Underwater Acoustic Monitoring at Wave and Tidal Energy Sites: Guidance Notes for Regulators

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Underwater Acoustic Monitoring at Wave and Tidal Energy Sites: Guidance Notes for Regulators

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1 Introduction

In April 2013 the European Marine Energy Centre (EMEC) facilitated an underwater acoustic workshop for marine renewables regulators and their statutory environmental advisors. The driver for the workshop was the need for a greater appreciation amongst regulators of the key aspects of underwater acoustic data gathering. Specifically: what needs to be measured; how measurement should be undertaken; common pitfalls to avoid; and what to look for in a data gathering and analysis report.

This document has been prepared as a key output of that workshop, to provide high level guidance on the assessment of underwater acoustic measurement activities. It aims to enable regulators to have informed discussions with developers of marine energy converter systems (MECS) from the initial scoping stages and aid the assessment of monitoring activities.

Whilst this guideline relates specifically to the use of passive acoustic data gathering, in future there is likely to be a need for an equivalent guideline for the use of active acoustic techniques. Whereas passive acoustic ('listening-in') techniques tend to be used to assess the sound output from devices and events, active acoustics (emitting sound and 'listening' for reflections) is being investigated as a monitoring tool, in particular to provide positioning and behavioural characteristics of objects.

2 Background

Underwater noise generation is likely to differ between different MECS developments, but may include relatively short-term construction noise, such as drilling and dredging, as well as long-term noise created by the mechanics of a device. There is currently a lack of consistency across measurement and assessment methods for underwater acoustic surveys, and there are high uncertainties in relation to assessing the impact of underwater noise from MECS on marine wildlife.

This document provides basic guidance for consistent measurement of noise; this requires a degree of flexibility in approach, allowing development and innovation in these methods as experience is gained, new technologies develop, and knowledge grows. This must be balanced against use of best available practice at a reasonable cost, including minimum requirements for the acoustic measurement system, measurement methods and reporting.

Whilst detailed guidance is clearly needed, it is beyond the scope of this document to produce a full set of guidance notes covering all aspects of underwater acoustic assessment. Additional information can be found in other relevant works, including: device measurement methods (Wilson *et al.*, 2011;Lepper *et al.*, 2012) and other on-going initiatives (Ainslie, 2011; De Jong *et al.*, 2011), as well as national and international standards development (ANSI, 2009; ANSI, 2012; IEC1995 ,1996; IEC60565, 2006; IEC60050, 1994; ISO 8000-8; 2007, ISO/TR35417, 2007; ISO/PAS 17208-1, 2012) and the preparation of industry guidance documents (Marine Management Organisation/The Crown Estate/Marine Scotland, 2013). It is hoped that the notes contained in this document, in combination with these works, will eventually lead to the establishment of best practice guidelines.

3 Noise Characteristics

The overall noise signature (i.e. 'acoustic signature') from man-made systems may be the result of a wide variety of individual sources within these systems. These individual sources may have individual spatial, spectral and temporal characteristics with no obvious correlation between them. In the case of both device operational noise and construction activities the measurement method used should include the capability to capture the spatial, spectral and temporal characteristics for the desired assessment criteria.

3.1 Spatial Characteristics

Source directivity – Direction of the noise
Many potential sources of anthropogenic noise currently being monitored, such as MECS, may radiate noise asymmetrically both in horizontal and vertical planes. A tidal stream device may have different source directivities in different planes, for example, in the plane in-line and perpendicular to the blades. These patterns may also vary with frequency.

Appropriate measurement methods should ideally be capable of capturing these variations. A full assessment of complex directivity patterns may not be pragmatic or cost-effective, so an assessment of the relative importance of measurements must be made in relation to the requirements for the measurement.

Near-field / far-field – Distance from the noise
Another important aspect of spatial sampling is the distance at which measurements are made. Almost all recordings of a physical system are made at some distance from the systems, in the acoustic *far-field,* where the sound waves appear to radiate from a single point. The received level (i.e. the acoustic signal that is recorded) is a function of the radiated energy at the source *and* propagation losses between that source and the recorder hydrophone. At distances closer than this, in the *near-field*, a complex sound field exists due to multiple arrivals of waves with different phases from different parts of the source (Urick, 1983).

Wave patterns in the *near-field* may have strong frequency dependence such that, at individual frequencies, relatively small changes in position can result in large variations in the amplitude of the sound field (referred to as interference). This can be particularly significant for large distributed sources, for example, a wind turbine foundation or a tidal turbine system distributed throughout the water column, or a wave energy device distributed through the water column and/or on the surface (Robinson and Lepper, 2013).

> **Caution**: Measurements within the near-field can be difficult to interpret and misleading, so appropriate consideration of near-field effects is extremely important.

However, good quality *far-field* measurements can be difficult to achieve. At distances far enough away to achieve a far-field measurement, device noise may:

- Be masked by ambient noise
- Be masked by other nearby sound sources.
- Have complex propagation paths as the measurement position moves further away.

The appropriateness of measurements made in the near-field or far-field of a particular source, and their subsequent interpretation, should be considered carefully and reported properly to allow subsequent evaluation. This evaluation is particularly crucial if the measured data is to be used later in conjunction with propagation loss models to interpret fields at other ranges and/or in other environments. The boundary between near-field and far-field is not clear cut and will vary from device to device and in different environments, water depth, etc. due to effects on sound propagation.

Sound propagation – Source level models

Measurements of underwater noise provide a direct assessment of the radiated noise level received at a specific point. For most purposes, it is more useful to predict the acoustic field at different ranges and in different environments, by using a **propagation model**. This involves measuring a device at a certain range and in a specific environment and **back modelling** the results to a theoretical point closer to the device to determine a *source level*. These source level terms are then **forward modelled** (i.e. propagating away from the device) to predict noise at other ranges and in other environments. Depending on the models used, a variety of terms for source level can be defined:

1. 'Effective source level' or 'Effective radiated noise level'

    - A simple, geometric model (e.g. 15.log (Range)) based on *radiated noise levels* that are calculated in terms of spherical spreading [ISO 17028, 2012].

        Caution: This metric is not a true source level and retains a dependency on the environment in which it was measured. It therefore cannot be used to predict the sound field generated by the source in another environment.

    - It may be successfully used for interpolation between measured data points at different ranges.

2. Mono-pole source level

    - These can be obtained from far-field measurements by using appropriate propagation models that take account of *all* propagation phenomena, such as sea surface and seabed interactions, bathymetry effects, spreading, absorption, etc. (Ainslie *et al*., 2012).
    - The source levels and similarly appropriate models can be used to predict far-field received levels if the source were placed in another environment.
    - Note: the source level can be used to predict received levels in the acoustic far-field, but not in the near-field.

3. Near-field models

    - Modelling techniques such as finite element analysis have recently been used to predict received levels in the near-field from first principles.
    - These models could potentially provide very accurate estimates of source level.

        Caution: they will first require validation with extensive measurement and/or modelling efforts, particularly from large distributed sources

All models can have a **high degree of uncertainty**, primarily due to uncertainty in input parameters, particularly environmental parameters. In the case of far-field measurements a common practice is to obtain multiple measurements at as many initial deployment sites as possible, usually on a radial transect to help validate subsequent modelling processes. This can be done with simultaneously operating multiple static systems or a moving receiver. In the latter case, however, at least one static system in the far-field should be used to monitor variation in the source over time.

Sound propagation – Environmental parameters
Interpretation of measured data made in the far field should carefully consider **local propagation conditions**. Measured levels are likely to change significantly in different environments, even with identically radiating sources.

For example, in **shallow water**, sound propagation is often highly complex due to:

- Strong surface/seabed interactions,
- Acoustic properties of the water column and sediment,
- Bathymetry variation along the path of the propagation, etc.

In such environments, frequency and temporal components can propagate in different ways and at different times. For example, low frequency components may travel more quickly through a solid seabed than the water column. Thus, **significant variations in received levels** can occur for identical sources across different propagation paths. Care should be taken in interpretation of received levels in relation to these potential variations and related propagation conditions.

Key acoustic properties that can affect sound propagation are:

- Water depth (source/receiver).
- Seabed bathymetry across the measurement path.
- Source distribution.
- Receiver position (depth and range).
- Hydrodynamic data including tidal status and wave height (related to wind speed).
- Water column acoustic properties (salinity, temperature, density) versus depth.
- Sediment type

Note: the last two parameters are used to derive acoustic wave properties such as sound velocity, density and frequency dependant attenuation factors.

Acoustic surveys should include detailed logging of as many of these environmental properties as appropriate. The use of CTD sondes (Conductivity, Temperature and Depth profilers) or sound velocity profilers has now become widespread in areas of known complex hydrodynamics, for example near shore, and estuarine areas with fresh/salt water interactions.

3.2 Spectral Characteristics

Noise measurement should include consideration of frequency range, or spectra, of the equipment and procedures used. Specifically, this should be in relation to:

1. Hearing ranges of marine species

    - This should include a capacity to assess radiated energy within the hearing capabilities of the primary species of interest.
    - In UK waters this may cover frequencies from a few tens of hertz for some fish species to frequencies in excess of 150kHz for cetaceans, e.g. the harbour porpoise.

2. Physiological damage to marine species

   - The measurements should include assessment of the likely spectral content of the noise from the physical device even if outside the hearing range of local species.
   - High intensity transient signals can potentially cause physiological damage at frequencies outside the marine species hearing range (Southall *et al., 2007*).

3. Device noise components

   - The inclusion of extra frequency bands also allows assessment of the device itself, for future impact assessments, as well as engineering assessment.
   - It also serves as a prudence check on unknown noise sources outside the device's dominant frequency range but potentially in a marine species hearing sensitivity range.

3.3 Temporal Characteristics

The measurement methods used should include capabilities to capture variations in radiated sound energy over time, as appropriate. These include:

- Variations as systems become more energetic (e.g. in higher wave, tidal flow or wind conditions).
- Variation of construction activities, such as marine percussive pilling and drilling, due to changes in hammer energy, penetration depth etc. (Robinson *et al.*, 2007).

Measurement methods and equipment should be capable of recording radiated sound continuously or using appropriate sampling regimes (duty-cycled). The data and time periods chosen should encompass the range of operational modes, sea-state conditions, tidal cycles, etc. that the systems are required to operate in, although this will inevitably be subject to equipment limitations.

3.4 Additional Noise Sources

Anthropomorphic noise sources

In many circumstances, it will be impractical to remove additional noise sources, such as vessels/devices in the area, from measured data. Pre-existing long term anthropogenic noise sources, such as boat traffic or acoustic deterrent devices, may be considered reasonable parts of the local baseline acoustic environment. However, care should be taken to avoid any short term noise contamination not representative of a typical baseline position, such as atypical passing vessels. Exclusion of data requires a subjective judgement to be made, and any such decisions should be reported and justified.

Environmental noise sources

Natural phenomena can make significant contributions to the overall noise signature, and these are not necessarily related to the device operation or indicative baseline condition. Examples include rain- or wind-derived noise. Another example may be measurements made during the presence of vocalising marine species such as passing marine mammals that may not be considered indicative of a baseline or of normal device operation.

However, some aspects of natural noise may be considered a reasonable part of the system noise signature, including such examples as the correlation of wind-derived noise with wind and wave based renewable energy systems. Similarly, sediment transport in high tidal flow areas is directly correlated to tidal state and therefore to device operational status and typical baseline conditions. Other natural noise sources, for example snapping shrimp, may be considered a representative longer term component of the baseline noise conditions.

Mitigation of additional noise sources
In order to reduce the effects of these additional noise sources on analysis, the use of measurement data gathered during non-representative anthropogenic or natural noise contributing events should be avoided.

4 Methods of Measurement

This section addresses the question of whether appropriate equipment and measurement approaches have been used to optimise the quality of data collected. Measurement data should be collected using methods appropriate for the desired analysis. For example, **recording systems** should have appropriate:

- Frequency bandwidth (for the whole system - hydrophone, preamplifiers, analogue to digital converters, sample rates, etc.)
- Low-noise performance (recorder and recording platform)
- Dynamic range (analogue and digital)
- Hydrophone performance (sensitivity versus frequency, operating depth/temperature, receiver directivity, noise performance, etc.)
- File storage type (lossless, dynamic range, meta-data, time stamps, etc.)
- Calibrations (e.g. full calibration before deployment, in-situ checks using pistonphone calibrator)

Approaches will likely vary between system types, noise characteristics, environments, and impact criteria under consideration (Cato, 2008, Dudzinski *et al.*, 2011, Harland, 2008). For example, assessment of noise in high tidal flow conditions will have different equipment limitations and measurement requirements to percussive piling operations for off-shore wind construction. A chosen deployment method is likely to be a compromise, balancing data requirements with measurement limitations.

4.1 Boat Based Surveys

Typical deployments may involve use of towed array systems, or suspended hydrophones from either a static or drifting vessel.

Advantages

✓ Boat based surveys have the advantage that they may provide data over a relatively **large area** fairly **quickly**.

Disadvantages

× Data gathering deployments are usually relatively **short term.** Therefore, they may not capture the full range of temporal variations due to operational state, tidal conditions, etc.

× Systems may also suffer from **parasitic noise** not directly related to measurement being carried out. Key sources of such noise include:

  - Surface heave noise, due to wave or swell action moving the hydrophone vertically, can create high amplitude, low frequency signals. This can be reduced using a variety of methods including elastic de-couplers and motion dampers, as well as high pass filters positioned before the Analogue to Digital Converter (ADC) in the measurement chain.
  - Vessel/platform radiated noise (generators, echo-sounders, machinery, crew, etc.). This can be reduced by ensuring that the vessel is made as quiet as possible, use of battery powered systems, etc.

- Wave slap on the vessel can cause additional radiated noise. This can be mitigated through appropriate vessel choice, work in lower sea-state conditions, and deployment on remote cables at greater distance from the vessel.
- Flow and strumming noise can occur if there is turbulent relative motion between the water, the hydrophone and its cables. This can be observed with both moored and drifting boat deployments. Vortex shedding techniques such as spiral fairings on cables or feathering can be used to mitigate strum effects. Effects of flow noise may be compared with data from appropriate baseline conditions.

4.2 Static Systems (moored and bottom-mounted hydrophones)

Longer term static systems, for example, cabled hydrophones or autonomous recorders, are becoming more widely available.

Advantages

- ✓ They can be used for **long term monitoring**, either continuously or duty cycled for periods of days or even months. A long-term deployment can cover a range of tidal cycles, weather conditions, entire piling sequences, etc.
- ✓ They generally suffer from **less deployment noise** than boat based surveys.

Disadvantages

- × They are by definition static and so measure in only **one location**
- × They have a higher risk of **data loss** (accidental damage, theft, etc.)

Caution: Direct placement of a hydrophone close to an **air cavity** (e.g. the housing of a recorder system) can cause interference affecting frequency response/directivity.

- × They may still suffer from **parasitic noise** effects:
  - Surfaced moored systems may suffer from surface wave motion and mooring noise. They also carry higher risk of interference from other ocean users. Seabed moored systems allow decoupling from surface motion.
  - Flow noise can be generated in a system in high current or high tidal flow areas, due to turbulent water flow past the hydrophone or the recorder body being shaken and vibrated. Strong correlation of tidal current with low frequency noise is indicative of flow noise. It can be mitigated by placement in lower current areas (for example closer to the seabed[†]), use of technologies such as *sonar domes*, and evaluation of flow noise contribution from baseline surveys and/or removal in post processing.
  - Cable strum can result from either electrical cables or mooring lines creating turbulent flow, resulting in a physical vibration of the cable. Mitigation techniques include placement in lower tidal flow areas (for example, closer to seabed[†]) and vortex shedding systems, which disrupt the stability of the turbulent flow, such as spiral fairings or *feathering* on cables. Noise contribution may also be removed in post processing with comparison to baseline surveys.

† Note: even with the advantage of reduced flow rates and therefore lower flow noise, it may not always be desirable to place a hydrophone close to the seabed since:

- Species of interest may predominantly occupy other areas in the water column.
- Seabed sediment transport in high flow areas can generate noise, and can cause debris to impact on the hydrophone.

4.3 Drifting Systems

Drifting systems are being increasingly used in high tidal flow areas to minimize the effects of flow noise. These are typically boat based or use drifting autonomous recorders, although boat based drift measurements may still suffer the effects described in section 4.1.

Advantages

✓ Drifting autonomous recorders, or drifting transmitters such as sono-buoys, move with the fluid flow caused by the current, **minimising flow noise**.

Disadvantages

× They provide **short-term dynamic snap-shots** of the baseline or device radiated noise at a specific time and under specific conditions. Determination of adequate spatial and temporal variation therefore requires **multiple drifter deployment**, balanced against cost, additional noise, safety, etc.

× These systems can still suffer from **surface heave motion**. This can be mitigated through use in lower sea-states, or by employing surface motion de-couplers.

× Accurate **time and position logging** is needed to determine relative device/environment positioning. For example, the range and aspect angle of radiated noise changes as a system drifts past the source. This can be mitigated through the use of on-board GPS or equivalent.

5 Reporting and Impact Metrics

It is vitally important that measurement and calculation methods are adequately reported, particularly in the absence of industry wide standardisation of these processes.

5.1 Equipment

Appropriate details of the **recording systems** used (as described in section 4) must be noted in reports. The calibration methods for the equipment should also be reported and appropriate **calibration factors** applied to all data.

5.2 Spectrum Presentation

Consistent methods should be used to **present spectral data**. Common methods include:

- spectral densities
- spectral levels
- narrowband/broadband levels
- third octave bands spectral levels
- averaged data

All of these methods can be appropriate, depending on the assessment being made.

5.3 Temporal Presentation

Similar consideration should be given to time variant characteristics of signals. Ambient as well as radiated noise can be extremely variable over a range of time periods, from one minute to the next, or over a period of days to months. Measurement methods should **capture and report this variance**, as appropriate. A recent useful trend has seen the reporting of the **statistical distribution** of this data, usually in multiple frequency bands (for example third octave bands or as power spectral densities). Techniques used include:

- Reporting of median values and the arithmetic means
- Maximum and minimum values observed
- Percentiles (i.e. 25% and 75%, 5-95%, etc.)
- Probability density functions (Merchant, 2013)

These methods can provide more information and a better representation of the data for decision making than is obtained from a single snap shot. However, the parameters and methods used for calculation must be adequately reported to allow comparison between data sets. Parameters which should be reported include:

- Data integration periods
- Frequency bandwidths

- Data window overlaps
- Window functions
- Sample rates
- Bit depths
- Recording system noise floors
- Scaling and calibration factors

5.4 Spatial presentation

Sound propagation
As described in section 3.1, it is imperative that the methods of the propagation models used are adequately reported, and any relevant environmental source data included. Guidance on reporting of metadata is provided by MEDIN, 2012. Relevant metadata to record may include:

- Sea-state
- Wind speed (and associated measurement height)
- Rate of rainfall and other precipitation, including snow
- Water depth and tidal variations in water depth
- Water temperature and air temperature
- Hydrophone depth in the water column (with consideration of the effect of strong tidal flow)
- GPS locations of sources, hydrophones and recording systems
- Seabed type
- Profile of conductivity, temperature and hydrostatic pressure as a function of depth in the water column using a CTD probe or velocimeter

5.5 Additional noise sources

Detailed reporting of additional noise sources should include:

Anthropomorphic noise sources
- Automatic Identification System (AIS) data for shipping
- Visual logs of traffic
- Presence of seal-scarers or other acoustic devices

Environmental noise sources
- Relevant environmental data (Sea-state, rainfall etc., as above)
- Presence of marine mammals, diving birds, snapping shrimp, etc.

  Caution: Device noise may be reported relative to the background noise of additional sources; however, the potential impact, particularly in noisy, high energy sites, is not well understood.

5.6 Marine Species Impact Metrics

Currently, a number of impact criteria are in common use in the UK. These include:

1. dB_{HT} developed by Nedwell *et al.*
    - a species-specific audiogram-weighted peak-peak acoustic pressure level

2. Criteria proposed by Southall *et al.*, 2007
    - un-weighted zero-peak Sound Pressure Level (SPL) metric and cumulative functional hearing groups
    - M-weighted Sound Exposure Level (SEL) metrics for physiological damage
    - SPL, calculated as a root mean square (RMS) value, for behavioural response metric

3. Additional marine mammal metrics are being considered for the Marine Strategy Framework Directive (EU TSG Noise, 2013) and for other species such as fish.

These metrics are all calculated in different ways and have different temporal (integration periods) and spectral (bandwidth) dependencies.

> **Caution**: In scientific, and in grey literature, there is often confusion between these metrics, primarily due to inadequate reporting of the measurement and calculation methods used. This makes comparison between data very difficult. Currently no standardisation exists for these methods; however, a number of *best practice* initiatives are underway.

6 Key Questions

The following key questions (based upon the three main sections of this document) should be asked when assessing the effectiveness of proposed underwater acoustic monitoring activities at wave and tidal energy sites.

6.1 Noise Characteristics

Spatial characteristics

- Does the measurement method capture appropriate spatial information, both in bearing and range, of radiated acoustic fields for the device / activity?

Spectral characteristics

- Does the measurement method capture appropriate spectral information on likely radiated noise of the device / activity?
- Does the measurement method capture appropriate spectral information for marine species of interest?

Temporal characteristics and models

- Does the measurement method capture appropriate temporal information for the activity duration, environmental conditions, operational modes, etc.?
- Have near-field and far-field effects been adequately considered?
- Is the spatial and temporal sampling of measurements appropriate to the modelling process?

6.2 Measurement Methods

- Are the spatial and temporal sampling properties of the measurement method appropriate to the measurement requirements?
- Have other non-representative noise sources been considered and appropriate mitigation applied in the measurement method and data analysis?
- Is additional meta-data collected/reported (for example, ship traffic, metrological data, hydrodynamic data, etc.) appropriate to the data analysis?

Boat-based surveys and static systems

- Have appropriate measures been taken to minimise the effects of surface wave motion?
- Have the effects of vessel noise (machinery, echo-sounders etc.) been minimised?
- Have surface effects due to the presence of the vessel such as *wave slap* been minimized in the recorded data?
- Have the effects of flow noise and cable strum been considered and minimised as appropriate?

6.3 Reporting

- Are the measurement and subsequent calculation methods appropriate (and justified against alternatives) to fulfil the assessment metrics required?
- Are measurement system properties adequate to measurement requirements and have they been adequately reported?
- Are calculation methods /parameters adequately reported?
- Does the report encompass potential variance in spectral and temporal effects?
- Has appropriate meta-data been collected and reported?

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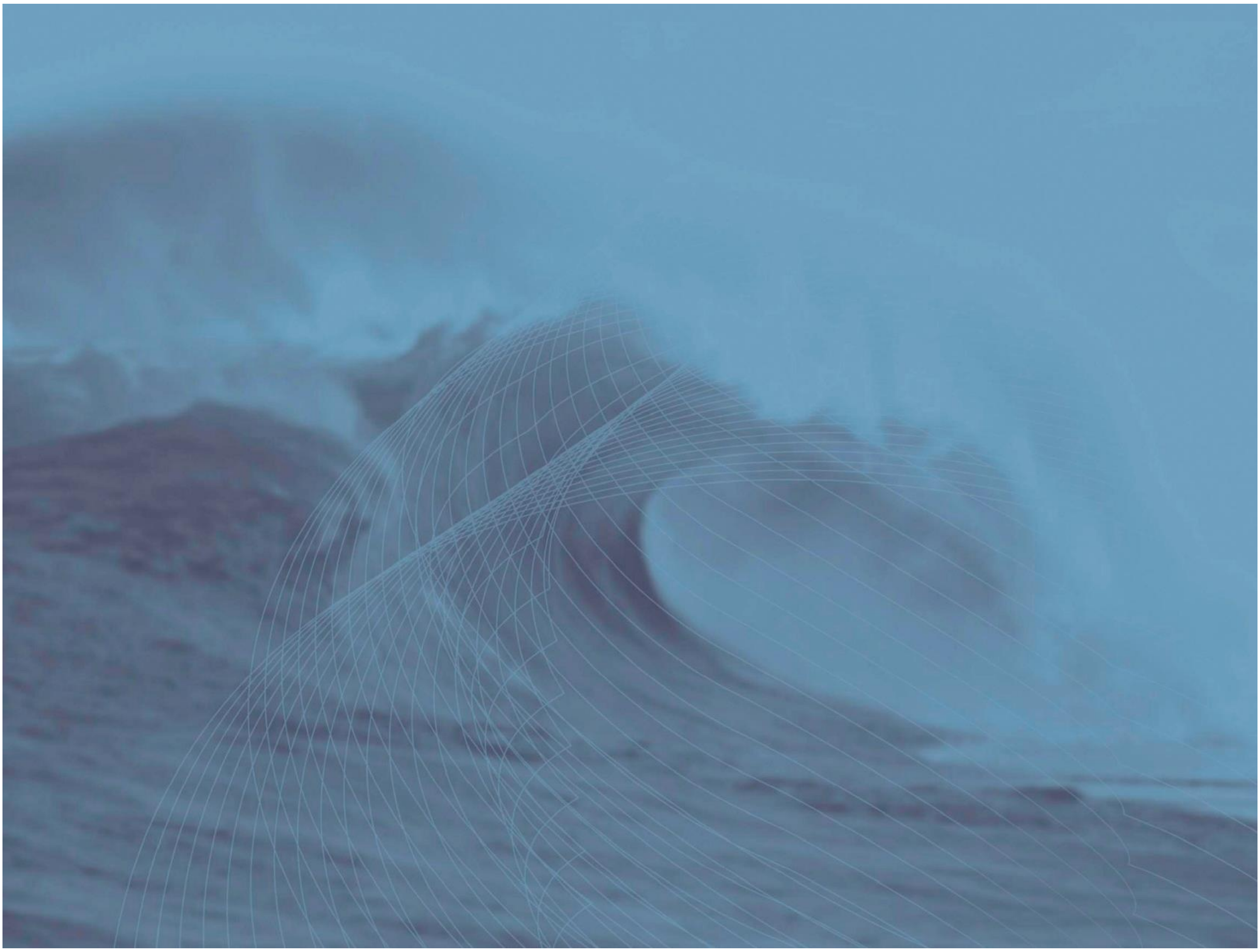

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