Hawaii National Marine Renewable Energy Center (HINMREC)

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Task 5: Wave Energy Conversion Device Performance

WEC Ocean Testing: Test Protocols Report

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Test Protocols Final Report

Hawaii National Marine Renewable Energy Center WEC Ocean Testing

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GL Garrad Hassan

TEST PROTOCOLS FINAL REPORT

HAWAII NATIONAL MARINE RENEWABLE ENERGY CENTER
WEC OCEAN TESTING

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REVISION HISTORY

Issue	Issue Date	Summary
A	30 September 2013	Initial issue for review
B	14 May 2014	Final Issue, incorporating Client feedback

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EXECUTIVE SUMMARY

Garrad Hassan America, Inc. (GL GH) has been contracted by The Research Corporation of the University of Hawaii (RCUH) to conduct a project for the Hawaii Natural Energy Institute at the University of Hawaii (HNEI-UH) supporting the institute's Hawaii National Marine Renewable Energy Center (HINMREC) wave energy testing program. HINMREC, under funding from the Wind and Water Program of the U.S. Department of Energy (DOE), is working in collaboration with the U.S. Navy to develop a Wave Energy Test Site (WETS) at the U.S. Marine Corps Base Hawaii - Kanehoe (MCBH-K) in Oahu, Hawaii.

WETS will provide a location for the ocean testing and demonstration of wave energy converter (WEC) devices. WEC technologies seek to convert the energy associated with the oscillatory motion of ocean surface waves into a more useful form – typically electricity. The WETS facility currently has one test berth established in 30m deep water, and is being expanded with two additional berths at 60m and 80m depths, with connection to the MCBH-K electricity grid.

Support of testing operations and the evaluation of WEC system performance are two of HINMREC's primary roles at the WETS. To facilitate this responsibility GL Garrad Hassan's expert wave energy team will provide wave energy test protocols, support HNEI-UH with processing performance data, and conduct independent numerical model verification exercises for HNEI-UH's WEC operational models.

This report presents the wave energy test protocols for HINMREC's use in the evaluation of WEC system performance at the test site. Both background information and practical advice are provided for analyzing both environmental and WEC data.

1 INTRODUCTION

This report is issued to the The Research Corporation of the University of Hawaii (RCUH or the "Client") pursuant to a written Agreement for Services effective 14 March 2013 and RCUH Purchase Order #Z10027978. The Client has requested that Garrad Hassan America, Inc. (GL GH) perform services, including the development of wave energy test protocols for the University of Hawaii, Wave Energy Test Site (HINMREC), under funding from the U.S. Department of Energy (DOE) is working in collaboration with the U.S. Navy to develop a Wave Energy Test Site (WETS or the "Project") located at U.S. Marine Corps Base Hawaii – Kanehoe (MCBH-K) in Oahu, Hawaii.

The scope of work conducted by GL GH consists of three main components:

1. Documentation of test protocols for wave energy converter (WEC) devices and support to the testing program
2. Verification of WEC performance models developed by UH HNEI
3. Verification of WEC array models developed by UH HNEI

The present document, entitled *Test Protocols Final Report*, forms part of the first project component listed above. The information presented in this report comprises the following information:

- A review of published test protocols and relevant standards
- An assessment of monitoring equipment and instrumentation
- Definition of WEC performance metrics
- Data post-processing recommendations

Section 2 of this report provides an overview of published test protocols and relevant standards. The requirements for monitoring of environmental data are discussed briefly in Section 3. A description of wave measurement instrumentation is presented in Section 4. The main post-processing guidelines are presented in Section 5 where quality controls, analysis methods, data archiving and presentation are discussed. Section 6 identifies and defines the primary performance metrics for WEC testing and Section 7 closes with a discussion of uncertainty analysis. To understand and apply the post-processing methods advocated in this report, it is useful to review some of the theory and definitions used to describe waves. This is generally standard material, available in academic and engineering literature, but to facilitate the reading of this report the relevant material has been summarized in Appendix A.

This document includes and builds upon information contained in a previous deliverable to RCUH: 702053-USSD-T-01– *Data Post-processing Guidelines*. The focus of the original technical note was an initial presentation of post-processing methods to be applied to wave data recorded during WEC testing. The following topics were addressed within the technical note:

- Quality checking
- Analysis methods
- Data archiving and presentation
- Uncertainty analysis

Another deliverable under the first project component (listed above as item 1.), 702053-USSD-T-02– *Operational Documentation*, is not included in this report and has been supplied separately to the Client. This document covered:

- Main activities, process and controls to be set in place at WETS to enable safe marine operations
- Overviews of main safety and operational issues to be considered at various project stages
- Checklists to assist both WETS management and device developers in preparatory works and daily marine operations for various phases of a typical test program

This *Test Protocols Final Report*, together with the *Operational Documentation* technical note, represents GL GH's documentation deliverables under the first component of the scope of work. However, GL GH will continue to provide support to UH HNEI as data is collected from the site to ensure that international best practices are followed, for the benefit of the testing program. The second and third components, for verification of WEC performance and array models respectively, will be also be completed over the remainder of the project in accordance to the Agreement for Services.

2 REVIEW OF PUBLISHED TEST PROTOCOLS AND RELEVANT STANDARDS

This section presents a review of existing international guidelines, standards (including draft standards) and test protocols directly applicable to WECs. In accordance with HINMREC's role at WETS, the focus of this report is on resource and performance assessment and sea testing to support WEC design, and only documentation related to these topics is reviewed here. Documentation for wave energy resource assessment, WEC design and performance assessment has been developed over the past few years, but no final national or international standards currently exist. This is due to the relative immaturity of the wave energy sector, and in the case of the International Electrotechnical Commission (IEC) – the international issuing body of the principal wind turbine performance assessment standard – a standard has deliberately been avoided. A decision was made to develop a '*technical specification*' rather than a standard until further knowledge and experience in the industry has been obtained.

Prior to the development of the IEC technical specifications, the European Marine Energy Test Centre (EMEC) commissioned a number of guidelines to create a Marine Renewable Energy Guides series. This series has continued to be developed, and now contains a range of documents for WECs including performance assessment, resource assessment, design basis, health & safety and grid connection. It's also worth noting that the EMEC performance and resource assessment documents have both fed into the development of the corresponding IEC technical specifications.

Performance assessment protocols were also developed under contract to the UK's Department of Trade & Industry (DTI), now re-formed into the UK's Department of Energy & Climate Change (DECC). The DTI device performance protocols were primarily developed to ensure uniform testing of device power curves and performance across applicants for the Marine Renewable Deployment Fund (MRDF) – a now-ceased UK government grant. An additional motive was to use these protocols as a 'trial run' for the development of future documentation.

EquiMar, a European Union (EU) consortium, produced an extensive suite of protocols for the evaluation of marine energy systems and the development of projects. As for the other sources, only those directly relevant to WEC design, resource and performance assessment are discussed here.

There are currently no dedicated standards in place for the design of WECs, but a number of organizations have produced documentation relating to their design and/or certification. These include the IEC and EMEC, as part of their series of marine energy documents discussed above, the Hydraulics and Maritime Research Centre (HMRC), and two certification agencies, namely Germanischer Lloyd (GL) and Det Norske Veritas (DNV) which have in September 2013 undergone a merger to form the DNV GL Group.

More generally, the documentation which is of relevance to sea trials of WECs is extensive, and apart from the review of documentation for design, resource assessment and performance assessment presented here, it can be noted that there are other topics of importance:

- Health & safety
- Manufacture / fabrication
- Transportation, loading and unloading
- Installation / construction
- Commissioning
- Maintenance
- Decommissioning

Due in large part to the maturity level of the wave energy industry, wave--specific documentation does not exist for the above topics, and typically best practice methods from offshore wind energy, maritime and other fields are applied in the relevant cases. It can also be noted that a previous deliverable[1] to the Client discussed operational issues, as well as activities, processes, controls and management/developer checklists for various phases of a typical sea testing program. Adoption and adaptation of best practices from other industries was also often the basis for much of the documentation discussed here that is specific to wave or marine energy and the test protocols proposed.

2.1 Design of WECs

Presently, there are no specific, dedicated standards for the design of WECs. In addition, there is limited experience in defining design load cases (DLCs) for any type of WEC. A design load basis, consisting of a combination of DLCs, can be considered as a map of expected critical load situations a WEC may experience during its lifetime.

A limited number of documents that specifically approach WEC design and certification have been published. These include:

- *Det Norske Veritas AS (DNV) Offshore Service Specification (OSS) 312 (DNV-OSS-312, October 2008)*. This document overviews the principles and procedures associated with the certification of WECs and/or tidal energy converters, including an overview of relevant documentation (Section 3). It does not, however, include technical provisions.
- *DNV's 'Guidelines on Design and Operation of Wave Energy Converters', May 2005, The Carbon Trust*. In the absence of a specific standard for WEC design, this document compiles a long list of related standards (in its Section 28[2]) and outlines methodologies for fatigue analysis (in its Appendix A) and wave load modeling (in its Appendix B).
- *The European Marine Energy Centre (EMEC) 'Guidelines for Design Basis of Marine Energy Conversion Systems', 2009*. This report overviews general aspects behind design basis documentation, covering both wave and tidal energy converters.
- IEC TC114/PT 62600-2 – Design Requirements. Although yet to be finalized, the draft technical specification / design requirements for marine energy systems under development by an IEC technical committee (*IEC TC114/PT 62600-2*) are particularly relevant for load calculations exercises.

In addition to documents outlined above, GL GH has performed extensive reviews of standards from the maritime, oil & gas and offshore wind sectors that are relevant to WEC design. GL GH considers that there are considerable similarities between the design of WECs and such structures / installations, which allows these documents to be a starting point when defining DLCs for WECs.

For load calculation and strength analysis GL GH typically follows the key documentation listed in Table 2-1 (see Section 2.5). Further documents that are relevant, in GL GH's opinion, for the description of the environmental conditions, mooring and structural analysis are also referred to in Table 2-1.

2.2 Resource Assessment

The principal documentation for WEC resource assessment is likely to be the IEC technical specification once finalized and published. In the meantime, the EMEC guidelines are a key source of publicly-available information. The key stages involved in undertaking a resource assessment are largely common across the IEC and EMEC documents. A brief review of the core documents is presented in the following subsections.

[1] 702053-USSD-T-02– Operational Documentation

[2] There are other documents in the public domain that overview applicable standards (e.g. http://www.oregonwave.org/wp-content/uploads/Wave-and-Current-Energy-Generating-Devices-MMS-2009.pdf).

2.2.1 IEC (International Electrotechnical Commission)

This document, issued by IEC, is part of a series of marine energy technical specifications. It is currently in draft form. Once published, this it is likely to become a primary source for wave energy resource assessment. A brief summary of the reference is given below.

- *IEC 62600-101 TS Ed. 1: Marine energy - Wave, tidal and other water current converters - Part 101: Wave energy resource assessment and characterization*. The focus of this document is resource assessment for wave energy technologies. It is a draft document that provides guidance for all stages of resource assessment (initial regional assessment through to detailed site assessment). The document is split into 4 main sections describing the principal data types, numerical modeling, data analysis, and reporting of results. The minimum requirements for data collection, data analysis and reporting (where relevant) are discussed in each section. Sensitivity analyses, evaluation of uncertainty and nearshore resource are described in further detail in annexes.

2.2.2 EMEC (European Marine Energy Centre)

This document, issued by EMEC, is part of a series of Marine Renewable Energy Guides which provide guidance for wave and tidal energy project developers. A brief summary of the key EMEC document is given below.

- *EMEC: Assessment of Wave Energy Resource*. The focus of this document is resource assessment for wave energy technologies. Initially a description of the resource is given, but the bulk of the document is concerned with discussion of the recommended measurements and wave modeling. This includes the role and principal types of measurements and modeling, comparison between measured data and the models, and methodologies for interpretation of the measurements and the modeled results. The methodology for combining an energy matrix for the site with a capture length matrix for a WEC device is provided, to produce a productivity matrix for an annual energy yield estimate. Finally, climate indices are discussed as well as reporting requirements.

2.2.3 EquiMar

The Equitable Testing and Evaluation of Marine Energy Extration Devices in terms of Performance, Cost, and Environmental Impact (EquiMar) documents, produced by the European Union (EU) EquiMar consortium, are part of a suite of protocols providing guidance on the evaluation of WECs and tidal energy converters and the development of projects. A brief summary of the key EquiMar documents is given below. EquiMar protocols 2.4 (Wave Model Intercomparison) and 2.6 (Extremes and Long Term Extrapolation) provide useful supporting information but are not discussed further here.

- *EquiMar: Deliverable D2.2; Wave and Tidal Resource Characterisation*. The focus of this document is resource assessment for wave and tidal stream technologies. Wave and tidal measurements are each briefly described, including types of data, types of instruments and quality control. A detailed description of wave parameterization is provided, including wave parameters for resource assessment, wave spectra, sea state statistics and wave-by-wave analysis. Tidal parameterization is discussed, focusing on tidal and turbulence analysis methods. Modeling methods for wave-current interaction, relevant to both wave and tidal technologies, are discussed. Finally, methods for assessing the spatial and temporal variation of the wave and tidal resource, separately, are presented.

- *EquiMar: Deliverable D2.3; Application of Numerical Models*. The focus of this document is resource assessment for wave and tidal stream technologies. The document is focused specifically on the use of numerical models in resource assessment, and their role in this context is first discussed. Wave and tidal resource modeling are each discussed in detail, including modeling overview, the principal models used, modeling processes, input data and interpretation of the results. The calibration and validation of numerical models is then discussed in detail.

- *EquiMar: Deliverable D2.7; Protocols for wave and tidal resource assessment*. The focus of this document is resource assessment for wave and tidal stream technologies. This document provides a summary of wave and tidal resource characterization and site assessment. Key areas discussed for each of wave and tidal include key parameters, measurement (including process, analysis methods and uncertainty), modeling (including boundary conditions, bathymetry and metocean conditions, and calibration and validation), and interpretation of results. Finally, site considerations including constraints and survivability, and reporting requirements are discussed.

2.3 Performance Assessment

As for resource assessment in Section 2.2, the principal documentation for WEC performance assessment is the IEC technical specification. The EMEC guidelines and DTI protocols have both fed into the IEC technical specification, so will be briefly reviewed here as well. The overall requirements are largely similar between the DTI and EMEC documents, but they differ in the details. As in Section 2.2, a brief review of the core documents is presented in the following subsections.

2.3.1 IEC (International Electrotechnical Commission)

This document, issued by the IEC, is part of a series of marine energy technical specifications. Published in August 2012, this document now constitutes the primary source of information for performance assessment of WECs. A brief summary of the reference is given below.

- *IEC 62600-100 TS Ed.1: Marine energy – Wave, tidal and other water current converters – Part 100: Power performance assessment of electricity producing wave energy converters*. The focus of this document is performance assessment for wave energy technologies. Initially the requirements for the test site characterization are discussed, followed by the methodology for data recording. The collection and analysis of resource and power data are each described in detail. Finally, the calculation methodology for power performance and mean annual energy production are described. An example of a normalized power matrix, a method for power loss compensation, the evaluation of uncertainty, and error analysis are described in further detail in annexes.

2.3.2 EMEC (European Marine Energy Centre)

This document, issued by EMEC, is part of a series of Marine Renewable Energy Guidelines which provide guidance for wave and tidal energy project developers. For performance assessment, the following reference has been produced for WECs:

- *EMEC: Assessment of Performance of Wave Energy Conversion Systems*. The focus of this document is performance assessment for wave energy technologies. The document describes the high level data requirements, including bathymetry, current speed and height, and waves. General measurement considerations, e.g. sample duration and frequency, are followed by detailed descriptions of the requirements for WEC power output, wave and meteorological measurements. The calculation of performance indicators is followed the required reporting format.

2.3.3 DTI (UK Department of Trade & Industry)

This document was issued by the UK's Department of Trade & Industry (DTI), now incorporated within the UK's Department of Energy & Climate Change (DECC), to provide guidance on the performance assessment of WECs.

Although it was specifically written for the now-ceased Marine Renewable Deployment Fund (MRDF) funding, it is applicable to all WEC performance testing.

- *DTI Preliminary Wave Energy Device Performance Protocol*. The focus of this document is performance assessment for wave energy technologies. Initially, the required project information prior to commissioning is listed. The bulk of the document is organized into 3 main sections, describing the resource measurements, device measurements and export measurements. Each section provides an explanation of the required data collection and data analysis. The reporting requirements are summarized in the final section of the document. Supporting commentary is provided in an additional report, including a range of definitions of the core performance variables and metrics.

2.3.4 EquiMar

These documents, produced by the European Union (EU) EquiMar consortium, are part of a suite of protocols providing guidance on the evaluation of WECs and tidal energy converters and the development of projects. A brief summary of the key EquiMar document related to performance assessment of sea trials is given below.

- *Equimar: Deliverable D4.1; Sea trial manual.* The focus of this document is to outline the prospective tasks to be undertaken during a sea trial, including notes on where procedures differ from those adopted during tank testing. This covers sea testing from 1:4 scale prototypes to full-scale, pre-commercial prototypes.

- *Equimar: Deliverable D4.2; Data Analysis and Presentation to Quantify Uncertainty.* The focus of this document is the provision of a methodology for the analysis and presentation of data obtained from sea trials. Particular attention is given to estimation of the uncertainty of the performance figures and device characteristics involved.

2.4 HMRC (Hydraulics and Maritime Research Centre)

It can also be noted that HMRC at University College Cork in Ireland has created a protocol for the development and evaluation of WEC technologies which has been adopted / modified in several of the above described documents. A brief summary of its contents is provided below.

- *Hydraulics and Maritime Research Centre (HMRC): Ocean Energy Development & Evaluation Protocol*. The focus of this document is a development and evaluation protocol for wave energy technologies. The document is focused on the evolution and improvement of the WEC itself, and does not consider generic aspects of wave energy extraction such as resource assessment, site surveys, grid connection, permissions or licenses, etc. The document is limited to buoyant-type devices, or those termed '*2nd Generation WECs*', and considers development up to and including prototypes or pilot devices.

2.5 Summary: Key Documentation (Protocols, Standards)

Table 2-1: Core documentation – WEC design

Doc. Reference	Title	Application / Relevance	Supporting Documents
DNV-OSS-312	Certification of Tidal and Wave Energy Converters	Guidance on overall procedures	DNV-OSS-304 Risk Based Verification of Offshore Structures DNV-OSS-102 Rules for Classification of Floating Production, Storage, and Loading Units
GL Rules and Guidelines IV-6-4	Structural Design	Overall description of environmental conditions and design loads (environmental, permanent, functional and accidental), including principles for structural design	DNV-RP-C205 Environmental Conditions and Environmental Loads GL Rules and Guidelines IV-6-3 Fixed Offshore Installations (Section 4 – TLPs) DNV-OS-C103 Structural Design of Column Stabilised Units (LRFD Method) DNV-RP-C204 Design against Accidental Loads API RP 2FPS Recommended Practice for Planning, Designing, and Constructing Floating Production Systems
DNV-OS-C101	Design of Offshore Steel Structures, General (LRFD Method)	Structural design and analysis (primary composite design)	GL Rules and Guidelines IV-6-4 Offshore Structures: Structural Design
DNV-OS-C501	Composite Components		GL Rules and Guidelines IV-2-5 and II-2-1 Fibre Reinforced Plastics and Bonding
DNV-OS-E301	Position Mooring	Mooring specification / load assessment	GL Noble Denton 0032/ND (2010) Guidelines for Moorings API RP 2SK (2005) Design and Analysis of Stationkeeping Systems for Floating Structures, 3rd ed., (with 2008 addendum)
ABS Pub# 115	Guide for the Fatigue Assessment of Offshore Structures	Overview of fatigue assessment methods in offshore installations (inc. safety factors)	DNV-RP-C206 Fatigue Methodology of Offshore Ships DNV-RP-C203 Fatigue Design of Offshore Steel Structures
DNV-RP-F205	Global Performance Analysis of Deepwater Floating Structures	Floater load models, de-coupled and coupled response analysis	GL Rules and Guidelines IV-6-4 Offshore Structures: Structural Design (Section 4.6)

Table 2-1: Core documentation – WEC design (conc.)

Doc. Reference	Title	Application / Relevance	Supporting Documents
IEC 88/379/NP (PEL/88_10_0084)	Standard for Floating Offshore Wind Turbines (FOWT)	Design Load Cases (DLCs) Strength analysis in FEM Floating support structures (at least partially)	DNV-OS-J101 Design of Offshore Wind Turbine Structures DNV Commentary and amendments to IEC 61400-3 concerning offshore floating turbines IEC 61400-3 Wind Turbines – Part 3: Design requirements for offshore turbines Lloyd's Register – Guidance on offshore wind farm certification. Section 4.2 – Loading on floating structures. Section 6.2 – Floating Structures GL Rules and Guidelines IV-2 Guideline for the Certification of Offshore Wind Turbines (namely Chapter 4 – Load Assumptions; and Chapter 5 – Strength Analyses ABS Guide for building and classing offshore wind turbine installations (2010)

Table 2-2: Core documentation – WEC resource assessment

Doc. Reference	Title	Application / Relevance	Supporting Documents
IEC 62600-101 TS Ed. 1	Wave energy resource assessment and characterization	Draft technical specification for resource assessment of WECs	NDBC, 2009: NDBC Technical Document 09-02, Handbook of Automated Data Quality Control Checks and Procedures WMO, 1998: Guide to wave analysis and forecasting, World Meteorological Office, second edition; WMO No.702 ISO Guide to uncertainty in measurement 1995, ISBN 92-67-10188-9
EMEC	Assessment of Wave Energy Resource	Guideline for resource assessment of WECs	DNV-RP-C205 Environmental Conditions and Environmental Loads
EquiMar D2.2	Wave and Tidal Resource Characterisation	Protocol for resource assessment	(see references section)
EquiMar D2.3	Application of Numerical Models	Protocol for the application of numerical models	(see references section)
EquiMar D2.7	Protocols for wave and tidal resource assessment	Protocol for resource assessment	(see references section)

Table 2-3: Core documentation – WEC performance assessment

Doc. Reference	Title	Application / Relevance	Supporting Documents
IEC 62600-100 TS Ed. 1	Power performance assessment of electricity producing wave energy converters	Draft technical specification for performance assessment of WECs	ISO 8601: Representation of dates and times ISO/IEC Guide 98-1:2009 Part 1: Introduction to the expression of uncertainty in measurement IEC TC114/PT62600-1 Terminology EquiMar, Protocols for the Equitable Assessment of Marine Energy Converters, Part II, Ch.I.A.1-I.A.5. NDBC Technical Document 2009-02. Handbook of Automated Data Quality Control Checks and Procedures. IEC 60688 ed2.2 Consol. with am1&2. Electrical measuring transducers for converting a.c. electrical quantities to analogue or digital signals IEC 60044-1 ed1.2 Consol. with am1&2. Instrument transformers - Part 1: current transformers IEC 60044-2 ed1.0 (1997-02) Instrument transformers - Part 2: Inductive voltage transformers IEC 61000-3 Electromagnetic compatibility (EMC)-Part 3
EMEC	Assessment of Performance of Wave Energy Conversion Systems	Guideline for performance assessment of WECs	IEC 60068-8, Power transducers IEC 60044-1, Current transformers IEC 60044-2, Voltage transformers
DTI	Preliminary wave energy device performance protocol	Protocol for performance assessment of WECs	(none in main text, see references in supporting commentary)
EquiMar D4.1	Sea Trial Manual	Outlines the prospective tasks to be undertaken during a sea trial	(see references section)
EquiMar D4.2	Data Analysis & Presentation To Quantify Uncertainty	Methodology for the analysis and presentation of data obtained from sea trials	(see references section)

3 ENVIRONMENTAL DATA REQUIREMENTS

The focus of the guidelines presented in this report is on the processing and analysis of environmental data obtained during WEC testing. It should be noted that this is a separate activity to resource assessment, which aims to establish the long term climatology at the site. Resource assessment generally takes place during the planning stages of establishing a test site, informing the planning of the WEC test program and (if applicable) the long term WEC performance / response prediction models. The long term climatology will usually be established using data from a numerical model. The ongoing in-situ data collection at the test site is invaluable for validation (and possibly calibration) of the long term data set and possibly also for validation of wave and wind forecasts used in operational planning.

However, the emphasis in this report is on understanding the environmental conditions experienced by a WEC during testing, so that the WEC response can be understood. The main existing standards and guidelines which are relevant to the present discussion are:

- *International Electrotechnical Commission (IEC) 62600-100 TS Ed.1: Marine energy – Part 100: Power performance assessment of electricity producing wave energy converters*. [1]
- *Equimar: Deliverable D4.1: Sea Trial Manual* [2]
- *European Marine Energy Centre (EMEC): Assessment of Performance of Wave Energy Conversion Systems* [3]
- The United Kingdom Department of Trade and Industry (*DTI): Preliminary Wave Energy Device Performance Protocol* [4]

There are a number of existing standards for the offshore oil and gas industry (e.g. [5-7]) which provide recommendations for metocean and environmental data. However, the focus of these documents is more related to establishing the long term statistics necessary for determining the design basis of offshore structures, and relatively little guidance is provided on measurement of waves for the purpose of analyzing the behavior of a floating offshore structure in the sea. This is related to the fact that these oil and gas structures are designed to be as unresponsive to waves as possible, so the main aim of wave monitoring at a site is to understand extreme responses. One exception to this is the recommendations for a wave measurement standard for the offshore oil and gas industry published by Tucker [8], which give specific guidance on the analysis of in-situ wave records.

The four WEC-specific documents listed above, together with the recommendations of Tucker [8], will therefore form the basis of the information presented in this report. Additional recommendations based on the experience of GL GH are included where appropriate, together with examples to illustrate the methods proposed. Wave energy converters are a nascent technology and as such the influence of various environmental parameters on machine behavior may not be fully understood at present. The IEC, EMEC and Equimar guidelines therefore all recommend to collect as complete a record as possible of environmental conditions during WEC sea trials. This data should include:

- Wave measurements
- Currents and water level
- Wind speed and direction
- Air and water temperature
- Air pressure
- Humidity

Since the primary environmental effect on the WEC is due to the waves, the focus in the following sections is on processing of wave measurements. Notes on the possible influence of other environmental parameters on WEC performance are presented in Section 7.

4 WAVE MEASUREMENT INSTRUMENTATION

4.1 Overview of wave measurement instrumentation

This section is intended to give an overview of the various types of wave measurement instruments (WMIs), their characteristics and limitations. It is not intended to provide an exhaustive review of specific models of WMI, or review the extensive academic literature on the subject. The main aim is to introduce the features of the data which are gathered from each type of instrument.

A summary of the main sources of wave data is presented in Table 4-1. The types of wave data can be divided into three categories: in-situ measurements, remote sensing measurements and modeled data. Of the types of in-situ measurements which are appropriate for condition monitoring during WEC testing, the focus of the following discussion will be on wave buoys, acoustic Doppler current profilers (ADCPs) and pressure gauges. There are a wide range of WMIs which are designed to be mounted on a fixed platform that are commonly used in the offshore industry such as laser altimeters, radars and wave staffs. However, these are less likely to be used in wave energy applications, due to the cost of installing an appropriate platform. There is also a wide range of instrumentation which can be used to measure waves in a tank environment, which is outside of the scope of the present discussion.

Land-based remote sensing equipment is currently being trialed at several wave energy test sites, with the WaveHub in the UK testing a HF radar system and the European Marine Energy Centre (EMEC) trialing an X-band radar for monitoring waves and currents at the tidal test site. However, due to the rather specialist software required to process radar measurements, the focus of the post-processing guidelines will be on the more commonly used wave buoys, ADCPs and pressure gauges .

Satellite based remote sensing data is a valuable source of accurate global measurements which can be used for climatological studies or validation of wave model data. However, the data are too sparse (both spatially and temporally) to provide condition monitoring data for WEC testing purposes.

Finally, it is worth noting that while wave model data is essential for long-term site assessments and forecasting, it is not suitable for providing estimates of the sea states experienced by WECs during testing. Model data are estimates rather than measurements and are therefore limited in the accuracy that can be achieved.

Table 4-1: Overview of sources of wave data

Category	Sub-category	Examples
In-situ measurements	Floating	Wave buoys
	Seabed-mounted	ADCP, Pressure sensor
	Platform-mounted	Laser altimeter, radar altimeter, resistance or capacitance wire gauges, sub-surface velocity sensors.
Remote sensing	Land-based	HF radar, X-band radar
	Satellite-based	Radar altimeter, synthetic aperture radar (SAR)
Wave model	Phase-averaged (spectral)	WAM, WaveWatch III, SWAN
	Phase-resolving	Mild-slope models, Boussinesq models

4.1.1 Eulerian and Lagrangian measurements

Before discussing the characteristics of each type of WMI, it is worth noting that there are some innate differences in the measurements made by buoys compared to a fixed instrument. Small wave buoys essentially follow the particle motions of the water surface whereas fixed instruments such as an ADCP measure the spatial profile of the waves. Particle-following and fixed measurements are known as Lagrangian and Eulerian measurements respectively, referring to the frame of reference in which measurements are made. For low amplitude waves the differences between Lagrangian and Eulerian measurements are small, but in steep waves the differences can be significant. There are pros and cons to both types of measurements. A Lagrangian device measuring the orbital motions of a water particle at a particular frequency will attribute all the wave energy to this frequency whereas an Eulerian device will distribute some of the energy among the harmonics of the orbital frequency. On the other hand Lagrangian devices are not capable of measuring some non-linear aspects of the wave profile. A detailed discussion of these effects can be found in [13-15].

4.1.2 Wave buoys

Wave buoys make measurements of wave properties by following the motion of the water surface. The displacement of the sea surface is inferred from the motions of the buoy, measured by accelerometers, tilt sensors and compasses. The accuracy of the inferred wave motions is dependent on the buoy response, the accuracy of the transfer function (from buoy motion to wave motion) and the sensor accuracy. One advantage to using buoys to measure waves is that the sea surface is usually well defined – it is the point at which the buoy floats. However, in high seas it is possible for the buoy to be dragged through or around wave crests. On the other hand, in rough conditions spray in the air or bubbles in the water can cause problems with devices that measure the waves from below or above the surface, such as ADCPs or laser altimeters.

The buoy response is governed by the size and shape of the buoy and its mooring. Designs of buoys vary, with dimensions ranging from small spherical buoys less than one meter in diameter, to large rectangular hulled buoys around 12m in length. Small buoys have the best surface following properties, with a spherical buoy 2m or less in diameter having effectively unity response for waves up to about 0.5Hz [10]. For larger buoys the response to shorter wavelengths is damped and the wave motions must be indirectly estimated through the Response Amplitude Operator (RAO) of the buoy [16, 17]. Meteorological institutions implementing wave measurement programs often require simultaneous measurements of winds (and other parameters) with waves, therefore the buoy size will be a compromise between a compact shape for good surface following properties and stability required for mounting an anemometer.

Moorings can affect the response of the buoy, by restricting its range of motion. If the mooring does not have sufficient flexibility it is possible for the buoy to be dragged through or around wave crests. The use of elastic moorings for wave buoys is discussed in [18, 19]. It is noted that for waves above the mass-spring resonance frequency, f_0, of the rubber cord and buoy combined, the buoy motions are not restricted by mooring forces, but for frequencies lower than f_0 the buoy does not perfectly follow the wave and heave energy is spread over a wide range of frequencies. For a Waverider buoy with the manufacturer's specified elastic mooring, f_0 is around 0.05Hz for vertical motions, but horizontal motions can be influenced by mooring forces at higher frequencies when the buoy is pulled to the end of its mooring by marine currents (see discussion in Section 5.1).

4.1.3 Pressure sensors

Pressure sensors can be used to measure wave properties in shallow water. The surface elevation can be inferred from the measured pressure time series using the transfer function between dynamic pressure and surface elevation defined in Table A-1. Measurements are restricted by the attenuation of the pressure signal with depth. Higher frequencies are attenuated faster than low frequencies, which penetrate further down the water column. This is illustrated in Figure 4-1, which shows the attenuation of wave dynamic pressure at the seabed with frequency for various water depths. The attenuation of the signal means that the highest frequency that can be measured with a pressure sensor on the seabed is dependent on the water depth.

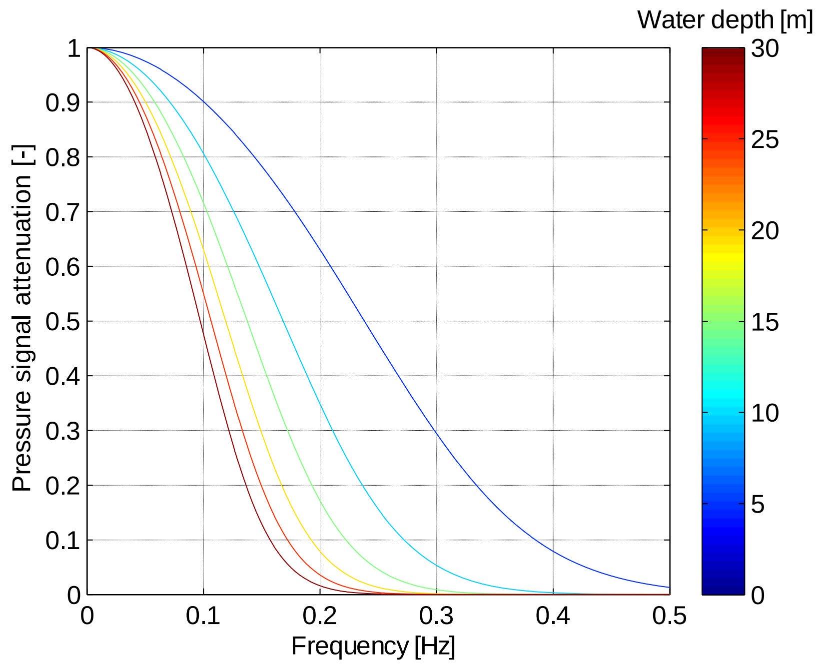

Figure 4-1: Attenuation of wave dynamic pressure at the seabed with frequency for various water depths (indicated by the color of the line)

The accuracy of measurements from pressure sensors is also affected by the indirect method by which the surface elevation is inferred. The inversion from pressure to surface elevation is based on the assumptions of linear theory, which can mean that the transfer function is less accurate in steep wave conditions. Also, any non-wave component of the dynamic pressure signal (e.g. signal noise or turbulence) will be attributed to wave action during the inversion process. In areas with strong current there can be significant turbulence in the water close to the seabed, if this turbulence is not filtered out of the pressure signal then it can cause errors in the inference of wave conditions.

Directional properties of the wave field can be inferred using an array of spatially separated pressure sensors, and using the relations between cross-spectra and directional distribution described in Section A3.2. The resolution of the array is dependent on the number of sensors used and the sensor layout (see [20]).

4.1.4 Acoustic Doppler Current Profilers (ADCPs)

The primary measurement made by an ADCP is of the water particle velocity through the water column. The water column velocity is inferred from the Doppler shift of an acoustic pulse emitted by sensors inclined at an angle to the vertical. ADCPs usually use three or four sensors inclined at around 25°. The along-beam velocities from each beam can be resolved into a single estimate of the *u*, *v* and *w* components of the velocity at a number of discrete depth bins throughout the water column. Surface elevation can be inferred directly from the velocity measurements using the transfer functions defined in Table A-1. However, this indirect method for measuring the surface elevation is subject to the same limitations as the inference of surface elevation from pressure sensors, namely:

- The velocity signal attenuates with depth, with the attenuation being larger at high frequencies
- The transfer function between surface elevation and water particle velocity is based on linear theory

- Any noise on the velocity signal (including perturbations from turbulence) needs to be filtered out before applying the transfer function.

To circumvent these restrictions, some ADCPs also include an additional vertically-oriented sensor which can track the surface elevation using an echo-ranging technique. Depending on the frequency of the acoustic pulse, the surface elevation can be measured in depths up to 100m. Some models of ADCP also incorporate a pressure sensor, which can be used to give a cross-check on the surface elevation spectrum.

Directional properties can be estimated from the cross-spectra between the surface elevation and near-surface horizontal velocity measured in the inclined beams. The distance between the beams at the surface is a function of the water depth and the angle of the beam. Aliasing due to the separation of the measurements imposes an upper frequency limit for directional measurements. For an ADCP with 3 beams at an angle of 25º to the vertical, the cut-off is 0.32Hz at a depth of 20m.

4.1.5 Comparison of in-situ measuring devices

Section 5 considers the post-processing of measurements from wave buoys, ADCPs and pressure sensors in general. The various properties measured by each instrument are listed in Table 4-2, together with the limitations of each type of instrument. The relations between these properties and the surface elevation are listed in Section A1.1 of Appendix A. These relations can be used to infer the surface elevation (and hence various wave parameters) and directional properties of the sea state, as described in Section A3.

Table 4-2: Properties measured by various types of WMI and associated limitations.

WMI	Properties measured	Limitations
Wave buoy	Surface elevation and either surface slope or horizontal displacements at surface (inferred from the accelerations and/or tilt of the buoy).	Hull-response limits high-frequency measurements (dependent on dimensions of buoy, but typically a spherical buoy of diameter <1m will have a unity response to waves of frequency <0.5Hz). Mooring response limits low-frequency measurements (dependent on type of mooring, typically vertical response is unaffected for wave frequencies >0.05Hz, horizontal motions may be affected at higher frequencies depending on length of mooring line). Buoys are difficult to moor in shallow water.
Pressure sensor	Pressure (normally at sea bed)	Attenuation of the pressure signal with depth limits high frequency measurements (see Figure 4-1). Inference of surface elevation based on linear theory. Signal noise and turbulence can affect accuracy of measurements.
ADCP	3-component (*u, v, w*) velocities at various depths through the water column. Surface elevation (measured by some types of ADCP). Pressure (measured by some types of ADCP).	Surface tracking is limited to depths up to ~100m. Signal noise and turbulence can affect accuracy of surface elevation inferred from water particle velocity.

4.2 Recommendations for sampling frequencies

The sampling frequency of the WMI is relevant to the estimation of wave spectra and the measurement of time-domain parameters such as individual wave heights and periods. For the estimation of wave spectra, it is necessary that the sampling frequency is sufficiently high that there is no significant energy in the wave spectrum above the Nyquist frequency (equal to half the sampling frequency). Any energy above the Nyquist frequency will be aliased and wrapped back onto the measured spectrum (see e.g. [10] for a discussion of aliasing). For WEC testing at full-scale, the highest frequencies of interest are generally below 0.5Hz, so a sampling rate of 1Hz or above is sufficient, provided that the data is filtered with a low pass filter to remove energy above the Nyquist frequency before spectral analysis. For sheltered sites used for testing scaled devices, where higher frequency components may have a more significant effect on WEC performance, a higher sampling frequency should be used.

For time-domain parameters a greater sampling rate is required to accurately estimate wave heights and periods. If a low sampling rate is used (relative to the wave period) then it is unlikely that the peak of a wave crest or trough will occur exactly when a sample is taken, causing a systematic underestimation of crest heights and trough depths. Tucker [8] notes that for a sinusoidal wave with a period of 10s sampled at 2Hz, the maximum error due to sampling would be 1%, with an average error of ~0.3%. Larger errors would be expected at shorter wave periods or lower sampling frequencies (e.g. using a sampling frequency of 1Hz would give a maximum error of 5% for a 10s wave, with a mean error of 1%).

However, it is important to note that time-domain parameters are generally less useful than frequency-domain parameters in WEC testing. It is not possible to deploy the WMI at the exact WEC location (see discussion in Section 4.4), so due to the spatial separation between the WMI and the WEC, the surface elevation measured by the WMI will be different to that experienced by the WEC. For example, the maximum wave height measured at the WMI will differ from that experienced by the WEC. In many situations, the distance between the WMI and the WEC will be sufficient for the sea states at each location to be considered a statistically independent realization of the underlying sea state (correlation scales of wave measurements are discussion in Section A6.2). Therefore the statistical description of the sea state given by the wave spectrum and frequency-domain parameters is more appropriate for understanding WEC performance.

There are also some innate limitations of WMIs which pose restrictions to the frequency components of the spectrum that can be measured (e.g. due to the hull and mooring response of a buoy, or related to the depth of deployment of a pressure gauge or ADCP)..These are discussed in Section 4.1.

Of the published test protocols, the IEC and DTI both recommend a sampling frequency of 1Hz or greater, while the Equimar guidelines recommend a sampling frequency (circa) 2Hz. All commercially available in-situ WMIs will meet the 1Hz recommendation, but some systems do not meet the 2Hz requirement. In the opinion of GL GH, a sampling frequency of greater than or equal to 1Hz is sufficient for accurate in-situ wave measurements.

4.3 Recommendations for record durations

The record duration affects the sampling variability of the wave measurements. Sampling variability refers to the random differences between the estimates of wave spectra and associated parameters and the long-term average for the sea state. The longer the duration of a record, the closer the measured values will be to the long-term average. However, there is a trade-off between the statistical stability of measured spectra and parameters and adequately sampling temporal variations in the sea state. The IEC, DTI and Equimar guidelines all recommend a minimum measurement duration of 20-30 minutes, while the EMEC guidelines recommend that records are analyzed in 30-minute sections and results from two adjacent records are averaged to provide a 60-minute sample. GL GH advocates that the EMEC guidelines on record durations are followed.

Examples of the sampling variability of some integrated parameters are given in Table 4-3 for JONSWAP spectra with peak enhancement factor $\gamma = 1$ (Bretschneider spectra) and $\gamma = 3.3$, calculated using the equations in Section A6.3. The sampling variability is given in terms of the coefficient of variation (C.O.V. – defined as the ratio of the standard deviation of a parameter, to its mean value) for various energy periods and measurement durations. For sample lengths above 20 minutes the parameter estimates are approximately normally distributed, so ~95% of samples are within 2*C.O.V. of the true value. A second point to note is that the C.O.V. scales with $\sqrt{T_e/\tau}$, where τ is the measurement duration, so the constant C.O.V.$\times\sqrt{\tau/T_e}$ is given at the bottom of the table. Finally, note that the C.O.V. increases with γ for H_s and P, because narrower-banded spectra give longer wave groups and thus larger variation in results over a given sample duration. However, the variability decreases with γ for T_e since the wave frequencies are more tightly concentrated around the peak period of the spectrum for larger values of γ.

Table 4-3: Examples of sampling variability in measured parameters for a Bretschenider spectrum with various periods and record durations

T_e [s]	Record duration [min]	Coefficient of variation [%]					
		H_s		T_e		P	
		$\gamma = 1$	$\gamma = 3.3$	$\gamma = 1$	$\gamma = 3.3$	$\gamma = 1$	$\gamma = 3.3$
5	20	3.3	4.2	1.4	1.1	7.3	9.1
	30	2.7	3.4	1.1	0.9	6.0	7.4
	60	1.9	2.4	0.8	0.7	4.2	5.2
10	20	4.7	5.9	2.0	1.6	10.3	12.9
	30	3.8	4.8	1.6	1.3	8.4	10.5
	60	2.7	3.4	1.1	0.9	6.0	7.4
15	20	5.7	7.2	2.4	2.0	12.7	15.7
	30	4.7	5.9	2.0	1.6	10.3	12.9
	60	3.3	4.2	1.4	1.1	7.3	9.1
Normalized values[1]:							
$\mathbf{C.O.V.} \times \sqrt{\tau / T_e}$ **[%]**		**51.3**	**64.8**	**21.7**	**17.8**	**113.3**	**140.9**

1. The normalized values can be used to calculate the C.O.V. for other measurement durations, τ, and energy periods, T_e, by multiplying the normalized value by $\sqrt{T_e/\tau}$.

4.4 Placement of WMI relative to WEC

The WMI should be located sufficiently close to the WEC that the measured wave conditions can be considered as the same as at the WEC location. There are several factors which can contribute to differences between the waves measured at the WMI and those experienced by the WEC:

- Random differences due to the finite measurement duration (sampling variability)
- Deterministic differences in sea states due to effects of depth, sheltering, bathymetry, currents, etc.
- Possible effects of the WEC on the waves measured at the WMI due to radiation and diffraction.

These factors are discussed in the following subsections.

4.4.1 Statistical and deterministic differences in sea state

To establish whether the WMI is located in a position which experiences the same sea state as the WEC, the IEC technical specification recommends that prior to the WEC testing, two WMIs are deployed at the proposed locations for the testing period. A deployment period of 3 months minimum is recommended, with 12 months being preferable in order to capture any seasonal changes in conditions. It is recommended that the differences in the wave measurements from the two WMIs are compared to determine if the wave conditions are statistically equivalent between the WMI and WEC locations. However, the IEC document defines statistical equivalence in a somewhat arbitrary way, seemingly without a proper understanding of the sampling properties of wave measurements. It notes that:

> "The sea state at the location of the WMI shall be representative of the sea state at the location of the WEC if the difference between the energy flux at the WMI and the WEC – as determined by the deployment of a minimum of two WMIs, one at the wave measurement location and one at the WEC location - is less than 10.0% for 90.0% of the records then it can be assumed that the wave field is statistically equivalent."

From the discussion of sampling properties of wave measurements presented in the previous section (and detailed in Section A6), the statistical differences between waves measured at two locations can be calculated, assuming that there are no deterministic changes in the sea state between the two locations. The percentage difference in the omnidirectional wave power experienced at two locations is shown in Figure 4-2 as a function of the measurement duration (calculated using Equation A.62 and assuming zero correlation in the wave conditions). The results are for Bretschneider spectra with various energy periods. It can be seen that for a spectrum with an energy period of 10 seconds and a sampling duration of 30 minutes the coefficient of variation is around 12%. The distribution of differences is approximately normal, so the non-exceedance probability of the differences can be calculated from the coefficient of variation. Figure 4-3 shows the non-exceedance probability of the absolute differences in omnidirectional wave power, over a measurement duration of 30 minutes, when the sea state has a Bretschneider spectrum with various energy periods. The plot indicates that the IEC requirements for what constitutes statistical equivalence will not be met when for a measurement duration of 30 minutes, even if there are no deterministic changes in the sea state between the two locations.

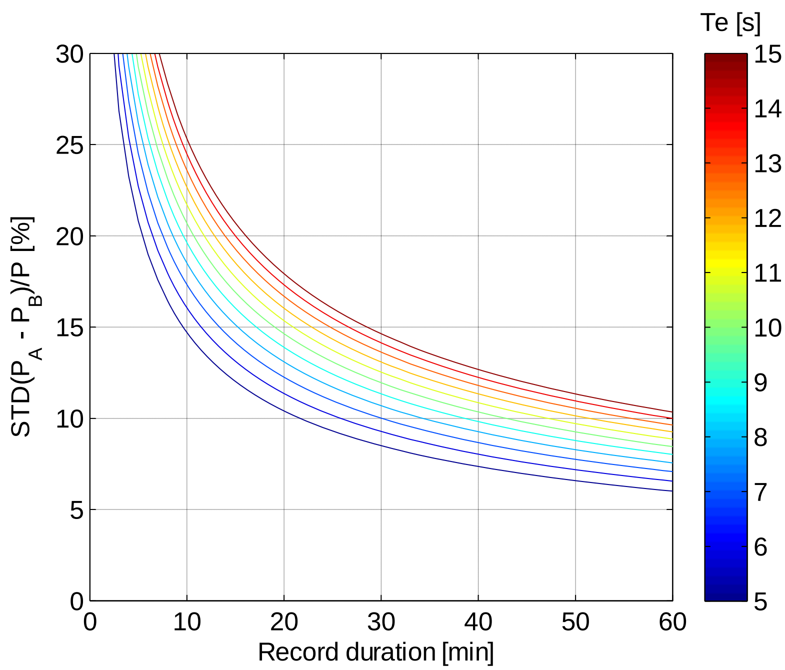

Figure 4-2: Coefficient of variation of differences in omnidirectional wave power experienced at two locations with no correlation in the wave conditions. Results are for Bretschneider spectra with various energy periods, indicated by the line color.

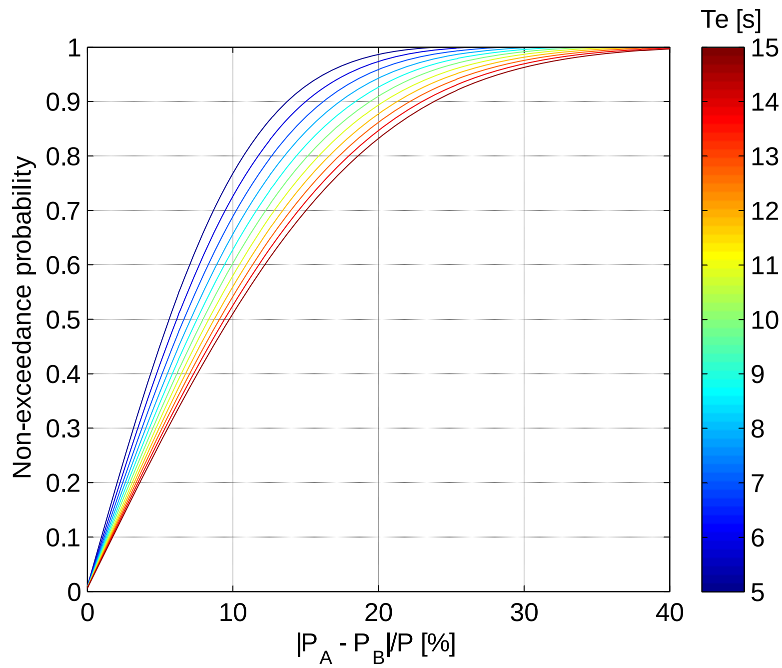

Figure 4-3: Non-exceedance probability of absolute differences in omnidirectional wave power experienced at two locations with no correlation in the wave conditions, measured for a duration of 30 minutes. Results are for Bretschneider spectra with various energy periods, indicated by the line color.

GL GH recommends that the statistical significance of the differences in the sea state at the WEC and WMI locations are determined via a test on the mean difference in omnidirectional wave power in each bin of the power matrix. Note that if there are deterministic differences in the sea states at each location, then the magnitude of the difference may be dependent on sea state (for example if differences are due to bathymetric effects, then longer period waves would be expected to exhibit greater differences than shorter period waves). The statistical significance of the difference omnidirectional wave power can be assessed as follows:

1. For each sea state in a bin, calculate the theoretical variance of the differences using equation A.62, accounting for any spatial correlation in conditions between locations using equation A.53.
2. Calculate the mean theoretical variance over all sea states in a single bin, denote this σ_{AB}^2.
3. Calculate the mean of the observed differences over the bin, denote this μ_{AB}.
4. If $|\mu_{AB}| > 1.96\sigma_{AB}/\sqrt{n}$, where n is the number of observations in the bin, then the mean difference is significant at the 95% confidence level.

4.4.2 Effect of spatial correlation in wave conditions

The relative separation between the WMI and the WEC affects the statistical variability of the differences in wave conditions experienced at each location. This can be beneficial if WEC data from the sea trials are used to validate a numerical model of WEC performance. As an indication of the correlation scales of wave conditions, Figure 4-4 shows the RMS difference in concurrent measurements of omnidirectional wave power, normalized by the difference at infinite separation (calculated assuming zero correlation in Equation A.62). Plots are shown for typical swell and wind sea directional distributions. It can be seen that for swell conditions correlation persists for several wave lengths in the down-wave direction, but decreases rapidly to zero in the cross-wave direction. For wind sea conditions, which have a larger directional spread, the correlation decreases more rapidly with separation in the down-wave direction.

Locating the WMI in an up-wave position from the WEC, relative to the climatic mean wave direction can therefore be beneficial for reducing the uncertainty in the input wave conditions in model validation exercises. An example of the effect of spatial correlation on model validation is presented in [23]. However, it is important to note that the proximity of the WMI to the WEC is limited by the need to avoid measuring diffracted and radiated waves from the WEC (see Section 4.4.4) and the length of the mooring if a wave buoy is used to measure the waves.

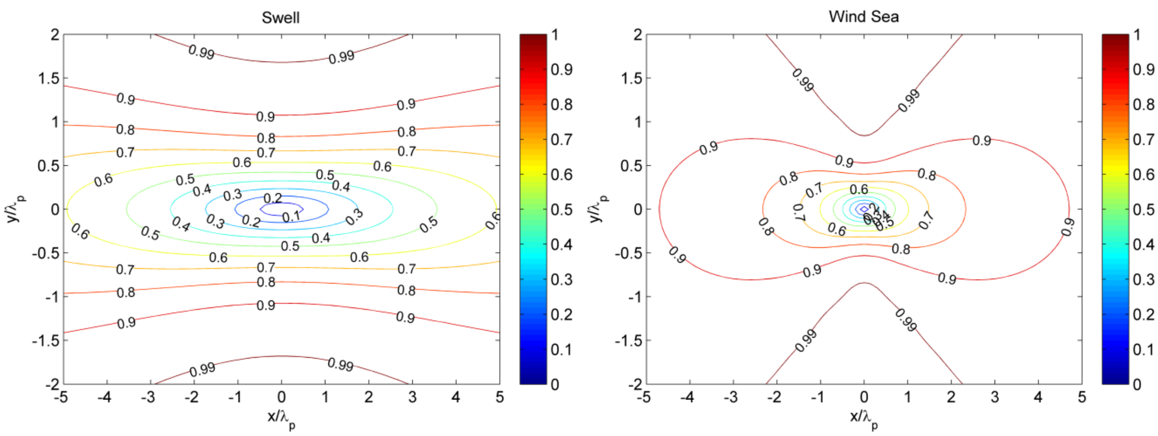

Figure 4-4: RMS difference in a measurement of omnidirectional wave power relative to a measurement at the origin, normalized by the difference at infinite separation. Separation distances are normalized by the peak wave length. Left hand plot is for a Bretschneider spectrum with a swell directional distribution [21]. Right hand plot is for a Bretschneider spectrum with a wind sea directional distribution [22]. Mean wave direction is parallel to the x-axis.

4.4.3 Use of a transfer function

The IEC technical specification notes that if deterministic differences are found between the wave conditions at the WMI and WEC location during the test site characterization, then a spatial transfer model should be used to estimate the wave conditions at the WEC based on the measured sea state. It recommends that a numerical model of the site is established to propagate the wave conditions measured at the WMI to the WEC location. The document suggests that "The spatial transfer model shall be acceptable if it predicts the energy flux at the WEC to within 10.0% of the measured energy flux for 90.0% of the records". As noted previously, these conditions are unlikely to be met unless the WMI is situated very close to the WEC location. Therefore GL GH recommends that the method outlined in Section 4.4.1 is applied to test if the spatial transfer model is adequate.

GL GH recommends that whenever possible the WMI should be positioned such that the deterministic differences in the sea state between the WEC and WMI are minimized, removing the need for a transfer model.

Measurements of the random and deterministic differences in wave conditions over an area around 500m × 500m in a water depth of 30-40m were presented in [24]. It was demonstrated that at these depths and separation distances there could be significant changes in the longer period components of the wave spectrum, illustrating the need for careful characterization of the test site prior to deploying a WEC.

4.4.4 Effect of radiated and diffracted waves from the WEC

The presence of a WEC can have an influence on the surrounding wave field. The incident waves will be diffracted by the WEC and the WEC will also radiate waves as it moves in the water. These effects can be quantified using a linear diffraction code such as WAMIT[3] or AQWA[4] to calculate diffracted and radiated wave field around the WEC. For any

[3] http://www.wamit.com/
[4] http://www.ansys.com/Products/Other+Products/ANSYS+AQWA

sea state the amplitude of the diffracted wave field can be calculated based on the incident waves alone. However, to calculate the amplitude of the radiated wave field, the device motions in all relevant degree of freedom must be calculated. It is not possible to subtract the diffracted or radiated waves from the measured waves, as the waves incident at the WEC will not be known and these are required to calculate the amplitudes and phases of the diffracted and radiated waves. Moreover, validation of the radiation and diffraction model would require tank testing in controlled conditions.

The IEC technical specification contains a section titled “Correction for WEC interference” which recommends that the WMI is placed in a location where the average radiated wave energy has decayed by at least 90%. However, due to the difficulties in establishing the exact influence of the WEC on the measured waves, GL GH recommends that the radiation and diffraction model is used only to find a location for the WMI relative to the WEC where the influence of radiated and diffracted waves is minimized, and no attempt is made to correct for the influence of the WEC. It is further recommended that the analysis is conducted for a range of sea states covering the scatter diagram, and the amplitude of the radiated and diffracted wave fields is quantified at the WMI location, relative to each incident sea state.

5 WAVE DATA POST-PROCESSING GUIDELINES

5.1 Quality controls

Quality assurance of data is imperative when defining performance metrics. Quality checks can be applied at various levels of processing:

- Transmission quality (if applicable)
- Raw time series
- Spectra
- Parameter (absolute values and relations to other parameters e.g. steepness, wind-wave direction, etc.)

Transmission checks will only be applicable for data that is telemetered to shore in real time. Checks are normally applied by the receiving software, and archived in the raw data files. The checks can include a transmission status parameters and a cyclical index to indicate data continuity (jumps in the index would indicate a dropout in either the transmission or receiver).

An ongoing collaborative effort to develop standards for quality assurance and quality controls for oceanographic data is being run by the US Integrated Ocean Observing System (IOOS), called QARTOD (Quality Assurance of Real-Time Oceanographic Data). The project aims to consolidate experience from multiple agencies and produce guidelines for quality controls. The conclusions of the wave working group were reported in a document titled "Real-Time Quality Control Tests for In Situ Ocean Surface Waves" [9]. Another extensive list of quality controls for wave measurements was published by the US National Data Buoy Center [11]. Due to the large number of tests available, the details will not be repeated here and the reader is referred to the documents above. Some points on quality checks for spectra which are useful to understand are presented below. A useful tabulated summary of the tests applied by various bodies can be found at:

http://cdip.ucsd.edu/documents/index/product_docs/qc_summaries/waves/waves_table.php

A spike in a time series appears as white noise in the spectrum, i.e. a constant spectral density with frequency added to the true spectrum. This type of error is quite apparent when spectra are plotted on log-log axes, and can be used to form a quality control for the data. Tucker [8] noted that the Phillips spectrum, which describes the part of the spectrum in equilibrium with the local wind, can be used to place an upper limit on the acceptable levels of energy at each frequency. The form proposed by Philips was:

$$E(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \qquad [5.1]$$

where $\alpha = 0.0081$ is an empirical constant. There is some debate in the literature about whether the energy in the spectrum should fall off with f^{-4} or f^{-5}. Most recent theoretical and empirical evidence suggests that an f^{-4} high-frequency tail is more appropriate (see [12] for a review). At low frequencies, most standard models for the frequency spectrum predict a sharp fall-off of energy below the spectral peak, so a similar limit can be established. However, for buoys, the mooring response will affect the spectrum at low frequencies (see Section 3.1), so the cut-off applied at low-frequencies is a function of the combined buoy and mooring response rather than of the sea state.

The procedure is illustrated using data from a Datawell Waverider buoy located off the north east coast of Oahu (Hawaii), around 10km from the WETS site (NDBC buoy number 51202, CDIP buoy 098). Six years of raw data was downloaded from the CDIP website[5], covering the period Jan 2002 – Sep 2007. The spectra have been analyzed in

[5] http://cdip.ucsd.edu/?ximg=search&xsearch=98&xsearch_type=Station_ID

30-minute segments and averaged over 10 harmonics. Spectra from two consecutive 30-minute records are then averaged to give spectral estimates with 40 degrees of freedom. Figure 5-1 shows an over-plot of all measured spectra (43,785 in total). The black lines indicate the high and low frequency cut-offs for applied in the quality checks. For this dataset a f^{-4} high-frequency tail was found to be more appropriate than a f^{-5} tail. The cut-offs applied are:

$$E(f) < 0.0061f^{-4} \quad [5.2]$$

$$E(f) < 435f^{2.5} \text{ for } f < 0.035 \quad [5.3]$$

where the values of the constants have been found by fitting to the data. The red lines indicate spectra failing the high frequency test and the green lines indicate spectra failing the low frequency test. Blue lines indicate spectra passing quality control. Spectra with unrealistic white noise levels due to spikes in the time series are clearly evident. In this case, no quality checks were applied to the raw time series of buoy motions, in order to illustrate the efficacy of the spectral tests. However, it is not suggested that spectral checks should replace time series checks. Instead it is suggested that they are used as a second check, to flag records which are not caught by the initial time series checks.

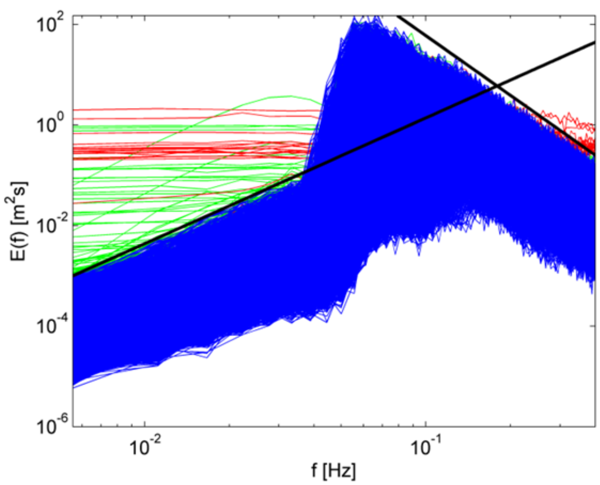

Figure 5-1: Plot of all measured spectra from CDIP buoy 098. Black lines show the high and low frequency cut-offs for QC. Red lines indicate spectra failing the high frequency test and green lines indicate spectra failing the low frequency test. Blue lines indicate spectra passing quality control.

A similar method can be used to check the horizontal motions measured by an in-situ device (i.e. a buoy or ADCP), since the auto-spectra of the horizontal measurements (slopes, displacements or velocities) are related to the auto-spectrum of the surface elevation by [A.28]. However, it should be noted that the horizontal motions are more sensitive to the mooring response than the vertical motions, so the same low frequency cut-off is not applicable. Figure 5-2 shows the surface elevation spectra inferred from the spectra of horizontal displacements using equation [A.28]. The blue lines indicate the same records as shown in Figure 5-1, with the black lines showing the same high and low frequency cut-offs. It is clear that the high-frequency limit is still applicable, but there is an extra peak in the low-frequency part of the spectrum due to the mooring response, which makes the low-frequency limit inapplicable.

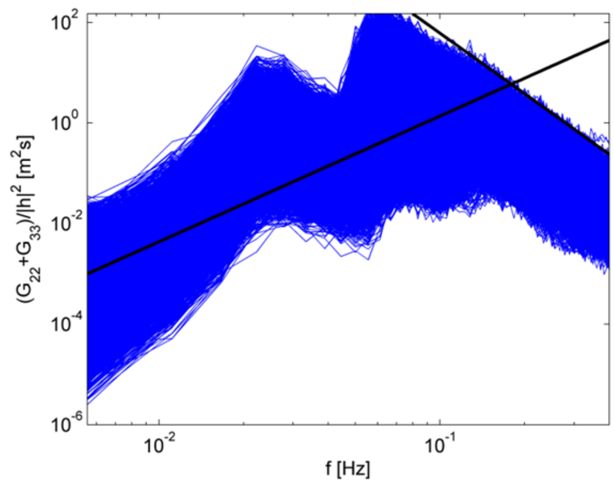

Figure 5-2: Surface elevation spectra inferred from the spectra of horizontal displacements using [A.28]. Blue lines indicate the same records as shown in Figure 5-1. Black lines show the same high and low frequency cut-offs as applied in Figure 5-1.

At the high-frequency end of the spectrum there are some small violations of the empirical limit applied to the surface elevation spectra. A check ratio can be defined using [A.28], as

$$R = |h|\sqrt{\frac{G_{11}}{G_{22}+G_{33}}} \qquad [5.4]$$

If the linear relations between the surface elevation and horizontal properties (defined in Table A-1) are valid then the check ratio should have a value close to unity (with deviations allowing for sampling effects). Significant deviations indicate that the relations are not valid and directional properties cannot be accurately inferred. As mentioned above, in the case of buoy data, the mooring response has a significant effect on the horizontal motions at low frequencies, imposing a low frequency cut-off on the directional data. Marine currents can also affect the validity of the relations in Table A-1 and hence the check ratio. As wave-current interactions are strongest at higher frequencies, the response is most pronounced in this range. Figure 5-3 shows time series of measured spectra and check ratios from a buoy located in Waimea Bay, Oahu (NDBC buoy number 51201, CDIP buoy 106). The spectra have been analyzed in the same way as those from CDIP buoy 098. The upper plot shows a time series of measured spectra in logarithmic scale, the central plot shows the sum of the horizontal spectra, and the lower plot shows the check ratio. There is a constant low-frequency response visible in the horizontal displacement spectra. This is caused by the response of the moorings when the buoy is dragged to the edge of its range by tidal currents. This causes the check ratio to be constantly less than unity at low frequencies. At higher frequencies a clear modulation is visible in the check ratio at a period of around 12 hours and with greatest effect at high frequency, consistent with modulations caused by tidal currents. Data from this buoy has been used as an example as the tidal effects are greater at this location than at buoy 098, close to the WETS site. However, the mooring effect is common to all wave buoys with an elastic mooring. It is recommended that the check ratio is used to define a low-frequency cut-off for directional analysis.

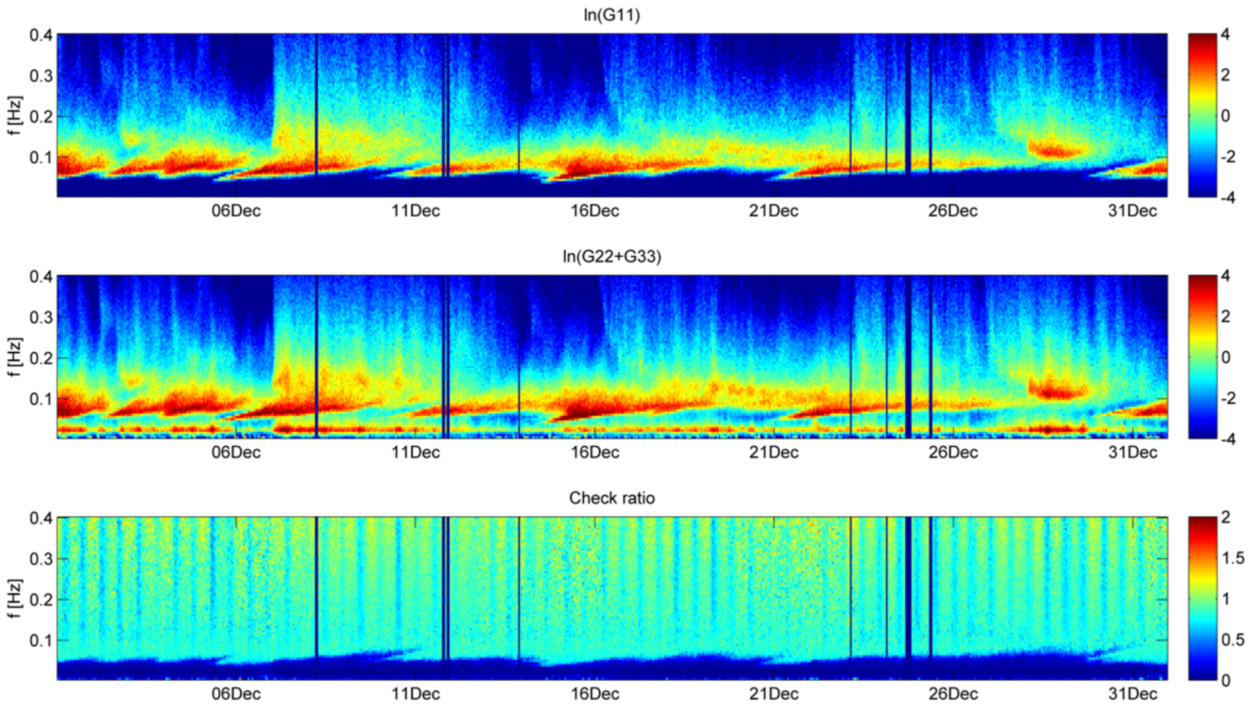

Figure 5-3: Spectral time series from buoy CDIP buoy 106 for Dec 2002. Upper plot: Surface elevation spectra. Middle: Sum of horizontal displacement spectra. Lower plot: Check ratio.

5.2 Analysis methods

In this section a discussion of the methods used to analyze the measured data is presented. The details of the methods are given in Appendix A. The section is intended to describe what analysis should be conducted and to explain the rationale behind the recommendations. A summary table of parameters to be archive is presented in Section 5.3.

5.2.1 Time-domain analysis

As discussed in Section 4.2, time-domain parameters estimated from the WMI are less useful for understanding the wave field experienced by the WEC, than the statistical description of the sea state given by frequency-domain (spectral) parameters. While the Equimar Sea Trials Manual mentions time-domain analysis, this is more due to the historical use of these parameters than their usefulness in assessment of WEC performance. The IEC, EMEC and DTI guidelines all recommend that the analysis is based on frequency-domain parameters only. In the opinion of GL GH, time domain parameters do not need to be computed routinely, and can be computed from the raw data by users at a later date if required[6].

[6] Time domain WEC parameters such as min/max PTO joint displacements or loads are obviously of interest. However, they are unlikely to correspond to time domain wave parameters, since the spatial separation between the WEC and WMI means that the waves experienced at each location are statistically independent in many cases. It is more informative to correlate time domain WEC parameters to frequency domain wave parameters (e.g. H_s, T_e, etc.).

5.2.2 Frequency-domain analysis

Auto-spectra and cross-spectra

A brief introduction to frequency-domain (or spectral) analysis of the sea state is presented in Appendix A. There are differing recommendations in the IEC, EMEC and DTI guidelines about appropriate frequency range and resolution for spectra. These are summarized in Table 5-1 below. Tucker [8] noted that a frequency resolution of 0.01Hz, which was commonly used at the time, is inadequate to properly resolve the shape of spectra around the peak. However, it is important to note that the choice of frequency resolution is a balance between obtaining statistically stable results (in terms of the sampling properties described in Section A6.1) and adequately resolving the shape of the spectrum. This, in turn, is related to the measurement duration, discussed in Section 4.3.

It is therefore recommended that measured time series are analyzed in 30-minute blocks using a fast Fourier transform (FFT) with no segmenting or windowing, and two adjacent records are averaged to provide a 60-minute sample (see recommendations in Section 4.3). It is recommended that spectra and cross-spectra from the 30-minute records are averaged over 10 harmonics to give a frequency resolution of $10/1800 = 0.00556\text{Hz}$. Averaging spectra from two adjacent 30-minute records (keeping the same frequency resolution) will give spectral estimates with 40 degrees of freedom and a coefficient of variation of $1/\sqrt{20} = 22\%$ (see Section A6.1). The sampling duration is dependent to some extent on the type of WMI used and the firmware used may not allow the output of contiguous 30-minute records. For WMIs that do not output contiguous 30-minute records, it is recommended that spectra and cross-spectra are averaged over 10 harmonics.

Table 5-1: Recommendations for frequency range and resolution from published guidelines

Reference	Frequency resolution	Frequency range
IEC TS 62600-100	Max. 0.015Hz	0.033 – 0.5Hz
EMEC	Max. 0.010Hz	0.04 – 0.5Hz
DTI Preliminary Protocol	Max. 0.005Hz for frequencies below 0.1Hz Max. 0.010Hz for frequencies above 0.1Hz	0.05 – 0.5Hz
Tucker [8]	0.005Hz for frequencies below 0.3Hz	-

Directional spectral data

The estimation of directional properties of the sea state is discussed in Section A3.2 and A.3.3. It is important to reemphasize here that only four independent directional quantities can be estimated at each frequency, from which the directional distribution can be estimated. However, a mean direction and directional spread can be calculated at each frequency without having to estimate the directional distribution. The guidelines provided by the IEC, EMEC, DTI and Tucker [8] all recommend that these model-free directional parameters (defined in equations [A.37] and [A.40]) should be calculated and archived at each frequency. It is recommended that auto-spectra and cross-spectra should be averaged over 10 harmonics before calculating the directional Fourier coefficients used to define the frequency-dependent mean direction and spread.

No guidance on appropriate methods for estimating the directional distribution are provided in the IEC, EMEC or DTI guidelines, and it is not in fact a requirement to archive directional spectra. However, directional spectra are sometimes useful in assessing the performance of a WEC (in numerical model validation exercises, for example) so some recommendations are made here. As with the model-free directional parameters, it is recommended that auto-spectra and cross-spectra should be averaged over at least 10 harmonics before being used in estimation of the directional distribution. A very brief overview of methods for estimating the directional distribution is presented in Section A3.3, with references given for further details. It is recommended that a data-adaptive method is used (such as the iterated maximum likelihood method or the maximum entropy method) and that methods such as truncated Fourier series or the standard (non-iterated) maximum likelihood method are avoided.

Spectral parameters

Spectral parameters are defined in Sections A4 and A5. It is recommended that the spectrally-averaged directional spread (*SDIR* – Eq. [A.43]) is calculated using the model-free definition of frequency-dependent directional spread defined in [A.40]. Of the parameters defined, it is recommended that the peak period T_p and peak direction D_p are not used, since although they are conceptually simple to understand due to their use in defining theoretical spectra, they have a higher sampling variability than integrated parameters based on spectral moments, since they are a property of a single frequency component rather than the whole spectrum. The sampling properties of spectral parameters are defined in Section A6.3 and A6.4. It is recommended that these estimates of the sampling variance are archived along with the parameter estimates themselves.

5.3 Data archiving and presentation

It is recommended that data is archived at three levels, covering raw data, spectral data and parametric data. The rationale behind archiving several levels of data is so that it can be quickly accessed at the appropriate level of detail. The recommendation to make raw data available to developers at a later date is so that alternative analysis techniques can be applied at a later date if so desired. The data and variables to archive at each level are summarized in Table 5-2 to Table 5-4. Note that each level of data archiving has its own quality control flags (see discussion in Section 5.1).

Table 5-2: Recommendations for archiving of raw data from WMI

Description	Notes
Raw data files	Raw files containing time series and other data either from receiving software or archived on the WMI.
Metadata on measurements	All necessary supporting information on the measurement system, setup and deployment. E.g. device type, properties measured, record duration, sampling frequency, water depth, deployment location lat/lon, system variables, observations/issues on deployment, etc.
Quality check flags	Together with documentation of quality checks applied and interpretation of flags.

Table 5-3: Recommendations for frequency-dependent parameters to archive

Parameter	Description	Notes
$E(f)$	Spectrum of surface elevation	
$G_{AB}(f)$	Cross-spectra of measurements[7]	For $A \leq B$, real and imaginary components
$\theta_m(f)$	Mean direction	Defined in terms of the directional Fourier coefficients
$\sigma_c(f)$	Directional spread	
-	Quality check flags	Together with documentation of quality checks applied and interpretation of flags.

[7] Note that although the four directional Fourier coefficients can be written in terms of the cross-spectra, as described in Section A3.2, some information is discarded on the co- and quad-spectra which are assumed to be zero, but are non-zero in practice. It is therefore recommended to archive the cross-spectra rather than the directional Fourier coefficients.

Table 5-4: Recommendations for frequency dependent parameters to archive

Parameter	Description	Notes
m_n	Spectral moments	$n = -1, 0, 1, 2.$
H_s	Significant wave height	Calculated over valid frequency range for omnidirectional measurements
T_e	Energy period	
P_{omni}	Omnidirectional wave power per meter	
P_{net}	Directionally resolved wave power per meter	Calculated over valid frequency range for directional measurements
$MDIR$	Spectrally averaged mean direction	
$SDIR$	Spectrally averaged directional spread	
θ_P	Power-weighted mean direction	
$\mathrm{Var}(\hat{H}_s)$	Variance in estimate of significant wave height	The number of degrees of freedom of each spectral ordinate should be accounted for.
$\mathrm{Var}(\hat{T}_e)$	Variance in estimate of energy period	
$\mathrm{Var}(\hat{P}_{omni})$	Variance in estimate of omnidirectional power	
$\mathrm{Var}(\widehat{MDIR})$	Variance in estimate of *MDIR*	
$\mathrm{Var}(\widehat{SDIR})$	Variance in estimate of *SDIR*	
-	Quality check flags	Together with documentation of quality checks applied and interpretation of flags.

Although presentation of the wave data is typically a responsibility of the WEC developer, more than the test center operator, it can be useful for the test center operator to provide some analysis of the measured site data to help inform decisions made by WEC developers. Data can be presented at various levels of detail, analogous to the three archiving levels described above:

- Time series of raw data
- Spectral time series
- Parameter time series

Time series of raw data should be available to verify the efficacy of quality controls if necessary, as a visual check is often the most effective way of confirming that the data has no unusual features. An example of a spectral time series plot is shown in Figure 5-4. The upper plot illustrates the time-evolution of the omnidirectional spectrum, while the middle and lower plots summarize the directional properties of the spectra. The dark vertical lines indicate missing data due to drop-outs or quality controls. It is evident that the swell direction is consistently from around 300 degrees during this period, while the direction of the higher frequency components varies between North and South West. There is a consistent pattern of low spreading values at the peak of the spectrum or where a secondary wind-sea peak is present. Time series of several integrated parameters for the same period are shown in Figure 5-5.

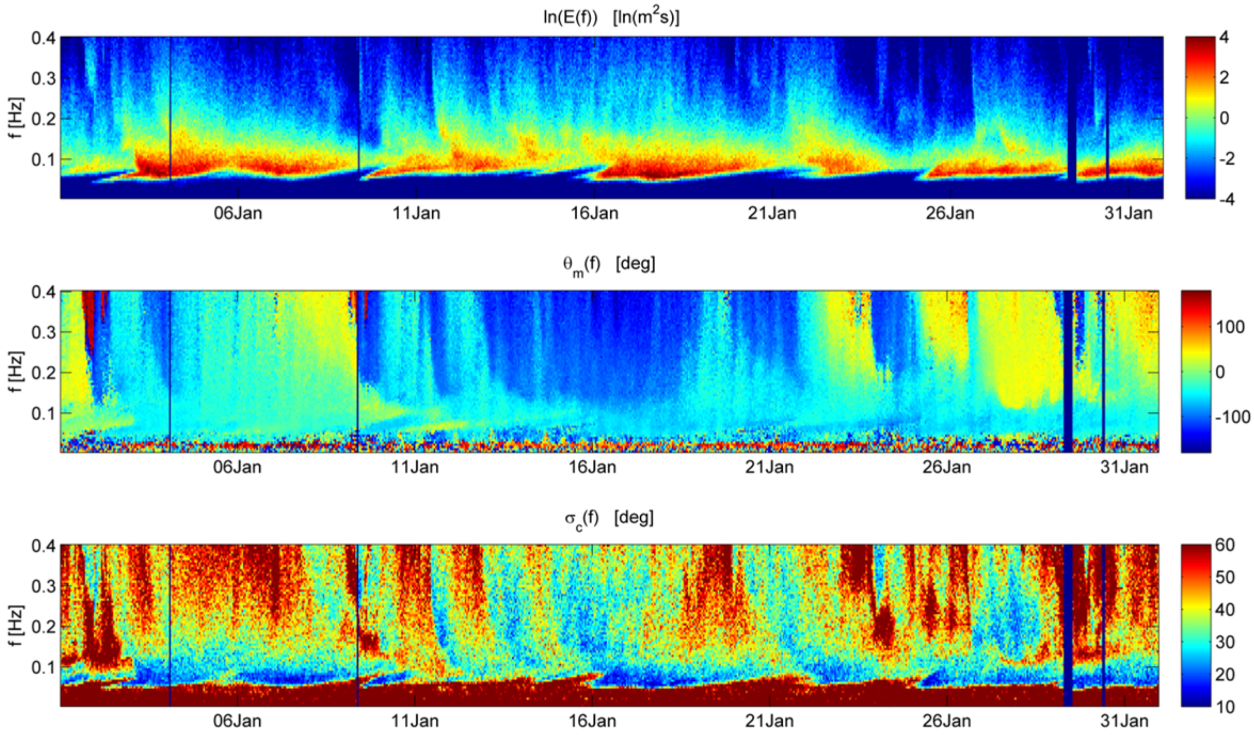

Figure 5-4: Time series of surface elevation spectra (upper plot), frequency-dependent mean direction (middle) and frequency-dependent directional spreading (lower plot). Data for Jan 2005 from CDIP buoy 198.

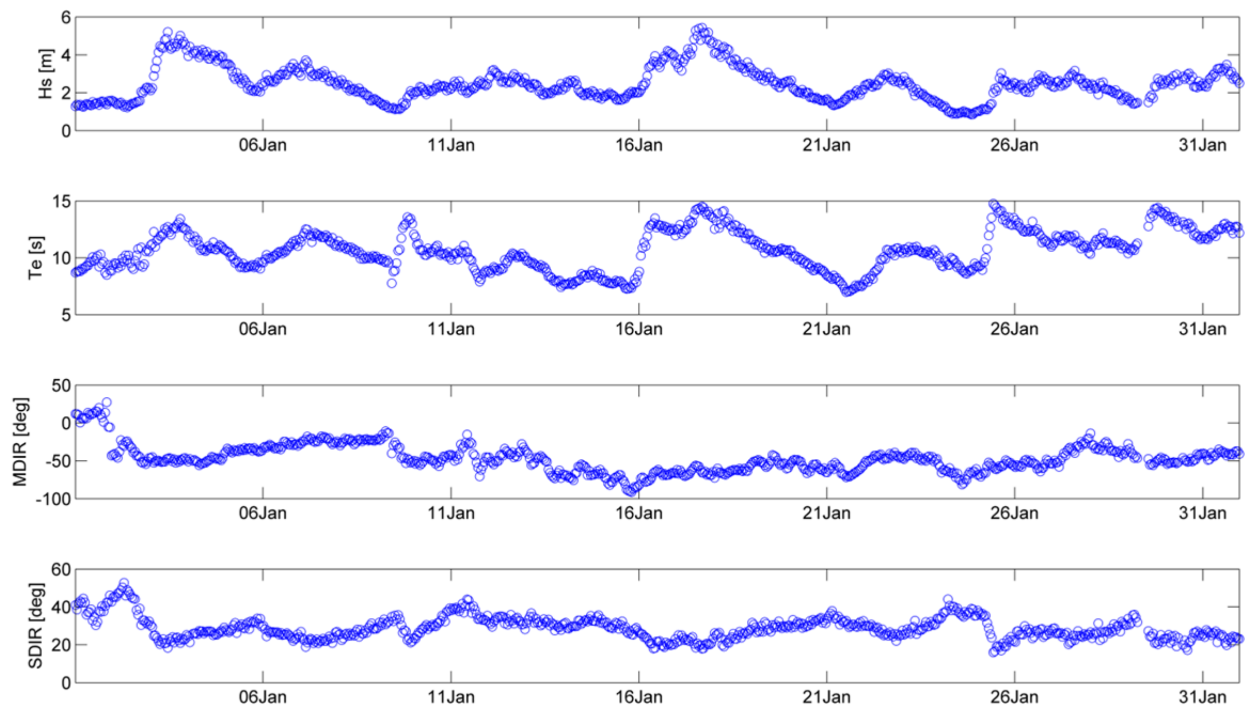

Figure 5-5: Time series of integrated spectral parameters for the same period shown in Figure 5-4

The parametric data measured on site can also be presented in a similar way to the long-term wave climate data from the resource analysis, in terms of scatter diagrams (indicating the joint occurrence of H_s and T_e), wave roses (indicating the joint occurrence of H_s and *MDIR*) or exceedance plots for individual variables.

A type of analysis which may be beneficial to a WEC developer, which is not typically provided as part of the long-term resource data, is to examine the range of spectral shapes. As discussed in Section 6, A WEC power matrix is typically specified in terms of H_s and T_e. However, for a given H_s and T_e there will be a range of spectral shapes, which may have an influence on WEC performance. The range of shapes for a given H_s and T_e can be visualized by plotting all spectra within a certain range. Due to the variation of H_s and T_e within the bin, it is helpful to non-dimensionalize the spectra by plotting $E(f)/m_{-1}$ against f/f_e, where $f_e = 1/T_e$. Under this normalization, the area under each curve (i.e. normalized spectrum) is the same, since $\int E(f/f_e)/m_{-1} \cdot df/f_e = 1$. Examples are given in Figure 5-6 and Figure 5-7 of individual normalized spectra and the mean value in each range, using data from CDIP buoy 198. The advantage of using the normalization is evident in Figure 5-7, where the mean spectral shape for a range of values of T_e can be compared on a single plot. It is apparent from Figure 5-7 that the spectra get narrower at longer periods and in steep conditions, where the spectrum is forced towards a JONSWAP shape.

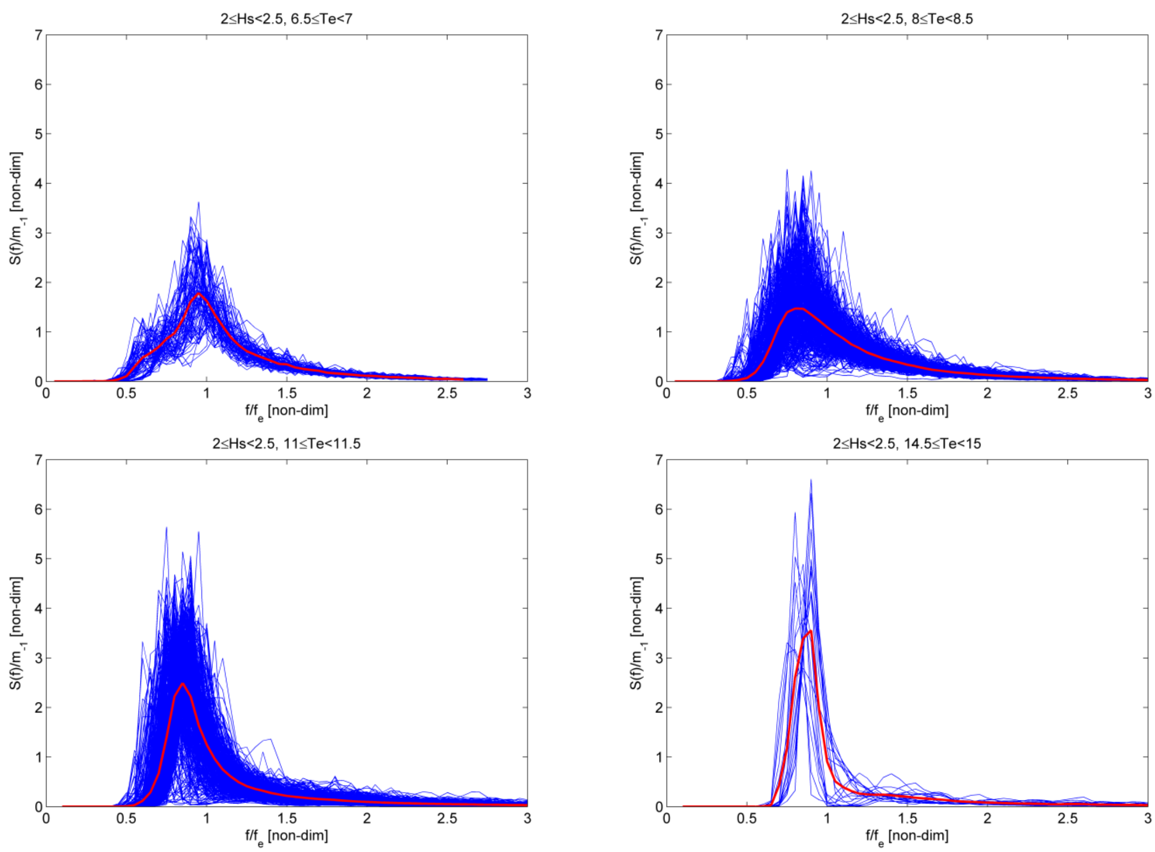

Figure 5-6: Normalized spectra for $2 \leq H_s < 2.5$ and various ranges of T_e. Blue lines indicate individual measured spectra. Red lines indicate the mean shape in each range.

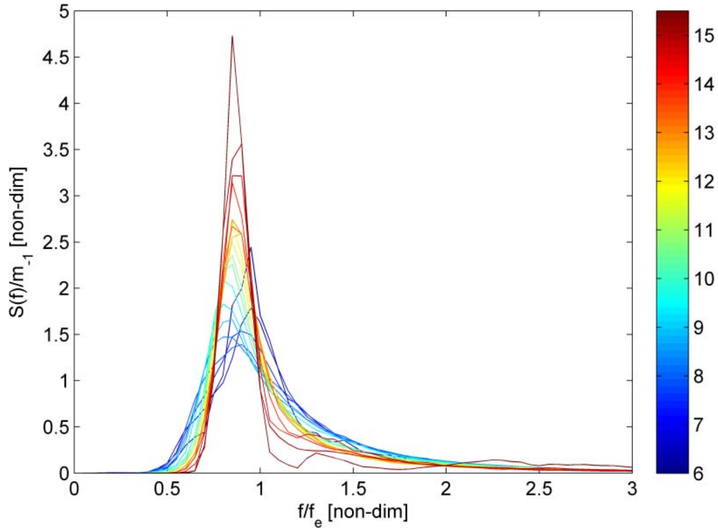

Figure 5-7: Mean measured normalized spectral shape for spectra for $2 \leq H_s < 2.5$ and T_e range indicated by the color scale (in seconds)

6 WEC PERFORMANCE METRICS

In this section, the recommended methodology for deriving estimates of performance from the WECs being tested at HINMREC is described. It is derived from a number of protocols that have been published in recent years on the subject:

- *IEC 62600-100 TS Ed.1: Marine energy – Wave, tidal and other water current converters – Part 100: Power performance assessment of electricity producing wave energy converters*.
- *Equimar: Deliverable D4.2: Data Analysis & Presentation To Quantify Uncertainty.*
- *EMEC: Assessment of Performance of Wave Energy Conversion Systems*.
- *DTI Preliminary Wave Energy Device Performance Protocol*.

The main reference for WEC performance assessment should be taken to be the IEC technical specifications now that is has been published. However, the other guidelines (Equimar, EMEC and DTI) are also useful sources of information. While the DTI, EMEC and IEC guides present largely the same methodology (with some parts clearly shared verbatim), the Equimar documents take a slightly different approach with the intention that the guidance should be useful for devices at a number of different stages of development. The details in the methodologies differ between documents and these are highlighted in the following subsections, along with the common approach.

6.1 WEC measurements

It is understood that no device subsystem parameters will be recorded by HINMREC and that only the environmental input (waves) and the device output (power at generator terminal) are required. Nonetheless, a brief summary of the types of data that could be monitored by the developers or others in a more detailed approach are given below. For further details on this topic, the reader is referred to *Equimar: Deliverable D4.1: Sea Trial Manual.* Finally, data instrumentation and acquisition are discussed in relation to the recording of total WEC power output for derivation of further performance metrics.

The following types of machine and moorings data may be monitored which will be invaluable for numerical model validation and concept development but are of secondary importance to overall performance assessment:

- Body motions[8]
- Joint / PTO motions (displacements / velocities), forces and power (mechanically absorbed and electrical)
- Other PTO system parameters: temperature, vibration, chamber pressure, accumulator loads, etc.
- Machine heading (if applicable), so that this can be quantified relative to the mean wave direction and any misalignment can be accounted for (especially in numerical simulations)
- Moorings, including loads and global WEC motions (if available/appropriate).
- Hull pressure
- Stresses
- Vibrations

During sea trials, the status of the machine and network should be monitored and recorded at all times. This allows filtering to be applied after the data has been recorded so that performance estimates may be derived for defined conditions (e.g. a single control strategy when both device and network are available). It also allows the effect of such parameters on performance to be investigated. The DTI protocol recommends the following states be recorded:

[8] This is dependent on the WEC type, but in each case at least the prime mover if not the reaction frame should be monitored.

- Device status:
  - Device available
  - Off-line for maintenance
  - Constrained availability – (reduced output requested by network operator)
  - Off-site for maintenance
  - Off-line for device fault
  - Off-line for project fault
  - Off-line for network fault
  - Available at reduced capacity (partial fault)
  - Device under manual operation
- Network status:
  - Device connected to network
  - Electrical fault on the project side of the network connection
  - Network lost
  - Constrained generation requested by the network operator
- System identifier:
  - Hardware variations (e.g. physical alterations to the WEC)
  - Operating policy (e.g. the sea state parameters at which changes in the control procedure are triggered)
  - Control algorithm (e.g. algorithm version number)

The IEC, EMEC and DTI documents all recommend that for the purposes of WEC performance assessment, power should be measured at or as close as possible to the electrical output terminals of the WEC. This is defined for an AC grid-connected WEC as the point where the output power is in the form of AC at the network frequency. The Equimar *Deliverable D4.2* document also highlights this as the default location for full-scale WECs but notes that performance assessment can be applied at any stage of the power conversion process in terms of an associated 'efficiency'. Furthermore, an intermediate conversion step may be more appropriate for early stage scale WECs where the PTO is not fully representative of the full-scale system.

It is recommended that the net electric power of the WEC be measured using a power measurement device such as a transducer whose operating range is such that all positive and negative peaks of power (corresponding to import and export of power) can be measured. The IEC *62600-100 TS Ed.1* specification should be referred to for further technical details on the instrumentation requirements.

The amount of data collected should be dependent on the design operating envelope. That is to say sufficient data should be collected for all operational, environmental, and machine conditions. Clearly if the effect of parameters other than H_s and T_e are to be used (e.g. depth) to characterize performance, then a greater number of samples will need to be taken in total in order to give an adequate number of samples in each discrete set of conditions. It is important that wave and machine measurements are made simultaneously to allow correlation between the two sets of variables to be analyzed. The delay due to the time it takes for waves to travel between the wave measurement instrument and the WEC should be corrected for.

The sampling frequency for power (electrical or mechanical) is recommended to be at least 2Hz. The IEC specification recommends that the signal should have been subjected to an antialiasing filter. The time series should be split up into discrete records over which a number of statistics are derived. The IEC specification recommends a minimum sample of 20 minutes and a maximum of 1 hour, while the EMEC document recommends 1 hour and the DTI document suggests 30 minutes. GL GH recommends that the EMEC guidelines are followed, where records are analyzed in 30 minute sections and results from two adjacent records are averaged to provide a 60 minute sample (see Section 4.3).

For each time- and date-stamped sample, a record of the power production, alongside the sea state information should be kept. The following statistics should be recorded for the power production in each sample:

- Mean power generated – P_{mean}
- Maximum power generated - P_{max}
- Minimum power generated - P_{min}
- Standard deviation of instantaneous power about the mean power – P_{STD} (to record the variation of device power delivery to the network)

It is also recommended that the full time series of power production is kept for use in further validation exercises and to enable re-processing of data if there is later found to be a problem with the data or processing methodology. Time series quality checks (searching for spikes, gaps, etc. in the data) can be carried out in such cases. The ability to capture this information is clearly dependent on the data storage capabilities available. Therefore GL GH recommends that capabilities are assessed and a plan made in consideration of data storage constraints, prior to any testing campaign.

6.2 Quality controls and pre-processing

Before deriving performance metrics, data should first be filtered to remove records where the device or the network is not fully functioning for any reason, using the quality control flags recorded with the sample data.

The data collected may be split into separate data sets depending on the status of the system. That is to say, the performance analysis described in the following sections may be carried out for multiple control algorithms, hardware variations and operating policies but each setting should be treated separately in the analysis. Note that even though a single control algorithm may lead to different PTO force characteristics being applied in different sea states, all such data points may still be treated as part of the same analysis. A similar process of data separation may be performed for all optional performance-related parameters (e.g. water depth), which may first require binning. Alternatively, the entire data set may be treated as a whole, with any parameters affecting performance in excess of H_s and T_e considered extensions of the two dimensional performance matrix described in the next section. In such cases, it is still recommended that H_s and T_e form the first two dimensions.

The method proposed in the Equimar protocol mentions the further screening of data from the valid data set after it has been binned by the wave parameters (see the following subsection 6.3). This is expanded upon by Kofoed et al. [25] with a recommendation that if the WEC under consideration is still at the development stage, data points having especially low or high performances values should be excluded from the analysis. The reason given is that they are not favourable and increase the uncertainty of the resulting performance metrics. Further justification is provided from the assertion that such points probably derive from either inaccurate wave measurements or some occasional beneficial event. However, GL GH considers that this approach is flawed because no evidence-based grounds on which to exclude data are required. Therefore genuine variations in performance will be masked and the reasons behind undesirable variations will remain unknown. A more valid approach for such screening is to instead filter data out on the basis of clearly defined cases (e.g. neglecting control strategies that lead to low performance), once they are suspected or known.

6.3 Overview of performance metrics

There are several motivations for deriving the power performance of a WEC. The primary purpose is so that a WEC tested at one site can be assessed in the context of deployment at another site. This may be carried out, for example, by project developers wishing to estimate the annual energy yield of a potential project with a given WEC (although it should be noted that the power matrix recorded at one site may not be directly transferable to another site, since some parameters which affect WEC response that may not have been included in the power matrix could vary between sites – see Section 7.3). Secondly, certain stakeholders may wish to verify the claims a device manufacturer makes about performance. This group may include, project developers and technology investors. Finally, performance metrics are critical for the device developers themselves in order to investigate the impact of various environmental and device parameters on the efficiency of various stages of the power conversion process. Such data also allows the validation of numerical models which in turn helps the developer to progress the design.

For detailed investigation of WEC subsystems, there are a large number of metrics associated with performance. Since the analysis of these will not be performed by HINMREC, their derivation does not fall under the scope of this report. However, they are summarized below for completeness. Variables of interest include:

- Motions (displacement, velocity, acceleration)
- Forces
- Power per PTO (for devices with multiple PTOs per machine) and in total
- Capture width / relative capture width (described below)

Metrics for these quantities may be presented in various ways, including:

- Statistics: Root-mean-squared (RMS) / Standard deviation, Average, Maximum, Minimum
- Frequency response curves (computed by decomposing the time-series into spectral components using Fourier analysis. Note that uncertainties in the sea state at the WEC will affect the accuracy of this type of plot and that any nonlinearities in the system will result in a different curves for each sea state)
- Parameter dependency plots (e.g. PTO force vs. joint displacement)

However, the principal way of summarizing total WEC performance is via a normalized '*power matrix*'. This uses the following definition of capture width (sometimes called capture length) for a sea state:

$$L = \frac{P}{J} \qquad [6.1]$$

where P is the average power absorbed in a certain sea state and J is the average power contained in a that same sea state per unit width (omnidirectional wave energy flux). The relative capture width is defined as:

$$\epsilon = \frac{P}{Jw} \qquad [6.2]$$

where w is some characteristic dimension of the WEC (usually its width, and sometimes defined as the width with respect to the mean wave direction). This intuitively is the proportion of the wave power incident to the WEC's width that is converted to electrical power, although of course this is does not have an upper bound of 1. Furthermore, it is not appropriate to compare one WEC to another based on relative capture width alone since narrow devices are then shown in an unfairly favorable light. A normalized power matrix can be defined as a table of capture width or relative capture width values for a set of conditions normally described by bins of discrete H_s and T_e pairs. Note that the independent variables can be extended to include more environmental parameters such as water depth, mean wave direction or current speed.

The use of capture width or relative capture width to form the normalized power matrix does not make any difference for yield calculations; it is simply a matter of presentation. The IEC specification favors the former, while the Equimar protocol uses the latter in order to maintain consistency with the analysis of similar 'efficiencies' at various other points of the power conversion chain. Some analysts use a power matrix where the values in the table represent absorbed power directly. However, this approach is not recommended because this leads to a greater variation of values within each cell and so is more sensitive to the method of binning used to form it.

While a power matrix (normalized or otherwise) is a WEC-specific metric, there may also be a desire to estimate long-term performance of a particular WEC at a given site. This is where the '*annual energy yield*' (or equivalently '*mean annual energy production*') is useful. As derived quantities from measured data, all of the aforementioned metrics are subject to uncertainty. Further details on this subject are contained in Section 7 and in the Equimar protocol.

6.4 Estimation of performance metrics from measured data

The procedure for calculating the normalized power matrix using the capture width values from each recorded sample is described in this subsection (the same process applies if the relative capture width as well). First, the data should be binned using ranges of H_s and T_e. The IEC and EMEC documents recommend a maximum bin width in H_s of 0.5 meters and in T_e of 1.0 seconds. Figure 6-1 illustrates an example normalized power matrix. Binning can also be performed with respect to other parameters (e.g. depth) if it reduces the variability within each cell, in which case an H_s / T_e table should then still be produced for each bin of the additional parameters. Note that the greater the number of additional parameters, the greater the amount of data that is required to produce reliable statistics in each cell.

		Average capture length for each bin [m]																	
Significant wave height H_{m0} [m]	7,5																		
	7,0													3,88	3,15		2,91		
	6,5											5,00		4,35	4,14		3,18	2,70	
	6,0										7,12		5,65	5,29	5,21	4,10	3,32		
	5,5							5,59	8,73	9,73	8,85	7,52	6,71	6,44	5,35	4,53	3,34	2,98	
	5,0							7,09	8,13	9,41	10,03	9,28	8,41	7,27	5,86	4,41	3,68	2,74	
	4,5						2,90	5,59	8,54	9,30	10,09	9,85	8,94	7,18	5,55	4,53	3,22	2,95	
	4,0						4,23	5,93	8,63	9,52	9,99	9,97	9,45	7,29	5,14	4,30	3,64		
	3,5					1,34	2,90	5,94	8,54	9,52	10,03	10,02	9,42	7,38	5,70	4,46	3,47		
	3,0					0,53	3,32	5,89	8,54	9,24	10,04	10,05	9,28	7,23	5,37	4,49		3,04	
	2,5					1,23	3,01	6,04	8,17	9,41	10,10	10,03	9,56	7,30	5,49	4,66	3,51	3,02	
	2,0				0,09	0,90	3,24	6,64	8,61	9,45	9,96	10,05	9,42	7,31	5,59	4,37	3,51	3,12	
	1,5			0,01	0,20	1,07	2,69	6,35	8,39	9,47	10,06	10,05	9,45	7,16	5,51	4,53	3,59	3,21	
	1,0			0,01	0,15	0,97	3,55	5,99	8,51	9,46	10,06	10,00	9,47	7,34		4,07	3,33		
	0,5																		
		1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0	11,0	12,0	13,0	14,0	15,0	16,0	17,0	18,0
		Energy period T_e [s]																	

Figure 6-1: Example normalized power matrix – average capture length. Source: IEC Technical specification - Power performance assessment of electricity producing wave energy converters.

The Equimar protocol suggests the creation of custom "zones" of the power matrix by combining data from several adjacent bins of the matrix if appropriate. This allows performance to be analyzed when data points are not abundant (e.g. in the early stages of testing or for prototype devices) because it reduces the number of areas of the power matrix that can't be considered reliable because they are empty or contain too few data points. It is recommended, however, that each zone should represent at most 20% of annual available energy at the site and that all zones should contain enough points to adequately represent the variability within that zone. The Equimar protocol suggests that five points per bin should be adequate in "usual circumstances". However, GL GH feels that this is unlikely to be adequate to derive statistically reliable figures for the mean capture width (or power) within each bin. It is noted that the estimate of the mean capture width within a bin will have a variance of σ^2/n, where σ^2 is variance in the capture width within a bin and n is the number of samples in the bin (although this assumes that all n records are independent, which may not be the case if the records all come from a single event, due to temporal correlation in the environmental parameters). The value of σ^2 will vary depending on the sea state and is dependent on multiple factors (e.g. the record duration, the sensitivity of the WEC response to parameters not included in the power matrix, the bin size, etc.). It is therefore recommended that the number of data points defined as being sufficient to quantify performance is specified relative to the desired variance in the estimate of the mean measured capture width.

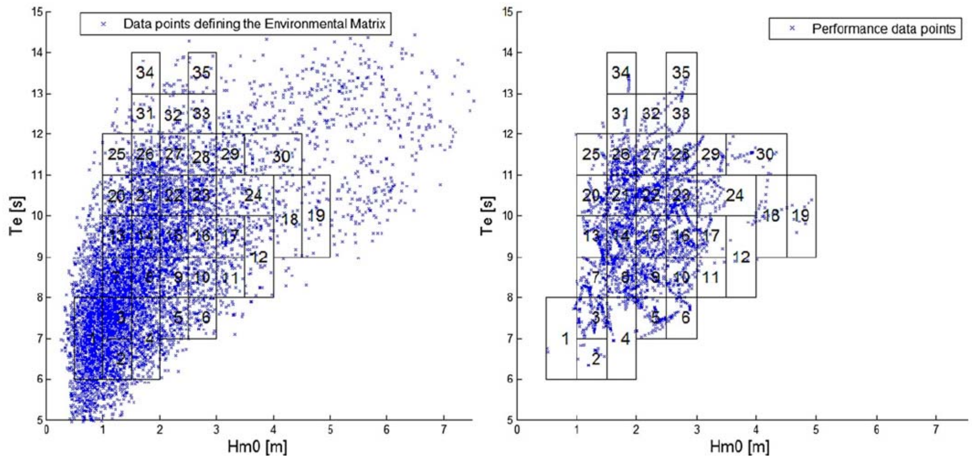

Figure 6-2: The data points defining the environmental matrix (left) and the available performance data points (right), both with the zones overlaid. Source: Kofoed et al. (2013).

The following statistics should then be derived for the normalized power data in each bin (or zone if used):

- Average (Mean)
- Standard deviation
- Maximum
- Minimum
- Number of records

The power matrix can be obtained by re-dimensionalizing the normalized power matrix using the wave energy flux for the center of the bin (calculated with a standard spectral shape) or the device width multiplied by the same in the case of the capture length and relative capture length matrices respectively. This introduces a small amount of error compared to directly binning power values, due to the fact that the wave energy flux for each sample is not exactly equal to that at the center of the bin (this effect is likely to be significant at the edges of the power matrix, where data are gathered towards one side of the bin). GL GH would recommend that the mean measured wave power for each bin is archived along with the normalized power matrix, so that this can be used for re-dimensionalization. Alternatively, if the normalized power matrix is to be re-dimensionalized for use at another site, it is recommend that the mean measured wave power per bin for the target site is used.

The IEC document recommends that calculation of the *mean annual energy production* (MAEP) at a given location should be performed assuming 100% availability (to allow fair comparisons with other WECs). It may be computed using resource time-series data (averages of over each sea state sample) as follows:

$$MAEP = \frac{T}{n}\sum_{i=1}^{i=n} L_i . J_i \qquad [6.3]$$

where T is the average length of a year (8766h), n is the number of sea states, J_i is the omnidirectional wave energy flux per sea state and L_i is the capture width per sea state. Here, the capture width is calculated for each sea state by linear interpolation of the normalized power matrix to the required spectral parameters of the sea state, assuming that the capture widths in the matrix apply at the center of each bin. The IEC specification recommends this method of calculating MAEP if a time-series of the wave resource exists at the location being assessed (10 years is recommended as a minimum).

If only a scatter diagram exists – that is to say sea states have been binned already into spectral parameter ranges, etc. – the IEC specification allows an alternative methodology (which is perhaps more common). This involves linear interpolation (if necessary) of the normalized power matrix onto the scatter diagram bin centers, in a similar way to the method described in the previous paragraph. The contributions from each bin of the scatter diagram are then weighted by the frequencies of occurrence for each sea state (assuming they sum to unity):

$$MAEP_{ALT} = T\sum_{i=1}^{i=N} L_i . J_i . f_i \qquad [6.4]$$

$$\sum_{i=1}^{i=N} f_i = 1 \qquad [6.5]$$

Here, the subscript i indexes the bins of the scatter diagram, N is the number of bins and f_i is the frequency of occurrence of sea state i. (Note that the IEC document has a misprint in the formula for $MAEP_{ALT}$, and multiplies the summation by T/N, rather than T). The Equimar protocol recommends a similar methodology, after first converting values of relative capture width (or other efficiency values) and spectral parameters for each cell of the scatter diagram into values for each larger 'zone'.

There may be a situation in which the normalized power matrix is not complete with respect to desired range of site conditions. This may be because, for example, testing has not been performed for as long as would be desired or the normalized power matrix is being used at a different location (perhaps at a different scale) to the one at which it was derived. In such a case, the IEC specification recommends testing for completeness as follows. Two versions of the MAEP parameter are calculated: one assuming zero capture width in all empty bins and one assuming empty bins are filled with the average values from adjacent filled bins. If the difference between these two figures is less than 5% then the power matrix is considered adequate (i.e. the number of empty bins is not significant). The Equimar protocol (being more focussed on the early stages of WEC development) allows similar interpolation / extrapolation for empty cells in the normalized power matrix as well as calculation using validated numerical models as long as they are clearly marked as such.

6.5 Testing at scale

If scaled devices are tested at scale in the open ocean, full-scale performance estimates may be derived using scaling laws. The regime employed for the majority of relevant WEC variables is Froude scaling, described in more detail in Section 6.5.1. In particular, this can be applied to the independent and dependent variables of the normalized power matrix, subject to the caveats given in the following subsection.

It should be noted that not all processes and quantities are suitable for scaling using the Froude law. In particular, electrical losses do not fall under this regime. Therefore, although at full scale it is desirable to measure output power from the WEC as close as possible to the point of grid connection, at partial scale it may be more representative to measure the power at an earlier stage of the power conversion process. The Equimar protocol recommends this approach which can be pursued further by deriving 'efficiency' values analogous to the relative capture width for various stages of the conversion chain. These may be binned in a similar way to the normalized power matrix before the scaling law appropriate to the process under consideration is applied. However, some phenomena are difficult or impossible to represent well at partial scale (e.g. viscous losses, mooring stiffness. etc.) and so will not be well represented when scaled up. This adds to the uncertainty in deriving full-scale performance metrics from partial scale data.

The process of scaling the normalized performance matrix begins with scaling the independent variables (H_s, T_e, and any other selected parameters) and the dependent variable (capture width) according to the appropriate scaling law. Note that if the relative capture width is used, no scaling is required as it is a non-dimensional ratio, whereas the capture width does require scaling since it has dimensions of length. If the 'zoning' approach of the Equimar protocol is used, the boundaries of these areas may need refining with reference to the full-scale scatter diagram to which the normalized power matrix is to be applied. For example, some zones may no longer cover areas of the parameter space with any occurrences and vice-versa.

It is likely that after scaling, there will be areas of the scatter diagram for which no scaled performance data exists. In this case, the Equimar protocol recommends filling in the gaps using one of a number of methods:

- Interpolation/extrapolation of results from surrounding cells.
- Numerical modeling. In this case it is recommended that such models have been validated as far as possible against tank and at-sea experimental data.
- Derivation from experimental tank tests. Clearly, it is important if this method is used that the model tested in the tank corresponds to the design iteration tested at sea (i.e. same device design, albeit at a different scale)

Once the full-scale normalized power matrix has been derived in this way, the calculation of mean annual energy production may proceed as before.

6.5.1 Scaling laws

To infer the behavior of a full-scale device from tests with a scale prototype, the device must be in geometric, kinematic and dynamic similarity with the full-scale WEC. Geometric similarity requires that there is a fixed ratio of dimensions between the prototype and the full-scale device, kinematic similarity requires that there is a fixed ratio of velocities between the prototype and the full-scale device and dynamic similarity requires that there is a fixed ratio of forces between the prototype and the full-scale device. Due to the wide range of forces which act on a WEC, it is not possible to scale all of these at the same ratio. The approach taken in WEC testing is to use a scaling criterion which keeps the dominant forces acting on the WEC in a fixed ratio.

The motion of a WEC in ocean waves is primarily governed by gravitational and inertial forces. The ratio between inertial and gravitational forces is represented by the Froude number, F_n, given by:

$$F_n = \frac{U}{\sqrt{gL}} \qquad [6.6]$$

where U and L (in this subsection only) are representative velocity and length scales respectively, and g is the modulus of the acceleration due to gravity. Froude scaling can be described as the set of laws which maintain the same Froude number at model scale and full-scale.

Under Froude scaling all lengths (e.g. WEC geometry, water depth, wave height, wavelength, etc.) are scaled by the same factor k. Scaling factors for other quantities calculated from [6.6] are presented in Table 6-1.

Table 6-1: Froude scaling factors for relevant physical quantities

Quantity	Scale factor
Length	k
Angle	1
Time	$k^{0.5}$
Linear velocity	$k^{0.5}$
Angular velocity	$k^{-0.5}$
Linear acceleration	1
Angular acceleration	k^{-1}
Volume	k^{3}
Density	r
Mass	rk^{3}
Force	rk^{3}
Moment	rk^{4}
Power	$rk^{3.5}$
Linear stiffness	k^{2}
Angular stiffness	k^{4}
Linear damping	$k^{2.5}$
Angular damping	$k^{4.5}$

Froude scaling laws are valid when gravitational and inertial forces are dominant and viscous forces can be disregarded. Froude scaling does not maintain the correct ratio between inertial and viscous forces. To maintain this ratio at partial scale the Reynolds number, R_e, would need be the same, where

$$R_e = \frac{UL}{\nu} \qquad [6.7]$$

and ν is the kinematic viscosity of the fluid. Since the kinematic viscosity is a property of the fluid and the ratio between *U* and *L* is determined by the Froude number, it is not possible to simultaneously maintain the same Froude and Reynolds numbers at partial scale. This means that viscous effects, such as vortex shedding and drag, may not be correctly scaled. Such effects may be more significant at reduced scale (e.g. viscous damping on the hull and mooring lines will be greater at model scale than at full-scale). However since gravitational forces normally have the dominant effect on WEC motion, Froude scaling is typically used for WEC modeling.

Other viscous properties include surface tension effects. These are generally considered negligible for wavelengths greater than 0.1 meter (a period of about 0.25 seconds in deep water) and so their effect on scale tests at sea can be neglected.

6.6 Data archiving and presentation

All of the data described in Section 6.1 that has been collected should be archived if at all possible to allow later analysis and re-analysis if any changes to the processing methodology are subsequently made.

As far as the presentation of results goes, there are two key audiences for reporting: staff internal to the WEC technology developer and secondly, a wider audience potentially including future investors and other key stakeholders. It is clear that the level of detail and the sensitivity of what can be presented will be different in each case. For example, time-series results relating to WEC subsystems are likely to be useful for the technology developer to aid further development, but not appropriate for a more widely circulated report (unless for academic purposes). As well as the quantitative results, reports for the device developer should additionally include a log of the sea trials, summarizing the main milestones achieved and all events that required intervention, with any unusual events (e.g. malfunctioning of sensors) noted.

It is useful to include examples of detailed results in the reporting to aid understanding of the performance of the WEC as a whole. Examples may be: time series of motions, forces, power, etc. as well as any analysis, graphs and statistics regarding the main WEC subsystems defined in Section 6.3. Figure 6-3 shows an example of a time series plot for data collected at the Pico OWC plant.

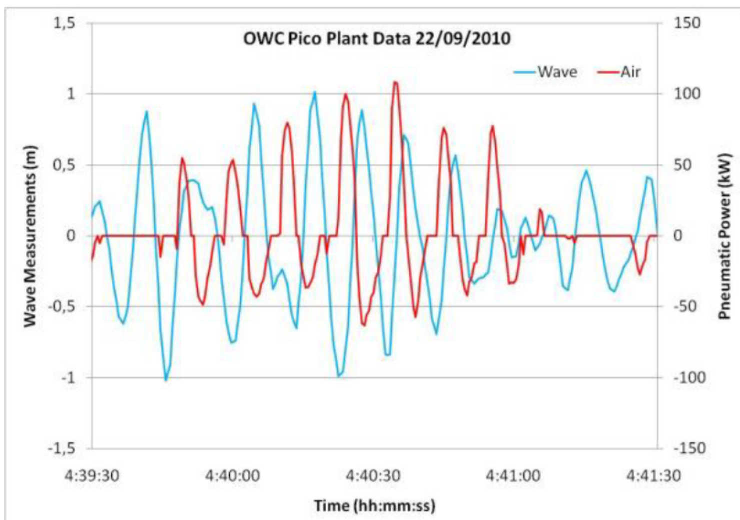

Figure 6-3: Example for time domain records of incident energy level & hydrodynamic energy absorbed: wave height measured in front of Pico OWC and absorbed power by the chamber ("Pneumatic Power"). Source: Equimar Deliverable 4.1 Sea Trials Manual.

Many of the referenced documents on performance assessment methodologies recommend the provision of time series for total WEC power output (averaged over the duration of each sample), alongside wave energy flux (scaled by device width, for example, if deemed appropriate). This allows an overall appreciation of power variability, the effect of individual climatic events and the variation in WEC efficiency (in converting wave to electrical power) with sea state.

The measured normalized power matrix should be reported as the central result of the analysis. The Equimar protocol recommends presentation of a matrix derived from hydrodynamically absorbed power (usually defined as the product of the force applied by the PTO and the velocity of the prime mover) as well as one based on electrically delivered power. It is therefore crucial in any report to state alongside the presentation of any power matrix what exactly it refers to, and the assumptions and methodology that has been used to generate it. This allows fair comparison of the results with other sets relating to the same device and indeed other WECs.

The recommendations for the exact presentation of the power matrix vary between the different documents. Equimar recommends listing detailed results per 'zone' (see Section 6.4). The more conventional way of displaying a power matrix is as a 2D table of normalized power values as a function of H_s and T_e. To aid visualization, the cells are sometimes colored dependent on the magnitude of their contents. Because of the familiarity of this arrangement it is recommended that should other parameters be included in the binning, results relating to bins of these variables should be presented as separate sheets of a standard H_s and T_e power matrix. The mean, minimum, maximum, standard deviation and number of records can either be presented in separate tables or together in one. Sometimes scatter diagram data may also be combined with performance data as shown in Figure 6-5.

Performance from the sea trials performed at *Point 3 in Danish North Sea*													
Environmental parameters						Non-dimensional parameters				Performance parameters			
Zone	H_{mo}	T_e	P_{wave}	Prob	$P_{wave.}$Prob	η	s	n	CI	P	s	CI	P.Prob
	[m]	[s]	[kW]	[-]	[kW]	[-]	[-]	[-]	[-]	[kW]	[kW]	[kW]	[kW]
1	1	5,6	118	0,468	55	0,195	0,041	80	0,009	23	4,8	1,1	11
2	2	7,0	591	0,226	133	0,284	0,062	67	0,015	168	36,6	8,9	38
3	3	8,4	1595	0,108	172	0,152	0,044	48	0,013	242	70,2	20,4	26
4	4	9,5	3207	0,051	164	0,098	0,029	13	0,017	314	93,0	55,7	16
5	5	11,2	5907	0,024	142	0,063	0,015	27	0,006	372	88,6	35,0	9
6	6	13,0	9873	0,012	118	0,038	0,017	5	0,020	375	167,8	193,0	5
Weighted average			785			0,133	0,090		0,090	104	71,0	70,9	
Total				0,889	785								104
Yearly Production [MWh/y]										915			
Load factor [-] (400kW installed capacity)										0,26			

Figure 6-4: Example of the performance table of a wave energy converter (based on illustrative values). Source: Equimar Deliverable 4.2 Data Analysis & Presentation To Quantify Uncertainty.

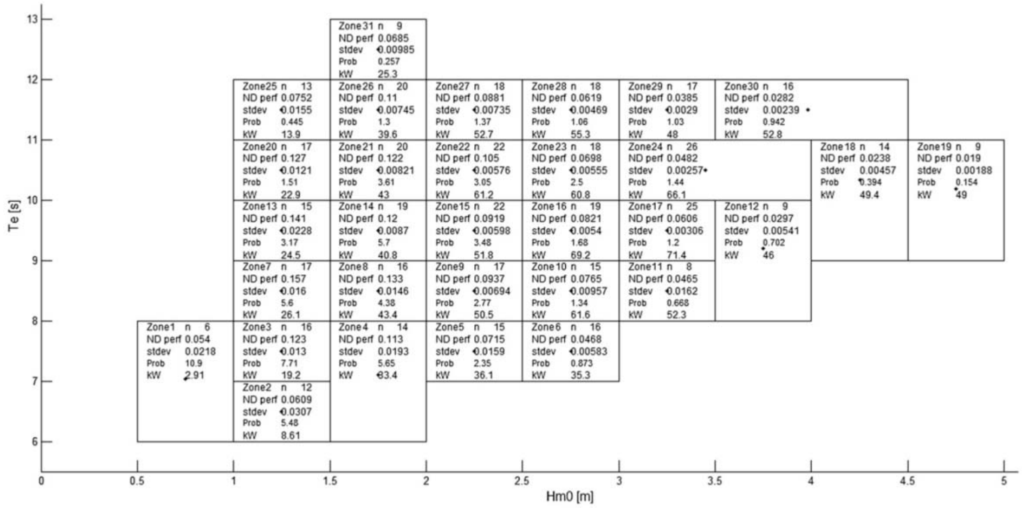

Fig. 5. Overview table containing some of the main environmental and performance parameters.

Figure 6-5: Example overview table containing some of the main environmental and performance parameters. Source: Kofoed et al. (2013).

Mean annual energy production may simply be presented as a single figure for each site of interest. In this case, it is informative for the reader if they are presented with the corresponding normalized power matrix and scatter diagram, plotted on the same scale (see Figure 6-6).

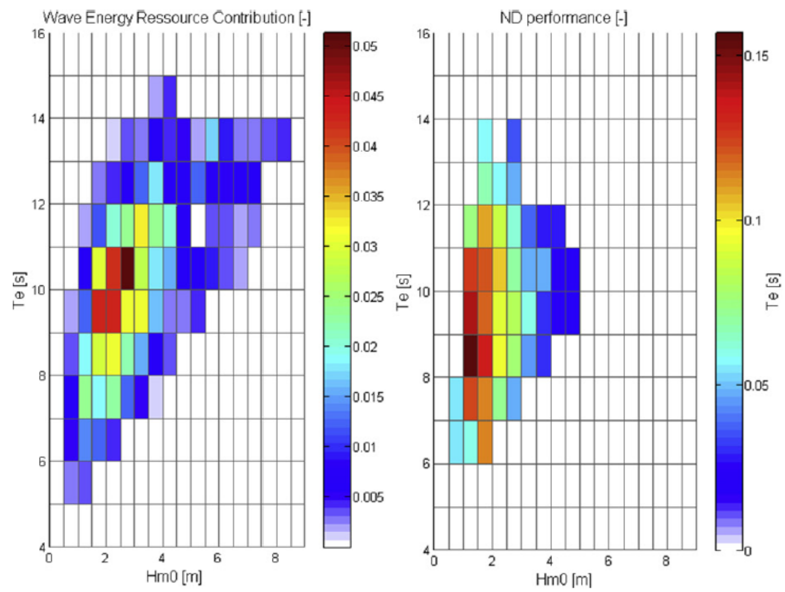

Figure 6-6: Example overview graphs of the wave energy contribution of each bin, and the corresponding non-dimensional performance. Source: Kofoed et al. (2013).

7 UNCERTAINTY ANALYSIS

The discussion of uncertainty in this section is related to the question of how accurately the WEC response can be determined in response to a particular sea state. The discussion is split into three sections: the first part considers the uncertainties in the sea state experienced by WEC and the second considers the uncertainties in the WEC response. The final section discusses the uncertainties in the measured power matrix.

7.1 Uncertainties in the sea state experienced by the WEC

The analysis of the uncertainty in the sea state experienced by the WEC can be split into a number of categories:

- Precision and accuracy of the WMI
- Uncertainties relating to the analysis methods used
- Statistical differences between the sea state at the WMI and the WEC
- Deterministic differences between the sea state at the WMI and the WEC
- The influence of the WEC on the measured sea state

The characteristics of various types of WMI were discussed in Section 4.1. Wave buoys and ADCPs can typically make accurate and precise measurements of the sea states they experience. Wave buoy manufacturer's specifications typically state that heave displacement accuracy is better than 1%, and ADCP water velocity measurements better than 1%. The innate limitations of the devices (related to the high and low frequency cut offs) are generally the limit factors to the measurements. However the frequency response of a WEC usually falls within the range of frequencies which can be accurately measured by the WMI.

Provided that the WMI is correctly installed and calibrated, the main component of the uncertainty in the sea state experienced by the WEC is due to the difference in the sea state measured by the WMI and experienced by the WEC. These differences can be both statistical and deterministic in nature, and were discussed in Sections 4.4.1 and 4.4.2. Moving the WMI closer to the WEC can reduce both the statistical and deterministic differences in the sea state, but can risk biasing the measurements if the WMI is situated in a location which is influenced by radiated and diffracted waves from the WEC (see Section 4.4.4). It is therefore recommended that the location of the WMI relative to the WEC is carefully considered, following the recommendations in Section 4.4, and the uncertainties from each factor are quantified for the particular site and WEC in question.

The uncertainties related to the analysis methods used refers to the validity of the assumptions which are made. Some concepts and parameters give a valid description of the sea state, irrespective of the validity of the assumptions which underpin them. For example, the concept of the wave spectrum is usually invoked via a description of the sea surface as the superposition of a number of freely-propagating (i.e. non-interacting) sinusoidal components. This is known not to be the case, but nevertheless the spectrum is still a valid description of the surface elevation at a point, as long as it is acknowledged that components may interact and that energy in the spectrum at certain frequencies may correspond to bound harmonics of components at another frequency (i.e. nonlinear components of waves at one frequency which propagate at the same velocity, but appear in the spectrum at other frequencies). Similarly, the omnidirectional parameters such as H_s and T_e can be understood as a description of the surface elevation without reference to a particular hydrodynamic theory.

However, other parameters do explicitly require the assumptions of linear theory in their derivation, such as the wave power per meter crest length or directional properties. The estimation of directional properties is based on relationships between wave properties derived from linear theory and which assume the absence of currents. As discussed in Section 5.1, the relations can be verified via a 'check ratio' (Equation [5.4]). However, the determination of the directional distribution is inherently uncertain, due to innate limitations in the information that can be discerned from measurements (see discussion in Section A3.3). It is therefore necessary to make assumptions about the shape of the directional distribution in order to estimate it from measurements.

7.2 Uncertainties in the WEC response

The WEC response is generally known with greater accuracy than the sea state. The uncertainties in the WEC response can be split into the following categories:

- Sensor precision and accuracy
- Measurement limitations
- Undetected malfunctions

Measurement limitations refer to the fact that it may not be possible to directly measure a variable of interest. For instance the measurement of force applied at a joint may not include the friction within the joint. This would result in an underestimate of the applied force, which could bias model validation studies or cause an underestimate of the absorbed power.

Undetected malfunctions can also cause biases in the measured response. For instance, a leak in a hydraulic circuit could affect measurements of the applied PTO force, or damage to a joint may result in restricted or excessive movement. It is therefore recommended that the WEC equipped with fault detection systems and that data are thoroughly screened following retrieval of the WEC, so that records which were potentially affected by malfunctions which were undetected during testing can be flagged.

7.3 Uncertainties in the measured power matrix

The measured power matrix, discussed in Section 6, will contain a range of observed power values within each bin. Provided that the data has been screened for erroneous measurements (WEC or wave) and that the dataset is for a single machine control strategy (which may incorporate varying PTO settings with sea state), the variability in the measured mean WEC power within each bin is a result of:

- Finite bin size (i.e. sea state parameters and hence WEC performance vary over the bin)
- Sampling variability (i.e. the measured sea state parameters are not exactly the same as the parameters of the sea state experienced by the WEC)
- Influence of variables not used to form the power matrix (e.g. wave direction, machine heading relative to the mean wave direction, water depth, currents, spectral shape, etc.)

All of the aforementioned guidelines recommend that the power matrix should record the standard deviation, maximum and minimum of the observations within each bin, together with the mean value. Koefed et al. [25] note that for short-term datasets, temporal correlations in the observations can cause the variability to be underestimated within low-occurrence bins. If there are only a few observations within a bin, which are all from the same event, then it is possible that other environmental factors (e.g. spectral shape, direction, etc.) could be approximately constant over the event, meaning that the full range of events is not captured. However, as this is more problematic for low-occurrence bins, the effect on the predicted energy yield is likely to be low.

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APPENDIX A THEORY AND DEFINITIONS

A1 Wave Kinematics – Linear Theory

In many situations, the kinematics of wave motion can be well modeled using linear (Airy) wave theory, where it is assumed that the wave height is small compared with the wave length and water depth. In particular, most of the terminology used for describing a sea state can be understood in terms of linear theory. The methods used to estimate directional and sampling properties of the sea state are also based on linear theory. Nonlinear aspects become important for steep waves and shallow water and are essential for understanding the evolution of the wave spectrum as waves are generated, propagate, and dissipate. However, even when nonlinear aspects cannot be considered insignificant, much of the terminology used to describe the sea state based on linear theory is still applicable.

A1.1 Relations between surface elevation and other kinematic properties

Under the linear model, the surface elevation η is decomposed as a sum of freely-propagating regular wave components with various amplitudes a_j, angular frequencies ω_j, directions θ_j and phases ϕ_j:

$$\eta(x,y,t) = \mathrm{Re}\left[\sum_j a_j \exp\left(i \cdot \psi_j(x,y,t)\right)\right], \qquad [A.1]$$

where

$$\psi_j(x,y,t) = k_j\left(x\cos\theta_j + y\sin\theta_j\right) + \omega_j t + \phi_j, \qquad [A.2]$$

and $k_j = 2\pi/\lambda_j$ is wavenumber and λ_j is wavelength of the j^{th} component. Other wave properties, such as particle displacements, velocities and accelerations, can then be written as the product of the components of the surface elevation and a transfer function $H_m(f,\theta)$:

$$P_m(x,y,z,t) = \mathrm{Re}\left[\sum_j H_m(f_j,\theta_j) a_j \exp\left(i \cdot \psi_j(x,y,t)\right)\right]. \qquad [A.3]$$

The transfer function can be decomposed in the form:

$$H_m(f,\theta) = h_m(f)\cos^{\alpha_m}\theta \sin^{\beta_m}\theta \qquad [A.4]$$

These quantities are listed in Table A-1 for various wave properties.

A1.2 The dispersion relation, phase velocity and group velocity

The equation that governs the relationship between wavelength and period is called the dispersion relation. It is given by:

$$\omega^2 = gk\tanh kd, \qquad [A.5]$$

where g is the acceleration due to gravity and d is the water depth. When the ratio of water depth to wavelength is large (i.e. in deep water) then $\tanh kd \to 1$ and $\omega^2 = gk$. Deep water is taken to mean depths greater than $\lambda/2$, where $\tanh kd > 0.996$. In shallower water, where the approximation $\tanh kd = 1$ is no longer valid, there is no analytic solution to the dispersion equation and numerical methods must be used to solve for *k*. A Newton-Raphson iterative scheme with an initial guess of $k = \omega^2/g$ can be used in this case and will typically converge to an accurate solution within a few iterations.

The speed at which wave crests pass a fixed point is called the phase speed, denoted c_p, and is given by

$$c_p = \frac{\lambda}{T} = \frac{\omega}{k}. \quad [A.6]$$

Substituting [A.5] gives

$$c_p = \left(\frac{g}{k}\tanh kd\right)^{\frac{1}{2}}. \quad [A.7]$$

For deep water, $\tanh kd \to 1$, and the phase speed is given by

$$c_p(deep) = \left(\frac{g}{k}\right)^{\frac{1}{2}}. \quad [A.8]$$

For very shallow water, $\tanh kd \to kd$ and the phase speed is given by

$$c_p(shallow) \approx (gd)^{\frac{1}{2}}. \quad [A.9]$$

Equation [A.5] is called the dispersion relation because it governs how waves of different periods and wavelengths disperse from a fixed point. From [A.9] we see that in very shallow water, the phase speed is no longer dependent on wavelength and in this case, the waves are referred to as non-dispersive.

The speed at which the energy propagates is known as the group speed, is denoted c_g, and is given by

$$c_g = \frac{d\omega}{dk}. \quad [A.10]$$

Substituting [A.5] and rearranging gives

$$c_g = \frac{1}{2}c_p\left(1 + \frac{2kd}{\sinh 2kd}\right). \quad [A.11]$$

For deep and shallow water, this reduces to

$$c_g(deep) = \frac{c_p}{2}, \qquad c_g(shallow) \approx c_p. \quad [A.12]$$

Table A-1: Transfer functions between surface elevation and various wave properties

Property		$h_m(f)$	α_m	β_m
Displacement	x-axis	$i\frac{\cosh(k(d+z))}{\sinh(kd)}$	1	0
	y-axis	$i\frac{\cosh(k(d+z))}{\sinh(kd)}$	0	1
	z-axis	$\frac{\sinh(k(d+z))}{\sinh(kd)}$	0	0
Velocity	x-axis	$\omega\frac{\cosh(k(d+z))}{\sinh(kd)}$	1	0
	y-axis	$\omega\frac{\cosh(k(d+z))}{\sinh(kd)}$	0	1
	z-axis	$-i\omega\frac{\sinh(k(d+z))}{\sinh(kd)}$	0	0
Acceleration	x-axis	$-i\omega^2\frac{\cosh(k(d+z))}{\sinh(kd)}$	1	0
	y-axis	$-i\omega^2\frac{\cosh(k(d+z))}{\sinh(kd)}$	0	1
	z-axis	$-\omega^2\frac{\sinh(k(d+z))}{\sinh(kd)}$	0	0
Surface slope	x-axis	ik	1	0
	y-axis	ik	0	1
Dynamic pressure		$\rho g\frac{\cosh(k(d+z))}{\cosh(kd)}$	0	0

d is water depth, ρ is water density, g is gravitational acceleration
Note that z is positive upwards from the free surface so that $z + d = 0$ at the sea bed.

A2 The Wave Spectrum

The directional wave variance spectrum $S(f,\theta)$ describes how the energy in the wave field is distributed with frequency and direction. For small δf and $\delta\theta$, the directional spectrum is related to the components of the surface elevation in [A.1] by

$$S(f,\theta)\delta f\delta\theta = \sum_{f}^{f+\delta f}\sum_{\theta}^{\theta+\delta\theta}\frac{1}{2}a_j^2. \qquad [A.13]$$

That is, the spectral density is the sum of the variances of the individual sinusoidal components over a given frequency and directional range.

The directional spectrum can be decomposed into two functions, one representing the total energy at each frequency and the other describing how the energy at each frequency is distributed with direction:

$$S(f,\theta) = E(f)D(f,\theta). \quad \text{[A.14]}$$

$E(f)$ is called the omnidirectional spectrum or frequency spectrum and is related to the directional spectrum by

$$E(f) = \int_0^{2\pi} S(f,\theta)d\theta. \quad \text{[A.15]}$$

$D(f,\theta)$ is called the directional spreading function or directional distribution and satisfies two properties:

$$1.\ D(f,\theta) \geq 0 \ \text{ over } [0\ 2\pi]. \quad \text{[A.16]}$$

$$2.\ \int_0^{2\pi} D(f,\theta) = 1. \quad \text{[A.17]}$$

A3 Estimation from measurements

A3.1 Definition of auto-spectra and cross-spectra

Suppose that measurements of wave properties P_A and P_B (i.e. quantities listed in Table A-1) are made at locations (x_A, y_A, z_A) and (x_B, y_B, z_B). Denote the raw samples as $P_{A,0}, \cdots, P_{A,N-1}$ and $P_{B,0}, \cdots, P_{B,N-1}$, where the sampling frequency f_s and the duration of the record is $\tau = N/f_s$. Let $X_{A0}, \cdots, X_{A,N-1}$ and $X_{B0}, \cdots, X_{B,N-1}$ be the discrete Fourier transforms of $P_{A,0}, \cdots, P_{A,N-1}$ and $P_{B,0}, \cdots, P_{B,N-1}$ respectively. Estimates of the auto-spectra $\hat{G}_{AA}(f_j)$ and $\hat{G}_{BB}(f_j)$ of the wave properties P_A and P_B and the cross-spectrum $\hat{G}_{AB}(f_j)$ between the wave properties P_A and P_B, are defined as:

$$\hat{G}_{AA}(f_j) = \frac{2}{\tau f_s^2} X_{Aj}^* X_{Aj}, \qquad \hat{G}_{BB}(f_j) = \frac{2}{\tau f_s^2} X_{Bj}^* X_{Bj}, \quad \text{[A.18]}$$

$$\hat{G}_{AB}(f_j) = \frac{2}{\tau f_s^2} X_{Aj}^* X_{Bj}, \quad \text{[A.19]}$$

where $f_j = j/\tau$, $j = 0, \dots, N-1$, and the notation $\hat{x}$ is used to denote an estimate of quantity x. The sampling properties of the estimates of the auto- and cross-spectra are discussed in Section A6.

A3.2 The relationship between cross-spectra, the directional spectrum and directional Fourier coefficients

It can be shown that the directional spectrum is related to the cross-spectra between wave properties P_A and P_B by (see e.g. Isobe *et al*., 1984)

$$G_{AB}(f) = \int_0^{2\pi} H_A(f,\theta) H_B^*(f,\theta) \exp\Big(-ik\big((x_B - x_A)\cos\theta + (y_B - y_A)\sin\theta\big)\Big) S(f,\theta)\mathrm{d}\theta, \quad \text{[A.20]}$$

where $H_A(f,\theta)$ and $H_B(f,\theta)$ are the transfer functions listed in Table A-1 and * denotes the complex conjugate. This relation between the directional spectrum and the cross-spectra between wave properties can be used to estimate the omnidirectional and directional spectrum as follows.

The directional distribution can be expressed in terms as a Fourier series as:

$$D(f,\theta) = \frac{1}{2\pi} + \sum_{n=1}^{\infty} (a_n \cos n\theta + b_n \sin n\theta). \qquad [A.21]$$

In-situ wave measurements from buoys comprise a triplet of measurements of surface-elevation and either horizontal displacements, velocities or surface slopes. If the surface elevation signal is denoted P_1, the x-axis measurement (slope, displacement or velocity) is denoted P_2 and the y-axis measurement is denoted P_3 then the following relations between the directional Fourier coefficients and the cross-spectra each signal can be calculated using [A.20] and [A.21] (noting that the horizontal separation of measurements is zero in this case):

$$G_{11}(f) = E(f) \qquad [A.22]$$

$$G_{22}(f) = \tfrac{1}{2}|h|^2 E(f)\big(1 + a_2(f)\big) \qquad [A.23]$$

$$G_{33}(f) = \tfrac{1}{2}|h|^2 E(f)\big(1 - a_2(f)\big) \qquad [A.24]$$

$$G_{12}(f) = hE(f)a_1(f) \qquad [A.25]$$

$$G_{13}(f) = hE(f)b_1(f) \qquad [A.26]$$

$$G_{23}(f) = \tfrac{1}{2}|h|^2 E(f)b_2(f) \qquad [A.27]$$

where $h = h_2 = h_3$ as listed in Table A-1. Note that $G_{AB} = G_{BA}^*$, so there are only six unique entries in the cross-spectral matrix. Moreover,

$$G_{22} + G_{33} = |h|^2 G_{11} \qquad [A.28]$$

It is thus only possible to estimate five independent quantities at each frequency, one of which is used to estimate the frequency spectrum and the other four are used to estimate the directional distribution.

The cross-spectra are often written in terms of the real and imaginary parts as $G_{AB} = C_{AB} + iQ_{AB}$, where C_{AB} and Q_{AB} are referred to as the coincident-spectrum (or co-spectrum) and quadrature-spectrum or (quad-spectrum), respectively. All the auto spectra are real quantities and from [A.27] we have $Q_{23} = 0$. For heave-displacement or heave-slope measurements $C_{12} = C_{13} = 0$ and for heave-velocity measurements $Q_{12} = Q_{13} = 0$. It is important to note that in general the estimates of Q_{23}, C_{12} and C_{13} (or Q_{12} and Q_{13} in the case of heave-velocity measurements) will not be exactly zero due to sampling variability. The directional Fourier coefficients are therefore defined in terms of the co- and quad-spectra that are theoretically non-zero as the corresponding real or imaginary components may be non-zero in practice. The definitions are given in Table A-2, obtained by rearranging [A.22] - [A.28].

Table A-2: Definition of directional Fourier coefficients in terms of measured co- and quad-spectra

Directional Fourier coefficient	**Heave-slope or heave-displacement measurements (e.g. wave buoys)**	**Heave-velocity measurements (e.g. ADCP)**
a_1	$\frac{Q_{12}}{\sqrt{C_{11}(C_{22}+C_{33})}}$	$\frac{C_{12}}{\sqrt{C_{11}(C_{22}+C_{33})}}$
b_1	$\frac{Q_{13}}{\sqrt{C_{11}(C_{22}+C_{33})}}$	$\frac{C_{13}}{\sqrt{C_{11}(C_{22}+C_{33})}}$
a_2	$\frac{C_{22}-C_{33}}{C_{22}+C_{33}}$	$\frac{C_{22}-C_{33}}{C_{22}+C_{33}}$
b_2	$\frac{2C_{23}}{C_{22}+C_{33}}$	$\frac{2C_{23}}{C_{22}+C_{33}}$

A3.3 Estimation of the directional distribution

The auto-spectrum of surface elevation $\hat{G}_{11}(f)$ is an estimator for the omnidirectional spectrum $E(f)$ and is straightforward to calculate using an FFT. However, the estimation of the directional distribution from measurements is more complicated. This is because only the first two Fourier coefficients from a theoretically infinite series can be estimated from a single point measurement such as a buoy. It is therefore necessary to either pre-assume a shape for the directional distribution or to apply some kind of statistical fitting method. Numerous methods have been proposed, the majority of which use either the measured cross-spectra or directional Fourier coefficients as the input. A useful overview of methods is presented by Benoit *et al*. (1997). The important point to note is that different estimates of the directional distribution are obtained from different methods. The simplest methods, which approximate the directional distribution by a truncated Fourier series using only the first two coefficients are known to overestimate the width of the directional distribution (and hence the directional spread, defined in Section A5).

For buoy and ADCP data, the most popular methods for estimating the directional distribution are the maximum likelihood method (MLM) and the maximum entropy method (MEM). There are several MLM and MEM methods, each with a trade-off between the accuracy of the estimate and the computational requirements. The simplest MLM estimator is known to overestimate the directional spread, whereas the iterated methods proposed by Pawka (1983), Oltman-Shay and Guza (1984), and Krogstad *et al*. (1988) produce an improved estimate where the cross-spectra of the estimated distribution are closer to the cross-spectra of the measurements.

Of the MEM methods, The MEM estimate of Lygre and Krogstad (1986) can be expressed as an analytical function of the measured cross-spectra and is therefore quick to compute. However, it has been shown to produce double peaks in cases of unimodal directional distributions (see e.g. Brissette and Tsanis, 1994). The MEM estimate of Kobune and Hashimoto (1986) is more computationally intensive, but has been shown to produce more robust estimates of the directional distribution. However, there are occasions when the algorithm proposed by Kobune and Hashimoto will fail to converge. In these situations, the approximation scheme of Kim *et al.* (1994) can be used to find a solution.

A4 Non-directional spectral parameters

Wave height and period parameters are defined in terms of moments of the omnidirectional spectrum. The n^{th} moment of the spectrum is defined as:

$$m_n = \int_0^\infty f^n E(f) df \qquad [A.29]$$

Wave height and period spectral parameters are defined as follows:

Significant wave height	$H_s = 4\sqrt{m_0}$	[A.30]
Energy period	$T_e = m_{-1}/m_0$	[A.31]
Mean period	$T_m = m_0/m_1$	[A.32]
Zero-crossing period	$T_z = \sqrt{m_0/m_2}$	[A.33]
Peak period	$T_p = 1/f_p$	[A.34]

where f_p is the peak frequency, the frequency at which $E(f)$ takes its maximum value.

The omnidirectional wave power per meter of crest length is:

$$P_{omni} = \rho g \int_0^{\infty} c_g(f) E(f) df \quad \text{[A.35]}$$

where ρ is the density of sea water.

A5 Directional parameters

A5.1 Frequency-dependent directional parameters

The mean direction at each frequency is given by:

$$\theta_m(f) = \mathrm{ATAN2}\left[\int_0^{2\pi} D(f,\theta)\sin\theta\, d\theta\,, \int_0^{2\pi} D(f,\theta)\cos\theta\, d\theta\right] \quad \text{[A.36]}$$

where $\mathrm{ATAN2}(y,x)$ is the four-quadrant inverse tangent function, which uses logic on the signs of *x* and *y* to resolve the 180° ambiguity in direction. Note that the first directional Fourier coefficients are defined as $a_1 = \int_0^{2\pi} D(f,\theta)\cos\theta\, d\theta$ and $b_1 = \int_0^{2\pi} D(f,\theta)\sin\theta\, d\theta$, and can therefore be interpreted as the x and y components of the directional distribution. So the mean direction can be calculated using the directional Fourier coefficients estimated from the cross-spectra (as defined in Table A-2), without having to estimate the directional distribution, as:

$$\theta_m(f) = \mathrm{ATAN2}[b_1, a_1] \quad \text{[A.37]}$$

There are two commonly used definitions of the spread of energy about the mean direction at each frequency, defined either in terms of line moments or circular moments (denoted with the subscripts 'l' and 'c' respectively):

$$\sigma_l(f) = \left[\int_0^{2\pi} D(f,\theta)\big(\theta - \theta_m(f)\big)^2 d\theta\right]^{1/2} \quad \text{[A.38]}$$

$$\sigma_c(f) = \left[\int_0^{2\pi} D(f,\theta)\left(2\sin\left(\frac{\theta - \theta_m(f)}{2}\right)\right)^2 d\theta\right]^{1/2} \quad \text{[A.39]}$$

The circular moment definition approximates the line moment definition for narrow directional bandwidths since $2\sin(x/2) \approx x$ for small values of x. Moreover, Kuik *et al.* (1988) showed that $\sigma_c(f)$ can be formulated in terms of the directional Fourier coefficients, without the need to estimate the directional spreading function $D(f,\theta)$, as:

$$\sigma_c(f) = [2(1-\alpha_1)]^{1/2}, \qquad \text{[A.40]}$$

where

$$\alpha_1 = (a_1^2 + b_1^2)^{1/2}. \qquad \text{[A.41]}$$

A5.2 Integrated directional parameters

Spectrally weighted mean direction and spreading parameters can be defined as follows:

$$MDIR = \text{ATAN2}\left[\int_0^\infty E(f)\sin\theta_m(f)\,df, \int_0^{2\pi} E(f)\cos\theta_m(f)\,df\right], \qquad \text{[A.42]}$$

$$SDIR = \frac{1}{m_0}\int_0^\infty E(f)\sigma(f)df, \qquad \text{[A.43]}$$

where $\sigma(f)$ is either $\sigma_l(f)$ or $\sigma_c(f)$.

A power-weighted mean direction over the spectrum can be defined as:

$$\theta_P = \text{ATAN2}[P_N, P_E], \qquad \text{[A.44]}$$

where

$$P_E = \rho g \int_0^\infty E(f)c_g(f)a_1(f)df, \qquad P_N = \rho g \int_0^\infty E(f)c_g(f)b_1(f)df. \qquad \text{[A.45]}$$

Note that the symbol θ_P is also sometimes used to denote the peak direction [$D_p = \theta_m(f_p)$, the mean direction at the peak frequency] and care should be taken to distinguish between the two parameters.

Finally, a directionally resolved or net power can be defined as the modulus of the vector sum of power over frequency:

$$P_{net} = \sqrt{P_E^2 + P_N^2}. \qquad \text{[A.46]}$$

A6 Sampling variability

A6.1 Sampling properties of auto-spectra and cross-spectra

The standard linear model for ocean waves assumes that the sea surface elevation $\eta(t)$ is a stationary (time invariant) and spatially homogeneous Gaussian process with zero mean and directional spectrum $S(f,\theta)$. If estimates of auto-spectra and cross-spectra are defined using equations [A.18] and [A.19], and averaged over M harmonics then the estimates are chi-squared random variables with variance (see e.g. Bendat and Piersol, 2010):

$$\text{Var}(\hat{G}_{AA}) = \frac{1}{M}G_{AA}^2 \qquad \text{[A.47]}$$

$$\mathrm{Var}\left(\left|\hat{G}_{AB}\right|\right) = \frac{1}{M} G_{AA} G_{BB} \qquad [A.48]$$

$$\mathrm{Var}\left(\hat{C}_{AA}\right) = \frac{1}{2M} \left(G_{AA} G_{BB} + C_{AB}^2 - Q_{AB}^2\right) \qquad [A.49]$$

$$\mathrm{Var}\left(\hat{Q}_{AA}\right) = \frac{1}{2M} \left(G_{AA} G_{BB} - C_{AB}^2 + Q_{AB}^2\right) \qquad [A.50]$$

The level of smoothing is therefore a compromise between achieving a low variance and maintaining adequate frequency resolution. Note that for longer measurement durations, a more stable estimate can be achieved for a given frequency resolution, since raw harmonics are obtained at a resolution of $\Delta f = 1/\tau$, where τ is the measurement duration.

A6.2 Spatial correlation in spectral estimates

The covariance between estimates of auto-spectra is given by (Bendat and Piersol, 2010):

$$\mathrm{Cov}\left(\hat{G}_{AA}, \hat{G}_{BB}\right) = \frac{1}{M} |G_{AB}|^2 \qquad [A.51]$$

From [A.47] and [A.51] it can be seen that the correlation between spectral estimates is given by:

$$\mathrm{Cor}\left(\hat{G}_{AA}, \hat{G}_{BB}\right) = \frac{\mathrm{Cov}\left(\hat{G}_{AA}, \hat{G}_{BB}\right)}{\sqrt{\mathrm{Var}\left(\hat{G}_{AA}\right)\mathrm{Var}\left(\hat{G}_{BB}\right)}} = \frac{|G_{AB}|^2}{G_{AA} G_{BB}} \equiv \gamma_{AB}^2, \qquad [A.52]$$

where the quantity γ_{AB} is known as the coherence function. If $\hat{G}_{AA}$ and $\hat{G}_{BB}$ are both estimates of the surface elevation then using [A.20] with $H_A(f,\theta) = H_B(f,\theta) = 1$, gives:

$$\gamma_{AB} = \frac{|G_{AB}(f)|}{E(f)} = \left| \int_0^{2\pi} \exp(-i\mathbf{k}\cdot\mathbf{x})\, D(f,\theta) \mathrm{d}\theta \right|. \qquad [A.53]$$

where $\mathbf{k} = (k\cos\theta, k\sin\theta)$ is the wavenumber vector and $\mathbf{x}$ is the horizontal vector separation between the locations at which surface elevation is measured. Hence the coherence/correlation in spectral estimates is dependent only on the directional distribution and the separation between the two points. Equation [A.53] can be used to produce spatial maps of the correlation pattern in spectral estimates.

A6.3 Sampling properties of omnidirectional parameters

For spectral parameters defined in terms of spectral moments, Krogstad *et al.* (1999) note that the variance of the estimates can be calculated using a Taylor series expansion as:

$$\mathrm{Var}\left(\hat{H}_s\right) = 4 \frac{m_{00}}{m_0}. \qquad [A.54]$$

$$\mathrm{Var}\left(\hat{T}_e\right) = T_e^2 \left(\frac{m_{-1-1}}{m_{-1}^2} - 2\frac{m_{-10}}{m_{-1} m_0} + \frac{m_{00}}{m_0^2} \right) \qquad [A.55]$$

$$\mathrm{Var}\left(\hat{T}_m\right) = T_m^2 \left(\frac{m_{00}}{m_0^2} - 2\frac{m_{01}}{m_0 m_1} + \frac{m_{11}}{m_1^2} \right) \qquad [A.56]$$

$$\mathrm{Var}(\hat{T}_z) = \frac{T_z^2}{4}\left(\frac{m_{00}}{m_0^2} - 2\frac{m_{02}}{m_0 m_2} + \frac{m_{22}}{m_2^2}\right) \tag{A.57}$$

where m_{rs} is the covariance in estimates of spectral moments, given by:

$$m_{rs} = \mathrm{Cov}(\hat{m}_r, \hat{m}_s) = \frac{1}{\tau}\int_0^\infty f^{r+s} E^2(f) df + O(N^{-2}). \tag{A.58}$$

To avoid confusion, it should be understood that m_0 is the variance of the sea surface elevation, whereas m_{00} is the variance of the estimate of m_0. When estimating the covariance between spectral estimates from measured data it is important to note that the expected value of $\hat{E}^2(f)$ is dependent on the level of smoothing:

$$\langle \hat{E}^2(f) \rangle = (1 + 1/M) E^2(f), \tag{A.59}$$

where *M* is the number of harmonics that spectral estimates are smoothed over. Therefore the level of smoothing needs to be taken into account as follows:

$$\hat{m}_{rs} = \frac{M}{1+M} \cdot \frac{1}{\tau} \sum f_j^{r+s} \hat{E}^2(f_j) \triangle f. \tag{A.60}$$

Estimates of moments and spectral parameters can be substituted in place of the 'true' values in [A.54] - [A.57].

Similarly, the variance in the estimate of omnidirectional wave power is given by:

$$\mathrm{Var}(\hat{P}_{omni}) = \frac{M}{1+M} \cdot \frac{1}{\tau} \sum \hat{P}_j^2 \triangle f. \tag{A.61}$$

where $\hat{P}_j = \rho g c_g(f_j) \hat{E}(f_j)$ is the estimate of power per meter crest length at each discrete frequency.

Finally, it can be shown that the variance of the difference in the omnidirectional wave power per meter crest length experienced at two locations can be calculated as (see Mackay and Ashton, 2013):

$$\mathrm{Var}(\hat{P}_A - \hat{P}_B) = \frac{M}{1+M} \cdot \frac{1}{\tau} \sum 2\hat{P}_j^2 \left(1 - \gamma_{AB}^2(f_j)\right) \triangle f. \tag{A.62}$$

A6.4 Sampling properties of directional parameters

The sampling variability of the frequency-dependent directional parameters θ_m and σ_c are given by Kuik *et al*. (1988) as:

$$\mathrm{Var}(\hat{\theta}_m) = \frac{1-\alpha_2}{M\alpha_1^2}, \tag{A.63}$$

$$\mathrm{Var}(\hat{\sigma}_c) = \frac{\alpha_1^2}{M(1-\alpha_1)}\left[\alpha_1^2 + \frac{\alpha_2^2 + \beta_2^2 - 1}{4} + \frac{(1+\alpha_2)(\alpha_1^{-2} - 2)}{2}\right], \tag{A.64}$$

where *M* is the number of harmonics that cross-spectra are averaged over (assuming that they are calculated using an FFT with no windowing or overlapping) and α_1, α_2, β_1 and β_2 are the centered directional Fourier coefficients:

$$\alpha_1 = \int_0^{2\pi} D(f,\theta)\cos(\theta-\theta_m)\,d\theta = (a_1^2+b_1^2)^{1/2}\,, \quad [A.65]$$

$$\alpha_2 = \int_0^{2\pi} D(f,\theta)\cos\big(2(\theta-\theta_m)\big)\,d\theta = a_2\cos(2\theta_m)+b_2\sin(2\theta_m), \quad [A.66]$$

$$\beta_1 = \int_0^{2\pi} D(f,\theta)\sin(\theta-\theta_m)\,d\theta = b_1\cos(\theta_m)-a_1\sin(\theta_m), \quad [A.67]$$

$$\beta_2 = \int_0^{2\pi} D(f,\theta)\sin\big(2(\theta-\theta_m)\big)\,d\theta = b_2\cos(2\theta_m)-a_2\sin(2\theta_m), \quad [A.68]$$

For the integrated parameters *MDIR* and *SDIR*, the sampling variance can be calculated as the weighted sum of the variance of $\hat{\theta}_m$ and $\hat{\sigma}_c$ at each discrete frequency:

$$\mathrm{Var}(MDIR) = \frac{M}{1+M}\sum \hat{E}^2(f_j)\mathrm{Var}\left(\hat{\theta}_m(f_j)\right)\,\Delta f, \quad [A.69]$$

$$\mathrm{Var}(SDIR) = \frac{M}{1+M}\sum \hat{E}^2(f_j)\mathrm{Var}\left(\hat{\sigma}_c(f_j)\right)\,\Delta f. \quad [A.70]$$

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