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EMS wave logger data processing

Processing data from a pressure gauge

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EMS wave logger data processing

Introduction

Waves can be measured in several ways. One way of measuring waves is by measuring the wave pressure at a certain depth using a pressure sensor and calculate the wave information from the pressure record. The EMS wave logger[1]uses a Honeywell MLH 050 PGP 06A pressure sensor. The information is stored by the logger on a SD card. The software in the logger controls the sample durations (from 1 to 30 minutes) and the sample intervals (from 15 min to 3 hours). The sampling rate is fixed to 4 Hz.

Wave pressure

In a regular, small amplitude wave the instantaneous water level is given by:

$$\eta = a \sin\theta \qquad (1)$$

Under a regular, small amplitude wave the pressure is given by:

$$p = -\rho g z + \rho g a \frac{\cosh k(h+z)}{\cosh kh} \sin\theta \qquad (2)$$

in which:

η	instantaneous water level (m)
p	pressure at the requested location (Pa)
ρ	density of the water (kg/m^3)
g	acceleration of gravity (m/s^2)
z	depth of the pressure (note: under water z is negative) (m)
a	amplitude of the wave (m)
k	wave number = $2\pi/L$
θ	phase angle of the wave (rad)
L	local wave length (m)

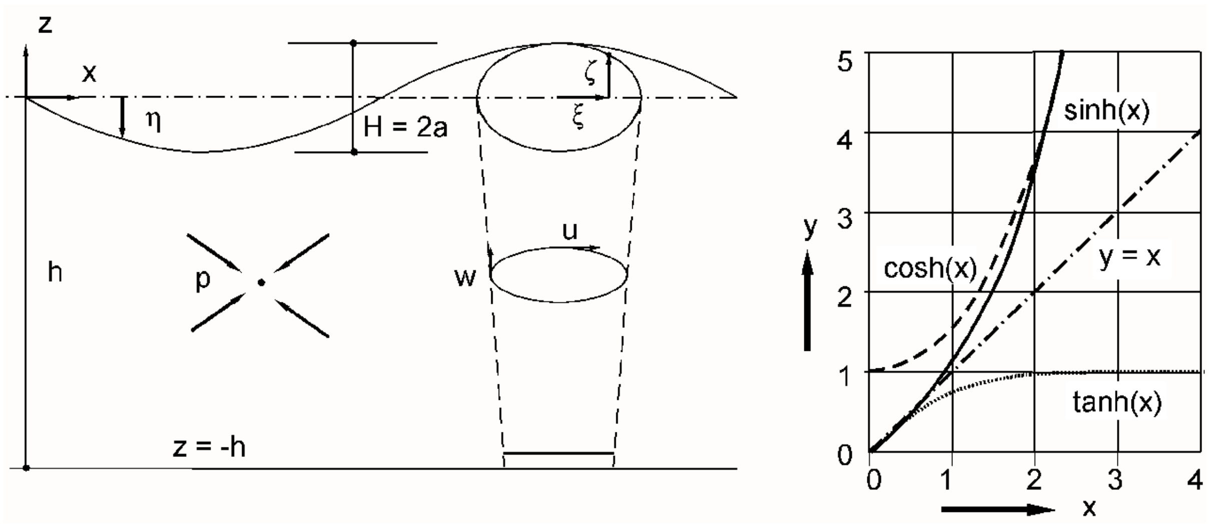


Figure 1: definitions in the wave pressure equation.

When inserting eq. (1) into eq. (2) leads to:

$$p = -\rho g z + \rho g \eta \frac{\cosh k(h+z)}{\cosh kh} \qquad (3)$$

[1] The wave logger is produced by Environmental Mapping & Surveying, Durban, South Africa; see also Appendix 1.

In order to do this correct, the density of water needs to be known. This parameter (Rho) has to be set in the script. For fresh water ρ=1000, for sea water one should raise ρ up to 1030 kg/m^3.

Subtracting the hydrostatic pressure leads to:

$$\Delta p = \rho g \eta \frac{\cosh k(h+z)}{\cosh kh}$$
$$\eta = \frac{\Delta p}{\rho g} \frac{\cosh kh}{\cosh k(h+z)} \qquad (4)$$

And in case the pressure is measured at the bottom, this reduces to:

$$\eta = \frac{\Delta p}{\rho g} \cosh kh \qquad (5)$$

Eq. (5) can be used to calculate the surface elevation from the pressure record. However, one should realise that this derivation is only valid for regular, small amplitude waves.

In shallow water usually waves cannot be considered small amplitude waves, and second order theory should be applied to describe the water surface elevation. The main difference between first order and higher order waves is the exact shape of the surface. Wave height and wave period are not very different. Because of this, first order wave theory is acceptable for this purpose.

In important drawback of determining wave heights from pressure records is that small, short waves cannot be measured at larger water depths.

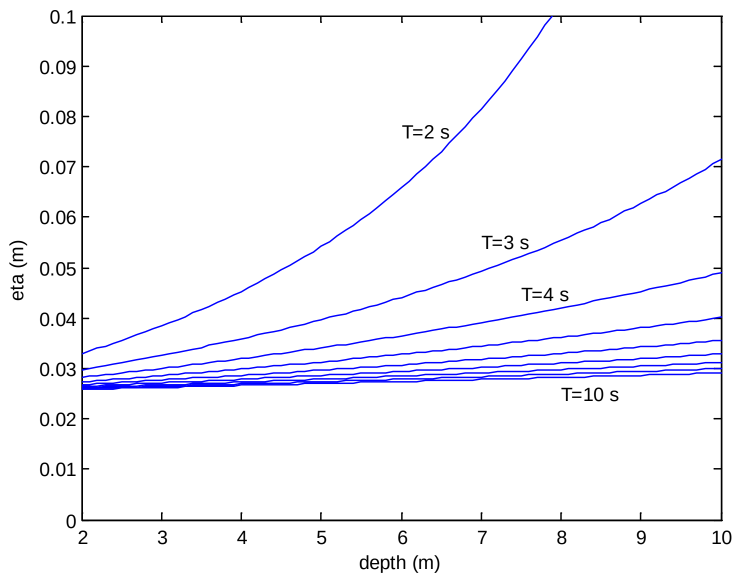


Figure 2: accuracy of the calculated water elevation as a function of water depth and wave period

The accuracy of the wave logger is in the order of 250 Pa. In fig. 2. the accuracy of the calculated water elevation is plotted as a function of the water depth and the wave period.

It is clear from the figure that in larger water depths the accuracy decreases significantly for the shorter wave periods. In general one may conclude that up to a water depth of 10 waves with a period of 5 seconds and larger are quite accurate.

Irregular waves (time domain)

In case of irregular waves the above theory is still valid, but cannot be applied without restrictions.

A real surface record may look like figure 3.

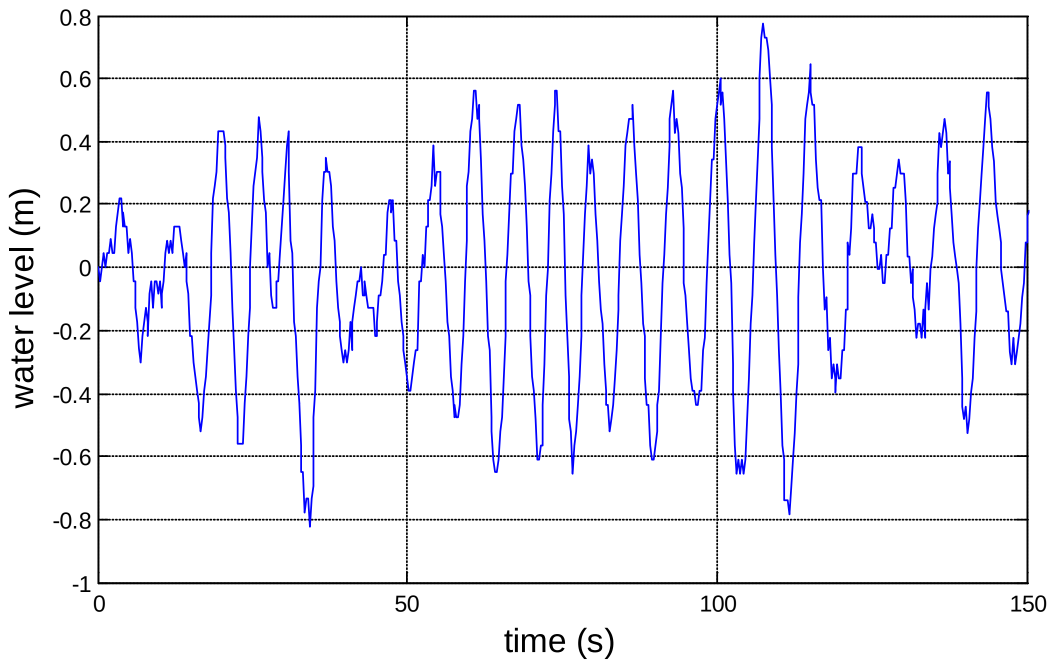


Figure 3: example of a surface water level record

As can be seen all individual waves have different periods and heights. To calculate back from a pressure record to a water surface level the individual wave periods should be known. In theory one could split a pressure record into individual waves and then calculate the resulting surface elevation for each individual wave. However this usually leads to large errors with shorter waves. Therefore one can better first calculate the average wave period in the whole record (i.e. the total observation period divided by the number of waves) and use that wave period for the calculation.
When doing so, the short waves in the wave field are not really accounted for. But these waves are also the lower waves, and therefore usually not the most relevant part of the wave height distribution.

For the time domain analysis therefore a surface elevation is generated using eq. (5) and the mean period of the observation time.
With a counting algorithm then the individual waves are distinguished in this generated surface elevation record. To separate the waves the downward crossing method is used. From each wave the height is determined.

In order to calculate the water surface from the pressure record, the period has be known. The period is included in k in eq. (2). The program has two methods to do this. In method 1 the average period (observation time/number of waves) is used. In method 2 the period of each individual wave is calculated and used. Method 1 goes wrong with a wide spectrum. Method 2 goes wrong in deep water. Small pressure variations in deep water are translated to huge, ridiculously short waves. This is physically not correct. Therefore the wave steepness is limited to a maximum value for individual waves (this max value is called “steepnesss” in the Matlab script).

In general method 2 with a correct limitation of the steepness is the preferred method.
Also waves which are smaller than a given value (Hminimum) are considered not to be real.
The value of Hminimum depends on the accuracy to the pressure sensor and the waterdepth.
In shallow water the value of Hminimum can be very small. In deep water Hminimum is approx.. 10 cm.

Subsequently the waves are sorted on individual height.
In the Matlab script the array with sorted wave heights is called “Hsorted”. The number of waves found is called “counter”. In this report the following notation is used:

N	Number of waves
H_i	individual wave
H_{mean}	average wave height
H_{rms}	root mean square wave height
$H_{1/3}$	Significant wave height

In the next step the time domain variables are determined:

$$H_{mean} = \frac{1}{N}\sum H_i \tag{6}$$

$$H_{rms} = \frac{1}{N}\sqrt{\sum H_i^2} \tag{7}$$

$$H_s = H_{1/3} = \frac{1}{N/3}\sum_{\frac{2}{3}N}^{N} H_i \tag{8}$$

Also are determined the wave height exceeded by 2%, 1% and 0.1% of the waves. These wave heights are determined in three ways:

a. Directly from the observations;
b. Using a Rayleigh distribution;
c. Using the Composite Weibull Distribution according to Battjes and Groenendijk [2000].

With method b a Rayleigh distribution of the waves is assumed. This assumption is usually correct in deep water. For the Rayleigh distribution is valid:

$$\begin{aligned} H_{2\%} &= 1.40 H_s \\ H_{1\%} &= 1.50 H_s \\ H_{0.1\%} &= 1.85 H_s \end{aligned} \tag{9}$$

The equation for the Rayleigh distribution is:

$$P\{\underline{H} > H\} = \exp\left[-1\left(\frac{H}{H_s}\right)^2\right] \tag{10}$$

In shallow water the highest waves in the record are already broken. Therefore the Rayleigh distribution is not valid any more. Battjes and Groenendijk [2000] suggested a approximation of this distribution using:

$$\Pr(\underline{H} \le H) = \begin{cases} F_1(H) = 1 - \exp\left[-\left(\frac{H}{H_1}\right)^2\right] & H \le H_{tr} \\ F_2(H) = 1 - \exp\left[-\left(\frac{H}{H_2}\right)^{3.6}\right] & H > H_{tr} \end{cases} \tag{11}$$

Below a transitional value of the wave height (H_{tr}), the Rayleigh distribution remains valid. Above this value the exponent in the distribution has a different value (3.6). The values H_1

and H_2 were fitted from measurements and tabulated in the original paper. These values depend on the water depth and the bed slope. Figure 4 below shows the ratio $H_{x\%}/H_{rms}$ for various values of H_{tr}/H_{rms}.

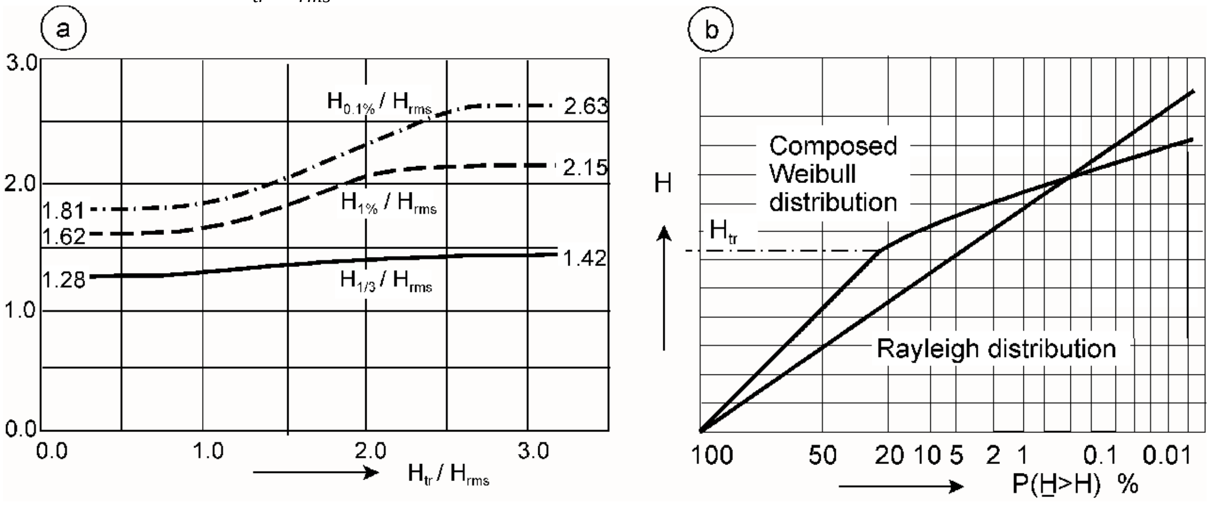


Figure 4: Wave height distribution in shallow water (Battjes/Groenendijk, 2000)

The parameters from the Composite Weibull Distribution are loaded into the script from the matlab script BG.

Note that in case of a limited number of waves in the record (<1000), no observed value of $H_{0.1\%}$ can be determined. The script gives then as output NaN (Not a Number).

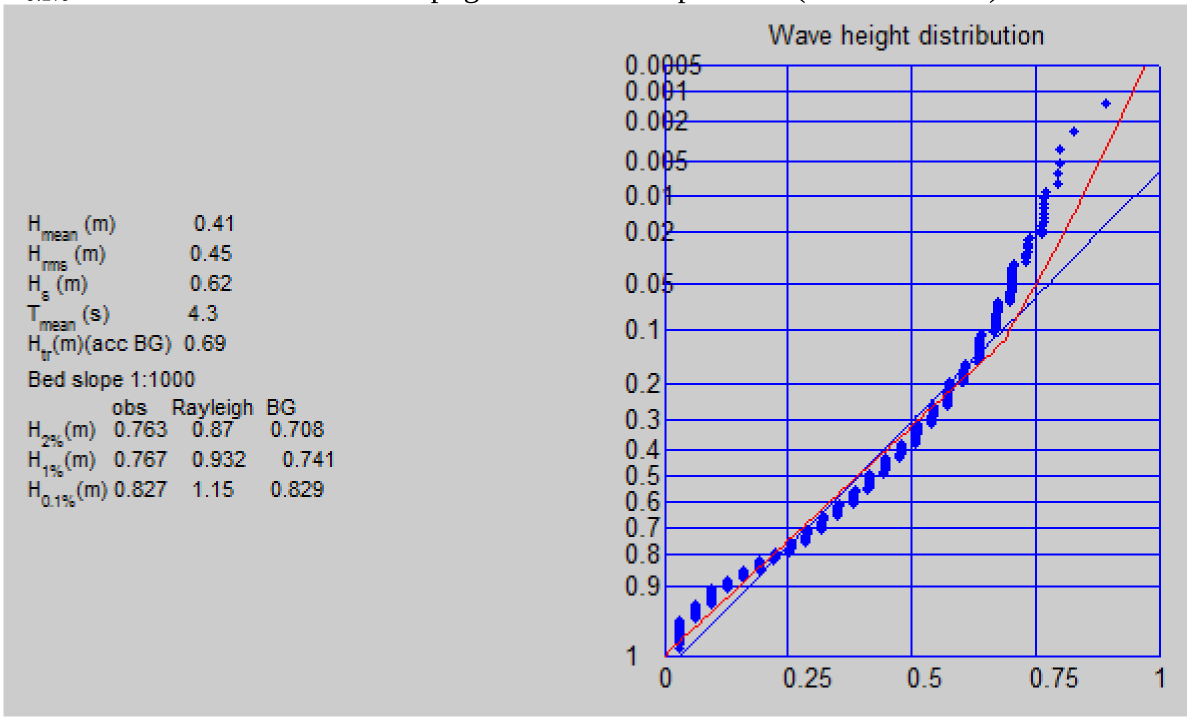

```
H_mean (m)          0.41
H_rms (m)           0.45
H_s (m)             0.62
T_mean (s)          4.3
H_tr(m)(acc BG)     0.69
Bed slope 1:1000
            obs    Rayleigh   BG
H_2%(m)     0.763   0.87      0.708
H_1%(m)     0.767   0.932     0.741
H_0.1%(m)   0.827   1.15      0.829
```

Figure 5: example of the output of a wave height distribution

In the output of the script the blue line is the Rayleigh fit, the red line the Battjes-Groenendijk fit and the blue crosses the observed data. This dataset was observed on a natural beach in very shallow water (1.9 m).

The extreme wave heights in the record are relevant for the design of coastal structures. The stability of armour units depends on the highest values in the record. Assuming a Rayleigh distribution usually gives a significant overestimation in relatively shallow water, leading to a too heavy structure. Note that with a frequency domain analysis (see below) one cannot determine these highest waves in the record.

Irregular waves (frequency domain)

The time domain analysis is not very accurate in determining the periods of the wave. Also it does not give information on the shape of the wave spectrum. Therefore a frequency domain analysis is needed. In principle two methods are possible:

1. Determine the surface elevation of the water and apply spectral analysis on this surface elevation;
2. Determine the spectrum of the pressure and calculate from the pressure spectrum the surface elevation spectrum (wave energy spectrum).

Method 1 is standard in case the surface elevation was measured directly (e.g. with wave buoys or step gauges). However, when applying this method for pressure records, inaccuracies are included because of the fact that the calculated surface elevation is smoothed and does not contain all period information any more.
Therefore for pressure data method 2 is to be preferred.

In the script the pressure record is processed by the script crosgk. This script, developed by Klopman of Deltares, determines the power cross spectrum using a Fast Fourier Method. This results in a pressure spectrum:

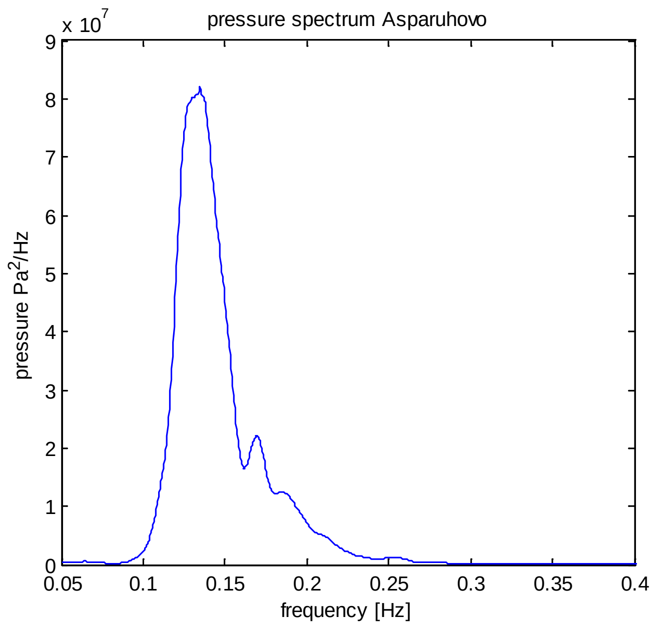


Figure 6: A pressure spectrum derived from the pressure data

A certain degree of smoothing of the spectrum is recommended. This value can be set by changing the parameter M in the script. M=0 is no smoothing. Practical values for M are between 20 and 100.
For each frequency bin one can calculate from the pressure value the elevation value (on the vertical axis is the pressure in Pa^2/Hz, in the wave energy spectrum we need m^2/Hz). This means that the same formula can be used as was applied in the time domain analysis (eq. (5)). Now the exact value for the period is known, because that is given by the number of the frequency bin.
This process results in the energy spectrum:

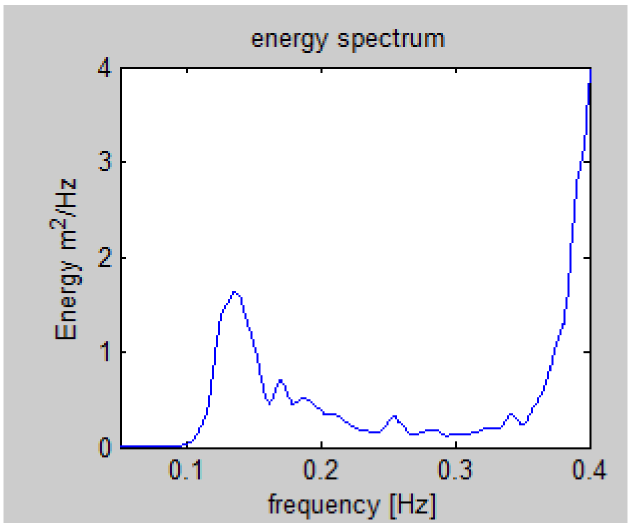


Figure 7: The energy spectrum calculated from the pressure spectrum of figure 6.

It is clear that the peak at the right side of the spectrum is an artefact. It is caused by the fact that a small value of the pressure is multiplied with an extremely high multiplier. This has no physical meaning. The above data were measured on a water depth of 8.5 m. Small variations in the pressure (less than the accuracy of the meter) are interpreted by eq. (5) as being caused by huge waves of very short periods. While in reality these variations are only random noise.

Therefore the spectrum should be cut off in this case at a value of approximately 0.28 Hz (see also figure 6). With the parameters “cutoff” and “high” this is realized. The variable “cutoff” limits the analysis, while “high” only changes the axis of the plot. See figure 8 for the result.

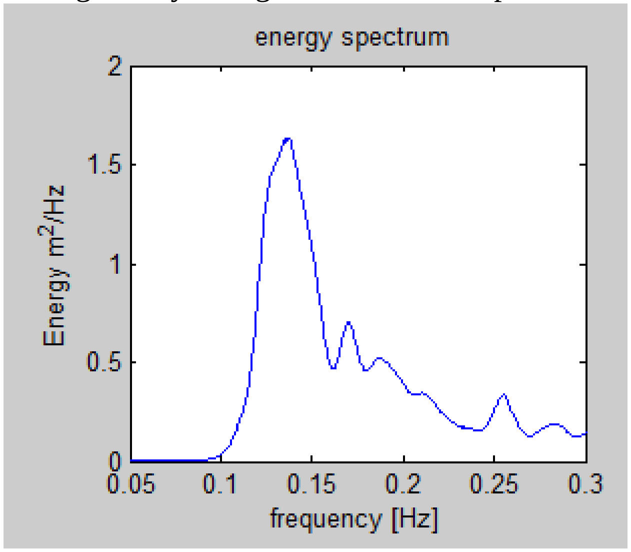


Figure 8: corrected wave energy spectrum using the parameters “cutoff” and “high”

One can determine the values for “cutoff” and “high” by using the plot of the pressure spectrum. This plot is not printed on default, only when the parameter “extraplot” is set to 1. There is also a value “low”. This value should be used for deleting long periodic waves which have nothing to do with the waves to be analysed (e.g. seiches).

From the spectrum various moments are computed. A moment of a spectrum is the product of arm and area. For higher order moments, one raises the arm to a certain power. The zero-th order moment is the area multiplied with the arm to the power zero, which is in fact only the surface area. The zero-th order moment gives the total energy in the spectrum. The general equation of the moment is:

$$m_n = \int_0^\infty f^n S(f)df \tag{12}$$

The zero-th and the 1st order moment are:

$$\begin{aligned} m_0 &= \int_0^\infty S(f)df \approx \frac{1}{2}\sum_{i=1}^{N} e_i^2 \\ m_1 &= \int_0^\infty f \cdot S(f)df \approx \frac{1}{2}\sum_{i=1}^{N} f \cdot e_i^2 \end{aligned} \tag{13}$$

The script calculates m_{-1}, m_0, m_1 and m_2. From these moments the following values are calculated:

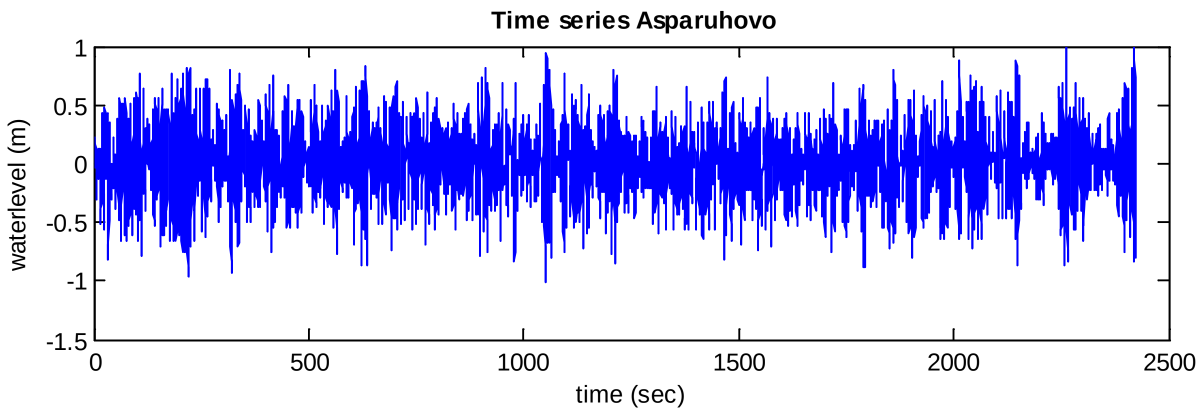
$$\begin{aligned} H_{rms} &= \sqrt{8m_0} \\ H_{m0} &= 4\sqrt{m_0} \end{aligned} \tag{14}$$

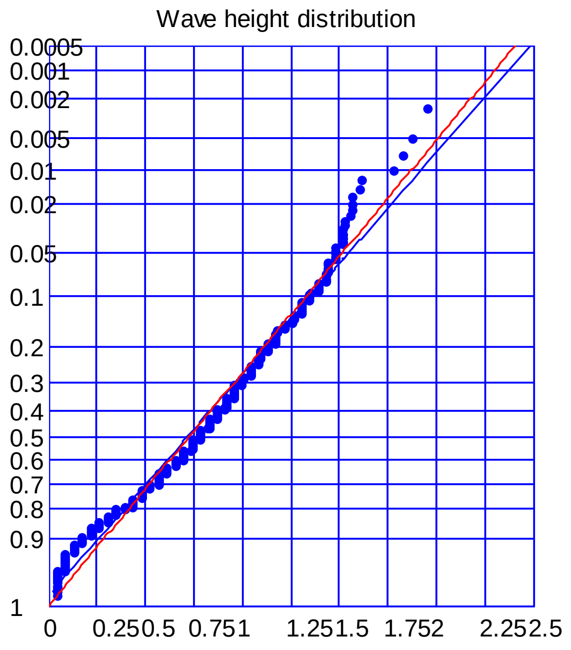
and

$$\begin{aligned} T_m &= \sqrt{\frac{m_0}{m_2}} \\ T_{0,1} &= \frac{m_0}{m_1} \\ T_{-1,0} &= \frac{m_{-1}}{m_0} \end{aligned} \tag{15}$$

One should expect that H_{m0} and $H_{1/3}$ are equal. If this is not the case, one should verify if the settings of the cutoff parameters.

An overview of all standard output of the script is given on the next page.

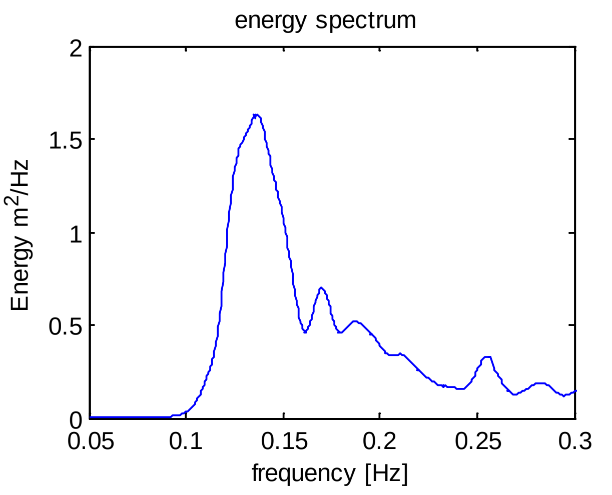




H_{mean} (m)	0.77		
H_{rms} (m)	0.87		
H_s (m)	1.2		
T_{mean} (s)	6.1		
H_{tr}(m)(acc BG)	3		

Bed slope 1:1000

	obs	Rayleigh	BG
$H_{2\%}$(m)	1.56	1.72	1.73
$H_{1\%}$(m)	1.61	1.84	1.88
$H_{0.1\%}$(m)	NaN	2.27	2.3



H_{rms} (m)	1.2
H_{m0} (m)	1.7
T_m (s)	3.5
$T_{m0,1}$ (s)	3.8
$T_{m-1,0}$(s)	4.8
T_{peak}(s)	2.5

Average depht (m)	8.5
water density (kgm^3)	1018

Calibration

The pressure sensor of the wave logger has been calibrated in a deep water pit. From this calibration was the following relation found:

$$p = 254V - 43250 \quad \text{(Pa)} \qquad (16)$$

In this formula a correction is included for the atmospheric pressure. Variations in the atmospheric pressure have influence on the results, but this effect is very small.
V is the reading from the wavelogger.

The wavelogger has been applied also during one of the Bardex experiments at the large wave flume of Deltares, Netherlands (the Deltaflume). In this flume prototype size waves can be generated. The flume is equipped with standard high performance wave gauges with a very high sampling interval (20 Hz). Appendix 2 shows a comparison of the data from the EMS wavelogger, processed with the TU Delft script and the results from Deltares equipment in the flume.

User Manual

The data are processed by the Matlab script Wavelogger.m. This script processes files with one observation only. The Wavelogger produces one single datafile with all observations in sequence[2]. The first step in processing is splitting the data from the logger in separate files. This can be done by any program. A nice tool is the program TextSplitter.exe.
Load the output file from the Wavelogger into this program, enter the number of observations and let te program slit the datafile into separate chunck of file. When the file is large, this may take several minutes; be patient. The number of observations can be found at the end of the file. The observation number is the number after $D,.
It is recommended to avoiud filenames with an underscore (‘_’), because this symbol makes that letters are printed as subscript in the Matlab script.
All observations from one ensemble should have the same name, and a different number, e.g.: Logger2-012Part1.txt; Logger2-012Part2.txt; Logger2-012Part3.txt;…..etc

Both individual observations as well as a batch of observations can be processed by the Matlab scripts wavelogger.m.
In case of a single observation:
In line 12 and 13 one should NofFiles and StartFile to 1.
Then in lines 58 to 72 the other input paramters can be set.

In case of processing multiple observations set NofFiles to the number of observations. If one intends to skip the first files (because they do not contain information), set the StartFile to a higher number. This might be useful when the Wavelogger already started to observe before it was placed on its final location.
In case of multiple observations no plots of individual observations are made (like spectra and exceedance lines). In the command window the number of processed files is shown, so one can follow the progress of the calculation.

After completion of all processing the data are written to an outputfile. This file has the same name as the inputfiles of the observations (but without the sequence number) and the extension .mat (e.g. Logger2-012Part.mat)

[2] Note that this version of the matlab script requires a heading with the following form: $S,1,12:0:3,63,6/7/12. In newer versions of the Wavelogger this header is: $S, BurstIndex,2012-11-01T00:00:00Z,Temp.

One can plot the results with the Matlab script PlotSeries.m. In this script one can set the first point to be plotted (startpunt) and the last point (eindpunt). This means that if one has a record of 600 points and on intends to plot the series from 10 to 595, startpunt=10 and eindpunt=5.

In summary, the following input values can be given in the Matlab script:

Line nr	Variable name	Default value	description
7	Rho	1030	Density of the water (kg/m^3)
8	g	9.81	Acceleration of gravity (m/s^s)
9	Avolt	254.1	Calibration value A of the pressure meter (Pa/V)
10	Bvolt	-43250	Calibration value B of the pressure meter (Pa)
11	TanAlfa	0.001	Bed slope in Battjes-Groenendijk calculations
12	NofFiles	1	Number of input files to be processed
13	StartFile	1	First input file to be processed
58	M	25	Smooth factor for the wave spectrum, a low value M=25, high value M=100
60	high	0.4	highest frequency for plots
61	low	0.05	Lowest frequency for plots
62	cutoff	0.08	parameter to eliminate noise from the tail of the spectrum when the spectral value is less than a "cutoff"-fraction of the maximum value, then the spectral value is set to exact zero
66	extraplot	2	extraplot = 0 gives no plots, 1= only summary 2=include pressure, 3=include depth, 4= include pressure
68	method	2	method=1 uses T_m for calculating wave height from pressure method=2 uses real period per wave
70	steepness	0.03	Maximum allowed wave steepness for individual waves
71	Hminimum	0.10	minimum wave height to be considered
72	interval	0.25	interval is the sample frequency interval of the sensor do not change this value unless another wavelogger is used

References

BATTJES, J.A., GROENENDIJK, H.W. [2000] Wave height distribution on shallow foreshores, *Coastal Eng. Vol 40, pp 161-182.*

Appendix 1 Description of the wave logger

The pressure meter of Environment Mapping & Surveying (EMS) is an instrument which measures the pressure at the bottom of a liquid body, such as a lake, sea, et cetera. With those measured values, the wave height and wave period can be easily found.
Two non-directional wave loggers are shown on Figure 1.

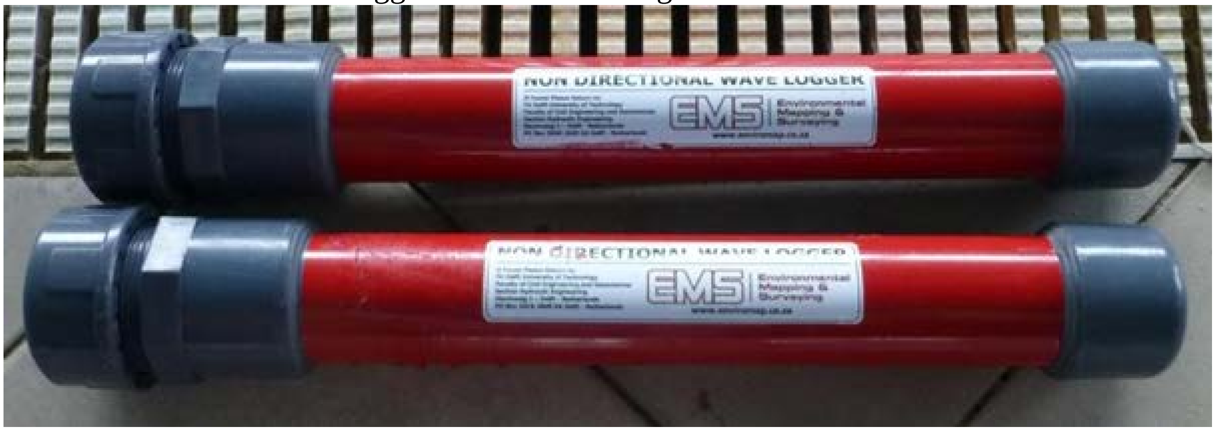

NON DIRECTIONAL WAVE LOGGER
EMS
Environmental Mapping & Surveying
NON DIRECTIONAL WAVE LOGGER
EMS
Environmental Mapping & Surveying

Figure 1: Environment Mapping & Surveying (EMS) non-directional wave loggers
If more than one wave logger is used, it is recommended to identify each wave logger by assigning a number to each one of them in order to recognize the output information when the measurements are finished.
The following sections describe the different components of one each logger and its functioning.

Housing
The housing is made from rigid PVC pipe. The fittings have been thermo welded to each other. There is a single o-ring seal for the unit. This o-ring should be kept clean and silicon applied after each deployment. The seal is compressed with the screw on the end cap.

Pressure sensor
The wave logger has a Honeywell MLH pressure sensor. More information can be found at:
http://sensing.honeywell.com/index.php?ci_id=3108&la_id=1&pr_id=31550
The sensor has the following characteristics:

- MLH 050 PGP 06 A
- 50 psi gage
- Flying leads (20 AWG - 6 in)
- 1/6 in 27 NPT
- 0.5 Vdc to 4.5 Vdc ratiometric from 5 Vdc excitation

It can be found for sale at Mouser for €91.81 each:
http://nl.mouser.com/Search/ProductDetail.aspx?qs=pLJKYPamQJz9Ny66tbLCUQ%3D%3D
The pressure sensor has been soldered directly to the controller board. If for any reason, the logger is taken apart, make note of the pin outs, reversing the voltage to the sensor will destroy it! The sensor has a stainless steel membrane which is exposed to the water. This hole should be kept clean and no tools should be used remove debris as this will damage the membrane.

Batteries
Each wave logger needs one D Cell 3.6v Lithium Ion 16500Ah battery.

It is sufficient with a Lithium-Thionyl ER34615 3.6V D SO Soldertag 10766 (10 Ah); price: € 14.52. The soldertag is otiose; therefore it has to be removed in order to work well. This can be done easily with nose pliers.
In 2012 we purchased these batteries at Batterypoint.nl
Battery and wave logger internal layout is shown in Figure 2.

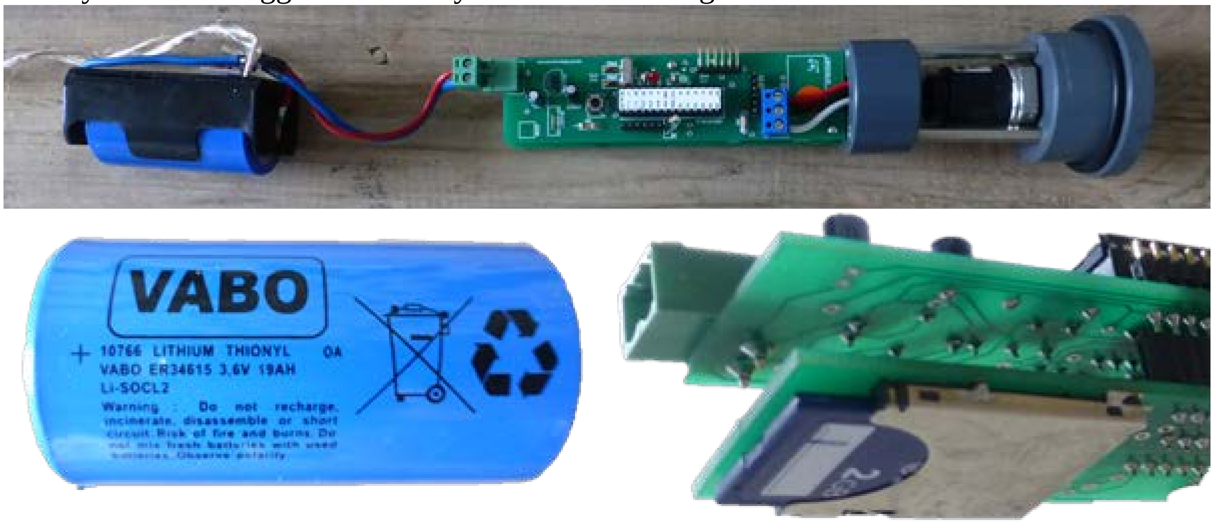


Figure 2: Wave logger details: battery, SD Card, et cetera

SD-Card
All SD cards used should be formatted FAT16. Some SD cards may not work due to speeds and or capacity.

Modifications done 01/01/2013:

1. The on board voltage regulator was removed and then it was added a 5V step up converter for Li batteries. This improves standby current draw considerably, but the unit can only be used with 3.6v batteries (and not any more with 4 AA batteries as the previous version). The unit should operate for at least 30 - 40 days on all configurations on one D Cell 3.6v.
2. A push button was added to close the file when the unit is logging if it is desired. If the bottom is pushed, the data is safe and both LEDs remain on.
3. New double sided silk screened PCB’s was added.
4. Header format was changed to $S, BurstIndex,2012-11-01T00:00:00Z,Temp.
5. Burst Duration Options were added (1min, 5min, 10min, 20min, 30min).
6. Sample Intervals were added (15min, 30min, 60min & 180min); e.g. if 15min is chosen, log times will be 0:00, 0:15, 0:30, 0:45. Also e.g. if 180min is chosen, log times will be 0:00, 03:00, 06:00, 09:00, et cetera.

USB Cable:
The supplied USB cable has a built in FTDI chip, a driver may be installed and can be found here: http://www.ftdichip.com/FTDrivers.htm.
After driver’s installation, the cable is energized with 5V from the computer’s USB port. It is therefore necessary to connect the cable to the wave logger in the correct orientation or damage will result.
A connector near the green LED should be used. It is labelled GND FTDI Tx Rx. The black wire on the USB cable must be on the "GND" side.
After installation, device manager of Windows should be checked. Under “Ports” a USB serial port with a COM number should be found. Usually the COM number is COM6. For port settings see next section.
Configuring the Unit:

The device may be configured via the supplied USB cable. Any terminal program may be used to communicate with the device (Hyper Terminal is recommended). The date and time of the unit can be checked and changed and the sampling duration may be adopted.

Method (NOTE: the sequence of the actions below is of utmost importance!!)

- ➢ Remove power to the unit.
- ➢ Plug in the USB cable to the computer.
- ➢ Start Hyper Terminal or some other terminal program.
- ➢ Select to COM port that corresponds with the FDTI USB cable.
- **Com port settings:**
  - Baud Rate: 9600.
  - Data Bits: 8
  - Parity: None
  - Stop Bits: 1
  - Flow Control: None
- ➢ Open the port.
- ➢ Connect the USB FTDI cable to the device (take note of orientation, black= GND).
- ➢ Connect power to the unit.
- ➢ Two LED’s blink alternatively.
- ➢ In the terminal window, text should appear, prompting the user to enter the "M" (capital M) key to enter the setup.
- ➢ Follow the instructions on screen to complete the setup.

Note: the sequence of the above actions is essential, any other sequence will result in non-functioning !!!!
Hyperterminal is standard included in Windows XP and earlier. In Windows7 it is no longer included. However, you may copy the Hyperterminal files from an XP computer and run them (without installation) in Windows7.

Leds

Green slow blinking:	waiting time between intervals
Green no blinking:	measuring
Green & red fast blinking:	starting to measure
Green &red blinking:	waiting for data input via hyperterminal
Green & red permanent:	measuring stopped; data are written to SD card
Red permanent only	Error SD card

Data logging

The unit will log data to a file called "datalog.txt". This file is created by the unit if it does not exist. If a file is present, it will be appended to. If you would like to deploy the instrument, it is recommended that you remove the existing datalog.txt from the SD card, so that only new data will be written.
The data is only saved to the file when the SD card is closed by the microcontroller at the end of each burst period. Therefore if the green LED is still flashing and power is removed the last burst will NOT be written to the card. There is a push button to close the file at any moment. When pushing the button, all data will be saved and both LEDs go solid.
The device is setup to log once per hour, when the minute variable is 0. The user may only change the number of samples to be recorded (done the menu).

The following file format is used to store data....
Data File Structure
$S (header), burst number, Date,Time , Temp ($S, BurstIndex,2012-11-01T00:00:00Z,Temp)
This is followed by the data at a rate of 4 Hz.

$D (header), Num (burst number), Raw ADC Reading
……
……
……
$E (header), Num (burst number). End Time

Calibration
Each individual wave logger has to be calibrated in order to get the right converting of Volts to pressure. Note that each individual wave logger will have its own calibration values, which means that each wave logger has to be calibrated before (or after) measuring waves for the first time.
The relation between pressure P and Volts V_m can be described as:

$$P = A * V_m + B$$

A and B are calibration coefficients. In order to obtain these coefficients, some different values for the pressure and measured Volts should be known. This is done by measuring the pressure in constant water depth, for example in a swimming pool. It Is advised to do it at several different water depths. The pressure can be determined when the water depth is known:

$$P = \rho * g * h$$

The best method is to lower the wave logger to a certain depth and keep it at that specific depth for several minutes. After that, the wave logger should be kept at another depth for a few extra minutes and so on, for at least three different water depths, however four or five different water levels is recommended.
When the results of this measurement are plotted, either vertical (fast water depth changing) or diagonal (slow water depth changing) lines represent the lowering or brining up of the wave logger. The horizontal lines represent the time the wave logger was laying at a certain depth. The average value of this horizontal line is used as V_m for that specific depth. The pressure can be determined since the water depth, the gravity acceleration and the density are known.
When these values are known, the points are plotted in a graph with V_m on the horizontal axis and P on the vertical axis. With a calculation spread sheet computer program is possible to make a trend line of these points. This trend line gives the calibration coefficients, since it describes the relation between V_m and P as:

$$P = A * V_m + B$$

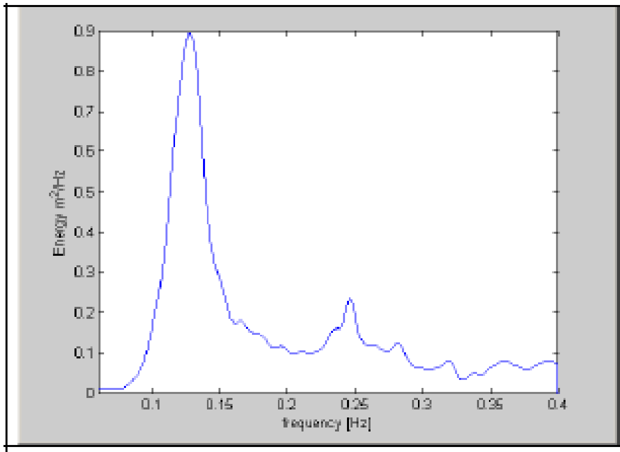
The values obtained for A and B are the calibration coefficients for that specific wave logger; these values should be used when the wave logger is used to measure wave heights.

Calibration values
For the sensors of Delft University the following calibration values have been found in 2013:

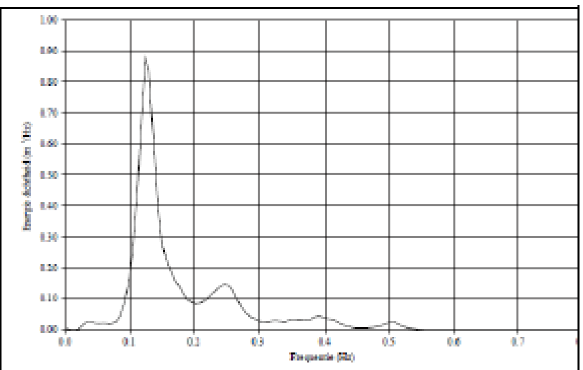
Wave Logger I:	Avolt = 477.66 - Bvolt = -43812.10
Wave Logger III:	Avolt = 457.45 - Bvolt = -49879.95

Appendix 2: Wave logger calibration

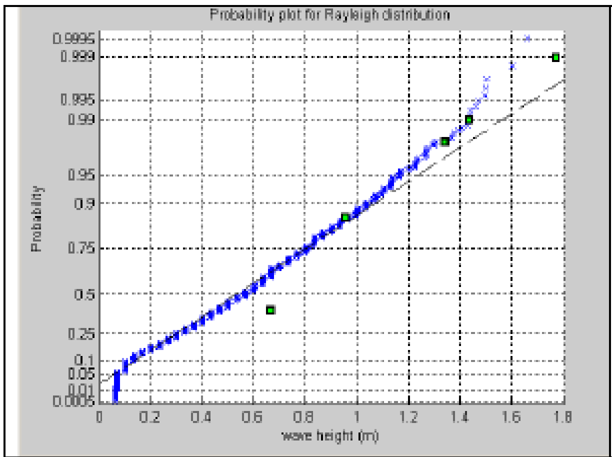
Calibration test EMS wave logger - 7 June 2012 - Deltaflume, Deltares



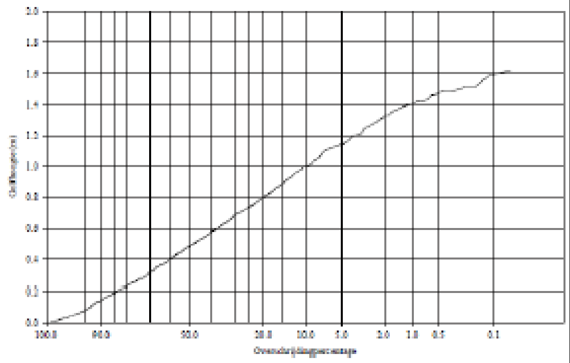
Measured spectrum with EMS wave logger



Measured spectrum according to Deltares equipment



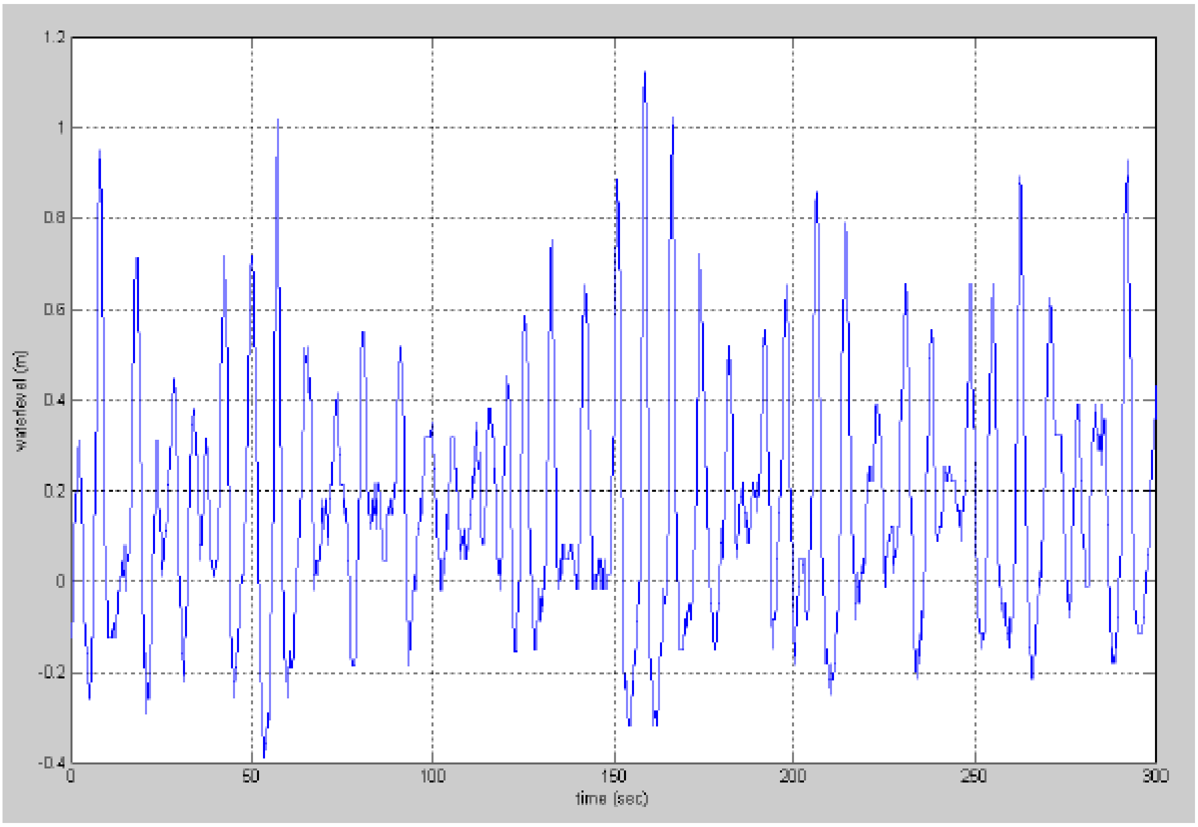
Measured exceedance line with EMS wave logger



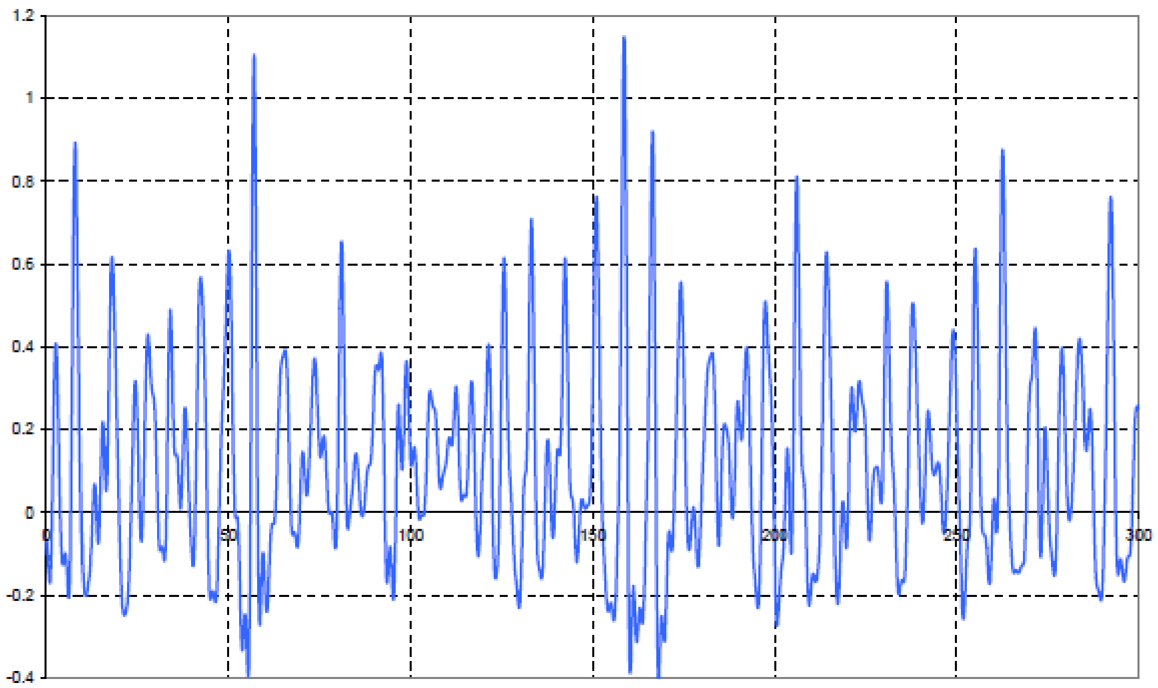
Measured spectrum according to Deltares equipment

measured unit	EMS wave logger	Deltares Equipment
Hm0	0.93	0.93
H1/3	0.96	0.94
H2%	1.34	1.38
Hmax	1.66	1.79
T01	5.47	5.53
T02		4.88
Tm-1,0	6.50	7.90
Tpeak	7.87	7.94
Sampling frequency	4 Hz	20 Hz

Calibration test EMS wave logger - 7 June 2012 - Deltaflume, Deltares



Wave surface elevation measured with EMS wave logger



Wave surface elevation measured with Deltares equipment
The measurements by EMS wave logger and Deltares Equipment were not at exactly the same location.

Appendix 3: Matlab scripts

Wavelogger.m

```
% Script for processing pressure data from the EMS wavelogger
% Script developed by H.J. Verhagen, Delft University of Technology
% February 2013
clear;
clc;
%define basic variables
Rho=1030;
g=9.81;
Avolt=254.1;        %Calibration value A of the pressure meter
Bvolt=-43250;       %Calibration value B of the pressure meter
TanAlfa = 0.001;    %bedslope
NofFiles=1;         % number of files to be processed
StartFile=1;        % first file to be processed
for ii=StartFile:NofFiles
 if (ii==StartFile)
     [FileName,PathName] = uigetfile('*.txt','Select the wavelogger file');
     end;
 if (NofFiles==1)
  fid=fopen([PathName,FileName]);
  [pathstr, heading,ext]=fileparts(FileName);
 else
  if(ii==StartFile)
     [pathstr, heading,ext]=fileparts(FileName);
     heading=heading(1:(length(heading)-1));
     end;
  tellerstring=int2str(ii);
  FileName=([heading,tellerstring,'.txt']);
  fid=fopen([PathName,FileName]);
  end;

     % heading is caption of figures, default heading=FileName
     % if needed assign other value to heading here
     % heading = 'fill in your heading';

HDRS = textscan(fid,'%s %d %s %d %s',1, 'delimiter',',');
tijd=HDRS{3};
temp=HDRS{4};
date=HDRS{5};
ccc=1;
n=0;

while ccc==1
  DATA = textscan(fid,'%s %d %d d','delimiter',',');
  ccc=strcmpi(DATA{1},'$D');
  n=n+1;
  %transformation from Volts to pressure using calibration constants Avolt
  %and Bvolt
  %Avolt has dimension Pa/V, Bvolt has dimension Pa
  if (ccc==1) q(n)=Avolt*DATA{3}+Bvolt+0.1;
      end;
end;
n=n-1;      %count number of samples
fclose(fid);
P=double(q');

% additional input data for spectrum
%===================================
M = 50;         % higher values of M give more smoothing of the spectrum
                % low value for M is 20, high value for M is 100
high = 0.25;    % highest frequency for plots  default high=0.4
low = 0.05;     % lowest frequency for plots   default low =0.05
cutoff=0.10;    % parameter to eliminate noise from the tail of the spectrum
                % when the spectral value is less than "cutoff" % of the max
                % value, then the spectral value is set to exact zero;
                % default = 0.08
extraplot = 2;  % extraplot = 0 gives no plots, 1= only summary
                % 2=include prssure, 3=include depth, 4= include pressure
method=2;       % method=1 uses Tm for calculating waveheight from pressure
                % method=2 uses rea period per wave
steepness=0.03;% max allowed wave steepness individual waves, default 0.05
Hminimum=0.10;  % minimum waveheigth to be considered default .10 m
interval=.25;   % interval is the sample frequency interval of the sensor
                % do not change this value unless another wavelogger is used
%==========================================================================
if(NofFiles>1)extraplot=0;end; %in case of multiple files plotting
individual
                                %files is blocked
tottime=n*interval;    %calculate total duration of observation in sec
ttime=(interval:interval:tottime); %create array with time
time=ttime.';           %change orientation of matrix
% calculate regression coefficients to compensate for change in waterlevel
% during the observations

if (extraplot>3)
    figure;
    plot(time,P);
    xlabel('time (sec)');
    ylabel('pressure (Pa)');
    title(['observed total pressure ',heading]);
end;
BB=polyfit(time,P,1); %regression analysis to determine real waterdepth at
any moment
                      %and correct for hydrostatic pressure
Intercept=BB(2);
Slope=BB(1);
Pwave=P-Intercept-time*Slope;

Pstatic=P-Pwave;      %Hydrostatic pressure
Depth=Pstatic/Rho/g;
AverageDepth=mean(Depth);

%Optional figure to plot waterdepth as function of time
if (extraplot>2)
   figure
   plot(time,Depth);
   ylabel('depth (m)');
   xlabel('time (sec)');
   title(['average waterdepth ',heading]);

%Optional figure to plot wave pressure as function of time
   figure
   plot(time,Pwave);
   xlabel('time (sec)');
   ylabel('pressure (Pa)');
   title(['presure variations ',heading]);
end;
%==========================================================================
%Time domain analysis
counter=0;
Pmin=0;
```

```
Pmax=0;
period=0;
start=1;
if (method==1)
%loop to find individual pressure waves, needed to find number of waves
%using mean period
  for k=1:n-1
    if(Pwave(k+1)*Pwave(k)<0 && Pwave(k+1)<0)  %new wave starts at k+1
        counter=counter+1;   % counter is number of found waves
        Pmax=0;
        Pmin=0;
    end;
    if(Pwave(k)>Pmax)  Pmax=Pwave(k);
    end;
    if (Pwave(k)<Pmin) Pmin=Pwave(k);
    end;
  end;
  %counter = number of waves found

  Tmean=n*interval/counter;
  %loop to estimate water level variations
  for k=1:n
        period=Tmean;
        L0=g/2/pi*period*period;
        if (Depth(k)/L0 < 0.36)
            L=sqrt(g*Depth(k))*(1-Depth(k)/L0)*period;
        else
            L=L0;
        end;
        eta(k)=(Pwave(k))/Rho/g*cosh(2*pi/L*Depth(k));
  end;

  %loop to find individual waves from waterlevel record (eta)
  counter2=0;
  etamax=0;
  etamin=0;
  for k=1:n-1
    if(eta(k+1)*eta(k)<0 && eta(k+1)<0)  %new wave starts at k+1
        counter2=counter2+1;
        H(counter2)=etamax-etamin;
        etamax=0;
        etamin=0;
    end;
    if(eta(k)>etamax)  etamax=eta(k);
      end;
    if (eta(k)<etamin) etamin=eta(k);
      end;
  end;
  % vector H contains all individual waves
  % sort H to make exceedance graph
else
  eta(1:n)=0;
  % Method 2 starts here================================================
  %loop to find individual pressure waves, needed to find number of waves
  %using mean period
  for k=1:n-1
    if(Pwave(k+1)*Pwave(k)<0 && Pwave(k+1)<0)  %new wave starts at k+1
        counter=counter+1;   % counter is number of found waves
        TT(counter)=period;
        L0=g/2/pi*period*period;
        if (Depth(k)/L0 < 0.36)
            L=sqrt(g*Depth(k))*(1-Depth(k)/L0)*period;
        else
```

```
                L=L0;
            end
            H(counter)=(Pmax-Pmin)/Rho/g*cosh(2*pi/L*Depth(k));
            Hunreduced=H(counter);
            Hreduced=H(counter);
            if (H(counter)>steepness*L)
                H(counter)=steepness*L;
                Hreduced=H(counter);
                end;
            if (H(counter)<Hminimum)
                 Hreduced=Hminimum;
                 counter=counter-1;
                end;
            reduction=Hreduced/Hunreduced;
            for jj=start:k
                eta(jj)=(Pwave(jj))/Rho/g*cosh(2*pi/L*Depth(jj))*reduction;
                end;
            start=k+1;           % remember startpoint for next wave
            Pmax=0;
            Pmin=0;
            period=0;
        end;
        period=period+interval;
        if(Pwave(k)>Pmax)  Pmax=Pwave(k);
        end;
        if (Pwave(k)<Pmin) Pmin=Pwave(k);
        end;
    end;
end;

  % counter = number of waves found
  % vector H contains all individual waves
  % sort H to make exceedance graph


if (extraplot>0)
 figure;
 subplot(4,1,1);
 plot(time,eta);
 xlabel('time (sec)');
 ylabel('waterlevel (m)');
 title([heading,date,tijd]);
end;
%end waterlevel loop

counter=length(H);
for k=1 : counter
prob(k)= (counter-k+1)/counter;
end;

Hsorted=sort(H);
Hmean=mean(Hsorted);
Hrms = sqrt(mean(Hsorted.^2)); % rms wave height

from=round(2*counter/3);
to=round(counter);
Hs=mean(Hsorted(from:to)); %H 1/3, or significant wave height

Tsorted=sort(TT);
Tmean=mean(TT);
from=round(2*counter/3);
to=round(counter);
```

```
T3=mean(Tsorted(from:to)); %T 1/3, or significant wave period

%calculation of the H2%
Twopercent=round(counter-counter/50);
if (Twopercent==counter)
  H2percentMeasured=NaN;
  else
  H2percentMeasured=Hsorted(Twopercent);
  end;
H2percRayleigh=1.4*Hs;
%caculation of the H1%
Onepercent=round(counter-counter/100);
if (Onepercent==counter)
  H1percentMeasured=NaN;
  else
  H1percentMeasured=Hsorted(Onepercent);
  end;
H1percRayleigh=1.5*Hs;
%calculation of the H0.1%
Onepermille=round(counter-counter/1000);
if (Onepermille==counter)
  H1permilleMeasured=NaN;
  else
  H1permilleMeasured=Hsorted(Onepermille);
  end;
H1permilleRayleigh=1.85*Hs;

% Compositie weibull ditribution for shallow water
% source: Wave height distributions on shallow foreshores
%         Coastal Engineering, Volume 40, Issue 3, June 2000, Pages 161-182
%         Jurjen A Battjes, Heiko W Groenendijk

Htr=(0.35+5.8*TanAlfa)*AverageDepth; % Transistion wave height acc. to BG
(eq. 8)

H3=Hrms*BG(Htr,3);
H10=Hrms*BG(Htr,10);
H2=Hrms*BG(Htr,0.02);
H1=Hrms*BG(Htr,0.01);
H01=Hrms*BG(Htr,0.001);

%plot Rayleigh graph
if(extraplot>0)
 h = axes('Position',[0 0 1 1],'Visible','off');
 axes('Position',[.45 .40 .45 .30])

  for i=1:counter
     probsorted2(i)=1-i/(counter+1);
  end;
 maxh=1.3*Hsorted(counter);
 step=1;
 if (maxh<5.1) step=0.5;end;
 if (maxh<2.6) step=0.25;end;
 xmark=[0:step:maxh];
 coef=Rayleigh(Hsorted,probsorted2,xmark,Hrms,Htr);
 title('Wave height distribution (m) ');
 string=num2str(Hmean,2);
 str(1)= {['H_{mean} (m)             ',string]};
 string=num2str(Hrms,2);
 str(2)= {['H_{rms} (m)              ',string]};
 string=num2str(Hs,2);
 str(3)= {['H_{s} (m)                 ',string]};
 string=num2str(Tmean,2);
 str(4)= {['T_{mean} (s)             ',string]};
 string=num2str(T3,2);
 str(5)= {['T_{1/3} (s)              ',string]};
 string=num2str(Htr,2);
 str(6)= {['H_{tr}(m)(acc BG)  '   ,string]};
 string=num2str(1/TanAlfa);
 str(7)= {['Bed slope 1:',string]};
 str(8)={'              obs     Rayleigh  BG'};
 string=num2str(H2percentMeasured,3);
stringB=num2str(H2percRayleigh,3);stringC=num2str(H2,3);
 str(9)= {['H_{2%}(m)   ',string,'    ',stringB,'      ',stringC]};
 string=num2str(H1percentMeasured,3);
stringB=num2str(H1percRayleigh,3);;stringC=num2str(H1,3);
 str(10)= {['H_{1%}(m)   ',string,'    ',stringB,'      ',stringC]};
 string=num2str(H1permilleMeasured,3);
stringB=num2str(H1permilleRayleigh,3);;stringC=num2str(H01,3);
 str(11)= {['H_{0.1%}(m) ',string,'    ',stringB,'      ',stringC]};
 set(gcf,'CurrentAxes',h)
 text(.1,.55,str,'FontSize',8)
end;




%=====================================================================
% simple script utilizing crosgk (by G. Klopman) to obtain
% spectral estimate
%=====================================================================
% data  contains the data
% N  is the number of samples per data segment (power of 2)
% M  is the number of frequency bins over which is smoothed (optional),
%    no smoothing for M=1 (default)
% DT is the time step (optional), default DT=1
% DW is the data window type (optional): DW = 1 for Hann window (default)
%                                         DW = 2 for rectangular window
% stats : display resolution, degrees of freedom (optimal, YES=1, NO=0)
%
% Output:
% P contains the (cross-)spectral estimates: column 1= Pxx, 2= Pyy, 3= Pxy
% F contains the frequencies at which P is given load time series

DT = interval;
    data = Pwave;
    [P,F,dof]=crosgk(data,data,length(data),M,DT,1,0);

 %recalcultate pressure spectrum to energy spectrum
  energy=1:length(F);  % length (F) is number of frequency bins
  for i=1:length(F)
      energy(i)=0;
  end;
  m0=0;   %zero-th moment
  m1=0;   %first moment
  m2=0;   %second moment
  m01=0;  %first negative moment {m(-1,0)}
  deltaF= F(31)-F(30);

  emax=0;
  prmax=0;  %maximum value of pressure energy
  % claculation loop to transform pressure spectrum to energy spectrum and
  % to calculate the moments of the spectrum
  % low and high frequencies are deleted, range from 200 to 0.2*max
  % frequency bin, 200 means f= 200*deltaF, which is approx. 30 seconds
  % 0.2*length(F)*deltaF = 0.4, so Tmin - 2.5 seconds
```

```
%loop to determine maximum value of pressure spectrum
for i=50:2000
    if (sqrt(P(i,1))>prmax) prmax=sqrt(P(i,1));
    end;
end;
for i=50:2000
    T=1/F(i);
    pr=sqrt(P(i,1));   %pr=pressure value in pressure spectrum
    L0=1.56*T*T;
    if (AverageDepth/L0<0.36)
        L=sqrt(g*AverageDepth)*(1-AverageDepth/L0)*T;
        else
        L=L0;
        end;
    energy(i)=(pr/(Rho*g)*cosh(2*pi/L*AverageDepth))^2;
                                  % e=energy density in Hz/m2
    if (pr<cutoff*prmax)
        energy(i)=0;
        end;
    if energy(i)>emax
        emax=energy(i);
        Tpeak=T;
        end;
    m0 =m0 +energy(i)*deltaF;
    m1 =m1 +energy(i)*deltaF*F(i);
    m2 =m2 +energy(i)*deltaF*F(i)^2;
    if (F(i)>0)
        m01=m01+energy(i)*deltaF/F(i);
        end;
end;

Hm0=4*sqrt(m0);    %one may assume Hs = Hm0
Hrmss=sqrt(8*m0);   %root mean square height from spectrum
Tm=sqrt(m0/m2);    %spectral approximation of mean period
T01=m0/m1;         %Period based on first moment
T10=m01/m0;        %Period based on first negative moment


% plot spectrum and print output
if(extraplot>0)
 h = axes('Position',[0 0 1 1],'Visible','off');
 axes('Position',[.45 .05 .45 .20])
 plot(F,energy)
 axis([low high 0 10000])
 axis 'auto y'
 xlabel('frequency [Hz]');
 ylabel ('Energy m^2/Hz');
 title('energy spectrum ');
 string=num2str(Hrmss,2);
 str(1)= {['H_{rms} (m) ',string]};
 string=num2str(Hm0,2);
 str(2)= {['H_{m0} (m)  ',string]};
 string=num2str(Tm,2);
 str(3)= {['T_{m} (s)    ',string]};
 string=num2str(T01,2);
 str(4)= {['T_{m0,1} (s) ',string]};
 string=num2str(T10,2);
 str(5)= {['T_{m-1,0}(s) ',string]};
 string=num2str(Tpeak,2);
 str(6)= {['T_{peak}(s)  ',string]};
 str(7)={' '};
 str(8)={' '};
```

```
   string=num2str(AverageDepth,2);
   str(9)={['Average depht (m) ',string]};
   string=num2str(Rho);
   str(10)={['water density (kgm^{3})    ',string]};
   str(11)={' '};
   set(gcf,'CurrentAxes',h)
   text(.1,.15,str,'FontSize',8)
  end;

 %Optional plot pressure spectrum
if (extraplot>1)
    figure
    plot(F,P(:,1))     % P is pressure^2/Hz
    axis ([low high 0 1500])
    axis 'auto y'
    xlabel('frequency [Hz]');
    ylabel ('pressure Pa^2/Hz');
    title(['pressure spectrum ',heading]);
end;

StUitvoer(ii,1)=date;
StUitvoer(ii,2)=tijd;

uitvoer(ii,1)=ii;
uitvoer(ii,2)=AverageDepth;
uitvoer(ii,4)=Hs;
uitvoer(ii,5)=Hm0;
uitvoer(ii,6)=Tmean;
uitvoer(ii,7)=Tm;
uitvoer(ii,8)=T10;
uitvoer(ii,9)=Tpeak;
disp(ii);
end;

MeanDepth=0;
for (ii=StartFile:NofFiles)
MeanDepth=MeanDepth+uitvoer(ii,2);
end;
MeanDepth=MeanDepth/(NofFiles-StartFile);
for(ii=StartFile:NofFiles)
uitvoer(ii,3)=uitvoer(ii,2)-MeanDepth;
end;
savefile=([heading,'.mat']);
save (savefile,'StUitvoer','uitvoer');
```

Rayleigh.m

```
function coef = rayleigh(xi,yi,xmark,Hrms,Htr)
% ----------------------------------------------------------------
%     function coef = rayleigh(xi,yi,xmark)
%
%  Rayleigh Probability Paper: The paper is marked with probability
%  of exceedance [0.002, 0.005, 0.01, 0.05, 0.1:0.1:0.9]  (horizontal
%  lines associated with these values are drawn).  In addition, it draws
%  the linear curve fitting for input data points.
%
%  xi = horizontal input (physical quantity)
%  yi = vertical input (in probability of exceedance)
%  xmark = vertical grid lines to be plotted
%  coef = slope and intercept of the linear regression line.
x = xmark;
poe = [1:-0.1:0.1, 0.05,0.02,0.01,0.005,0.002,0.001,0.0005]; % prob.of
exceedance
y = sqrt(-log(poe));
n = length(y);
m = length(x);
axis([x(1) x(m) y(1) y(n)]);
dx = abs(x(m)-x(1))/25;
xh = [x(1) x(m)];
% working on horizontal line
for k=1:n,
    yh=[y(k) y(k)];
    line(xh,yh);
    text(x(1)-2*dx,y(k),num2str(poe(k)));  % prob. of exceedance
end
% set(gca,'linestyle',':');
% working on vertical line (horizontal scale)
dy=abs(y(n)-y(1))/25;
yv=[y(1),y(n)];
for k=1:m,
    xv=[x(k) x(k)];
    line(xv,yv);
    text(x(k)-dx/4,y(1)-dy,num2str(xmark(k)));
end
axis('off');
% x is wave height
% y is probability (correct numbers)
% z is scaled probability for Rayleigh paper
% plotting data points, convert probabilities for plot
%
zi = sqrt(-log(yi));
hold on
plot(xi,zi,'.')
%
% to draw regression line
%
coef=polyfit(xi,zi,1);
xa = 0.5 * min(xi);
xb = 1.5 * max(xi);
xx = [xa xi xb];
yy = polyval(coef,xx);
plot(xx,yy,'-');
%
H1=BG(Htr/Hrms,1);
H2=BG(Htr/Hrms,2);
xxx=[xmark(1):.01:xmark(m)];
lxxx=length(xxx);
%calculate plot with CWD of Battjes Groenendijk
```

```
for j=1:lxxx
  if (xxx(j)<Htr)
    yyy(j)=1-exp(-power((xxx(j)/(H1*Hrms)),2.0));  %BG 2
    else
    yyy(j)=1-exp(-power((xxx(j)/(H2*Hrms)),3.6));  %BG 3.6
    end;
end;
%convert probabilities to scale for plot
zzz=sqrt(-log(1-yyy));
hold on

plot(xxx,zzz,'r');
```

crosgk.m

```
function [P,F,dof]=crosgk(X,Y,N,M,DT,DW,stats);
% CROSGK   Power cross-spectrum computation, with smoothing in the
%          frequency domain
%
% Usage: [P,F]=CROSGK(X,Y,N,M,DT,DW,stats)
%
% Input:
% X  contains the data of series 1
% Y  contains the data of series 2
% N  is the number of samples per data segment (power of 2)
% M  is the number of frequency bins over which is smoothed (optional),
%    no smoothing for M=1 (default)
% DT is the time step (optional), default DT=1
% DW is the data window type (optional): DW = 1 for Hann window (default)
%                                        DW = 2 for rectangular window
% stats : display resolution, degrees of freedom (optimal, YES=1, NO=0)
%
% Output:
% P contains the (cross-)spectral estimates: column 1 = Pxx, 2 = Pyy, 3 =
Pxy
% F contains the frequencies at which P is given
%
%
% Gert Klopman, Delft Hydraulics, 1995
%
if nargin < 4,
  M = 1;
end;
if nargin < 5,
    DT = 1;
end;
if nargin < 6,
  DW = 1;
end;
if nargin < 7,
  stats = 1;
end;
df = 1 / (N * DT) ;
% data window
w = [];
if DW == 1,
  % Hann
  w  = hanning(N);
  dj = N/2;
else,
  % rectangle
  w  = ones(N,1);
  dj = N;
end;
varw = sum (w.^2) / N ;


% summation over segments

nx     = max(size(X));
ny     = max(size(Y));
avgx   = sum(X) / nx;
avgy   = sum(Y) / ny;
px     = zeros(size(w));
py     = zeros(size(w));
```

```
Pxx   = zeros(size(w));
Pxy   = zeros(size(w));
Pyy   = zeros(size(w));
ns    = 0;

for j=[1:dj:nx-N+1],

  ns = ns + 1;

  %   compute FFT of signals

  px = X([j:j+N-1]') - avgx;
  px = w .* px ;
  px = fft(px) ;

  py = Y([j:j+N-1]') - avgy;
  py = w .* py ;
  py = fft(py) ;

  % compute periodogram

  Pxx = Pxx + px .* conj(px) ;
  Pyy = Pyy + py .* conj(py) ;
  Pxy = Pxy + py .* conj(px) ;

end;

Pxx = (2 / (ns * (N^2) * varw * df)) * Pxx ;
Pyy = (2 / (ns * (N^2) * varw * df)) * Pyy ;
Pxy = (2 / (ns * (N^2) * varw * df)) * Pxy ;

% smoothing

if M>1,
  w = [];
  w = hamming(M);
  w = w / sum(w);
  w = [w(ceil((M+1)/2):M); zeros(N-M,1); w(1:ceil((M+1)/2)-1)];
  w = fft(w);
  Pxx = fft(Pxx);
  Pyy = fft(Pyy);
  Pxy = fft(Pxy);
  Pxx = ifft(w .* Pxx);
  Pyy = ifft(w .* Pyy);
  Pxy = ifft(w .* Pxy);
end;

Pxx = Pxx(1:N/2);
Pyy = Pyy(1:N/2);
Pxy = Pxy(1:N/2);

% frequencies

F = [];
F = ([1:1:N/2]' - 1) * df;

% signal variance

if DW == 1,
  nn = (ns + 1) * N / 2;
else,
  nn = ns * N;
end;
avgx  = sum (X(1:nn)) / nn;
varx  = sum ((X(1:nn) - avgx).^2) / (nn - 1);
avgy  = sum (Y(1:nn)) / nn;
vary  = sum ((Y(1:nn) - avgy).^2) / (nn - 1);
covxy = sum ((X(1:nn) - avgx) .* (Y(1:nn) - avgy)) / (nn - 1);

m0xx    = (0.5 * Pxx(1) + sum(Pxx(2:N/2-1)) + 0.5 * Pxx(N/2)) * df;
m0yy    = (0.5 * Pyy(1) + sum(Pyy(2:N/2-1)) + 0.5 * Pyy(N/2)) * df;
m0xy    = (0.5 * Pxy(1) + sum(Pxy(2:N/2-1)) + 0.5 * Pxy(N/2)) * df;

%disp(['m0x / varx = ' num2str(m0xx./varx) '  ;  m0y / vary = '
num2str(m0yy./vary) '  ; m0xy / varxy = ' num2str(real(m0xy)./covxy) '  '])


Pxx = Pxx * (varx  / m0xx);
Pyy = Pyy * (vary  / m0yy);
Pxy = Pxy * (covxy / real(m0xy));

P = [Pxx, Pyy, Pxy];

% output spectrum characteristics
dof = floor(2*ns*(M+1)/2/(3-DW));
if stats == 1
fprintf('number of samples used : %8.0f\n', nn);
fprintf('degrees of freedom     : %8.0f\n', floor(2*ns*(M+1)/2/(3-DW)));
fprintf('resolution             : %13.5f\n', (3-DW)*df*(M+1)/2);
end
%
```

BG.m

```
function [Hnorm]=BG(Htr,Proba);
% Function developed by H.J. Verhagen, Delft University of Technology
% January 2013

% Input:
% Htr - H transition acc Battjes-Groenendijk (eq 8 in paper)

% Proba code for required exceendandce:
%     Proba = 3     ==> H1/3
%     Proba = 10    ==> H1/10
%     Proba = 0.02  ==> H2%
%     Proba = 0.01  ==> H1%
%     Proba = 0.001 ==> H0.1%

% Output Hnorm

% source: Wave height distributions on shallow foreshores
%         Coastal Engineering, Volume 40, Issue 3, June 2000, Pages 161-182
%         Jurjen A Battjes, Heiko W Groenendijk

%table from Battjes groenendijk
% Htr     H1      H2       H1/3    H1/10    H2%      H1%      H0.1%
BGtable=[
0.05    12.193  1.060   1.279   1.466   1.548   1.620   1.813
0.1     7.003   1.060   1.279   1.466   1.548   1.620   1.813
0.15    5.063   1.060   1.279   1.466   1.548   1.620   1.813
0.2     4.022   1.060   1.279   1.466   1.548   1.620   1.813
0.25    3.365   1.060   1.279   1.466   1.548   1.620   1.813
0.3     2.908   1.060   1.279   1.466   1.548   1.620   1.813
0.35    2.571   1.060   1.279   1.466   1.548   1.620   1.813
0.4     2.311   1.060   1.279   1.466   1.548   1.620   1.813
0.45    2.104   1.060   1.279   1.466   1.549   1.620   1.813
0.5     1.936   1.061   1.280   1.467   1.549   1.621   1.814
0.55    1.796   1.061   1.281   1.468   1.550   1.622   1.815
0.6     1.678   1.062   1.282   1.469   1.552   1.624   1.817
0.65    1.578   1.064   1.284   1.471   1.554   1.626   1.820
0.7     1.492   1.066   1.286   1.474   1.557   1.629   1.823
0.75    1.419   1.069   1.290   1.478   1.561   1.634   1.828
0.8     1.356   1.073   1.294   1.483   1.567   1.639   1.835
0.85    1.302   1.077   1.300   1.490   1.573   1.646   1.843
0.9     1.256   1.083   1.307   1.498   1.582   1.655   1.852
0.95    1.216   1.090   1.315   1.507   1.591   1.665   1.864
1       1.182   1.097   1.324   1.518   1.603   1.677   1.877
1.05    1.153   1.106   1.335   1.530   1.616   1.690   1.892
1.1     1.128   1.116   1.346   1.543   1.630   1.705   1.909
1.15    1.108   1.126   1.359   1.558   1.645   1.721   1.927
1.2     1.090   1.138   1.371   1.573   1.662   1.739   1.946
1.25    1.075   1.150   1.381   1.590   1.679   1.757   1.967
1.3     1.063   1.162   1.389   1.607   1.698   1.776   1.988
1.35    1.052   1.175   1.395   1.626   1.717   1.796   2.011
1.4     1.043   1.189   1.399   1.644   1.737   1.817   2.034
1.45    1.036   1.203   1.403   1.664   1.757   1.838   2.058
1.5     1.030   1.217   1.406   1.683   1.778   1.860   2.082
1.55    1.024   1.231   1.408   1.703   1.799   1.882   2.106
1.6     1.020   1.246   1.410   1.721   1.820   1.904   2.131
1.65    1.016   1.261   1.411   1.736   1.841   1.927   2.156
1.7     1.013   1.275   1.412   1.749   1.863   1.949   2.182
1.75    1.011   1.290   1.413   1.759   1.884   1.972   2.207
1.8     1.009   1.305   1.413   1.767   1.906   1.994   2.232
1.85    1.007   1.320   1.414   1.773   1.927   2.017   2.257
1.9      1.006   1.334   1.414   1.779   1.949   2.039   2.282
1.95     1.004   1.349   1.415   1.783   1.970   2.062   2.307
2        1.004   1.363   1.415   1.786   1.985   2.084   2.332
2.05     1.003   1.378   1.415   1.789   1.983   2.106   2.357
2.1      1.002   1.392   1.415   1.791   1.982   2.128   2.382
2.15     1.002   1.407   1.415   1.793   1.981   2.150   2.406
2.2      1.001   1.421   1.415   1.795   1.981   2.149   2.430
2.25     1.001   1.435   1.415   1.796   1.980   2.148   2.454
2.3      1.001   1.449   1.415   1.797   1.979   2.148   2.478
2.35     1.001   1.462   1.415   1.797   1.979   2.147   2.502
2.4      1.000   1.476   1.416   1.798   1.979   2.147   2.525
2.45     1.000   1.490   1.416   1.798   1.979   2.147   2.548
2.5      1.000   1.503   1.416   1.799   1.978   2.147   2.571
2.55     1.000   1.516   1.416   1.799   1.978   2.146   2.593
2.6      1.000   1.529   1.416   1.799   1.978   2.146   2.616
2.65     1.000   1.542   1.416   1.799   1.978   2.146   2.629
2.7      1.000   1.555   1.416   1.799   1.978   2.146   2.629
2.75     1.000   1.568   1.416   1.800   1.978   2.146   2.628
2.8      1.000   1.580   1.416   1.800   1.978   2.146   2.628
2.85     1.000   1.593   1.416   1.800   1.978   2.146   2.628
2.9      1.000   1.605   1.416   1.800   1.978   2.146   2.628
2.95     1.000   1.617   1.416   1.800   1.978   2.146   2.628
3        1.000   1.630   1.416   1.800   1.978   2.146   2.628];

j=0;
 if (Proba==1)     j=2; end;
 if (Proba==2)     j=3; end;
 if (Proba==3)     j=4; end;
 if (Proba==10)    j=5; end;
 if (Proba==0.02)  j=6; end;
 if (Proba==0.01)  j=7; end;
 if (Proba==0.001) j=8; end;
  i=round(Htr/0.05);
 if (Htr>3)    i=60; end;
 if (Htr<.05) i=1;   end;

 if(j==0)
   Hnorm=NaN;
   else
   Hnorm=BGtable(i,j);
   end;
end
```

PlotSeries.m

```
[FileName,PathName] = uigetfile('*.mat','Select the datafile to be
plotted');
[pathstr, heading,ext]=fileparts(FileName);
load(FileName);
k=length(uitvoer);
for i=1:k
day(i)=uitvoer(i,1:1)/24;
end;
startpunt=35;
eindpunt=15;
datum=StUitvoer(startpunt,1);
tijd=StUitvoer(startpunt,2);
subplot(3,1,1);
 hlines(3)=plot(day(startpunt:k-eindpunt),uitvoer(startpunt:k-
eindpunt,3:3),'b');
 xlabel('days)');
 ylabel('waterlevel (m)');
 title(['{\bf',heading,datum,tijd,'}']);
 set(hlines(3),'Displayname','tide')
 legend('Location','WestOutside')
subplot(3,1,2);
 hlines(4)=plot(day(startpunt:k-eindpunt),uitvoer(startpunt:k-
eindpunt,4:4),'b');
 hold on;
 hlines(5)=plot(day(startpunt:k-eindpunt),uitvoer(startpunt:k-
eindpunt,5:5),'r');
 xlabel('days');
 ylabel('wave height (m)');
 set(hlines(4),'Displayname','H_{1/3}')
 set(hlines(5),'Displayname','H_{m0}')
 legend('Location','WestOutside')
subplot(3,1,3);
 hlines(9)=plot(day(startpunt:k-eindpunt),uitvoer(startpunt:k-
eindpunt,9:9),'b');
 hold on;
 hlines(8)=plot(day(startpunt:k-eindpunt),uitvoer(startpunt:k-
eindpunt,8:8),'r');
 hold on;
 hlines(7)=plot(day(startpunt:k-eindpunt),uitvoer(startpunt:k-
eindpunt,7:7),'m');
 hold on;
 hlines(6)=plot(day(startpunt:k-eindpunt),uitvoer(startpunt:k-
eindpunt,6:6),'g');
 set(hlines(6),'Displayname','T_{mean}')
 set(hlines(7),'Displayname','T_{m0,2}')
 set(hlines(8),'Displayname','T_{m-1,0}')
 set(hlines(9),'Displayname','T_{peak}')
 legend('Location','WestOutside')
 xlabel('days');
 ylabel('wve period (s)');
```