MARINET

Marine Renewables Infrastructure Network

Work Package 2: Standards and best practice

D2.14 Wave data presentation and storage review

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ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for Emerging Energy Technologies) is an EC-funded consortium of 29 partners bringing together a network of 42 specialist marine renewable energy testing facilities. MARINET offers periods of free access to these facilities at no cost to research groups and companies. The network also conducts coordinated research to improve testing capabilities, implements common testing standards and provides training and networking opportunities in order to enhance expertise in the industry. The aim of the MARINET initiative is to accelerate the development of marine renewable energy technology.

Companies and research groups who are interested in availing of access to test facilities free of charge can avail of a range of infrastructures to test devices at any scale in areas such as wave energy, tidal energy and offshore-wind energy or to conduct specific tests on cross-cutting areas such as power take-off systems, grid integration, moorings and environmental data. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users.

MARINET is consists of five main areas of focus or 'Work Packages': Management & Administration, Standardisation & Best Practice, Transnational Access & Networking, Research and Training & Dissemination. The initiative runs for four years until 2015.

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Sustainable Energy Authority of Ireland (SEAI_OEDU)

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Legal Disclaimer

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EXECUTIVE SUMMARY

The research and testing for wave energy devices generates large amounts of experimental data. Recording, processing, presenting and archiving methods vary among the different MaRINET facilities; due to different instrumentation, user requirements and experimental set-up.

This document provides a review of the methodologies for wave data storage and presentation techniques at the different facilities allowing the generation of common protocol or the benchmarking of results and presented in a concise format to facilitate comparison of results in a harmonised way.

The document identifies, through the use of a questionnaire, storage requirements for wave data collected at eleven MaRINET facilities, both at laboratory and field scale, and reports the most common ways to represent wave data.

Discrepancies in data storage amongst the different facilities were noted when the data was collected in proprietary format. A wider agreement among the facilities was found in the ways wave data are represented. In both cases stronger agreement could be reached by following suggested guidelines, existing standards and creating wave data standards for the wave energy industry.

CONTENTS

1 INTRODUCTION

Large datasets are generated while monitoring wave conditions under both laboratory and field conditions. The manner in which this data is processed, presented and stored varies amongst the different MaRINET facilities due to differing methodologies, instrumentation and user requirements.

Typically, primary wave buoy data are provided in proprietary format. Subsequently the data given to the final users of the facilities contains standard information such as spectral moments, energy period mean direction etc, which may be prepared in a variety of ways.

A review of the methodologies for wave data storage in place at the different MaRINET facilities is presented in this document. This allows for the identification of storage requirements and representation techniques in order to facilitate the generation of common protocols.

1.1 SCOPE OF THIS DOCUMENT

The purpose of this document is to review the methodology for storing and presenting wave data at the different MaRINET facilities, in order to allow for normalisation of datasets and to facilitate the cross-comparison of results.

A review of wave data presentation format standards is presented in Section 2, data storage information for the different MaRINET facilities is given in Section 3 and Section 4 discusses data presentation.

This document considers the following aspects of wave data storage and presentation:

- Data storage at laboratory facilities and test centres, including storage requirement and data availability
- Wave data representation, including common nomenclature used and graphs developed

This document does not consider:

- Experimental setup and methodology employed to gather the wave data
- Information on the type of analysis carried out on the wave data to derive graphical representation of wave data.

2 WAVE DATA STANDARDS

Over the past 50 years, measurements of wind generated waves have been collected and used for a variety of coastal applications from coastal protection to shipping (Jensen, Swail, Lee, & Reilly, 2010). In recent years the number of applications for which ocean waves are monitored and the number of sites being monitored has increased. This increase has prompted researchers to look into the creation of standards for the acquisition and presentation of oceanographic data, through the organization of multidisciplinary workshops and organizations, such as:

- The Intergovernmental Oceanographic Commission (IOC) established by UNESCO
- The Joint WMO-IMO Technical Commission for Oceanographic Marine Methodology (JCOMM, www.jcomm.info): established for the collaboration of worldwide marine meteorological and oceanographic communities in order to respond to interdisciplinary requirements for met/ocean observations, data management and service products.
- The Alliance for Coastal Technologies (ACT, www.act-us.info), which comprises research institutions, resource managers, and private sector companies to aid the development and adoption of effective ocean sensors and platforms.
- The Ocean Data Standards Pilot Project (ODS, http://www.oceandatastandards.org); aiming to obtain agreement and commitment

The assessment of wave energy resources is one of the newest coastal applications requiring the collection of wave data.

It is important to note that one fundamental aspect of the development of the wave energy sector is the testing of the devices at laboratory scale. This requires that similarity is ensured between model scale and field conditions, both in terms of quality of the waves generated and of the post-processing analysis carried out. A set of recommended procedures and guidelines were generated by the International Towing Tank Conference (ITTC) and (http://ittc.sname.org/archive.htm) outlining laboratory procedures for wave measurement and model test experiments. Of particular relevance for the wave energy sectors are the following procedures:

- Testing and Extrapolation Methods, Resistance, Uncertainty Analysis Spreadsheet for Wave Profile Measurements (ITTC 7.5-02-02-06, http://ittc.sname.org/2006_recomm_proc/7.5-02-02-06.pdf)(ITTC, 2002)
- Testing and Extrapolation Methods Loads and Responses, Ocean Engineering, Laboratory Modelling of Multidirectional Irregular Wave Spectra (ITTC 7.5-02-07-02.1, http://ittc.sname.org/2006_recomm_proc/7.5-02-07-01.1.pdf) (ITTC, 2005a)
- Testing and Extrapolation Methods, Loads and Responses, Ocean Engineering Floating Offshore Platform Experiments (ITTC 7.5-02-07-03.1, http://ittc.sname.org/2006_recomm_proc/7.5-02-07-03.1.pdf) (ITTC, 2005b)
- Wave Energy Converter Model Test Experiments (ITTC 7.5-02-07-03.7, http://ittc.sname.org/CD%202011/pdf%20Procedures%202011/7.5-02-07-03.7.pdf) (ITTC, 2011)

Unified information for the provision and exchange of wave data were presented by UNESCO (UNESCO, 1987), providing information on the procedures and format to allow the exchange of measured wave data, providing information on the wave parameters that need to be presented and how they should be represented. This consisted in a list of common nomenclature used, as well as information on how to present the data (Figure 1).

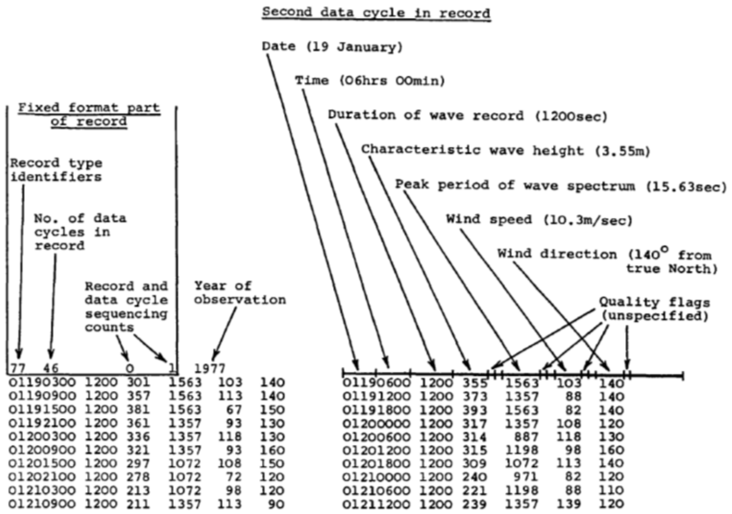

Figure 1: Wave data representation according to (UNESCO, 1987)

These guidelines were amended and updated by the World Meteorological Organization (WMO, 1998) who provided coding for the report of spectral wave information collected from a sea station as well as information on wave analysis and forecast that can be carried out from displacement data obtained from wave buoys and other instrumentation at sea. Similarly, the oil industry has developed standard for the analysis of wave parameters obtained at sea (Tucker, 1993).

ACT found that the majority of coastal users collecting wave data, despite different uses, requires the so-called ‘First Five Fourier Parameters’ (Alliance for coastal technologies, 2007), defined as:

1. Directional Spectra E, function of the wave energy density S, of the wave frequency f and of the direction θ
2. The first Fourier coefficient, Mean direction $a_1(f)$
3. The second Fourier coefficient, Directional spread $b_1(f)$
4. The third Fourier coefficient, Skewness $a_2(f)$
5. The fourth Fourier coefficient, Kurtosis $b_2(f)$

Through these 5 parameters it is possible to express the directional wave spectra E(f, θ) as an infinite Fourier series:

$$E(f,\theta) = S(f)[a_1\cos(\theta) + b_1\sin(\theta) + a_2\cos(2\theta) + b_2\sin(2\theta)] \quad [1]$$

The ACT report suggested that wave monitoring instrumentation should be able to provide at least the ‘First 5’ parameters; however, according to the users some equipment may be required to provide further Fourier moments.

The directional spectrum is generated from mathematical estimates such as the Maximum Likelihood and the Maximum Entropy Methods. The directional spectra represents therefore an interpretation of nature, rather than an exact observation (Jensen et al., 2010). The spectrum, calculated from time series of vertical displacement of the water surface, is dependent on the configuration of the device, as well as on the sampling frequency and the type of mathematical method employed.

Recommendations were made by the ACT to allow for wave data standardization and inter-comparison between different datasets, gathered from different wave instruments such us wave rider buoys, ADCPs or HF radar, as follows:

- Standardize data output and sensor/data interoperability, thus ensuring that different wave sensors are measuring and providing the desired values
- Standardize the performance of wave sensors. ACT defined as standard instrument a Datawell Waverider MK III wave buoy, calibrated against a fixed test rig equipped with pressure sensors and compass (Alliance for coastal technologies, 2012)

- Establishment of a reference data set for the evaluation of the data analysis algorithm (Maximum Entropy or Maximum Likelihood Methods), available at http://cdip.ucsd.edu/documents/index/product_docs/cdiptool/DOWNLOAD/data_sample.txt

Recommendations made from ACT were included in the US National Operation Wave Observation Plan, developed by the US Integrated Ocean Observing System (IOOS) (IOOS, 2009).
One of the requirements of the IOOS is for the wave data provider to use a standard metadata format, based on the WMO F291 format (http://www.nodc.noaa.gov/General/NODC-Archive/f291.html). The WMO alphanumeric formats are the standard for distributing real-time data among the government and commercial meteorological community, as well as the wave and ocean modelling communities.

The IOOS aim is to work towards the adoption of ISO Certificates (International Organization for Standardization) and the generation of ISO metadata standards. Each data attribute (e.g. unit of measure, reporting convention, precision, and code definition) will be encoded and delivered in valid XML format, whilst real time data are available in ASCII format.

The work carried out from IOOS resulted in the generation of the “Wave Instrument Intercomparison Tool” developed by the Coastal Data Information Programme (CDIP, cdip.ucsd.edu) at Scripps Institution of Oceanography. The WaveEVALTOOL (http://cdip.ucsd.edu/documents/index/product_docs/cdiptool/?xitem=documentation) allows for the evaluation of wave data acquired from different instrumentation, through the comparison of spectral components with standard methods (Figure 2).

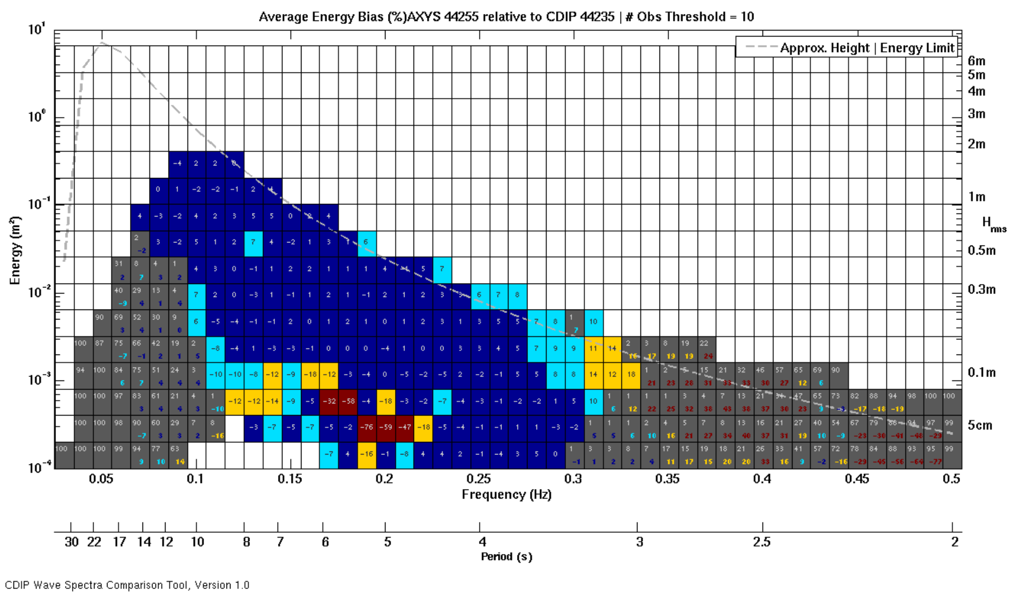

Figure 2: Spectral energy comparison between two co-located wave buoys in the Pacific Ocean. Biases are expressed as %. Note biases less than 5-percent, (dark blue), from 5- to 10-percent (light blue), 10- to 20-percent (yellow), greater than 20-percent (red). Grey areas with values defined in the boxes indicate NO data from one of the two buoy (Jensen et al., 2010)**.**

The WaveEVALTOOL was developed to be used for a wide range of wave instrumentation presented in the ACT protocol (Alliance for coastal technologies, 2012); and the data presented has to comply with the formats and templates provided by CPID, including Spectral File Format, Header for wave data generated from wave buoy and moored station and metadata form generator (http://cdip.ucsd.edu/themes/user_groups/engineers?d2=p68). Information on the type of instrumentation used, as well as on the sampling frequency and accuracy are needed to ensure effective and accurate comparison.

The results of the above collaboration have seen the generation of two ISO protocols for wave data:

- ISO8601:2004 – Standard for the Representation of Date and Time in Oceanographic Data Exchange (Ocean Standards, 2010a)

- ISO3166-1 and ISO3166-3 – Recommendation to Adopt ISO 3166-1 and 3166-3 Country Codes as the Standard for Identifying Countries in Oceanographic Data Exchange (Ocean Standards, 2010b)

The development of the wave energy industry requires continuous monitoring of wave conditions at a given wave energy installation. Wave monitoring is required for different applications: evaluating the available resources at a given site and their seasonal variability, to allow for device optimization through the identification and provision of sea-state information to the device developer, to assess changes in the coastal morphology and physical processes as a result of the installation of wave energy converters.

Protocols for the assessment of wave energy resources have been produced by the FP7 funded project Equimar (Equimar, 2010) and by EMEC (EMEC, 2012). The latter document has been submitted as the basis for the international standard IEC (International Electro-technical Commission) TS 62600-101 Wave energy resource characterization and assessment, due to be published in 2013.

The EMEC report presents guidelines for the storage of wave data collected for wave energy purpose:

- Data should have a common structure
- Data records should be consolidated in data files containing at least one month's worth of data.
- Data files should contain a series of data and no-data records, and they shall be preceded by a header containing information detailing the sampling configuration, data processing and recording of the data.

In particular, each record should contain the following components (EMEC, 2012):

1. Date and time stamp.
2. Depth in metres. Tidal variations should be included where relevant.
3. A frequency listing containing information about the variance spectrum and its directional characteristics as well as the power spectrum.
4. A number of derived parameters including the power, mean direction, wave height and period.
5. Quality control flags

The fundamental components required by the EMEC guidelines are similar to those established by JCOMM and CDIP for the comparison and exchange wave data.

There is a wealth of information on guidelines and standards that the wave energy industry could use as reference and template for the sharing of wave data.

3 DATA STORAGE INFORMATION

In order to prepare efficiently for the collection of wave data, whether these are obtained during a series of laboratory experiments or during monitoring of wave conditions at sea, it is important to have a clear idea of the storage requirements of the data, how these can be accessed and the format in which they are stored.
The following sections provide information on wave data storage for the different MaRINET facilities. Section 2.1 provides data storage review of the MaRINET laboratory facilities both in 2D wave tanks and 3D wave basins, while section 2.2 provides data storage information for wave data acquired at field conditions.

3.1 Laboratory Conditions

The following table presents data storage information from the following laboratory facilities:

1. Aalborg University (AAU), Denmark: 2D wave tank and 3D wave basin
2. Leibniz Universität Hannover (LUH), Germany: 2D Wave Flume
3. Hydraulic and Maritime Research Centre (HMRC), University College Cork, Ireland: 2D wave flume and 3D wave basin

4. Edinburgh University, United Kingdom: Wave Basin.
5. Plymouth University, United Kingdom: Coast Lab Facilities

	AAU – 2D	AAU – 3D	LUH - HANNOVER	HMRC – 2D	HMRC - 3D	EDINBURGH	PLYMOUTH
Instrument Type & Number	Conductance type wave gauge: 3	Wave Gauges: 9	Resistive / capacity gauge: 17	Conductance type wave gauge (3) Reflective marker & digital camera	Conductance type wave gauge (1)	Calibrated Wave Gauges	Conductance type wave gauge # to be defined
Sampling Frequency	10-50 Hz	10-50 Hz	10-100 Hz	32 Hz (synchronized with wave generation)	32Hz (synchronized with wave generation)	User Defined	128Hz
Data Acquisition Running Time	30 minutes	30 minutes	60 minutes	Regular: 64 seconds (2048 samples) Irregular: 256 seconds (8192 samples)	256 seconds (8192 samples)	User Defined	To be defined after commissioning of facilities
Software for sampling, processing and storage			Custom software is used for data acquisition, processing and storage. ASCII files can be generated for data sharing	Labview is used for sampling, real time display and initial storing of data. Post processing is routinely done using Matlab and Excel.	Labview is used for sampling, real time display and initial storing of data. Post processing is routinely done using Matlab and Excel.	WaveLab 3 is used for logging data. Data processing is dependent on user preferences. Standard procedures are in place for data acquisition	Labview is used for logging data. Data processing user dependent
Storage Information:	Data stored as txt file in time series of surface elevation. Data format is not proprietary, unrestricted	Text files (csv) of spectrum saved 1 file/spectrum. Filename provides time information which is repeated in comment lines along with spatial location of measurement.	Raw data saved in proprietary binary format. Processed data is saved in colon separated format with 28 header rows providing processing information. ASCII files of raw data can be stored in space separated format with multiple header rows (3 rows providing parameter and units, plus 1 for each selected channel)	Raw data saved in ASCII files. Parametric data usually stored in tab separated format. One metadata header line provides parameter name with units in brackets.	Raw data saved in ASCII files. Parametric data usually stored in tab separated format. One metadata header line provides parameter name with units in brackets.		To be defined after commissioning of facilities
Storage Size Requirements	200 kb per wave channel	200 kb per wave channel	5 kBytes/second (all sensors at 100 Hz)	1MB/hour per channel 500kB/seaway (3 probes @256secs)	1MB/hour per channel 250kB/seaway (1 probe)	Dependent on user specification	To be defined after commissioning of facilities
Storage Mode			Raw and processed data	Data stored on	Data stored on	Data is backed up	To be defined

	AAU – 2D	AAU – 3D	LUH - HANNOVER	HMRC – 2D	HMRC - 3D	EDINBURGH	PLYMOUTH
(include general use and backup)			are backed up on hard drive and to networked computer for a minimum of 3 years.	laboratory computer and on CD/DVD for distribution. Back up of data is stored on CD/DVD.	laboratory computer and on DVD for distribution. Back up of data is stored on DVD.	and available to the users.	after commissioning of facilities
Storage Access: location			Raw data are available on LAN. Processed data are available upon request to laboratory staff.	Raw and processed data is supplied to client. Raw and processed data is available to HMRC staff subject to confidentiality agreements.	Raw and processed data is supplied to client upon request. Raw and processed data is available to HMRC staff subject to confidentiality agreements.		To be defined after commissioning of facilities

3.2 Field Conditions Storage Information

The following table presents storage information for 3D irregular wave measurements carried out at the following field locations:

1. European Marine Energy Centre (EMEC), Scotland, United Kingdom: Wave test site and Scale Wave test site
2. Ente Vasco de la Energia (EVE), Basque Country, Spain: Biscay Marine Energy Platform (BIMEP) test centre.
3. Plymouth University, United Kingdom: Monitoring of Wave Hub with directional wave buoy and HF Radar.
4. Sustainable Energy Agency of Ireland (SEAI), Ireland: Monitoring of AMETS test centre
5. University of Exeter (UNEXE), United Kingdom: Monitoring of Wave Hub with directional wave buoy and ADCP
6. Wave Energy Centre (WAVEC), Portugal: Monitoring of Pico Power Plant wave conditions

	EMEC	EMEC SCALE	EVE	PU BUOY	PU HF RADAR	SEAI	UNEXE ADCP	UNEXE BUOY	WAVEC
Instrument Type & Number	Datawell Directional Waverider Buoy	TRIAXYS™ Directional Wave Monitoring Buoy	Directional wavescan buoy	Seawatch Mini II wave buoy (4)	WERA HF radar (2 stations)	Datawell Make III Directional Waverider Buoy	RDI Workhorse Sentinel ADCP, 300 KHz, modified with a 5th vertical beam for surface measurements	Seawatch Mini II wave buoy (4)	Acoustic Doppler Current Meter: 1
Sampling Frequency	3.84Hz	4Hz	2 Hz		continuous	1.28 Hz	2 Hz	2 Hz	1 Hz

	EMEC	EMEC SCALE	EVE	PU BUOY	PU HF RADAR	SEAI	UNEXE ADCP	UNEXE BUOY	WAVEC
Data Acquisition running time (typical duration of experiments)	Indefinite	Indefinite	2048 samples per hour of heave roll and pitch	30 minutes sampling of wave conditions carried continuously over the year.	17 min:45 sec	30 minutes	Recent deployments: 20 minutes out of every 30 minutes. Previous deployments: Continuous recording.	32 minutes	34.1 minutes
Software (sampling, processing, storage)	Data acquisition and processing by proprietary RfBbuoy /W@ves21 software. Data format in W@ves21 output No special storage arrangements	Data sampling and processing onboard TRIAXYS buoy by custom processor. Data acquisition by TRIAXYS Waveview software. No special storage arrangements	Onboard Time series analysed in time domain and frequency domain to derive all directional wave parameters and spectra. Custom software is utilized for post processing.	Wave Sense III is used for data processing and output generation. Analysis in both time and frequency domain.	Data sampling and processing by system manufacturer WERA, Helzel Messtechnik and post processing by Seaview sensing	Data analysis carried out at HMRC-UCC using MATLAB	RDI'sWavesMon processing software (for wave data) or WinADCP software for current velocities	Fugro Oceanor processing software	Aquadopp - sampling QuickWave - non-graphical wave processing tool (to obtain wave spectra)
Storage Information: Format and type	Raw data in ASCII readable encoded hexadecimal. Parameters and Tables in CSV-like format but with custom headers. Filename provides time information for spectra.	Raw data in ASCII readable encoded hexadecimal. Parameters and Tables in ASCII tables with headers. Filename provides time information	Raw data saved in proprietary binary format. Processed and cleaned time series of heave roll pitch and compass stored in TXT format. Text files of parametric data stored with 2 header lines providing parameter name and units. Text files of spectrum saved 1 file/spectrum.	Raw data stored in .pff proprietary format. Files can be export in txt and tab separated format.	Raw data stored in various binary files that contain information about the chirps, number of antennas and Mode Bits. Parametric data is stored in ascii files. Wave directional spectra information stored in Mysql database	Text files (csv) of spectrum saved 1 file/spectrum. Filename provides time information which is repeated in comment lines along with spatial location of measurement.	Raw wave and current data stored in .000 format (also called .PD0 format)	Raw data stored in binary .pff format	Raw data saved in proprietary binary format. Data processed with Aquadopp saved in .dia format. Data is processed with QuickWave software produced as • .wap - wave parameters • .was - frequency spectra; • .wdr - distributions wave direction; • .wds - full

	EMEC	EMEC SCALE	EVE	PU BUOY	PU HF RADAR	SEAI	UNEXE ADCP	UNEXE BUOY	WAVEC
			(Raw and smoothed spectra) Text files of time domain analysis of heave, saved 1 file/hour.						directional spectra; • .wcf Fourier coefficients; • .wst Time Series • .wbd wave for wind sea and swell
Storage Size Requirements	7 MB/day/buoy	0.25 MB/day/buoy	500 MB/year	Radio: 2kB/day Hard drive: 7MB/day/buoy	1 Gb/day	7 MB/day/buoy	~ 3.3MB/hr	~ 1GB/yr	0.65 MB/day, for 34.1 min measurements every 3 hours. Maximum storage: 90 MB
Storage Mode (include general use and backup)	Data available on server. Monthly tape backups maintained.	Data available on server. Monthly tape backups maintained.	Processed data and parametric data are backed up.	Data stored on internal hard drive. Processed data saved on computer and backed up on cloud. 3 Monthly download missions at location are required.	Data stored in each station and backed up to external NAS driver and server at the University.		Raw data currently stored and backed up as .000 files on personal pc. Storage database currently under construction.	Raw data stored as binary .pff files with automated back-up. Storage database currently under construction.	Data is stored in the device's internal memory. When the maximum storage is reached the data is recovered at location.
Storage Access: location	Data available on application to EMEC.	Data available on application to EMEC.	Data are available upon request to EVE.	Data available to members of research group. Metadata to become publically available.			Raw data is available upon request to members of the research group.	Raw data is available upon request to laboratory staff. Parametric data are available in near real-time on a secure connection.	Data from the campaigns is stored at WavEC and is accessible upon request.

4 WAVE DATA REPRESENTATION

Graphical representation of wave data is often used to present information on the type of sea conditions generated in particular facilities or to determine the dominant sea state at a given test centre. Representations of wave data are used to identify the dominant direction of the incoming waves, as well as providing information on the seasonal variations.

This section aims to provide an overview of the methods for wave data presentation with respect to both laboratory and field conditions. An overview of the main wave characteristics is presented in section 4.1. Further details are available in MaRINET Deliverable D2.1.

4.1 IMPORTANT WAVE CHARACTERISTICS

4.1.1 Time domain (Height, period and direction)

One of the most important analyses of the surface elevation time histories is that of zero-upcross (ZUC) waves (Tucker, 1993), allowing to determine the main wave characteristics. Time domain (TD) characteristics of waves are determined through a wave by wave analysis of the surface elevation at a given location. Through this type of analysis it is possible to determine both individual and integrated wave parameters.

Significant Wave Height

The significant wave height, normally represented by $H_{1/3}$ or H_s is defined as the average of the largest 1/3 waves in a record. The determination of $H_{1/3}$ is based on the zero up-crossing method.

Significant Wave Period

The significant wave period, represented by $T_{1/3}$ or T_s is defined as the average period of the largest 1/3 waves in a record.

Mean Wave Height

The mean wave height, H_{mean}, is defined as the average of the wave heights in a record.

Mean Wave Period

The mean wave period, T_z, is defined as the average of the wave periods determined by a zero up-crossing analysis of the time series. T_z. is normally preferred to T_s.

Maximum Wave Height

The maximum wave height, H_{max}, represents the maximum value of the wave height measured over a given period of time.

Maximum Wave Period

The maximum wave period, T_{max}, represents the maximum value of the discrete wave periods measured.

Wave Steepness

The wave steepness, *s*, relates to the wave height of the waves with the wavelength (*L*) associated to its relevant period. It can be determined on a wave by wave base or as H_{mean}/L_{mean}.

4.1.2 Frequency domain (1D spectra)

The determination of wave parameters in the frequency domain is obtained through a spectral analysis of the wave records, based on the energy spectrum of the wave records. This relates the spectral density (m^2s) with the frequency, as seen in Section 2. The energy spectrum, *S*, can be represented as a discrete function of the frequency *f*, discrete spectra; or as a function of global wave parameters, parametric spectra. Parameters are computed through a Fourier analysis of the time series data, with a recommended spectral resolution of 0.05 Hz (Tucker, 1993).

Spectral Moments

The spectral moments are the foundations of the spectral analysis and most wave characteristics can be determined through them. The n^{th} spectral moment can be defined as follows:

$$m_n = \int_0^\infty f^n S(f) df \quad [2]$$

The most commonly used moments are m_{-1}, m_0, m_2, and m_4; with the zero-th spectral moment m_0 representing the variance of the elevation time series.

Significant Wave Height

H_{m0} is the representation of the significant wave height in the frequency domain. It is determined assuming narrow banded Gaussian wave process. H_{m0} is related to m_0 as follows:

$$H_{m0} = 4m_0^{1/2} \quad [3]$$

Mean Wave Period

There are two main ways to represent the mean wave in the frequency domain. The mean energy period can be determined through the following relationships:

$$T_{01} = \frac{m_0}{m_1} \quad [4]$$

And

$$T_{02} = \sqrt{\frac{m_0}{m_2}} \quad [5]$$

T_{02} provides an approximation of the time domain mean wave period T_z.

Peak Wave Period

The peak period T_p represents the dominant wave system in a given sea state. T_p is given by the following conditions:

$$T_p = 1/\mathrm{f_p}$$
$$\mathrm{S(f}_p) = \mathrm{Max[S(f}_p)]$$

[6]

Energy Wave Period

The energy period T_e is determined from the spectra and it is used to describe the wave resources for wave energy applications. T_e can be considered as a representation of T_{02}, but its value is less influenced by the higher frequency energy. T_e is given by the following relation:

$$T_e = \frac{m_{-1}}{m_0}$$

[7]

Spectral Bandwidth

The spectral bandwidth allows assessment of the wave resource in a given area with higher accuracy. The spectral bandwidth is characterized through a number of dimensionless parameters. However, the use of the narrowness parameter, υ, is recommended to allow for the bandwidth of the sea state process. The spectral bandwidth parameter is somewhat sensitive to the high-frequency contents of the spectrum. The following formulation for υ is suggested as it mitigates higher orders:

$$\upsilon = \left[\frac{m_0 \cdot m_2}{m_1^2} - 1\right]^{1/2}$$

[8]

Wave Power

The wave power P_w provides an indication of the power available per unit of crest length in an undirectional sea. P_w is given by:

$$P_w = \rho \cdot g \int S(f) \cdot c_g \, df$$

[9]

where c_g represents the wave group velocity.
For deep water cases,

Wave Steepness

The wave steepness *s* is used to characterize a particular sea state. The peak steepness is given by the following relation:

$$s_p = \frac{H_{m0}}{L_p}$$

[10]

The wavelength L_p is determined through the dispersion coefficient and is associated to T_p.

Fourier Moments

The first four Fourier moments, which are used for the definition of the wave energy spectra as presented in Section 2 are determined from the directional spreading function $D(\theta,f)$ as follows:

$$a_1(f) = \int_0^{2\pi} d\theta \cos\theta D(\theta, f)$$
$$b_1(f) = \int_0^{2\pi} d\theta \sin\theta D(\theta, f)$$
$$a_2(f) = \int_0^{2\pi} d\theta \cos 2\theta D(\theta, f)$$
$$b_2(f) = \int_0^{2\pi} d\theta \sin 2\theta D(\theta, f)$$

[11]

Where $a_1(f)$ represents Mean direction (first Fourier coefficient), $b_1(f)$ is the directional spread (second Fourier coefficient), $a_2(f)$ is the skewness (third Fourier coefficient) and $b_2(f)$ represents the kurtosis (fourth Fourier coefficient).

4.2 Laboratory Conditions

The following table displays information on the type of wave data monitored at the different Marinet facilities and the type of outputs generated.

	AAU – 2D	AAU – 3D	LUH - HANNOVER	HMRC – 2D	HMRC - 3D	EDINBURGH	PLYMOUTH
Outputs: Parameters	**Time domain (TD):** number of waves, H_{mean}, T_{mean}, T_s, H_s, H_{max}, reflection coefficient, incident and reflective wave height. **Frequency domain(FD):** H_{m0}, T_p,	**TD**: number of waves, H_{mean}, T_{mean}, T_s, H_s, H_{max}, reflection coefficient **FD:** H_{m0}, T_p, Wave Power	**TD:** number of waves, H_{max}, H_m, T(Hmax), T(Hm), T_m, reflection coefficient **FD:**f_{min}, f_{max}, Δf, f_{peak}, T_p,T_{m10},H_{m0}, Incident Wave Height. Reflected Wave Height.	**Real time:** Time series of water surface elevation for both monochromatic & panchromatic wave conditions. **Post processing TD & FD:** e.g. no. of waves, H, T, H_{max}, T_m, H_s, $H_{1/3}$, $T_{1/3}$, H_{max}, reflection coefficient, H_{mo}, T_p, T_e incident wave height and reflected wave height	**Real time:** Time series of water surface elevation **Post processing TD & FD:** parameters as required by project e.g. no. of waves, H_m, T_m, H_s, $H_{1/3}$, $T_{1/3}$, H_{max}, reflection coefficient, H_{mo}, T_p, T_e	User defined	To be defined after commissioning of facilities
Outputs: Matrix	Joint distribution of wave height and period. Frequency spectra	Directional spectra	Time series of incident and reflected waves, Frequency spectra, summary of output parameters	As required by project: e.g.: Joint distribution of wave height and period. 1D frequency spectra	As required by project: e.g.: Joint distribution of wave height and period. 1D frequency spectra	User defined	To be defined after commissioning of facilities
Outputs: Graphics	Wave height distribution, incident and reflected	Wave height distribution, incident and reflected	Time series, frequency spectra Incident and	Incident waves and reflected waves, wave height	Incident waves and reflected waves,		To be defined after commissioning of facilities

	waves, spectral density, directional spectra	waves, spectral density, directional spectra	reflected waves, zero crossings, local maxima and minima	distribution, spectral density, power matrix	wave height distribution, spectral density, power matrix		

4.2.1 Example Wave Data Representation Methods

4.2.1.1 Time Series

Time series of wave data are generated representing the surface elevation of the wave on the y-axis of a plot (expressed either in [m] or [mm]) with the x-axis representing the time in [s]. These often are plotted separately as incident and reflected waves. The analysis of the incident and reflected waves is often carried out in post processing of the experimental data sets. Examples of time series are presented in Figure 3 , Figure 4 and Figure 5. Figure 6 presents a time series generated at HRMC including incident and reflected waves in the time domain.

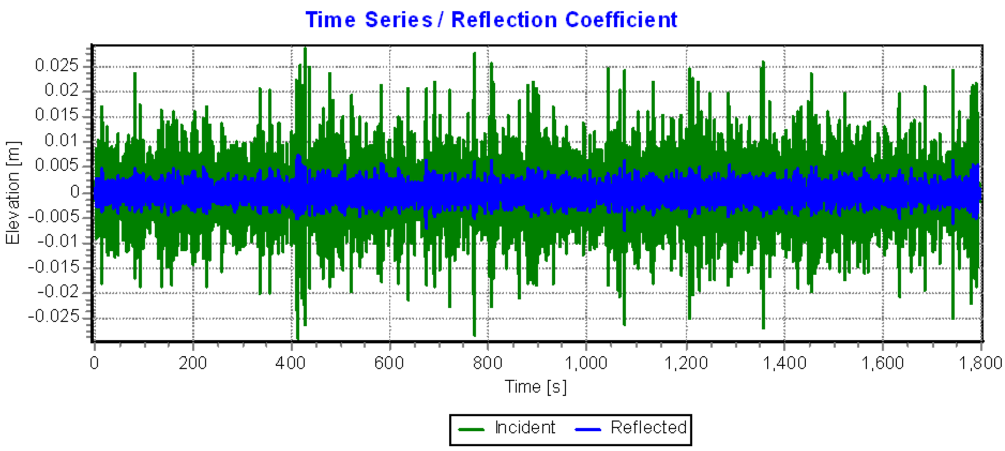

Figure 3: Wave Data Time Series Generated at AAU (x-axis: time [s], y-axis: height [m])

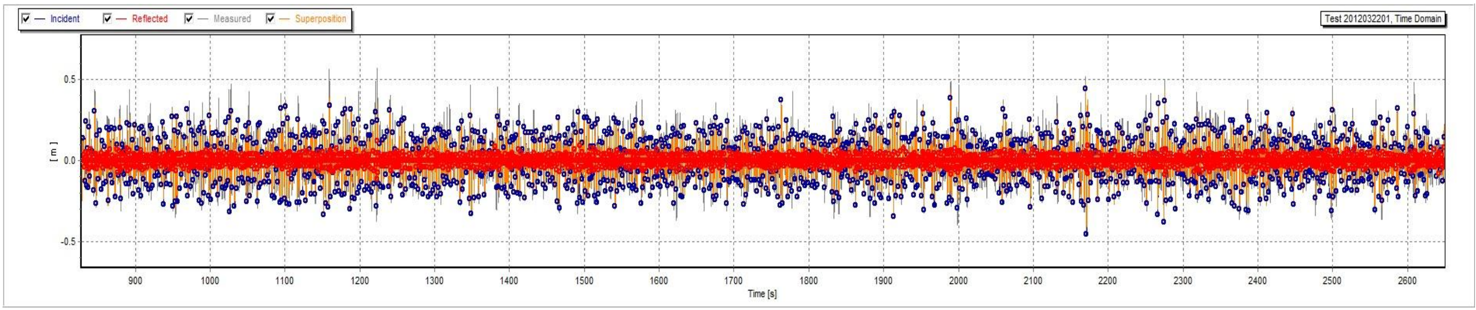

Figure 4: Wave Data time series generated at LUH (x-axis: time [s], y-axis: height [m])

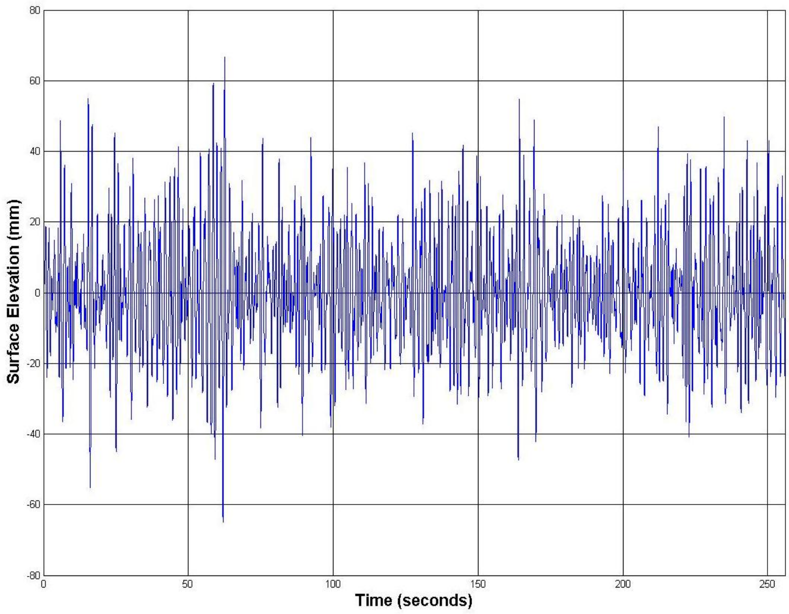

Figure 5: Typical surface elevation time series generated at HMRC (x-axis: time [s], y-axis: height [mm])

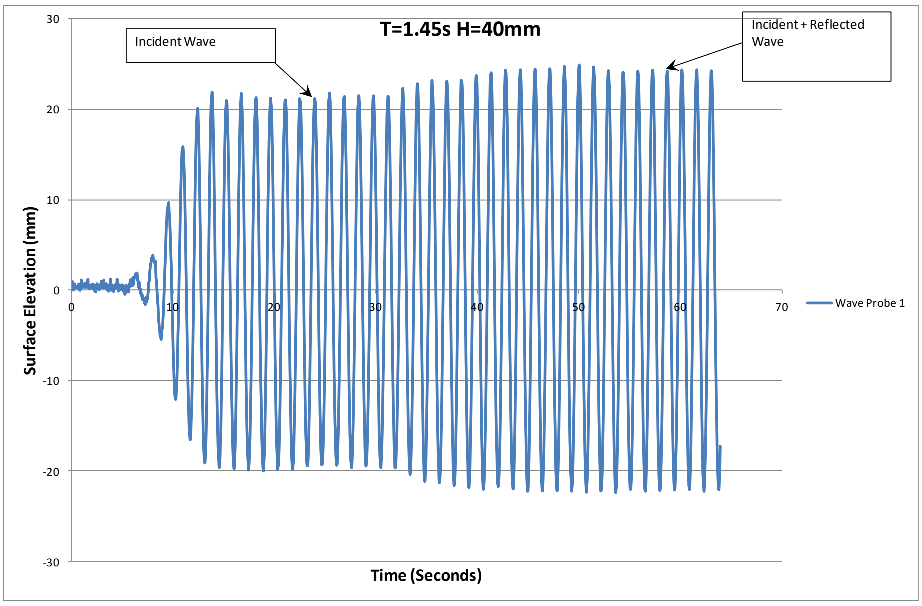

Figure 6: Incident and Reflected regular wave measurement at HMRC (x-axis: time [s], y-axis: height [mm])

4.2.1.2 Wave height distribution

It has been shown (WMO, 1998) that coastal wave records tend to follow the Rayleigh distribution. Wave height distribution diagrams may be used to compare the waves measured in lab conditions with the ideal Rayleigh distribution. Examples are presented in Figure 7 and Figure 8.

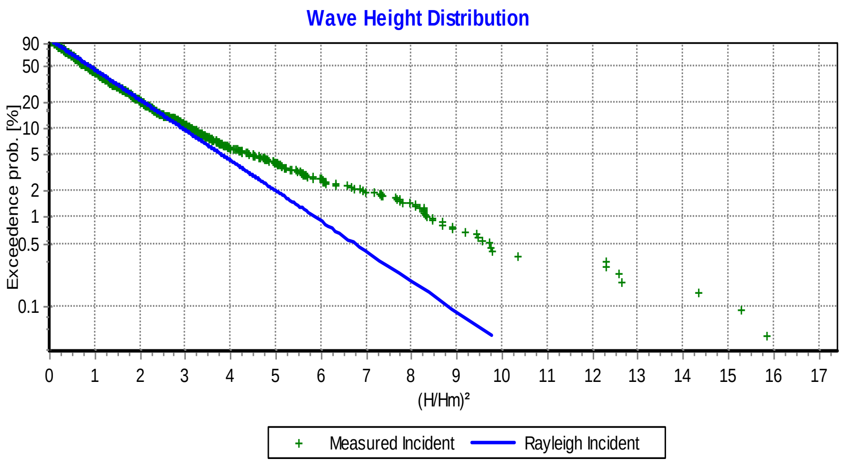

Figure 7: Wave Height distribution generated at AAU (x-axis: $(H/Hm)^2$ y-axis: probability)

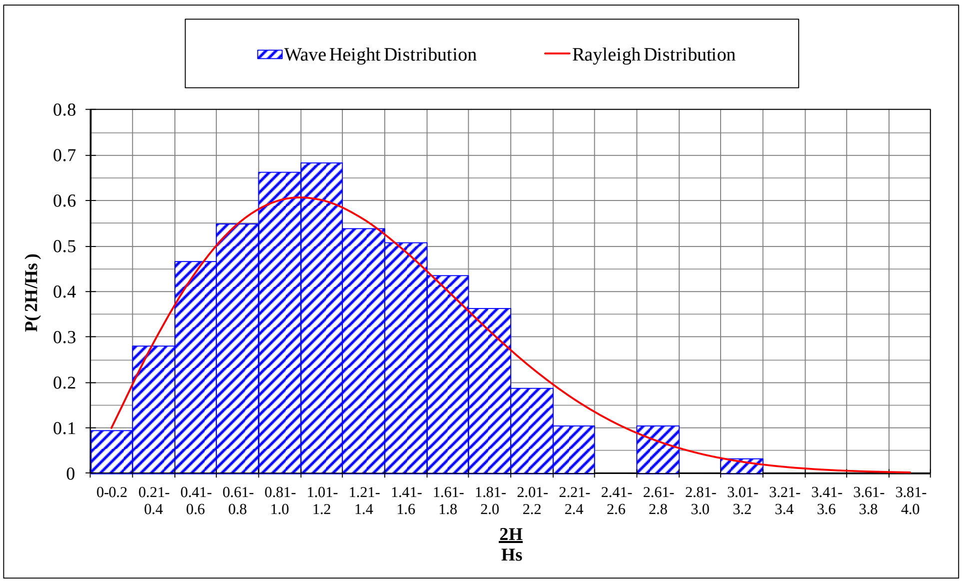

Figure 8: Wave height distribution generated at HMRC for Bretschneider sea states (x-axis: 2H/Hs y-axis: probability)

4.2.1.3 Joint distribution of wave height and period

The joint distribution of wave height and period provides information on the number of waves generated, or measured, with a given wave period *T* and a given wave height *H*. Examples of joint distribution of wave height for an irregular wave train generated at lab conditions are shown in Figure 9 and Figure 10.

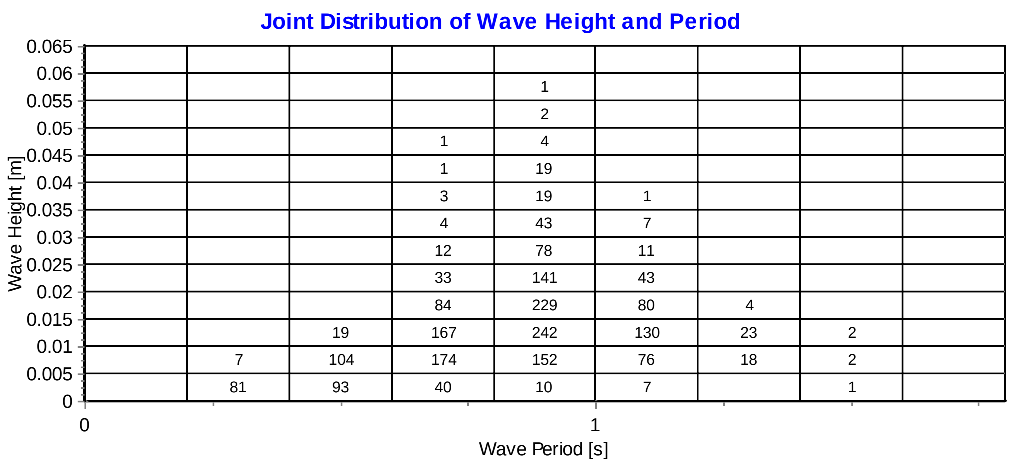

Figure 9: Joint distribution of wave height and period at AAU. (Value displayed is no per bin)

SEVENTH FRAMEWORK PROGRAMME

Wave Height	Wave Period (sec)								
mm	0-0.25	0.25-0.5	0.5-0.75	0.75-1.0	1.0-1.25	1.25-1.5	1.5-1.75	1.75-2.0	2.0-2.25
120-130									
110-120									
100-110			1						
90-100						1			
80-90			1						
70-80			1		2	3	1		
60-70		1		3	3				
50-60		1	3	8	6	2	1		
40-50		4	7	6	9	6			
30-40		5	13	4	8	8			
20-30		6	17	12	5	2			
10-20		9	19	7	3		1		
0-10		9	30	4	6	1	1		

Figure 10: Joint distribution of wave height and period for Hs = 60mm and Tz = 0.15s at HMRC. Value displayed: No. per bin.

4.2.1.4 Spectral Density

The spectral density diagram presents information on the energy present for each wave frequency. Spectral diagrams are generated through a Fast Fourier Transform of the wave elevation time series. Examples of spectral diagrams are presented in Figure 11, Figure 12 and Figure 13.

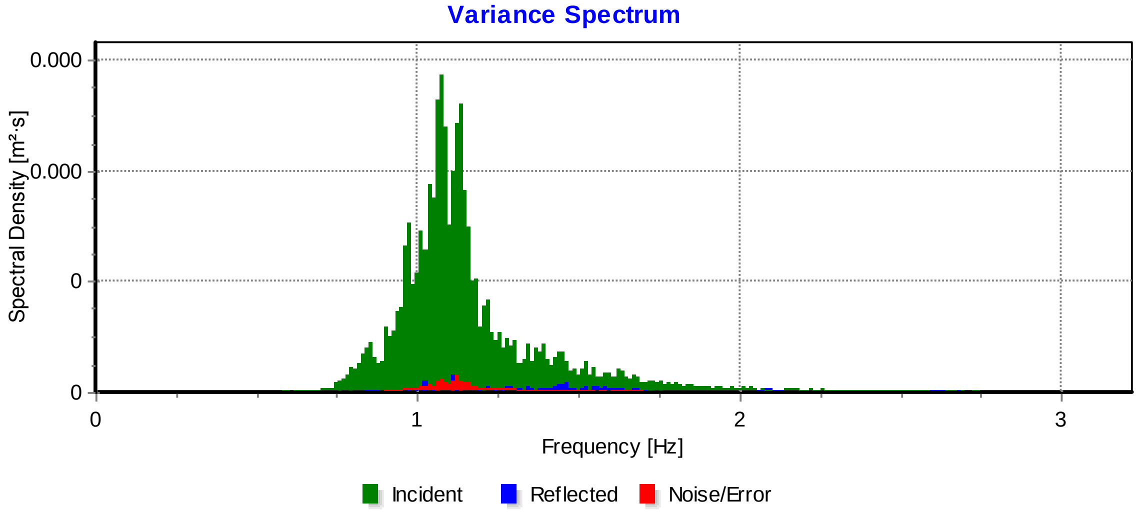

Figure 11: Spectral Density graph generated at AAU.

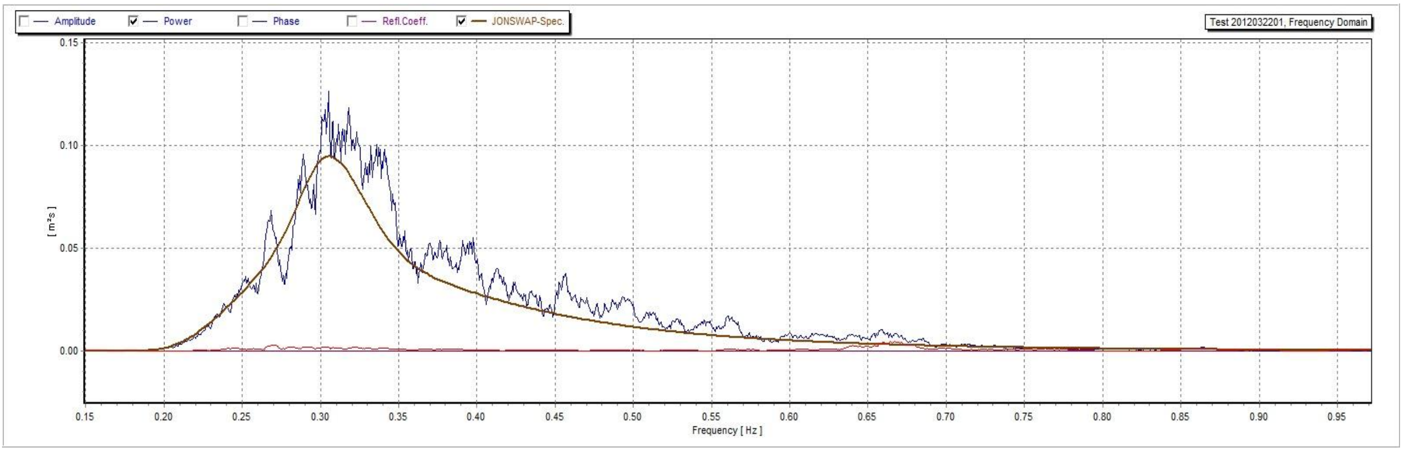

Figure 12: Spectral density graph generated at LUH.

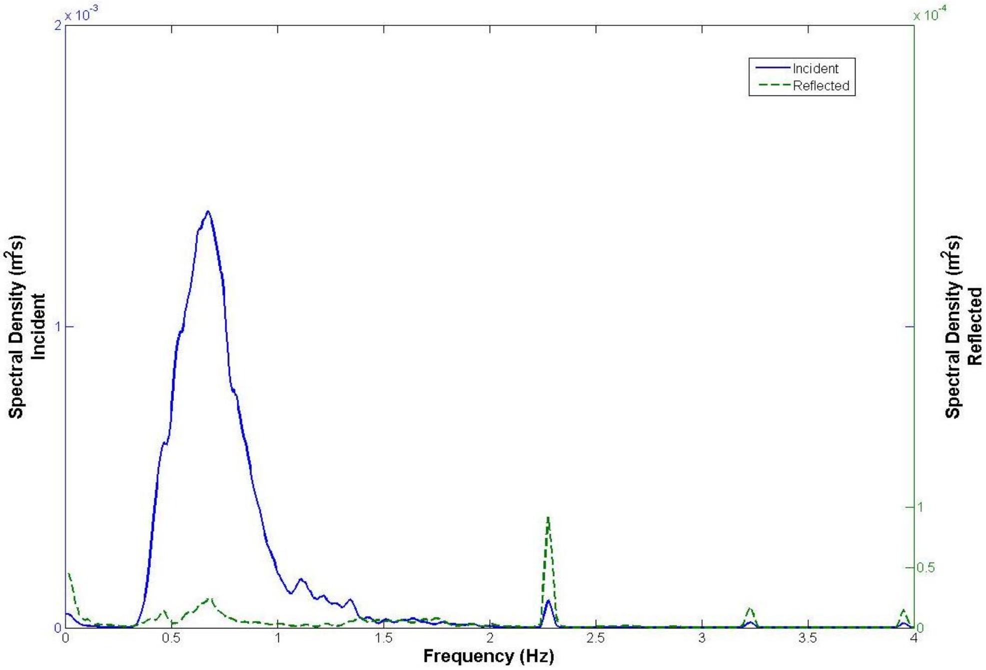

Figure 13: Spectral density graph generated at HMRC.

4.2.1.5 Directional Spectra

The directional spectra provides information on the energy density of the wave for a given frequency and a given wave direction. It is often approximated by determining the mean direction for each component of the frequency spectrum. Whether a complete spectrum is collected or not can often be hidden by the presentation. An example of directional spectra is presented in Figure 14.

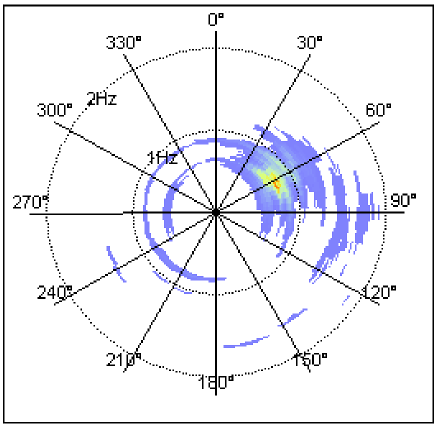

Figure 14: Directional spectra generated at AAU 3D basin. The spectrum identifies the main direction of the incoming wave and their frequency component. For the case in example the mean direction is of 60° with *F=0.8Hz*

4.2.1.6 Min, Max and Zero Crossing

Zero crossing graphs are used to identify the maximum and minimum of the wave components and number of waves, as presented in Figure 15.

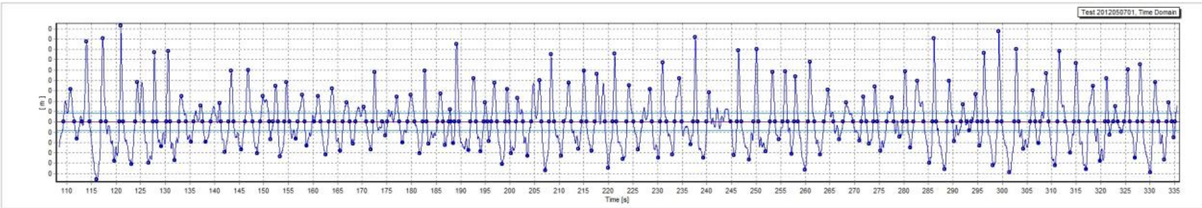

Figure 15: Zero crossing analysis carried out at LUH, identifying fully developed waves for TD analysis.

4.3 Field Conditions

A broader range of wave data is obtained when monitoring the sea state in field conditions. The table below provides an overview of the wave parameters measured and determined at the different facilities.

	EMEC	EMEC SCALE	EVE	PU BUOY	PU HF RADAR	SEAI	UNEXE ADCP	UNEXE BUOY	WAVEC
Outputs: Parameters	**Time domain (TD):** • Percentage of data with no reception errors [%] • H_{max} • T_{max} • $H_{1/10}$ • $T_{1/10}$ • $H_{1/3}$ • $T_{1/3}$ • H_{av} • T_{av} • E_{ps} (bandwidth parameter) • #Waves **Frequency domain (FD):** • T_p • Dirp • Sprp • T_z • H_{m0} • T_l • T1, • Tc • Tdw2 • Tdw1 • Tpc • nu • eps • QP • Ss **Status:**	**TD:** • # of zero crossings • H_{av} • T_z • H_{max} • $H_{1/3}$ • $T_{1/3}$ • $H_{1/10}$ • $T_{1/10}$ • Wave steepness **FD:** • T_m (mean period) • T_p (peak period)= 1 / f_p • T_{p5} (peak period estimate) • H_{m0} 4*√(m0) • Dir_m (mean direction) • Spr_m (mean spread) • Sea Surface Temperature	**TD:** • number of waves • H_m • T_m • T_s • H_s • H_{rms} • $H_{1/3}$ • $T_{1/3}$ • $H_{1/10}$ • $T_{1/10}$ • H_{max} • T_{max} • H/T of waves • Listed decreasing, length of the groups of waves exceeding H_s • Asymmetry • Variance. • Rayleigh and Normal adjust of temporal series. **FD:** • H_{m0} • T_p • T_{m02} • T_{m01} • T_e • θ_p • θ_m	**TD + FD:** • H_{max} • H_{mean} • $H_{1/3}$ • H_{m0} • T_p • T_e • T_z • T_{02} • θ_p • θ_m • Lambda (spectral width) • Sigmap (spreading at peak)	• H_{m0} (different freq ranges) • T_p • Complete directional energy spectrum • Data Quality Parameters	**TD**: • number of waves • H_m • T_m • T_s • H_s • $H_{1/3}$ • $T_{1/3}$ • H_{max} **FD:** • H_{m0} • T_{02}	Time series of surface elevation and orbital velocities, that can be processed further to obtain spectra and spectral parameters as required.	Time series of heave and east/north displacement. These are the only files stored. From these, spectra and spectral parameters can be calculated as required.	• H_s • T_{m02} • T_z • T_p • Peak direction (DirTp) • Directional spread • Mean direction • Unidirectivity index • Mean Pressure • Current speed • Current direction

	EMEC	EMEC SCALE	EVE	PU BUOY	PU HF RADAR	SEAI	UNEXE ADCP	UNEXE BUOY	WAVEC
	• Sea Surface Temperature		• m_0 • m_1 • m_{-1} • m_2 • ep_1 • ep_2						
Outputs: Matrix	Integral Spectra Directional Spectra	Integral Spectra Directional Spectra Directional Fourier Coefficients				**TD:** 1800 second time series of • Buoy status • Heave • North • West **FD:** At each frequency component: • Normalised spectral density • Direction • Spread • Skewness • Kurtosis	2-D and directional spectra calculated via WavesMon software, bi-variate distributions of wave height and period may be produced from spectral parameters	2-D and directional spectra calculated from displacement time series as required, bi-variate distributions of wave height and period may be produced from spectral parameters	Frequency spectra; distributions of mean wave direction per frequency band; full directional spectra
Outputs: Graphics	Spectra and displacement figures from W@ves21. Other figures post processed in MATLAB, EXCEL, etc	Post processed in MATLAB, EXCEL, etc	Frequency Spectra	Not yet produced	Time Series Spectral Density Directional spectra	Wave height distribution, incident and reflected; Spectral density, incident and reflected Directional Spectra	No graphical output stored	No graphical output stored	

4.3.1 Example Wave Data Representation Methods

4.3.1.1 Time Series

Time series of wave height or heave motion can be presented continuously or for representative value of *H* determined over normally a 30 minute interval (H_s or H_{m0}). Time series of raw (non-process data) are shown in Figure 16 (heave, north and east displacement of the buoy) Figure 17 (heave) and Figure 18 (heave). Parametric time series of processed data are presented in Figure 19, Figure 20 and Figure 21.

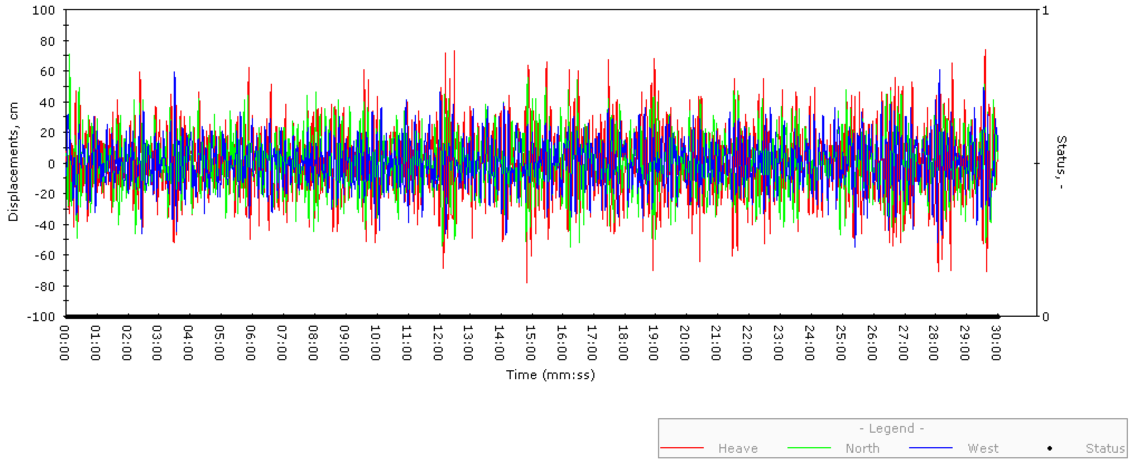

Figure 16: Time series of buoy displacement data at EMEC.

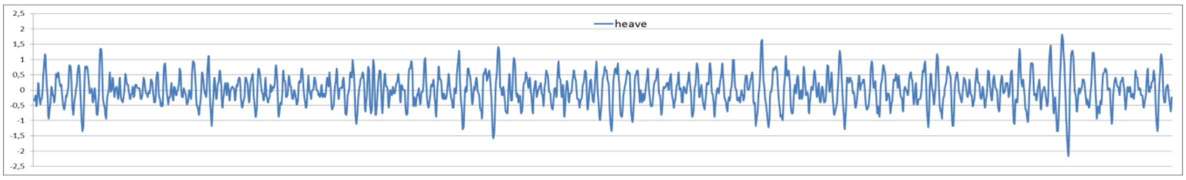

Figure 17: Heave time series generated at EVE.

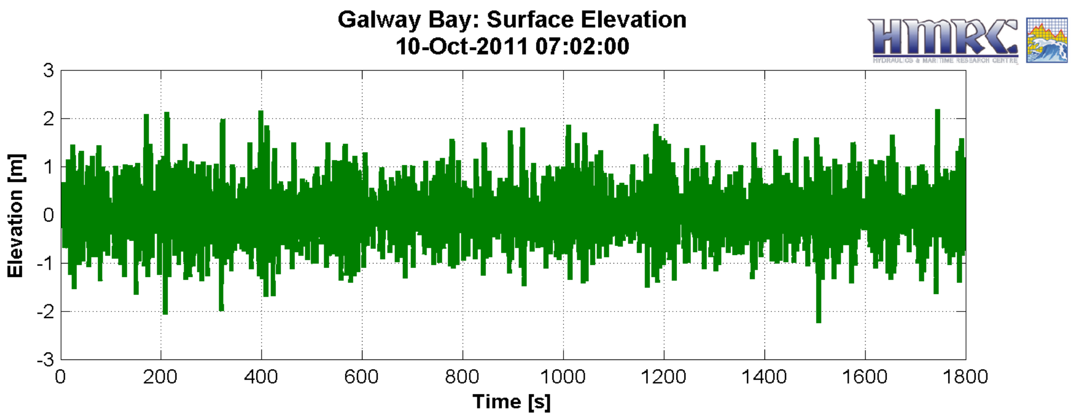

Figure 18: Displacement time series generated at SEAI.

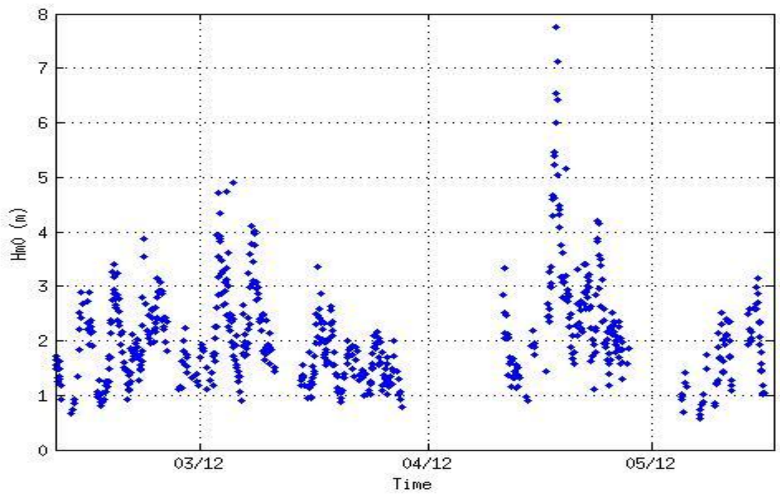

Figure 19: Time series of Hm0 obtained from the HF Radar at Plymouth University.

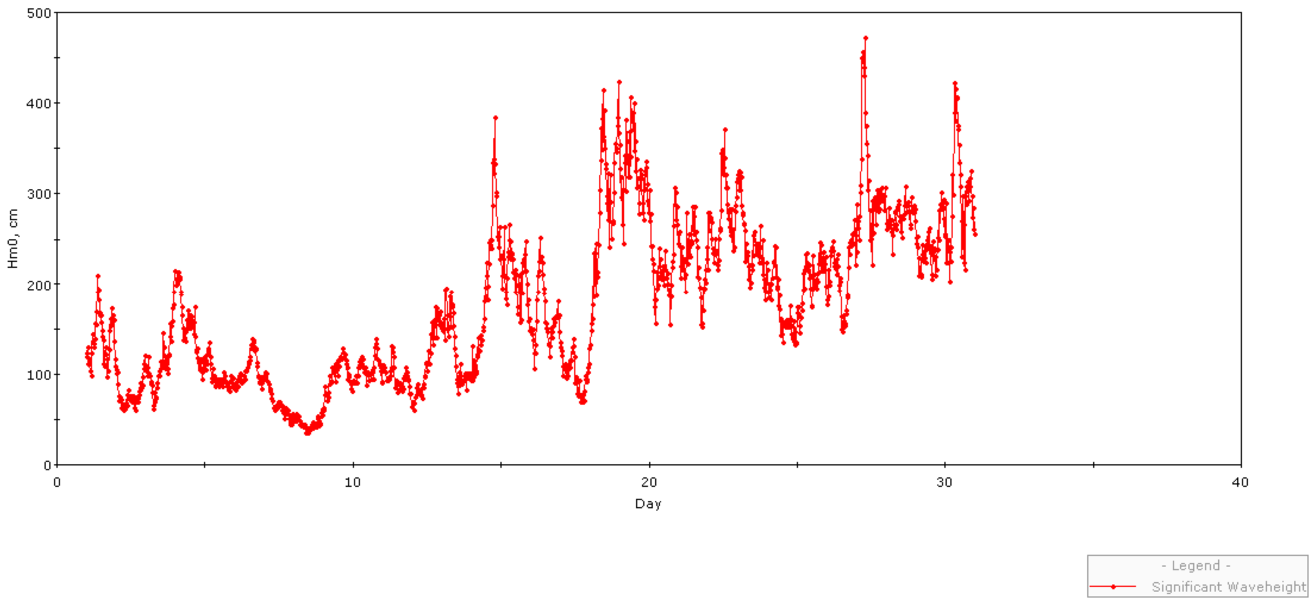

Figure 20 Time Series of Hm0 obtained from wave buoy at EMEC

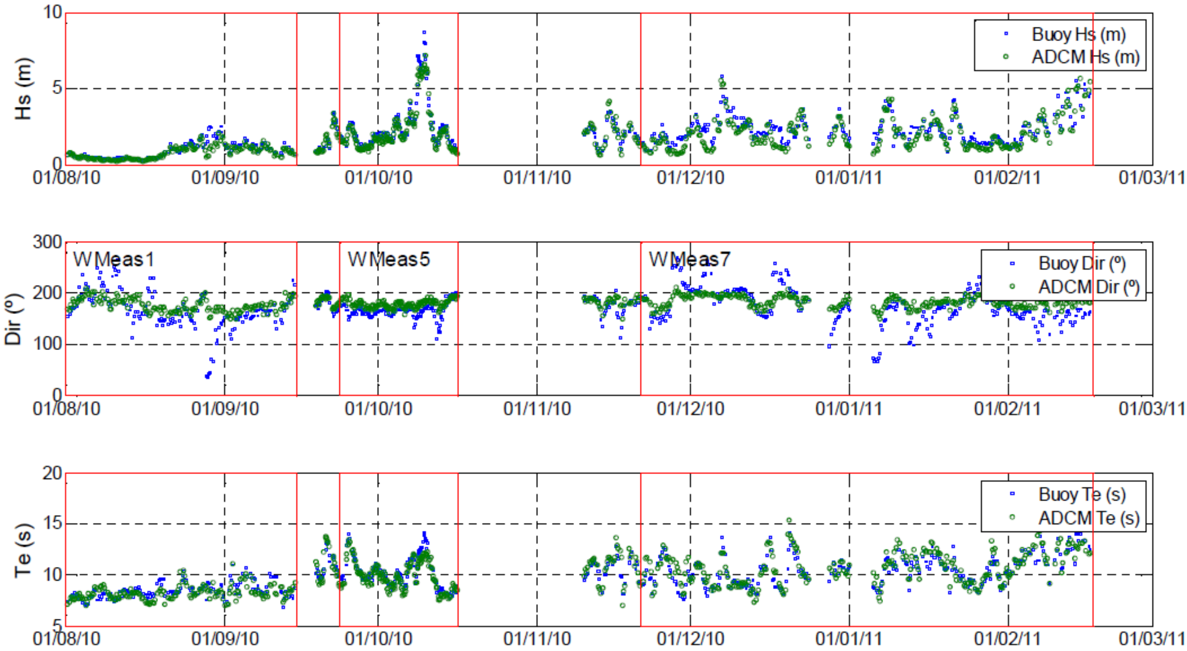

Figure 21: Parameter time series generated at WAVEC and comparison between ADCM and Wave buoy data.

4.3.1.2 Spectral Density

Spectral diagrams are used to identify the energy content of each frequency component at a given site. These are often coupled with the spectral direction and spreading coefficient to allow for the determination of the frequency spectra. The generation of the graph presented in Figures 19 to 23 depends therefore on the specific instrument used to collect the vertical displacement information and to filters applied in determining the spectral density S(f). Mathematical tools, such as the WAVEVALT tool (available at http://cdip.ucsd.edu/documents/index/product_docs/cdiptool/?xitem=documentation) have been developed to assess the discrepancies between different buoys.

Example of spectral density diagrams generated at the difference facilities are presented in Figure 22, Figure 23, Figure 24, Figure 25 andFigure 26.

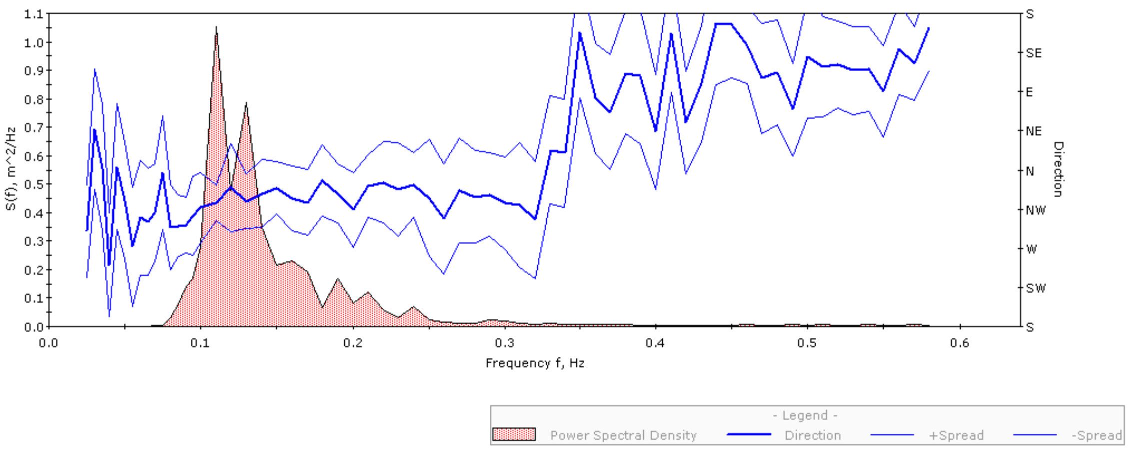

Figure 22:Example of Spectral density graph generated at EMEC, including direction and spread of the waves

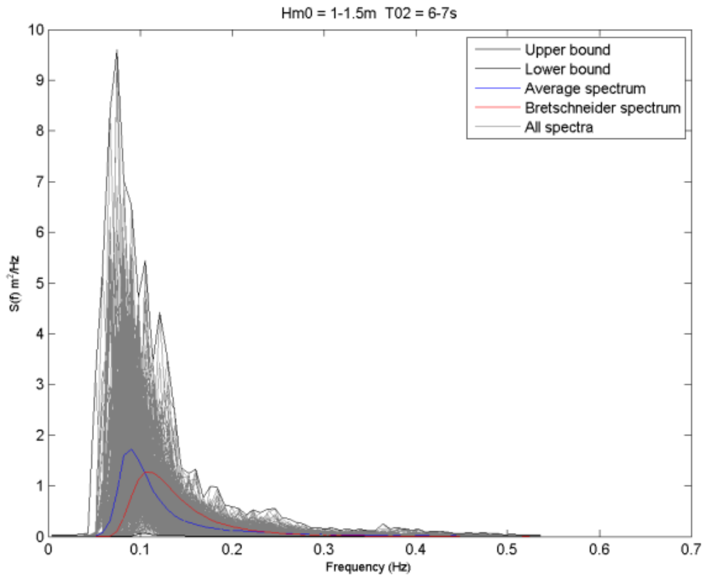

Figure 23: Spectral density graph generated at EVE.

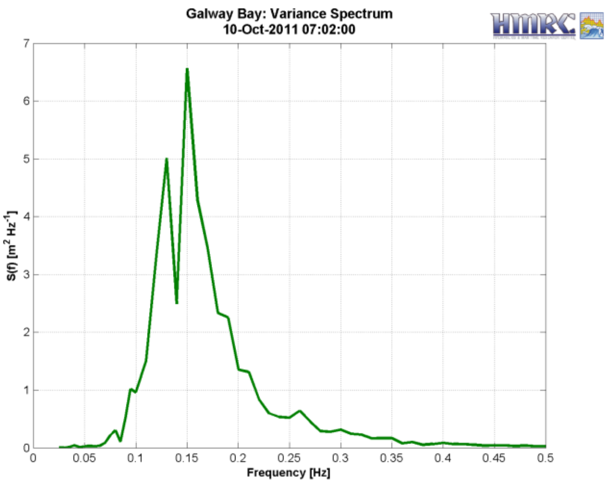

Figure 24: Spectral density diagram generated at SEAI.

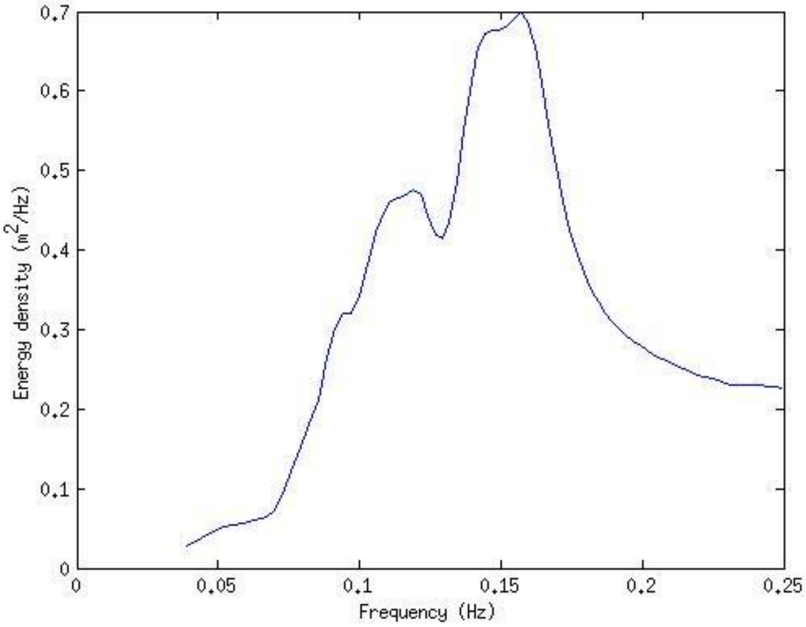

Figure 25: Spectral density diagram generated by the HF Radar at PU.

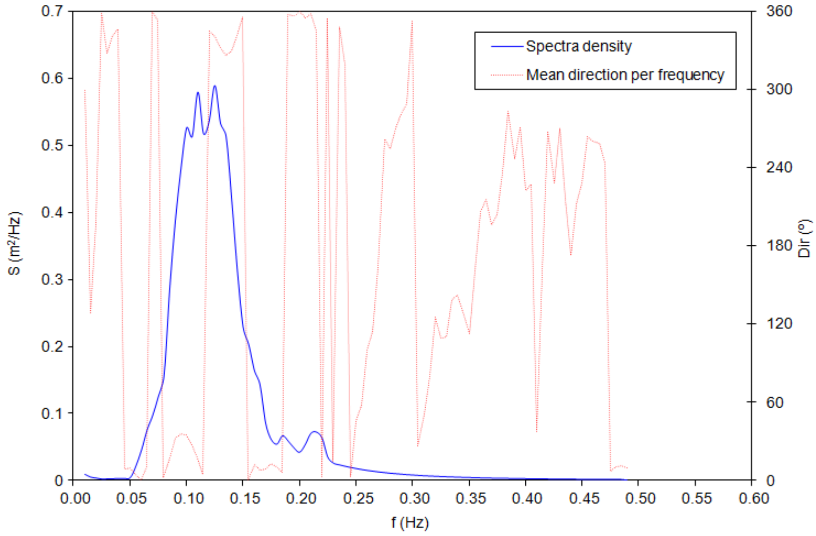

Figure 26: Spectral Density diagram generated at WAVEC, including the mean wave direction

4.3.1.3 Directional Spectra

Directional spectra show the directions that individual wave components are travelling (Figure 27). Directional wave information is derived from buoy motions through the analysis of the heave-pitch-roll motions of the buoy as highlighted in Benoit (Benoit, 2011) . The determination of such information is dependent on both the power transfer function and phase responses associated with the buoy. A crucial role in the evaluation of the directional parameters is played by the measurement system installed on the buoy and by the moorings.

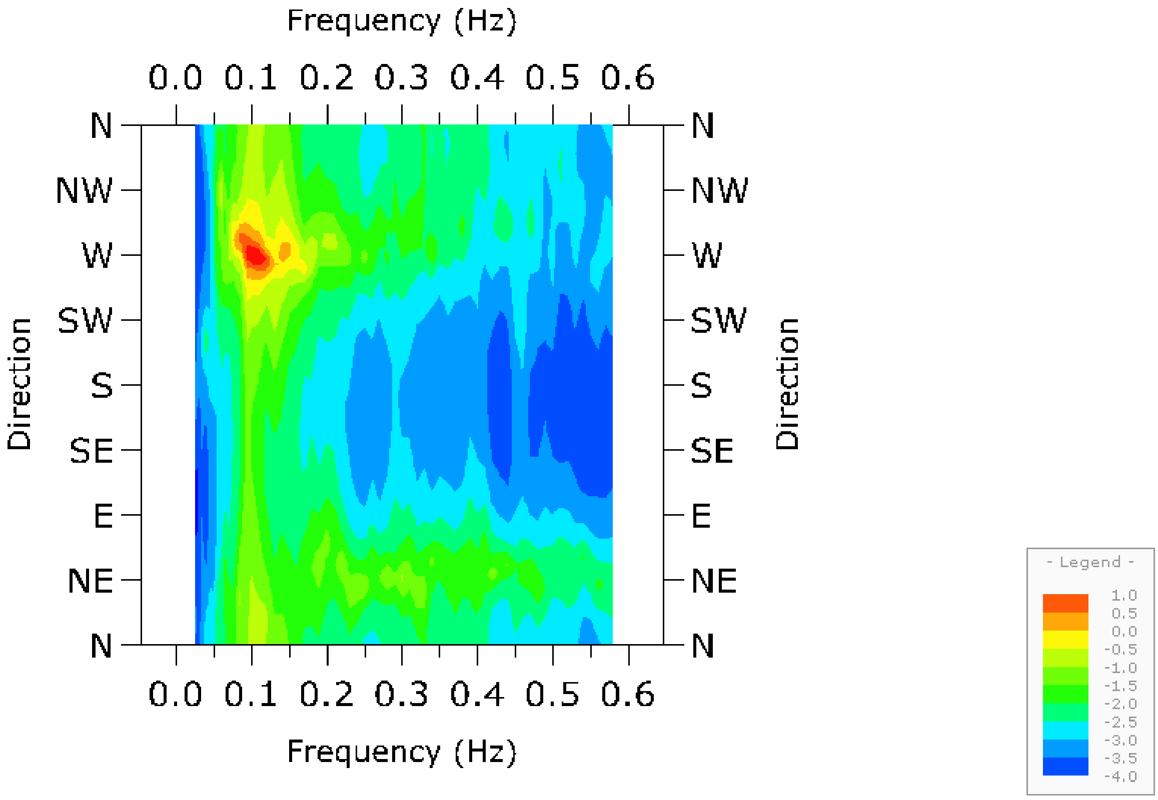

Figure 27: Directional wave spectrum from EMEC wave buoy

4.3.1.4 Scatter Diagram

Scatter diagrams present the possibility of occurrence of a particular sea state identified normally by T_p or T_e and H_s or H_{m0} at a particular location. A scatter diagram provides useful information on the dominant sea conditions at a given site and help wave energy developers to tune their device to a favourable conditions as well as preparing for extreme case loading. Scatter diagrams can be shown either in graphical form or expressed as a matrix. Figure 28 and Figure 29 present example of scatter diagrams generated at EMEC and SEAI respectively.

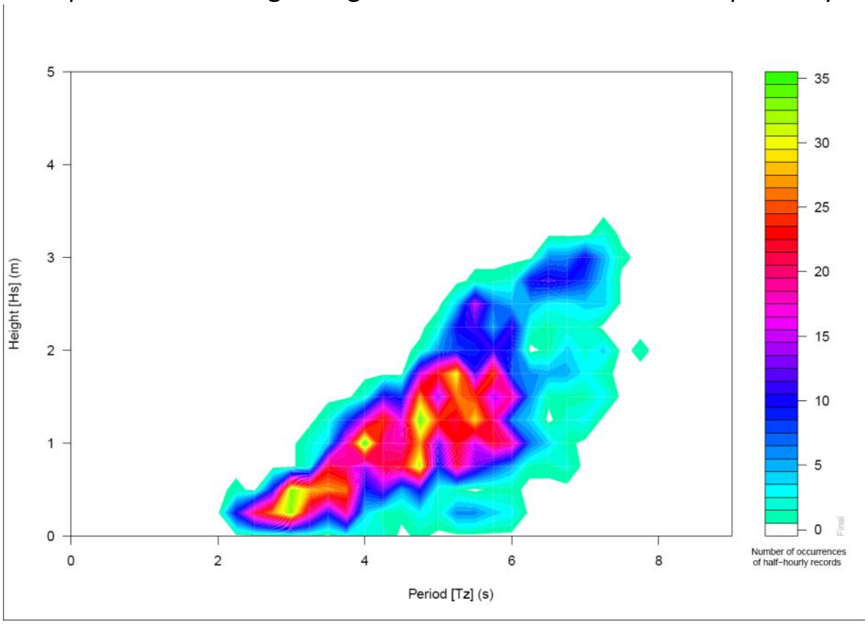

Figure 28: Scatter Diagram generated at EMEC.

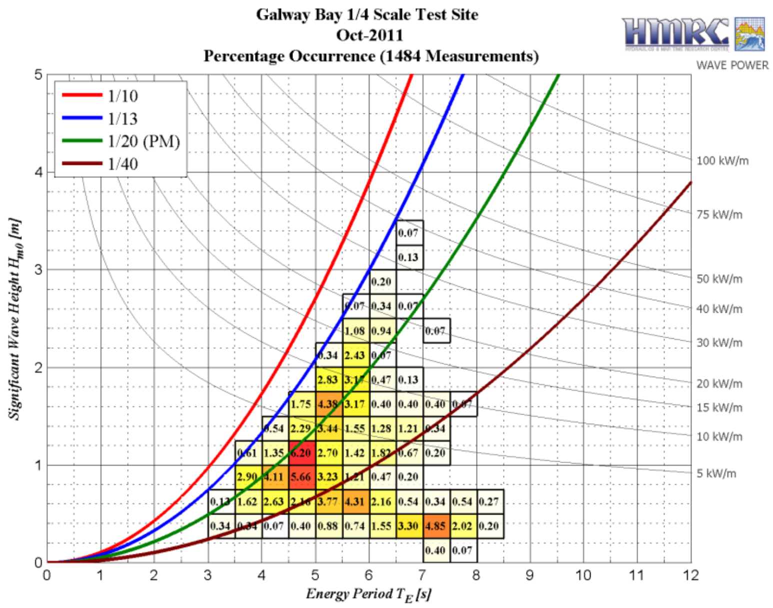

Figure 29: Scatter Diagram generated at SEAI.

4.3.1.5 Power Matrix

A power matrix (Figure 30) is used to determine the expected power output of a wave energy converter for a given test site. It is normally derived from the interpolation of the device characteristics with the scatter diagram of the installation location.

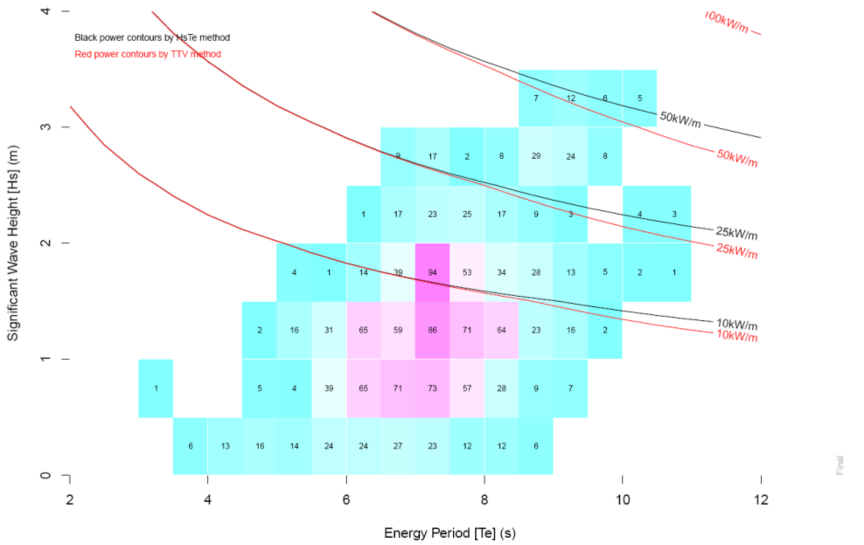

Figure 30: Power Matrix generated at EMEC.

4.3.1.6 Wave Rose

A wave rose is an aggregate of measurements of direction and wave height generated typically over a month or a year of observations. Figure 31 and Figure 32 show examples of Wave Roses generated at EMEC and SEAI.

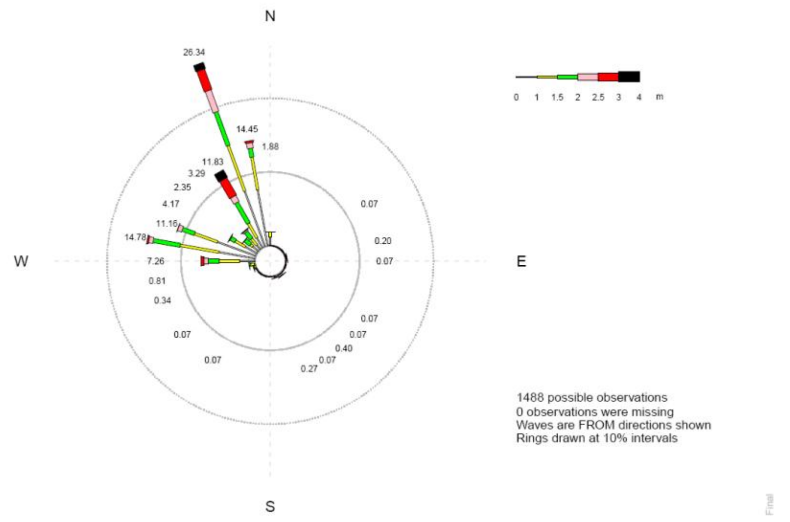

Figure 31: Wave Rose generated at EMEC.

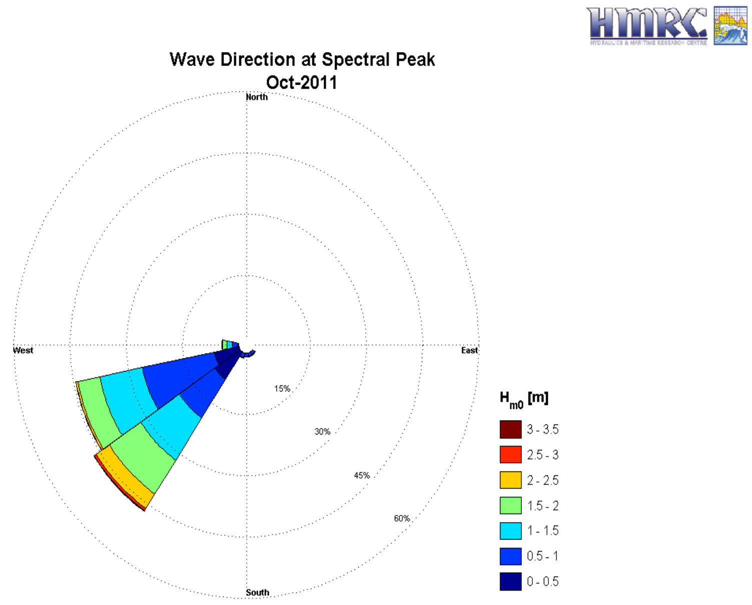

Figure 32: Wave Rose generated at SEAI.

4.3.1.7 Wave Height distribution

Figure 35 and Figure 36 present wave height distribution graph generated at EVE and SEAI, generated according to the methods presented in Section4.2.1.2.

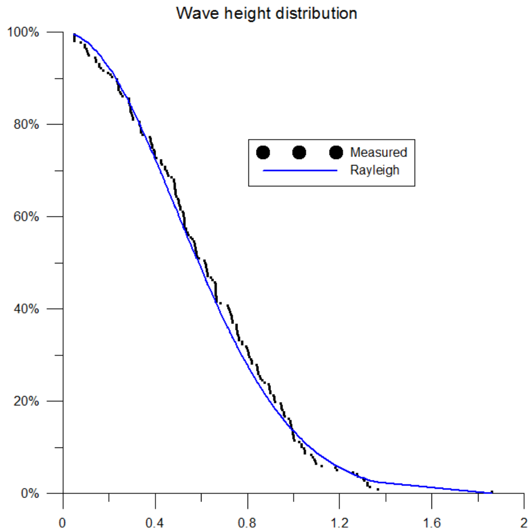

Figure 33: Wave Height Distribution at EVE (x-axis Hm/Hs; y-axis: probability)

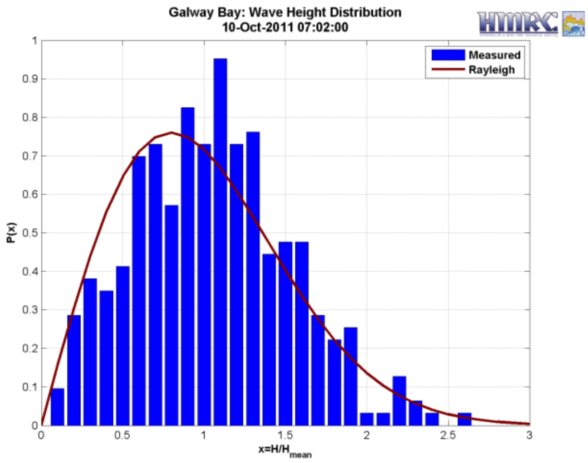

Figure 34: Wave Height distribution generated at SEAI.

4.3.1.8 Joint distribution of wave height and period

The joint distribution of wave height and period can be produced from wave measurements as seen presented in Figure 35 and Figure 36.

Height [Hs] in m	Energy Period [Te] in seconds																TOTAL
	(3,3.5]	(3.5,4]	(4,4.5]	(4.5,5]	(5,5.5]	(5.5,6]	(6,6.5]	(6.5,7]	(7,7.5]	(7.5,8]	(8,8.5]	(8.5,9]	(9,9.5]	(9.5,10]	(10,10.5]	(10.5,11]	
(0,0.5]	0	6	13	16	14	24	24	27	23	12	12	6	0	0	0	0	**177**
(0.5,1]	1	0	0	5	4	39	65	71	73	57	28	9	7	0	0	0	**359**
(1,1.5]	0	0	0	2	16	31	65	59	86	71	64	23	16	2	0	0	**435**
(1.5,2]	0	0	0	0	4	1	14	39	94	53	34	28	13	5	2	1	**288**
(2,2.5]	0	0	0	0	0	0	1	17	23	25	17	9	3	0	4	3	**102**
(2.5,3]	0	0	0	0	0	0	0	9	17	2	8	29	24	8	0	0	**97**
(3,3.5]	0	0	0	0	0	0	0	0	0	0	0	7	12	6	5	0	**30**
TOTAL	**1**	**6**	**13**	**23**	**38**	**95**	**169**	**222**	**316**	**220**	**163**	**111**	**75**	**21**	**11**	**4**	**1488**

Figure 35: Example of joint distribution of height and period (value displayed: count)

Table 5.1: Joint distribution of significant wave height (Hs) and peak period (Tp) at the buoy BIMEP.

Tp(s)/Hs(m)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	TOTAL
0-2	0	0	0	0	0	0	0	0	0	0	0
2-4	0.41	0.09	0	0	0	0	0	0	0	0	0.5
4-6	5.36	4.26	0	0	0	0	0	0	0	0	9.62
6-8	3.98	8.7	0.64	0.37	0	0	0	0	0	0	13.69
8-10	13.14	11.86	0.96	1.1	0.5	0.09	0	0	0	0	27.65
10-12	5.36	15.2	7.42	2.84	1.88	0.23	0.09	0	0	0	33.02
12-14	1.42	3.43	2.84	1.69	1.42	0.87	0.18	0.09	0	0	11.94
14-16	0.27	0.46	0.32	0.96	0.87	0.09	0.23	0.09	0	0	3.29
16-18	0	0.14	0	0	0.09	0	0.05	0	0	0	0.28
18-20	0	0	0	0	0	0	0	0	0	0	0
TOTAL	29.94	44.14	12.18	6.96	4.76	1.28	0.55	0.18	0	0	99.99

Figure 36: Joint distribution of significant wave height and peak period for the BIMEP site – generated by EVE

4.3.1.9 Other graphs

Example of distribution by peak direction and wave height

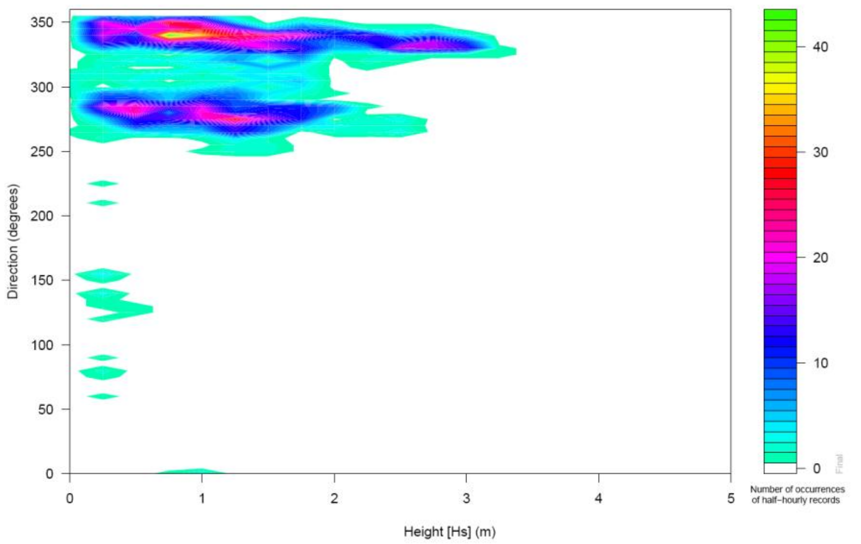

Figure 37: Example of distribution by peak direction and wave height generated at EMEC.

Example of time series of spectra

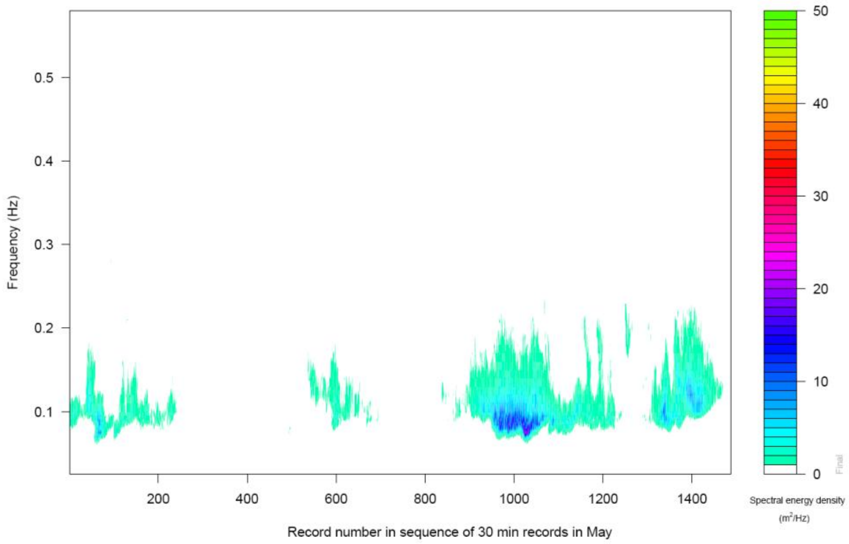

Figure 38: Example of time series of spectra generated at EMEC.

Example of half-hourly and monthly best direction

In order to be able to provide an indication of the effect of directionality on the wave spectra, the "best direction" is evaluated. A directional estimate of the net power flux, P_{flux}, in direction ϕ is obtained by multiplying the energy of each spectral component resolved in direction ϕ by the group velocity (*Cg*):

$$P_{flux}(\phi) = \rho g \int Cg(f) S(f) \cos(\phi - \theta(f)) \mathrm{d}f$$

Where ϕ is the directional alignment to the waves and θ is the spectral wave direction.

The above calculation is repeated for ϕ = 0 to 360 degrees in one degree increments, finding the power flux for every direction. $D\delta$ is the best direction (i.e. ϕ for max {P_{flux}(ϕ)}) found by this means. Examples of half-hourly and monthly best direction and of half-hourly and monthly directionality coefficient generated at EMEC are presented in Figure 39 and Figure 40 respectively.

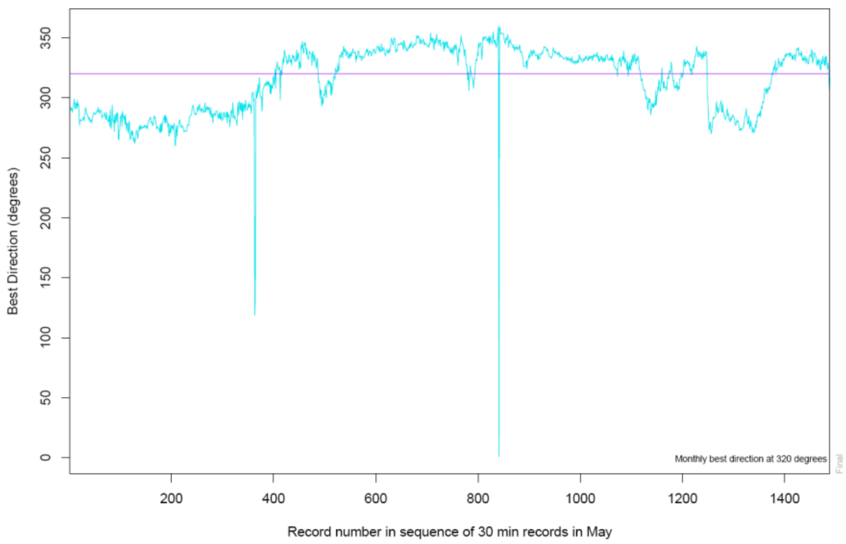

Figure 39: Example of half-hourly and monthly best direction generated at EMEC.

Example of half-hourly and monthly directionality coefficient

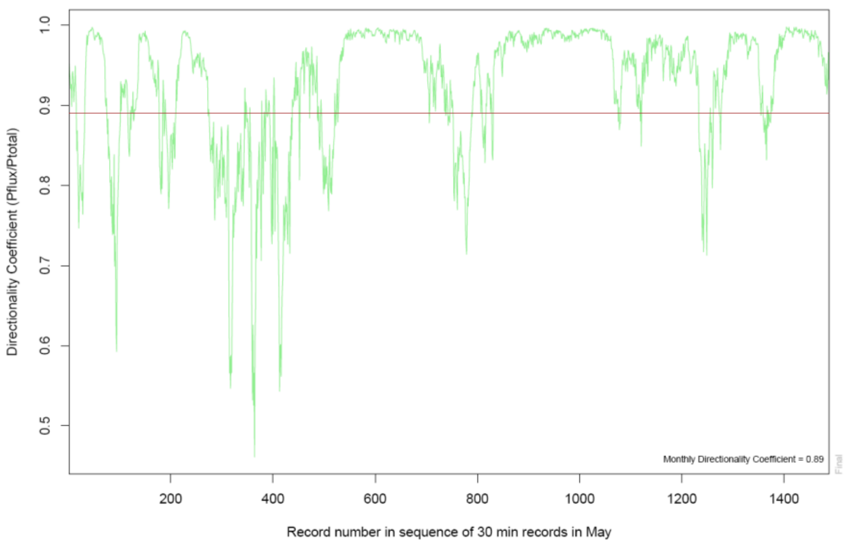

Figure 40: Example of half-hourly and monthly directionality coefficient generated at EMEC.

5 CONCLUSIONS AND RECOMMENDATIONS

Large amounts of wave data are generated at the different MaRiNET facilities. The purpose of this review is to identify how wave data is stored, accessed and represented and to provide useful information for future use.

Despite wave data being dependent on the needs of the final user, the following general points can be concluded from this review:

1. Data Storage: The size of the wave dataset is strongly dependent on the type of measurements being carried out. In the case of laboratory measurements, the data collected is rarely presented in proprietary format. Common procedures amongst partners include storage on hard drive or CD/DVD.

   Wave data collected in field conditions normally have a requirement of about 7MB of data per day. However the size of the files is dependent on the parameters monitored, the accuracy of monitoring and the file format that the data is stored in. Most waverider buoys and ADCPs store information in a proprietary format. This generates discrepancies in the nomenclature used, as well as different requirements in terms of storage of the information.

   The use of common headers for files and the creation of standards at industry level will allow for a more consistent way to storage data and for cross-comparison between the different facilities.

2. Data presentation: Examples of graphical representation for both laboratory and field conditions are reported herein. In general terms, the procedures used in different facilities to give a graphical representation of wave data are very similar. However, discrepancies are often found in the wave parameters used to generate the various diagrams, for example, choice of H_{m0} and T_e when generating scatter diagrams, power matrixes and joint wave height and period distributions-. Consistency in the use of these parameters as recommended by the Equimar[1] guidelines would allow for greater uniformity and for easier benchmarking of the data.

[1] Equimar Deliverable 2.2 "Wave and Tidal Resource Characterisation", and Deliverable 2.7 "Protocols for wave and tidal resource assessment".

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7 APPENDICES

Symbol Used	Definition
H_s, $H_{1/3}$	Average of the third highest waves
H_{max}	Height of the highest wave
H_{mean}, H_m	Average height of individual waves
H_{m0}	Estimate of H_s , $4\sqrt{m_0}$
T_s	Average period of the one third highest waves
T_z	Average period of individual waves
T_p	Peak period
T_{02}	Mean ZUC period $\sqrt{m_0 / m_2}$
T_e	Energy period m_{-1} / m_0
s	Wave steepness
S	Spectral density
m_0, m_1, m_2, m_4,	Moments of the spectrum about the origin $\int f^k S(f)df$
θ_p	Peak direction = θp ∣ S(fp,θp) = Max[S(f,θ)]
θ_m	Mean direction = (180/π)*arg[a+i*b]
Λ	Spectral bandwidth = m0^2 / ∫S(f)^2*df
σ_p	Peak's directional spreading
σ_m	Mean directional spreading
P_w	Omnidirectional wave power / unit of crest length
$P_{average}$	Average power generated
Prob	Probability occurrence of a given sea state defined by H_s and T_p
η	Efficiency of conversion
$P_{flux}(\phi)$	Directional power flux in direction ϕ
$D\delta$	Best direction