MARINET

Marine Renewables Infrastructure Network

Work Package 2: Standards and Best Practice

D2.1 Wave Instrumentation Database

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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 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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EXECUTIVE SUMMARY

This document provides an introduction to wave measurement techniques and a description of the equipment in use by the MARINET partners.

The initial section gives a short overview of the main wave characteristics, including wave height, period and direction. Also covered in this section is an overview of wave frequency domain, wave direction and spreading, 1D and 2D spectra. Following this is an explanation of how these parameters can be measured to provide a data set that describes the wave climate at the measurement location.

An overview of the equipment options and their basic operating principles is presented for both open-sea and tank based equipment. Commonly used open-sea sensors within the MARINET facilities include wave measuring buoys, acoustic profilers and radar and satellite systems. Tank measurement sensors include both capacitance and conductance probes, optical and video systems, pressure sensors and acoustic point measurement devices. A full catalogue of the sensors used by the partners is summarised in an equipment database.

The principal outcome of this deliverable is a common information source for all MARINET partners to cross reference. This will be of key importance in synchronising the various approaches across Europe and working towards the creation of best practice methodologies for wave measurement.

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1 INTRODUCTION

At present there is no standardisation of instrumentation across the MaRINET facilities for the measurement of wave parameters. This deliverable provides a catalogue which lists all the wave measurement equipment currently in use. The principal outcome of this will be a common information source that the various MaRINET facilities can cross reference when upgrading or replacing existing equipment. This will help the various facilities to standardise the instrumentation that they use and allow the transferability of results between different testing centres to be simplified.

As an introduction to the instrumentation catalogue, Section 2 provides a short overview of the principles behind wave measurement. This is classified by measurement in time and frequency domain and details the parameters commonly used in most measurement techniques.

The analysis of measured water levels to determine these characteristics is outlined in section 3. This section also summaries the purpose of these parameters in the estimation of wave energy in a sea-state.

The principal types of measurement equipment used in the open sea are described in section 4, and the principal types of laboratory sensors are described in section 5.

The equipment currently in use at the MaRINET facilities has been collated into a database which is detailed in section 6 for the open sea devices, and section 7 for the laboratory devices. The equipment database is only a snapshot of the equipment in use when the facilities were surveyed. This does not represent an endorsement for any particular manufacturer and when new equipment becomes available this may supersede the instrumentation listed here.

This deliverable feeds directly into D2.5 (report on instrumentation best practice) where a gap analysis will be undertaken to identify where instrumentation is not available for specific monitoring requirements, unique to the testing of marine renewables. Following this new types of instrumentation and data reductions (due to built-in intelligence) will be investigated for consistency and accuracy over a range of applications in Work Package 4 as these have the potential to reduce data generation requirements and speed up the testing process. In parallel this deliverable will also feed D2.9 (Standards for Wave Data Analysis, Archival and Presentation), which will look at the outputs from these instruments.

2 IMPORTANT WAVE CHARACTERISTICS

This section provides an overview of the specific wave parameters that are likely to be measured in tank and open sea facilities.

2.1 Time Domain (Height, Period and Direction)

Time domain 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 wave in a record. The determination of $H_{1/3}$ is based on the zero up-crossing method.

Historically, the significant wave height corresponds to the wave height reported by a trained visual observer. The energy available in a sea-state is a function of $H_{1/3}$

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.

The maximum wave-height is an important parameter for designing WEC survivability in a sea-state.

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}.

The wave steepness is an important parameter for designing WEC survivability in a sea-state.

2.2 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. 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.

The frequency spectrum, *S=S(f)*, shows the overall energy resource in a sea-state. Because a WEC is typically a resonant oscillator, the matching of a WEC to a spectrum is a requirement for effective energy capture.

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:

$$m_n = \int_0^\infty f^n S(f) df \qquad [1]$$

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:

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

This agrees very closely with the time-domain parameter above

Mean Wave Period

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

$$T_{01} = \frac{m_0}{m_1} \qquad [3]$$

And

$$T_{02} = \sqrt{\frac{m_0}{m_2}} \qquad [4]$$

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:

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

[5]

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 the mean period, but its value is less influenced by the higher frequency energy. T_e is given by the following relation:

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

[6]

The energy period of a sea-state is a single value that corresponds to the energy in the irregular wave train. It provides an indication of how a device might perform in the sea state

Spectral Bandwidth

The spectral bandwidth allows assessment of the wave resources 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:

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

[7]

The bandwidth of a sea-state indicates the degree of tuning (or resonance) that a WEC will need to capture energy from the sea-state.

Wave Power

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

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

[8]

where c_g represents the wave group velocity.

For deep water cases, refer to equations [28] through [32].

Wave Steepness

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

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

[9]

The wavelength L_p is determined through the dispersion coefficient and is associated to T_p. This corresponds to the steepness parameter derived in the time-domain.

2.3 Direction and Spreading (2d Spectra)

The energy spectrum can be provided in both directional and non-directional form. The non-directional and directional forms of the spectrum are conventionally described as *S(f)* and *E(f,ϑ)* respectively. The directional spectrum is derived by adding the directional distribution, *D(f,ϑ)*, to *S(f)* as follows:

$$E(f,\theta) = S(f).D(f,\theta)$$

[10]

Whilst the energy of the spectrum provides information on the mean energy available at a given frequency, by including the directional distribution component it is possible to determine the direction of the energy propagation. The directional distribution, *D(f,ϑ)*, describes the proportion of the energy propagating in a given direction for a particular frequency of the spectrum. The directional distribution provides a more accurate indication of the wave prediction. Unidirectional spectra can over-predict the significant wave height by over 20% compared to directional spectra models.

The directionality and spreading of a sea-state are important for a WEC that has a preferred axis for energy capture

D(f,ϑ) can be defined by a matrix providing a set of discrete values over a range of frequencies and directions. However, the directional distribution is more commonly described as a Fourier series for a particular frequency:

$$\hat{D}(f,\theta) = \frac{1}{2\pi} + \frac{1}{\pi}\sum_{n=1}^{N}[a_n \cos(n\theta) + b_n \sin(n\theta)]$$

[11]

The Fourier coefficients, a_n and b_n, are normally obtained from a buoy or other single point measurement device, with the devices usually providing only four coefficients: a_1, b_1, a_2, b_2.

The directional distribution function is estimated from measured data. A variety of methods have been developed to determine *D(f,ϑ)*, which can be separate in three main groups:

1. Fourier Series Decomposition Methods: Truncated and Weighted methods are used.
2. Parametrical methods: direct and statistical fitting
3. Maximum Likelihood Methods: Bayesian Directional Methods (BDM), Maximum Likelihood Method (MLM), Maximum Entropy Method (MEM).

Fitted spreading functions such as the *cos2s* function can be used to determine *D(f,ϑ)* when measured data are not available:

$$D(f,\theta) = N(s)\cos^{2s}\left(\frac{\theta-\theta_m}{2}\right) = \frac{2^{2s-1}}{\pi}\frac{\Gamma^2(s+1)}{\Gamma(2s+1)}\cos^{2s}\left(\frac{\theta-\theta_m}{2}\right)$$

[12]

Where *Γ* represents the Gamma function, *s* is the spreading parameter, *ϑ*, is the wave direction and ϑ_m the mean wave direction. The spreading parameter is a function of the wave frequency and wind speed. Three main formulations are used to derive the spreading parameter: the Longuet-Higgins et al. (1963) method which assumes *s* as a constant, the Mitsuaysu et al. (1975) method and the Hasselman et al. (1981) method. When *s* is assumed constant, the *cos2s* formulation reaches the limit of the *cosn* model:

$$D(f,\theta) = \begin{cases} \dfrac{\Gamma\left(1+\frac{n}{2}\right)}{\sqrt{\pi}\,\Gamma\left(\frac{1}{2}+\frac{n}{2}\right)}\cos^n(\theta-\theta_m) & for -\pi/2 < \theta-\theta_m < +\pi/2 \\ 0 & elsewhere \end{cases}$$

[13]

An alternative description of the directional distribution is provided by the Wrapped-Normal distribution given by:

$$D(f,\theta) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(\frac{(\theta-\theta_m)^2}{2\sigma^2}\right)$$

[14]

where *σ= σ (f)* is the root mean square angular spread.

The composite directional spectrum provides useful inputs for shallow water spectral transformation, allowing the calculation of the directional spectra in the near-shore region, accounting for effects such as refraction and non-linear interaction to mention a few.

The spreading function can be combined with either measured or empirical one dimensional spectra such as the JONSWAP or Bretschneider to provide input for numerical and physical modelling of wave energy converters.

3 MEASURED WAVE DATA

This section describes how the specific wave parameters, outlined in the previous section, can be measured to provide a data set that describes the wave climate at the measured location.

3.1 Water Surface Elevation Time History

3.1.1 Time Domain Analysis

An individual wave is defined by the surface elevation measured between two consecutive similar crossings of the mean water level. Therefore, there are two analysis options available: up-crossing and down-crossing. In a linear sea, the average value of the derived parameters will be insensitive to the choice of crossing method. Non-linear effects, however, may introduce variations when examining values such as H_{max}. Horizontal asymmetry may potentially produce a change in the relationship between trough elevations preceding and succeeding the wave crest. Other time domain parameters, outlined below, are defined by values taken relative to the wave crest and are therefore insensitive to the choice of zero-crossing method.

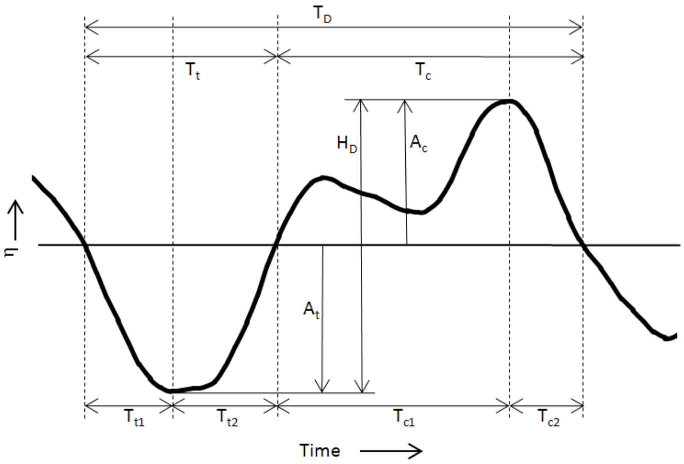


Figure 1: Zero down-crossing wave with definitions.

The definitions of individual wave height (HD) and period (TD) are described graphically in Figure 1 for a zero down-crossing wave. For a zero up-crossing wave the height and period and denoted as HU and TU respectively. Also illustrated are the time intervals associated with describing portions of an individual down-crossing wave. The simplest time interval is the zero crossing period. The wave may then be further decomposed into its crest and trough components. The associated durations are usually referred to as the crest and trough period (T_c and T_t respectively), although the use of term “period” is not strictly correct. The crest and troughs may be further divided into their “front” and “back” sections. Thus a zero down-crossing wave is described by two elevation parameters (A_c and A_t) and four time parameters (denoted here as T_{t1}, T_{t2}, T_{c1}, T_{c2}). The successive wave parameters are denoted as (T'_{t1}, T'_{t2}, T'_{c1}, T'_{c2}).

The simplest parameter available to characterise the shape of an individual wave is the steepness, *s*, described in deep water in [15].

$$s = \frac{2 \cdot \pi \cdot H}{g \cdot T^2}$$

[15]

H and *T* are the wave height and period respectively. The calculation of steepness for the wave associated with a particular crest will be dependent upon the choice of zero crossing method. The steepness is also a simple definition of wave shape, as it gives no indication of the shape between the crest and the preceding trough. An alternative measure is the crest front steepness (Myrhaug and Kjeldsen, 1986), s_{cr}, as described in [16].

$$s_{cr} = \frac{A_{cr}}{(g/2 \cdot \pi) \cdot T_D \cdot T_{c1}}. \quad [16]$$

The steepness and crest front steepness are defined as ratio of vertical amplitude (wave height or crest elevation) to horizontal length (e.g. wavelength). While this approach is intuitive, it is complicated by the fact that it is not possible to calculate the length of a portion of a wave (e.g. T_{c1}) from its duration. In an attempt to overcome this limitation, Guedes Soares, et al. (2004) described a number of "coefficients of steepness" to characterise different aspects of the wave shape. These dimensionless coefficients characterise the relationship between an elevation parameter and the duration of part(s) of the wave without the complication of attempting to calculate horizontal lengths. Selected coefficients described by Guedes Soares, et al. (2004) are reproduced below in equations 17 to 22. The convention here is to describe steepness parameters in lowercase and steepness coefficients in uppercase.

Coefficients of down-crossing & up-crossing steepness:

$$S_D = \frac{H_D}{g \cdot T_D^2} \quad [17]$$

$$S_U = \frac{H_U}{g \cdot T_U^2} \quad [18]$$

Coefficients of front & back steepness:

$$S_f = \frac{H_D}{g(T_{t2} + T_{c1})^2} \quad [19]$$

$$S_b = \frac{H_U}{g(T_{c2} + T'_{c1})^2} \quad [20]$$

Coefficients of crest front & back steepness:

$$S_{cf} = \frac{A_{cr}}{g \cdot T_{c1}^2} \quad [21]$$

$$S_{cb} = \frac{A_{cr}}{g \cdot T_{c2}^2} \quad [22]$$

The choice of coefficients effectively allows the wave to be characterised as a whole (*SD/U*), from crest to trough (*Sf/b*) and for the crest itself (*Scf/cb*). Similar coefficients are available to characterise the trough (*Stf/tb*), although these are not explored here.

3.1.2 Data Analysis Methodology

An elevation time-series consists of a number of discrete data points, usually logged at a constant frequency. If the sampling rate is high, relative to the height and length of the wave, the value of the zero-crossing and turning points may be taken as the nearest appropriate data point. This will introduce an inaccuracy when calculating the individual periods and the values of the crest and trough amplitudes will be underestimated.

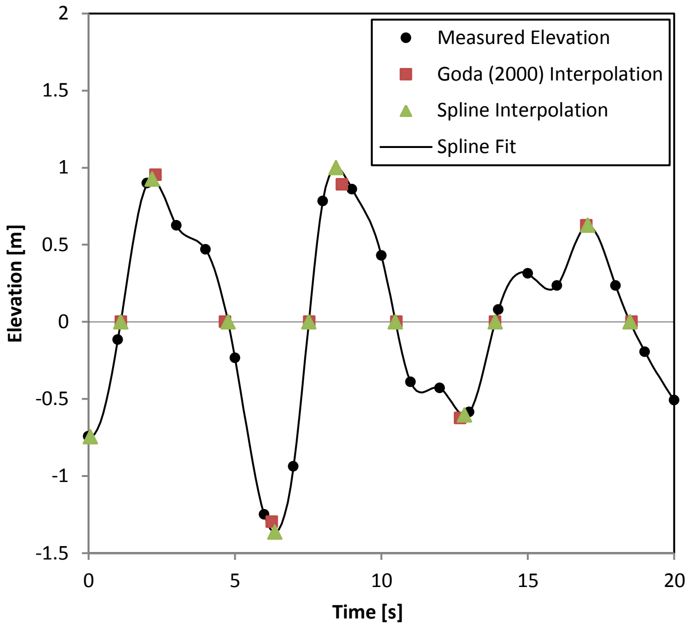


Figure 2: Zero-crossing, crest and troughs interpolated using the method of Goda (2000) and a least-squares fit cubic spline (piecewise polynomial).

Goda (2000) recommends a simple linear interpolation for the calculation of the zero crossing point and a parabolic fit, using three data points, for the calculation of the crest and trough amplitude. While this method is straightforward to apply, the linear interpolation is visually incorrect when sample rate is relatively low. Anomalies may also be encountered when the linear interpolation and parabolic fit share the same data points, as may occur with the smallest waves in a record. While these small waves may not be of interest they may introduce practical difficulties when processing large datasets.

The alternative approach is to fit a piecewise polynomial (cubic spline) to the elevation time series using a least-squares method. The region between each data point is described by a degree 4 polynomial, as illustrated in Figure 2. Zero-crossing points may be interpolated by taking the roots of the polynomials crossing the mean water level. Crests and troughs are identified from the derivatives of the polynomials. During the course of the analysis this methodology was found to be extremely robust and avoided the multiple errors found when the data was analysed using a combination of linear and parabolic interpolation.

3.2 Seaway Summary Statistics

The local state of the sea surface in deep water conditions may be quite accurately described by the stationary Gaussian process described above on a scale of tens of kilometres and minutes. In these circumstances the local behaviour of the waves is determined by the 2D wave spectrum $S(f,\theta)$. The information contained in the spectrum is usually condensed in mean height, period and direction wave parameters. These are typically expressed as a function of the *n*-th moment spectral moment (c.f. equation [1]).

$$m_n = \int_0^{2\pi} \int_0^{\infty} f^n S(f,\theta) df d\theta$$

[23]

The most widely used wave height parameter is the significant wave height H_s, described above. Historically, this was defined as the average of the highest one third of the up-crossing trough to crest wave heights. It agrees closely with the spectral estimate.

$$H_{m_0} = 4{m_0}^{1/2} \cong H_s$$

[24]

where m_0 is the zeroth spectral moment.

To describe wave period, several parameters are commonly used. The spectral parameter T_{m02} reasonably corresponds to the mean zero-crossing period (the average time elapsed between two sequential crests). As it depends on m_2, this parameter is very sensitive to the high frequency spectral tail, which typically presents significant variability and low energy contents. The mean energy period T_e or T_{m-10}, which is more adequate for wave energy resource assessment purposes, is defined by

$$T_{m-10} = \frac{m_{-1}}{m_0}$$

[25]

Given that $T = 1/f$, T_{m-10} corresponds to an average value of T weighted by the spectral distribution. This parameter mainly depends on the lower frequency band of the spectrum where most of the energy is concentrated.

The total wave power level or flux of energy per unit crest length is given by

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} S(f,\theta) c_g(f,h) df d\theta$$

[26]

(c.f. equation [8]), where ρ is the water density and g is the acceleration due to gravity. The group velocity, c_g, corresponds to the velocity at which the energy propagates and is defined by

$$c_g = \frac{\partial \omega}{\partial k}$$

[27]

In deep water conditions (in practice when water depth h is larger than half wavelength) c_g simplifies to

$$c_g = \frac{g}{4\pi f}$$

[28]

Therefore the wave power is given by

$$P = \frac{\rho g^2}{4\pi} \int_0^{2\pi} \int_0^{\infty} S(f,\theta) f^{-1} df d\theta = \frac{\rho g^2}{4\pi} m_{-1}$$

[29]

which can be expressed in terms of H_{m0} (i.e., H_s) and T_{m-10} by

$$P = \frac{\rho g^2}{64\pi} H_{m0}{}^2 T_{m-10}$$

[30]

Assuming that the sea water density is ρ = 1025 kgm^{-3}, if H_{m0} is expressed in meters and T_{m-10} in seconds, the power level in kWm^{-1} will be given by

$$P = 0.4906 H_{m0}{}^2 T_{m-10}$$

[31]

The mean wave direction may be obtained from the 2D spectrum by

$$\bar{\theta} = \arctan \frac{\int_0^{2\pi} \int_0^{\infty} S(f,\theta) \sin(\theta) d\theta df}{\int_0^{2\pi} \int_0^{\infty} S(f,\theta) \cos(\theta) d\theta df}$$

[32]

4 TYPES OF OPEN SEA MEASUREMENT EQUIPMENT

The MaRINET consortium includes a range of open sea test facilities that are used for testing Wave Energy Convertors (WECs). At these facilities the wave climate is measured to provide data for device design, marine operations and performance assessment.

4.1 Pitch/Roll/Heave Buoys

One of the most commonly used instruments for open-sea directional wave measurement is the surface following buoy. These devices fall into two categories based on the hydrodynamic principles employed in their operation: Pitch-Roll-Heave (PRH) buoys that follow the surface slope, and particle following buoys that follow the sea surface water particle orbits.

4.1.1 Operating Principle

PRH buoys were the earliest directional wave buoys to be developed and were first deployed in the 1960s (Cartwright and Smith, 1964). They follow the surface slope of the waves, measuring time series of the vertical (heave) acceleration and two orthogonal components of the surface slope (pitch and roll). From each triplet of time series wave measurements, a directional spectrum can be estimated using the theory of Longuet-Higgins (Longuet-Higgins et al., 1963) to calculate the auto- and cross-spectra between the records, and spectral parameters can thus be computed. Data is typically processed on-board, and both raw and processed data may be stored or transmitted to shore via a radio or satellite link.

One of the key challenges in the development of PRH buoys was the provision of a true vertical reference in a self-contained buoy. This was achieved in the 1980s with the development of the Datawell Hippy sensor (Datawell, 2012), a gravity-stabilised platform on which an accelerometer for measuring the vertical acceleration is mounted. Although still in use in some of the offshore buoy networks, the Hippy has increasingly been replaced by more robust sensors such as the Seatex Motion Reference Unit (MRU-6) (Kongsberg Maritime, 2012) and the Oceanor WaveSense (Fugro Oceanor, 2012), both of which utilise solid-state sensors with low power requirements and no moving parts. A key aspect of the PRH buoys is their mooring system; this must be designed so that it does not produce tilt forces acting on the buoy (Tucker and Pitt, 2001).

4.1.2 Fields Measured

In their primary role of wave measurement, PRH buoys record vertical acceleration and two orthogonal components of surface slope. These are processed on-board the buoy to provide:

- Time series of the sea surface displacement
- Omni-directional and directional spectra
- Integrated spectral parameters, e.g. significant wave height, mean period, energy period.

Additional oceanographic sensors recording parameters such as surface current velocities and directions, temperature, salinity and meteorological data may also be integrated into the buoy setup.

Measurement accuracies of PRH buoys compare well to other direct measurement techniques. The Oceanor Wavescan buoy, for example, provides the accuracies shown in Table 1.

Parameter	Range	Accuracy
Heave, surge, sway	+/- 25m	< 10cm
Direction	0 - 360°	0.3°
Wave period	2 – 30s	< 2% of value

Table 1: Accuracies for wave parameters and directional wave sensor data for the Oceanor Wavescan buoy (Fugro, 2004).

4.1.3 Method of Operation

PRH buoys are designed to operate in offshore locations, and are typically deployed from an ocean-going vessel with heavy lifting capabilities. In normal conditions and areas with heavy marine traffic, the buoy mooring would comprise a single point taut mooring. However, in hostile and deep water environments, an s-mooring should be used, as illustrated in Figure 3. Prior to deployment, buoys should be calibrated on land using a test rig that replicates the motion of the buoy. All operational buoys should periodically be brought ashore and re-calibrated to maintain measurement accuracy.

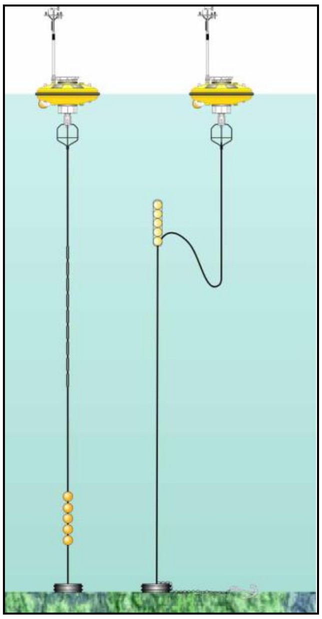


Figure 3: Potential PRH buoy mooring options: single point taut mooring (left) and s-mooring (right) (Source: Fugro, 2004).

4.1.4 Specific Devices

One of the most widely used devices of this type is the Oceanor Wavescan buoy (see Figure 4). This discus-shaped buoy has a diameter of 2.8m and weighs approximately 920kg. It is a metocean buoy, providing directional wave parameters, sea surface temperature, salinity and temperature profiles, surface current parameters and meteorological data. It is particularly suited to deep-water measurements and areas with severe currents (Fugro, 2004). Other examples of PRH buoys include the NDBC discus buoys, widely deployed as part of the US national buoy network.

Figure 4: Fugro Oceanor Wavescan buoy (source: Fugro, 2004)

4.1.5 Considerations

PRH buoys are used world-wide for long-term wave measurement programmes. However for marine energy resource assessment purposes, which are likely to involve shorter term deployments in coastal regions, displacement buoys may be a better option due to their lower cost, smaller size, increased robustness, and less complex moorings.

4.2 Displacement Buoys

Displacement buoys are used to measure the motion of the water surface, including 'heave' surface elevations, acceleration and slopes of the water surface. They provide information regarding the direction of propagation of the waves as well as values of the directional spreading coefficient for each frequency component. From the analysis of the vertical motion of the buoy it is possible to determine wave heights and periods, whilst directional information is obtained from the horizontal displacement of the buoys. The directional spectrum can therefore be calculated with one of the methods highlighted in section 2.3.

The wave profile is measured by following the orbits of the water particles at the water surface and is defined through the use of a combination of accelerometers, gyroscopes and a compass. The output generated by wave buoys comprises of a triplet of measurements related to the vertical and horizontal (north and east) movements of the buoy. These data are later processed, often directly on the device, to determine the variance density spectrum and the directional distribution. The data acquired from the buoys are sent via a radio or a satellite signal to a receiving shore station where they are further processed.

4.2.1 Operating Principle

Displacement buoys operate on the principle that the buoy would follow exactly the motion of the water surface particle when wave forces are exerted upon them in a defined range of frequencies. The main operational differences among buoys available on the market are due to the instrumentation installed on the devices and on the type of measuring technique used to extract wave parameters. Currently three main manufacturers produce directional wave buoys: Datawell, Fugro-Oceanor and Axys. The Datawell Directional Waverider buoys are equipped with heave-pitch-roll sensors, two horizontal hull-fixed accelerometers, and compass to determine directional wave information. TRIAXYS buoys use three accelerometers to measure total accelerations along the mutually orthogonal X, Y, Z axes of the buoy, three angular rate sensors to measure rotation rates about the roll, pitch and yaw axes, and a gimbaled compass to measure sensor heading. Fugro-Oceanor Seawatch Mini Buoys are equipped with the Wavesense III wave sensor which comprises accelerometers, rate gyros and magnetometers mounted orthogonally to provide basic data, which are processed to provide heave, roll, pitch, surge, sway and compass time series.

4.2.2 Fields Measured

The majority of buoys provide real time series of the heave motion, north and east displacements of the buoy as well as directional spectra information. Time domain and frequency domain parameters, presented in sections 2.1 and 2.2 are derived from either zero-up-crossing analysis or spectral analysis of the time series. Sampling frequency of the different buoys and their accuracy is dependent on the type of sensor installed on the device. Data acquisition frequency varies between 2-4 Hz according to the make, as shown in table 2. Detailed information on the three main types of buoys is presented in section 4.2.4.

MAKE	Diameter	Mass	Digitising Frequency	Period response	Accuracy
Datawell Directional Waverider MKIII	0.9 m	225 kg	3.84 Hz	1.6 - 30 s	Wave Elevation:0.01m Direction: 2°
Oceanor Seawatch mini MKII	1.25 m	320 kg	2 Hz	1 - 30 s	Wave Elevation: <0.1 m Period: <2% Direction: 0.3°
TRIAXYS Directional Wave Buoy	1.1 m	197 kg	4Hz	1.6 - 30 s	Wave Elevation: 0.01m Period:2% Direction:3°

Table 2: Features of directional wave buoys (Source: www.datawell.nl, www.oceanor.no, www.axystechnologies.com)

4.2.3 Method of Operation

Deployment procedures for wave buoys varies according to the make of buoy, however due to the highly sensitive equipment careful attention is required not to damage the sensors during the handling of the buoy. To allow free movement of the buoy, at least one section of the moorings is typically composed of elastic material. Deployment procedures are often provided by manufacturer or evaluated on a case by case basis. The standard mooring configurations often consist of the buoy being attached to an elastic mooring rope, frequently equipped with an additional floating device, connected to an anchor weighting more than 400kg via a set of galvanised shackles and swivels. Double anchor mooring configurations may be required if the buoy is to be deployed in an area subject to high tidal range and strong currents, as in the case of the Oceanor Seawatch Mini Buoy deployed at Wave Hub by Plymouth University. In this case, the wave buoy is connected to a surface float by a length of stainless steel chain, and the surface float is then attached to a two-point mooring system consisting of 2 steel anchors via a mooring rope that is half elastic and half braided floating line. The total weight of the anchors exceeds 1300 kg.

The deployment procedure consists firstly to check that buoy is functioning properly. The mooring system is then fully assembled and all connections are checked and secured. The buoy is then deployed by first releasing the two surface buoys into the water, while the steel anchors remain on board. Once the buoys are clear, the steel anchors are then rigged in such a way that they are lowered in a controlled fashion and then released once the secondary anchor has reached the bottom. As soon as this happens, a GPS position is logged for the location of the anchors and the buoy is monitored to make sure that the system was deployed properly and that the orientations of both buoys are correct. Post-deployment, the position of the buoy continues to be monitored using the internal GPS. An independent GPS tag may be added to the buoy, to allow for emergency retrieval of the buoy in the case of detachment from the moorings or loss of radio signal with shore station.

The operating procedure of wave buoys is often user defined and programmed prior the deployment of the wave buoy on site, typical mode of operation of wave buoys are:

- Raw mode: heave, north and east position of the buoy are transmitted in real time to the shore where they will be processed. This method requires continuous operation of the radio system and is highly expensive in terms of battery power. Raw mode is used to validate control mechanisms for wave energy converters.
- Time series mode: The buoy operates for a short period of time (17-30 minutes) acquiring heave, north and east position of the buoy and stored on the internal hard drive. Data can be sent over radio or retrieved by on-site download.
- Spectral mode: The buoy operates for a short period of time (17-30 minutes) and data is processed on board to produce a directional spectrum and its parameters, which are then sent to shore via a radio link.
- Parametrical mode: A range of time and frequency domain parameters are calculated on the buoy and sent to shore for further analysis.

According to the specific of each manufacturer a particular wave buoy could work in one or more modes at the same time.

The calibration of wave buoys sensors is often carried out in accordance with the buoy manufacturer and might require the device to be sent back for inspection. Oceanor recommends recalibrating the wavesensor every three years. This procedure is undertaken directly by a qualified technician.

4.2.4 Specific Devices

The Directional Waverider Mark III represents one of the most widely used directional buoys, with the current make of the buoy of spherical shape and a diameter of 0.9 m. Wave height measurements are obtained through a single accelerometer mounted on a stabilized platform. Wave direction is determined from horizontal movement of the buoy, measured by two additional accelerometers, pitch and roll sensors and a compass. The buoy provides real time measurements of the wave height. Directional spectra information and heave information are provided every 30 minutes. This type of buoy offers a range of communication systems though HF link (radio, up to 50 km), Argos, Iridium, Orbcomm, GSM and GPS. According to the configuration chosen the buoy could provide outputs of three dimensional displacements in the form of time series at 1.28Hz, or heave and directional spectra information (first five Fourier parameters) at 0.58Hz. Figure 5 shows the Datawell Directional Waverider Mark III in operation.

Figure 5: Datawell Waverider buoy mark III

The Fugro-Oceanor Seawatch Mini II Buoy (Figure 6) is a compact, spherical shaped buoy with a diameter of 1.25 m. The buoy is equipped with the Fugro-Oceanor Wavesense III data sensor and can be used to measure wave height and north/east measurements in real time as well as providing half-hourly information on wave directionality and wave parameters in both the time and the frequency domain. Directional spreading and Fourier coefficients are determined using the Longuet-Higgins method. Outputs from the wave sensor include approximately 45 wave parameters, the first five Fourier coefficients for frequency between 0.04 to 0.5Hz. The spectral resolution is of $0.4m^2/Hz$. The buoy can be equipped with other sensor to measure temperature, pH, salinity profiles and other characteristics. The buoy offers communication link via UHF (radio), Inmarsat-C, iridium, GSM and GPS. The buoys have the capacity to internally store up to 10 years of wave data, which can be retrieved remotely as well as by on-site download.

Figure 6: Fugro-Oceanor Seawatch Mini II buoy

The TRIAXYS directional wave buoy comprises three accelerometers, three rate gyros and a compass, enclosed in a spherical buoy with a 1.1 m diameter (Figure 7). The buoy is equipped with an internal controller which provides data logging and data processing routines. The buoy computes wave directionality and spectral width in the frequency domain, whilst the full spectrum is determined through the Maximum Entropy Method. Outputs from the wave sensor include approximately 20 statistical values, the first five Fourier coefficients for frequency between 0.03 to 0.64Hz.

Figure 7: TRIAXYS directional wave buoy

4.2.5 Considerations

A series of considerations have to be taken into account before the deployment and during the operational phase of a wave buoy, including:

- Mooring design: This should be designed in order to allow free movement of the buoy and should not create impedance to the device. The mooring design should take into consideration the location where the buoy will be deployed in terms of water depth, current and wave climate (extreme waves).
- Calibration: The buoy should be calibrated before deployment and post-recovery to assure integrity in the data collected.

- Directional measurement: Compass should be correctly headed, according to the manufacturer's instruction, to ensure accuracy in directional movements.
- Battery life and buoy recovery: The battery life of the buoy is dependent on the mode of operation selected, requiring recovery trips to be planned for regular checks and for battery replacement. The use of GPS tag to monitor the buoy exiting its geofence is recommended in case the buoy becomes detached from the mooring.
- Data transmission: Data transmission via radio and satellite links is subject to weather conditions. Transmission could be interrupted in stormy wave conditions and during bad weather windows.
- Frequency response: The response of particle-following waves could be affected at both low and high wave frequencies. In the first scenario noise could be superimposed affecting the wave measurements. At high frequency the buoy may be forced not to follow the water surface causing errors in the evaluation of the trough of the waves. This is known as wave jumping. Low pass and high pass filters can be applied to the time series, however this often results in the loss of second-order non-linear part of the waves.

4.3 Acoustic Profilers

4.3.1 Operating Principle

The basic principle behind wave measurement by ADCPs (Acoustic Doppler Current Profilers or simply Acoustic Doppler Profilers) is that the wave orbital velocities below the surface can be measured. The ADCP measures the flow velocity of the water by transmitting short sound pulses of known frequency and measuring the Doppler shift of the signal reflected in scatterers assumed to be passively following the flow. In order to transmit and receive the acoustic signals, ADCPs use piezoelectric oscillators. Since at least 3 vector components have to be estimated to measure 3D velocities, ADCPs typically include 4 transistors: 3 for measuring velocity (u, v, and w) and a 4^{th} redundant transducer for error checking.

ADCPs for wave measurement purposes are bottom mounted, upward facing and include a pressure sensor, featuring the capacity to measure flow velocity at several depth levels, typically up to 128 levels, with each series of pulses. The along-beam component of the orbital velocity for each depth cell is used to construct a virtual array (Strong and Brumley, 2003). In other words, each cell in each beam is taken as an independent sensor in an array, as shown in Figure 8. The wave measurement uses the phase differences on the spatially separated virtual array. Cross-spectra, to which the directional (2D) spectrum is linearly related for a given frequency, are calculated between every sensor. Linear wave theory is used to translate the measurement from velocity spectra at various depths to surface displacement.

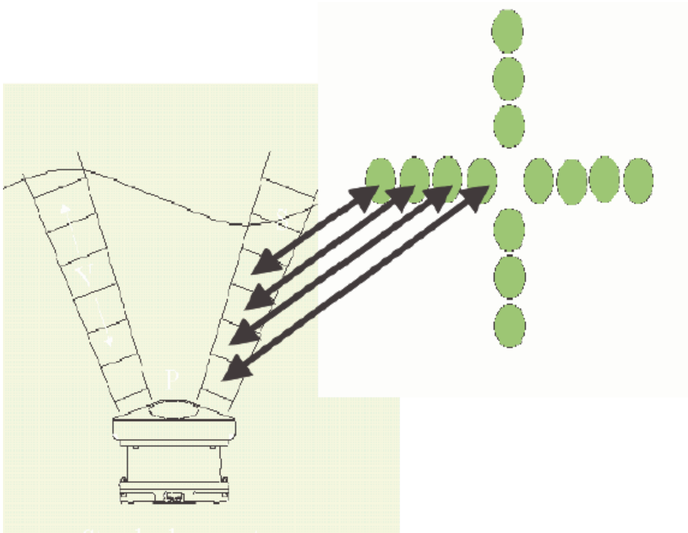


Figure 8: Virtual ADCP measured velocity array.

The technique of measuring the wave orbital velocity up close to the surface and then translating it to a surface displacement spectrum provides a measure of both directional and non-directional waves. ADCPs provide two additional non-directional waves measurement methods: surface track (i.e., measuring the echo from the surface) and the pressure sensor derived spectrum (a traditional technique). Comparatively, the orbital velocity measurement method provides a better frequency response, given that the measurements can be made farther up in the water column where the exponential attenuation of wave energy with depth is less significant. Surface track is a direct measurement of the surface, not frequency dependent except for the resolution of the echolocation of the surface. The pressure sensor technique presents several limitations due to the fact that the actual measurement is made on the deep sea bottom. Nevertheless, the possibility of three independent non-directional wave spectra measurements in one instrument allows for identifying error sources and ensuring data quality.

4.3.2 Fields Measured

The ADCP measures the flow velocity profile, hence the wave orbital velocities, over the entire water column. In general, it may typically measure a water column up to 1000 m long. There is, however, a limiting range above which the energy of the returned signal is too low to render it useful, in particular for wave measurement purposes. A compromise between high frequency pulses, which yield more precise data, and low frequency pulses, which travel farther in the water, must be achieved in every case. ADCPs working frequencies range from 38 kHz to a few MHz. In situations in which the suspended particles in water are not sufficient, as in the Tropics, the pulses may not hit enough particles to be able to produce reliable data. On the other hand, in some cases bubbles in turbulent water or schools of swimming marine life may be the cause of instruments' miscalculations.

The ADCP is not able to measure the flow very close to it and there is a maximum reach of its capabilities to measure correctly. Typical measurement ranges of ADCPs commonly used for wave study purposes vary between a 0.6-2.5 m (minimum) and a 60-150 m (maximum). This depends on the instrument working frequency and on the environmental conditions, including temperature, salinity and ocean backscatter. Minimum profile resolutions may go from 5 cm up to 25 cm. Working frequencies range between 300 kHz and 1200 KHz, typically depending on the deployment depth, i.e. on the intended measuring range.

The main purpose of the ADCP pressure sensor is to measure the mean water depth, so that the orbital velocity measurements may be accurately translated to the surface. A secondary purpose is to provide a second redundant measurement of the non-directional wave statistics. Typical ranges are around 2000 m, with ±5 m accuracy.

4.3.3 Method of Operation

ADCPs used in wave measurements are bottom-mounted, requiring anchoring, batteries and an internal data logger. They are typically mounted in a weighted PVC cage, tethered with a lanyard and featuring a multi-mode recovery system. When the deployment depth is not suitable for conventional SCUBA diving or the use of the snag-line, recovery may be accomplished via the release of a buoyant vinyl float with a line attached, activated from the surface. An additional time-out release back-up system is typically recommended for deep deployments.
Generally, ADCPs have no external read-out, so the data must be stored locally until the device is recovered. The data may then be manipulated on a computer. Several software programs designed to work with ADCP data are available.

ADCP calibration procedures include determining the orientation of each transducer with respect to the bow and the compass calibration. The compass calibration algorithm corrects the distortions caused by the different magnetic signature of each new battery to produce an accurate measurement. Non-negligible divergences between orbital velocity wave spectra and pressure or surface track spectra may be associated to pressure sensor malfunctions. Long submerging periods associated with constant pressure sensor depth readings larger than the surface track depth may imply that the pressure sensor has drifted and needs to be zeroed at the surface again. An offset in the pressure measurement does not significantly affect the pressure spectrum but it does have an immediate effect on the orbital velocity spectrum, given that the positioning of the velocity bins below the surface is determined by the mean water depth measured by the pressure sensor.

4.3.4 Specific Devices

Teledyne RD Instruments manufactures some of the most well-known acoustic profilers. Workhorse Sentinel, Figure 9a, is one of the most popular Teledyne RDI Instruments' ADCPs. It has a 20º angle, 4-beam convex configuration and features the ability to transmit real-time data to shore via a cable link or an acoustic modem. Alternatively, data can be stored internally for short or long-term deployment. The long white cylindrical pack below the transducers head accommodates a 400 Wh battery. The available versions include 300, 600 or 1200 KHz working frequencies, which corresponds to 165 m, 70 m or 24 m ranges respectively.

The Sentinel V ADCP, shown in Figure 9b, is another product from Teledyne RD Instruments and differs from the Workhorse Sentinel by integrating a 5th beam. This provides a third vertical velocity measurement and a 5th range to the surface measurement, allowing for enhanced wave measurement and error checking capabilities. It is available in 20 m, 50 m and 100 m profiling ranges and holds the capability of high-speed wireless data download.

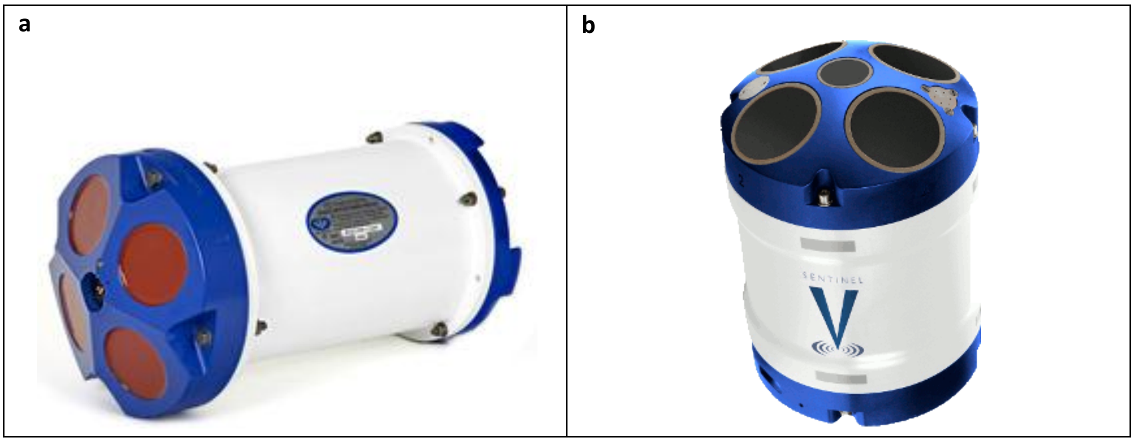


Figure 9: Teledyne RD Instruments a) Workhorse Sentinel and b) Sentinel V ADCPs.

The AWAC manufactured by Nortek, Figure 10a, features 4 beams (one vertical, three slanted at 25°) and uses the Acoustic Surface Tracking (AST) method to derive wave parameters based on time series analyses. It is available in 400, 600 or 1 MHz working frequencies, to which correspond 100 m, 60 m or 35 m ranges respectively.

The Aquadop (Figure 10b), also produced by Nortek, is an acoustic current meter that may be configured to burst sample velocity and pressure at 1 Hz in order to produce directional wave measurements. This method, known as the PUV measurement method, is most suitable for shallow water deployments (typically from 2 m to 10 m).

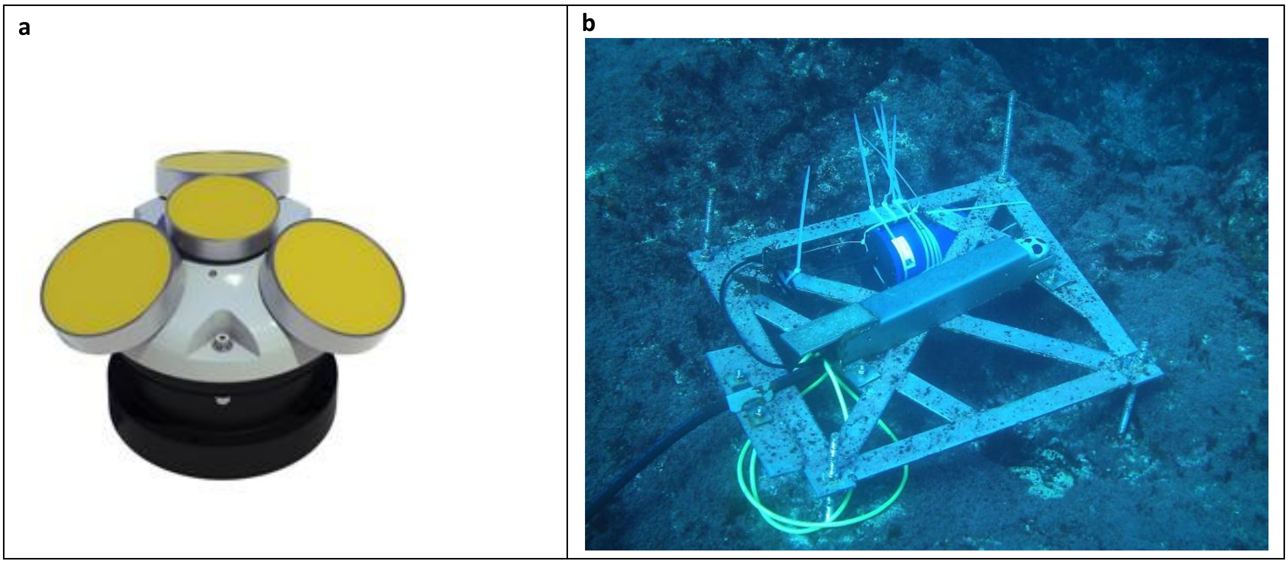


Figure 10: Nortek's a) AWAC and b) Aquadop deployed off the Pico (Azores) OWC plant.

4.3.5 Considerations

One of the greatest advantages of acoustic profilers when compared to directional wave buoys is that they operate with less risk of loss or damage. Besides 2D wave spectra, the ADCP also holds the capability of measuring velocity profiles of the mean flow and water level. The spatially distributed nature of the time series from which the wave characteristics are derived give the instrument some of the advantages of a pressure array with simpler logistics and lower depth limitations. One other advantage is that no moving parts subject to biofouling are used. Since it is an acoustic instrument, it contributes to noise pollution in the ocean, which may imply a certain degree of interference with cetacean navigation and echolocation, depending on the frequency and power of the instrument.

4.4 Radar

The difficulties relating to the deployment of in-situ sensors into a harsh marine environment which are inherent in the wave measuring techniques most commonly used can largely be avoided through the use of remote sensing techniques. Such remote sensing techniques also typically have the benefit of providing spatial distribution of wave measurements in contrast to the single point measurements of most in-situ techniques. While satellite observations represented the earliest methods of wave remote sensing, recent developments in land based remote sensing of waves by radar show promise.

4.4.1 Operating Principles

There are two different approaches for measuring waves using radar, namely high frequency (HF) radar and X-band radar. The HF radar systems [frequency O(10-50 MHz)] were originally developed to measure surface currents over a large spatial area and measurement ranges of greater than 100 km can be realised. Surface current detection is a relatively robust measurement, obtained by determining changes in the Doppler shift of the radar reflections which are Bragg scattered from surface gravity waves with half the wave length of transmitted radar signal (Figure 11).

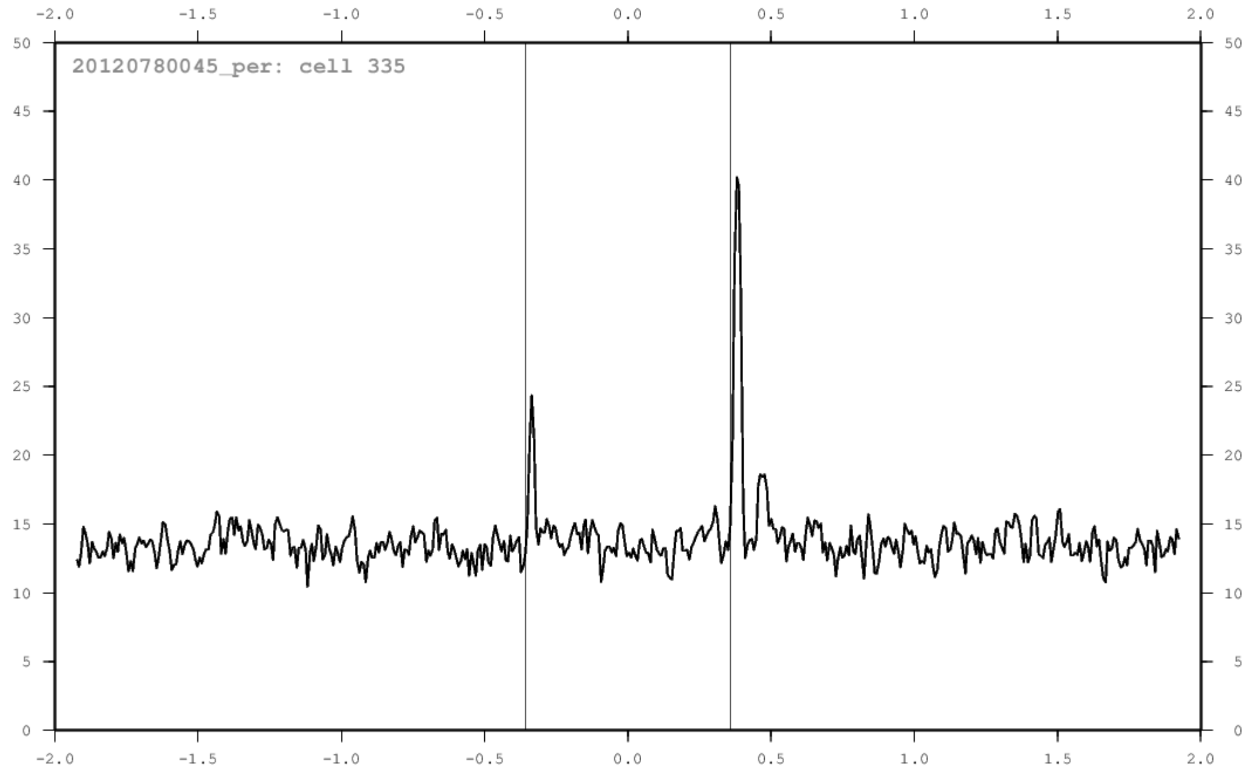


Figure 11: Plot of an observed spectrum of electromagnetic energy derived from the reflected radar signal which clearly demonstrates the energy peaks related to Bragg scattering. Vertical lines indicate location of expected frequencies for Bragg scattering and differences between the observed and expected frequency are proportional to the mean current. Spectral wave information is derived from the shape of the shoulders of the Bragg energy peaks.

Determination of wave spectral information is a 2nd order measurement which is derived from the shape of the spectra of the reflected energy. Since the wave measurement is derived from the reflection spectra, HF radar measurements represent time averaged measurements only. Due to the importance of the shape of the spectra, averages of at least 15 minutes are required. By using multiple sites which contain both directional transmit antennas and multi-element receive antennas, it is possible to estimate independent directional estimates over a large area (figure 12).

The so called X-band radar technique, which has reduced spatial coverage [O(km)] but enhanced spatial [O(m)] and temporal [O(s)] resolution, is based on devices which operate at standard navigation radar frequencies [O(10 GHz)]. Returns from these images give a representation of the instantaneous roughness of the sea surface and can be processed to provide wave spectral and directional information. Some success has been achieved in retrieving amplitude information through the application of empirical relations.

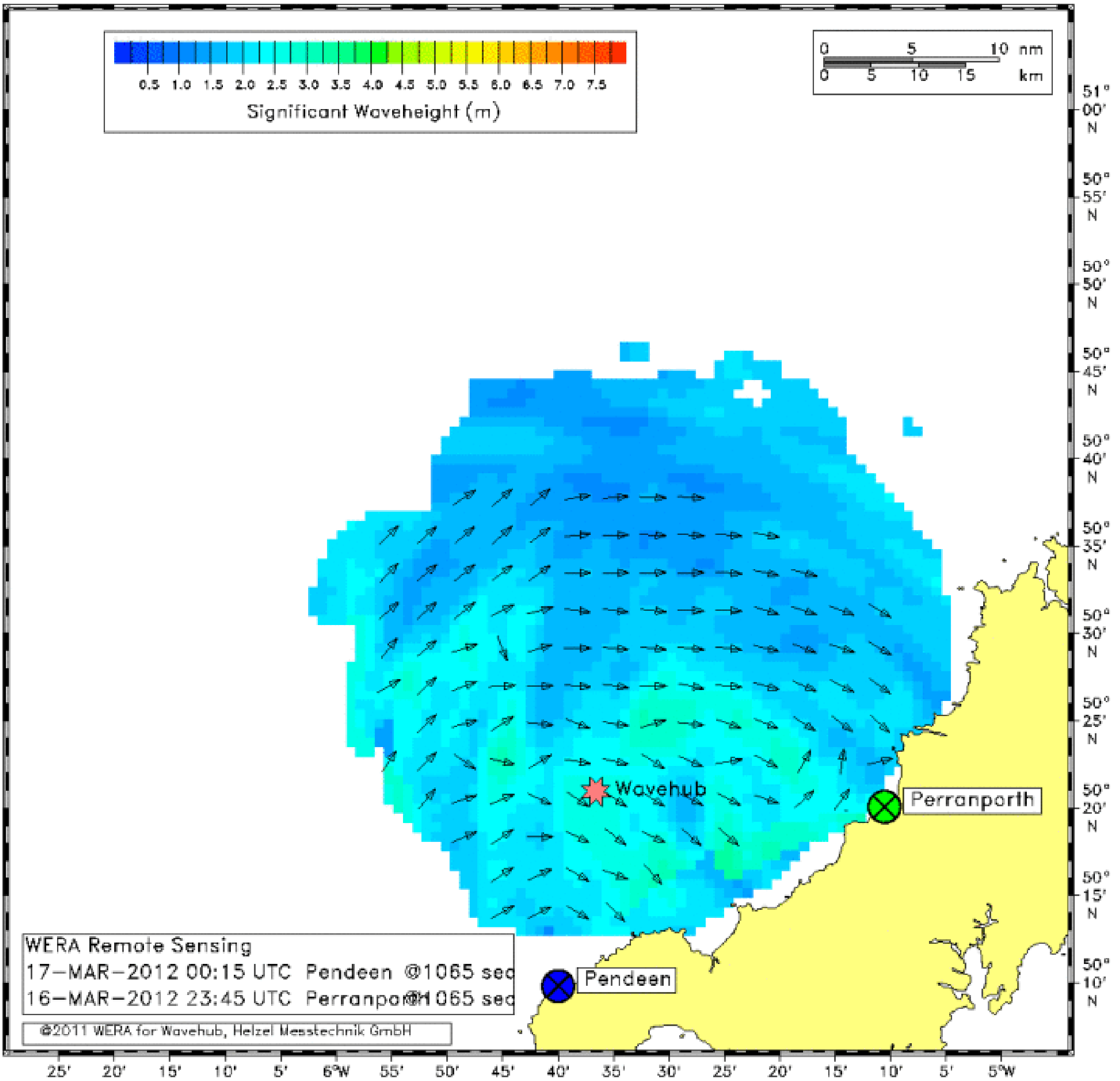


Figure 12: Example of spatial coverage available from HF radar measurements of waves. Colours indicate Hmo and arrows indicate peak direction.

4.4.2 Fields Measured

HF radar systems provide very good estimates of oceanic surface current magnitude and direction. All subsequent measurements are largely second order accuracy and include multiple estimates of parametric wave fields such as H_s and T_p, complete estimates of directional wave energy spectra from which most other parameters can be calculated and estimates of wind speed and direction.

4.4.3 Specific Devices

A number of commercial HF radar systems have been developed. The characteristics of the three systems most used are presented in Table 3.

MAKE	Frequency	Range	Spatial Resolution	Temporal Resolution	Comments
WERA HF Radar	5-50MHz	65-110 km @8MHz 30-15 km @16MHZ 15-30 km @30MHz	250 m (short range applications).	15 minutes	12-16 linear receivers installed onshore. Wave height and period could be determined form a device only.
SeaSonde	4.3-45MHz	140-220 km @5MHz 20-75 km @20MHz 15-20 km @40MHz	200-500 m (short range applications)		Antenna mounted onshore or offshore requiring 350-550 W power. Transmitting requires 80W at peak and 40W on average
Pisces	6-40MHz	150 km @10Mhz	750 m- 20 Km	5 minutes	

Table 3: Some examples of commercial high frequency radar systems.

4.4.4 Considerations

HF radar installations generally represent a steep up-front investment for purchase and installation. However maintenance and operational costs are minimal in comparison to operations at sea. Such systems are particularly attractive when multiple measurements or complete spatial coverage in the area of interest is desired. Finally, due to permanent terrestrial connection to power grids and communication networks, such systems are typically more reliable than sea based alternatives.

4.5 Satellite

4.5.1 Operating Principle

Satellite-based wave measurement differs significantly from the previous technologies discussed due to the extensive spatial coverage it provides. Two types of satellite-borne remote sensors are used for wave measurement: radar altimeter and synthetic aperture radar (SAR). These are discussed below, and further detail can be found in Krogstad and Barstow (1999). As the satellites orbit the Earth, wave measurements are taken along a track below their orbit. However, the width of the track limits the spatial resolution, and the temporal resolution is defined by the satellites' repeat cycles, i.e. the length of time until they return to a track, often many days (see Figure 13).

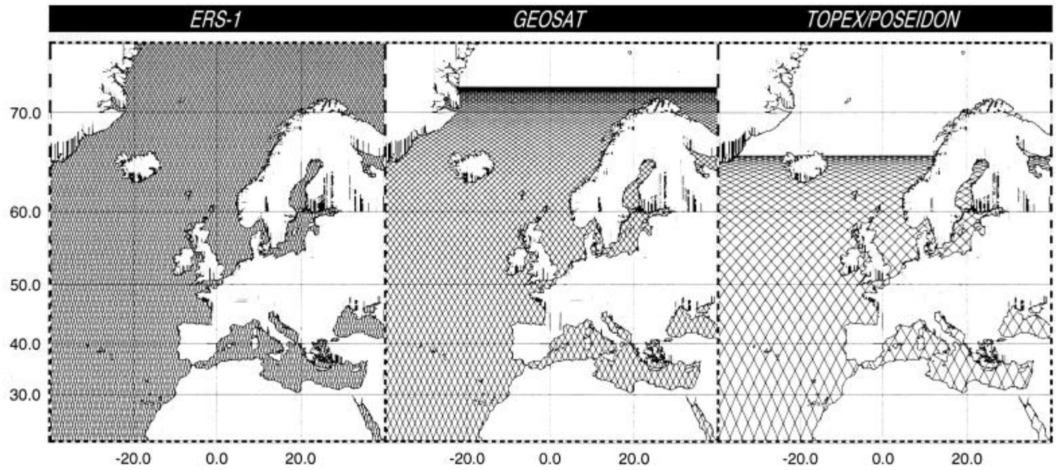


Figure 13: Satellite tracks from three missions for Europe and the north-east Atlantic. The wider the track spacing, the shorter the time interval between repeat cycles (from Krogstad and Barstow, 1999).

4.5.2 Fields Measured

4.5.2.1 Radar Altimeters

Radar altimeters measure the range from the satellite to the sea surface within a few centimetres accuracy, and this allows the significant wave height over the footprint of the radar (a few km) to be calculated. However, care must be taken with the quality control and calibration of the processed data. Values can be calibrated against in-situ measurements from instruments such as wave buoys to improve their accuracy, using a calibration relation of the form $H_{scorr} = aH_s + b$ (Krogstad and Barstow, 1999). It is also possible to derive wave periods from altimeter data; however research into methodologies is still on-going.

4.5.2.2 Synthetic Aperture Radar (SAR)

SAR is the only satellite-borne sensor able to measure the directional characteristics of wave fields. It produces high resolution images of the sea surface from which directional spectra can be derived using a defined transform. However, the resolution of the instruments limits observations to waves longer than approximately 50m (corresponding to 5.7s period in deep water).

4.5.3 Method of Operation

4.5.3.1 Radar Altimeters

Radar altimeters emit high frequency pulses vertically downward to measure the range to the ocean surface. The roughness of the sea surface, caused by surface waves, leads to backscatter in the pulse. The amount of distortion in the leading edge of the return pulse relates to significant wave height over the radar footprint, and the wind speed can be found from the strength of the backscatter signal. The spatial resolution of altimeter data is generally no better than 7km. For coastal data, valid results are only obtained when the satellite approaches the land from the sea; when passing from land to sea, the first few measurements are often missing or biased.

4.5.3.2 Synthetic Aperture Radar (SAR)

SAR produces high resolution images of the sea surface from backscattered radiation across swaths along its tracks. Swaths are typically 100km wide, and typical spatial resolution for SAR images is approximately 30m, with accuracy to 0.2m for significant wave height (ESA Earthnet Online, 2012). The images produced are not true surface images; they must be operated on with complex SAR-to-wave algorithms to produce a directional wave spectrum in the approximate period range of 8-25s. This limits the use of SAR in many cases to swell observation.

4.5.4 Specific Devices

Successful satellite missions that have collected long-term wave datasets are listed in Table 4. Currently operating satellites include Envisat (launched 2002) and the Topex/Poseidon follow-ons Jason-1 (launched 2002) and Jason-2 (launched 2008) (Cruz, 2008).

Satellite name	Operator	Instrument type	Repeat cycle	Dates
Geosat	US Navy	Radar altimeter	17 days	1985-89
ERS-1	ESA	Radar altimeter/SAR	35 days	1991-96
Topex-Poseidon	NASA/CNES	Radar altimeter	10 days	1992-2005
ERS-2	ESA	Radar altimeter/SAR	35 days	1996-2003
Envisat	ESA	Radar altimeter/SAR	35 days	2002-date
Jason-1	NASA/CNES	Radar altimeter	10 days	2002-date
Jason-2	NASA/CNES	Radar altimeter	10 days	2008-date

Table 4: Previous and ongoing satellite missions that have collected long-term wave data (Cruz, 2008).

4.5.5 Considerations

The temporal resolution due to repeat cycle periods and the limited tracks make satellite measurement less-suited to short-term, site-specific measurement such as marine renewable resource assessment studies. However, the long-term datasets provided play a key role in determining ocean-scale sea state variability, and as such may prove useful in identifying trends in the wave climate for a particular site, and benchmarking shorter-term measurements against long-term trends.

5 TYPES OF TANK MEASUREMENT EQUIPMENT

The MaRINET consortium also includes a wide range of tank based test facilities that are used for testing Wave Energy Convertors (WECs). At these facilities the wave climate is primarily measured to aid devising design at the lower technology development levels.

5.1 Conductance Probes

5.1.1 Operating Principle

Conductance probes are arguably the most common water surface elevation gauge and are present in all types of hydraulic laboratories. The instrument is a simple, robust device that works on the principle of measuring a current flowing between two parallel stainless steel rods. The probe is energised with a high frequency square wave voltage that minimises polarisation effects. The rods dip into the water and the current that flows between them is proportional to the rod's wetted surface. The amperage signal is fed into an associated conditioning box to be converted into a varying voltage relative to the wave height.

The standard form of the probe is two 3mm SS rods placed 12.5mm apart, as shown in Figure 14. The rod length can be selected to suit the facility, or wave generation capabilities. Other basic constrictions are possible. When probes are used in close proximity to each other it is necessary for them to be energised at different frequencies to avoid interference.

Figure 14: Wave Probe

5.1.2 Fields Measured

The range of this type of probe depends on the physical size of the wires. Several different scales are available to suit the hydrodynamic facility's wave generating capability. The absolute accuracy of conductance probes is a direct function of the full scale measurement and the type of analogue to digital converter incorporated in the data acquisition system. With modern 12bit (and above) A-D units, (i.e. 4096 unit resolution) accuracy is rarely a problem with this type of sensor.

5.1.3 Method of Operation

A fixing frame is always required with this type of gauge. This must be a sturdy structure to prevent movement and vibration of the probes. In large deep water facilities a mobile carriage is commonly used. The rods, connecting block and metered vertical bar are then fixed to the frame.

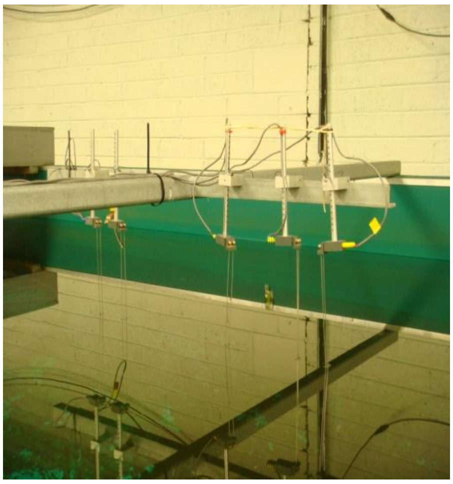


Figure 15: Fixing Frame

One or more wave probes may be deployed, depending on the type of wave measurements to be made, see Figure 15. A single probe can only furnish the water surface vertical movement at the measuring station, that is, all the combined wave systems present in the tank. Multiple sensors strategically place can provide sufficient signals to be analysed for both incident and reflected waves. If radiated waves are also present it is more difficult to separate these out.

The recommended MaRINET practice would be to install the probe, or probe array, at the mobile test station prior to mooring the model to obtain the uncontaminated wave measurements, both monochromatic and panchromatic. Depending on the number of probes deployed, the incident and reflected seaways can be obtained.

If real time records are also to be taken there can be an advantage if the probes are movable, transversely and, more importantly, longitudinally. This can help accommodate any extreme surge or sway present in moored type devices.

The usual practice when installing wave probes is to immerse the rods to half their length. This can be adjusted if storm seas are to be the main seaways under test since they are not symmetric about still water. In this instance the freeboard may be slightly greater than the draft of the rods to physically protect the connection block. At the static SWL datum a balance gauge on the conditioning box is set to zero. This adjusts the electronics such that the full immersion is equivalent to 10 volts.

The probe may now be calibrated for water surface level to output voltage as follows. The rods are raised and lowered by a fixed, known amount through the water surface and the corresponding change in voltage output noted. The operation is facilitated by means of the metered bar which has a series of holes drilled along its length, accurately spaced at 10mm. A pin is used to secure the probe at each hole in the bar and the corresponding voltage output noted. A graph of the readings can be produced, as shown in Figure 16. From this the volts per mm immersion are obtained and this calibration value can be incorporated into the data acquisition program such that a direct wave height is produced in the file.

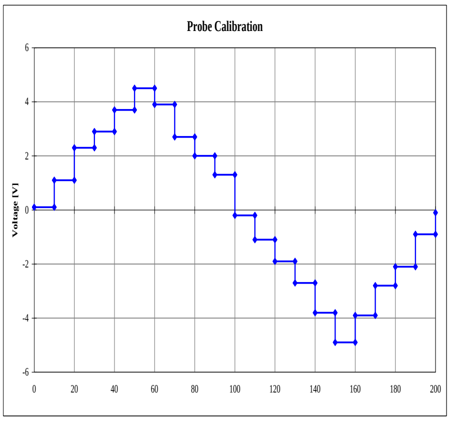


Figure 16: Calibration

It is important to regularly verify the calibration figures since changes in the water mass electrical conductivity will affect the readings. This is usually caused by temperature variations in the laboratory so, to minimise the need for re-calibration, this should be stabilised. Also, in large tanks the water has high thermal capacity so the temperature will have low variance in the short term. Changes in water depth are best compensated for in the zero off-set in the data acquisition software. If the conditioning box balance gauge is moved the whole probe settings are in error and the calibration procedure must be repeated.

5.1.4 Specific Devices

There are several manufacturers of conductance probes and the ancillary equipment that is required to operate them. One of the most well-known companies is Churchill Controls. There are also online resources that describe how to make resistance type probes, including the conditioning electronics required to convert the current modulation to a voltage change representative of the water surface elevation profile being measured.

5.1.5 Considerations

There are a number of benefits realised when using this device. Conductance probes are easy to calibrate and use and are easy to handle due to their size and weight. In addition to this, they are robust and are also available in various sizes to match different applications.

However, there are also some negative aspects involved with the use of conductance probes. Regular calibration is required to ensure accuracy, the mounting frame needs to be static to avoid errors and a signal conditioning box connected to the voltage based data acquisition systems is required. In addition to this, accumulation of material at the water surface can affect the flow of water around the rods and must be avoided. Thin films of contaminants, such as oil, will have a serious detrimental effect on performance and must be avoided. Water conductivity changes must also be accommodated, but this is only a real consideration in small tanks.

5.2 Capacitance Probes

5.2.1 Operating Principle

Since water is a conductive surface, the combination of the water and the sensor can be treated as a capacitor.
Generally, capacitance is defined with respect to the ratio of the conductor areas in contact with the dielectric. In the case of the capacitance gauge, the area of the conducting core is constant for a given wire but the area of the second conductor, the contact area of the dielectric with the water, varies with wave height (see Figure 17). This area is linearly dependant of the immersion of the wire (h), for a constant wire diameter.
When a wave is passing, the variation of the wire immersion is generating a variation of capacitance which can be measured by the electronic box.

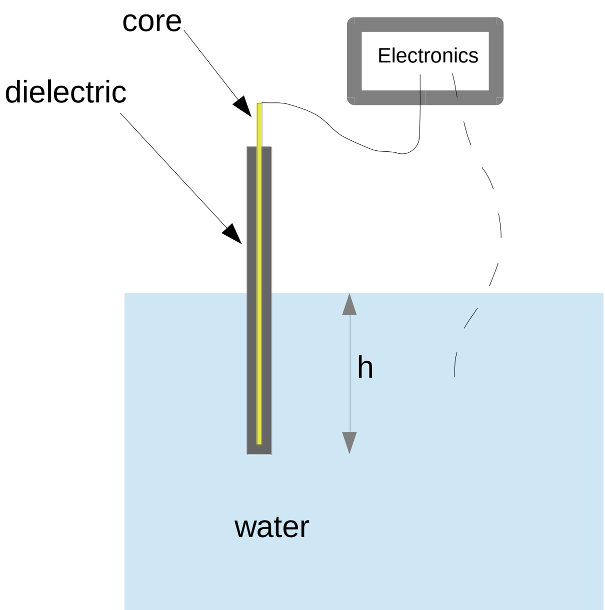


Figure 17: Sketch of a capacitance probe in the water

A capacitance gauge is made up of two main components: the sensor itself and the electronic box which delivers a suitable signal to the sensor. The sensor consists of a thin insulated wire, held taut in a vertical position by a supporting frame which passes through the surface of the water, as shown in Figure 18. The core of the wire has high electrical conductivity and is completely insulated from the surrounding water. The insulation layer is a dielectric material with a very high permittivity. In most cases, the core is made of copper and the dielectric is Teflon (PTFE). Care should be taken to get an accurate insulation of the submerged wire end: some coating has to be put on the tip.

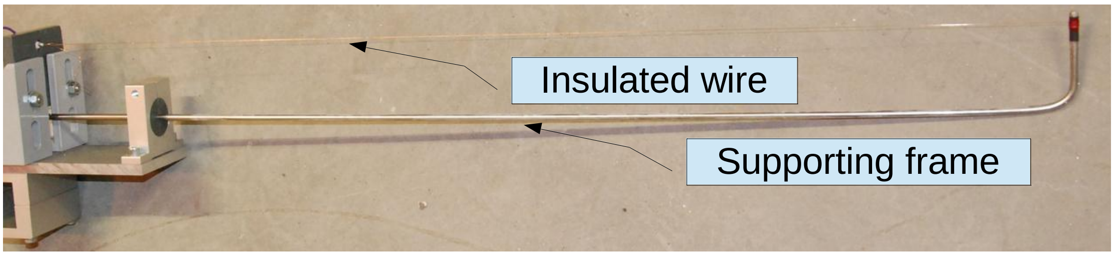


Figure 18: Picture of a in-house developed capacitance wave gauge (ECN).

A coaxial cable is used to connect the sensor to the electronic box dedicated to the signal conversion, filtering and amplification. It can be noted that the water is in fact a ground of the system with a constant, and null, electrical potential. It implies then some electrical circuitry does not require a physical link between the water and the reference potential of the electronics. The capacitive wave gauge can then consist of a single wire.

The electronics are used to determine the variation of the sensor capacitance and to convert the variation into analogue voltage signals. This signal can then be logged according to the needs of the activity.

The measurement of the capacitance is performed either by analogue or by fully digital circuitry. The capacitance is assumed to vary linearly with the immersion of the wire so the electronics must be adjusted to provide a linear output. The temperature must be held constant in order to keep a constant sensitivity for a given wire (total length, nature and thickness of the insulation, diameter of the wire).

The operator can usually adjust several parameters according to the objective of the tests:

- The capacitance range has to be adjusted to the total length of the wire giving then the larger admissible range of measurements.
- Filters, both threshold and cut-off frequencies, may be adjusted to remove potential electromagnetic noises.
- The offset of the signal, zero level, can be tuned to the initial immersion of the wire.
- The output gain (sensitivity in mm/V) is tuned with respect to the expected wave height.

5.2.2 Fields Measured

Capacitance probes are similar to conductance probes as they give point measurements of wave fields. It is then necessary to locate several probes in an array to describe directional wave patterns.

The output of a capacitance gauge being linearly dependant of the wave height, its signal is convenient to be implemented easily in algorithms or command & control loops (PTO's, etc).

The unique taut wire makes it convenient to directly mount capacitance gauges on the models in order to measure wave run-up, internal motion of fluids etc., without perturbing the flows. In this case the supporting rod is not needed and the wire is taut directly along the chosen surface at a short distance; several millimetres as minimum.

5.2.3 Method of Operation

The capacitance wave gauge has to be calibrated first, using the accurate wire length and adjusted electronic parameters. As seen on Figure 19, several probes can be easily calibrated on the same time mounting them on a vertically moving frame, either continuously or step by step. Signals from the probes are logged instantaneously with the immersions and the slopes of the curves indicate the sensitivity. Dynamic calibration of the vertical motion may also be useful to check the dynamic bandwidth of the electronics. Once calibrated the gauges keep their sensitivity for several days as long as the electronics are accurately designed. They have to be carefully installed in the wave tank to measure the waves.

5.2.4 Specific Devices

Many laboratories are developing their own capacitance probes according to their research domain, including: CNR-INSEAN, LUH, Artelia and ECN. Some of these laboratories also produce these devices for commercial distribution. Some companies are publicly selling capacitance wave gauges, among other, the main ones are RBR Ltd and Akamina Technologies Inc.

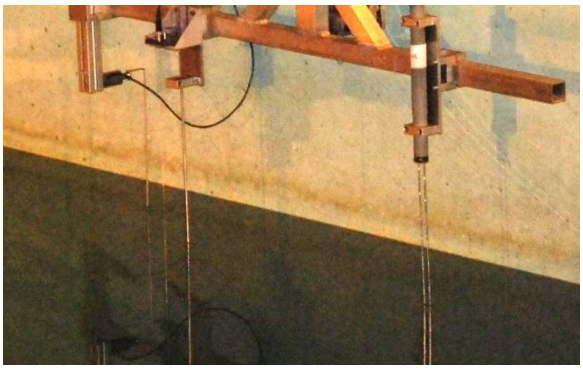


Figure 19: Three wave gauges on a calibration frame: on the right a regular resistive wave gauge (2 vertical rods) and on the left two different capacitive wave gauges.

As an example, on the left of Figure 19, two capacitance wave gauges are installed on a calibration frame at Ecole Centrale Nantes. Two different electronics are connected to these gauges and compared to the behaviour of a resistive wave gauge, seen here at the right hand side of Figure 19. The thin active wire of each capacitance gauge is hardly seen on the picture instead of the supporting rod.

5.2.5 Considerations

When the capacitance gauges have only one vertical wire piercing the water surface, the following advantages are realised:

- Minimal obstruction to the wave front
- Minimal distortion of the wave shape
- Calibrations of capacitance gauges, gain and offset, are stable with time and roughly not drifting
- This probe is effective in both fresh and salt-water, making it suitable for both tank testing and field measurements
- The signal output is linear even for a long wire, allowing their use for large wave height measurements.

However, there are some conditions that may be considered as disadvantages. At least they must be assessed with regards to the objectives of the tests.

- The insulation layer must have a constant thickness along the length of the wire in order to ensure a linear variation with immersion. Particular care should also be taken to avoid any breach of the insulating layer: it would first generate electronic noises and unexpected capacitance variation but it would also generate a slow corrosion of the wire core which would affect efficiency of the gauge.
- The wire needs to be efficiently taut but it could be still vibrating under large waves.
- The use of electronic filters may lead to introduce unexpected delays and changes in phase signal. This delay has to be carefully determined when the sampling frequency is over 30 - 40Hz and / or if time-domain analysis is performed on co-located probes.
- The low tension electrical power of the electronics has to be delivered at a high standard in order to keep the electronics at a constant voltage.

5.3 Wave Slope Optical Wave Gauges (WSOPG)

5.3.1 Operating Principles

Optical Wave Gauges (OPGs) are generally non-intrusive, which allows them to be used for even the smallest and steepest waves, whilst still being applicable to waves in the usual gravity wave range. Most of these systems rely in some way on LASERs. One of the first such applications to characterise wave fields relied on the Light Detection and Ranging (LIDAR) technique. A typical LIDAR system consists of a LASER source and a photo sensor. The system is located above the water surface with the LASER beaming vertically downwards. Some of the LASER light is scattered by the water surface and bounces back towards the source where it is collected by the photo sensor. The distance between the LIDAR system and the water surface is derived from the time taken by the LASER light to travel from the source to the water surface and back, providing a time history of surface elevation. LIDARs have often been used for field measurements over large areas by mounting them on planes or satellites.

Another technique that uses LASERs to characterise wave fields measures the wave slope by exploiting the difference in refraction index between air and water. A LASER source is located below the water surface and is beaming vertically upwards. As the beam reaches the air-water interface, it is deflected from vertical according to Snell's law. The deflection angle is a function of the water surface angle to the vertical and of the ratio of the water refraction index to that of air. The deflected beam is collected above the water surface by an aspheric lens which focuses it on a photo detector. The lens is designed in such a way that the distance of the resulting LASER spot on the photo detector plan to the optical axis is proportional to the beam angle of incidence onto the lens. This technique does not actually measure wave height but wave slope. It is mainly used for spectral analysis of small waves such as capillary waves. Although this system does not directly interfere with the water surface where the slope is measured, it is still intrusive in that it requires the laser source to be located at some depth below the water surface. Recently, an alternative approach based upon optical triangulation has been developed. In such a system, all components are located above water so the system is truly non-intrusive.

5.3.2 Method of Operation

A Laser beam is pointed vertically downwards at the water surface. Where the laser beam meets the water, the beam generates a spot of scattered light prolonged by a line of scattered light below the water surface. These are imaged off-axis by a digital camera in a fixed position relative to the laser, as shown in Figure 20 andFigure 21. The spot position is extracted from the image and then transformed into a height value using a polynomial best-fit function established by an initial calibration. Figure 22 shows a laser triangulation system installed in a narrow wave flume.

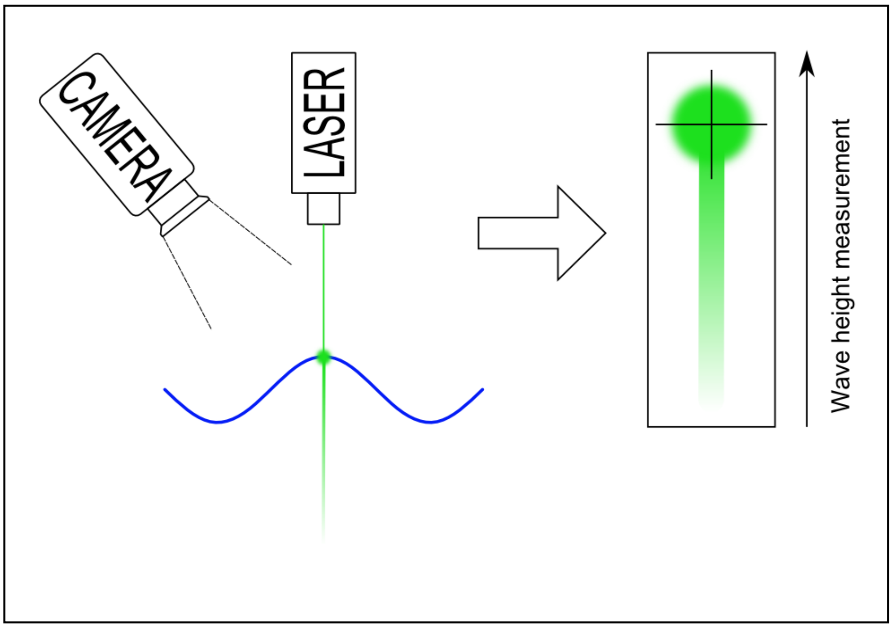


Figure 20: Spot Image at Wave Peak

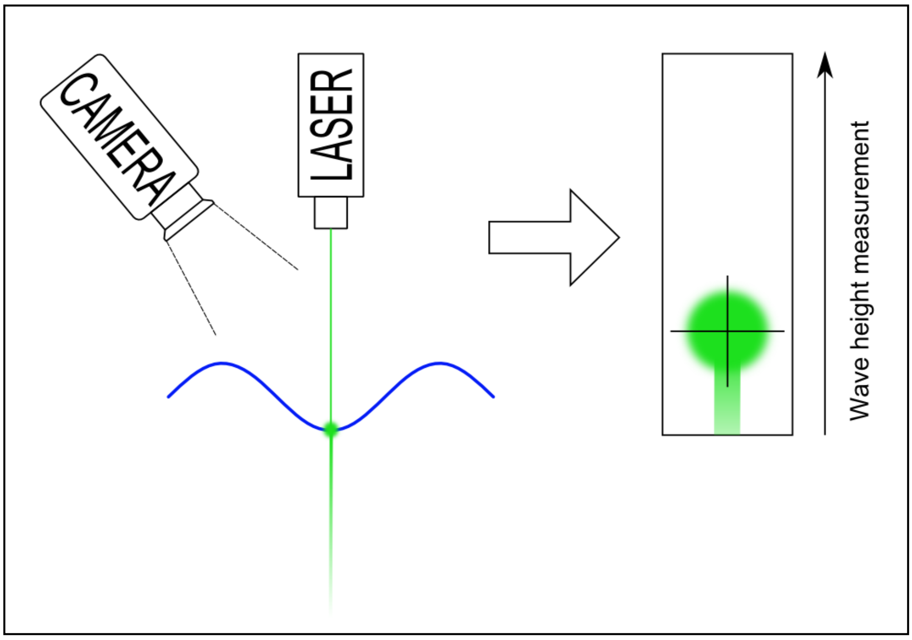


Figure 21: Spot Image at Wave Trough

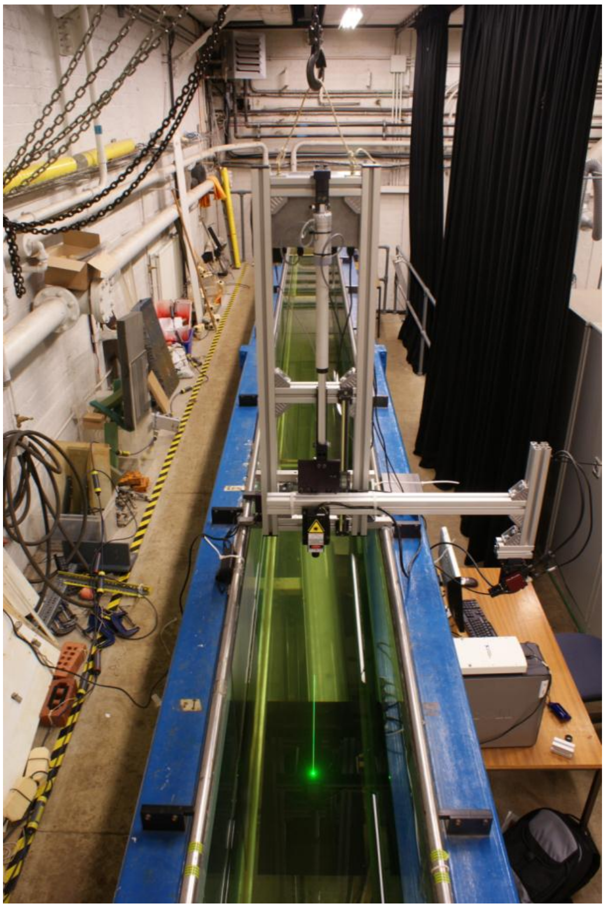


Figure 22: Optical Triangulation Wave Gauge in use

5.3.3 Fields Measured

Optical gauges are generally single point instruments which can measure wave height and period to sub mm accuracy and are not prone to the distortions due to the meniscus effect that can cause hysteresis in wire probe type devices. In principle, they can be used in a multi-point or scanning more to cover a surface. The limitations on this have yet to be investigated thoroughly but it is anticipated that there will be tests on this practice within the Marinet programme.

5.3.4 Specific Devices

These devices are still at the developmental stage and being used in laboratories such as the University of Edinburgh. As yet no commercial systems are available.

5.3.5 Considerations

Although the OPG is still a technology in the initial stages of development, it is already demonstrating some very significant benefits in wave tank applications, such as:

- Non-contact
- Wave elevation measured at a precise location
- Adjustable resolution as a function of range
- sub-millimetre accuracy over 300mm typical
- Straightforward and durable calibration

5.4 Video

5.4.1 Operating Principle

A standard system for monitoring motion in wave tanks is the optical, infra-red, digital camera as shown in Figure 23. Although usually employed to track the movement of floating bodies the system can be used to monitor water surface elevation. Active, or passive, reflective markers are attached to a body and their location continuously recorded by the system. A marker can similarly be affixed to a buoyant, surface following buoy, thereby measuring the wave profile time history.

For the passive marker methods the camera emits a pulsed infra-red beam which is reflected back to the camera lens, an array of infra-red sensors. The marker position in 2-dimensional space is thus recorded. When more than one camera is deployed the associated software converts the 2-dimensional location into a 3-dimensional image. The longitudinal, transverse and vertical (x, y, z axes) position of each marker relative to a global co-ordinate system is recorded. If more than three space related markers are used, a rotational matrix algorithm can be activated to obtain the six degrees of freedom of a body. If only one transverse motion is possible the marker time series can be obtained directly from one marker.

Figure 23: Digital Camera

5.4.2 Fields Measured

As with most wave probe type sensors the video system measures the water surface elevation at one station as a time history. This signal can then be analysed using either time or frequency domain methods to obtain the wave characteristics. In the case of regular, monochromatic waves this can simply be the wave height and period. For irregular, panchromatic seaways the full spectral profile (frequency composition) can be obtained from which the summary statistics can be generated (H_{m0}, T_e, T_p, T_z etc). Since one buoy can only measure at one station it is not possible to separate the incident and reflected wave systems.

The accuracy of a digital video camera and associated software is a function of the measuring volume which in turn is related to the distance of the camera from the object and the lenses used. In older systems this was an important consideration but newer motion measuring hardware has more pixel resolution which overcomes this drawback. It should be noted, however, that the measurement volume is set during calibration and, although the viewing volume can be operator adjusted to suit individual test programs this will not affect the actual level of measurement accuracy of the cameras.

5.4.3 Method of Operation

As with the other types of wave gauges there are two fundamental ways to use this method of water surface tracking. Firstly the marker buoy can be located independently at the selected device deployment station in a wave tank (basin, flume of tow tank), as shown in Figure 24, and prior to model instillation. The combined incident and reflected waves at that particular site will then be registered as a digitised water surface elevation time history. These will be the wave forces exciting the later deployed scaled device but cannot be separated into the individual components.

Alternatively, the marker buoy can be located at a selected station to monitor real time waves during test runs. The marker should be positioned in the far field such that contamination of the surface profile from model radiated waves will be minimised. They will however, be present, as will downstream beach reflections, so the marker record should only be used as a guide to the actual energy input calculations.

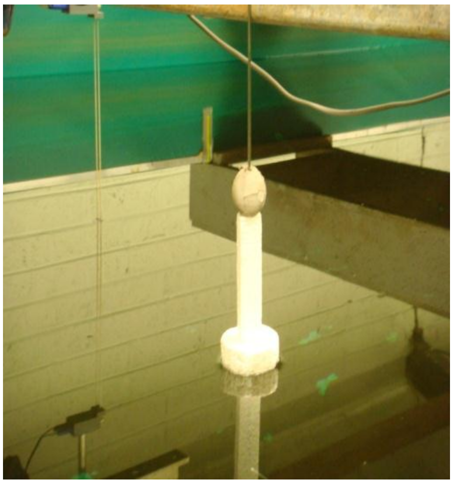


Figure 24: Marker Buoy

To keep the buoy and marker on station and restrict the motion to heave only (vertical translation) they are threaded onto a wire line, or stiff rod, as shown in Figure 24. It is important that the buoy has no motion response characteristics, such as resonance, and that it follows the water surface with acceptable fidelity.

The advantage of using the camera based system is that if body motions are the only parameters being measured during device trials only one data acquisition logging computer is required. It should be noted, however, that motion only records are rare.

Motion monitoring camera systems are supplied with special calibration frames. Before the system is activated for actual test runs the whole unit must be pre-calibrated. Once this has been conducted, however, the system should be stable for a reasonable period of time, providing the camera locations relative to each other do not change. They can be moved, relocated or re-oriented if the absolute distance between individual cameras remains the same.

An accurately manufactured 3-dimensional space frame with strategically placed reflective markers is deployed in the measurement zone. It is convenient to locate this such that the global reference axes provide a suitable origin. The global co-ordinate system can be seen as the larger axes in Figure 25. A corresponding marker location file is referenced by the software and the pixel size fixed. The accuracy of the system is a function of the monitoring zone, which in turn is related to the distance from the camera to the object. The total view zone must be selected to ensure a sufficiently large water surface is covered by the calibration.

Following the static calibration a dynamic check is made across the monitoring zone. A metered wand is also supplied with the hardware. Two reflective markers of accurately known separation are fixed on this bar. These are moved throughout the measuring zone at any orientation and attitude and at differing speeds. A software program calculates the instantaneous marker relationship to each other and calculates the statistical error.

It would be recommended that the camera-buoy water surface elevation system is then checked simultaneously against a standard wave probe record.

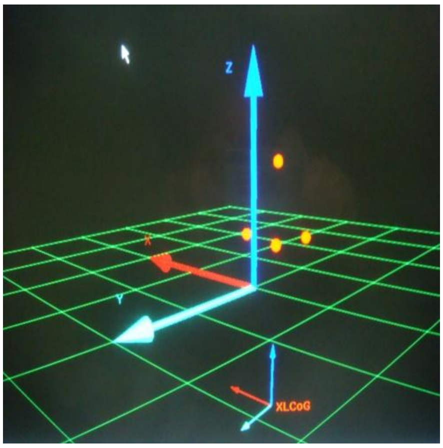


Figure 25: Calibration

5.4.4 Specific Devices

There are several companies manufacturing non-contact, remote motion monitoring systems. Most concentrate on the medical field or, more recently, the film and computer game industry. Most digital camera sets can be adapted for hydraulic laboratory use but a few companies, such as Qualisys of Sweden, specifically target maritime application. Probably the key issue when selecting a particular manufactures product is whether passive or active markers are used.

Passive makers are specially coated spheres that reflect an active infrared pulse emitted from the receiving cameras. A drawback of this type of approach is that if two markers cross in the cameras view the 3D conversion software can lose identity of the markers. A second approach is to use active markers and passive cameras. There are usually small LED emitters that are attached to the body to be monitored. Associated software can ensure this type of marker is never confused. The disadvantage is that a connation block is required for each LED and this can be relatively heavy for small scale models. Also, battery life can be limited when button cells are used to restrict weight. Finally, being of small diameter almost anything (electrical cable, bungee support) can briefly block the light from the camera. This can lead to several gaps in the final signal record.

5.4.5 Considerations

There are some important factors relating to the use of video in wave measurement that must be taken into consideration. This system benefits from low power requirements and is immune to signal degradation due to water contact. In addition to this, no recalibration is required if properties of the water change (temperature for example), nor does a change in the water level affect readings. All of the motion data recorded by this system can be in a single file for ease of use. Since the recording system does not come into contact with the water, there are no meniscus effect upon the readings.

However, the marker buoy must not interfere with the wave profile, must not have resonance characteristics and must be designed in such a way that the reflective marker does not come into contact with the water. The recording system requires a reasonably solid deployment frame. Additionally, this system does not resolve different wave systems.

5.5 Acoustic Point Measurement

Many of the details and background of the theory relating to the use Acoustic Point Measurement for measuring wave characteristics is covered in section 4.3.

5.5.1 Operating Principle

The use of acoustic instrumentation in field conditions has become common with devices such as Doppler profiles being used for velocity profiling and echo sounders being used for bathymetry or even wave height measurements. All such devices rely upon the scatter of acoustic pulses off impurities carried in the flow. The Doppler shift in the echo allows a calculation of the velocity of the flow, assuming the impurities are accurately tracking the fluid motion. The instrument measures the fluid velocity at a point. Wave motion is then calculated subsequently assuming wave orbital properties of the flow.

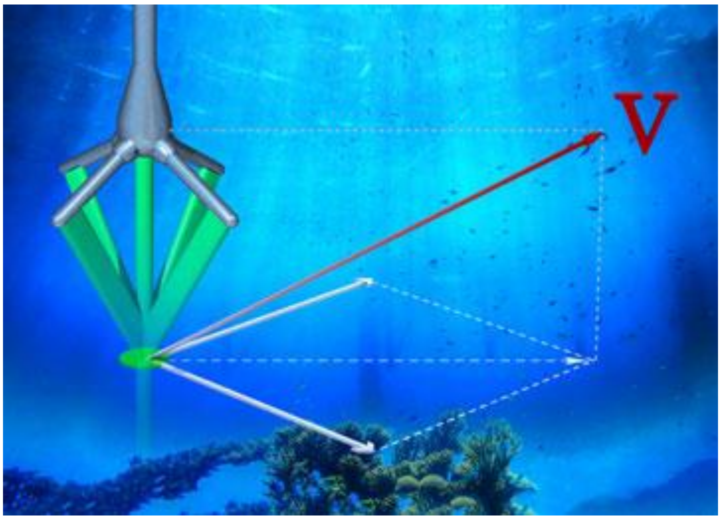


Figure 26: Schematic of the sampling volume in relation to the transducers

5.5.2 Fields Measured

Unlike the diverging beam profiler typically used in the field, a "point" measurement Acoustic Doppler device provides a spatial average velocity over a small volume measured typically in volumes less than a cubic centimetre.

5.5.3 Specific Devices

There are some highly robust flow measurement systems, such as the NORTEK Vectrino, as shown in Figure 27, which is very effectively used to make accurate velocity measurement under waves and in currents. This is a point measuring Doppler device which utilises the Doppler shift from acoustic pulses scattered of moving seed particles within a flow.

Figure 27: A NORTEK Vectrino Flow Measurement System

Figure 28 shows the acoustic head of a Vectrino, in which pulses are emitted from the central transmitter and scattered echoes are recorded in the multiple receivers allowing a three dimensional flow velocity signal to be determined at a nominal sampling volume measured typically in a few cubic millimetres. The sampling volume is located away from the sensor, as shown in Figure 26, to provide undisturbed measurements.

Figure 28: Vectrino head showing transmitter and receivers

5.5.4 Considerations

In enclosed environments such as flumes and basins, acoustic instrumentation can suffer from problems associated with reflection and reverberation.

5.6 Pressure Sensor

5.6.1 Operating Principle

Pressure sensors, also known as pressure transducers, can be used to measure the pressure of gases or liquids. There are many different designs of pressure transducers, varying with the applications and conditions that they are utilised in. Many pressure sensors are based on a piezoresistive silicon sensor. The stainless steel part is laser-welded to a stainless steel tube which contains the amplifier. The backside of the sensor is ventilated to the atmosphere so the measurement is relative to atmospheric pressure. Other sensors commonly use the piezoelectric effect in certain

materials to measure the strain on the mechanism due to pressure. Materials such as quartz, machined silicon and some ceramics exhibit this effect where a charge accumulates in response to applied stress.
Another types of pressure measuring instrument consists of two main parts, an elastic material which will deform when exposed to a pressurized medium and an electrical device which detects the deformation. The most common method of utilising the elastic material is to form it into a thin flexible membrane called a diaphragm. The electrical device which is combined with the diaphragm to create a pressure transducer can be based on a resistive, capacitive or inductive principle of operation.

The pressure sensor generates an electronic signal as a function of the pressure imposed by the water. The estimation of the wave height is possible after analysis of the surface elevation signal, given by the change in pressure when the troughs and the wave crests are passing over the instrument (figure 29). The final calculated surface elevation is provide by means of a calibration function.

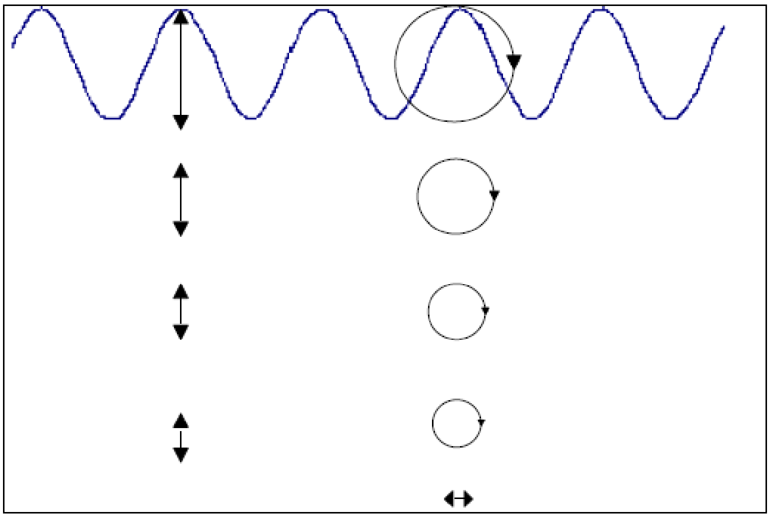


Figure 29. The pressure sensor detects a pressure variations during the alternation of troughs and the wave crests.

5.6.2 Fields Measured

The pressure range of pressure transducers varies by design and application, and can be anywhere between 1 bar and > 650 bar as required. However, since the water pressure at a depth of 40m is equal to 5 bar, a device with high sensitivity between 0.5 and 3 bar would be most suitable.

Typical operating temperature ranges of pressure transducers vary in the same way that pressure ranges do, with devices having possible ranges of -45°C to 85°C, far exceeding any possible marine application.

The accuracy of a typical marine pressure transducer is generally between 0.1% and 1% of the full calibrated scale of the pressure. This figure is dependent on the application and design of the device.

5.6.3 Method of Operation

For use in tank testing, the pressure transducer can be deployed in a number of ways. The device can be attached to a frame that is then fixed to the floor of the tank. Alternatively, the device can be attached to a test structure at a known depth. Care must be taken to ensure that the frame or structure is attached securely as any movement post-calibration would introduce errors in the pressure measurements.

Before the transducer is deployed, it is necessary to perform a “dry” calibration in order to determine the level of electronic noise in the instrument. If the devices have not been calibrated by the manufacturer within the prior six months then a “wet” calibration is also required. The wet calibration involves taking pressure readings at a series of known depths of water, in order to establish baseline measurements against which the sample measurements can be compared.

5.6.4 Specific Devices

Pressure transducers are very versatile devices which can be used for a number of different applications, including depth testing, altitude testing and leak testing in machinery. As such, pressure transducers vary in design, performance and technology depending on the specific application that the device is used for.

One example of a pressure transducer that is suitable for use for depth testing is the Depth and Level Transmitter PSL range, manufactured by HF. Jensen (figure 30). This device is robust and housed in a tough stainless steel casing, but with a diameter of 20mm is small enough to be easily handled. This device can be manufactured to give a pressure range of anywhere between 0.2 - 10 bar gauge. With a temperature range of 0^oC to 70^oC, this device is well designed for marine applications. In addition to this, the readings are accurate to within 0.06% of the calibrated span and the 4 – 20mA output can be easily converted to give data on wave parameters.

Figure 30: PSL pressure transducer, manufactured by H. F. Jensen.

Another example is the GE Druck RTX 1930 (figure 31). This is also manufactured in stainless steel, and can measure pressures between 0.06 – 68 bar, with adjustable range limits within this band. The accuracy is also 0.06%

Figure 31. RTX pressure transducer, manufactured by GE Druck.

5.6.5 Considerations

There are several factors to take into account when considering the use of pressure transducers for the measurement of wave parameters. These factors include the low cost of the devices, the ease of use and the low susceptibility to damage, due to the position low in the water column.

In order to convert the pressure signal to a surface elevation signal, assumptions about the transfer function are needed. Also required is information on the water density and the barometric pressure. In addition to this, pressure transmitters have a relatively poor response to high frequency waves due to water depth pressure attenuation (Jones and Monismith, 2007). The transducers are also prone to drift from an initial 'zero' setting.

In the presence of currents, linear wave theory is altered due to the Doppler-shift in the wave frequency resulting from the advection of waves by the current. Not including this effect when measuring with this instrument can lead to an underestimation of the wave spectral energy for an opposing current and an overestimation for a following current. This effect becomes significant when the current is similar in magnitude to the phase velocity of the waves and becomes increasingly important in the higher frequency range.

5.7 3 Probe Array (Long Crested Seaways)

The previous chapters in section five provided an overview of equipment that is used in tank based wave measurements. Key techniques when measuring the wave climate in tanks involves 3 probe arrays (for assessing wave reflections in long crested seaways) or 7 probe arrays (for assessing reflection and directionality in short crested seaways). A description of these techniques is provided in the following two chapters.

5.7.1 Operating Principle

In hydraulic laboratory enclosed wave tanks it is inevitable that some contamination of the wave field occurs due to reflections from the retaining walls, primarily the downstream end. Usually an energy absorbing beach is located along the back wall to minimise this but frequency dependant wave reflections still occur. Being concomitant with the progressive incident wave these reflected waves crate a partial standing wave longitudinally down the tank. Because the reflected wave is smaller than the incident wave the antinodes are less than twice the progressive wave whilst the nodes are greater than zero. The resulting wave height envelope can best be seen during regular wave generation, as shown in Figure 32. As the combined progressive wave travels along the tank the crest will vary from a maximum of incident plus reflected ($a_i + a_r$) to a minimum of incident minus reflected ($a_i - a_r$) wave. Where these nodes and antinodes occur is a function of the wave period whilst the magnitude depends on the efficiency of the beach. So, temporally the same sinusoidal water surface oscillation occurs at every station whilst spatially the surface excursion will depend on the measuring position along the wetted envelope.

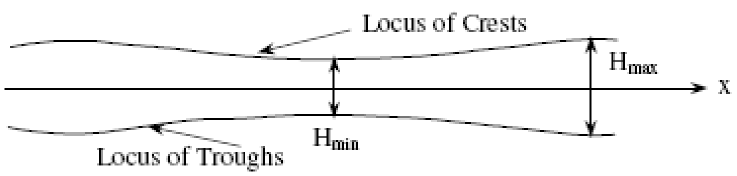


Figure 32: Partial standing wave envelope

5.7.2 Fields Measured

It can be important to be able to separate these concurrent waves into the true incident and the reflected components. This is usually achieved by deploying a number of the facilities operational type sensor but in a specific configuration. The relationships between the individual probe signals can be analysed to obtain the two water surface elevation components. The actual methodology employed for this wave component separation depends on the nature of the seaways being produced. The most straight forward approach can be used if the waves are long crested.

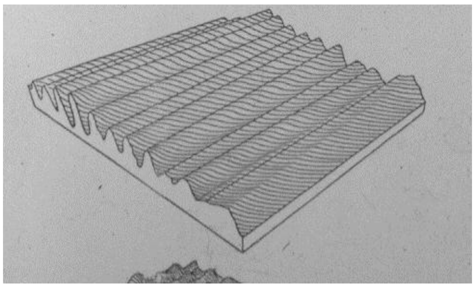


Figure 33: A long crested seaway

All monochromatic waves are long crested in nature, that is, they are generated by a single, regular paddle motion and the wave crest and troughs extend for the full width of the tank. Multi-frequency, panchromatic sea states can be either long or short crested. An example of a long crested seaway is shown in Figure 33. As in the previous case only one transverse paddle stroke is activated but now the time series signal to the paddle is irregular and a corresponding sea is generated with an uneven longitudinal surface contour but plain transverse profile. Long crested irregular seaways rarely occur in nature but such wave conditions offer a useful tool in wave energy device testing. They should, however, always be augmented with short crested trials.

5.7.3 Method of Operation

There are several methods that can be used to separate the incident and reflected waves, the simplest being appropriate for single frequency regular waves. For this a single probe can be used to measure the surface profile before reflected wave arrive back to the monitoring station, as shown in Figure 34. Alternatively, two probes can be spaced ¼λ apart and moved along the wave profile until a maxima and minima oscillation are recorded. These are the two extreme cases outlined above.

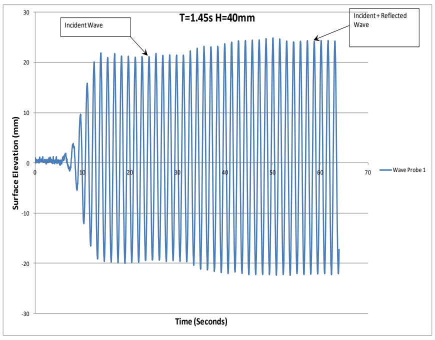


Figure 34: Regular wave reflections

Real seaways cannot be de-composed in this manner so a more sophisticated approach is adopted, such as that developed by Mansard and Funke. This method requires a simultaneous measurement of the waves at three positions in the tank which are in close proximity to each other and on a line parallel to the direction of wave propagation. A least squared method is then applied to the Fourier coefficients of each signal to separate the co-existing spectra into its two components.

Figure 35: Real sea probe spacing

The measuring probes must be located at specified stations which are linked to the seaway summary period as shown in Figure 35. Each probe will measure the linear superposition of incident and reflected spectra corresponding to the probe location. Certain probe spacing's produce singularities in the results, so these locations must be avoided.

5.7.4 Considerations

As with other similar techniques, the Mansard and Funke method makes certain assumptions. Firstly, that the waves can be described as a linear superposition of an infinite number of discrete components, each of which has a unique frequency, amplitude and phase. Secondly, these wave components travel at appropriate, individual phase velocities described by the classical dispersion relationship.

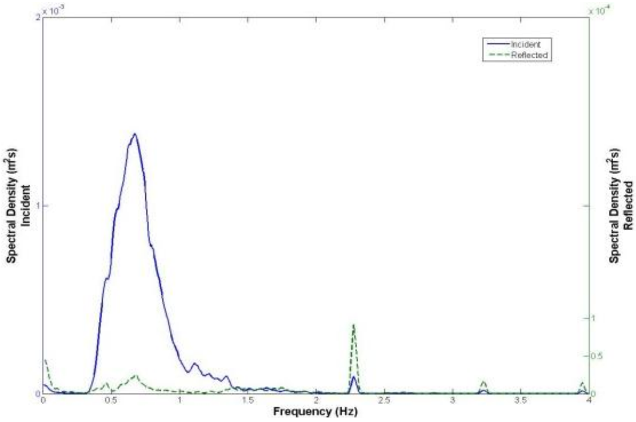


Figure 36: Real sea probe spacing

Mansard and Funke supplied the algorithms for analysing the individual probe signals which, during post-processing of the data, produce the spectral ordinates of the separated incident and reflected seaways, shown graphically in Figure 36. If a Fourier technique is used to generate the irregular wave pattern it is advisable to collect the water surface record for the same duration as the generation period. This will be a 2^n number of data points that forces the spectral ordinates to be the same for generation and analysis to minimise energy leakage between the harmonic frequency components. The question of enforced periodicity can also arise but this does not affect the analysis process.

A spectral ordinate smoothing technique is required to reduce the erratic variation of reflection coefficient spectrum, which could be a multiple degree of freedom sectioning of the raw time series.

5.8 7 Probe Array (Short Crested Seaways)

5.8.1 Operating Principle

Short-crested waves (or wind waves) are generated and influenced by the local wind field. Wind waves are normally relatively steep (high and short) and are generally both irregular and directional, for which reason it is difficult to distinguish defined wave fronts (Figure 37). A short crested wave field is normally referred to as a three-dimensional wave field. This implies introduction of an additional parameter, namely the direction of travel. The directional wave spectrum, $S\eta(f, \theta)$, is considered a product of the uni-directional spectrum, $S\eta(f)$, and a spreading function, $D(f, \theta)$, where f is the wave frequency, θ the angle of wave propagation. An example of $S\eta(f, \theta)$ is given inFigure 38.

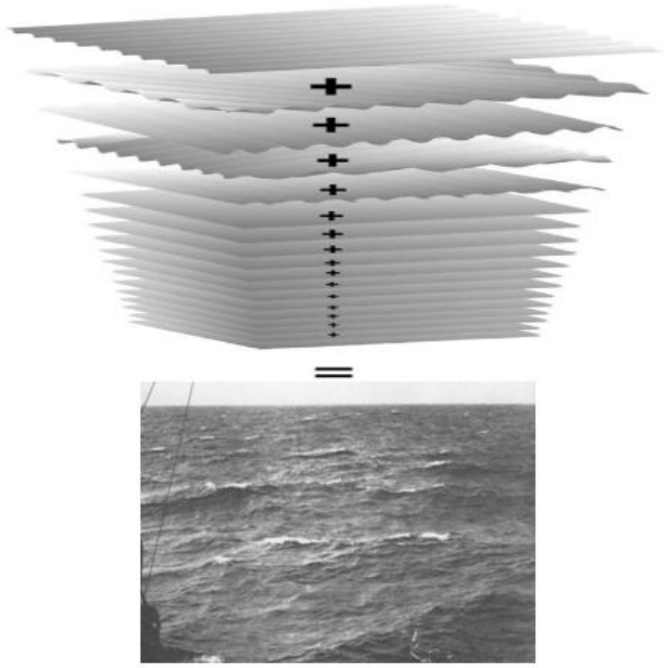


Figure 37. Short crested waves in the sea.

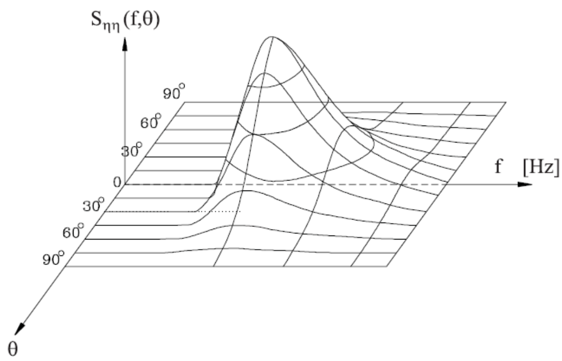


Figure 38. Directional wave spectrum

5.8.2 Fields Measured

It is important from an engineering point of view, to have knowledge of a three-dimensional structure of ocean waves for: design of offshore structures, sediment transport and induced motions of floating bodies. When short crested wave are generated in the laboratory different waves travel in different directions with different frequencies. Short crested waves are generated in the laboratory using a multi element array of paddles and applying a control signal to each paddle. All the generated waves will be partially reflected by the tank or by the tested structures themselves. The way the generated waves will be reflected depend on their characteristics, namely the wave high, period and direction of incidence. It is then important to be able to measure the surface elevation, the wave direction and separate the incident from the reflected component (with its own direction).

5.8.3 Method of Operation

A two dimensional wave field is commonly described in the frequency domain by use of the wave spectrum, i.e. the auto spectrum of the wave elevation process. Now in the three dimensional case a directional spreading function depending on frequency and direction of travel is introduced. The combination of the wave spectrum and the spreading function is the directional wave spectrum. Having determined the directional wave spectrum the wave field is fully described in the frequency domain (Frigaard and Andersen, 2012).

An expression which relates known and measured numbers to the directional wave spectrum or the directional spreading function is then established. The Cross-correlation function between η1 and η2 (surface elevation of Gauge 1 and Gauge 2) leads to the central equation for determination of the spreading function. The geometry is represented by r12 and β12 (Figure 39). This equation cannot be solved analytically. Therefore methods have been proposed in order to make a reliable estimate.

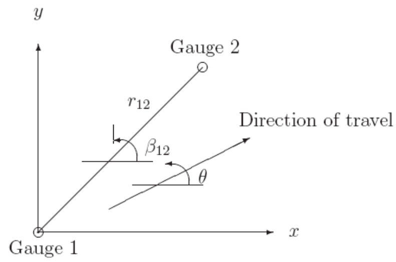


Figure 39. Definition of geometrical parameters.

The aim of the different methods of data analysis is to establish an expression which relates known and measured numbers to the directional wave spectrum or the directional spreading function. It is common to all methods that they initially suggest some shape of the directional spreading function. That may either be a parameterized analytic expression or a number of discrete values making a step curve. The next step is to fit the unknown parameters to the measured data. The reliability of the fit depends on the reliability of the measured data but also on the number of coefficients to fit, i.e. the more coefficients the less reliability. This is a problem as a high resolution requires many coefficients.

One of the methods is In the Maximum Likelihood Method, MLM. In this case the directional spectrum is calculated from minimizing the errors between measured wave data (cross-correlations) and fitted directional spectrum. This is achieved by use of the Maximum Likelihood technique, which has named the method.

The Bayesian Directional spectrum estimation Method, BDM is in principle similar to MLM, however, it makes use of a Bayesian approach in order to estimate the most likely estimate of the directional spectrum. BDM has been presented by Hashimoto et al. (1987). It is assumed, that the directional spreading function $H(\omega, \vartheta)$ can be expressed as a piecewise constant function, which takes only positive values.

During the derivation of BDM it has been presumed that:

- All values in the spreading functions are larger than zero
- The spreading functions are smooth (the smoothness being dependent on one parameter)
- The errors on the spectral estimates are outcomes of a Gaussian distribution function

The BDM turns out to be a very useful and reliable method for estimation of directional wave spectra. Some inaccuracy arises when a reflected wave system is involved, but it is still sufficiently reliable.
In order to measure the directional wave spectrum in a wave tank and being able to separate incident from reflected waves, a minimum of three wave gauges placed in triangle formation is required. The higher is the number of gauges, the higher is the definition. The number of unique cross-spectra is N(N-1)/2 with N being the number of gauges in array. Geometry of array and gauge spacing relative to the wave length are important for the reliability of the results. The number of gauges is though more important than the geometry.

For few gauges the array should be chosen carefully. For higher number of gauges the array configuration is less important. According to Davis and Regier (1977) the important parameter in the design of an array is the co-array (spatial lags between gauges for a given wave direction). An optimum array should have a co-array with lags evenly distributed in both space and direction.

It was demonstrated that as the number of wave probes increases, the directional resolution shown by the BDM is improved. In particular, for the wave probe arrays consisting more than or equal to four probes, it is seen that the BDM shows a better directional resolution; for this reason AAU uses 7 wave gauges (=15 number of number of complex cross-spectra), which allows a definition of 360˚/15=24˚ (Figure 40 and Figure 41).

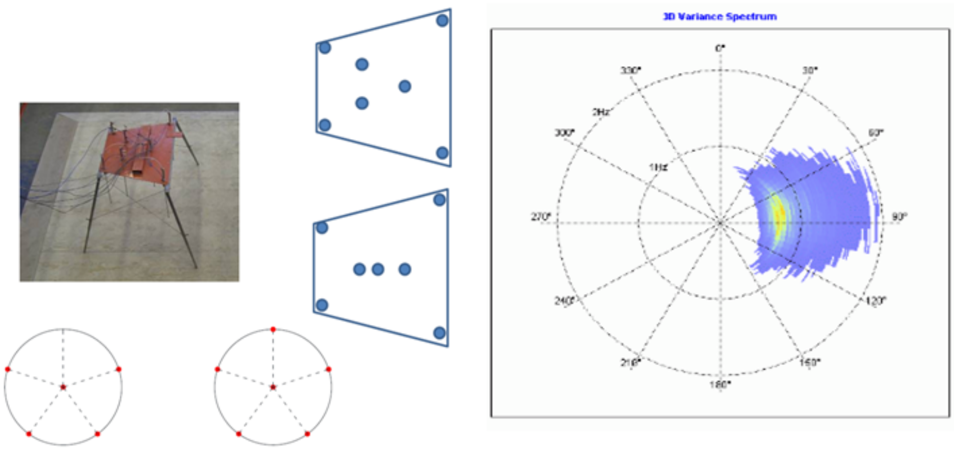


Figure 40. 5-gagues, 6-gauges and two different 7-gauges configurations and relative graphic results (using BDM method).

5.8.4 Considerations

Conductivity While the MLM (and BDM) provides reasonable results for directional wave spectra containing incident waves only the methods becomes less reliable when reflections occur (Figure 41). This problem happens because there is a co-relation of the phases of the incident and reflected waves.

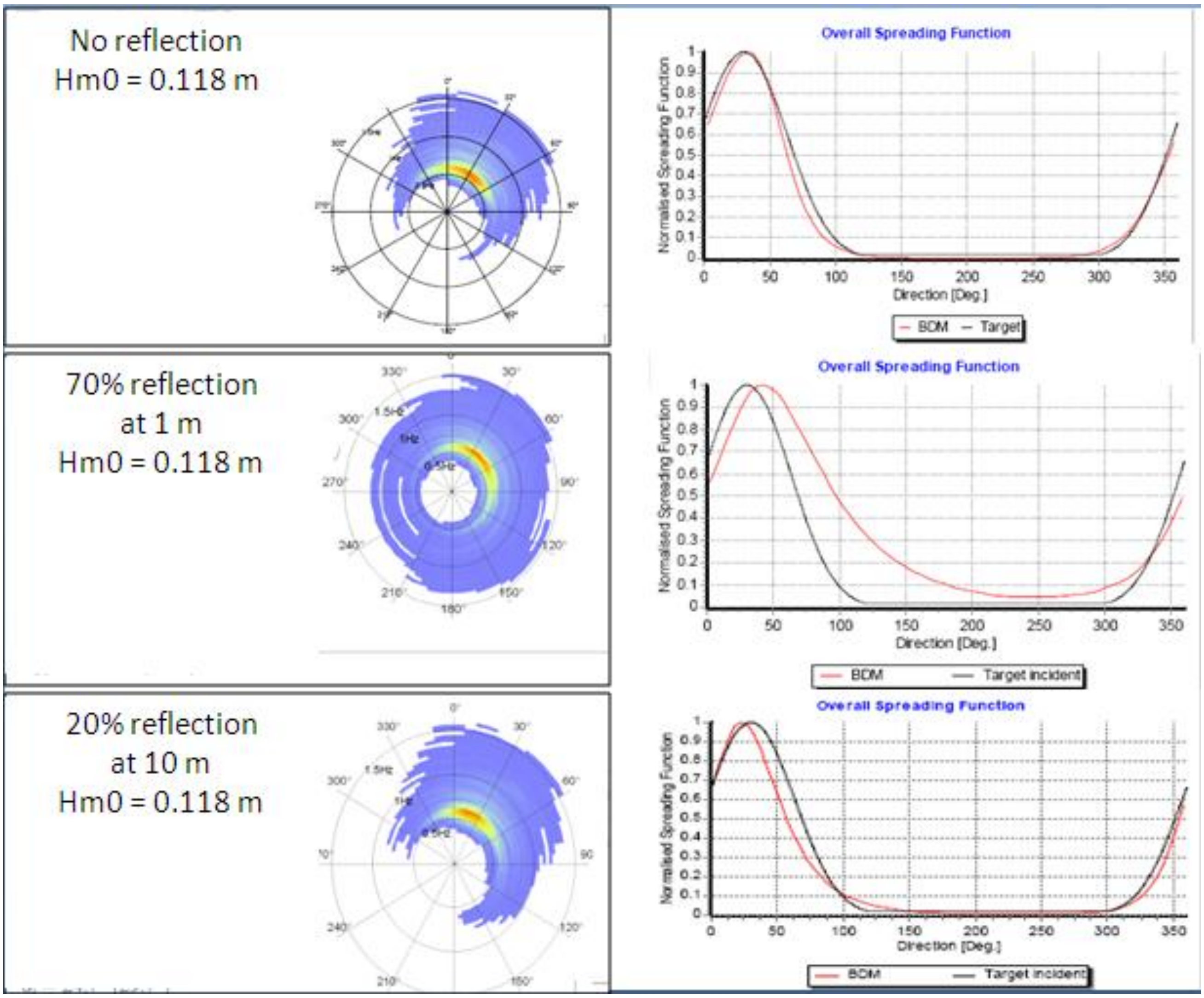


Figure 41. Performance of the BDM method with different reflections in the 3D wave energy basin at Aalborg University.

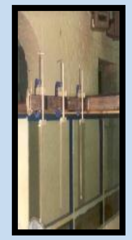
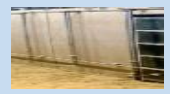
6 OPEN SEA FACILITIES INSTRUMENT CATALOGUE

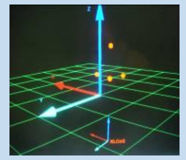
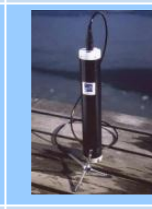
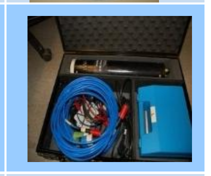
Ref	Instrument Category	Test Site	Instrument type	Manufacturer	Mooring / Fixing	Operating Principle	Purpose of instrumentation	Location of instrumentation in Water Column	Displacement Measurement Range	Frequency Measurement Range	Accuracy	Typical Sampling Frequency	Typical Reporting Frequency	Image
01	Heave/ Pitch/ Roll Buoy	SEAI EVE	Wavescan Met-Ocean Buoy	Fugro-Oceanor	Clump weight and bungee mooring	Heave/slope accelerometers	Wave Measurements & atmospherics	Up to 500m	±25m	2 - 30s	<5cm	2Hz	30 mins continuous	
02	Displacement Buoy	Uni_ EXE UoP AAU	SeaWatch Mini II	Fugro Oceanor	Clump weight and bungee mooring	Surface following accelerometer, rate gyros for roll and pitching motions	Wave measurement	Actual 53m No depth range	±20m	0.04 - 0.5Hz	Acceleration 0.02 m/s2	2Hz / 1Hz	30mins / 1Hr	
03	Displacement Buoy	EMEC ECN SEAI	Directional Waverider Buoy Mk iii	Datawell	Clump weight and bungee mooring	Surface following accelerometer	Wave Measurement	8-150m+	±20m	1.6-30s	>99%	3.84Hz	30 mins continuous	
04	Displacement Buoy	SEAI	Non-directional Waverider FL	Datawell	Clump weight and bungee mooring	Surface following accelerometer	Wave Height & Period	25m	±20m	1.6-30s	Error <10% of full scale	2.56Hz	30 mins continuous	
05	Displacement Buoy	EMEC	TRIAXYS Directional Wave Buoy	Axys Technologies Inc.	Clump weight and bungee mooring	Surface following accelerometer	Wave measurements	8-150m+	±20m	1.6-30s	Better than 2%	4Hz	30 mins continuous	
06	Radar	UoP	WERA HF radar system	Helzel Messtechnik GmbH	A pair of shore based 16 antenna phased array radar stations	The system continuously emits radio waves that interact with ocean surface through Bragg scattering. Shape of back scattered spectra is related to the surface gravity wave spectra which is derived through data inversion.	Surface currents, waves and wind measurements	Shore based	0.5 – 8.0 m	2.5-25s period	~10% wave height	Continuous during 17min:45sec	1 hour	

07	Acoustic Profilers	Uni_EXE UoP EMEC AAU ECN	RDI Workhorse Sentinal ADCP, 600 KHz, with optional 5th vertical beam	Teledyne RDI	Bottom-mounted in anti-trawl frame, ~200lb of lead weight for extra stability or vessel mounted.	Measurement of acoustic back scatter	Wave measurement / current profile. The optional 5th vertical beam directly measures the surface elevation, and may also be set to measure the vertical component of current velocity.	Seabed or vessel mounted	Depth dependent	0.05-1.0 Hz (depth dependent) (usual range of interest for waves is 0.05-0.5 Hz) Surface track >1s period	error <1% full scale	2 Hz	Variable (1 sec - 30 mins)	
08	Acoustic Profilers	Uni_EXE EMEC EVE	RDI Workhorse Sentinal ADCP, 300 KHz, with optional 5th vertical beam	Teledyne RDI	Bottom-mounted in anti-trawl frame, ~200lb of lead weight for extra stability or vessel mounted.	Measurement of acoustic back scatter	Wave measurement / current profile. The optional 5th vertical beam directly measures the surface elevation, and may also be set to measure the vertical component of current velocity.	Seabed or vessel mounted	Depth dependent	0.05-1.0 Hz (depth dependent) (usual range of interest for waves is 0.05-0.5 Hz) Surface track >1s period	<1%	2 Hz	Variable (1 sec - 30 mins)	
08	Acoustic Profilers	EMEC	Nortek AWAC-AST 600 KHz	Nortek	Bottom-mounted in anti-trawl frame, ~200lb of lead weight for extra stability or vessel mounted.	Measurement of acoustic back scatter	Wave measurement / current profile. The 4th vertical beam directly measures the surface elevation.	Seabed or vessel mounted	Depth dependent	0.01-1.0 Hz (depth dependent) usual range of interest for waves is 0.05-0.5 Hz)	<1%	2 Hz	Variable (1 sec - 30 mins)	

Table5.5: Open sea instrumentation catalogue

7 TANK FACILITIES INSTRUMENT CATALOGUE

Ref	Instrument Category	Test Site	Instrument type	Manufacturer	Mooring/ Fixing	Operating Principle	Purpose of instrumentation	Location of Instrumentation in Water Column	Displacement Measurement Range	Frequency Measurement Range	Accuracy	Typical Sampling Frequency	Typical Reporting Frequency	Image
01	Cond. Probe	LUH	2D current meter	NSW	Wall mounting	Electro magnetic	Flow measurement	0-7m	+/- 2.5 m/s	Not applicable	+/- 4%	3-20 Hz	Not applicable	
02	Cond. Probe	UCC	Parallel stainless steel wires	Churchill Controls	Calibrated stand	Conductivity probes	Water surface elevation measurement	As required in tank	±150mm	0.5 to 2.5 seconds	0.25mm	32Hz	mono = 64secs,	
03	Cond. Probe	ECN	Resistive wave gauge	ECN	Fixed according the need	Resistive measurement of 2 immersed small stainless steel rods	Local measurement of free surface elevations	HOET (large wave tank)	+- 0,1m to +- 0,7m	1Hz – 1kHz	+-0,5mm	32-256Hz	Not available	Not available
04	Cond. Probe	UoP	Wavegauge	Edinburgh Designs	Tank wall or gantry	Resistance	Measure wave height	Surface of tank	700mm	16Hz -512Hz	0.10%	128Hz	128Hz	Not available
05	Cond. Probe	UEDIN	Wave gauges	EDL	Overhead gantry / frame	Conductimetric	Wave height measurement	All	n/a	Not available	< 0.5%	32Hz	32Hz	Not available
06	Cap. Probe	LUH	Wave gauge	Unknown	Wall mounting	Resistive / capacity gauge	Surface displacement	2-7m	2-7m	Not applicable	+/- 10 mm	50 Hz	Not applicable	
07	Optical	UEDIN	ADV (Vectrino)	Nortek	Overhead gantry / frame	ADV	3-component point velocity measurements	Fluids Lab (Sanderson)	n/a	0 – 10	+/-0.5% of measured value +/- 1mm/s	25Hz	25Hz	Not available
08	Optical	UEDIN	LDV system (3-components)	Dantec	Motorised translation table (3-axis)	LDV	Up to 3-component pointwise velocity measurements	Fluids Lab (Sanderson)	n/a	Not available	0.5 – 1% typical	Seeding- and flow-dependent, up to kHz rate	Seeding- and flow-dependent, up to kHz rate	Not available

09	Optical	UEDIN	Laser wave gauge	UoE/LIS	Overhead gantry / frame	Optical Triangulation	Wave height measurement	Mobile	n/a	Not available	<0.5mm	60Hz	60Hz	Not available
10	Video	UEDIN	2D and 3D/Stereo PIV system	LaVision	Gantry / crane	PIV	3-component planar velocity vector field mapping, up to 350x250mm field of view approx.	Curved Tank	n/a	Not available	+/-2 to 3% in good conditions	5Hz	5Hz	Not available
11	Video	UEDIN	Qualisys system	Qualisys	Camera tripod heads	Stereo-photogrammetry	6-DoF motion tracking	Curved Tank	n/a	Not available	Unknown	up to 1kHz	up to 1kHz	Not available
12	Video	UCC	Reflective Markers	Qualisys	Taut cable	Motion measurement	Water surface elevation	As required in tank	±500mm	0.5 to 2.5 secs	0.5mm	32Hz	mono = 64 secs	
13	Acoustic	LUH	Acoustic Doppler Velocimeter (ADV), Vector type	Nortek	Wall mounting	Acoustic	Flow and turbulence measurement	0-7m	+/- 2.5m/s	Not applicable	+/- 0.5	64 Hz	Not applicable	
14	Acoustic	LUH	single beam echosounder PA 500	Tritech	Wall or floor mounting	Echosound backscatter	Depth and wave height	0-7m	0.1-10 m	Not applicable	Unknown	500 Hz	Not applicable	
15	Acoustic	LUH	AQUAscat 1000	AQUAscat	Floor mounting	Acoustic	Suspended particle concentrations	0-7m	0.1-20 g/l, 150 cm	Not applicable	Unknown	100 Hz	Not applicable	
16	Acoustic	AAU	Ultrasonic sensor	honeywell	Not applicable	Sensor emits a sonic pulse and then waits for the returned echo reflecting off an object.	Movements (in particular: surge heave pitch)	On the model, with refelcting dry surface in front	0 - 1200 mm	Unknown	Unknown	10 - 20 Hz	1 - 30 min	
17	Acoustic	AAU	Ultrasonic flowmeter	DenshiKogyo Co., Ltd	Not applicable	Doppler effect	Current velocities measurments 2D and 3D	Unknown	0-10 m/s	Unknown	Unknown	Unknown	1 - 30 min	Not available
18	Pressure	AAU	Wave gauge	In house built (AAU)	Not applicable	Resistance	Surface elevation [m]	Between the wave generator and the model	0 - 0.20 m	1 - 12 s	Unknown	10 - 100 Hz	1 - 30 min	

19	Pressure	AAU	Pressure transducer	Druck RTX 1930, HF Jensen	Not applicable	Membrane with one or more strain gauges attached to it	Wave pressures	In front of the device	0 - 40 mH2O (10 bar gauge or absolute, 50 or 100 mWC gauge or absolute)	Not available	±0.06%	10 Hz	1 - 30 min	

Table5.6 Tank facilities instrumentation catalogue

8 CONCLUSIONS AND RECOMMENDATIONS

This report details the background and equipment presently in use by the MARINET partners.

Most open-sea facilities within the consortium are using a wave measuring buoy, supplemented by acoustic and radar measurements. There is a much greater variety in equipment types in use amongst the tank testing partners, but this can be broadly categorised into intrusive or non-intrusive equipment.

The primary measuring principal used by the wave sensors is first to establish the location of the water surface by the chosen sensor, and then to apply analysis methods to the resulting time series. This can be in either the time-domain or the frequency domain. Typical open-sea sensors provide the appropriate analysis software to do this. Tank sensors are more likely to leave the analysis methods to the user, but this is not always the case. Alternative measurement techniques include the use of acoustic profilers to provide a water-surface derived spectrum, which can also estimate spectra directly from wave orbital velocities. These units often also provide a pressure derived spectrum which may be incorporated in the output. One facility is also using radar sensors for open sea data collection which relies on the analysis of radio-wave scattering to provide a wave spectrum.

The supply of power and communication to and from the instrumentation is relatively straight forward for the tank based equipment. However open sea measurements are usually taken via sensors deployed on a buoy, which opens up the logistical challenge of recovering the data to the shore for processing. The usual solution is radio communication, formerly by direct FM transmitter/receiver pairs, but more recently satellite/mobile phone techniques have become available. Alternatively, an on-board logger may save data until the buoy is physically recovered. Alternative approaches to open sea data collection include sensors deployed on the seabed; again this requires data communication to the shore. This is typically done by retrieving the instrument and downloading the stored data, however expensive direct cabling or underwater modems are technically feasible alternatives.

The findings of the deliverable will be taken up in D2.5 (report on instrumentation best practice), D2.9 (Standards for Wave Data Analysis, Archival and Presentation) and various activities in Work Package 4. D2.5 will also identify where instrumentation is not available within the Marinet facilities for specific monitoring requirements, unique to the testing of marine renewables and will provide recommendations for filling the gaps identified.

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