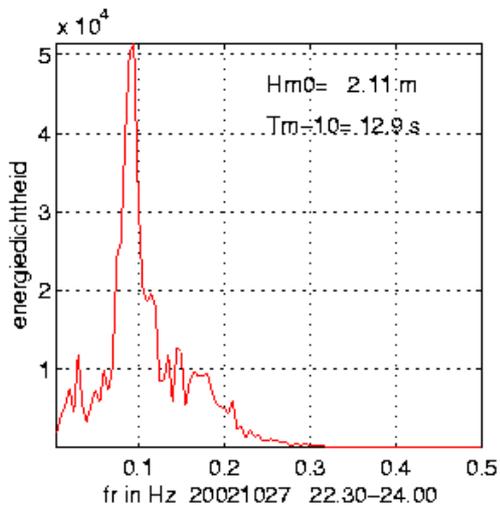
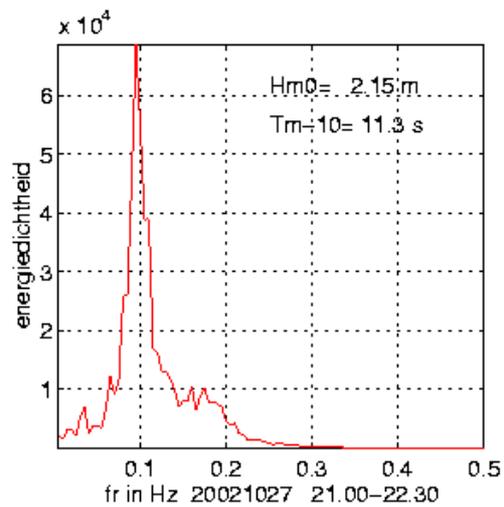
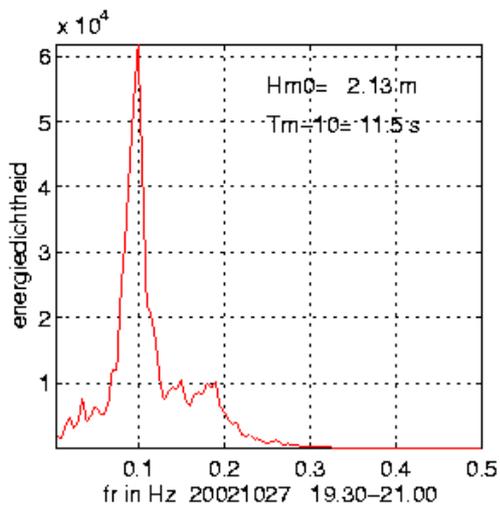
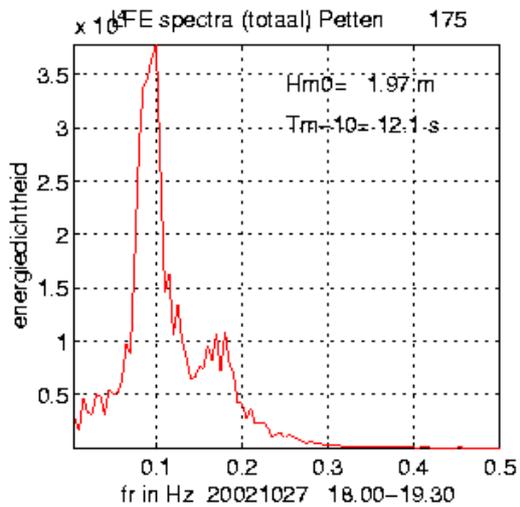
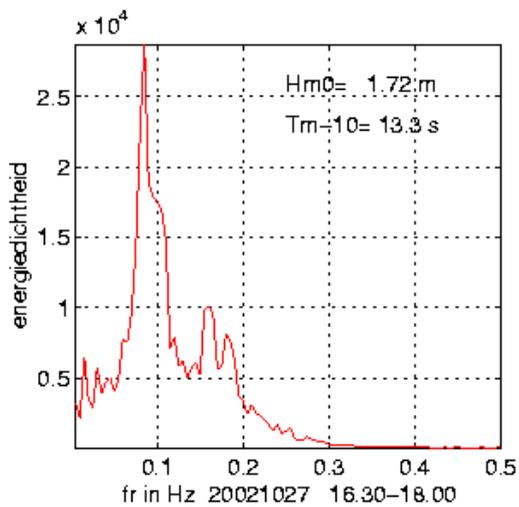




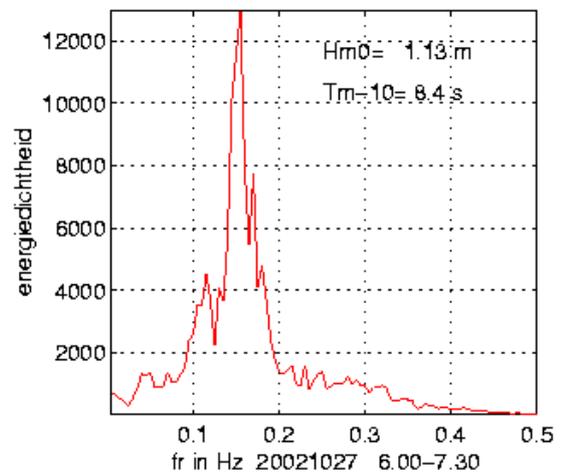
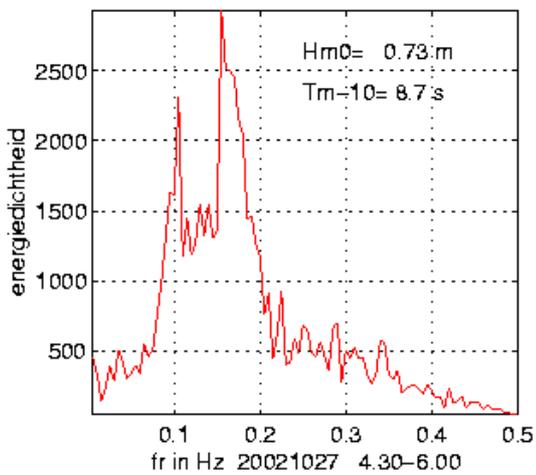
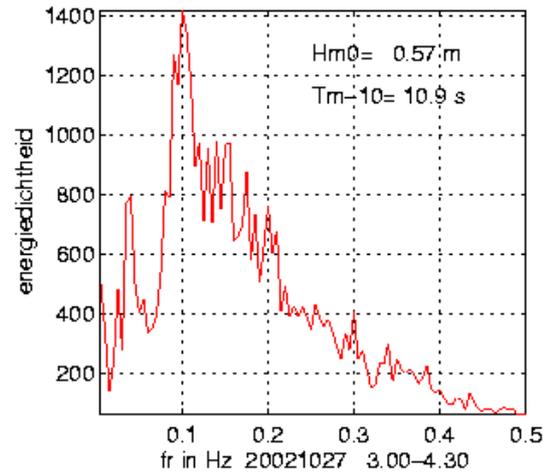
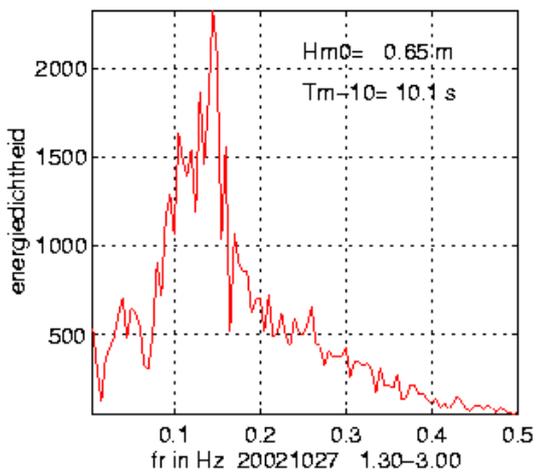
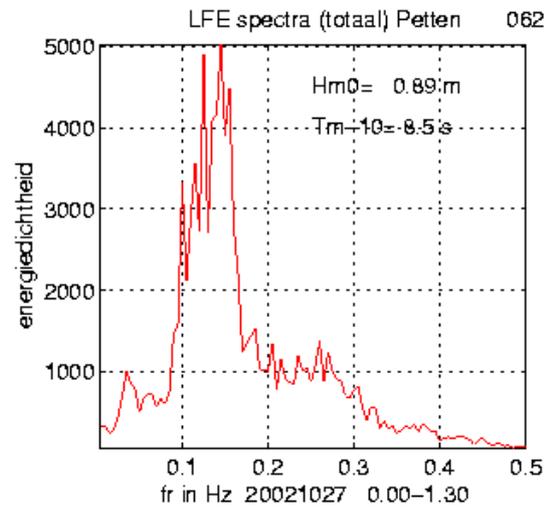
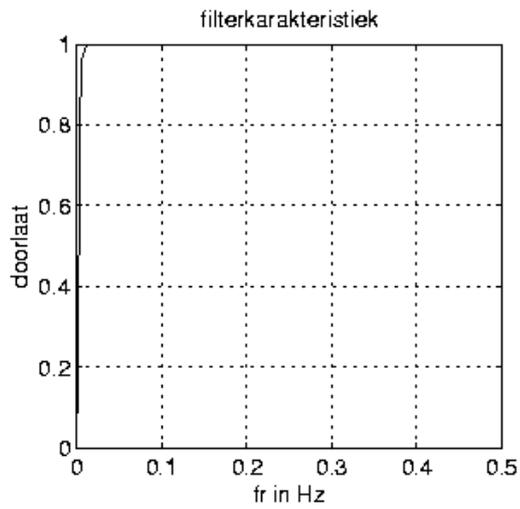




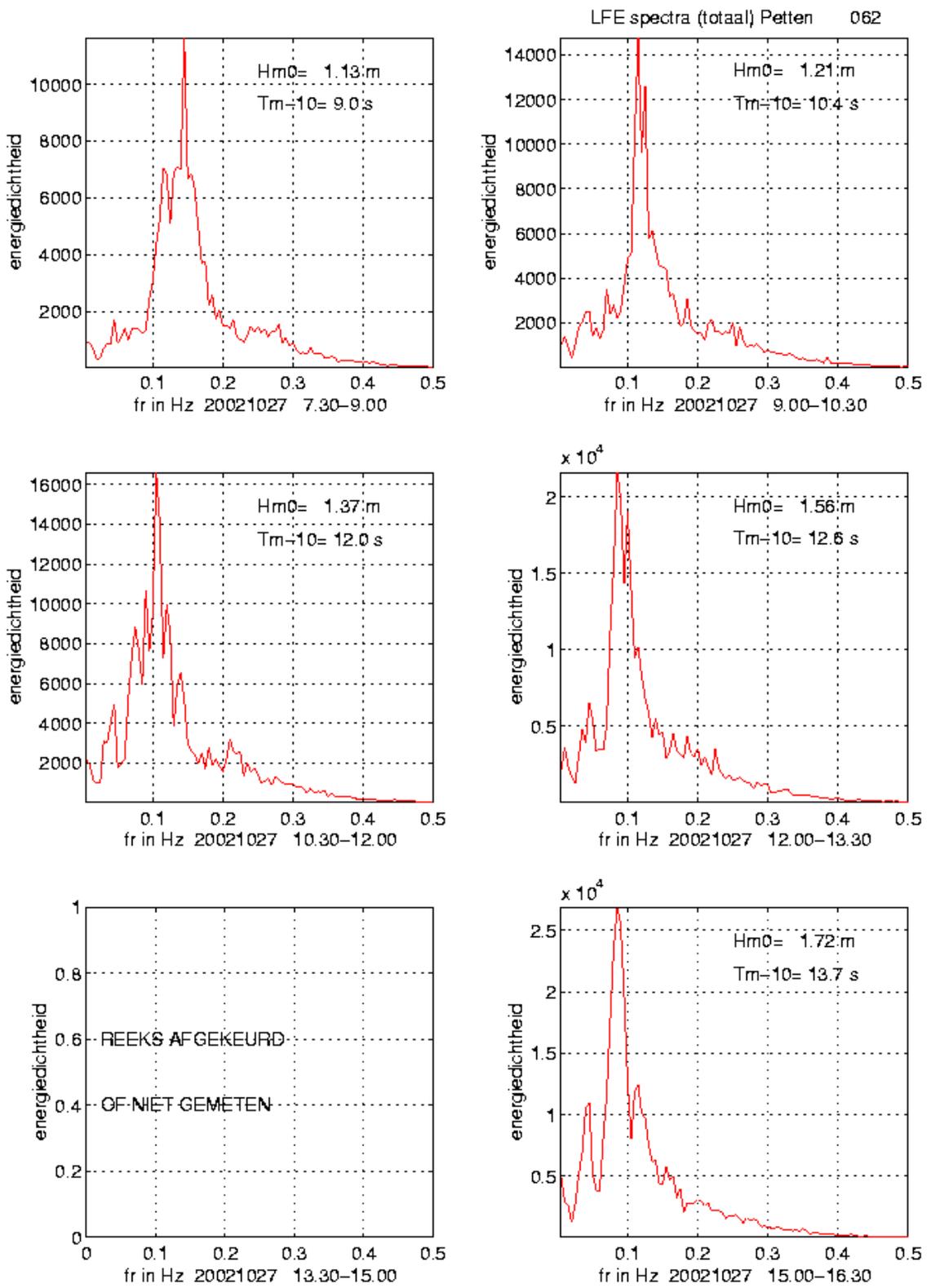




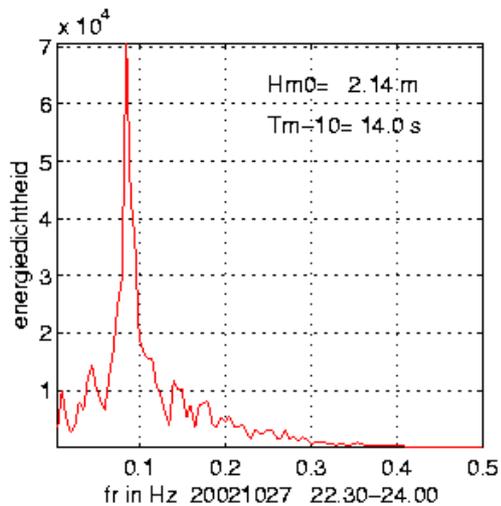
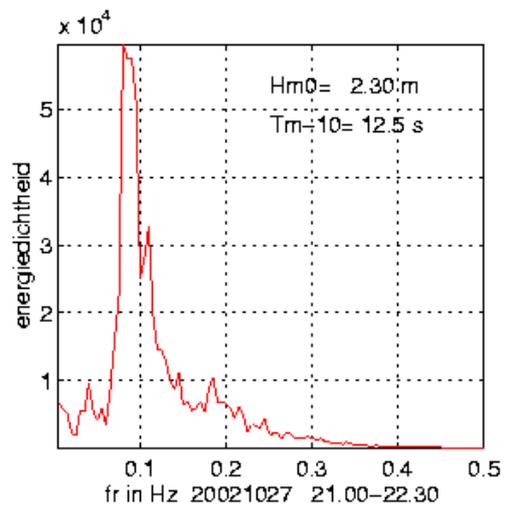
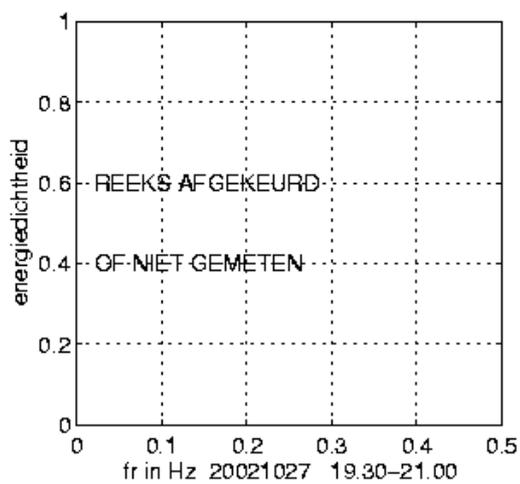
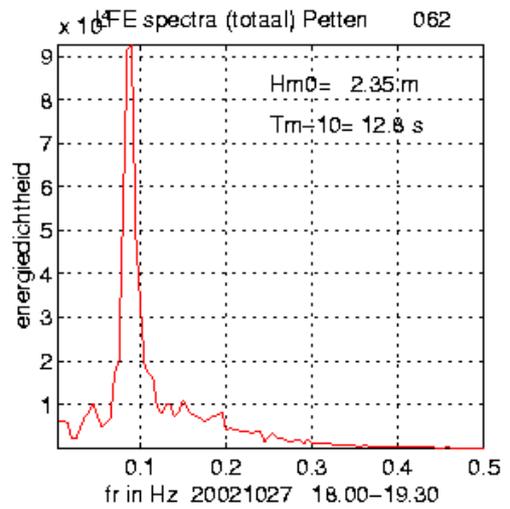
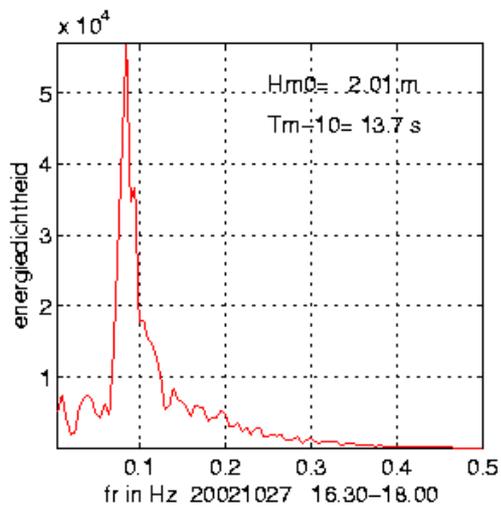






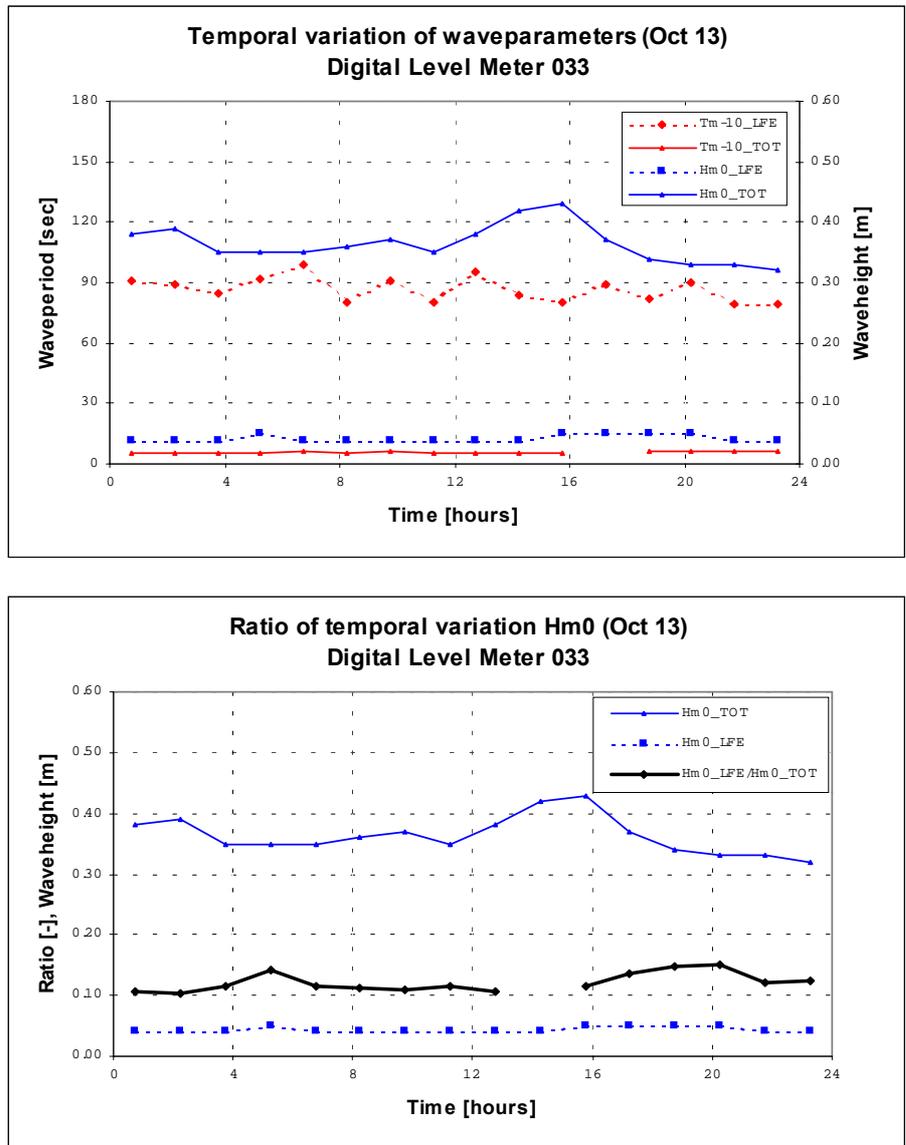




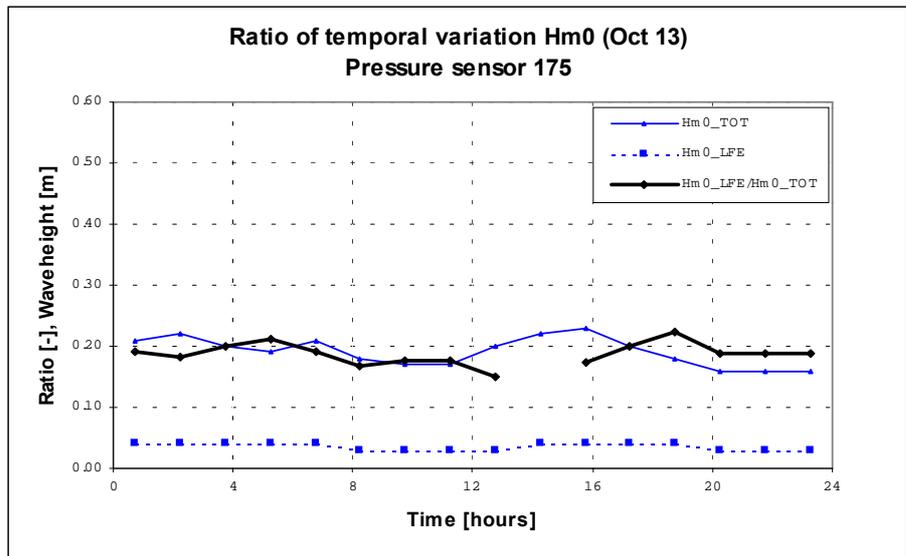
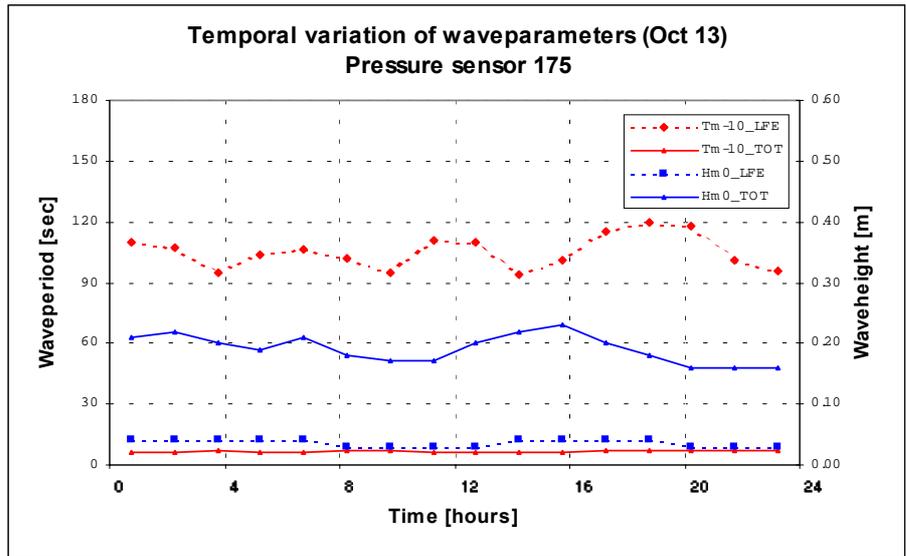




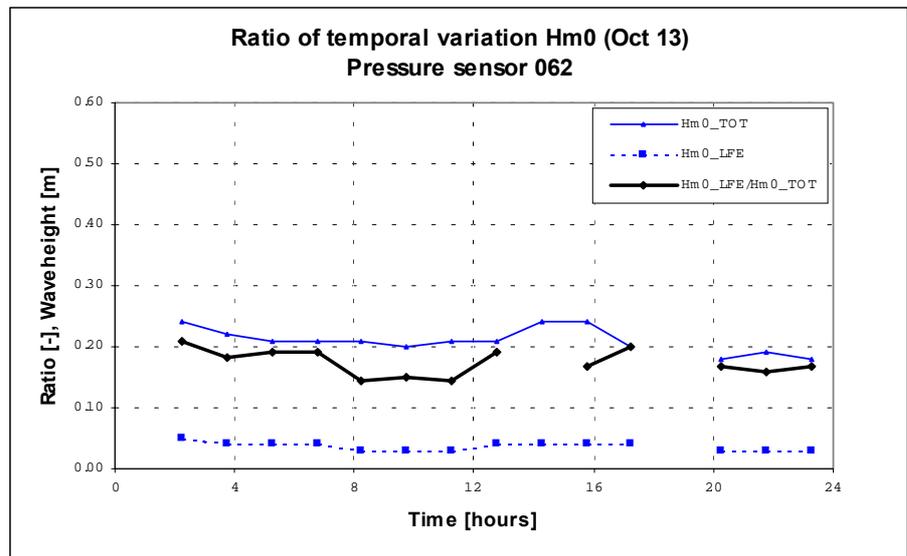
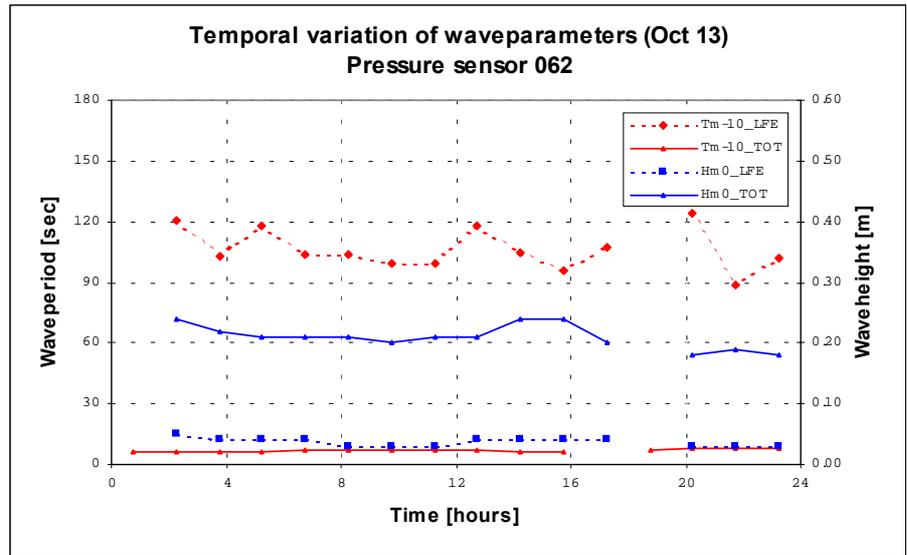
**Figure D.3** Developments through time  
13 October 2002





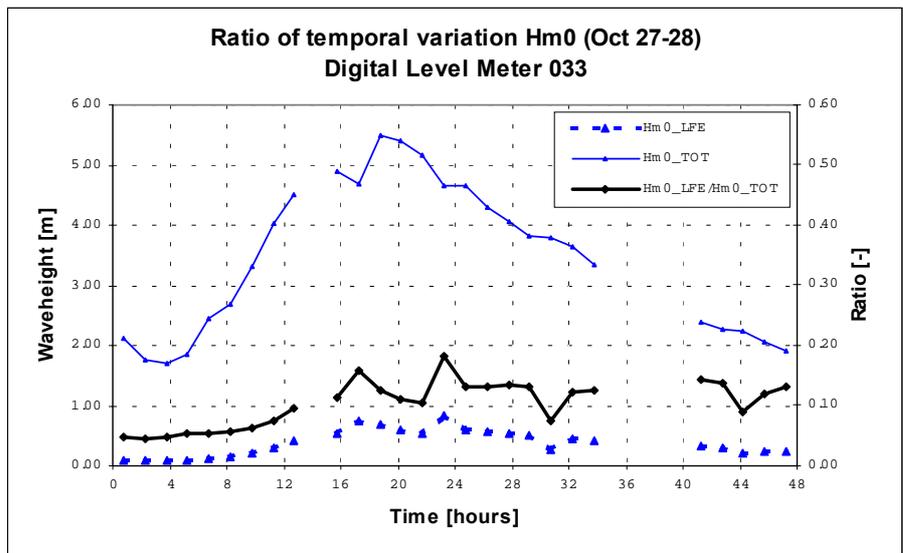
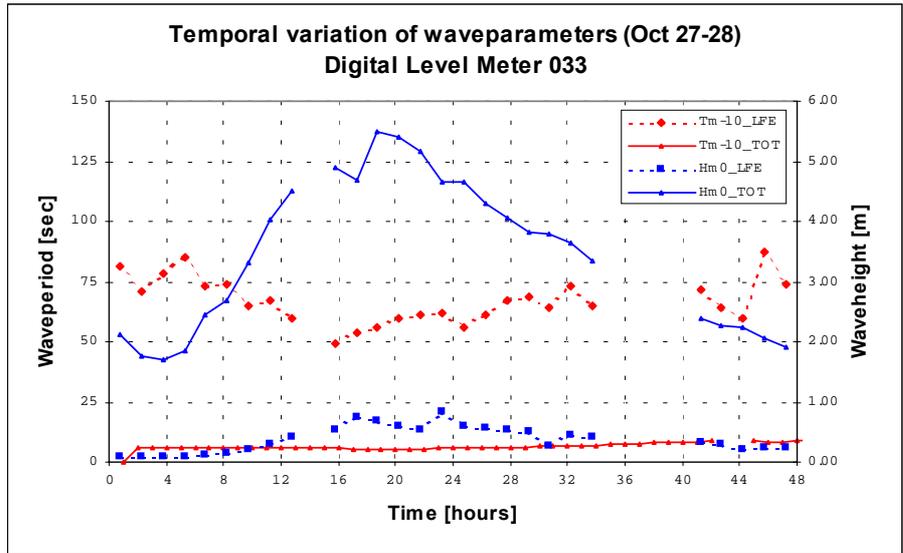




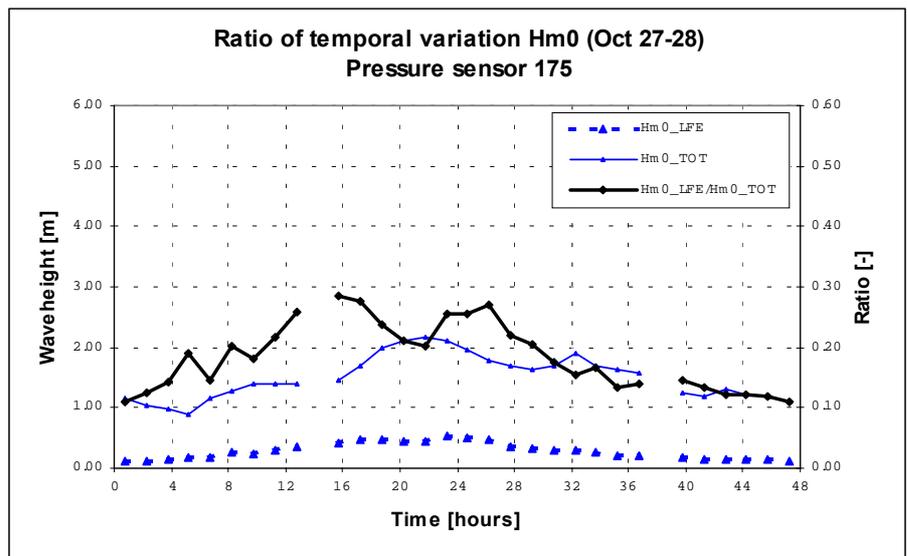
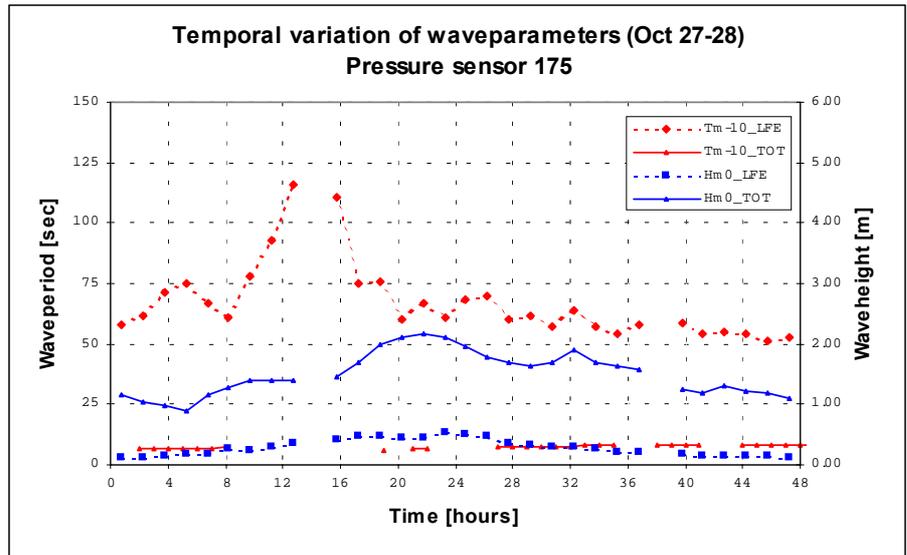




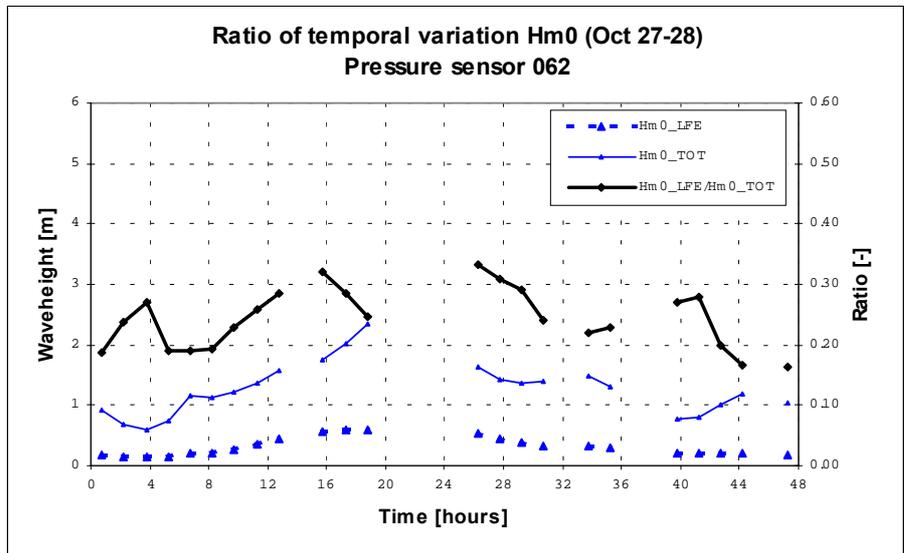
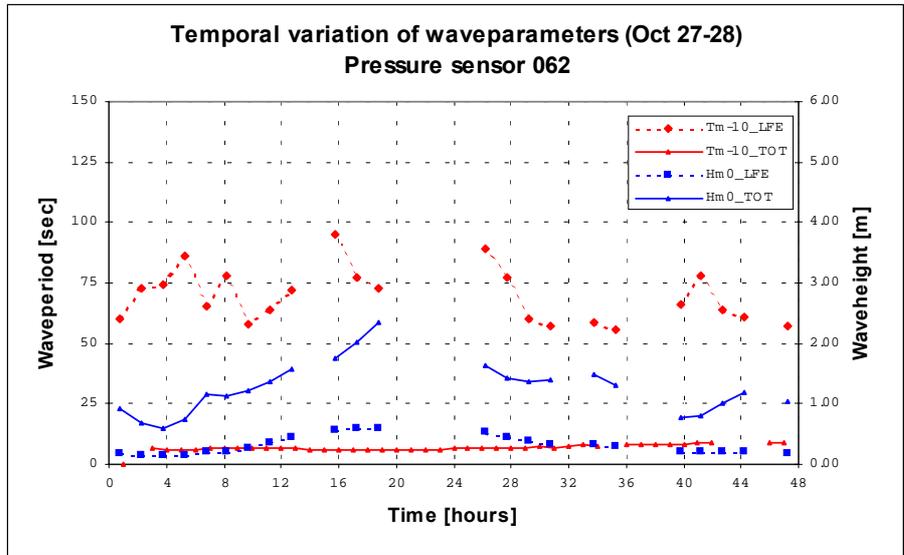
**Figure D.4** Developments through time 27-28 October 2002





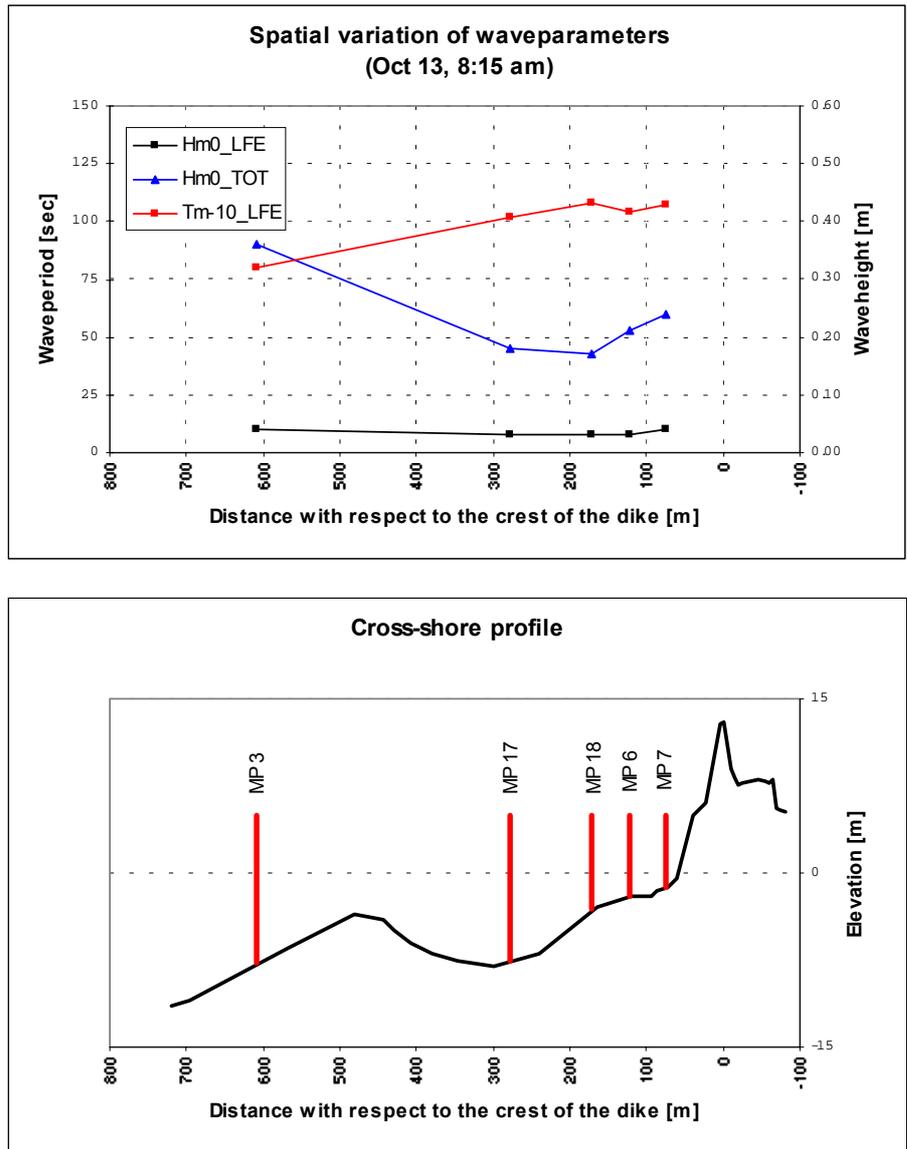






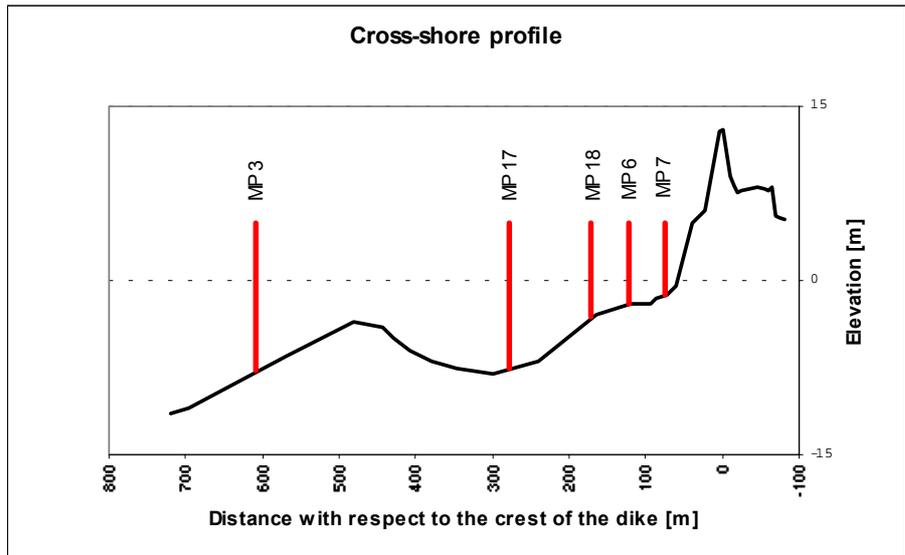
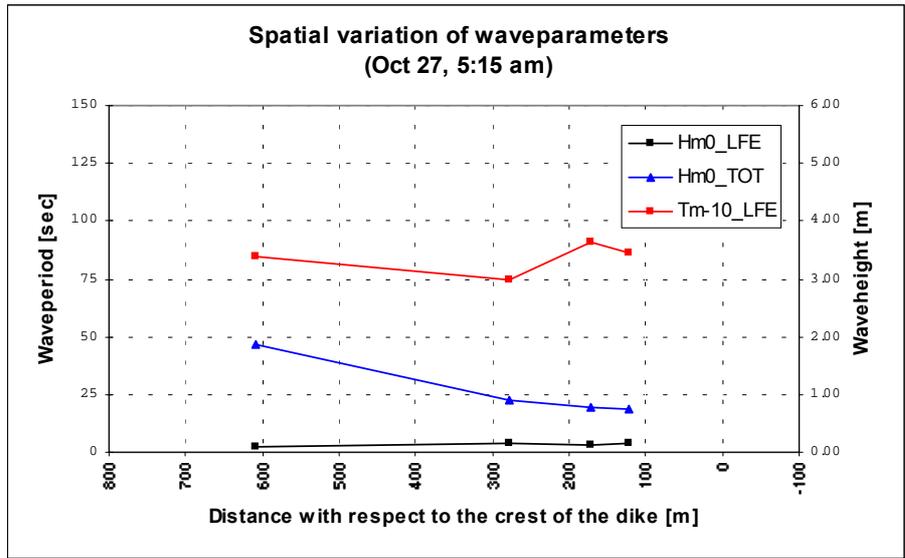


**Figure D.5** Spatial variations  
13 October 2002

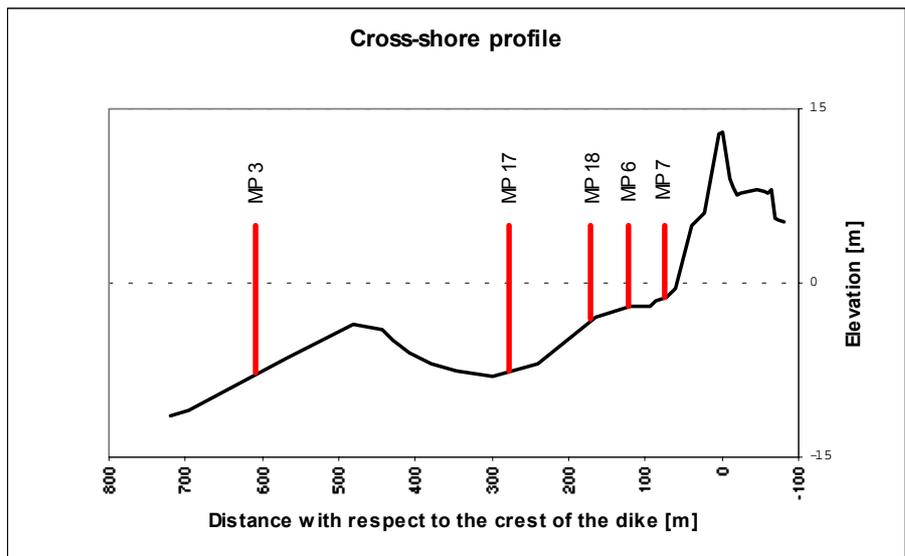
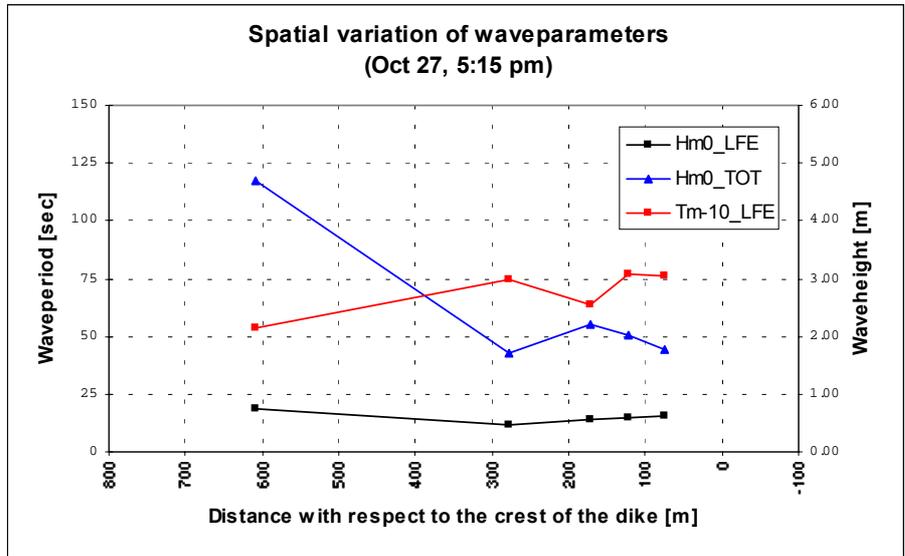




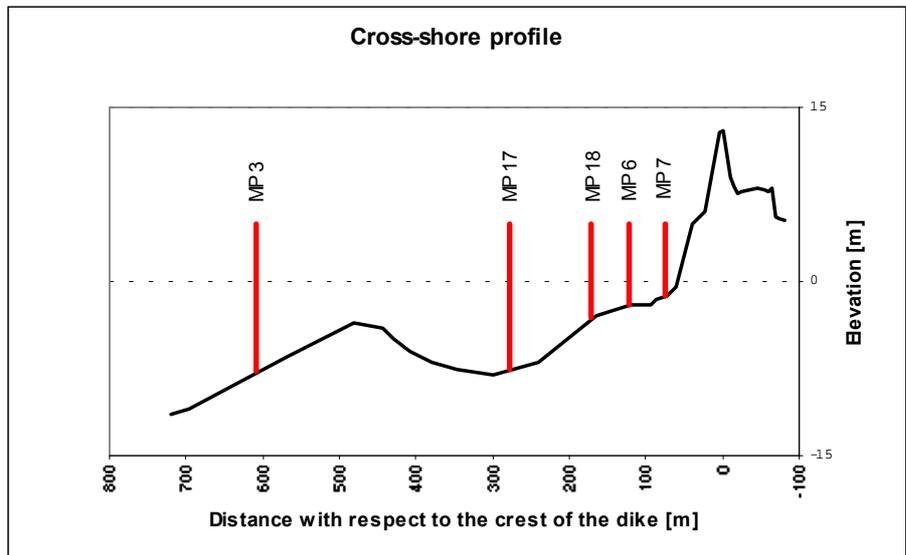
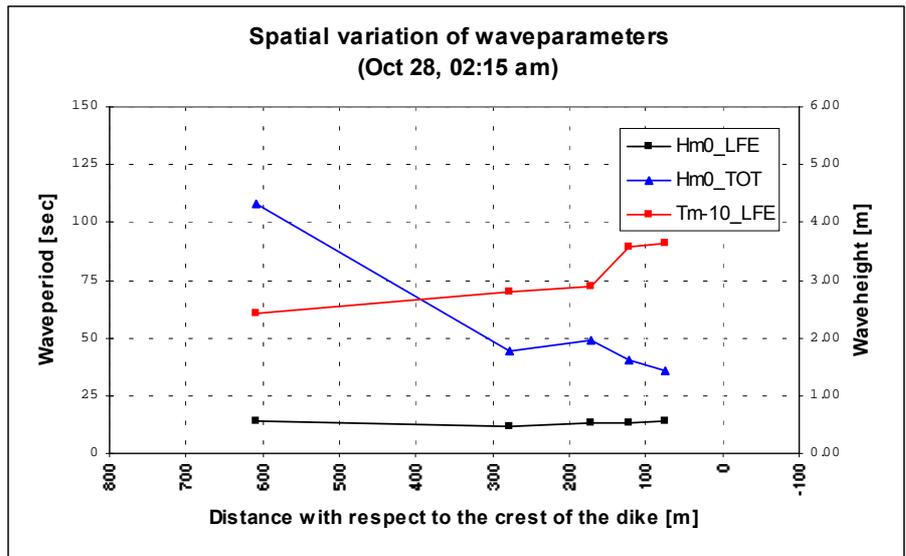
**Figure D.6** Spatial variations  
27-28 October  
2002





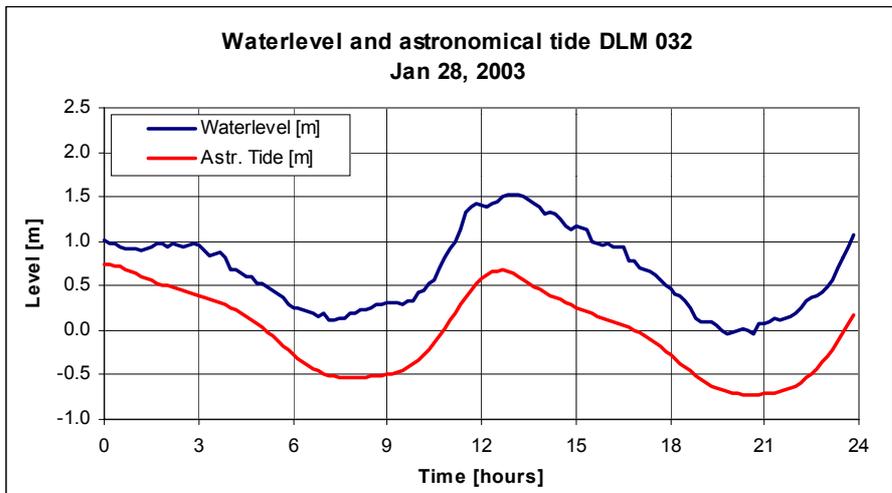
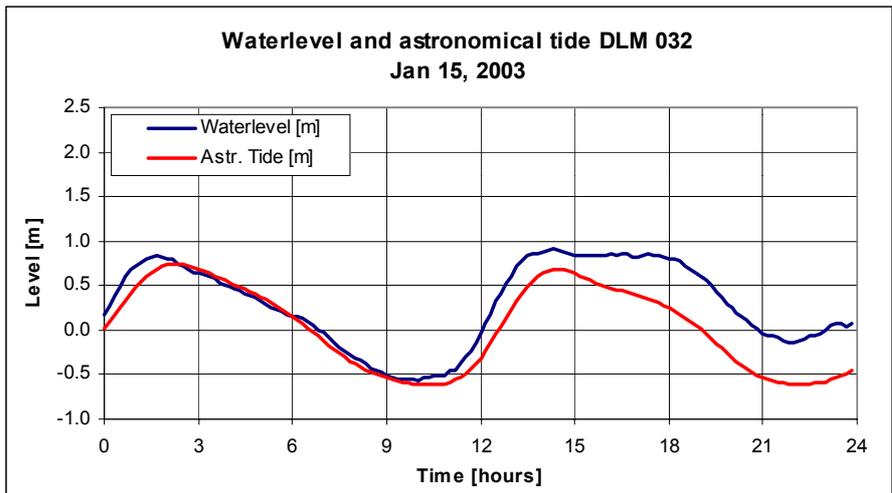
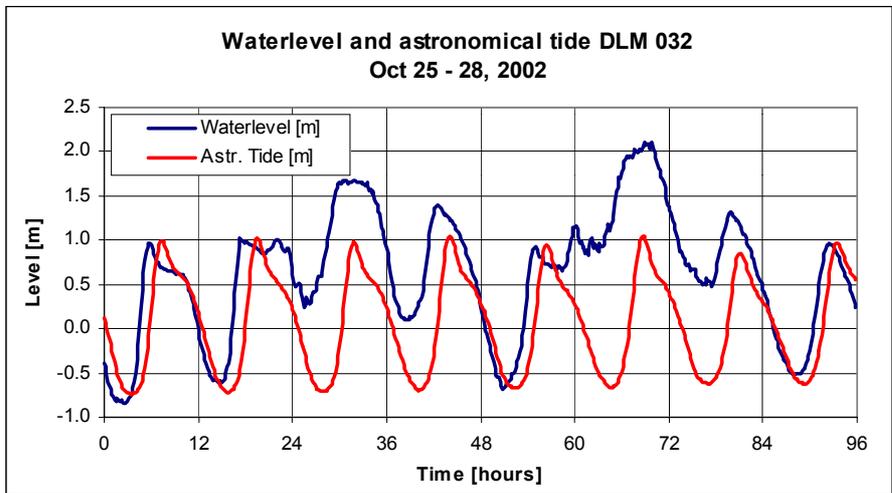




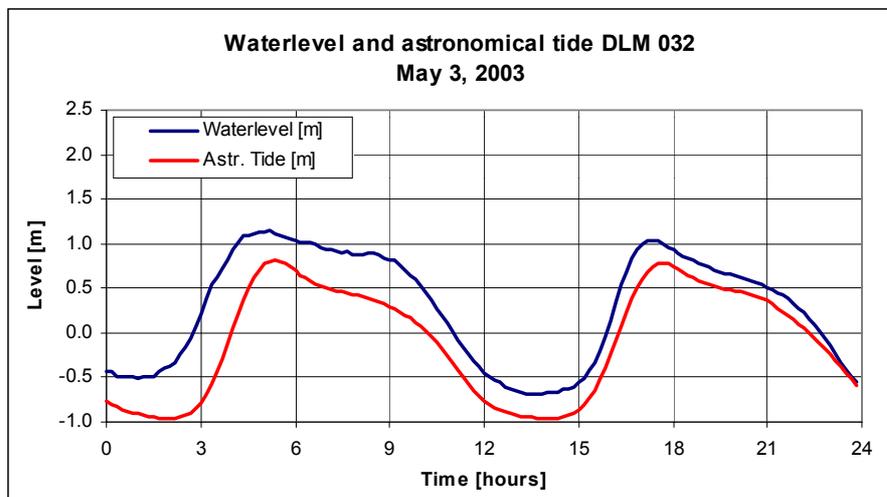
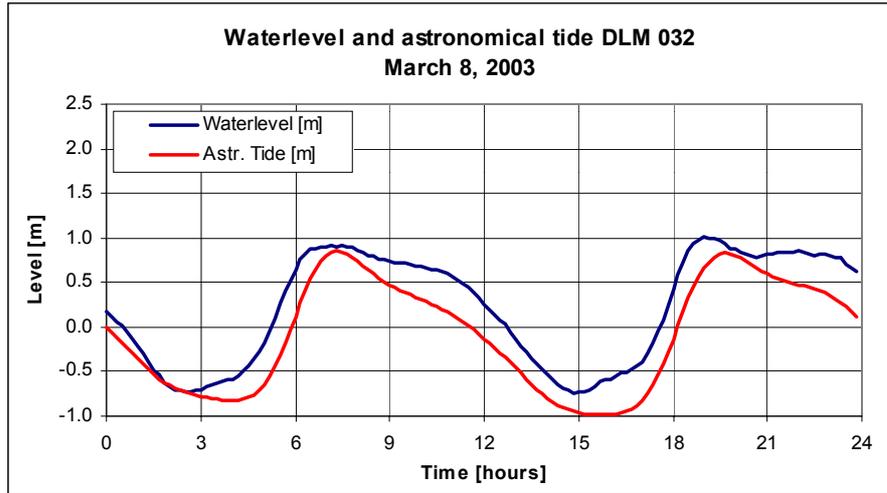




## Appendix E Water levels and astronomical Tide during Storm Periods









## **Appendix F Storm Period 25-28 October 2002**

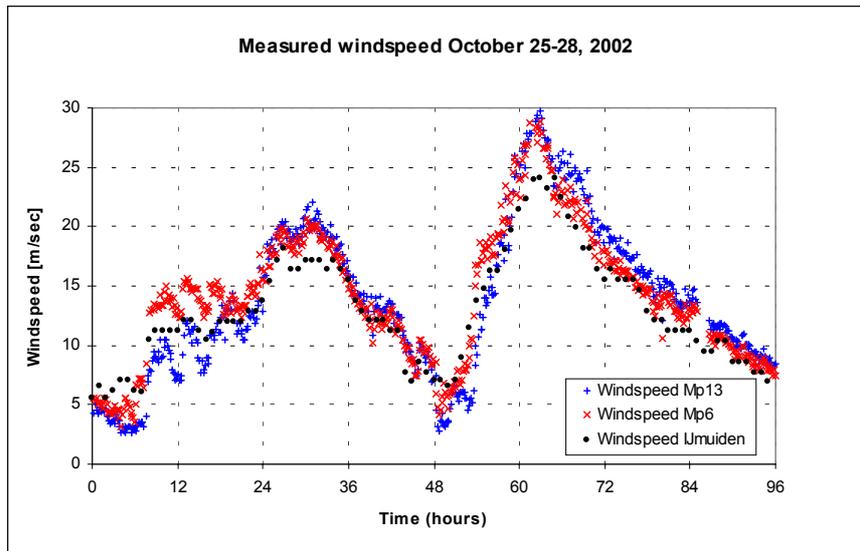
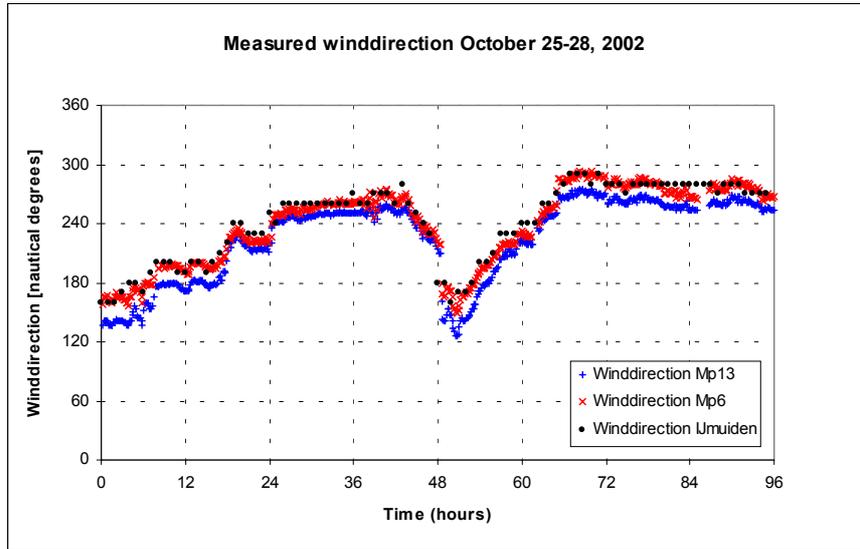
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- Figure F.4 Wave spectra 27 October 2002 (4pm)
- Figure F.5 Wave spectra 27 October 2002 (8pm)
- Figure F.6 Wave spectra 27 October 2002 (11:50pm)
- Figure F.7 Wave spectra 28 October 2002 (6am)
- Figure F.8 Hm0 and Tm-10

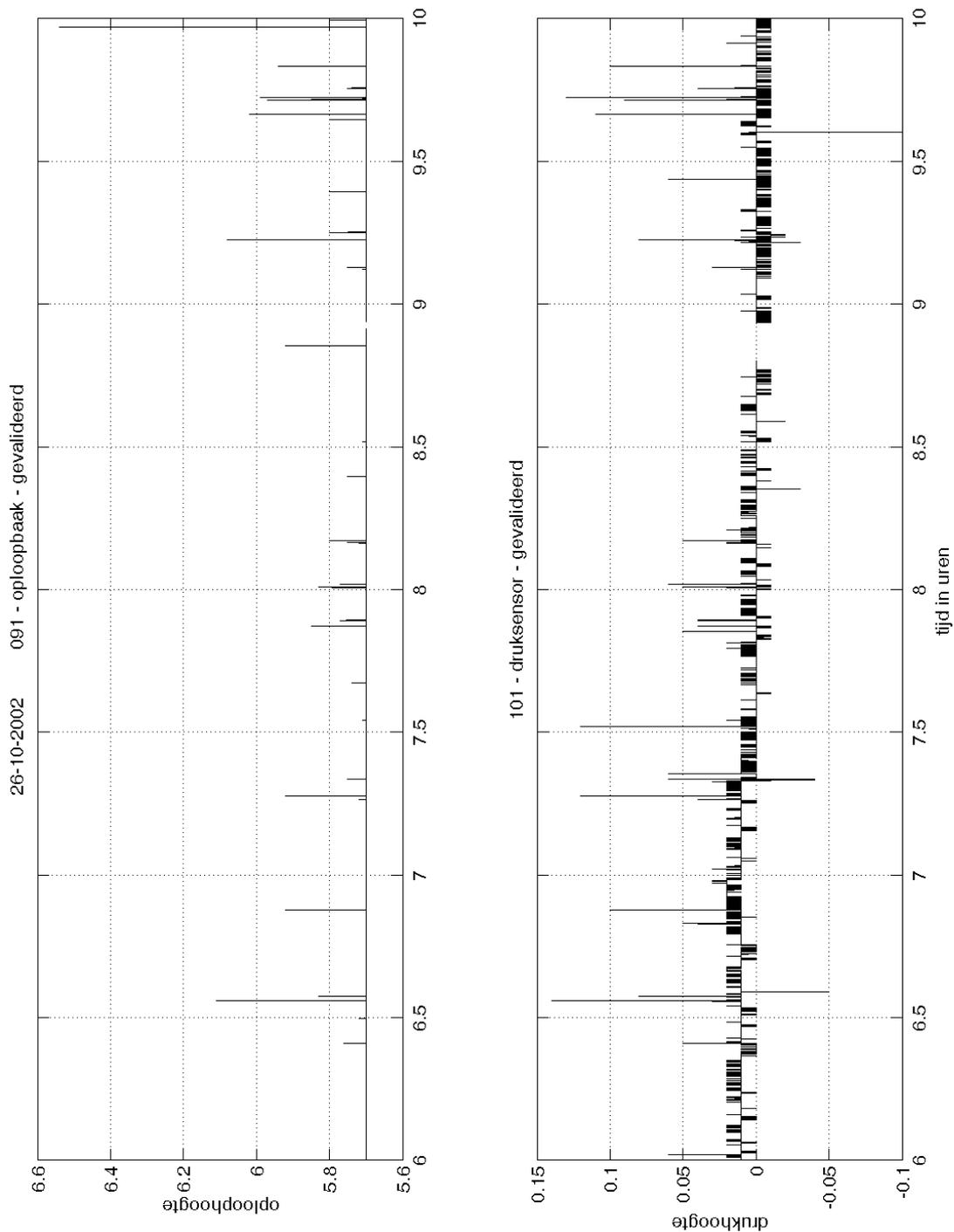


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**Figure F.1** Wind direction and wind speed

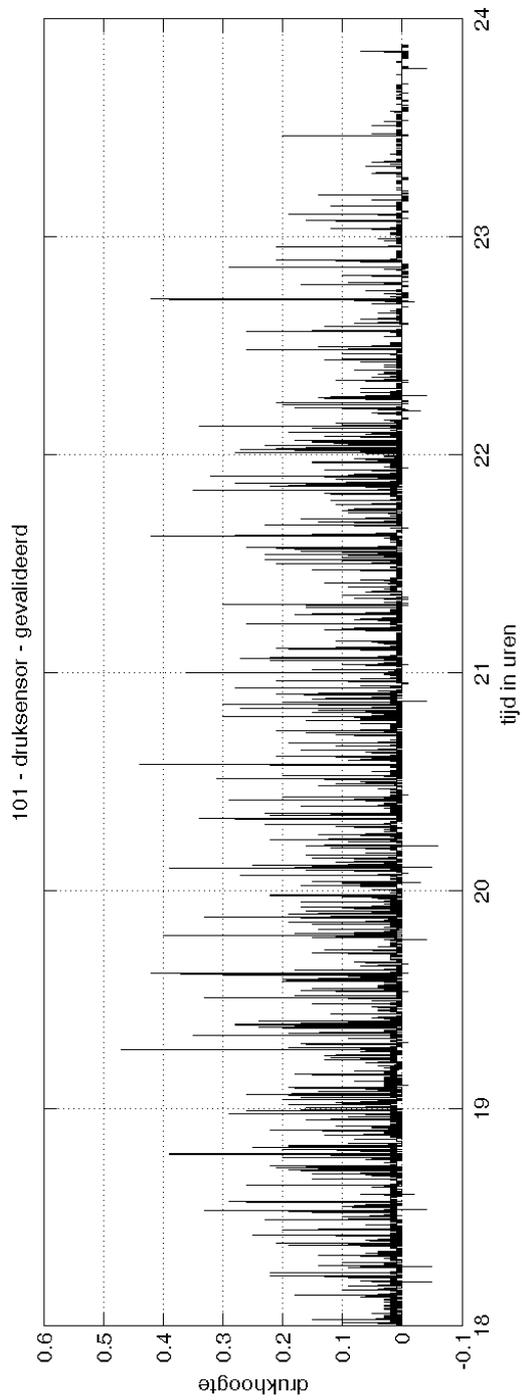
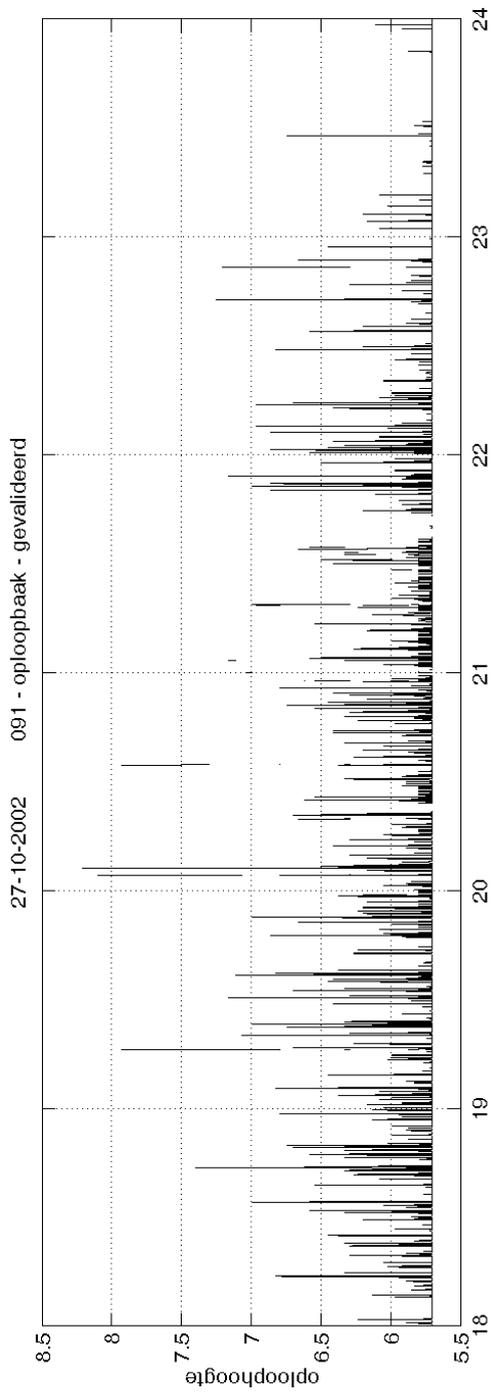




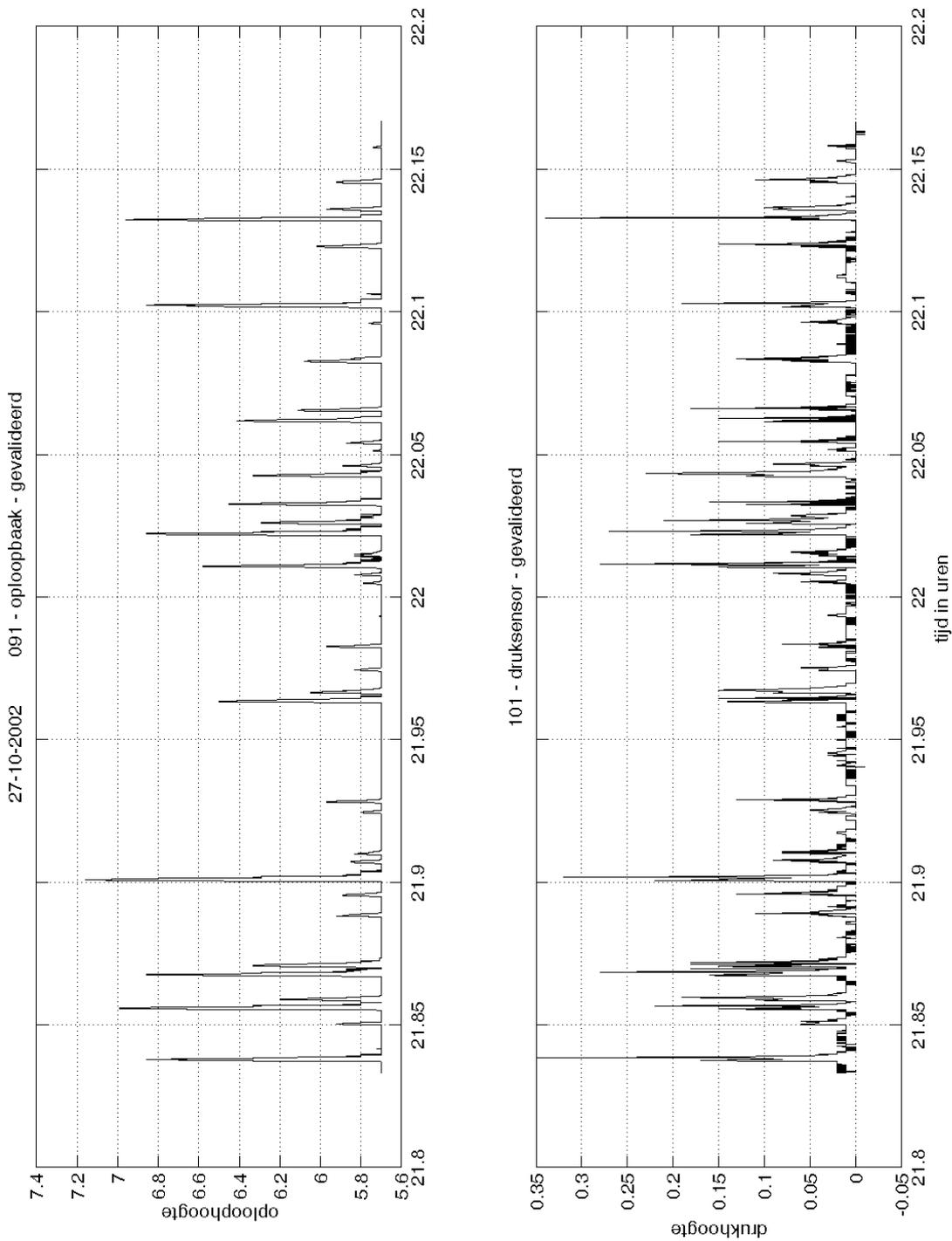
**Figure F.2** Wave run-up and pressure level





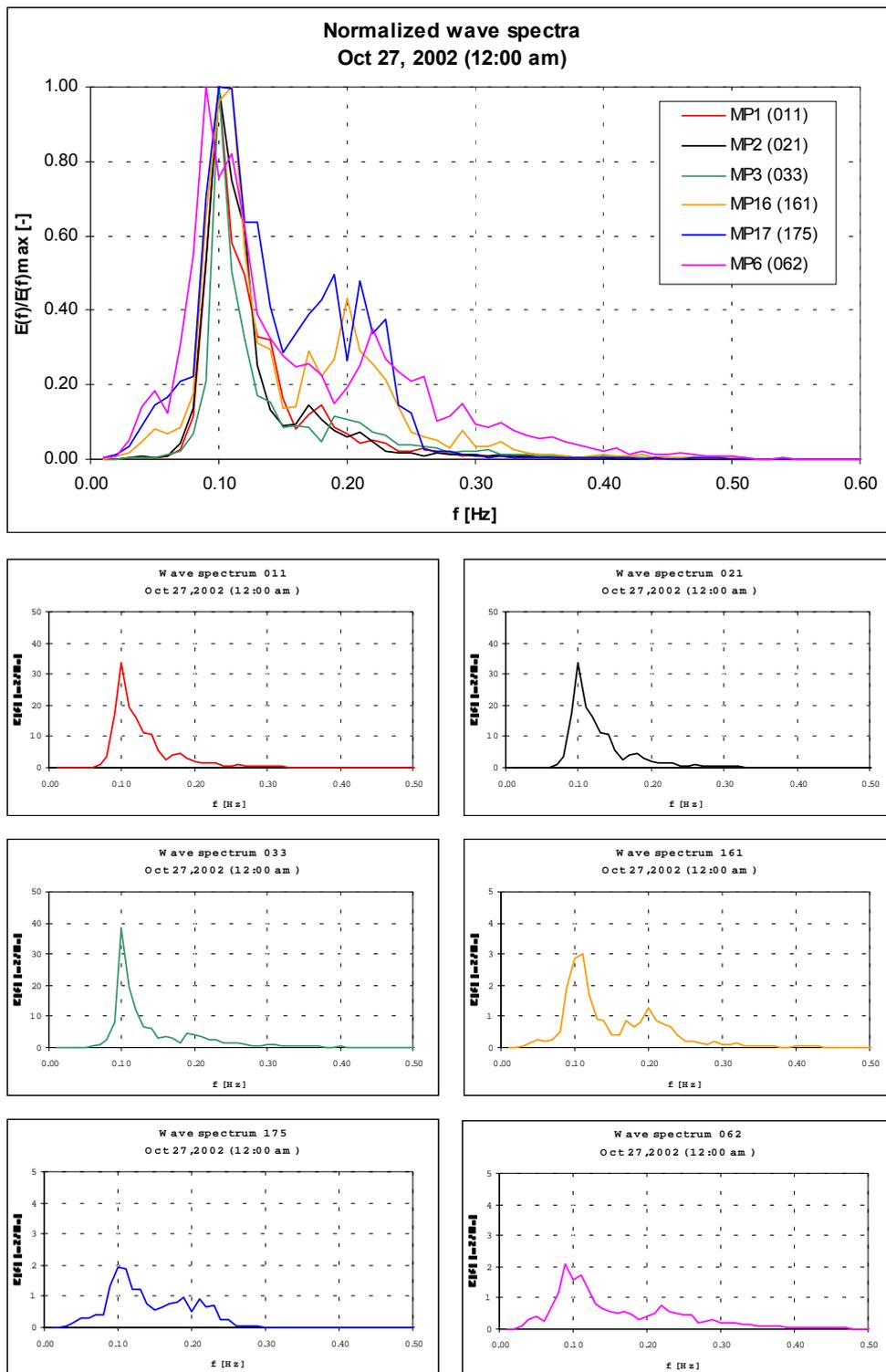






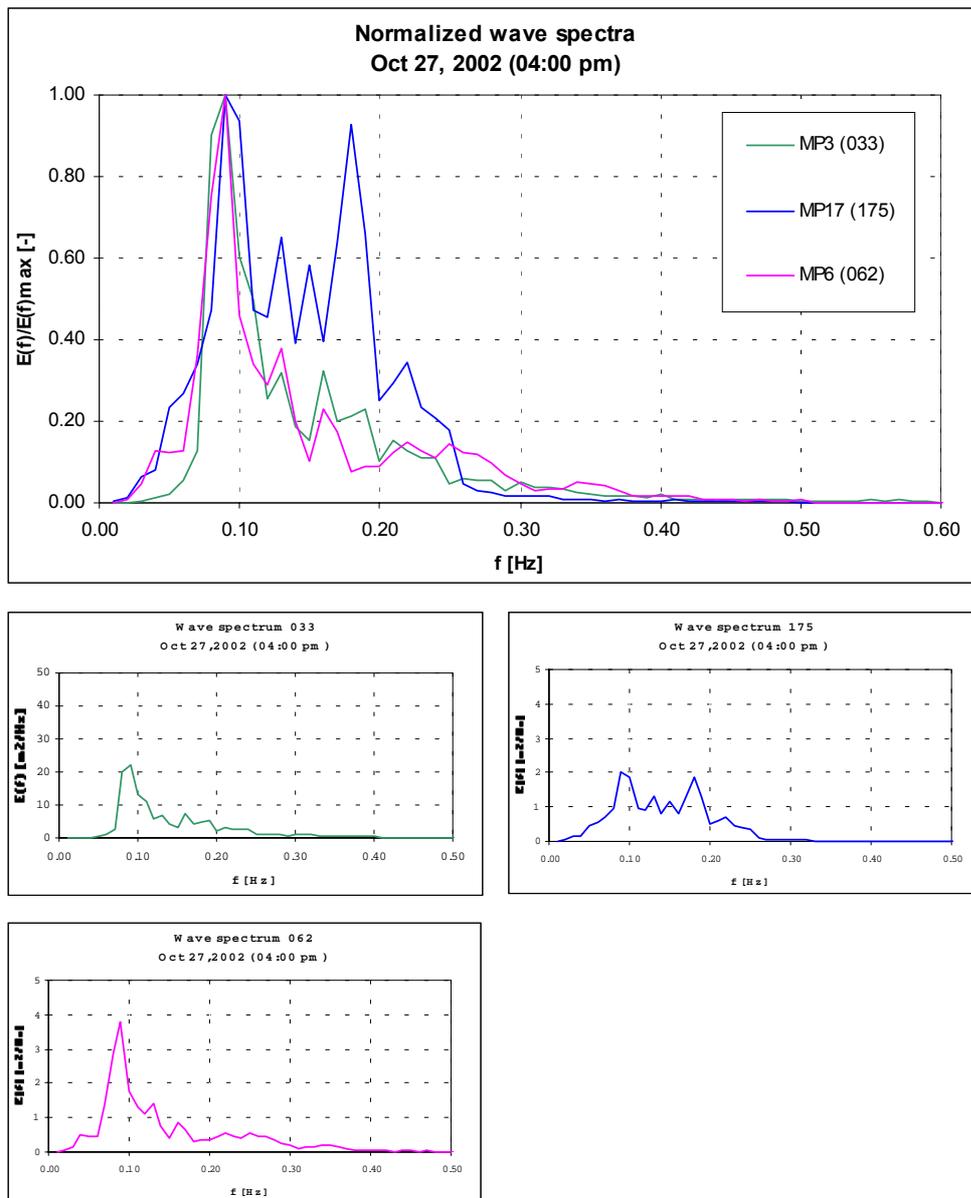


**Figure F.3** Wave spectra  
27 October 2002  
(12am)



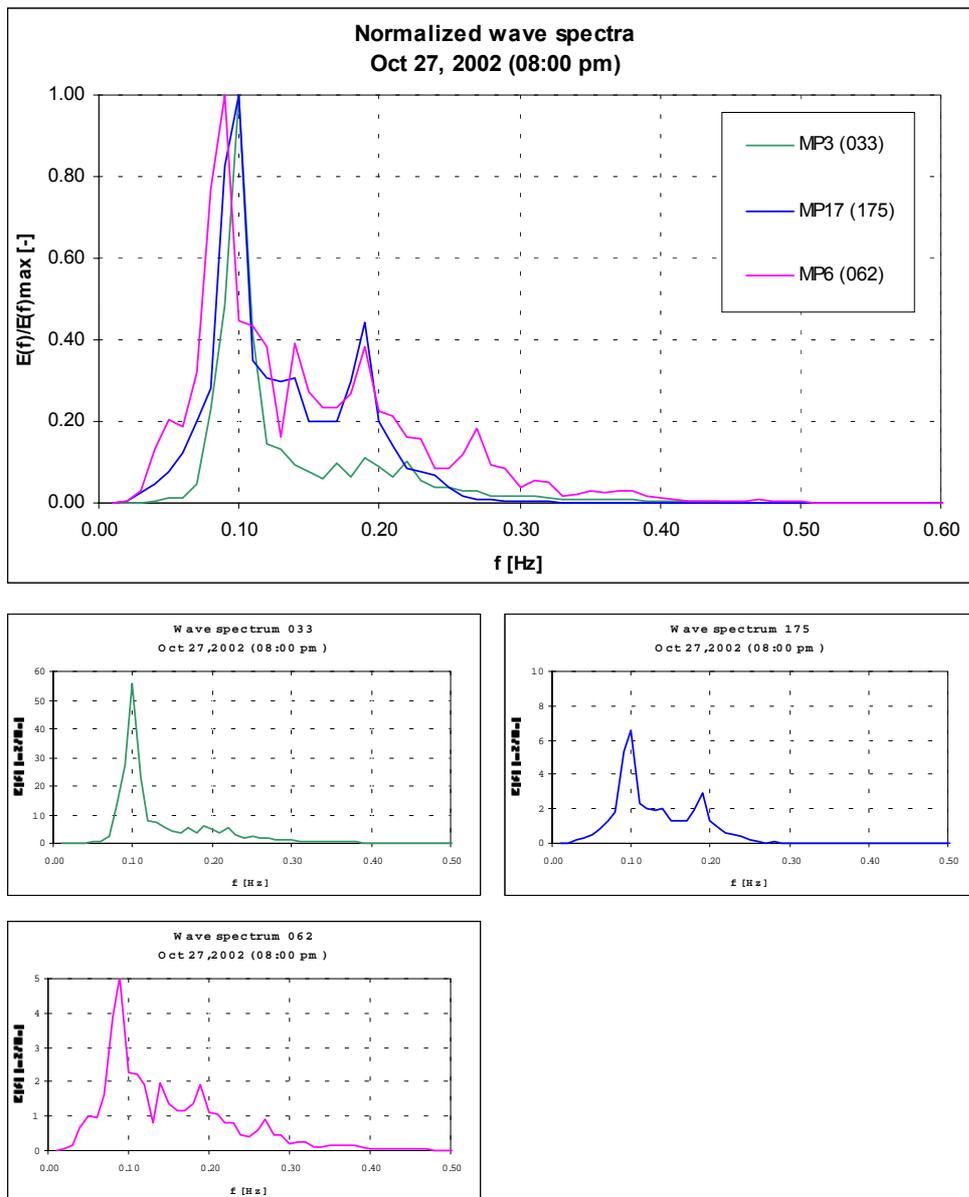


**Figure F.4** Wave spectra  
27 October 2002  
(4pm)



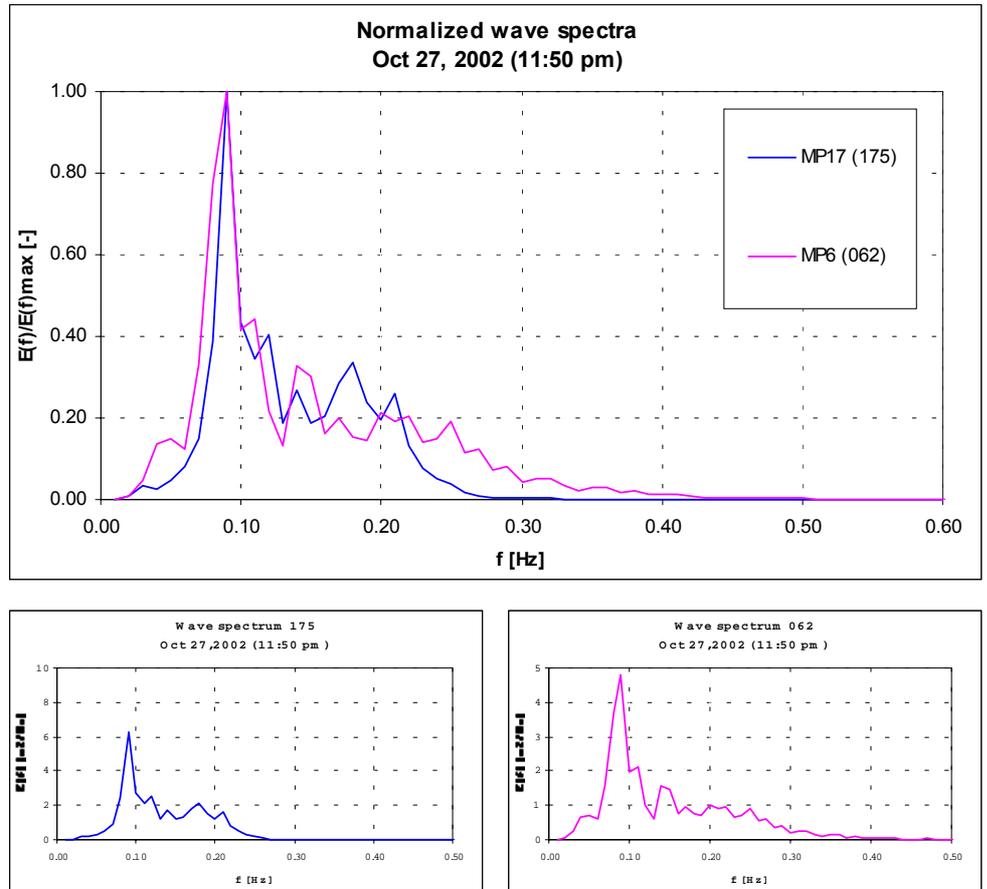


**Figure F.5** Wave spectra  
27 October 2002  
(8pm)



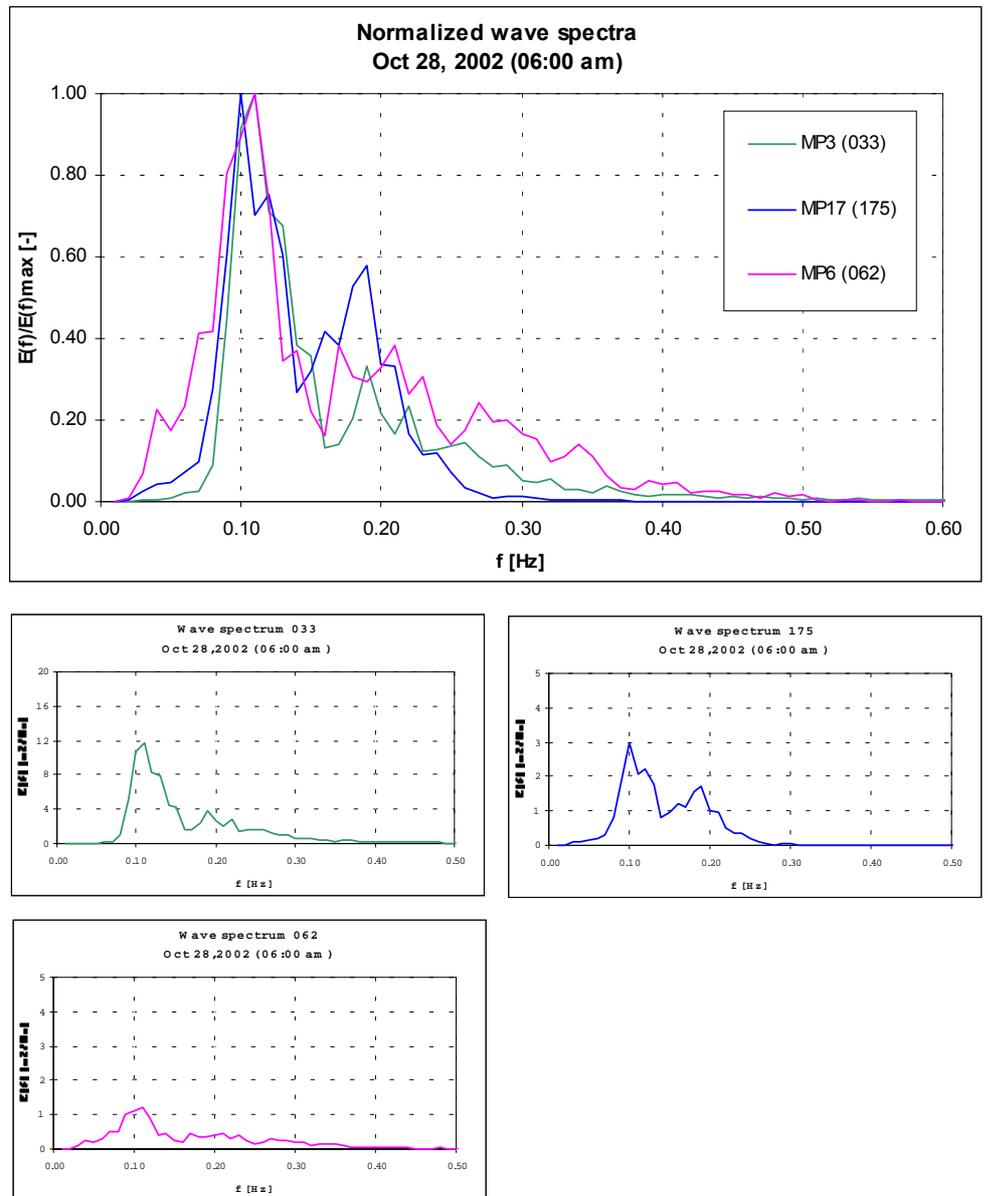


**Figure F.6** Wave spectra  
27 October 2002  
(11:50pm)





**Figure F.7** Wave spectra  
28 October 2002  
(6am)





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**Figure F.8** Hm0 and Tm-10

