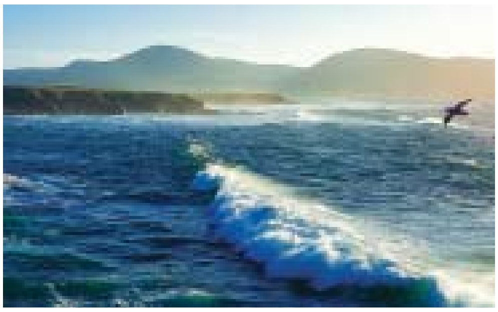
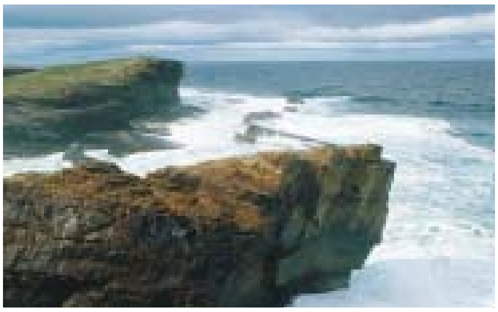
EMEC ORKNEY
The European Marine Energy Centre Ltd

This document is a draft and will be re-written. For complementary information, the document “Estimating power from wave measurements at the European Marine Energy Centre (EMEC) test site”, by E G Pitt, Applied Wave Research, 24 March 2005, is attached at the end.

PERFORMANCE ASSESSMENT_

FOR WAVE ENERGY CONVERSION SYSTEMS IN OPEN SEA TEST FACILITIES_

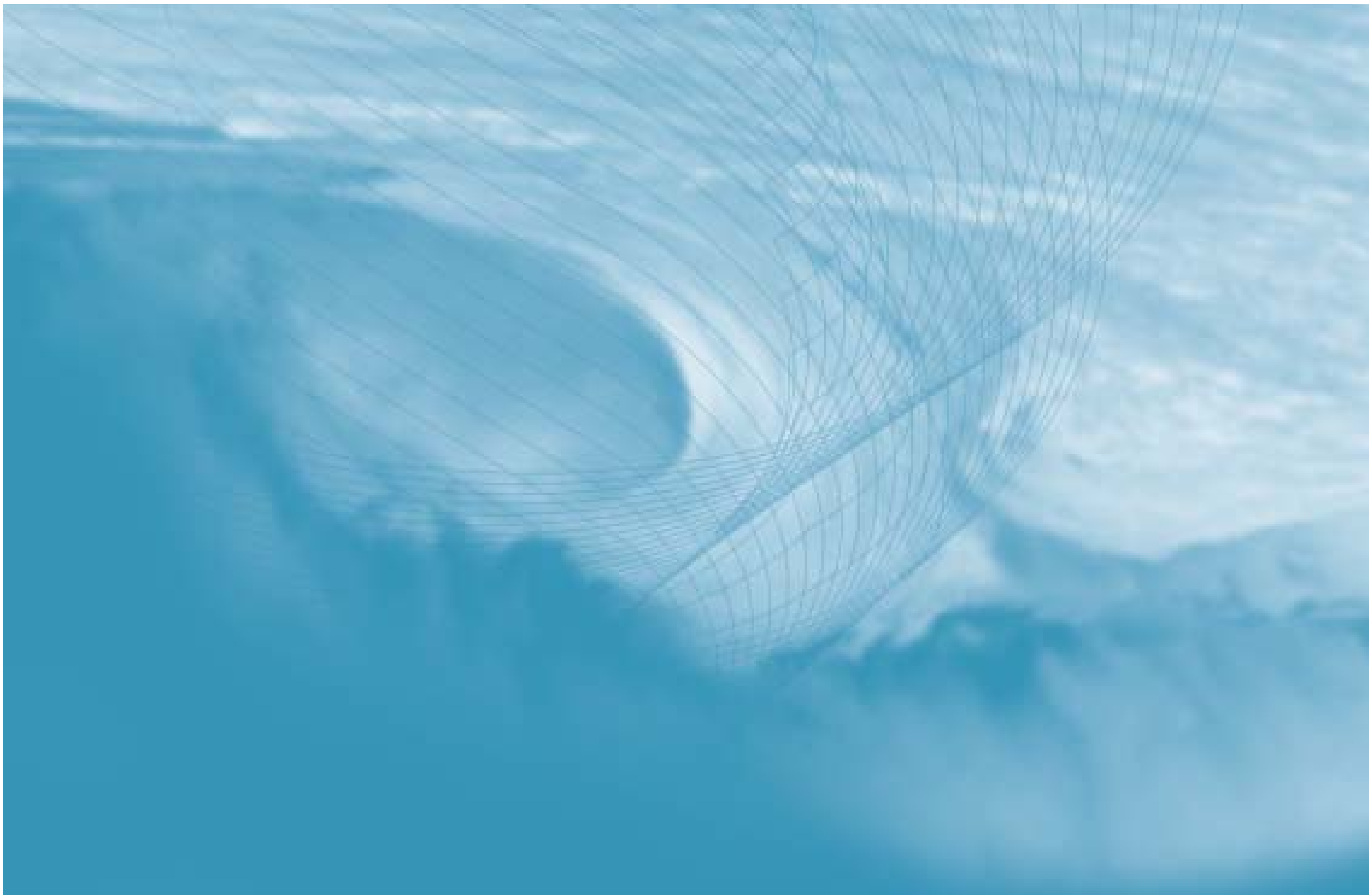




one NorthEast
The Development Agency for the North East of England

Highlands & Islands Enterprise

EMEC Orkney



Drafting Note_

This draft standard is a jointly funded initiative between One NorthEast and Highlands and Islands Enterprise. It is an interim publication, intended as a working draft so that the wave energy community may use it in testing, and document their experience of its usefulness.

In the text, a number of questions were raised during drafting, which have been collected in Annex 5. These cover specific areas where views of people with relevant expertise are requested on the basis of their experience of using the working document. Other comments are also welcomed and may be emailed to EMEC at info@emec.org.uk. They will be held for a period of around two years and will be utilised in revising the document and submitting it for further consultation.

The subsequent step is likely to be to send the revised draft to BSI for consideration for issue as a Publicly Available Specification (PAS) providing there is agreement to do so within the wave device community.

CONTENTS_

INTRODUCTION_

The purpose of this standard is to provide a uniform methodology that will ensure consistency and accuracy in the measurement and analysis of power performance of wave energy conversion systems (WECS).

The standard has been prepared with the anticipation that it would be applied by:

- **The WECS manufacturer endeavouring to meet well-defined power performance specifications and/or a possible declaration system.**
- **The purchaser of WECS in specifying performance requirements.**
- **The WECS operator who may be required to verify that the stated performance specifications are met.**
- **The WECS planner or regulation authority who must be able to accurately and fairly define power performance characteristics of WECS in response to regulations or permit requirements for new or modified installations.**

This standard provides guidance in the measurement, analysis, and reporting of power performance testing for WECS. The technically accurate measurement techniques recommended in this document should be applied by all parties to ensure that continuing development and operation of WECS is carried out in an atmosphere of consistent and accurate communication relative to environmental concerns. The standard presents measurement and reporting procedures expected to provide fair and suitably accurate results that can be replicated by others.

However, readers are advised that the method of assessment of wave energy in the observed wave spectra is a developing technique and evidence is still to be built up so that it may be satisfactorily transferred between different test and operating sites.

It is also a matter for further work to apply this standard to a variety of technologies of different WECS, in an effort to show comparability between the different types of device.

Revision of this working document will, it is hoped, capture future progress in both these respects.

1_GENERAL

1.1 SCOPE

This standard consists of a procedure for measuring the power performance characteristics of a single WECS and applies it to all WECS of whatever technology, situated in open sea and connected to the electrical power grid. It is applicable for the determination of both the absolute power performance and of the differences between the power performance characteristics of the various configurations of WECS. These may include a range of technologies for capture of wave energy and power take-off.

The WECS power performance characteristics are determined by the measured power matrix and the estimated annual energy production (AEP). The measured power matrix is determined by collecting simultaneous measurements of wave height, energy period, power output and meteorological conditions at the test site over a period long enough to establish a statistically significant database over a suitable range of wave conditions. The range of wave conditions for the test period at the test site should cover, as far as is practicable, the range of conditions likely to be encountered on an annual basis at the proposed locations of permanent deployment.

The AEP for any proposed deployment location is calculated by applying the measured power matrix to predicted or observed wave height and energy period frequency distributions for the deployment location, assuming 100% availability of the WEC.

The standard describes a measurement methodology for establishing the measured power matrix for a WEC in terms of the wave height, wave period and wave spectral characteristics recorded during the test period.

The standard requires an assessment of uncertainty sources and their combined effects.

The objective of the standard is to provide a sound and auditable procedure for establishing the power performance characteristics of a WEC in real sea conditions. This may then be used to predict AEP from the WEC for locations where it is to be permanently deployed.

1.2 NORMATIVE REFERENCES

IEC 60044-1: 1996, Instrument transformers – Part 1: Current transformers.

IEC 60186:1987, Voltage transformers (amended 1988 and 1995).

IEC 60688: 1992, Electrical measuring transducers for converting AC electrical quantities to analogue or digital signals.

ISO 2533: 1975, Standard atmosphere.

Guide to the expression of uncertainty in measurement, ISO information publications, 1995, ISBN 92-67-10188-9.

1.3 DEFINITIONS

For the purposes of this standard the following definitions apply:

1.3.1 Accuracy

Closeness of the agreement between the result of a measurement and the true value of the measurand.

1.3.2 Annual Energy Production

Estimate of the total energy production of a WECS during a one-year period by applying the measured power curve to different wave spectra assuming 100% availability.

1.3.3 Availability

Ratio of the total number of hours during a certain period, excluding the number of hours that the WECS could not be operated due to maintenance or fault conditions, to the total number of hours in the period, expressed as a percentage.

1.3.4 Complex Ocean Features

Ocean features surrounding the test site that have variations in topography or obstacles that may give rise to flow distortion.

1.3.5 Current Velocity

Velocity of the current (metres per second) measured in the area of the WECS under test, averaged over the top two metres of the water column for most WECS.

1.3.6 Data Set

Collection of data that was sampled over a continuous period.

1.3.7 Dead Spot

Point where wave energy is cancelled by reflection or refraction, causing wave energy to be reduced at a location below the surrounding level.

1.3.8 Extrapolated Power Matrix

Extension of the measured power matrix by estimating power output from the maximum measured wave height to cutout wave height for the WECS.

1.3.9 Hot Spot

Point where wave energy is concentrated by reflection or refraction causing wave energy to be reinforced at a location above its surroundings.

1.3.10 Measured Power Matrix

Table that represents the measured, corrected and normalised net power output of a WECS as a function of significant wave height and energy period measured under well-defined conditions.

1.3.11 Measurement Period

Period during which a statistically significant database has been collected for the power performance test.

1.3.12 Method of Bins

Data reduction that groups test data for a certain parameter into significant wave height and wave zero-crossing period or energy period intervals.

1.3.14 Net Electric Power Output

Measure of a component of the WECS electric power output that is delivered to the electrical power grid.

1.3.15 Power Coefficient

Ratio of the net electric power output of a WECS to the power available in the observed wave energy spectra.

1.3.16 Power Performance

Measure of the WECS ability to produce electric power and energy.

1.3.17 Rated Power

Quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device or equipment.

1.3.18 Significant Wave Height

A statistical representation of wave height occurring in a population of wave heights – usually calculated as 4 x root-mean-square water elevation. The highest wave in a 3-hour period will typically be about twice the significant wave height.

1.3.19 Standard Uncertainty

Uncertainty of the result of a measurement expressed as a standard deviation.

1.3.20 Test Site

Location of the WECS under test and its surroundings.

1.3.20 Uncertainty in Measurement

Parameter associated with the result of a measurement, which characterises the dispersion of the values that could reasonably be attributed to the measurand.

1.3.21 Wave Energy Period

For a simple "sinusoidal" wave train, wave energy period is the time between successive crests. For a mixed population of waves there are many possible definitions of "typical" wave period. Energy Period is the most relevant to wave power; it is defined such that a sinusoidal wave field consisting solely of waves of height equal to the Significant Wave Height and period equal to the Energy Period would have the same energy flux (wave power) as the actual wave field. For a random wave field Te is defined in terms of the moments of the energy spectrum

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

1.3.22 Wave Height

The vertical distance from crest to trough of a wave.

1.3.23 Zero-crossing Wave Period (T_z)

This is the average wave period of the zero up-crossing of waves. It is widely used as the wave period parameter in wave scatter diagrams.

1.4 SYMBOLS AND UNITS

D	Duration
E_i	Estimate of uncertainty in the i^{th} bin
f	Frequency
H_s	Significant wave height
L	Absorption length of WECS device
m_i	Spectral moment of waves in i^{th} bin
N_i	Number of independent measurements in i^{th} bin
O	Power operator
P_n	Normalised power output
P_{meas}	Measured power output
S	Wave spectrum
T_e	Wave energy period
T_z	Wave mean crossing period
λ	Spreading constant
θ	Direction of spectral component of sea-state
ρ	Reference water density at STP
σ	Given by: λ/T_e
ψ	Alignment of WECS (same origin basel as spectral component)

1.5 ABBREVIATIONS

AEP	Annual Energy Production
CDF	Common Data Format
PPT	Parts per thousand
STP	Standard temperature and pressure
VHF	Very High Frequency (radio)
UKMO	United Kingdom Meteorological Office
WECS	Wave energy conversion system

2_TEST CONDITIONS

2.1 WAVE ENERGY CONVERSION SYSTEM

As detailed in clause 6, the WECS shall be described and documented to identify uniquely the specific device that is tested.

2.2 TEST SITE

The test site shall be equipped with a meteorological station that will automatically record the wind speed and direction, wet bulb and dry bulb air temperatures and barometric pressure at intervals of one minute maximum. Precipitation rate may be measured over intervals up to 30 minutes. The meteorological station shall be sited as near to the offshore site as practicable. The data may be recorded as a series of thirty minute averages.

The bathymetry of the test site shall be surveyed and sidescan sonar surveys carried out. These ensure that the test area is free from obstacles or uneven seabed topology that could be considered to distort or interfere with wave consistency or WECS performance.

A simulation of test data from the site shall be carried out in order to check that no dead spot or hot spot in the wave environment is likely to be within 500m of the WECS under test. The simulation should also demonstrate that the wave measuring device (used to record the water surface elevation) is at a position where the wave environment is the same at the mean position of the WEC or that appropriate corrections can be made for the effects identified below.

The simulation shall utilise software that is based on a competent recognized method of modeling.

2.2.1 Sea-state Measurement and Energy Spectra.

Actual sea-state at the proposed test site should be measured by wave buoy or other device of at least comparable accuracy, from as early as possible in the development process. If feasible, it should be done on a continuous basis leading up to and in any event, throughout the test period. The wave measuring device should record data that allow the directional wave spectrum to be estimated.

The form chosen such that is has the lowest rms difference between it and the measured spectrum.

Particular care needs to be taken when there is a swell component from the same or a different direction from the wind-driven sea. The directional wave spectra should be checked for each measurement period to see if there is any significant bimodality in either frequency or direction. When categorising the data, distinction should be made between conditions when the directional spectra has a single peak, and those where there is any significant bimodality in the energy content.

Even for unimodal spectra the primary wave direction and the directional spreading of the energy should be recorded for each 3-hour measurement period. For devices that are not directionally sensitive (i.e. have uniform, omni-directional characteristics) it will not be necessary to collect directional information.

The sea-state should be represented on a scatter diagram of (H_S,T_Z) with the bins defined as in Section 4.6 – Database Presentation. The optimal relationship is likely to vary significantly between sites, in addition to between different WECS. The indicative energy output of the device may be obtained by integrating the power operator with the sea-state spectrum over the particular time period of interest, typically one or three hours.

By way of example, paragraph 1 of Annex 4 describes the background to and justification for choice of the Brechtsnieder spectral form, in preference to the Pierson-Moskowitz or Jonswap solutions for the typical mixed wind sea and swell conditions prevalent at the Orkney WECS site.

2.2.2 Transposing Performance Between Sites, Accounting for differences between wave measurement position and WEC position.

At any test location, the proximity of the wave measuring device(s) in relation to the WECS may vary, so consideration shall be given to the differences between the wave data measurement site and the WECS test site in terms of:

- Changes in water depth between the wave data position and the WECS test position, leading to increases or decreases in wave height at the test position, compared to the data position. Changes in water depth may lead to changes in wave steepness, particularly in shallow water, that may effect WECS performance.
- Bathymetry-induced refraction of waves from the data site to the test position, leading to focusing or spreading of wave energy from the data site to the test site.
- Tidal current-induced refraction of waves from the data position to the test position, again leading to focusing or spreading of wave energy from the data site to the test site.

As far as possible, it is necessary to choose the measurement and WECS locations so that no significant differences are evident. If, however, it is concluded that there will be significant modification of waves from the wave data measurement position to the WECS test position, then it will be necessary to acquire the wave data in the form of a directional spectral time series rather than a scatter diagram. Two–dimensional wave models may then be applied to convert the wave data time series to its corresponding counterpart at the WECS test position.

3_TEST EQUIPMENT

3.1 ELECTRIC POWER

The net electric power of the WECS shall be measured using a power measurement device (eg power transducer) and be based on measurements of current and voltage on each phase.

The class of current transformers shall meet the requirements of IEC 60044-1 and the class of voltage transformers, if used, shall meet the requirements of IEC 60186. They are all recommended to be of class 0.5 or better.

The accuracy of the power measurement device, if it is a power transducer, shall meet the requirements of IEC 60688 and is recommended to be of class 0.5 or better. If the power measurement device is not a power transducer, then the accuracy should be equivalent to class 0.5 power transducers. The operating range of the power measurement device shall be set to measure all positive and negative instantaneous power peaks generated by the WECS. As a guide, the full-scale range of the power measurement device should be set to –50% to 200% of the WECS full rated power. All data shall be periodically reviewed during the test to ensure that the range limits of the power measurement device have not been exceeded. The power measurement device shall be mounted at the network connection point to ensure that only the net active power output, delivered to the electrical power network, is measured.

3.2 WAVE MEASUREMENT

Wave rider buoys shall be installed at appropriate positions close to the WECS under test to give an acceptably accurate measure of wave conditions experienced by the WECS. The buoy(s) should measure accelerations in six directions to allow wave heights and periods to be calculated by a straightforward and specified method. The measurements should also allow the directional wave spectrum to be estimated. The buoys should be capable of recording data at 5Hz and transmitting by VHF radio to an onshore base station.

3.3 TIDAL STREAM AND CURRENT MEASUREMENT

Current measurement devices shall be deployed as appropriate to allow for corrections for current to be made to wave measurements. Where it is impractical to permanently site current measurement devices, currents should be measured at sufficiently regular intervals to predict the corrections required. Currents should be measured and averaged over the top 2m depth of the water column or as required to correspond to the approximate energy capture axis of the WECS if different.

The absolute accuracy of the current direction measurement shall be better than +/-5 degrees and current velocity better than +/- 0.1 m/sec, or +/- 5% of actual velocity, whichever is the greater.

3.4 SEA WATER DENSITY

Seawater density is a function of seawater temperature, salinity and pressure (depth) and is to be computed using the accepted UNESCO International Equation of State. Sea temperature and salinity should ideally be measured by the wave rider buoy(s) and corrected if necessary to reflect the depth of the energy capture axis of the device under test.

The absolute accuracy of sea temperature measurement shall be 0.2°C or better, the resolution shall be 0.05°C. The conductivity shall be continuously monitored if possible or failing that, monthly readings taken at the site. The absolute accuracy of the conductivity shall be given in the calculation.

3.5 PRECIPITATION

To distinguish measurements from dry and wet periods, precipitation should be monitored by the meteorological station or other suitable means and documented in the test report. A daily summary from hourly readings or similar would be advantageous.

3.6 WECS SYSTEM STATUS

At least one parameter that indicates the operational status of the WECS shall be monitored continuously. The status information shall be used in the determination of WECS availability. Note that the non-production of electric power from the device is not a suitable parameter to monitor, as there may be other reasons inhibiting production other than the availability of the WECS.

3.7 DATA ACQUISITION SYSTEM

A digital data acquisition system having a sampling rate of at least 2 Hz shall be used to collect measurements and store pre-processed data.

End-to-end calibration of the installed data acquisition system shall be performed for each signal. The uncertainty introduced by the data acquisition system should be negligible compared to the uncertainty of the sensors.

4_MEASUREMENT PROCEDURE

4.1 INTRODUCTION

The objective of the measurement procedure is to collect data that meet a set of clearly defined criteria. This ensures that the data are of sufficient quantity and quality to determine the power performance characteristics of the WECS accurately. The measurement procedure shall be documented as detailed in Clause 6 so that every procedural step can be reviewed |and repeated if necessary.

Accuracy of the measurements shall be expressed in terms of measurement uncertainty, as described in Annex 3. During the measurement period data should be periodically checked to ensure high quality test results. Test logs shall be maintained to document all important events during the power performance test.

4.2 WECS OPERATION

During the measurement period, the WECS shall be in normal operation as prescribed in the WECS operations manual, and the machine configuration shall not be changed. All data collected when the WECS is unavailable shall be discarded.

4.3 DATA COLLECTION

Data shall be collected continuously at a sampling rate of at least 2 Hz. Meteorological data may be sampled at a minimum rate of once per minute except precipitation (see 2.2 page 5).

The data acquisition system shall store sampled data or pre-processed data sets as described below, or both. The pre-processed data sets shall comprise the following information on the sampled data:

- Mean value.
- Standard deviation.
- Maximum value.
- Minimum value.

That is, using basic observer modeling techniques, together with information from a series of sensors on the equipment and using data from the test site, it is possible to predict the performance of the sensors. This technique can be used during the calibration of the equipment once on site, during the test and as a post-process data validation technique. It is desirable to have redundancy in the sensor systems where possible, to allow cross checks to ensure that data sets do not to have to be discarded because of a single sensor failure.

4.4 DATA SELECTION

Selected data sets shall be based on 30-minute periods derived from contiguous measured data. The mean and standard deviation values of each 30 minute period shall, when derived from preprocessed data sets, be calculated according to the following equations:

Data sets shall be excluded from the database under the following circumstances:

- WECS unavailable.
- Failure of test equipment.
- Failure of sensors recording essential environmental parameters.
- Any other definition.

Data sets collected under special operational conditions (eg definitions tba) that occur during the measurement period may be selected as a special database and the selection criteria shall be stated in the measurement report.

The total duration of each processed data set shall be 30 minutes. Temporally adjacent data sets shall not be separated by a time delay. Data shall be collected until the criteria in 4.6 (page 8) are satisfied.

Data Filtering – It is permitted to filter the measured data, although the full filtering algorithm must be reproduced within the benchmarking documentation. Active frequency rejection systems are the preferred option, using frequency domain based signal processing techniques.

Data Validation – Once the precision of the data has been fully defined and the data acquisition equipment calibrated, this can be used in conjunction with basic models of the product to enable validation of data as well as sensor validation.

Data from all measurement channels need to be synchronised in order that data from separate data acquisition units can be fully locked onto a consistent time frame. This will require a separate trigger signal to be distributed within the data logging system, either by a hardwired analogue signal or via a data synchronisation protocol via a communication network.

This technology will also enable multiple sampling regimes to be incorporated into the data logging system. For example, electrical power flow will need to be monitored on slow time frame if steady-state power flow data is required, although if harmonic content is to be fully analysed then the power will need to be sampled in the kHz range.

Adequate data protection should also be enabled within the data logging function, i.e. protection of data integrity as well as electrical signal integrity. In an electrically noisy environment and subject to the harsh conditions of the marine environment, the operation of electro-mechanical hardware can become affected.

4.5 DATA CORRECTION

Selected data sets shall be corrected for tidal stream velocity, seawater density and barometric pressure. The criteria for such corrections are:

Corrections for tidal stream velocity should only be attempted where there is clear empirical evidence of a relationship between power output and current velocity (e.g. from a number of power take off measurements at similar $[H_S,T_Z]$). Correction should be made from raw values to "zero-current conditions". Supporting documentation (see Section 6) must include the formulae for this correction, and also any known limitations of the WECS in currents.

Corrections for seawater density should be to a standard density of 1025 kg/m3 as described in Section 5.1. For devices that involve use of air, such as Wells turbines, corrections for air pressure and density and humidity to standard values may be necessary.

Data Trends – Using the observer modelling techniques in conjunction with statistical analysis it is possible to accurately determine the validity of certain data channels with respect to others, in order that the trend of the data can be fully assessed.

This can be used to determine whether the data is performing with respect to the predictions determined by section 4.4, thus enabling the identification of data streams or channels that are not performing to specification.

Correction Validation – Building upon the observer modelling techniques of the last section it is possible to predict data that is corrupted, and hence replace that information with model predictions. This technique will become more and more valid, the more data channels.

Selected data sets shall be corrected for tidal stream velocity, seawater density and barometric pressure. The criteria for such corrections must be stated in the report.

Corrections may be applied to measurements if it can be shown that better accuracy can be obtained.

4.6 DATABASE

Data Format – In order to enable the widest interpretation of the data and hence validation of the experimental trial, simple ASCII text files or net CDF are the preferred options. Data should be produced in terms of:

- Post conversion fixed point data.
- Scaling factors.
- Data resolution.
- Data accuracy.
- Time stamp.

Once stored in a text based spreadsheet format, further analysis can be performed using a variety of bespoke or custom signal processing systems and techniques. A spreadsheet file should be produced for each sampling frequency and should enable cross-referencing to other data spread sheets. This will enable the data to be fully reconstructed using database techniques.

Storage Format – All data should be stored in a text format that is universally readable, such as HTML or XML. Net CDF is the preferred compacted data format.

Data Security – The top-level data needs to be made available in order to ascertain the functionality and performance of the device under test. It is the joint responsibility of the test site and the device tester to secure commercially sensitive data while also enabling the production of evidence data to validate the performance of the device.

Database Presentation – After data normalisation (see 5.1 below) the selected data sets shall be sorted using the “method of bins” procedure (see 5.2 below). The selected data sets shall cover significant wave height range of (0 to 15m) and energy period range of (2-15 secs.). The significant wave height bins shall be divided into 0.5 metre contiguous bins, centred on integer multiples of 0.5 metres. The energy period bins shall be divided into 1.0 second contiguous bins centred on integer multiples of 1 second.

A distinction should be made between data collected when the directional energy spectra are unimodal and those collected when there is any significant bi-modality. Some devices are designed for, and are intended to be operated in, wind driven seas or swell coming from one predominant direction. For such devices, only test data recorded in such conditions should be used in estimating AEP. For devices that do not 'weather-vane' and whose performance is a function of wave direction, the data should be further segregated into directional bins of 15 degrees width. The angular direction should be measured between the device orientation and the peak of the directional spectrum.

For devices with omni-directional characteristics that are relatively unaffected by the directional spread of the seas and their short-crestedness, there may be no need to consider directional aspects. Similarly for devices whose performances is not sensitive to bi-modality in frequency there is no need to distinguish wind seas, swell and mixed seas. However, for devices that are affected in a non-negligible way by relative wave direction, by bimodality in wave frequency or bi-modality in wave direction, it is important that the measured data set is appropriately subdivided according to these wave characteristics.

The directional spectra for each three-hour period should be recorded if available. The principal direction of the wave energy, the directional spreading and whether or not the spectrum had any significant non-unimodal characteristics should all be recorded as a minimum. The directional spreading can be recorded as the spread parameters of the cosine spreading function, or as the directional standard deviation of the spectral energy at the peak frequency.

The database shall be considered complete when it has met the following criteria:

- Each "practicable" bin contains a minimum of 6 independent samples (where independence implies separation by a minimum of 24 hours from each other) totaling at least 180 minutes of sampled data. (Note that certain combinations of significant wave height and energy period cannot give rise to real waves in practice and will always remain empty.)
- The total duration of the measurement period includes a minimum of 5,000 -10,000 hours with the WECS available within its operating range.

The database shall be presented in the test report as detailed in clause 6.

5_DERIVED RESULTS

5.1 DATA NORMALISATION

The selected data sets shall be normalised to a reference water density. This shall be the average of the measured water density data at the test site rounded to the nearest 5 kg/m3. The other shall be the arbitrary seawater density [1025 kg/m3 at STP]. No water density normalisation is required to the actual water density if the average water density is within 1025 +/- 5 kg/m3.

The water density is determined using hydrometers for sampling at the devices draught to determine the specific gravity of seawater during test. The hydrometers should be checked for accuracy prior to test. Seawater temperature is to be recorded at the required draught to obtain a measured water density at STP.

Data normalisation shall be applied to the measured power output according to the equation:

$P_n = P_{meas}. [\rho 0/\rho_{meas}]$

Where,

P_n is the normalized power output.

P_{meas} is the measured power average over a period of [TBA by measurement study group].

$\rho 0$ is the reference water density at STP.

ρ_{meas} is the measured water density at STP.

Normalisation to standard values of temperature, density, etc of air is also recommended as appropriate to the device under test.

Normalisation to standard values of air temperature and density and humidity, is necessary as appropriate to the device under test.

5.2 DETERMINATION OF THE MEASURED POWER CURVE

The measured power curve is based on the "method of bins" for the normalized data sets using sea state bins with a wave height increment of 0.5 m and a period increment of 1.0 second.

For each bin i (corresponding to a range of [Hs, Te] as described above), the measured power is estimated as:-

$P_i = \Sigma_{j=1}^{Ni} \ P_{ij}/N_i$

where there are N_i independent measurements of normalised power, P_{ij}, satisfying the conditions for bin i.

A rudimentary estimate of the uncertainty in each P_i is given as:

$E_i = 2.0[\Sigma_j (P_{ij} - P_i)^2]^{1/2} / [N_i^{1/2}(N_i - 1)^{1/2}]$

Each element of the power matrix can then be quoted in the form $P_i(\pm E_i)$.

A simple power matrix can be employed for any of the following cases:

- The WEC can be shown to have sensibly constant output for Hs, Te bin irrespective of the directional spectra characteristics.
- The directional spectra characteristics at the test site do not vary significantly.
- The device will be employed at sites where the directional spectra characteristics do not vary significantly.

In the last case, the test data selected to estimate the power matrix must have spectral directional spectra characteristics that correspond to the deployment site.

In other cases, the power matrix will require additional dimensions to account for variations in directional spectra characteristics.

5.3 ANNUAL ENERGY PRODUCTION (AEP)

In the cases identified above where a simple power matrix is applicable, the AEP can be estimated as follows.

AEP is based on the expected frequency of occurrence of a particular "bin", f_i, and the estimated power yield, $P_i(\pm E_i)$, in that condition. AEP is always calculated on assumption of 100% availability.

If P_i is the expected power yield (in Watts) then 1.08E4 P_i Joules of energy can be expected in each 3 hour period satisfying the conditions of bin i. If in a typical year, fi periods of 3 hours satisfy the conditions of bin i, then the annual energy production can be calculated as

$$AEP = 1.084E4 \sum f_i P_i$$

The AEP shall be calculated in two ways, one designated AEP measured, the other AEP extrapolated. If the measured power matrix does not include data up to cut-off wave height and period, the power matrix shall be extrapolated from the maximum measured wave height up to a cut-out wave height for a given period.

AEP measured shall be obtained from the measured power matrix by assuming zero power for all wave heights, and periods above and below the range of the measured power matrix readings.

AEP extrapolated shall be obtained from the measured power matrix by assuming zero power for all wave heights below the lowest wave height in the measured power matrix. Above the measured power matrix wave height, constant power shall be used for waves between the highest wave height in the measured power matrix up to the cutout wave height for a given period.

AEP measured and AEP extrapolated shall be presented in the test report as detailed in clause 5. For all AEP calculations, the availability of the WECS shall be set at 100%.

It is important to note that $P_i(\pm E_i)$ is only a robust estimate of the expected power and its uncertainty in the conditions of bin i at the test site. Generally it may be expected that the AEP can be calculated for another site (with the appropriate f_i) if the "spectrum of seas" is similar. It has been demonstrated (see ANNEX 5) that the wave spectra at the Orkney Test Centre can be expected to yield similar AEP power on average to Bretschneider spectra of the same [Hs, Tz].

Therefore, there is reasonable confidence that calculations of AEP at any other site using a Bretschneider distribution is also a reasonable approximation of average conditions. Due consideration of the different mixture of wind, sea and swell, or directional spread, should be taken when estimating AEP at other sites.

In cases where the WEC is directionally sensitive and the directional spectra characteristics at the deployment site are not always similar to those measured at the test site, then the sub set of the test data which most closely maps onto deployment site characteristics should be used for estimating the AEP. The details of the process used and the extent of any discrepancies should be recorded in the test report.

Estimates of AEP measured shall be labelled as incomplete when calculations show the AEP measured is less than 95% of the AEP extrapolated.

Estimations of uncertainty in AEP can be calculated on the basis of the upper confidence limits, P_i - E_i, and the lower confidence limits, P_i - E_i of power in each bin, and the same frequencies of occurrence.

The uncertainties in the AEP only consider those uncertainties from the power performance test and not the uncertainties due to other important factors. These factors should be reported if allowances need to be made and/or caveats provided in the test report. Practical AEP forecasting should account for additional uncertainties. This should include effects associated with shallow water etc, and include availability of the WEC due to environmental effects associated with storm damage, marine growth, etc.

5.4 POWER COEFFICIENT

An empirical omni-directional power coefficient for the WECS may be added to the test results and presented as detailed in Clause 6.9 (page 13). The coefficient shall be determined according to the equation:

$$P_{ij} = (\rho g^2/4\pi)L_{ij}\int f^{-1}.\exp[-1/2\{(f - f_e/\sigma\}^2].\ S(f)df$$

where $f_e = 1/T_e$ and $\sigma = \lambda_{ij} f_e$. T_e is the energy period defined as $T_e = m_{-1}/m_0$ and S (f) is the spectral density of the incoming wave field. The "power coefficient of the device" is described by $[L_i, \lambda_i]$, where L is the "absorption length of the device" and λ describes its sensitivity to wave frequency.

The value of λ depends upon the WECS. Two alternatives are allowed. Either, the value of λ may be specified by the manufacturer. In this case, L_i can be calculated as the mean value of L_{ij} (each calculated from the equation) for all independent determinations within bin i. Alternatively, both L_{ij} and λ_i can be estimated by fitting to all data for each bin i. A "least squares error in P_{ij}" should be used as the criterion for fitting.

A matrix of $[L_i, \lambda_i]$ may be presented with the matrix of $[P_i]$. The former has distinct advantages for estimating AEP at another site where the wave spectrum is quite different.

6_REPORTING FORMAT

6.1 DESCRIPTION OF THE WECS

The specific WECS under test should be described, including, as a minimum:

- Make, type, serial number and production year.
- Description of energy capture technology, including cut off levels, depth below surface of the energy capture axis of the WECS.
- Description of power take-off system and rating – power, voltage, type of generation etc.
- Normal range of operating parameters – water depth, mooring type etc.

6.2 DESCRIPTION OF THE TEST SITE

The test site arrangement and general facilities should be provided. A map should be provided showing the berth location(s), water depth, plus prevailing wave and wind roses. The map should show the locations of measurement devices and the met station.

A general summary of the instrumentation and equipment at the test site should be provided, details of which will be expanded in section 6.4.

6.3 DESCRIPTION OF GRID CONDITIONS

The voltage, frequency and the permitted tolerances should be recorded here. Any prevailing grid conditions that may have limited power output should also be documented.

6.4 DESCRIPTION OF TEST EQUIPMENT

The test equipment, which should meet the general requirements in Clause 3, should be described in full. The sensors, data acquisition system and communication links should be described, and documentation showing the calibration details prevailing at the time of the testing should be provided.

6.5 DESCRIPTION OF MEASUREMENT PROCEDURE

A description of the measurement procedure, as outlined in Clause 4, should be provided, including: procedural steps, test conditions, sampling rates and measurement period. A copy of the test log book showing all significant events that may affect the test results is to be appended.

6.6 PRESENTATION OF DATA

Tabular and graphical data formats are required, giving statistics of measured power against wave height and energy period. Scatter plots of the mean, standard deviation and maximum and minimum power output as a function of wave heights and energy periods are to be provided.

Special databases, together with the criteria for their selection should also be presented in the formats given above.

6.7 PRESENTATION OF MEASURED POWER MATRIX

The curve shall be presented for the measured and standard seawater densities. The tables shall include normalised and average data values for each bin. The standard uncertainties shall be shown. Power against wave heights and energy periods shall be presented in the form of a matrix.

The power matrix should also be provided as a contour map indicating the optimum power capture with sea-state and frequency capabilities/limitations.

6.8 PRESENTATION OF ESTIMATED AEP

Presentation of the estimated AEP should also be in the form of a power matrix as illustrated below. This is based on Hs and Te axis with the power based on the number of sea-state events and its associated power rating. This is similar in presentation to the sea-state scatter diagram.

TABLE: ANNUAL POWER MATRIX

- Presentation of measured power matrix is based on a reference water density to normalise the presentation of data.
- The test site wave climate should also be supplied based on an HS, Tz scatter diagram.
- The presentation should include a power matrix constructed over a range of sea-states with Hs and Te based for the test site location. This assumes that an approach is developed to cater for the frequency banding characteristics of the device.
- The power matrix should also be provided as a contour map indicating the optimum power capture with sea-state and frequency capabilities/limitations.

6.9 PRESENTATION OF POWER COEFFICIENT

Presentation of the power coefficient is to include justification for the adoption of a particular frequency operator, λ_i, based on the findings during controlled testing of the device at scale model stage, where a frequency operator has been assumed in calculating L_i. This should be adequately demonstrated from previous results.

6.10 UNCERTAINTY ASSUMPTIONS

Provide uncertainty assumptions on all uncertainty components. Annex 3 should be used as guidance for preparation of uncertainty assumptions.

6.11 DEVIATIONS

Any deviations from the requirements of this standard shall be clearly documented in the test report and supported with a technical rationale for each deviation.

ANNEXES_

1 ASSESSMENT OF TEST SITE

- Layout.
- Separation between devices – 500m minimum.
- Freedom from obstructions on seabed within 500m of each device.
- Environmental impact statement.
- Survey requirements for the site: bathymetry, sidescan sonar, sub-seabed profiling, benthic survey and sampling and vibrocore samples from any proposed anchor or pile locations.
- Collection of wave climate data – ideally for 3 to 6 months prior to deployment of the device for test.
- Proximity to marine support services.
- Availability of emergency services and dive support facilities.

2 EVALUATION OF UNCERTAINTY IN MEASUREMENT

Requirements for determination of uncertainty in measurement set out in this annex. The theoretical basis for determination of uncertainty and worked examples of estimating uncertainty is given in Annex 4

Measured Power Curve shall be supplemented with an estimate of the uncertainty of the measurement based on the ISO publication “Guide to the Expression of Uncertainty in Measurement”.

In the ISO guide, there are two types of uncertainties: Category A, the magnitude of which can be deduced from measurements, and Category B, which are estimated by other means. In both cases, uncertainties are expressed as standard deviations and denoted “standard uncertainties”.

TABLE 2 LIST OF UNCERTAINTY COMPONENTS

Measured Parameter	Uncertainty Component	Uncertainty Category
Electric Power	Current transformers	B
	Voltage transformers	B
	Power transducer or measurement device	B
	Variability of electric power	A
Seastate Parameters	Wave rider accelerometers	A
	Wave height	B
	Wave period	B
	Current velocity	B
	Current direction	B
	Seawater density	A
Air Temperature	Temperature sensor	B
	Radiation shielding	B
Air Pressure	Pressure sensor	B
Data Acquisition	Signal transmission	B
System	System accuracy	B
	Signal conditioning	B

THE MEASURANDS

The measurands are the power curve determined by the measured and normalized bin values of electric power in each of the bins defined by intervals of energy period and significant wave height (see 5.2) and the estimated annual energy production (see 5.3). Uncertainties in the measurements are converted to uncertainty in the measurand by means of sensitivity factors.

Uncertainty components – Table 2 above contains a minimum list of uncertainty parameters to be included in the uncertainty analysis.

3 THEORETICAL BASIS FOR DETERMINING THE UNCERTAINTY OF MEASUREMENT USING THE METHOD OF BINS

(To be developed)

4 TECHNICAL BACKGROUND TO WAVE SPECTRA

This Annex is a summary of a report of analysis carried out on UKMO data from the area near Orkney from which some of the general guidance in the standard has been drawn. It is included for illustrative purposes.

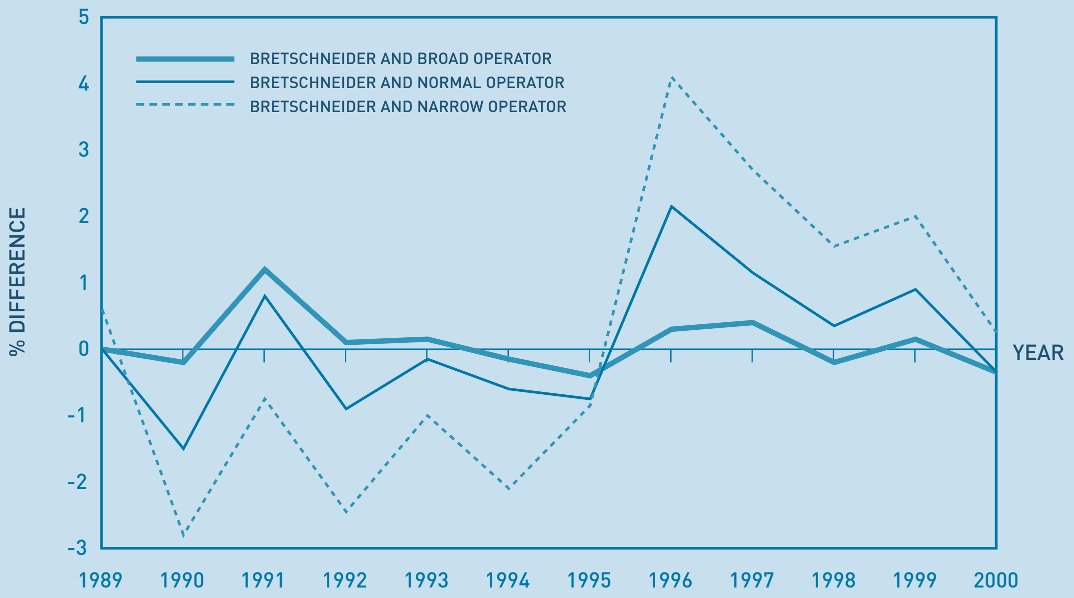
1 With significant wave height Hs and zero-crossing period Tz as the input to the synthetic spectrum, the Bretschneider solution provides a better fit to the UKMO spectral records than either the PM or the Jonswap spectra.

Mean differences between various synthetic spectra and the UKMO spectra for the period 1989 to 2000. Values are in square metres seconds.

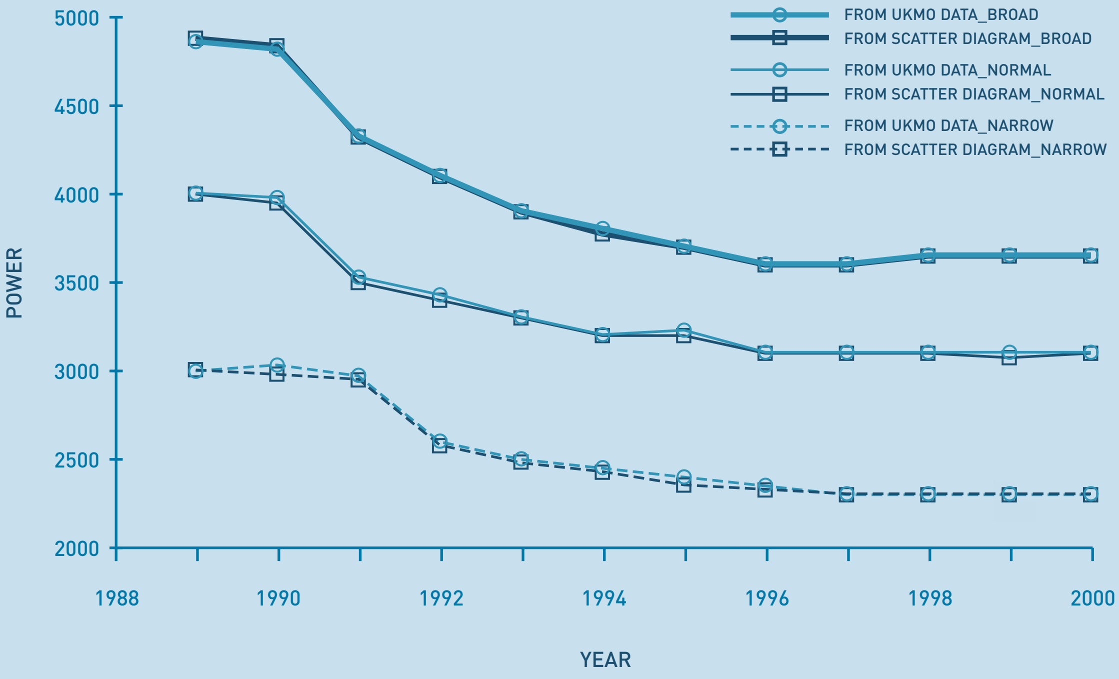
Type of Spectrum	Rms difference between UKMO and synthetic spectrum	Standard deviation
PM	4.27	7.7
Jonswap	6.57	12
Bretschneider	4.09	7.5

2 This standard does not necessarily recommend the use the of the Bretschneider spectrum in the format that uses wind speed as an input. However, when the significant wave height and zero-crossing period are already known by an alternative route, as they are in a scatter diagram or a wave spectral time series, then the Bretschneider format using (Hs, Tz) as input provides a satisfactory mean fit to the shapes of the frequency spectra. When used with a scatter diagram, it also delivers power predictions to good accuracy when compared with results obtained by processing the underlying raw spectral data.

YEARLY DIFFERENCES BETWEEN TOTAL POWER PREDICTED FROM RAW UKMO RECORDS AND FROM THE DERIVED SCATTER DIAGRAM IN CONJUNCTION WITH THE BRETSCHNEIDER SPECTRUM.

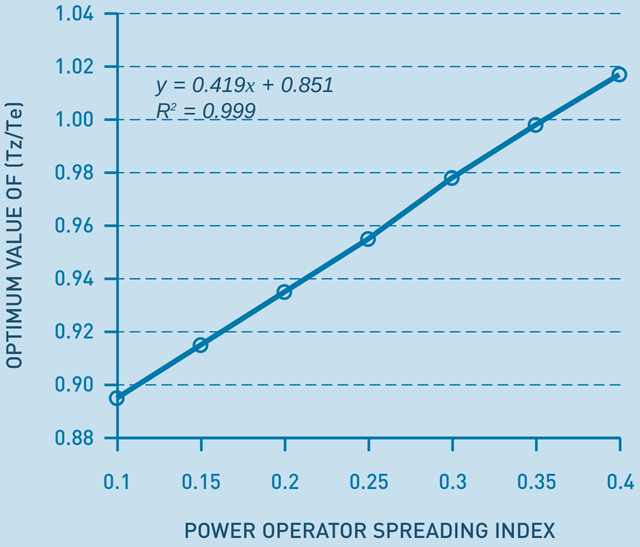


PREDICTED RUNNING AVERAGE POWER FOR THE THREE POWER OPERATORS USING RAW UKMO SPECTRAL RECORDS AND THE DERIVED SCATTER DIAGRAM IN CONJUNCTION WITH THE BRETSCHNEIDER SPECTRUM



3 In the use of a scatter diagram of (Hs, Tz), it remains necessary to know the energy period Te, in order to derive and apply the power operator. However, for a given bandwidth of operator, the Orkney data set indicates that there is a well-behaved linear relationship between the value of the bandwidth and the optimum value of (Tz/Te) to be used in the power predictions.

OPTIMUM VALUES OF (TZ/TE) FOR VARIOUS VALUES OF POWER OPERATOR SPREADING INDEX λ
WHEN USING THE BRETSCHNEIDER SPECTRUM IN CONJUNCTION WITH THE SCATTER DIAGRAM OF (HS,TZ)



4 The form of the generic power operator used in this standard is given by:

$O(f,\lambda,T_e) = \exp\{-[(f - f_e)/(\lambda f_e)]^2/2\}/f$

In the above expression, Te and fe are respectively the energy period and frequency of the spectrum and λ is the power operator spreading index. For a normal power operator, the value of the spreading index is taken to be 0.2. In the case of broad and narrow band power operators, values of 0.4 and 0.1 would be deemed appropriate.

The indicative energy output of the device may be obtained by integrating the power operator O(f,λ,Te) with the sea-state spectrum S(f):

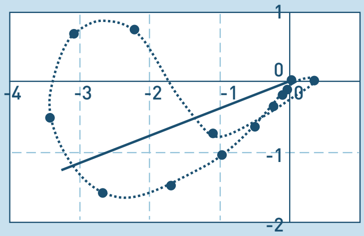
mean square response = $\int O(f,\lambda,T_e)\cdot S(f)df$

5 The application of a single peaked spectrum in the scatter diagram method is supported by the average annual properties of the underlying UKMO raw spectra, upon which the scatter diagrams are themselves based. At a site containing a strong swell influence, indicated by double peaks in the average long-term spectra, a more detailed approach would be required. One solution would be to directly use a UKMO wave model spectrum. Alternatively, it would be acceptable to use a time series of (Hs,Tz) in a form that presented swell and wind-sea separately and then to generate the spectrum using the Hubble and Ochi double peaked solution. The UKMO wave model also generates the swell and wind-sea timeseries .

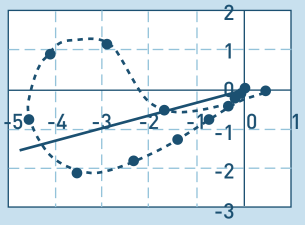
6 Polar diagrams of mean annual directional spectra provide a useful initial guide to the possible effects of machine directional sensitivity upon expected power capture.

Polar diagrams of mean directional spectra from the UKMO records for various thresholds of significant wave height covering the years 1989 to 2000.

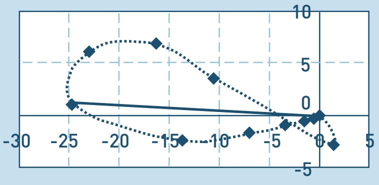
ALL WAVE HEIGHTS



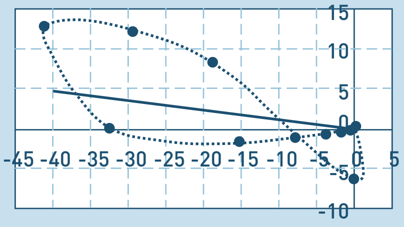
WAVE HEIGHTS
GREATER THAN OR EQUAL TO 1M



WAVE HEIGHTS
GREATER THAN OR EQUAL TO 4M



WAVE HEIGHTS
GREATER THAN OR EQUAL TO 5M

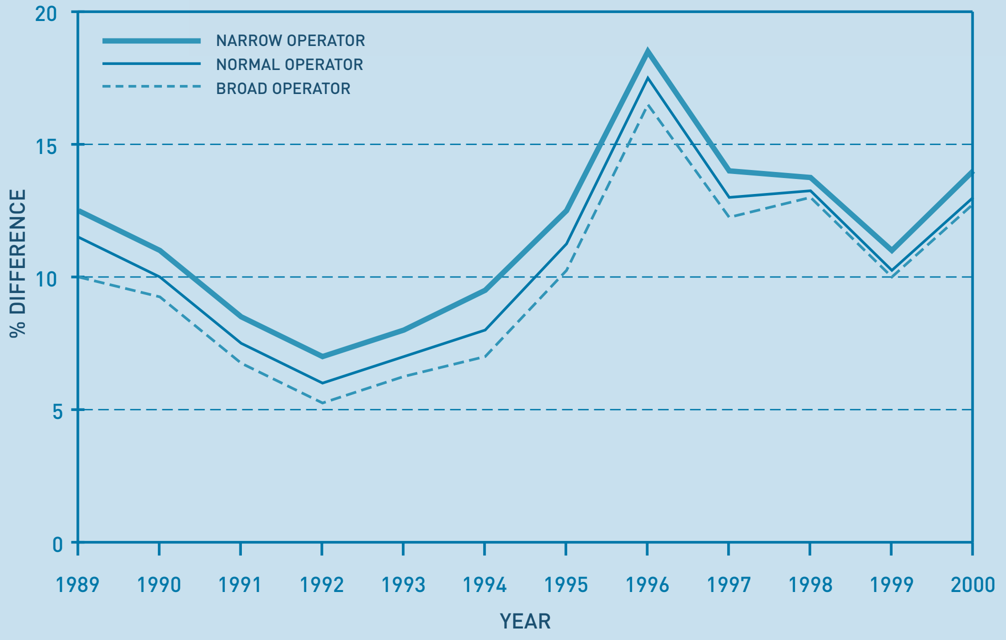


The distance of each point from the origin represents the value of the mean energy in that direction bin. The direction measured clockwise in degrees from the vertical ‘y’ or ‘north’ axis provides the angular direction from which that energy bin arises. The dashed line joins up the points in order of ascending value of the frequency bins, working in an anti-clockwise direction. The bold line denotes the mean energy-weighted sea-state direction.

See also the following Annex (5) on directionally sensitive WECS.

7 Annual differences in predicted power output between cosine-directional and omni-directional WECS depend more upon variations in sea-state directionality than upon the bandwidth of the machine power operator.

PERCENT DIFFERENCES BETWEEN MEAN ANNUAL ENERGY PREDICTIONS WITH AN OMNI-DIRECTIONAL WECS AND WITH A COSINE-POWER DIRECTIONAL WECS. BASED ON UKMO SPECTRAL RECORDS.



The power capture of a directional WECS is greater in years when the polar plot of the directional spectrum shows a clear focus, as in 1992 at the Orkney site. In years when the polar plot is more circular and therefore less focused, the energy capture is correspondingly lower, as in 1996.

5 DIRECTIONALLY SENSITIVE WECS

The impact of directionality on AEP may best be illustrated using a number of Polar diagrams showing mean energy for a range of thresholds of significant wave heights. When these are compared to the wave height operating range of the particular WECS, a conclusion may be drawn regarding sensitivity to the annual directionality variations. This should be included in the report as part of the commentary on the annual energy production for the device.

When the WECS to be installed is directionally sensitive, then it will be necessary to acquire site wave data in the form of a timeseries of directional spectra, irrespective of the relative location of the data and test sites.

- The predicted WECS mean square response for the sea-state specified by (Hs, Tz) may be obtained by integrating the frequency power operator O(f,λ,Te) with the spectrum S(f):

  $$P(H_s,T_z,\lambda) = \int S(f)\cdot O(f,\lambda,T_e)\,df$$

  In the above solution, the frequency power operator is taken to be of the frequency – response function type, namely:

  $$O(f,\lambda,T_e) \approx |H(f,\lambda,T_e)|^2$$

  In the expression for the power operator, λ denotes the spread of the power operator as defined in paragraph 5.4 (below) and Te represents the energy period of the sea-state spectrum.

- Annex 5, Paragraph 4 describes the form of power operator O(f,λ,Te) that has been used in the derivation of the results and conclusions. This form of O(f,λ,Te) requires knowledge of the sea-state energy period Te in order to obtain the power output from the spectrum. The study (referenced in Annex 5) found that, in order to obtain an accurate result for the power output from each (Hs, Tz) bin of the scatter diagram, then the optimal value of Te varied as a function of λ, the spreading constant of the power operator and of Tz, the sea-state mean crossing – period. Paragraph (3) of the section on wave data in the Draft Standard provides the recommended values for the ratio of (Tz/Te) for various values of λ.
- Once the power output has been obtained for each (Hs, Tz) bin of the scatter diagram, the mean square annual output may be obtained by summing over the set of bin values:

  Annual mean square power = $\sum_{H_s}\sum_{T_z}(8760/D)\cdot[PPT(H_s,T_z)/1000]\cdot P(H_s,T_z,\lambda)$

  In the above results, D is the duration in hours of each contributory sea-state in the scatter diagram. The term PPT(Hs,Tz) represents the parts per thousand during the year for which the sea-state (Hs,Tz) persists.

Should it be essential to apply a directional spectral timeseries then the following steps will be implemented:

- Where appropriate, the spectral timeseries at the wave data site shall be transformed to the WECS test site location by the application of two-dimensional wave modelling, which shall take into account refraction by bathymetry and currents under appropriate states of the tide. The result will be a directional spectral timeseries S(f,θ) that applies to the WECS test site.
- For a WECS that is sensitive to wave direction θ, then the mean square power output of each sea-state in the timeseries, characterised by S(f,θ) shall be predicted thus:

  $P = \int\int O(f,\lambda,T_e,\theta,\psi)\cdot S(f,\theta)\,df\,d\theta$

  In the above expression, θ represents the direction of each spectral component of the sea-state while ψ is the alignment of the WECS, relative to the same directional origin. For instance, it is possible that the WECS will be self-aligning to the energy-weighted mean direction of the sea-state.
- The energy period Te of each sea-state shall be calculated directly from the sea-state spectrum as follows:

  $T_e = m_{-1}/m_0$ where $m_n = \int f^n S(f)df$

  This form for Te will generally provide the input for the expression defining the power operator of the WECS.

  The significant wave height Hs and mean zero – crossing period Tz may further be obtained using spectral moments:

  $H_s = 4(m_0)^{1/2}$ and $T_z = (m_0/m_2)^{1/2}$
- The timeseries of predicted mean square power output derived from the spectral timeseries may be summarised in the form of a conventional scatter diagram based upon the axes (Hs,Tz). However, each bin of the scatter diagram shall contain the total output contributed by all the (Hs,Tz) sea-states held within that bin. In this way, the site and WECS performance characteristics may be represented in a form that can easily be assimilated.

6 QUESTIONS TO BE CONSIDERED BY USERS OF THIS DOCUMENT

6.1 Please identify other normative standards or reference material for this draft.

6.2 Comments on the collection of data and allocation of data between “bins”.
Also the size of bins should be commented upon.

6.3 Please comment on whether or not the “method of bins” should be a replica, with adjustments, of what is given in the BS EN 61400 – part 12, or whether a much simplified version is appropriate?

6.4 Please provide commentary on the mathematical approaches taken in this draft. In particular, if they are considered to be un-representative for a particular device, giving reasons.

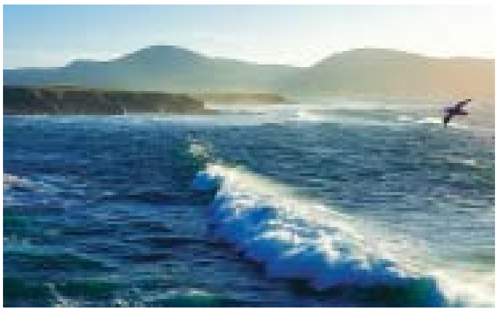
6.5 At present no uncertainty calculation has been included. Developers of devices are invited to suggest appropriate calculations in order that a common guideline may be drafted.

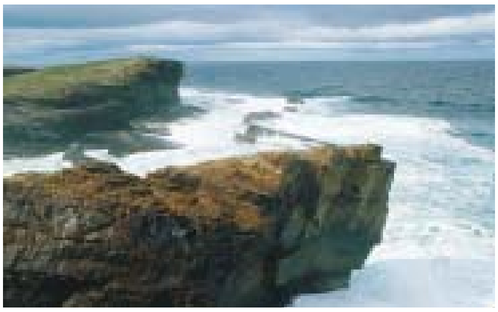
6.7 Any other points that cause difficulty or are unclear should be referred to EMEC.

In the event that any comments on the draft involve commercially sensitive material, EMEC is willing to enter into a non-disclosure agreement to facilitate progress. Careful consultation about later versions will be entered into with all developers who provide responses to amend the future versions.

7 BIBLIOGRAPHY

“Wave Device Performance Assessment Standards – 3333_i” - ABP Marine Environmental Research, July 2003.





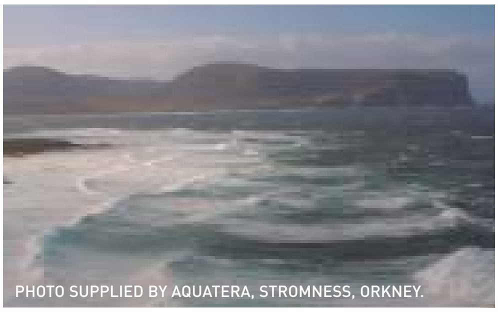
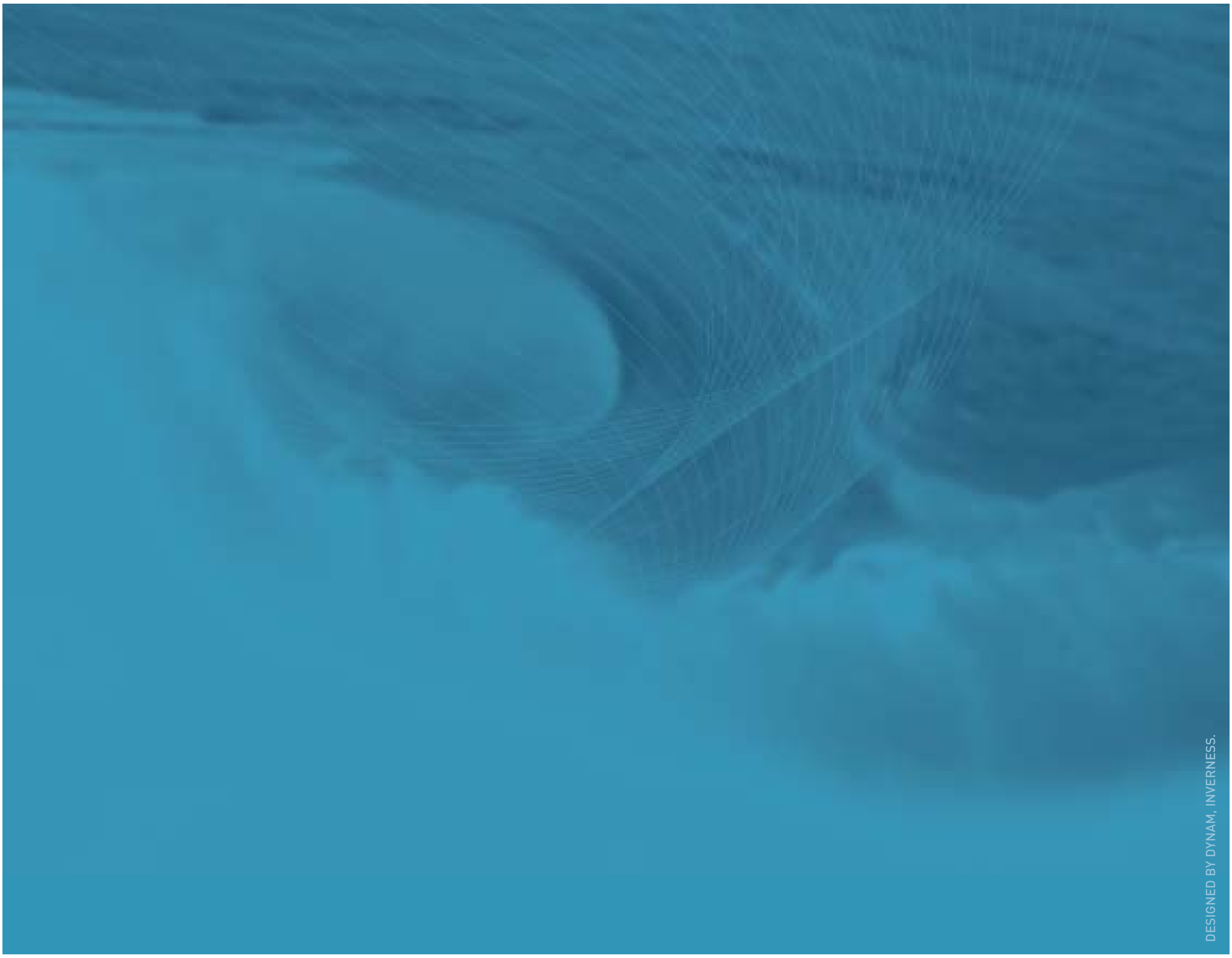


PHOTO SUPPLIED BY AQUATERA, STROMNESS, ORKNEY.



DESIGNED BY DYNAM, INVERNESS.

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Estimating power from wave measurements at the European Marine Energy Centre (EMEC) test site

E G Pitt, Applied Wave Research, 24 March 2005

1. Introduction

An accurate and detailed description of the wave conditions at the EMEC test site off Orkney is an essential part of the wave power generator test regime. Details of the wave conditions are required both hour by hour and also over the longer term so that reliable statistics can be assembled. Monitoring of the wave conditions is carried out using two Datawell Directional Waverider buoys which have been in operation for two years. The principal parameter of the wave field for this application is the energy flux or power and this study is concerned with estimating this as accurately as possible from the available measurements. Directional properties of the waves are also important, but these are not considered in this work.

The study used four months of half-hourly spectral data (5718 spectra) to investigate a number of estimators of power. The months used were June, July, November and December of 2003. We thus have two months of summer data and two months of winter data, and in Figure 1 we show average variance spectra for these two periods. The average spectra have been normalised by their respective maxima. Superimposed is a plot of group velocity for a depth of 50m. This has been normalised by the deep water value at each frequency. One of the main challenges in estimating power is immediately evident from this graph where it will be seen that the peaks of the spectra coincide rather closely with the maximum value of group velocity. The power is just the energy at each frequency (spectrum times density times g) times the group velocity at that frequency, summed over the spectrum. Thus, if we use the deep water value of group velocity, on the majority of occasions we will infer a lower value of power than actually existed at the time of the measurement.

1.1 A note on definitions

The moment-based definitions of Hs and Tz are used throughout this report (see Appendix 1).

2. Conclusions and recommendations

- The most accurate and straightforward method of estimating the power is directly from the spectrum using equation 6 in Appendix 1. This estimate is unbiased and using the standard 1600 second length record has a normalised standard error of about 10%. This can be reduced to about 7% by averaging adjacent spectra in pairs giving a one-hourly series of observations. This processing scheme is probably near-optimum and is strongly recommended. The present half-hour series is over-sampled with the individual spectra having unnecessarily large sampling errors.

- The Wavegen and the HsTe estimators are appropriate for deep water whereas as noted in the introduction this is effectively an intermediate depth site. The TTV estimator makes a correction for depth by supposing that all the variance (or energy) is being transported at a velocity appropriate to a frequency of 1/Te. For narrow spectra and for most unimodal spectra this is a fairly successful approximation. However, the depth correction is not exact with the consequence that there is still some residual bias for some spectra and some values of Te. It is the best approximation to use if there is some overriding impediment to using the spectrum.

3. Performance of the Estimators

3.1 Estimation from the spectrum

We use equation 6 in Appendix 1 adapted for use with measured spectra:

$$P = \rho g \sum_{i=1}^{i=64} S_i V_g(f_i)\Delta f_i$$

where

$V_g(f_i)$ is the group velocity at the ith frequency

S_i is the corresponding spectral estimate

Δf_i is the ith frequency increment, and

ρ and g have their usual meanings

The estimate is unbiased but is subject to statistical sampling variability. In order to quantify the variability we must briefly describe the Datawell spectrum analysis method.

The Datawell method takes eight contiguous sections of heave data each 200 seconds long. These are cosine tapered over one eighth of their length at each end before being Fourier transformed. Elementary spectra are formed from these transforms and are averaged over the eight sections to give a smoothed spectrum. The effective record length is 1600 seconds.

Section A1.5.2 of Ref 3 gives formulae for the variance of spectral moments and we adapt these:

$$Var(P) = \frac{(\rho g)^2}{1600}\sum_{i=1}^{64} S_i^2 V_g^2(f_i)\Delta f_i$$

The normalised standard deviation is found from $\dfrac{\sqrt{Var(P)}}{P}$

This quantity was calculated for all the spectra in the data set (5718 spectra) and the mean and standard deviation found. These were 8.9% and 2.1% respectively. However, the effect of the cosine tapering used in the analysis must be taken into account. This reduces the information content of the record and increases the variance by a factor of 1.185, and thus the standard deviation by 1.09. The normalised standard error in the power due to sampling variability is thus 9.7% ±2.3%. A useful improvement in the stability of the estimates can be obtained by averaging adjacent spectra in pairs to give a one-hourly time series of power. This reduces the standard deviation by a factor of 0.7071 to give 6.9% ±1.6%.

3.1.1 Statistical variability in the other estimators

The power, along with the spectral moments are weighted sums of the spectrum and all these quantities are correlated. Thus if on a particular occasion the power estimated from the spectrum is higher than the 'expected' value for the sea-state, the moments of the spectrum will also be higher. Therefore the variability in all moment-based estimates of power will be similar and moreover will be correlated.

3.2 The TTV approximation

This uses equation 10 of Appendix 1. In effect, all the variance in the spectrum is transported at a velocity appropriate to a frequency of 1/Te. Hs and Te were calculated from the spectra and the wavenumber k was calculated using the Newton-Raphson method with a depth of 50m. The calculation was carried out on all 5718 of the available spectra. Figure 2 shows a plot of the TTV estimate of power against the spectral estimate.

Best fit lines are drawn both constrained to pass through the origin and unconstrained. They are virtually indistinguishable. The correlation at 0.9993 is quite high. The mean difference was –0.56

kW/m and the rms difference was found to be 1.09 kW/m. If we scale the TTV estimates by 1.0221, the mean difference becomes 0.135 kW/m and the rms difference is reduced to 0.772 kW/m.

On the face of it this seems to be an accurate estimator, however investigation of its performance with respect to wave period reveals a more complicated story. Figure 3 shows the difference Power TTV minus Power Spectrum expressed as a percentage of Power Spectrum plotted against Te. There is a tendency for TTV to be correct at low values of Te, to underestimate at middle values of Te and to overestimate at high values of Te.

The implementation of this estimator does not require access to the spectral files (*.spt). Te can be had from

$T_e = \frac{(Tdw2)^2}{T_1}$ where Tdw2 and T_1 are available in the spectral history files (*.his). As long as the measurements are made in a constant depth we may calculate the wavenumber from

$k(f, h = 50m) = 4.066f^2 - 0.02859f + 0.004549$ where $f=1/Te$. This is a quadratic fit to a table of values calculated using a numerical procedure (Newton-Raphson), R^2 was 1.000.

3.3 Power from Hs and Te

This is equation 9 from Appendix 1. It is exact in deep water. Figure 4 shows a plot of Power spectrum against Power HsTe. Because no attempt has been made to correct for finite depth, values of Power HsTe must be corrected using the correlation results. The correlation coefficient, R^2, equals 0.9991 which is quite high. Of course, the correlation is valid only for a depth of 50m. The mean difference is -1.8 kW/m, and the rms difference is 3.72 kW/m. If the correction is applied, the mean difference becomes 0.0005 kW/m and the rms difference is 0.9 kW/m. Figure 5 shows the percentage difference (uncorrected) as a function of Te. As expected the difference is small at low values of Te, becoming larger as Te increases, but the relationship is far from simple. This estimator can be implemented from the spectral history files.

3.4 The Wavegen estimator

This is given by

$$P = 0.5495 H_s^2 T_z$$

Figure 6 shows a plot of Power Wavegen against Power spectrum for all the spectra. A least squares line has been drawn, and this shows that the estimator substantially underestimates the power. Moreover, the correlation coefficient is rather lower than the previous two estimates at R^2=0.9898. The mean difference is –4.62 kW/m and the rms difference is 8.37 kW/m. Figure 7 shows the percentage difference plotted against Te. The plot shows a large scatter of negative errors, with the errors tending to become larger for larger values of Te.

Table 1: Principal performance statistics

Estimator	Mean difference (estimator-power spectrum) (kW/m)	Rms of difference (estimator-power spectrum) (kW/m)	Correlation with power from the spectrum (estimator as independent variable)		
			Slope	Intercept (kW/m)	R^2
TTV	-0.56	1.09	1.019	0.194	0.9993
HsTe	-1.8	3.72	1.119	0.326	0.9991
Wavegen	-4.62	8.37	1.273	0.514	0.9898
TTV with correlation	0.13	0.77			
HsTe with correlation	0.0	0.90			

4. Acknowledgements

Colin Bullen of ICIT kindly supplied the data.

RegenSW consented to the reproduction of Appendix 1 from their Seapower SW Review.

5. References

1 Prof Julian Wolfram. 'EMEC – Estimation of incident power from wave buoy measurements'

2 Anon. 'EMEC Method Validation Statement: Wave Power Analyses'

3 Tucker M J & Pitt E G (2001) "Waves in Ocean Engineering" Elsevier Ocean Engineering Book Series, Vol 5, Elsevier, Kidlington, UK.

Appendix 1

Calculation of Wave Power

Note

The treatment given here is adapted from Tucker and Pitt (2001), Chapter 2.

Calculation of wave power

The energy flux due to a sinusoidal wave of amplitude *a* is given by:

$$P = \tfrac{1}{2}\rho g a^2 c_g \tag{1}$$

where c_g is the group velocity, ρ is the density of the water and g is the acceleration due to gravity. This is an application of Pointing's theorem. Alternatively a derivation from the hydrodynamics can be found in Kinsman (1965) or in Lamb (1932).

c_g is given by

$$c_g = \frac{1}{2} c_p \left(1 + \frac{2kh}{\sinh 2kh}\right) \tag{2}$$

where c_p is the phase velocity and is given by

$$c_p = \left(\frac{g}{k}\tanh kh\right)^{1/2} \tag{3}$$

Usually we will require the power as a function of frequency, *f*, rather than wavenumber, *k* (=2π/wavelength), so that we need the dispersion relation:

$$\omega^2 = gk\tanh kh \tag{4}$$

Where ω is the radian frequency $2\pi f$. *h* is the depth.

In deep water *kh* is large, so that tanh *kh* tends to unity and sinh *kh* tends to infinity. Using these in (2), (3) and (4) we get:

$$c_g = \frac{g}{4\pi f} \qquad \text{(deep water)} \tag{5}$$

For a unidirectional wave system we can generalise (1) to

$$P = \rho g \int c_g(f) S(f)\,\mathrm{d}f \tag{6}$$

where we have defined the spectrum *S* by

$$S(f)\Delta f = \sum \tfrac{1}{2} a_n^2$$

the sum being taken over those component wave trains whose frequencies lie in the range $f-\Delta f/2$ to $f+\Delta f/2$.

In deep water we substitute (5) into (6) to give

$$P_{deep} = \frac{\rho g^2}{4\pi}\int S(f) f^{-1}\mathrm{d}f = \frac{\rho g^2}{4\pi} m_{-1} \tag{7}$$

Where m_n is the n^{th} moment of the spectrum.

We define the energy period T_e as m_{-1}/m_0 to give

$$P_{deep} = (\rho g^2/4\pi)T_e m_0 = (\rho g^2/4\pi)T_e(H_s^2/16) \tag{8}$$

and finally, using $\rho = 1025$ kg/m^3, H_s in m, T_z in s,

$$P_{deep} = 0.49 H_s^2 T_e \ (kW/m) \ \text{very closely} \tag{9}$$

The power can be defined for a directional spectrum. In this case the result is to be interpreted as the energy flux across a unit diameter circle.

Approximate correction for depth when the spectrum is not available

We start with equation (8):

$$P_{deep} = (\rho g^2/4\pi)T_e m_0,$$

from equation (5) we can write for deep water, ie $h = \infty$

$$c_g(T_e, \infty) = \frac{gT_e}{4\pi} \text{ , so}$$

$P_{deep}(T_e) = \rho g c_g(T_e, \infty) m_0$, and we may propose that, approximately

$$P(T_e, h) \cong \rho g c_g(T_e, h) m_0 = \frac{\rho g}{16} c_g(T_e, h) H_s^2$$

Using $\rho = 1025$ kg/m^3, H_s in m, T_e in s, we get

$$P = 0.6286 c_g(T_e, h) H_s^2 \ k\text{W/m} \tag{10}$$

Calculation of Hs and Tz

Hs and Tz were required in comparisons between the spectral and non-spectral methods of estimating power. These were estimated from the spectrum using:

$$Hs = 4\sqrt{m_0} \text{ and}$$

$$Tz = \sqrt{\frac{m_0}{m_2}}$$

...where m_n is the n$^{\text{th}}$ moment of the spectrum.

References

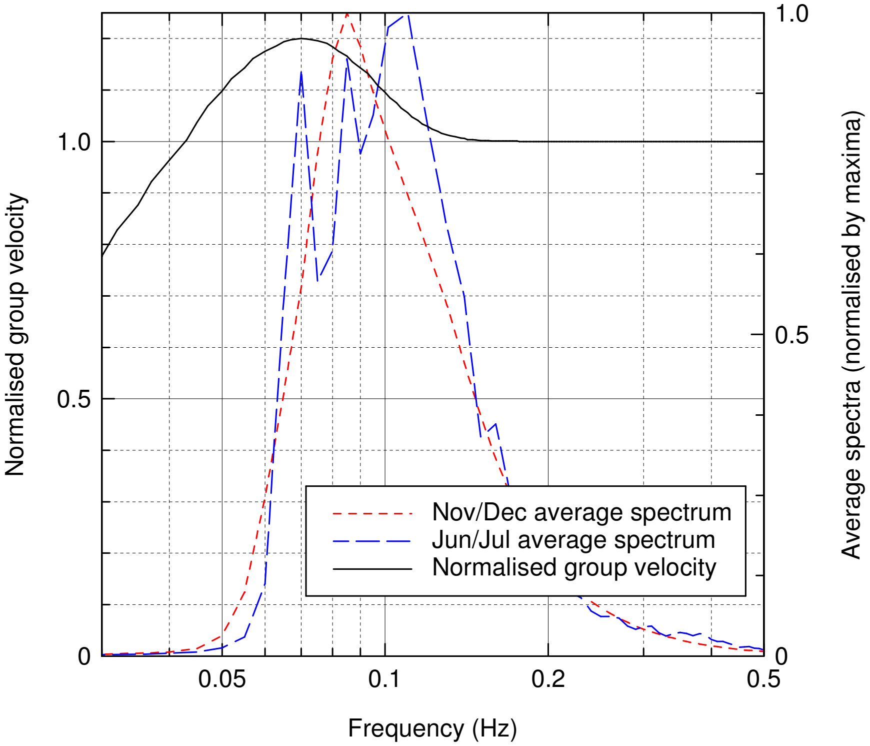
Kinsman, Blair (1965) "Wind Waves, their generation and propagation on the ocean surface". Prentice Hall, Englewood Cliffs, NJ.

Lamb, Sir Horace (1932) "Hydrodynamics" Sixth Edition, Cambridge University Press. Reissued by Dover Publications in 1945. (First edition published in 1879).

Tucker M J & Pitt E G (2001) "Waves in Ocean Engineering" Elsevier Ocean Engineering Book Series, Vol 5, Elsevier, Kidlington, UK.

Figures

Figure 1: Variation of group velocity with frequency in 50m depth



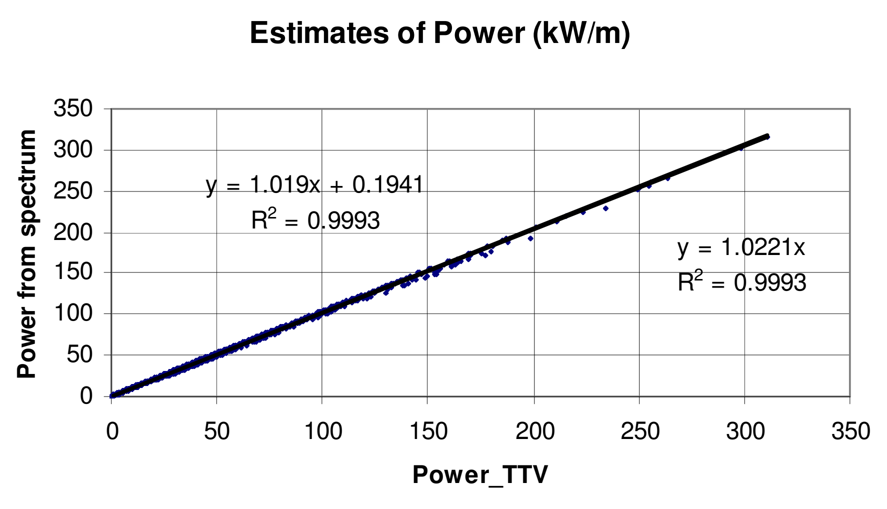


Figure 2: Correlation of Power_TTV and Power from spectrum

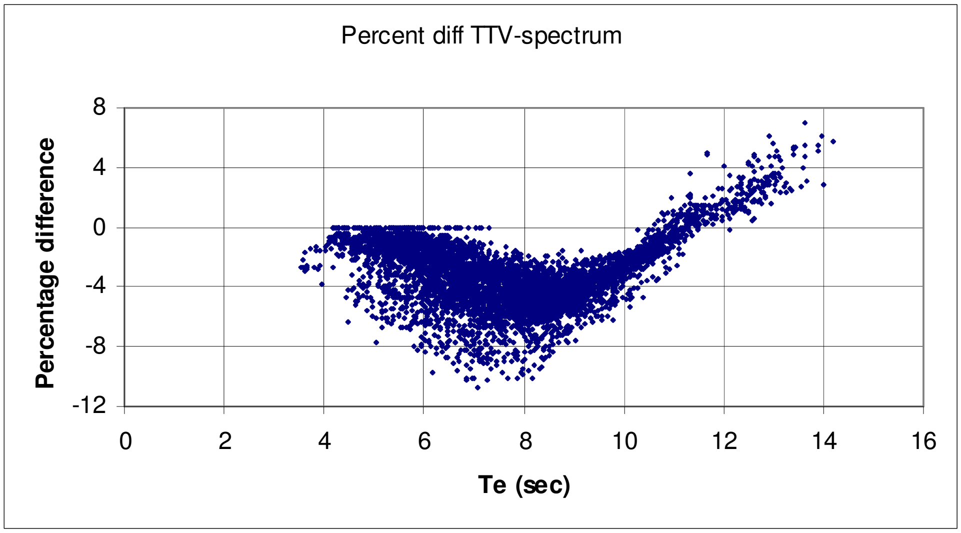


Figure 3: Percentage difference power TTV minus power spectrum plotted against Te

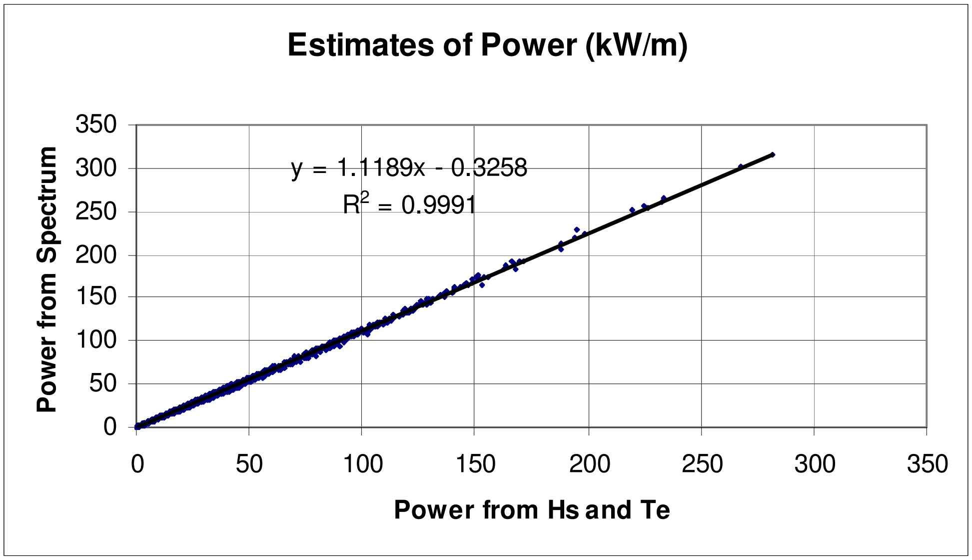


Figure 4: Correlation of Power from Hs and Te and Power from the spectrum

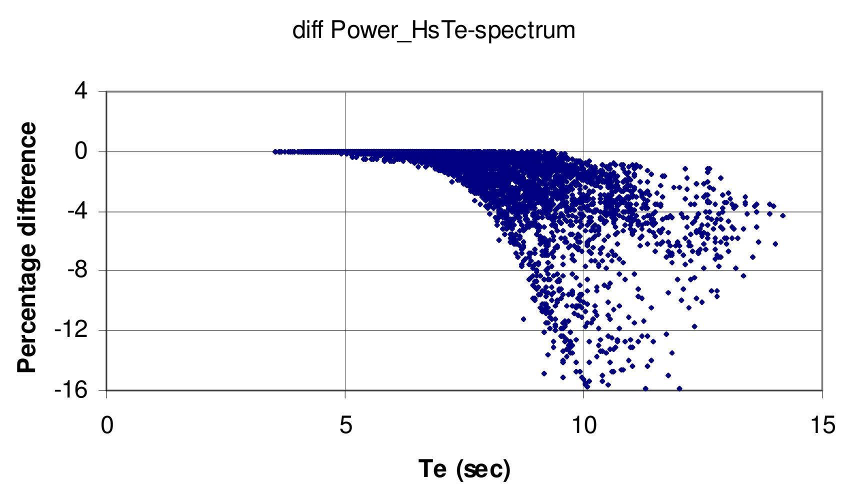


Figure 5: Percentage difference Power spectrum from Power HsTe plotted against Te

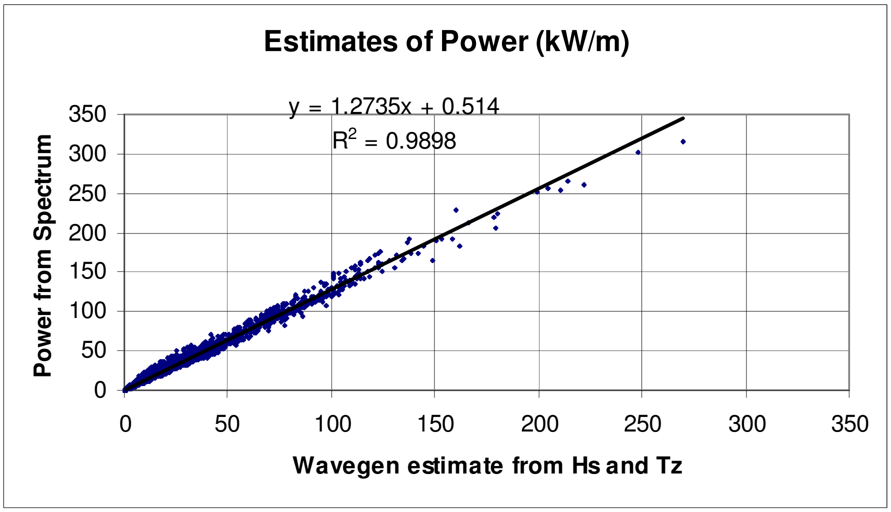


Figure 6: Correlation of power Wavegen and power spectrum

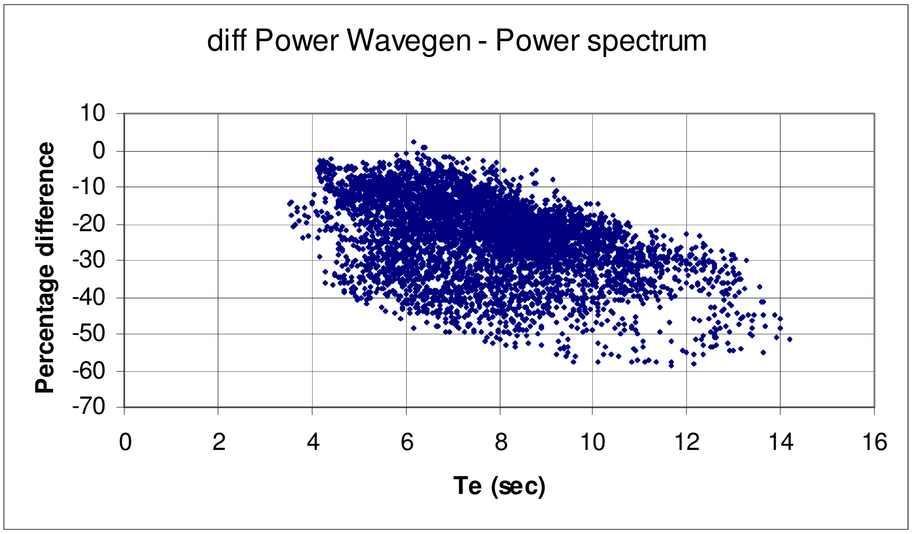


Figure 7: Percentage difference power Wavegen minus power spectrum plotted against Te

Appendix 2

Method for obtaining power from the Datawell spectra

Introduction

This Appendix does not deal with the design of a full processing scheme which would need to consider directional parameters, quality control and file handling issues. Instead we assume that we have a spectrum available to us consisting of a listing of frequency and spectral density.

Method

Since the frequencies are always the same these will not need to be read for each spectrum. There are 64 frequencies in the frequency list, these and the corresponding frequency increments are given by:

Quantity	Value	Remarks
Frequency f_n , n=1 to 16	0.025+(n-1)0.005 Hz	Upto and including 0.10 Hz
Frequency f_n , n=17,64	0.10+(n-16)0.01 Hz	0.11 Hz to 0.58 Hz
Frequency increment Δf_n , n=1,15	0.005 Hz	Upto and including 0.095 Hz
Frequency increment Δf_n , n=16	0.0075 Hz	At 0.01 Hz
Frequency increment Δf_n , n=17,64	0.01 Hz	0.11 Hz to 0.58 Hz

Table of frequencies and frequency increments for the Datawell spectra

The 64 values of the spectrum S_n are then read from the file. Strictly speaking what is read from the file is the spectrum normalised by its maximum. So the spectral peak always has a spectral density of one. Then multiply the spectrum by the value of the spectral density at the peak Smax, which is included as a parameter in the file.

We also need the group velocity at each frequency, $V_g(f_n)$. This is calculated from

$$V_g = \frac{1}{2}\left(\frac{g}{k}\tanh kh\right)^{1/2}\left(1+\frac{2kh}{\sinh 2kh}\right)$$

where h is the depth and k is the wavenumber = 2π/wavelength. k must be calculated from the dispersion relation,

$$\omega^2 = gk\tanh kh$$

Where ω is the radian frequency $2\pi f$..

Unfortunately, this equation cannot be solved explicitly for k in terms of f so a numerical procedure must be used. However, if we are considering only one depth we may form a table of k against f using the numerical procedure and approximate the resulting curve by a best fit polynomial. We have done this for h=50m. The resulting relationship is:

$$k(f, h = 50m) = 4.066f^2 - 0.02859f + 0.004549$$

In any case, we next set up a table of values of V_g evaluated at the 64 values of frequency, $V_g(f_n)$. Finally we calculate the power from

$$P = \rho g \sum_{i=1}^{i=64} S_i V_g \left(f_i\right) \Delta f_i$$

where

$V_g\,(f_i)$ is the group velocity at the *i*th frequency

S_i is the corresponding spectral estimate

Δf_i is the *i*th frequency increment, and

ρ and g have their usual meanings

Fortran90, and presumably other programming languages, provide syntax for forming such sums in one line of code.

In Fortran90 it looks like:

```
POWER=SUM (GROUP_VEL_ARRAY(1:64)*SPEC(1:64)*DEL_F(1:64))*ROG/1000.0  ! kW/m
```

For subsequent spectra we need only read in the 64 values of S_n and form the sum as above.