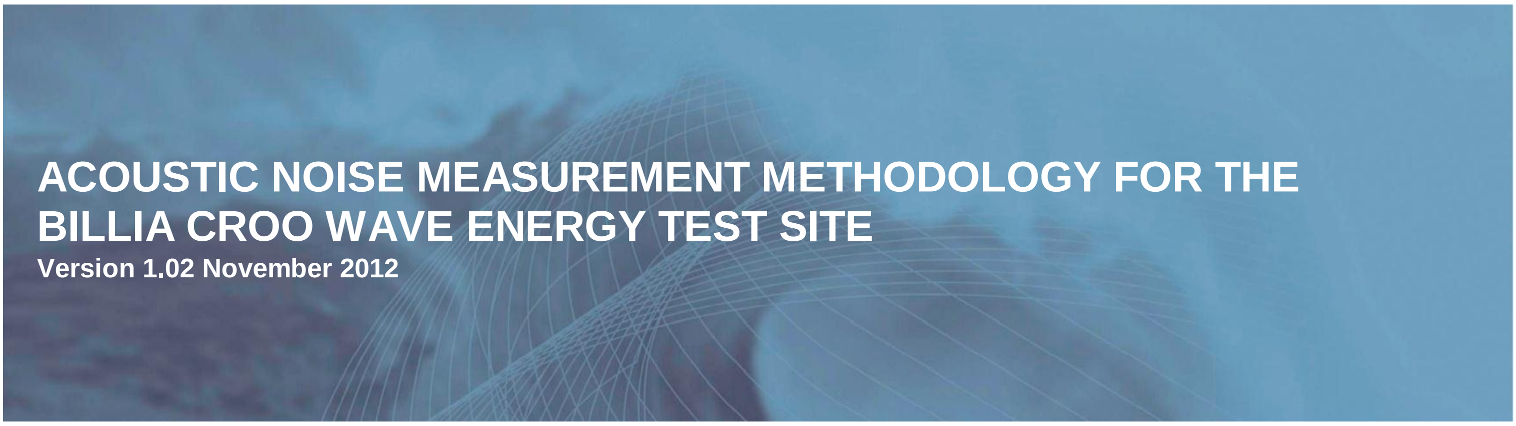
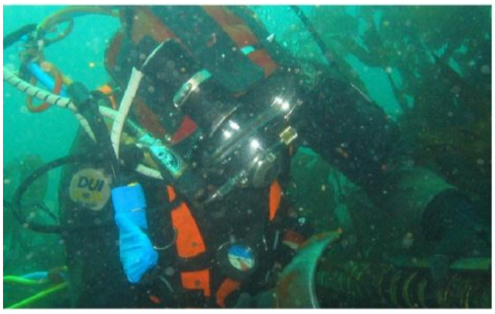


ACOUSTIC NOISE MEASUREMENT METHODOLOGY FOR THE BILLIA CROO WAVE ENERGY TEST SITE

Version 1.02 November 2012



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Preface

In 2010 the European Marine Energy Centre (EMEC) received research funding from the Scottish Government to investigate the acoustic output from wave energy devices operating in a high energy wave climate. This research will facilitate future studies into the effects of the acoustic output of wave energy converter devices on cetaceans, sea mammals and seabirds.

The project involved assessment of available techniques and development of a methodology appropriate to EMEC's Billia Croo wave test site to enable acoustic data collection and analysis, and subsequent use of the methodology to collect data from which an acoustic baseline description of the test site can be formed. The production of this acoustic characterisation of the Billia Croo test site will permit future comparison with data collected by developers testing devices at the EMEC wave test site using the same methodology and equipment.

This document forms the final report to the Scottish Government and comprises four main sections as detailed below, together with an Annex which describes how the methodology was used to measure the acoustic output from an operational wave energy converter device deployed at the Billia Croo test site. Section 1 provides a review of relevant background data, while Sections 2-4 provide details of the measurement methodology developed during the study to characterise noise for operational noise assessment of wave energy converter systems.

EMEC would like to thank the Scottish Government for continued support and funding of this project.

Preferred citation:

EMEC report "Acoustic Noise Measurement Methodology for the Billia Croo Wave Energy Test Site" (Lepper,P., Robinson,S., Harland,E., Theobald,P., Hastie,G., Quick,N. 2012).

SECTION 1:

BACKGROUND DATA REVIEW

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1. INTRODUCTION

1.1 BACKGROUND TO THE WORK

This report has been produced for the European Marine Energy Centre (EMEC) under contract EMEC_007_09. The report has been produced by a consortium led by Loughborough University in partnership with the National Physical Laboratory, Teddington, and Chickerell BioAcoustics of Chickerell, Dorset and the Sea Mammal Research Unit acting through SMRU Ltd.

The aim of the work under this contract is to provide an operational noise assessment methodology appropriate for use at the EMEC Wave Test Site, located off Billia Croo, Mainland, Orkney Islands. The methodology is intended to become the standard data collection methodology for characterising the baseline underwater noise at the site and will be offered to developers wishing, or being required by Regulators, to characterise the noise signature of their generating devices.

This report is the output from the first phase of the work, and provides a review of relevant background data related to the overall project aim stated above. These data provide the baseline for decisions made in the development of the proposed measurement methodology and include review of measurement methodologies from other industries (MOD, shipping, etc.), related standards, regulatory impact guidance and likely biological receptors.

The report is organized such that the main body contains a review of current measurement activities at the EMEC and other (UK and international) wave energy sites, a review of related acoustic noise measurement methodologies of other marine industries, and related standards and agreements in place and under development. In addition a review of likely biological receptors at the EMEC wave site has been carried out by SMRU Ltd.

1.2 EUROPEAN MARINE ENERGY CENTRE (EMEC)

The European Marine Energy Centre provides developers of wave and tidal energy convertor devices with performance testing facilities. It is located in the Orkney Islands off the north of Scotland. It has two principal grid-connected test sites, one for tidal devices and the other for wave devices, as well as two non-grid connected ‘nursery’ test sites.

Whilst EMEC’s primary focus is the provision of services to industry for the rigorous testing of marine energy convertor devices, it also participates in a variety of national and international research projects aimed at providing all the industry with essential information to progress. This includes projects aimed at improved characterisation of the marine resource as well as those aimed at providing the necessary information to progress licensing decision-making. In the longer term this research provision will extend to other areas of industry-related problems that can be tackled in some generic capacity.

Acoustic surveys have been carried out at the EMEC tidal site at the Fall of Warness, Eday, one of Orkney’s northern isles [EMEC, 2011a], and are now of interest to developers deploying at the wave test site.

The main Wave Test Site is located off Billia Croo on the west side of Mainland, the principal island of the Orkney group. It is to the north of the Hoy Mouth, the western entrance to Scapa Flow. This site is very exposed to the west and provides high energy waves to exercise devices under test. Figure 1 shows the cable routes for 5 berths and cardinal buoy positions of the Billia Croo wave test site.

Shoreside facilities provide cable connections from the test devices through a sub-station in Billia Croo and thence to the National Grid. There are also support facilities such as weather and oceanographic instrumentation and internet access.

1.3 UNDERWATER NOISE

Wave generation devices invariably use moving components and these will generate underwater noise. This noise may be caused by effects such as rubbing, strumming, turbulent flow, gearbox noise, moorings, wave interaction, etc.

There is concern that this noise, if sufficiently loud, will impact the marine environment. Of particular concern is the impact on species that utilise underwater sound as part of their survival strategy such as marine mammals and fish.

A number of organisations have made acoustic measurements at the site but these have been on an ad hoc basis. The aim of the current work is to produce a standardised methodology which can be used to characterise the baseline to measure the incremental noise signature produced by operational wave generation systems as they are introduced to the site.

Figure 1: The EMEC Wave Test Site, Billia Croo layout with 5 cabled berths
[Source curtsey of EMEC http://www.emec.org.uk/wave_site.asp]

1.4 AIMS OF THE REPORT

This report aims to provide the following:

- A brief description of the acoustic aspects of the Wave Test Site
- A review of acoustic measurements at other wave test sites
- A review of relevant international standards and agreements
- A review of likely biological receptors and potential physiological and behavioural response at the EMEC wave site

2. THE EUROPEAN MARINE ENERGY CENTRE WAVE TEST SITE

2.1 PHYSICAL

The Wave Test Site is located off Billia Croo, Orkney (see figure 1 above). The seabed shelves steeply initially to a water depth of 20 metres 400 metres offshore of Billia Croo, then more gradually to 70 metres at the West Cardinal Buoy 3.3 km off shore. Parallel to the shore the seabed shelves very gradually from a water depth at the South Cardinal Buoy of 40 metres to 50 metres at the North Cardinal Buoy, a distance of 4 km.

The seabed is rocky close to shore, changing to sand and broken shell in the deeper sections. There are moderate currents through the area but these are modified by the cross-flow of water entering and leaving Hoy Mouth resulting in circulating currents in the test area. Oceanographic fronts between water masses have also been observed in the northern part of the test site.

There is light shipping traffic passing through the test site consisting primarily of small fishing boats and pleasure craft. The ferry between Stromness and Wick passes to the south of the test site several times each day. Other shipping traffic passes through the test site or to the south of the test site on an irregular and infrequent basis. EMEC operate an AIS receiving station at Black Craig (the hilltop overlooking Billia Croo bay) and this will identify the passage of larger ships through the test area.

The main source of shipping noise on the test site is likely to be from boats servicing the site equipment and the installed generation systems. These vary from RIBs to large cable ships.

The EMEC AIS receiver stations at both the wave test site and tidal sites allow continuous monitoring of AIS enabled shipping traffic across an area of four and a half thousand km^2. An example snapshot of the Billia Croo site AIS output is shown in figure 2.

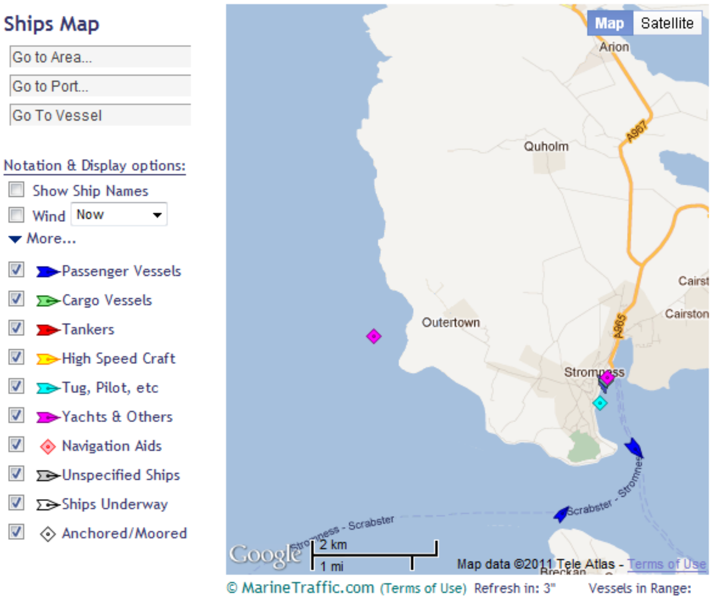

Figure 2: Example of AIS data across the EMEC wave test site and Stromness [Source: http://www.emec.org.uk/marine_traffic.asp]

EMEC Ltd also operate an extensive permitting policy, including notice to mariners for the wave site, allowing close monitoring of all onsite activities. A camera facility is also operated from Black Craig allowing real time viewing of on-site activity at Billia Croo.

2.2 OCEANOGRAPHIC DATA

EMEC have two Datawell directional waveriders [Datawell, 2011] deployed in the area to provide information on wave height and direction, figure 3.

Figure 3: positioning of wavewrider systems at EMEC wave test site.
[Source http://www.emec.org.uk/wave_data.asp]

The collected data is archived by EMEC and also summarised in periodic live reports (approximately 1 hour lag) available on the web [EMEC, 2011c]. Data collected includes:

Maximum Wave Height (H max)	1.82m
Significant Wave Height (H 1/3)	1.2349m
Maximum Wave Period (T max)	6.84s
Significant Wave Period (T 1/3)	6.48s
Peak Direction	290 deg

Table 1: Example output data form Datawell wave rider systems at the EMEC test site. [Source http://www.emec.org.uk/wave_data.asp]

Weather data including wind, precipitation and temperature are continuously collected from a station located at Billia Croo and tidal sites. This data is archived by EMEC. These also provide information on water temperature.

Analysis of the MetOcean data gathered at Billia Croo during 2006 - 2007 for EMEC was undertaken by the International Centre for Island Technology (ICIT). The reports produced are available to developers deploying at the wave site.

EMEC in collaboration with various Higher Education Institutes has also carried out various MetOcean Research programs. These include high resolution MetOcean modeling [Lawrence *et al*, 2009], Wave resource estimation [Cruz *et al,* 2007] and climate estimation [Venugopal & Smith, 2007].

In view of the previous history of the usage of Scapa Flow by the Royal Navy it is likely that there will be a significant amount of historic data from XBT drops either in the area or close by. These will be held at UKHO, Taunton.

3. MARINE MAMMAL SPECIES AT THE EMEC BILLIA CROO TEST SITE AND ASSOCIATED NOISE ASSESSMENT DATA

3.1 INTRODUCTION

EMEC have operated a visual watch for wildlife at the Wave Test Site since 2009. Key species of interest are seabirds, seals, cetaceans and basking sharks. Two experienced observers keep watch from a lookout hut on Black Craig overlooking the site (figure 4). Big Eye binoculars are used to help species identification. Various other research programmes aimed at biological interaction with marine renewable devices are on-going and planned at the EMEC centre.

Figure 4: Wildlife observers at Black Craig lookout, and view to south west [EMEC, 2011b]

Based on EMEC data [EMEC, 2010] and other sources, an assessment of a variety of marine species (seabirds, marine mammals, etc.) present at the wave test site shows how their presence varies through the year. Nine marine mammal species are known to occur regularly in coastal waters around Orkney: harbour porpoises, minke whales, Risso's dolphins, Atlantic white-sided dolphins, killer whales, long-finned pilot whales, white-beaked dolphins, grey seals, and harbour seals. There are occasional sightings of a further 14 cetacean species (fin whales, humpback whales, sei whales, blue whales, sperm whales, Sowerby's beaked whales, Cuvier's beaked whales, pygmy sperm whales, false killer whales, northern bottlenose whales, beluga whales, bottlenose dolphins, and short-beaked common dolphins) and four pinniped species (hooded seals, bearded seals, ringed seals, and walrus).

3.2 MARINE MAMMAL SPECIES PRESENT AT BILLIA CROO

3.2.1 Cetaceans

3.2.1.1 Harbour porpoise

Harbour porpoises are the most abundant cetaceans in the region [Hammond 2006; Hammond *et al,* 2002]; the area to the north of Scotland has some of the highest densities of porpoises recorded in the northeast Atlantic. Sightings rates are highest in summer, and it is clear that this is an important area for porpoises. This is supported by data from monthly land based visual observations at the Billia Croo wave site from February 2009 until March 2010 [EMEC, 2010]; harbour porpoises were the most commonly sighted species (figures 5 and 11).

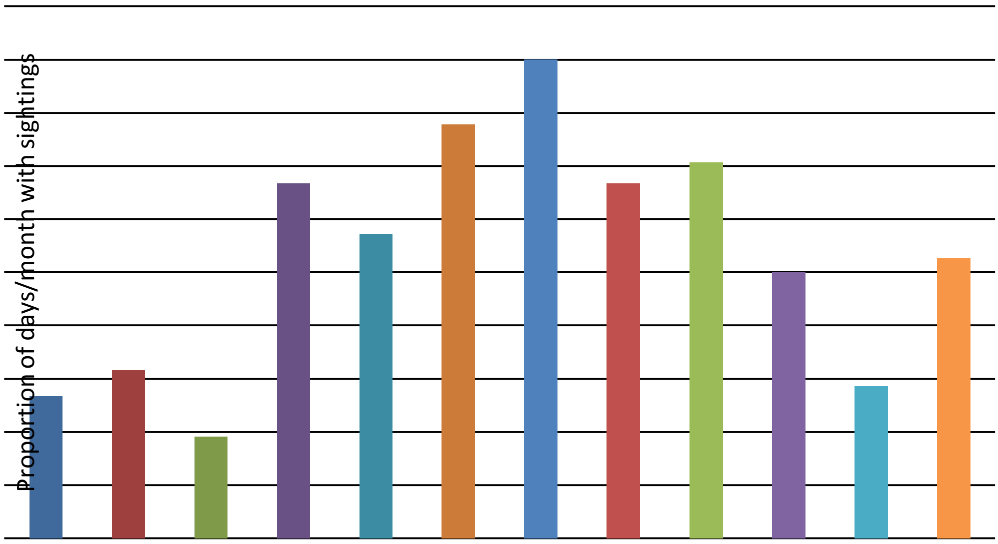

Figure 5: Seasonal variation in sightings of harbour porpoises from land based visual observations at the Billia Croo wave test site [EMEC, 2010]

3.2.1.2 Minke whale

Minke whales are the most abundant baleen whale around the UK and occur widely throughout northern UK waters [Hammond *et al*, 2002; Northridge *et al*, 1995; Reid *et al*, 2003]. Although the species occurs year round on the north-west European continental shelf, most sightings have been made between May and September; during July to September, aggregations of feeding individuals can be observed, particularly near shore [Reid *et al,* 2003]. Relatively small groups (up to two animals) were sighted throughout the late summer months (July - October), during land based visual observations at the Billia Croo wave site (Figures 6 and 11).

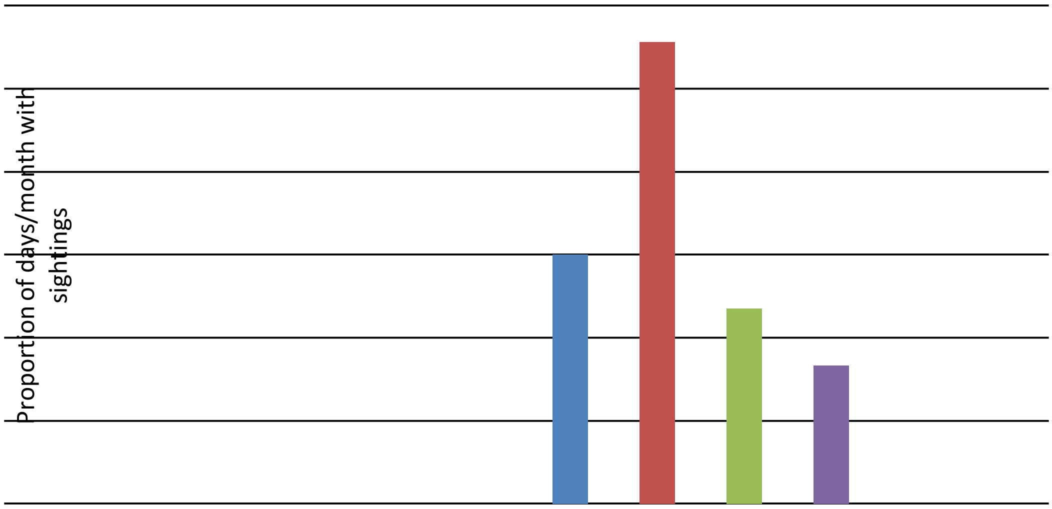

Figure 6: Seasonal variation in sightings of minke whales from land based visual observations at the Billia Croo wave test site [EMEC, 2010]

3.2.1.3 *Risso's dolphin*

Risso's dolphins are sighted in low numbers throughout Orkney waters. Relatively small groups (between one and twelve animals) were sighted between April and October, during land based visual observations at the Billia Croo wave site (Figures 7 and 11).

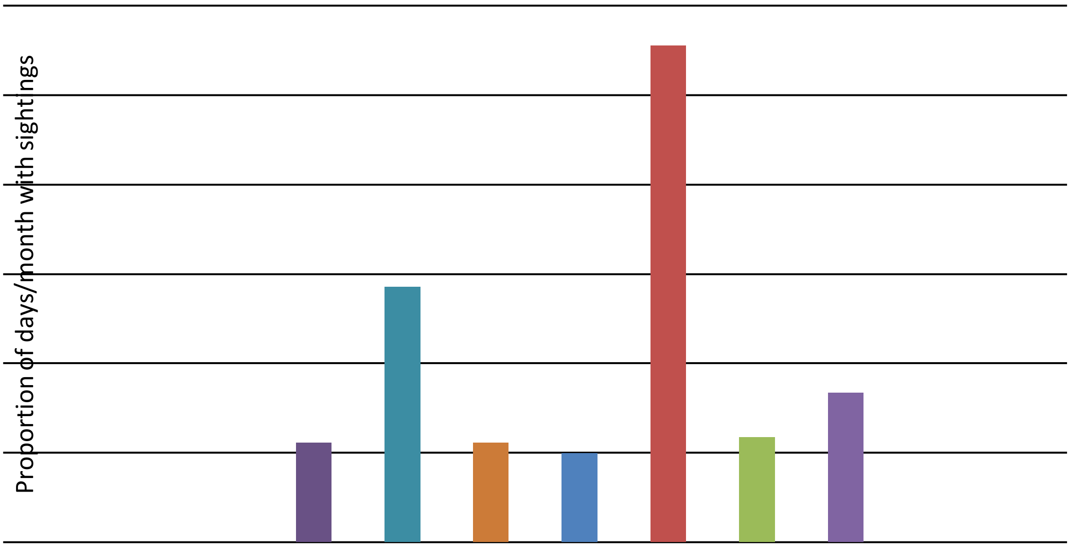

Figure 7: Seasonal variation in sightings of Risso's dolphins from land based visual observations at the Billia Croo wave test site [EMEC, 2010]

3.2.1.4 *Atlantic white sided dolphin*

The Atlantic white-sided dolphin is primarily an offshore species but does occur occasionally over the shelf, especially in summer. In some areas, their presence appears to be seasonal, with the bulk of sightings occurring between May and September [Northridge *et al*, 1995]. Relatively small groups (between one and eight animals) were sighted between May and August, during land based visual observations at the Billia Croo wave site (Figures 8 and 11).

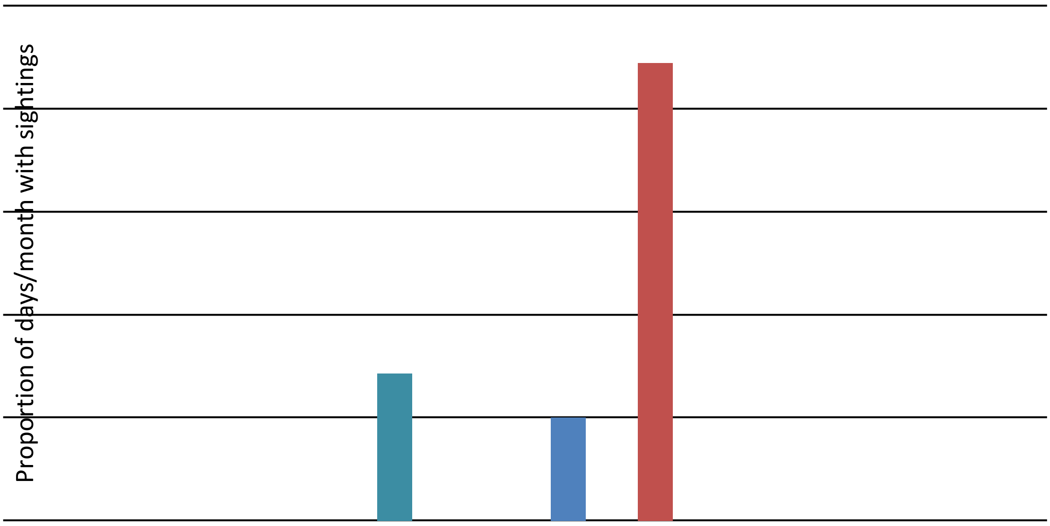

Figure 8: Seasonal variation in sightings of Atlantic white sided dolphins from land-based visual observations at the Billia Croo wave test site [EMEC, 2010]

3.2.1.5 Killer whale

Killer whales have been observed relatively frequently around Orkney. Seasonal movements may be driven by the distribution of prey; for example seals may be preyed upon during the pupping season when animals are close to shore [Reid *et al*, 2003]. However, only small numbers of sightings of groups (between two and five animals) were recorded during land based visual observations at the Billia Croo wave site (Figure 11).

3.2.1.6 Long-finned pilot whale

Pilot whales are found primarily along the shelf edge but have been observed occasionally in Orkney waters. However, only a single sighting of pilot whales was made during land based visual observations at the Billia Croo wave site (Figure 11).

3.2.1.7 Bottlenose dolphin

Around Scotland, bottlenose dolphins are rarely sighted outside coastal waters of north eastern Scotland and the outer Hebrides [Reid *et al,* 2003; Wilson *et al,* 1997]. Only a single sighting of bottlenose dolphins was made at the Billia Croo wave site (Figure 11).

3.2.1.8 White beaked dolphin

White-beaked dolphins are restricted to the North Atlantic; in the eastern North Atlantic their range extends from the British Isles to Spitsbergen. They are widely distributed on the continental shelf to the west of Orkney [Reid *et al*, 2003]. Although sighting surveys estimate (which include shelf waters around Shetland and Orkney, SCANS blocks D) 1,157 animals; there was only one sighting of white-beaked dolphins in SCANS block J (waters immediately adjacent to Shetland and Orkney) [Hammond *et al,* 2002]. Furthermore, no sightings of this species have been made during land-based observations at the Billia Croo wave site; however, a small number of unidentified sightings were tentatively classified as white beaked dolphins.

3.2.2 Pinnipeds

3.2.2.1 Grey seals

Approximately 45% of the world's grey seals breed in the UK and 90% of these breed at colonies in Scotland with the main concentrations in the Outer Hebrides and in Orkney [SCOS, 2009]. Grey seals breed in the autumn and in north and west Scotland, pupping occurs mainly between September and late November [SCOS, 2009]. Extensive information on the distribution of British grey seals at sea shows that they occur in relatively large numbers throughout Orkney waters. Models of habitat preference supported by the satellite telemetry data suggest that some of the most important areas used by grey seals appear to be close to Orkney and Shetland. These results are supported by the distribution of at sea sightings during cetacean surveys. Furthermore, relatively large numbers of confirmed sightings (large numbers of unidentified seal sightings have been made) of grey seals were made at the Billia Croo wave site throughout the year (Figures 9 and 11); numbers were highest between October and March.

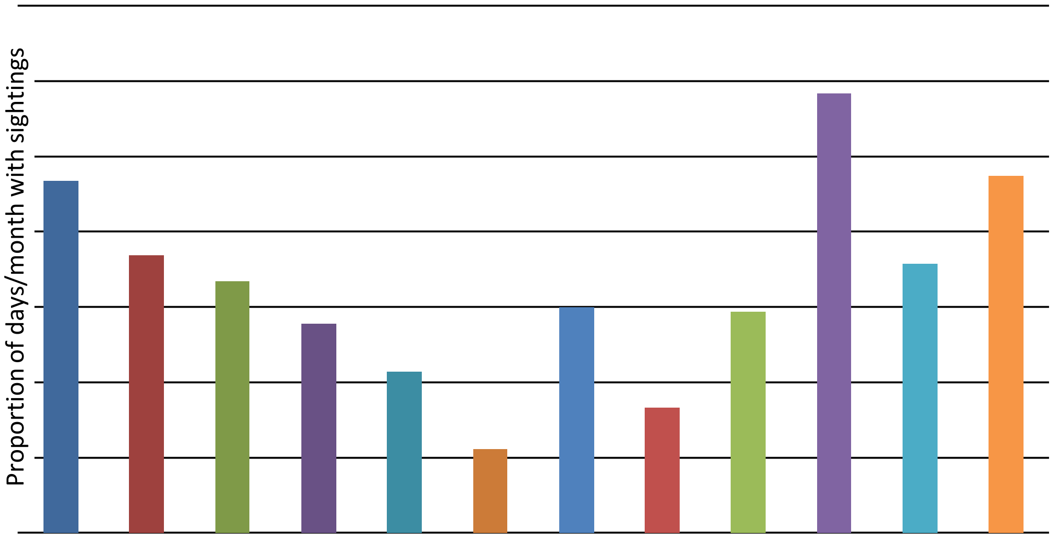

Figure 9: Seasonal variation in sightings of grey seals from land-based visual observations at the Billia Croo wave test site [EMEC, 2010].

3.2.2.2 Harbour seals

Approximately 30% of European harbour seals are found in the UK although this proportion has declined from approximately 40% in 2002. Harbour seals are widespread around the west coast of Scotland and throughout the Hebrides and Northern Isles [SCOS, 2009]. They are present throughout the year, on haul out sites in Orkney and along the north coast of Scotland. During the pupping and moulting seasons in June to September they spend less time at sea than at other times of the year. At sea sightings of harbour seals in this area are also concentrated in the south and close to Orkney and Shetland. Relatively small numbers of confirmed sightings (large numbers of unidentified seal sightings have been made) of harbour seals were made at the Billia Croo wave site (Figures 10 and 11). It is important to highlight that this species appears to be exhibiting a marked population decline in the region; counts in Orkney and Shetland in 2006 were 42% lower (95% confidence intervals 10%-62%) than in 2001 and results from 2007 confirmed the magnitude of the decline in Orkney [SCOS, 2009].

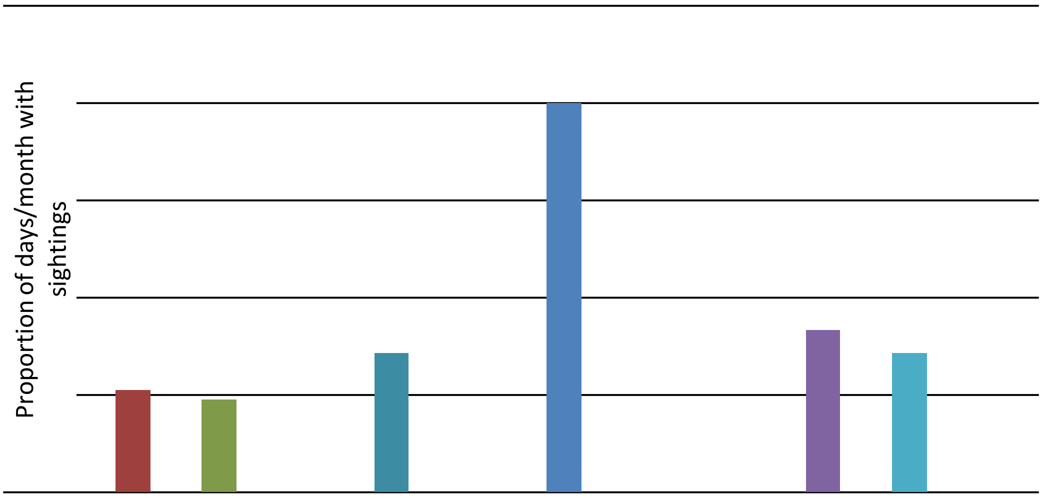

Figure 10: Seasonal variation in sightings of harbour seals from land-based visual observations at the Billia Croo wave test site [EMEC, 2010].

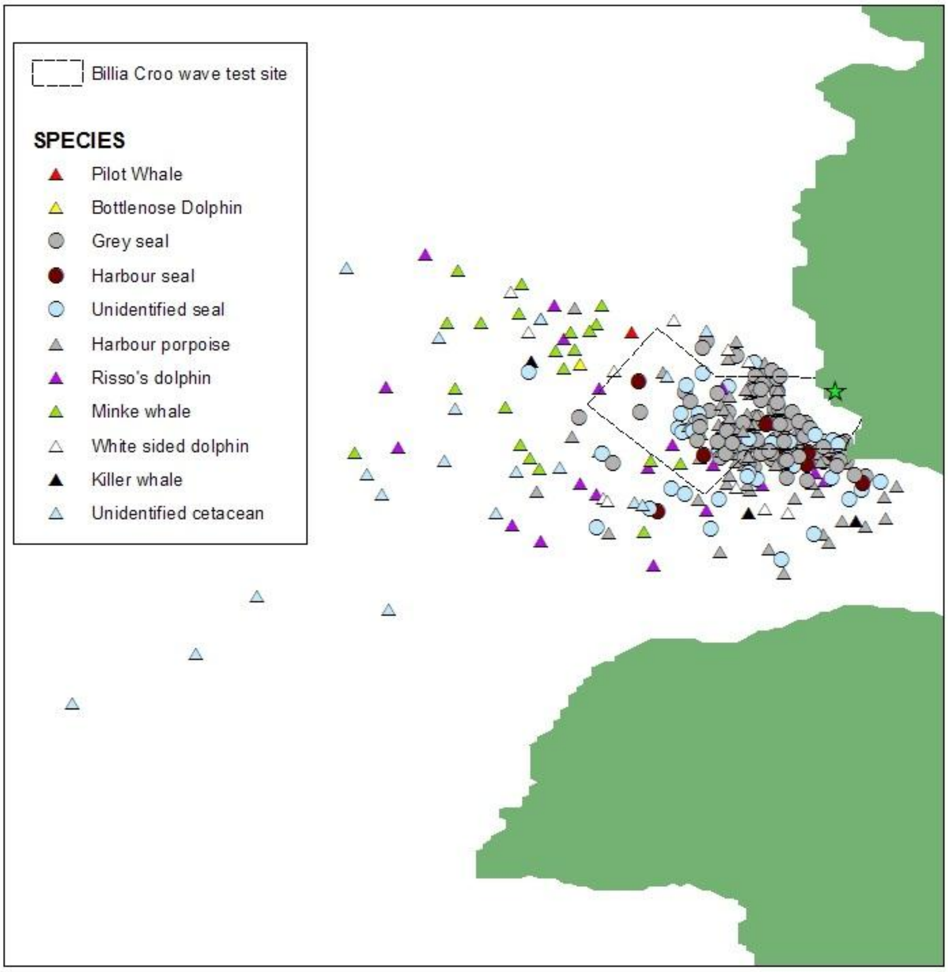

Figure 11: Sightings of marine mammals at the Billia Croo wave test site (dashed line). Data were collected from a land-based observation station (denoted by the star) between February 2009 and March 2010. It is important to highlight that neither spatial autocorrelation nor the influence of range on sighting probability have been accounted for in this figure.

3.3 HEARING SENSITIVITIES

An important concept when considering the hearing capabilities of animals is that of the auditory threshold (also called hearing threshold) [Johnson, 1967b]. The hearing threshold is the average sound pressure level that is just audible to a subject under quiet conditions. An audiogram is a plot of hearing threshold as a function of frequency. Audiograms are generally derived using two principal techniques; behaviourally (using measured behavioural responses to acoustic signals), and using Auditory Evoked Potentials (AEPs; based on electro-physiological responses to acoustic signals). It is important to highlight that the results from these two methods may not be directly comparable and a recent study by [Yuen *et al,* 2005] suggests that AEP measures of hearing do not yield as sensitive a measure as behavioural thresholds; thresholds gathered using behavioural methods [Yuen *et al,* 2005] were usually about 10 dB more sensitive than those obtained using AEPs with the same technique as that used in the present study.

3.3.1 Cetaceans

Behavioural audiograms have been reported for some cetacean species. In general toothed cetaceans, (dolphins and porpoises), are most sensitive to sounds above about 10 kHz and below this sensitivity deteriorates. In contrast, high frequency hearing is generally good with upper limits of sensitive hearing range ranging from 65 kHz to well above 100 kHz in most species. This is related to the use by these species of high frequency sound pulses for echolocation and moderately high frequency calls for communication.

3.3.1.1 Harbour porpoise

A small number of studies on harbour porpoise hearing sensitivity have been carried out; frequencies tested range between 0.25 and 190 kHz; results are relatively consistent suggesting that the greatest sensitivity of harbour porpoise hearing lies in the ultrasonic frequency range between 30 and 140 kHz and with reduced sensitivity towards lower frequencies [Anderson, 1970; Kastelein *et al,* 2002; Popov *et al,* 1986]. However, there are marked differences in threshold levels at the most sensitive frequencies (125-130 kHz) with sensitivity ranging from 9 dB re 1µPa [Bibikov, 1992] to 60 dB re 1µPa [Popov *et al,* 1986] which may be a result of differences in experimental design or individual porpoise variation. To support this high frequency hearing capability, [Au *et al,* 1999] described some characteristics of the echolocation signals of a harbour porpoise; the peak frequency is about 128 kHz with a -3 dB bandwidth of about 16 kHz,

3.3.1.2 Minke whale

There are currently no empirical audiograms for baleen whales; this is a clear data gap that limits the assessment of the impacts of noise on baleen whales. It is assumed that they are sensitive to sound of low and medium frequencies because they predominantly emit low frequency sounds, primarily at frequencies below 2 kHz [Mellinger *et al,* 2000] and in many cases predominantly infrasonic (<20 Hz) sounds. Baleen whales react behaviourally to low frequency calls from conspecifics; however, these observations do not provide accurate estimates of hearing thresholds. The dominant call of minke whales is a 200 - 400 Hz pulse. Although the anatomy of baleen whale ears also indicates that they are most sensitive to low frequencies, recent anatomical modelling work by [Ketten *et al,* 2007] has suggested that some baleen whales may have functional hearing capabilities at frequencies up to 30 kHz.

3.3.1.3 Risso's dolphin

A behavioural audiogram of a single female Risso's dolphin was carried out by [Nachtigall *et al,* 1995] Hearing thresholds were generally flat between 4 and 74 kHz (around 63.8-71.7 dB re 1µPa) with best hearing sensitivity between 8 and 16 kHz [Nachtigall *et al,* 1995]. More recently, an infant Risso's dolphin audiogram was measured using AEPs for frequencies between 4 and 150 kHz. The animal exhibited a wide range of best sensitivity, with the lowest threshold of 49.5 dB re 1µPa at 90 kHz. There was a gradual, low-frequency slope of 16.4 dB octave^{-1} and a sharp high-frequency increase of 95 dB octave^{-1} [Nachtigall *et al*, 2005].

Risso's dolphins produce tonal calls with a mean frequency of 11.3 kHz (range: 8.8-13.4 kHz) [Rendell *et al,* 1999] and relatively high frequency echolocation clicks with peak frequencies ranging from 40-110 kHz [Madsen *et al,* 2004]

3.3.1.4 Atlantic white sided dolphin

There are currently no published audiograms for Atlantic white sided dolphins. However, a recent study using AEPs of stranded dolphins has been carried out and although no results have been published, the authors note that audiograms were typically dolphin in nature with an upper frequency limit approaching 160 kHz [Houser *et al,* 2010].

3.3.1.5 Killer whale

Audiograms have been derived for 2 captive female killer whales using both behavioural and AEP techniques [Szymanski *et al,* 1998]. Frequencies between 4 and 100 kHz were tested using behavioural responses and between 1 and 100 kHz for AEPs. Results for both techniques suggest that most sensitive hearing occurred at 20 kHz with thresholds of 34 and 37 dB re 1 µPa for behavioural and AEP responses respectively [Szymanski *et al,* 1998]. Another study using behavioural responses by a single sub-adult male (frequencies between 0.5 and 31 kHz) suggested that the most sensitive region of killer whale hearing occurs at around 15 kHz with a threshold of 30 dB re 1µPa [Hall and Johnson, 1972].

Killer whales produce a range of tonal whistles with an average dominant frequency of 8.3 kHz and an average bandwidth of 4.5 kHz [Thomsen *et al,* 2001]; echolocation clicks had most of their energy in the spectra between 20 and 60 kHz [Au *et al,* 2004].

3.3.1.6 Long-finned pilot whale

A recent study of a rehabilitated captive long finned pilot whale derived an audiogram using AEPs that included measurements of nine frequencies from 4 to 100 kHz presented as sinusoidally amplitude-modulated tones [Pacini *et al,* 2010]. The region of best hearing was found to be between 11.2 and 50 kHz with thresholds below 70 dB re 1 µPa. The best hearing was found at 40 kHz with a 53.1 dB re 1 µPa threshold. Overall, threshold measurements had low values mainly because of the low ambient noise of the pool where the measurements were conducted. The slope of the thresholds became very steep above 50 kHz and the poorest sensitivity was measured at both ends of the frequency spectrum with 77 dB at 4 kHz and 124 dB re 1 µPa at 100 kHz [Pacini *et al,* 2010]. Long-finned pilot whales produce tonal calls with a mean frequency of 4.5 kHz (range: 3.5-5.8 kHz) [Rendell *et al,* 1999].

3.3.1.7 Bottlenose dolphin

Information on bottlenose dolphin hearing is relatively extensive when compared to most other marine mammals. A number of studies have described audiograms of captive dolphins [Brill *et al,* 2001; Johnson 1967a; Ljungblad *et al,* 1982; Popov and Supin, 1990; Schusterman, 1975], testing frequencies between 0.075 and 150 kHz; these report that the region of highest sensitivity generally lies between 14 and 80 kHz. More recently, a study involving a far larger sample size of dolphins (11 males and 3 females) was carried out to assess individual variation in hearing sensitivity [Popov *et al,* 2007]. Hearing thresholds were measured at frequencies from 8 to 152 kHz with ¼-octave steps. Most of the subjects had qualitatively similar audiograms. The averaged audiogram featured the best sensitivity (the threshold below 50 dB re 1 µPa) at 45 kHz. Thresholds rose slowly to lower frequencies (up to 65 dB at 8 kHz) and steeply at higher frequencies (up to 97 dB at 152 kHz).

Bottlenose dolphins produce relatively high frequency echolocation clicks with peak frequencies ranging from 40 - 140 kHz [Akamatsu *et al,* 1998] and mid frequency tonal whistles between 4 and 17 kHz [Janik, 2000].

3.3.1.8 White beaked dolphin

A recent study of two live captured white beaked dolphins was carried out using AEPs; frequencies between 16 and 215 kHz were tested. At very high frequencies, the slope of thresholds increased steeply beyond 128 kHz at a rate of 95 dB/octave. Maximum sensitivity was shown between 50 and 64 kHz. Measured areas of best sensitivity were between 45 and 128 kHz [Nachtigall *et al,* 2008].

White beaked dolphins produce tonal calls ranging from 3 to 35 kHz [Rasmussen and Miller, 2002] with a mean frequency of 11.2 kHz (range: 9.1 - 13.1 kHz) [Rendell *et al,* 1999] and clicks with a peak frequency at about 115 kHz and a second lower amplitude peak at about 250 kHz [Rasmussen and Miller, 2002].

3.3.2 Pinnipeds

Underwater audiograms have been derived for a range of phocid species and all show a similar pattern over the range of frequencies tested [Richardson *et al,* 1995). In general, phocid seals are less sensitive to high frequencies than odontocetes. At their best frequencies, odontocetes are around 20 - 30 dB re 1µPa more sensitive than phocids; however, below about 2 kHz phocids become relatively more sensitive.

3.3.2.1 Grey seals

No behavioural audiograms are available for grey seals, but AEP audiogram for a single animal showed a typical pinniped pattern over the range of frequencies tested [Ridgway and Joyce, 1975]. Sensitivity decreases rapidly at higher frequencies, but at low frequencies (0.1 kHz), the threshold was 96 dB re 1 µPa, indicating good low frequency hearing. The fact that grey seals make low frequency calls [Asselin *et al,* 1993] suggests that they also have good low frequency hearing. More recently, [Gotz and Janik, 2010] derived a composite audiogram for both harbour and grey seals which would be worth considering in noise assessment applications [Gotz and Janik, 2010].

3.3.2.2 Harbour seals

Behavioural audiograms have been measured for harbour seals with absolute thresholds ranging from around 62 to 72 dB re 1µPa within the most sensitive frequency range of 1 kHz to 32 kHz

[Kastak and Schusterman, 1998b; Mohl, 1968; Terhune, 1974]. As mentioned above, [Gotz and Janik, 2010] have recently derived a composite audiogram for both harbour and grey seals. Furthermore, underwater vocalisations of male harbour seals are generally below 2 kHz, supporting the evidence that they possess good low frequency hearing.

Table 2: Summary metrics of hearing sensitivity of marine mammals from underwater audiograms [Erbe, 2002; Gotz and Janik, 2010; Hall and Johnson, 1972; Kastak and Schusterman, 1998a; Møhl, 1968; Nachtigall *et al,* 1995; Nachtigall *et al* ,2008; Nedwell, *et al,* 2004; Pacini *et al,* 2010; Popov *et al,* 2007; Ridgway and Joyce, 1975; Szymanski *et al,* 1998; Terhune and Ronald, 1974] and vocal ranges [Asselin *et al,* 1993; Au *et al,* 1999; Janik, 2000; Mellinger *et al,* 2000; Rasmussen and Miller, 2002; Rendell *et al,* 1999; Van Parijs *et al,* 2000]. The table shows the lowest and highest frequencies tested and the frequency of best sensitivity [indicated by the lowest Threshold (dB re 1 µPa)]. It should be highlighted that differences in data collection methods may preclude direct comparisons in hearing threshold between species but as a measure of the range of hearing sensitivity and frequencies of highest sensitivity, these data are relevant.

Species		**Lowest frequency (kHz)**	**Threshold (dB re 1 µPa)**	**Most sensitive frequency (kHz)**	**Threshold (dB re 1 µPa)**	**Upper frequency (kHz)**	**Threshold (dB re 1 µPa)**	**Vocalisation low frequency (kHz)**	**Vocalisation high frequency (kHz)**
Cetaceans									
	Harbour porpoise	0.25	115	100	32	180	106	112 (clicks)	144 (clicks)
	White beaked dolphin	16	70	45	45	215	140	3 (whistles) 35-47 (clicks)	35 (whistles) 165-147 (clicks)
	Atlantic white sided dolphin[1]	16	70	45	45	215	140	-	-
	Killer whale	4	61	20	34	100	116	5.4 (whistles) 20 (clicks)	9.9 (whistles) 60 (clicks)
	Pilot whale	4	76.7	40	53.1	100	124.4	3.5 (whistles) 1 (clicks)	5.8 (whistles) 18 (clicks)
	Risso's dolphin	1.6	124	8	63.7	110	123	8.8 (whistles) 10 (clicks)	13.4 (whistles) 120 (clicks)
	Minke whale	-	-	-	-	-	-	0.06	2
	Bottlenose dolphin	8	65	45	50	152	97	40 (clicks) 4 (whistles)	140 (clicks) 17 (whistles)
Pinnipeds									
	Harbour seal	0.01	102	16	62	120	90	0.25	1.3
	Grey seal	1.4	83	25	61	150	148	0.1	3

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[1] Data on hearing thresholds taken from a closely related species; white beaked dolphin (*Lagenorhynchus albirostris*)

3.4 PHYSIOLOGICAL AND BEHAVIOURAL RESPONSES

Marine mammals exposed to anthropogenic sound may experience detrimental effects that include masking of biologically important signals, physical injury, psychological, behavioural and indirect effects that can range in extent from negligible to severe. This range is defined by the spatial relationship of the receiver and the sound source, the hearing sensitivity of the receiver, the acoustic characteristics of the vocalisation, and the acoustic characteristics of the anthropogenic noise. Marine mammals' hearing sensitivities cover a broad frequency range (see section 2) and as such the same sound source may elicit different behavioural and physiological effects in different species. In addition, within-species responses may vary depending on individual traits of exposed animals and the context in which they are exposed. Consequently, for many sound sources, responses are poorly described and predictions of potential effects are difficult. This is particularly true with respect to new and emerging technology within the marine renewable energy industry.

3.4.1 Masking

Masking is the process by which the detection of a biologically relevant acoustic signal (including communication calls to prey vocalisations or predator calls) is influenced by a second signal. In marine mammals, the masking effect is dependent on the bandwidth of the masking noise up to a critical bandwidth see [Fletcher, 1940] and the zone of masking can in theory extend as far as a zone of audibility if the acoustic communication signal is weak. For masking to occur there needs to be an overlap in the frequency range of signal and masker and the received level of the masker needs to exceed that of the signal. It is also important to consider that masking effects are likely to be attenuated if the masker and signal come from different directions. Although the concept of masking has been well described, there are currently no empirical studies that document its occurrence in free ranging animals.

3.4.2 Behavioural responses

Behavioural responses are influenced by a variety of factors including food motivation, learning processes (e.g. habituation), psycho-physiological features of a sound, and sensation levels [Götz and Janik, 2010]. This complexity of animal behaviour is also the most likely reason for the marked variation in responses found across studies. For example, while noise produced by acoustic deterrent devices was found to elicit behavioural avoidance responses that resulted in long-term habitat exclusion in odonotocetes [Morton and Symonds, 2002; Olesiuk *et al,* 2002], seals that commonly forage on farmed salmon showed little or no response to the same sound. [Jacobs and Terhune, 2002].

[Southall *et al,* 2007] have provided the first comprehensive review of data on the effects of noise on marine mammals and proposed noise exposure criteria for "functional hearing groups" of marine mammals exposed to pulsed and non-pulsed anthropogenic noise. They developed a weighting system that allows adjustment of received levels if the frequencies of the sounds fall outside the most sensitive hearing range of a species (M-weighting). These

M-weighting curves are relatively flat and only rise towards the very edge of the hearing range.

With respect to the dolphin and porpoise species at Billia Croo, the review by [Southall *et al,* 2007] suggests that these should be considered in the mid- and high-frequency cetacean groups respectively; minke whales would fall into the low frequency cetaceans. Behavioural response data for minke whales to noise is limited to a few studies [Palka and Hammond, 2001]; however, there are a number of studies on the responses of other baleen whales species to both pulsed [e.g. Ljungblad *et al*, 1988; Malme *et al,* 1983; McCauley *et al*, 1998; Richardson *et al,* 1986; Todd *et al,* 1996] and non-pulsed sounds [e.g. Baker *et al,* 1982; Frankel and Clark 1998; Malme *et al,* 1986; McCauley *et al,* 1996; Richardson *et al,* 1990]. From these studies behavioural thresholds of 224 dB re 1µPa (zero-peak sound pressure level) and 183 dB re 1µPa^2-s (sound exposure level: M-low frequency weighted) for single pulses have been recommended [Southall *et al,* 2007]. Although the data on responses to non-pulsed sounds for low frequency cetaceans are highly variable, it has been suggested that there is an increasing probability of avoidance in the 120-160 dB re 1µPa (RMS) range.

For the specific dolphin species identified in the Billia Croo wave test site, few data exist where behavioural responses have been measured together with calibrated received levels of sound at the animal [Buckstaff, 2004; Finneran and Schlundt, 2004; Morton and Symonds, 2002; Nachtigall *et al,* 2003; Palka and Hammond, 2001]. These, together with responses by a number of other species to pulsed [e.g. Akamatsu *et al*, 1993; Madsen and Mohl, 2000; Madsen *et al,* 2002] and non-pulsed [e.g. Gordon *et al,* 1992; Richardson *et al,* 1990; Watkins and Schevill, 1975] noise has been measured resulting in suggested behavioural thresholds of 224 dB re 1µPa (zero-peak sound pressure level) and 183 dB re 1µPa^2-s (sound exposure level: M-mid frequency weighted) for single pulses [Southall *et al,* 2007]. Data on responses to non-pulsed sounds for low frequency cetaceans are highly variable with some studies showing avoidance at levels of between 90-120 dB re 1µPa (RMS) range whilst other fail to show responses at levels up to 150 dB re 1µPa (RMS).

Harbour porpoises are the only cetacean in the Billia Croo wave test site that are generally considered a “high frequency” cetacean; there are a number of studies on non-pulsed noise for this species [e.g. Culik *et al,* 2001; Johnston, 2002; Kastelein *et al,* 2000; Kastelein *et al,* 2005; Kastelien *et al,* 1997; Olesiuk *et al,* 2001]. [Southall *et al,* 2007] concludes that behavioural thresholds of 224 dB re 1µPa (zero-peak sound pressure level) and 183 dB re 1µPa^2-s (sound exposure level: M-high frequency weighted) for single pulses are appropriate, and that they are relatively sensitive to non-pulsed noise at levels as low as 90 to 120 dB re 1µPa (RMS). However, some of the studies included in their review were conducted using sound types that are very different to the types of sound produced by wave devices [e.g. pure ultrasonic signals [e.g. Kastelein, 1997] or sound sources emitting long pulse trains [Olesiuk *et al,* 2002], so comparison is difficult. With respect to the spectral and temporal properties of the sound, a study that tested the effect of underwater data transmission sounds on harbour porpoise [Kastelein *et al,* 2005] is potentially most appropriate for wave devices; avoidance responses were found at average sound pressure levels of 97 dB re 1µPa.

Available data on behavioural responses by grey and harbour seals to noise is extremely limited [Kastelein *et al,* 2006]; however [Southall *et al,* 2007] concludes that behavioural thresholds of 212 dB re 1µPa (zero-peak) and 171 dB re 1µPa^2-s (sound exposure level: M-pinniped water weighted) for single pulses are appropriate, and that these species are likely to exhibit only mild avoidance responses to non-pulsed sound at received levels between 90 and 140 dB re 1µPa (RMS). However, for at least harbour seals, the upper end of this range may be an underestimate given that [Kastelein *et al,* 2006] demonstrated behavioural avoidance of harbour seals in response to artificial sounds used in acoustic data transmission devices at average received levels of 108 dB re 1 µPa (average across specimens and sound types). The sound types used in their study differed in their spectral properties; however, two of the tested sounds contained broadband features as well as tonal components that may be similar to some wave devices. Similarly, [Götz & Janik, 2010] showed sustained avoidance responses in wild grey seals at a received level of 135 dB re 1µPa (RMS) and sensation levels ranging from 59 to 79 dB (RMS) depending on sound type.

3.4.3 Auditory damage

Hearing damage initially manifests itself as a temporary, recoverable change of the hearing threshold (temporary threshold shift: TTS). Exposure to higher intensity or longer stimuli may eventually lead to chronic hearing damage (permanent threshold shift: PTS). The risk of hearing damage is therefore considered to be a function of both sound pressure level and exposure time [Eldred *et al,* 1955]. Therefore, the metric sound exposure level (SEL) or energy flux density has been suggested as measure for defining safe exposure levels. However, recent studies called for a revision of the concept that hearing damage can be modelled as a function of SEL in bottlenose dolphins [Mooney *et al,* 2009]. Despite this, given the overall lack of empirical data for seals and the harbour porpoises, sound exposure levels (SELs) currently represent the most appropriate approach.

Sound exposures that elicit TTS in cetaceans have been studied in two of the species that are present in the Billia Croo wave test site; harbour porpoises [Lucke *et al,* 2009] and bottlenose dolphins [Finneran *et al,* 2007; Finneran *et al,* 2000; Finneran *et al,* 2002; Nachtigall *et al,* 2003; Schlundt *et al,* 2000]. [Southall *et al,* 2007] injury criteria for all cetaceans are based on one of the bottlenose dolphin studies [Finneran *et al,* 2002] with a 6 dB to sound pressure levels and 15 dB to sound exposure levels to estimate PTS onset from pulsed (230 dB re 1 µPa (zero-peak) and 198 re 1µPa^2-s (SEL) for all cetaceans) and non-pulsed sound (230 dB re 1 µPa (zero-peak) and 215 re 1µPa^2-s (SEL) for all cetaceans). However, a more recent study into TTS in harbour porpoises from pulsed noise (seismic airgun) [Lucke *et al,* 2009] found that onset of TTS in harbour porpoises can occur at lower sound exposure levels of 164.3 dB re 1µPa^2-s suggesting that the [Southall *et al,* 2007] criteria for pulsed sounds may be an underestimate.

For pinnipeds, sound exposures that elicit TTS have been studied in harbour seals [Kastak and Schusterman, 1996; Kastak *et al,* 1999; Kastak *et al,* 2005]; as described above, these have been reviewed by [Southall *et al,* 2007] who derived PTS exposure criteria of 218 dB re 1 µPa (zero-peak) and 186 re 1µPa^2-s (SEL) for pulsed sounds, and 218 dB re 1 µPa (zero-peak) and 203 re 1µPa^2-s (SEL) for non-pulsed sounds.

In the context of wave devices which are generally likely to be moored in a single location for extended periods, there are currently no data available to indicate how hearing damage develops in marine mammals as a result of regular exposure to moderate received levels over periods of months or years. In humans, noise levels at industrial workplaces should not exceed 80-85 dBA if subjects are exposed for up to 8h a day [NIOSH 1998].

3.5 DATA GAPS

- Although data on marine mammal presence at the Billia Croo wave test site is relatively comprehensive, data on absolute density or abundance is lacking and would potentially limit critical noise assessments;
- Data on movements and residency of individual animals in the test site would potentially allow longer term effects of noise to be estimated;
- Auditory threshold data for a number of the species likely to be present in the test site is lacking. Specifically, no empirical data currently exist for minke whales (or any baleen whale) and Atlantic white-sided dolphins;
- There are currently no empirical studies on the occurrence or extent of masking from noise in marine mammals;
- There are currently no data available on how hearing damage develops in marine mammals as a result of regular exposure to moderate received levels over periods of months or years;
- A clear data gap when predicting the effects of any noise are the behavioural responses by different species to the measured noise. To make informed predictions there is a clear need to carry out controlled experiments to assess how different species respond to continuous or pulsed noise from wave energy devices.

4. MEASUREMENTS AT OTHER WAVE ENERGY SITES

4.1 OTHER EUROPEAN TEST SITES

The Peninsula Research Institute for Marine Renewable Energy (PRIMaRE) is a collaborative institute drawing from researchers at Exeter and Plymouth University, based in the south west of the UK, [PRIMaRE, 2011] directly linked to the WaveHub facility. PRIMaRE operate a one third scale test facility in Falmouth Bay in UK, to test mooring designs for wave renewable systems. In addition wave test facilities for multidirectional wave and variable tides are being built [Mueller *et al,* 2010].

Based off the UK's north coast of Cornwall, WaveHub is a subsea offshore connection facility designed for long term array level device testing across an 8 km^2 area with up to four developers operating at once. Array level testing is likely to take place after individual device testing has already been carried out at for example EMEC or Galway Bay test sites. Device testing may take place for years via a single cable to Hayle with an initial 16 MW capacity with potential to upgrade to 50 MW in the longer term [WaveHub, 2011].

With PRIMaRE, a series of baseline studies has taken place at the WavHub site. These include: passive acoustic monitoring of cetaceans [Chelonia, 2011a]; aerial surveys for large pelagic and pinniped species; broadband observations of pelagic and benthic acoustic environments; seabird censuses and monitoring benthic and pelagic environments; satellite tracking of marine species behaviour around site; and assessment of impact of anthropogenic noise on marine species [PRIMaRE, 2011].

WaveHub are currently commissioning a seabed autonomous recording system obtained from the Woods Hole Oceanographic Institute in the USA. A number of test deployments have been carried out in Falmouth Bay and it is hoped to carry out test deployments on the Wave Hub site later 2011.

The New and Renewable Energy Centre (NaREC) is a company based in the UK providing a range of services to the marine technology development industry, including wind, wave and tidal renewable systems,[NaREC, 2011]. Facilities include tidal test system (located at the river Tees barrage), and wave flume tank and linear test rig. The facility includes various sized dry docks that may be flooded, wave tank facilities and the subsea systems testing tank measuring (125 m x 25 m x 8.25 m). They have tested a large number of devices in scaled testing facilities and have designed, developed, assembled and deployed full scale prototype wave and tidal devices in the field.

The Hydraulics and Maritime Research Centre (HMRC) based at University College Cork, Ireland, operate the Ocean Wave Basin test facility with a 25 m x 18 m and 1 m deep tank with wave generation up to a significant height of 0.18 m and wave flume facility 26 m long, 3m wide and 1m deep [HMRC, 2011].

The Wave Ocean Energy (OE) Test Site is operated by the Republic of Ireland's Marine Institute in association with SEAI one mile East of Spiddal in Galway Bay. The OE Test Site has been used for testing scaled prototypes of wave energy devices [Lewis, 2008] and covers an area of 37 hectares in approximately 21-24 m of water for one quarter scale wave energy systems [Marine Institute, 2011]. Systems tested on site include the Seilean wave energy prototype in 2009 and the Wavebob prototype system 2006, 2007 and 2011 [Marine Institute, 2011].

The Belmullet wave energy test centre has been proposed by The Sustainable Energy Authority of Ireland (SEAI) to be located off Annagh Head, west of Belmullet in County Mayo [SEAI, 2011]. Wave energy machines will be temporarily moored to assess their efficiency and their survivability in open ocean conditions. The Integrated Marine Observation System provides regular (updated every 3 minutes) directional wave rider data from both Belmullet and Galway Bay [Marine Institute, 2011].

The Marine Institute has commissioned acoustic work to detect marine mammals and CPODs [Chelonia, 2011b] are being used in con junction with towed array surveys to determine which marine mammals are present at the Belmullet site.

The Wave Energy Centre [WavEC, 2011] in Portugal, founded in 2003, operate a test site consisting of a 320 km^2 pilot test zone off central Portugal with a capacity of up to 250 MW. WavEC was established to develop marine energy technologies but also co-ordinates or participates in R&D projects. Examples of such projects are Wavetrain2 [Wavetrain, 2011], CORES [CORES, 2011], EQUIMAR [EquiMar, 2011] and WAVEPLAM [WAVEPLAM, 2011]. More details can be found at [WavEC, 2011].

Since 2007 WavEC has been running the Wave Energy Acoustic Monitoring [WEAM, 2011] programme to provide equipment and methodology to make measurements of underwater noise associated with wave generation. This has the aims of:

- Characterising noise generation by wave energy prototypes and farms
- Developing a plan or guideline to perform acoustic monitoring
- Developing a fixed hydrophone calibrated system for long time series measurements

The WavEC researchers have completed initial baseline and device sound field measurements on two systems. They have completed background noise assessment at the Waveroller (surge convertor) site and planning operation noise trials for summer 2011. Background and operational noise measurements have been completed at the OWC-Pico Plant (Oscillating Water Column) in 2010 but the report on this work has not been issued at the time this report was prepared (pers. comms). Various conference papers / presentations associated with underwater noise assessment from the WavEC site have been produced [Patrício *et al, 2008, 2009a, 2009b,* Patrício, 2010, Moura *et al,* 2010].

The Nissum Bredning wave energy test facility in western Limfjord, Denmark was established in 2000 [Nissum Bredning, 2011]. The facility is a pier with laboratory and mooring facilities, in approximately 8 m of water in a sheltered bay. Over 30 different types of wave powers systems (up to around 1 quarter scale) have been tested here for periods from a few days to years. From 2003 to 2005 the Wave Dragon prototype system was tested in association with Aalborg University, Denmark with a prototype capacity of 0.02MW potentially up scaled to 7 MW [Wave dragon, 2011].

The Danish Wave Energy Centre (DanWEC, 2011) is located at Hanstholm is a centre organized by a collaboration of Port of Hanstholm, the Municipality of Thisted, Aalborg University as well as project owner Port Forum of Hanstholm. A one-half scale Wave Star system was tested in 2009 [Wave star, 2011] and a one-fifth scaled DEXAwave device is currently being tested at the site [DEXAwave, 2011].

France is developing the SEM-REV 1 km^2 test site 15 km west of the town of Le Croisic and it is expected to be commissioned summer 2011 (SEM-REV, 2011) with a planned 2.5 MW grid connection. Data from extensive oceanographic measurements leading up to the commissioning including deployment of wave measuring systems has been collected.

In Norway, the Marine Energy Test Centre (METCentre, 2011) is located on the west coast 13 km west of Karmøy near Hywind and has a 15 MW undersea cable connected to the national grid which can be used to test wave generation devices. It is primarily used to test floating wind generation system but it is believed that at least one wave energy system has used this facility.

Since 2002 the Wave Power Project has been under way by researchers from the department of Engineering Science, Division for Electricity, Uppsala University, Sweden being carried out at a Swedish test site at Lysekil [Lysekil, 2011]. With a total planned capacity of 10 kW deployed from 2005-2010. Research programmes include development and testing of new wave technologies and potential effects on birds and other marine species.

4.2 OUTSIDE EUROPE

A wide variety of ocean test facilities exist outside of Europe, including facilities for wave, tidal current system development as well as the hydrocarbon extraction industry. These are primarily concentrated in USA and Canada however there are growing developments outside these nations particularly in Brazil and China [Appleyard, 2010]. Table 3 below summarizes some of major US and Canadian facilities in operation and under development.

NNMREC:

In 2008 Oregon State University (OSU) and University of Washington (UW) established the Northwest National Marine Renewable Energy Center (NNMREC) to support wave and tidal energy development for the United States [NNMREC, 2008]. A site has been selected near Newport for a new wave energy test program with full scale individual device testing in 2010 and up to 5 devices in 2013 planned in water depths 40-50 m. Various tank and flume test facilities have been utilized including, directional tank (48.8 m x 26.6 m x 2.1 m deep),a large wave flume tank (104 m x 3.7 m x 4.6 m deep) and intermediate scale test facilities are operated at Yaquina Bay (7.6 m deep) and Puget Sound (16 m deep), [Mueller, 2010].

The Oregon Wave Energy Trust (OWET) commissioned a report from JASCO Applied Sciences [Austin *et al*, 2009] to assess underwater noise generated by wave energy devices. This report uses models to estimate the sound fields around a variety of wave generation devices and also provides a suggested noise assessment programme. No actual measurements are presented.

A research programme commissioned by the Oregon Dept. of Energy is looking at the provision of noise makers to deflect migrating grey whales away from planned wave generator buoys.

Oceanic Consulting Corp: The Oceanic Consulting Corp provide a range of facilities including a deep water 200-meter towing Tank, the offshore engineering basin, and a the 22-meter flume tank for an alliance of the National Research Council of Canada's Institute for Ocean Technology, and Memorial University's Ocean Engineering Research Centre and Marine Institute [Oceanicorp, 2011].
OTRC: Offshore Technology Research Centre (OTRC) allied with Texas A&M University, provide a range of facilities for the renewable and hydrocarbon extraction industries. Including wave basin located at the Texas A&M Research Park Campus [OTRC, 2011].
The Hawaiian National Marine Renewable Energy Center (HINMREC): The Hawaiian National Marine Renewable Energy Center (HINMREC) has been developing both wave energy conversion devices and ocean thermal energy conversion (OTEC) systems. HINMREC currently operates two sites on the island of Oahu at Keneohe and at Makapu'u. A commercial sized larger scale test site is under development on Maui, [HINMREC, 2011].
Fundy Ocean Research Centre for Energy (FORCE): The Fundy Ocean Research Centre for Energy (FORCE), located in the Bay of Fundy, Nova Scotia Canada is primarily dedicated to development of tidal flow devices [FORCE, 2011]. It operates a test site with a 10 km grid connected transmission line with capacity for up to 3 devices with total capacity of 5 MW.
New England Marine Renewable Centre (MREC): The New England Marine renewable Centre (MREC) is focused on development of wave, tidal and wind marine energy systems with a core of academic institutes from USA and Europe [MREC, 2011]. It has established a network of academic, developers and energy users. One key aim of this the establishment of permanent ocean test sites [Mueller, 2010].
Southeast National Marine Renewable Energy Centre (SNMREC): The Southeast National Marine Renewable Energy Centre (SNMREC) based the College of Engineering and Computer Science, Florida Atlantic University, USA provides tidal flow system laboratory testing facilities including flume tanks for scaled models, and is developing an open water test site 12 nm off Ft Laurdade, Florida for up to a 100 kW capacity. This will support prototype device testing for 1:20 scale system development. Larger scale 1:4 and 1:1 open water berths are planned. [SNMREC, 2011].

Table 3 Operational and planned US and Canadian test facilities used for wave and tidal current renewable energy system development

5. MEASUREMENTS IN OTHER MARINE INDUSTRIES

5.1 SHIPPING

Ships are extended sources of sound that consist of a highly complex series of mechanical sources within the vessel, each of which has its own vibration amplitude and frequency. These individual sources include the engine, transmission, and the propeller. For some applications, it is important to study these individual sources of sound. For example, there may be a desire to reduce the radiated noise (through noise-quietening techniques). This may be in order to meet a specification for a "quiet" vessel such as a fisheries research vessel, or for reasons of stealth in military applications. In such cases, the amplitude and frequency of individual sources of sound may require specific study. In applications where the sound field very close to the ship may be important, such as for mine avoidance, the interaction of these sources in the acoustic near-field may also require study.

However, when characterising the acoustic output of vessels for the purposes of environmental impact assessment, we may often restrict ourselves to the consideration of only the acoustic far-field, the region far from the source. In so doing, considerable simplification may be introduced, and the concept of Source Level may provide a useful output metric. With the Source Level, the source is simplified such that when viewed from a substantial range, the sound radiation appears to originate from a point (termed the acoustic centre). However, with ships there are further complications due to the proximity of the source to the medium boundaries. In practice, surface ships do not behave like point sources in free space because of the proximity to the water surface which is a strong reflector of the sound field. The reflections from the water surface cause interference with the direct sound waves from the source, a phenomenon often referred to as the *Lloyd's Mirror* effect. This can have a large impact on the sound radiation by surface ships.

When comparing published data for source levels of ships, it is important to be aware of the definition used, the measurement conditions, experimental procedures and environmental parameters, as well as inconsistencies in reference distances, units and bandwidths, all of which are may be stated in different ways in the literature. The data presented for ship source levels in the scientific literature commonly appear in two forms:

(i) dipole source level (sometimes termed the "affected source level")

This is the most common format found and is derived from measurements made of the noise radiated by the vessel where the scaling for distance from the source is undertaken using a model which does not take into account the effect of interference by reflections from the water surface (or seabed in shallow water). The water surface provides a strong reflector with the reflected sound inverted compared with the incident signal. For this reason, a surface ship may be considered as a dipole source consisting of the noise source on the ship and its image in the reflecting water surface. There are a number of examples where this format is adopted [Arveson & Vendittis, 2000, ANSI S12.64, 2009].

(ii) monopole source level

The second is that of a monopole source level consisting of a "point source" radiating the same energy in all directions (it is omnidirectional). Here, the source level is obtained using an appropriate acoustic propagation model of sufficient sophistication to account for all required aspects of the sound transmission. A propagation model describes how the acoustic energy varies as a function of acoustic frequency and range from the source. For accurate results, a model should include interactions with the sea surface and seabed, absorption in the water, and potentially other features such as variation of sound speed and bathymetry. This method requires an assumption for the effective location of the acoustic centre of the ship. This method is less prevalent in the scientific literature when describing ship noise, but has been used by some researchers [Wales & Heitmeyer, 2002].

The majority of acoustic energy radiated by shipping is in the frequency range 10 Hz to 10 kHz, with highest spectral levels at frequencies of 40-60 Hz. At low frequencies, there are typically tonal components from engine, propeller and reciprocating machinery, with broadband noise from cavitation dominating at kilohertz frequencies. There is strong evidence that for some vessels the noise correlates with ship speed, particularly for the cavitation noise [Arveson & Vendittis, 2000]. The radiated noise from ships is typically measured using a fixed series of measuring hydrophones located in pre-defined positions (a “noise range”), or using a smaller number of hydrophones deployed from a single buoy or auxiliary vessel [ANSI S12.64, 2009].

5.2 MILITARY

The radiated noise signature of military ships is of high importance and there are a number of installations in the UK and elsewhere which have been set up to measure this noise signature.

In the UK the main noise ranges are located at Portland on the south coast of England, Loch Goil and Loch Fyne in the Clyde Estuary, and off Rona in Western Scotland. Each consists of an array of hydrophones located on the seabed. These hydrophones pick up the sound from ships passing over them on prescribed tracks and at set speeds.

Portable ranges are also available which operate in a similar manner to the fixed ranges described above but usually with a limited number of hydrophones. They are used to check the noise signature of ships operating away from their home base.

The military have many years of experience of characterising the noise signature of their ships and also of methods to reduce this noise signature. However, the applicability to the characterisation of noise from a fixed installation in a hostile environment such as a wave or tidal generator is limited. Military ranges are deployed in areas specifically chosen to minimise ambient noise and provide a benign acoustic environment. This option is not available to the renewables industry.

The military operate a range of sophisticated passive sonar systems to search for the radiated noise from potential targets. In a simplified form this technology could be used as part of the measurement methodology to be used by EMEC. However, the classified nature of such equipment may prevent the use of such technology.

5.3 OIL AND GAS

The Oil and Gas Exploration and Production Industry (OGEP industry) generates underwater sound which has the potential to affect marine life. Approximately 6,200 OGEP installations are presently operating in the marine environment, 65% of these are located off the coast of North America, with the Gulf of Mexico area comprising almost all of these. In terms of activity, this is followed by the Asian Pacific region, the coasts of North-West Europe, the west coast of Africa and South America.

There are several major sources of sound common in the OGEP industry, including drilling noise, platform noise (for example from FPSOs), construction noise for building and securing platforms to the seabed (for example drilling and piling), noise from pipeline laying, explosive decommissioning, and vessel noise. However, the most significant source of underwater noise within the OGEP industry is that of geophysical surveying (also called seismic surveying). Here, powerful airgun arrays are used to generate low-frequency sound pulses which penetrate the seabed and provide geological images for the purpose of oil and gas prospecting. [DECC, 2010]

OGEP industry exploration began on the United Kingdom Continental Shelf (UKCS) in 1964, and there are currently 284 UKCS installations in production [DECC, 2011]. The first platform installations were predominantly in the southern North Sea, followed later by increased activity in the northern North Sea, the Moray Firth and the Irish Sea (UK West coast). The largest increase in platform numbers occurred during the late 1980s, and most recently, activity has moved into the central North Sea and to the west of the Shetland Islands, with an increase in platform numbers between 1997 and 2007. Seismic surveys have been carried out in the North Sea since 1963, (the majority have been 2D surveys, but with 3D surveys being carried out since 1978). Effort between 1996 and 2004 was variable in seismic survey quadrants of the UK East coast, with 2000 being the least active year in terms of surveys (210 km and 463 km^2 of 2D and 3D seismic activity, 5 respectively) and 1997 being the most active when 10,705 km (2D) and 6,441 km^2 (3D) of surveys 6 were undertaken (Data from www. http://www.ukdeal.co.uk; ASCOBANS 2005). [DECC, 2010, ASCOBANS, 2005].

The UK OGEP industry is heavily regulated, with licenses required from DECC before offshore activity can begin. The licensing requirements include an environmental impact statement, but do not routinely require the measurement of radiated noise, though this can be stipulated where this is considered to be a specific issue (for example during explosive decommissioning). There are no standardized methods of monitoring the noise radiated from such activity, and “best available technologies” are typically requested. For geophysical surveying, though acoustic measurements are not routinely required, mitigation strategies are required. These can include the use of marine mammal observers, soft-starts and even passive acoustic monitoring [JNCC, 2010a].

5.4 WIND FARMS

There are a total of 28 offshore windfarm developments in Round 1 and 2 which are complete or in progress in UK waters, and with the planned increase within the nine Round 3 zones, this is likely to represent the largest engineering intervention in UK coastal waters since the peak of the offshore oil and gas industry. Offshore windfarms contribute several potential noise sources which require consideration: (i) construction noise from marine piling; (ii) noise associated with the construction process (vessel noise, etc.); (iii) operational noise. Of these, marine piling noise causes greatest concern since it consists of a high-amplitude source of noise which is impulsive and low-frequency (majority of the acoustic energy is in the frequency range 100 Hz – 1 kHz) [Madsen *et al,* 2006].

Though the allocation and franchising process for seabed leases is controlled by Crown Estate, the environmental impact assessment is required by the marine license issued by DEFRA or the relevant devolved administration (previously operated via the Food and Environmental Protection Act (FEPA)). There are two stages to this: (i) an initial planning EIS stage where an estimate must be made of the likely radiated noise levels and a mitigation strategy prepared; (ii) a second stage where monitoring of the radiated noise during piling is required (with operational noise measurements also required on occasions). Throughout the process, conformance with JNCC guidelines is expected [JNCC, 2010b]. No limits are set for the radiated noise, and instead the impact is expected to be managed using mitigation strategies such as soft-starts, marine mammal observers, passive acoustic monitoring, and acoustic deterrent devices.

The typical requirements of a FEPA licence for windfarm development require:

(i) *Measurements of the noise generated by the* *<u>installation</u>* *of foundation pieces, with measurements taken at various distances for the first few foundation pieces (minimum of four) including during the 'soft start' procedure;*

(ii) *Subsea noise and vibration from the turbines to be assessed and monitored during the* *<u>operational</u>* *phase of the wind farm.*

From 6 April 2011, under the Marine (Scotland) Act 2010 the Scottish Government is responsible for the new marine licensing system for activities carried out in the Scottish inshore region of UK waters from 0-12 nautical miles (nm). Under the Marine and Coastal Access Act 2009, they are also the licensing and enforcement authority for the Scottish offshore region from 12-200nm (other than reserved matters). The new system largely replaces Part 2 of the Food and Environment Protection Act 1985 (FEPA) and Part 2 of the Coast Protection Act 1949 (CPA).

Measuring the construction noise from marine piling is difficult due to the nature of the source and the reverberant shallow-water environment [Ainslie *et al,* 2010]. There are no standardised methods for measuring piling noise, in England and Wales JNCC recommends that "Best Available Technologies" be used. Typically, sampled measurements are made as a function of range from the driven pile to provide some empirical estimate of propagation loss [Robinson *et al,* 2009, Nedwell *et al,* 2007]. In an attempt to determine the time variation in the source output as the hammer energy is increased during the soft start, some researchers have also used fixed recording buoys to record the entire piling sequence [Robinson *et al,* 2007]. A number of studies have reported the frequency and temporal characteristics of the noise radiated during piling for windfarms [Bailey *et al,* 2010, Reinhall and Dahl, 2010, Lepper *et al*, 2009, Matushek and Betke, 2009, Lepper and Robinson, 2008, De Jong and Ainslie, 2008].

5.5 DREDGING

Marine aggregate extraction is the dredging of sand and gravel from the seabed, specifically used in the building and construction industry. It is vital to UK industry with the area of seabed dredged in 2008 being 137.9 km^2, with over 20 million tonnes of sand and gravel typically extracted per year in licensed areas around UK waters [BMAPA, 2009]. The type of vessel used for marine aggregate extraction, particularly in the UK, is the trailing suction hopper dredger (TSHD). This type of dredger lowers a drag head and suction pipe to the sea floor, in water depths of up to 50 m, to extract the sand or gravel, depositing it in a hopper on the vessel for dockside unloading. The vessel will often screen the dredged material for granular size and return the unwanted material and water over the side.

Consideration of the noise radiated during marine aggregate extraction operations has been limited. The most extensive early measurements were undertaken in the Beaufort Sea during oil exploration in the 1980's [Greene, 1985, Greene, 1987]. Other measurements have been undertaken around Sakhalin Island, reported by Ainslie *et al* [Ainslie *et al,* 2009].

In the UK, early studies were either confined to desk based activities [Defra, 2003, Thomsen *et al,* 2009] or a small number of measurements which were very limited in scope [Wareham and Roberts, 2002]. However, a recent study funded by the UK Marine Aggregate Levy Sustainability Fund (MALSF) provided more comprehensive results [Robinson *et al,* 2011]. This study adopted as a method a version of the ANSI S12.64 standard modified for shallow water. The study concluded that for the UK dredger vessels measured, source levels at frequencies below 500 Hz are generally in line with those expected for a cargo ship travelling at modest speed; source levels at frequencies above 1 kHz show elevated levels of broadband noise generated by the aggregate extraction process, with the elevated broadband noise being dependent on the aggregate type being extracted – gravel generating higher noise levels than sand. [Robinson *et al,* 2011]. These conclusions were broadly in line with those of a recent Dutch study [TNO, 2010].

5.6 CONSTRUCTION

A number of studies have reported the frequency and temporal characteristics of the noise radiated during piling for windfarms (see section 5.4) However, there are very few studies of the noise radiated by marine piling for other seabed mounted structures of the oil and gas industry [McHugh, 2005].

6. RELEVANT INTERNATIONAL STANDARDS AND AGREEMENTS

Currently there are no available international standards describing procedures for measurement of the radiated underwater noise. However, there are some national standards available, and work is underway in ISO to address some of the requirements.

6.1 ANSI

A recently published US standard is available for the measurement of noise radiated by commercial vessels in deep water: ANSI/ASA S12.64-2009/Part 1 [ANSI S12.64, 2009]. This document requires that the measurements be made in relatively deep water: a minimum depth of 75 m or one ship length, whichever is greater (though even deeper water is preferred). A feature of the ANSI S12.64 method is the measurement of the radiated noise at "beam aspect" as the vessel transits past the measurement station. The radiated noise is detected by hydrophones suspended in the water column beneath the measuring station (a survey vessel or measuring buoy). Depending on the accuracy grade required, measurements may be made with one, two or three hydrophones. The recommended measurement range from the source vessel is 100 m (or one overall ship length). The measurement data is recorded over an azimuth angular window of ±30º centred on the Closest Point of Approach (CPA). Depending on the grade of the measurement, the data window is analysed as a whole, or is divided into shorter windows of no shorter than one second length for analysis, with the data corrected for the range variation. To calculate the source level, the received levels are corrected for the range from the source using a simple spherical-spreading correction, producing a source level term described in ANSI S12.64 as the "affected source level". This parameter is related to the monopole source level but includes the effect of the reflected energy from the water surface. In effect, this is a form of dipole source level, where the vessel is being treated as a noise source in combination with its "image" in the plane of the water surface. This is the format used for most of the data for vessel noise that is available in the scientific literature.

6.2 ISO

Work being undertaken by the International Organization for Standardization (ISO) to develop standards for measurement of underwater noise. The work is underway in two separate Technical Committees: TC8 (Shipping and Maritime Technology); and TC43 (Acoustics).

In TC8, Working Group 6 of Sub-Committee 2 is developing a standard for measurement of noise radiated from commercial ships. This has reached a Committee Draft stage, but is unlikely to produce a published standard until 2012.

In TC43, work has also been proposed to set up a new Sub-Committee on underwater acoustics. Priorities for standards development include measuring marine piling noise, and it is likely that a modified version of the ANSI S12.64 ship noise standard will be published as a Publicly Available Specification by ISO.

6.3 MARINE STRATEGY FRAMEWORK DIRECTIVE

The MSFD requires Member States to put in place measures to achieve Good Environmental Status by 2020 [MSFD, 2008]. Member States are required to produce a Marine Strategy for their waters, in collaboration with other Member States in their marine region. This entails:

- *An initial assessment of the current environmental status of a Member State's marine waters (by July 2012).*
- *A determination of what Good Environmental Status means for those waters (by July 2012).*
- *Establishment of targets and indicators designed to show the achievement of Good Environmental Status (by July 2012).*
- *Establishment of a monitoring programme to measure progress toward achieving Good Environmental Status (by July 2014).*
- *Establishment of a programme of measures designed to achieve or maintain Good Environmental Status (designed by Dec 2015 and implemented by Dec 2016).*

The MSFD was fully transposed into UK law on the 15th July 2010. This put in place a clear legal framework for the implementation of the Directive by 2020. The MSFD contains 11 descriptors covering different aspects of environmental management. Descriptor 11 requires that "Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment". Descriptor 11 contains two indicators: [Tasker *et al,* 2010]

11.1 Distribution in time and place of loud, low and mid frequency impulsive sounds

"Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1μPa^2·s) or as peak sound pressure level (in dB re 1μPa$_{peak}$) at one metre, measured over the frequency band 10 Hz to 10 kHz."

11.2 Continuous low frequency sound

Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate.

Currently, the EU has set up a working group to provide guidance on the implementation of the indicators, and Regulators are working on how to implement the Directive within the UK. With regard to marine renewable energy devices, indicator 11.1 is likely to be relevant only if the construction or positioning of the devices requires the use of techniques such as marine piling which are sources of loud impulsive low-frequency noise. In this case, the construction may fall under the management process under development by Regulators to limit the number of days per year during which such activity may take place. It is unlikely that indicator 11.2 will be relevant unless there are loud sources of continuous low frequency noise which would raise the annual averages in specific areas.

6.4 OSPAR

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the "OSPAR Convention") is a legal instrument guiding international cooperation on the protection of the marine environment of the North-East Atlantic. The Convention entered into force on 25 March 1998. It has been ratified by Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Sweden, Switzerland and the United Kingdom and approved by the European Community and Spain. Work under the Convention is managed by the OSPAR Commission, made up of representatives of the Governments of 15 Contracting Parties and the European Commission, representing the European Union.

OSPAR assists in the sharing of knowledge and understanding between Contracting Parties and other international organisations (for example International Maritime Organisation), and the coordination of data and measures specific to the OSPAR regions (reported via Quality Status Reports (QSR). A number of reports have been issued by OSPAR as part of their Biodiversity Series which summarise knowledge with regard to the impact of noise on the marine environment [OSPAR 2009a, OSPAR 2009b]. Specific summary reports have been issued covering the impact of offshore windfarms [OSPAR 2008], and other marine renewable energy devices [OSPAR 2006]. The latter report is of particular interest, though it is now five years old and does not contain the latest information.

6.5 OTHER RELEVANT STANDARDS

There are two other standards relevant to this report, both of which are related to the noise radiated by ships.

The ICES:209 report was produced by the International Council for Exploration of the Sea and describes the criteria for radiated noise levels which must be achieved by vessels used as research vessels, specifically those used in fisheries acoustics. The report provides a target source level spectrum which has been cited by a number of other researchers as criteria for a vessel to be regarded as quiet. However, the report does not describe a measurement method [ICES, 1995].

A Norwegian standard has also been produced by Det Norske Veritas: DNV Rules for classification of ships, part 6 chapter 24: Silent Class Notation. [DNV, 2010]. As with ICES 209, the aim of this document is to set the criteria for maximum allowable noise levels for various operations, in this case by seismic, fisheries and research vessels. However, this document does give a brief description of a test procedure in an appendix. The procedure requires a minimum water depth of 30 m and hydrophone ranges of between 150 m and 250 m. The data is recorded over 30 second windows with 10 second windows used for range correction. The propagation correction is achieved with very simple geometric spreading laws.

6.6 UK REGULATIONS

Under regulation 39 of the Offshore Marine Conservation (Natural Habitats etc.)(Amendment) Regulations 2009, regulation 39 of The Conservation (Natural Habitats, &c.) Amendment (Scotland) Regulations 2007, and Regulation 41 of the Conservation of Habitats and Species Regulations 2010 (which apply in inshore waters in other parts of Great Britain) it is an offence to deliberately capture, kill or injure, to deliberately disturb animals of European Protected Species, which includes all species of cetaceans, the Atlantic sturgeon and turtles occurring within EU waters.

> *A person is guilty of an offence if he —*
> *"(a) deliberately captures, injures, or kills any wild animal of a European protected species;*
>
> *(b) deliberately disturbs wild animals of any such species*
>
> *For the purposes of paragraph (b), disturbance of animals includes in particular any disturbance which is likely:*
>
> *(a) To impair their ability*
>   *(i) to survive, to breed or reproduce, or to rear or nurture their young*
>   *(ii) in the case of animals of a hibernating or migratory species, to hibernate or migrate;*
>
> *or*
>
> *(b) To affect significantly the local distribution or abundance of the species to which they belong."*

Draft guidance on implementation of these regulations in English and Welsh waters has been provided by JNCC [JNCC, 2010a & 2010b] for other marine operations.

In Scottish waters under the Marine (Scotland) Act 2010 the Scottish Government is responsible for the new marine licensing system for activities carried out in the Scottish inshore region of UK waters from 0-12 nautical miles (nm) effective from 6 April 2011. Under the Marine and Coastal Access Act 2009, they are also the licensing and enforcement authority for the Scottish offshore region from 12-200nm (other than reserved matters) [The Scottish Government, 2011].

"The EU Council Directive 85/337/EEC requires an Environmental Impact Assessment (EIA) to be carried out for plans or projects. This requirement has been transposed into Scottish law. An EIA is used as a means of drawing together, in a systematic way, an assessment of a project's likely significant environment effects." [Marine Scotland, 2011]

When an EIA is required, three processes are to be carried out:

(a) "The developer must compile detailed information about the likely significant environmental effects. To help the developer, public authorities must make available any relevant environmental information in their possession. The developer can also ask MSLOT for their opinion on what information needs to be included. The information finally compiled by the developer is known as an 'Environmental Statement' (ES)."

(b) "The ES must be publicized. Public authorities with relevant environmental responsibilities and the public must be given an opportunity to give their views about the project and ES."

(c) *"The ES, together with any other information, comments and representations made on it, will be taken into account by MSLOT (The Scottish Government Licensing Operations Team) in deciding whether or not to give consent for the development. The public must be informed of the decision and the main reasons for it."*

Activities requiring a Marine Licence under these Acts include:

- Coastal and marine developments
- Windfarms
- Wave and tidal power
- Removal and disposal of marine dredged material at sea

7. SUMMARY

This report provides a summary of the background data review conducted related to the development of an underwater noise assessment measurement methodology at the EMEC wave energy test site.

These data include review of current and previously conducted acoustic research used at wave energy sites both UK and internationally. Very little acoustic work has to date been conducted on wave energy systems with virtually no data in the open domain. This lack of baseline and variety of potential system types is likely to require flexibility in the development of any measurement methodology.

To supplement this data underwater noise assessment methodologies in other marine operation have also been reviewed and where appropriate lessons learned will be used to inform the development of the wave energy measurement methodology. These operations include, military, marine piling, dredging *etc*. Also related standards both from UK and internationally have been considered as well as regulator recommendations as appropriate. These include ISO and ANSI shipping measurement standards under development and regulatory guidelines from OSPAR, Marine strategy Framework, UK regulation, *etc*. The later guidelines and regulations are likely to directly inform current and future Environmental Impact Assessments for wave Energy System developers at the EMEC and other sites and therefore any developed measurement methodology must provide appropriate metrics and data to full fill these requirements.

In view of potential biological impacts an extensive review of potential marine mammal receptors and abundance at the EMEC wave energy site has been conducted. These data and survey of physiological and behavioural response of other marine species have been used to inform the measurement methodology development process. All these data will be used to inform any developed methodology with influences including:

- Regulator and licensing requirements
- Source characteristics
- Hearing and sensitivity of likely receptors
- Impact criteria (measurement metrics SEL, peak, RMS etc.)
- Frequency bands and dynamic ranges of sensors requirements
- Spatial distribution of sensors (received levels, source levels)
- Temporal variation in source (system operational status)
- Weather / oceanographic conditions
- Practicality and cost
- Safety

8. GLOSSARY

ANSI	American National Standards Institute
CORES	Components for Ocean Renewable Energy Systems (CORES) project. Currently on-going under FP7, and aims to develop new components and concepts and to test them on an offshore platform in order to create a model based on reliable data stemming from these tests
DECC	Department of Energy and Climate Change (UK)
DEFRA	Department for Environment, Food and Rural Affairs (UK)
EIA	Environmental Impact Assessment
EMEC	European Marine Energy Centre, located in Stromness, Orkney, Scotland.
ES	Environmental Statement
FEPA	Food and Environmental Protection Act
FPSO	Floating Production Storage and Offloading platform used in the Oil and Gas offshore industry
EQUIMAR	EQUItable comparison of MARine devices. Equimar is an EU-funded project with more than 60 developers, academics, engineers and conservationists from 11 countries working together to produce one set of protocols or guidelines against which every device can be measured.
FFT	Fast Fourier Transform
ICES	International Council for Exploration of the Sea
ISO	International Organization for Standardization
JASCO	JASCO Research is an international company providing consulting services to the Marine Industrial, Oceanographic, Oil & Gas, Fisheries, Defence and IT sectors.
JNCC	Joint Nature Conservation Committee
MALSF	Marine Aggregate Levy Sustainability Fund
MEDIN	Marine Environmental Data and Information Network. MEDIN is a partnership of UK organisations committed to improving access to marine data. MEDIN sits alongside its sibling working group the Underwater Sound Forum (USF). Both groups report directly to the Marine Science Coordination Committee (MSCC)

MSLOT	The Scottish Government Marine Scotland Licensing Operations Team
NaREC	Independent company involved in all aspects of the marine technology development process
NPL	National Physical Laboratory
NNMREC	Northwest National Marine Renewable Energy Center
NOAA	National Oceanic and Atmospheric Administration
OGEP	Oil and Gas Exploration and Production Technologies.
OSPAR	OSlo-PARis Convention. OSPAR is the mechanism by which fifteen Governments of the western coasts and catchments of Europe, together with the European Community, cooperate to protect the marine environment of the North-East Atlantic
OSU	Oregon State University
OTEC	Ocean Thermal Energy Conversion
OWET	Oregon Wave Energy Trust
PRIMaRE	Peninsula Research Institute for Marine Renewable Energy
RMS	Root Mean Square
SEAI	Sustainable Energy Authority of Ireland
SMRU	Sea Mammal Research Unit, St Andrews, Scotland
SMRU Ltd	A company set up to make the expertise of SMRU (the Sea Mammal Research Unit at St Andrews University) available to industry, their advisors and Regulators to address challenges related to environmental regulations concerning marine mammals
TSHD	Trailing Suction Hopper Dredger
UKCS	United Kingdom Continental Shelf
UKHO	UK Hydrographic Office, located at Taunton. UK.
UW	University of Washington
WAVEPLAM	WAVe Energy PLAnning and Marketing project. WAVEPLAM aims to develop tools, establish methods and standards, and create conditions to speed up the introduction of ocean energy onto the European renewable energy market.

WEAM	Wave Energy Acoustic Monitoring
WEC	Wave Energy Conversion
XBT	Expendable Bathythermograph, dropped from a ship and measures the temperature as it falls through the water
Zero-peak	Maximum signal amplitude positive or negative from the at rest zero mean position.

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SECTION 2:

PROVISIONAL MEASUREMENT METHODOLOGY

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1 INTRODUCTION

This methodology has been produced by a consortium of Loughborough University, the National Physical Laboratory and Chickerell BioAcoustics. The work is part of a contract from the European Marine Energy Centre (EMEC), Orkney, Scotland. The aim of this document is to set out a provisional methodology for characterising the sound field around wave generation systems installed at the Billia Croo Wave Test Site that can be used by EMEC and developers to assess the noise field around such devices.

This methodology has been based on the following work also carried out as part of the contract with EMEC:

- A review of current and developing UK and European guidelines has been carried out to ensure collected data falls in line with current and possible future requirements of the consenting processes followed by the developers and EMEC
- Identification of the marine receptors likely to be present at the EMEC wave test site and the particular characteristics of sounds that are likely to affect them
- A review of appropriate current and developing measurement standards and methodologies for the sound output from other marine activities such a shipping, dredging etc

The proposed methodology will be tested as operational devices become available and will be revised in the light of experience gained from measuring such systems.

2 RATIONALE

The current guidelines/regulations typically require that developers produce an Environmental Impact Assessment (EIA) to determine the potential impact on key marine species. Within the UK JNCC currently recommends the use of impact criteria such as that proposed by Southall *et al*, 2007 for marine mammals. This practice is becoming widely established *e.g.* Round 3 wind farm development.

Various other criteria exist in European countries such as Germany and the Netherlands. In addition, the developing Good Environmental Status (GES) indicators are being produced under EU regulations.

All of these criteria have common features. Typically the process involves initial assessment of the sound field in the vicinity of a noise-generating system using a variety of metrics. These levels are then compared with pre-defined impact thresholds and appropriate mitigation actions set out if they are required.

The EIA process often requires prediction of likely sound fields in advance of system construction. The actual sound levels at a fixed distance from a source are likely to be dependent on the source characteristics and the local acoustic environment. The acoustic environment depends on bottom topography, seabed type, water depth, water properties and sea state. Sound propagation can be very complex in shallow waters because of interactions with the sea surface and seabed and within the water column. In order to predict the sound field we need to understand the characteristics of the sound source and then use propagation models to predict the likely sound field around an operational generation system.

This proposed methodology aims to provide the means of measuring the sound field at various distances away from the source in order to estimate the sound source characteristics to allow modelling of the sound field at other ranges.

In order to determine the sound source characteristics an assessment of the propagation loss between the sound source and the measurement location is needed. The sound source characteristics, perhaps encapsulated into a broadband or frequency dependent source level, need to be described as independently of the environment as possible. To do this the methodology used allows capture of data on identical bearings but varying ranges. However the potential exists for system noise to be below ambient levels at longer ranges needed due to safety considerations potentially limiting determination characteristics at the source. This data however is still useful to determine that noise levels at these ranges are below background levels and will add significantly to the understanding of the source acoustic output.

3 DEVICE CONSIDERATIONS

In the review of current and developing wave renewable energy systems a number of key characteristics have been identified and are listed below. The wave devices generally fall into two classes: mobile and static. Mobile systems are usually of the attenuator[2] type *e.g.* Pelamis, which need to align themselves with the prevalent wave direction. Static devices include point absorbers, oscillating wave surge converters *e.g*. Oyster, oscillating water column devices and submerged pressure differential devices. Note that this methodology is not suitable for overtopping devices which will need a specific methodology for each site.

The two classes of devices differ in a number of key features:

- *Position*
  - The mobile type of system usually rotates in a circle around a single mooring point depending on the tidal flow and direction and strength of waves and wind.
  - The static type of system is usually on a fixed, stationary foundation and is not free to change position.
- *Directivity*
  - A mobile system is likely to have a sound field that is axis-symmetric in elevation. The sound field may change along its length. Any directionality will be averaged out in time as the device will lie at a number of angles. There may also be noise generated by the mooring system.
  - A static system is generally operated fixed in orientation. Any directionality will be fixed relative to the seabed, although it may be modified by any vertical movements associated with the operation of the device.
- *Operational mode*
  - Both classes of system involve significant mechanical movement which is translated to electrical energy through a number of possible processes. These processes may generate noise. There may be additional noises peripheral to the energy generation method associated with mechanisms such as wave slap *etc*. It is likely that these noises will be dependent on sea state and tidal conditions.

Because of these differences two methodologies are proposed. The intention is to capture similar datasets to allow direct comparison between generation systems. The methods

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[2] See the EMEC website www.emec.org.uk/wave_energy_devices.asp for a definition of the different types of wave generator.

proposed allow for a range of operational states to be measured to provide as full a characterisation of the noise field as possible.

4 METHODOLOGY

4.1 METHOD 1: MOBILE SYSTEMS

A mobile system will generally swing in a circle from a single point mooring as the tide, wave and wind directions change. This will be referred to as the watch circle.

Figure 1 illustrates a plan view of the proposed measurement methodology. The system will move within the watch circle but will generally have preferred directions determined by the tidal flow. The proposed methodology deploys a number of recorders to capture the sound field while the unit is located at one of these preferred directions and is likely to be reasonably stable in position for up to half a tidal cycle. The recorders will be autonomous recording hydrophones and will be acoustically isolated from the surface to minimise the effects of surface interaction noise. They will be deployed outside of the watch circle to avoid any danger of entanglement as the generation system moves around the watch circle.

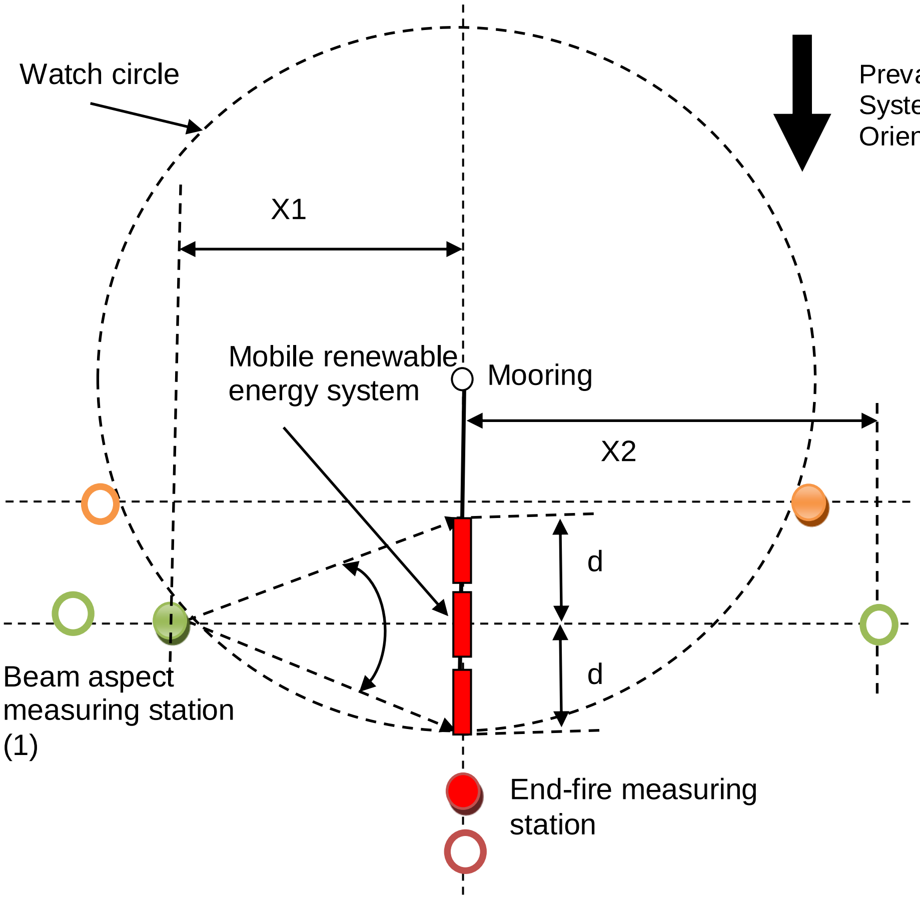

Figure 1: Plan of proposed mobile system measurement methodology. The dashed circle line (watch circle) shows trajectory of a moored system and circles indicate proposed positions of hydrophones.

Depending on the number of hydrophone units available the recommended choice of locations will be:

Three hydrophones:	Red and (solid and either open green positions) green positions
Four hydrophones:	Red, green (solid and either open green positions) and opposite orange position
Five hydrophones:	Both Red, green (solid and either open green positions) and one orange position

The aim is to measure at least the beam and end-fire aspect noise levels. In order to better understand source characteristics a determination of the local propagation conditions is also required. In the case of the beam aspect two options are proposed. Either an additional hydrophone station on the opposite side (shown in figure 2) and at a different range, or on an orthogonal transect on the same side (both options shown as the open green circles). Similarly two stations at differing range from the prominent end-fire position will allow local propagation conditions to be estimated. The addition of the orange hydrophone stations will also allow a greater range of aspect angles to be measured. It is anticipated that the system will not always lie along the anticipated radial of the watch circle and will swing depending on the tidal state and wind strength and direction. This movement will allow the fine detail of the radiation pattern to be explored and angular averaging should be possible. It is proposed that in initial trials a combination of these deployments will be used to best determine optimum configuration which will be dependent on system noise levels, directivity, array position *etc*.

It is essential that the system developer makes available the actual location(s) of the generation system during the measurement period. This is required to allow the exact aspect to be determined in order to investigate the radiation pattern. It will also be needed to accurately determine range when using the propagation models to estimated the source level of the radiated noise.

Figure 2 shows a vertical section of the optimum beam aspect position.

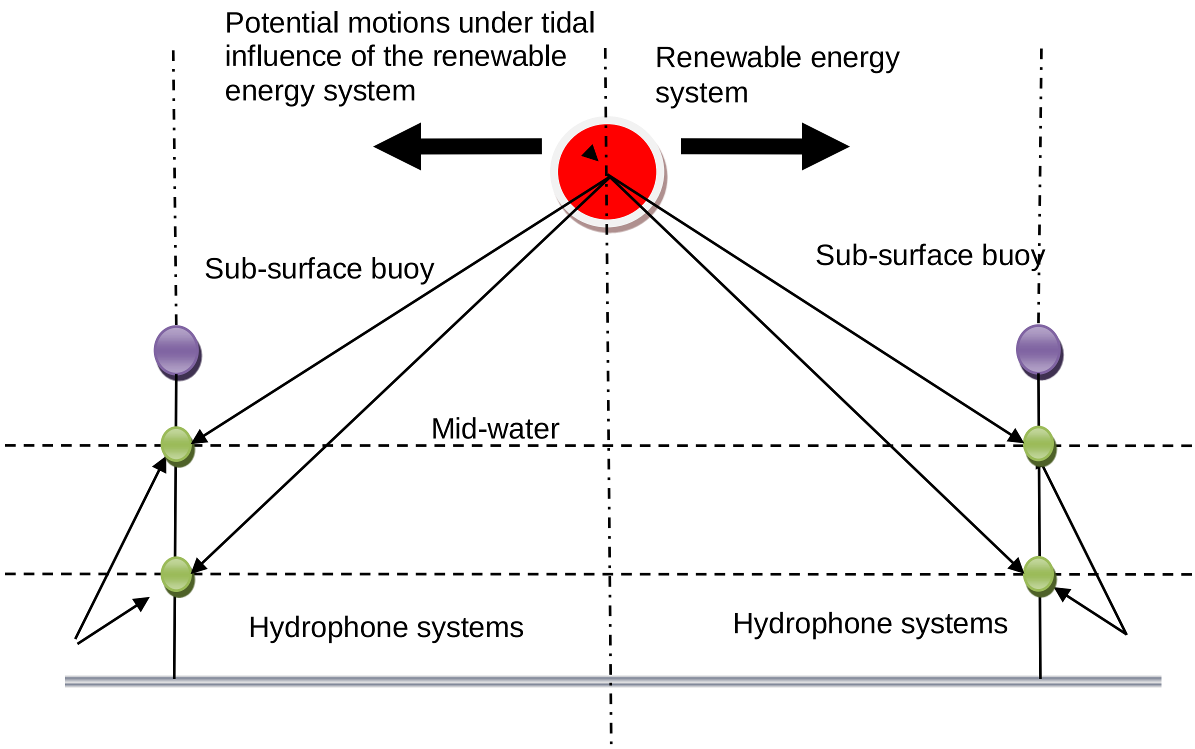

Figure 2: Cross section at beam aspect

This shows the deployment of two hydrophone units in the green positions of figure 1. In each case the units use two hydrophones mounted one above the other and kept in position by a sinker and a sub-surface buoy. Depending on the autonomous hydrophone unit chosen there may be one or more hydrophone channels. A single hydrophone should be deployed at mid-water depth. If additional hydrophone channels are available then these should be distributed evenly through the water column. Additional hydrophones will allow the vertical radiation pattern to be explored and the source level of the radiated noise to be better estimated.

Note that for safety reasons this methodology uses hydrophones deployed outside of the watch circle. There is a possibility that noise levels may be too low to be heard above the background levels. Under these circumstances the hydrophone units will need to be redeployed within the watch circle. This could be achieved by using a deployment method that has no surface presence and will require the use of acoustic releases. However, moving the measuring hydrophone too close to the sound source may put it into the near field of the sound source making source level estimation more difficult.

One of the difficulties may be characterising noise from the mooring system and wave impact noise on the generation system. The orange positions in figure 1 will give the best sample of this noise, but the increased range resulting from the requirement to stay outside of the watch circle may give insufficient signal/noise ratio for this to be possible. Using the alternative deployment method to allow the hydrophone to be moved inside the watch circle will help, but under no circumstances can the deployed hydrophone be moved closer than the radius of the potential motion of the system or moorings to avoid possibility of fouling.

4.2 METHOD 2: STATIC SYSTEMS

Static generation systems are usually fixed to the sea bed and although there may be moving parts, they will move within a predictable and small volume. This allows the hydrophones to be deployed closer than in the case of mobile systems.

The proposed methodology assumes deployment of up to five hydrophone units around the generation system. It is recognised that this may not always be possible due to seabed instrumentation and cabling in use by the developers. Assuming that four hydrophones are possible the aim is to deploy the hydrophones around the unit on orthogonal axes (see figure 3). Depending on the size of the generation system, care will need to be taken to avoid near-field effects. Factors such as water depth and noise levels will lead to a choice of offset distances X1, X2, Y1 and Y2 as depicted in figure 3. Each of the hydrophone positions may have one or more hydrophones in a vertical column. Multiple hydrophones sample the vertical distribution better than a single hydrophone and provide a better average of the sound field. It is recognised this may not be possible depending on the depth of water around the unit. High frequency measurements can be made with either fixed hydrophones or a drifting buoy unit/small boat deployment. Where possible the developer should be encouraged to fit a hydrophone system as part of their instrumentation package so that extended timelines of radiated noise can be obtained. This will allow the detailed characterisation to be placed in the context of the extended timeline from the developer's hydrophone.

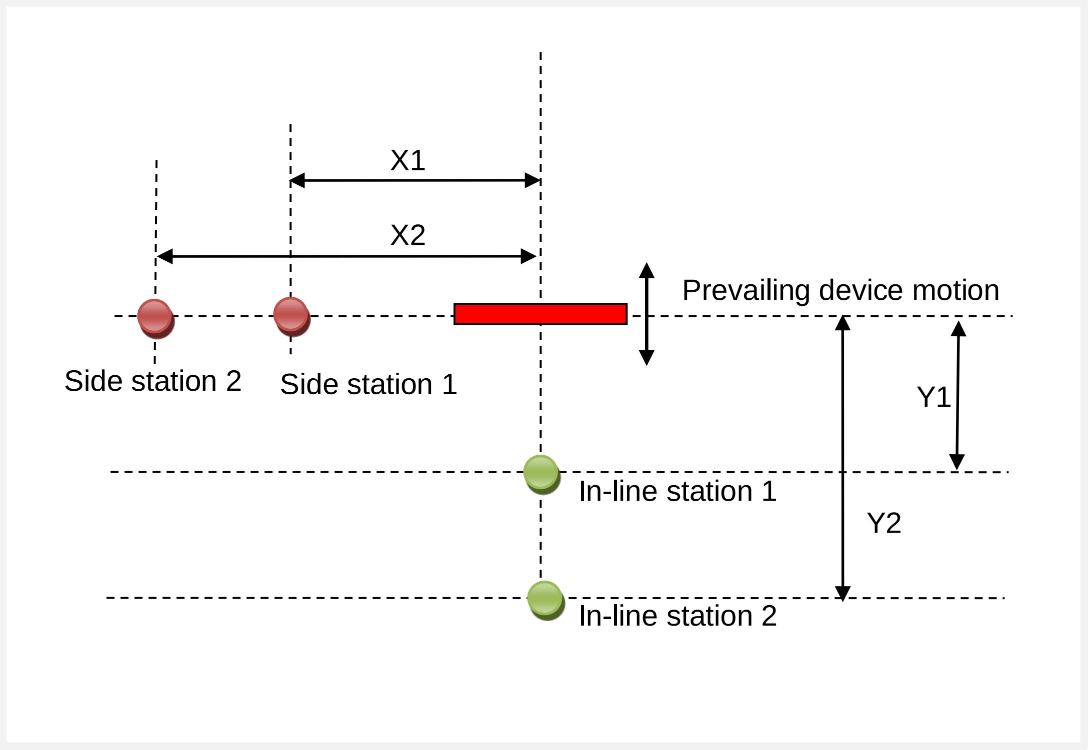

Figure 3: Plan of proposed static system measurement methodology.

5 RECORDING DURATION AND BANDWIDTH

The use of autonomous recording hydrophones allows much longer deployments than the use of manned hydrophone systems. This will allow data to be collected covering multiple tidal cycles and varying wind and wave conditions. They will also allow data to be collected under high sea state conditions when manned data collection would not be possible.

One of the problems of extended deployment periods is that of data storage. For a given amount of memory this can either be used for high bandwidth/short record time or low bandwidth/high record time applications. It is relatively easy to achieve 32 gigabytes of storage using current memory cards. At 24 kHz bandwidth and two channels of data this will give just over 2 days of record time. By using specially designed recorders this could be increased to 128 gigabytes giving over 8 days of continuous data.

The highest frequency used by a potential marine receptor is around 150 kHz. If we record a single channel with a bandwidth of 192 kHz then the 32 gigabyte system would record for just over 12 hours. Another problem with measuring the higher frequency content is the increasing attenuation at higher frequencies resulting in a need to record closer to the generation system. The only solution to this may be to use a surface deployed hydrophone either from a boat or from a buoy that drifts past the generation system.

Using a drifting hydrophone in conjunction with a long term bottomed deployment will put the surface measurements in to the context of the extended dataset from the bottomed recorders.

6 NON-ACOUSTIC DATA

In addition to the above acoustic measurements as much as possible of the following data also needs to be collected while recording acoustic data:

- GPS positions of all recorders and sound sources
- Wave height, period and direction
- Wind speed and direction
- Precipitation
- Shipping movements within acoustic range of the test site
- Sound velocity profiles (carried out periodically)

7 DATA PROCESSING

The overall aim of the measurements is to provide information on the following device characteristics:

- Variation of sound level with frequency
- Variation of sound level with bearing
- Variation of sound level with wave height
- Attempt to identify dominant sound sources
- Absolute levels of sound put into the water

The subsequent analysis of collected data will use optimised processing routines within packages such as MATLAB and LABVIEW to achieve these aims.

Data collected will ideally be in the form of continuous (or suitably duty-cycled) long term sound recordings of sufficient bandwidth. All system hydrophone sensitivities and electronic gains will be fully calibrated both before and after deployment and where possible *in situ* calibration tones will be used. Recording systems should be synchronized to GPS accuracy before deployment and re-checked after retrieval. Data should be stored in a lossless format such as 'wav' file.

7.1 BROADBAND DATA ANALYSIS:

The intention as outlined above is to provide data suitable for sound field estimation. To this end various processes and metrics should be estimated. In the case of potential impact studies, such as that proposed by Southall *et al.* 2007, various metrics are required. These include peak (maximum zero-to-maximum positive or maximum zero-to-negative excursion) in dB re 1µPa and Sound Exposure Level (SEL) dB re 1 μPa^2s. In the case of SEL it may be used both for short term transients and for more stable exposure signals. In either case the integration period and bandwidth should be stated. For transient or pulse-like signals a 90% energy criteria is proposed and for more stable SEL measurements one second integration time will be used as suggested by Madsen, 2005. Additional other commonly used metrics for impact criteria include RMS where again bandwidth and integration period must be stated [Madsen, 2005].

7.2 SPECTRAL ANALYSIS:

Various spectral analysis techniques are proposed, these are chosen to provide time-frequency analysis both for long term data trends and analysis of short term 'event' signals. In the case of data sets of <24 hours duration long term spectral averaging (LTSA) is proposed. In this case linear FFT analysis will be performed and the resulting spectra averaged over 60 second periods. For longer data sets the averaging window may be extended to 10 minutes. Data within that period will be spectrally averaged using a Welch average technique. These data will then form linear time versus frequency plots. In addition, averaged third octave band (TOB) analysis will be used, again averaged across 1 minute or 10 minute windows, and results given either for specific frequency bands or a combined frequency versus time plots. All absolute level plots will be corrected for system sensitivities and windowing functions used.

For long term broadband noise sources power spectral density (PSD) will be determined. Data will be described as a spectral density using dB re 1 $\mu Pa^2/Hz$. In the case of tonal components they will be described as spectral levels using dB re 1 µPa. For short term 'events' both spectral density and spectral level will be used as appropriate for broadband and tonal signals respectively. Un-averaged third octave band analysis may also be used as appropriate but again the integration period must be stated.

7.3 DATA PROCESSING METHODOLOGY

The flow chart shown in figure 4 outlines the proposed data analysis methodology.

The long term spectral averaging will be carried out first and used to identify time variant / stable noise characteristics and interesting specific noise events. These events will then be analysed in turn using either power spectral density, spectral level or third octave bands analysis and correlated where possible with known device status, weather conditions *etc.* Using these data and propagation loss modelling, source characteristics can then be estimated.

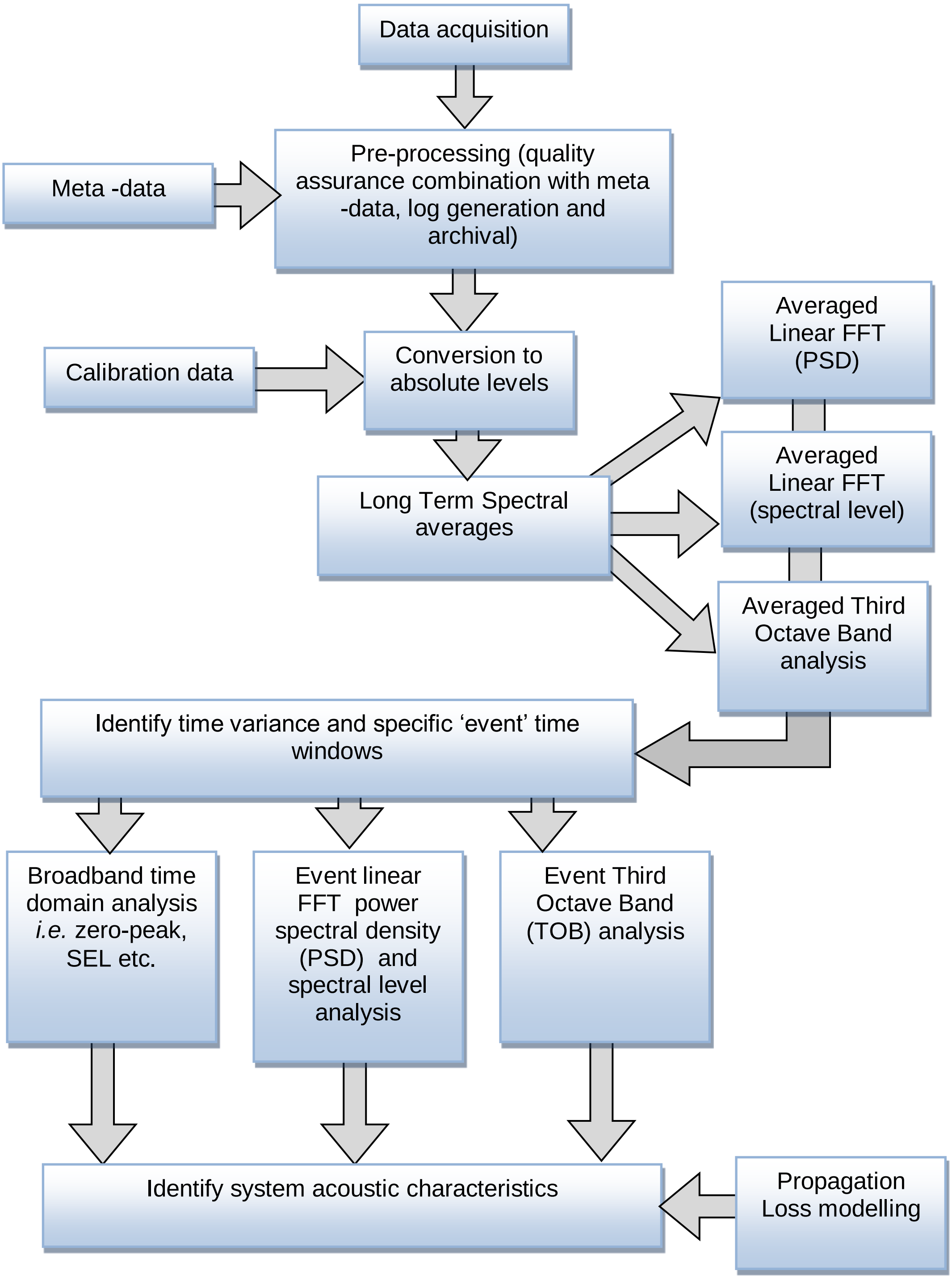

Figure 4: Proposed data analysis process

8 CONCLUSIONS

Methodologies for measuring underwater noise output from wave energy converters have been developed. These acoustic noise measurement methodologies have been proposed for two general classes of wave energy convertor device that may be present at the EMEC site: mobile systems and static systems (fixed position but distributed throughout the water column). Both methodologies employ the use of long term recording systems designed to assess long term variance in acoustic output due to device operation status, weather, tidal conditions *etc*. Multiple recording systems will be deployed at different ranges on single transects for the device to allow assessment of local propagation loss conditions, and therefore estimate ‘at source’ absolute levels. In addition, multiple aspect angles of the systems will be measured simultaneously to assess potential directivities of the source. It is identified that long term recordings at the complete hearing bandwidth of all potential receptors (~150 kHz) is often a limited compromise of bandwidth versus record time. It is anticipated that the majority of signals of interest will be for frequencies below 48 kHz (with higher frequencies more highly attenuated with range). Several systems exist that can be used to make continuous recordings at these lower bandwidths for periods of days to allow assessment of long term operational and environmental noise variation. However it is also felt important to sample higher bandwidth (up to 150 kHz) at regular intervals. In this case two technical solutions are proposed these include bottom mounted high-bandwidth recorders with a suitable duty cycle and/or the use of wide bandwidth ‘drifting systems’. Either solution can be used simultaneously with a longer term recording system to augment long term data sets with sampled wideband data.

A provisional data processing protocol is outlined based on likely signal types and data requirements for system noise assessment. This is designed to provide a comprehensive analysis of the system acoustic output in a variety of operational modes leading to suitable data for future impact assessments.

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SECTION 3:

ACOUSTIC BASELINE MEASUREMENT

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1 INTRODUCTION

This background noise assessment of the EMEC wave site has been produced by a consortium of Loughborough University, Chickerell BioAcoustics, the National Physical Laboratory and SMRU Ltd. The work is part of a contract from the European Marine Energy Centre (EMEC), Orkney, Scotland. The aim of this document is to set out the methodology used and present results of the noise field assessment of the Billia Croo wave test site.

The site itself is used as a test centre for wave energy converter (WEC) systems with a variety of seabed hubs for device deployment and testing. A noise contribution across the site prior to device installation is required to inform the regulatory process for the installation and operation of WECs. This assessment will also inform the development of an underwater noise measurement methodology to be developed under contract by the above partners for WEC operation noise characteristics and forms part of a number of on-going acoustic research programmes taking place at the four EMEC test sites.

The wave test site itself is an open sea-way with maximum water depths of 60-70 m leading up to the beach at Billia Croo. Background noise contributions are likely from a wide variety of sources including sea-state / weather variation, site mooring systems, boat traffic, etc, and as such are likely to be highly variable both temporally and spatially. The measurement methodology and subsequent data analysis used was designed to allow assessment of spatial and temporal variations in noise levels across the site. Data included in this assessment comes from three measurement trials conducted in June and July 2010 and May 2011.

2 MEASURMENT METHODOLOGY

2.1 EQUIPMENT SPECIFICATIONS, DEPLOYMENT AND DATA COLLECTION

Underwater sound data were collected using (i) autonomous recording units and (ii) cabled hydrophones deployed from a vessel.

Longer-term data collection was made using acoustic recorders on seabed mounted frames. Each frame consisted of a steel tripod with a cross-strut at the base to hold the frame rigid. A hydrophone was mounted at the centre of the frame using nylon rope secured between the top (apex) and bottom strut of the frame, in such a way that it would be suspended in the water without direct contact with the frame or surrounding apparatus. Watertight autonomous recorders were used with each frame to house the recording equipment and electronics. The height of the frame apex was 1.2 m with the triangular base 1.5 m length sides. Figure 2-1 a) shows four frames on Flamborough Light ready for deployment. Figure 2-1 b) shows the autonomous DAQ system and hydrophone on an individual frame.

Figure 2-1a): Assembled frames housing DAQ pod and hydrophone on board, with anchor and weight ready for deployment.

Figure 2-1b): Autonomous DAQ and hydrophone on board mounted on seabed frame.

Each recording pod contained an M-Audio Micro Track (Avid Technology, Inc., Burlington, MA, USA) digital recorder, battery power supply and a specially designed pre-amplifier circuit with adjustable gain. The three assembled frames were labeled A, C and D and consisted of the following equipment: frame A housed a SRD Ltd, HS70 hydrophone ('H7', sensitivity at 500 Hz -199.5 dB re 1 V µPa^{-1}) 0.82 m from the seabed, Micro Track II recorder with 32 GB card and pre-amp gain setting of 26 dB. Frame C housed a SRD Ltd, HS70 hydrophone ('H6', sensitivity at 500 Hz -199.5 dB re 1 V µPa^{-1}) 0.82 m from the seabed, Micro Track II recorder with 32 GB card and pre-amp gain setting of 26 dB. Frame D housed a SRD Ltd, HS70 hydrophone ('H3', sensitivity at 500 Hz -197.8 dB re 1 V µPa^{-1}) 0.53 m from the seabed, Micro Track I recorder with 64 GB card and pre-amp gain setting of 26 dB.

In addition to the frame recording units, an autonomous Sub-Surface Buoy (SSB) was also used to gather shorter periods of data in various locations. The SSB consisted of two identical SRD Ltd, HS70 hydrophones (sensitivity at 500 Hz -199 dB re 1 V µPa^{-1}), mounted on rope and suspended approximately 3 and 5.5 m from the seabed by a marker buoy and float. Figure 2-2 shows a schematic of the deployment configuration.

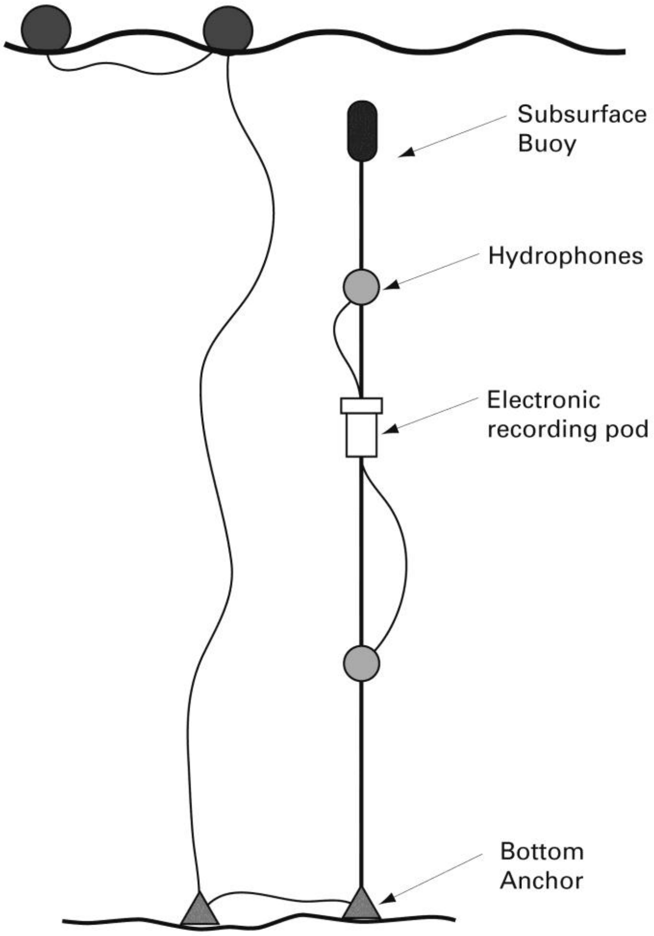

Figure 2-2: Sub-surface buoy (SSB) configuration used for short duration deployments.

Hydrophones were connected to an autonomous recorder unit that recorded from both hydrophones simultaneously. The recorder unit used had an overall system sensitivities of 174 dB re 1 V µPa^{-1} and 151 dB re 1 V µPa^{-1} for a 'inner site' recordings.

A further data collection system was employed, directly collecting data from hydrophones deployed over the side of the boat (Figure 2-3). This was achieved using either a pair of low noise Reson 4032 hydrophones and or a RESON 4032 and a broadband Reson 4014 hydrophone. These were connected via a pre-amplifiers to a National Instruments USB DAQ system (NI USB-6251) directly to laptop hard drive using bespoke Labview software. The DAQ system has a maximum aggregate sample rate of 1.25 MSs^{-1} to a 16 bit resolutions allowing data acquisition on up to three simultaneous channels to a 150 kHz bandwidth or a 500 kHz bandwidth on a single channel. All systems were battery powered eliminating the need for generator power during noise measurements minimising both acoustic radiated noise from the vessel and electronic interference. All hydrophones used were calibrated to traceable National standards by the National Physical Laboratory across the frequency band of interest.

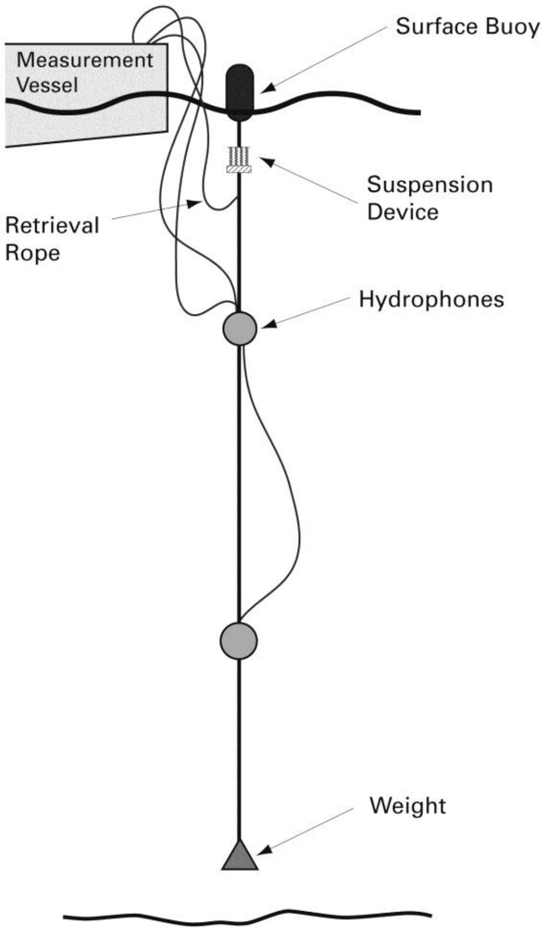

Figure 2-3: Boat-based broadband hydrophone deployments

Figure 2-4: Boat-deployed hydrophones (RESON 4032) ready for deployment.

Deployment and boat-based measurements were made from the local vessel the Flamborough Light. She is a 19 m wooden ex-scalloper based out of Stromness shown in figure 2-5. Vessel and crew are regularly used for deployment work at both the EMEC and wave site. The Flamborough Light has a large open back deck ideally suited to hydrophone and frame deployment. During boat based work the vessel is allowed to drift 'silent' with all generators, and engines off.

Figure 2:5: Deployment vessel the Flamborough Light

2.2 DEPLOYMENT

The location of acoustic system deployment sites around the study area are shown in figure 2-6). Locations were marked manually using GPS. Prior to deployment, rope was affixed to the apex of the frame and the frame then lowered to the seabed. This was then followed by a 15 kg anchor and a smaller (10 kg) purse weight. Lastly a lifting line was affixed to a marker buoy and float to mark the location of the frame on the surface and facilitate retrieval. Frames were left on the seabed and continuously recorded data up to storage capacity before retrieval. Frame A was deployed at 13:21 on the 26th July 2010 to the north of the site, frame C was deployed at 13:36 on the 26th July 2010 to the west of the site and frame D was deployed at 13:47 on the 26th July 2010 to the south of the site.

SSBs were deployed at two locations within the study site and two additional inner locations, figure 2-6. These were left to record for 2-4 hours before retrieval and were deployed at 10:10 on the 27th July 2010 (east SSB), 09:40 on the 28th July 2010 (inner site 1), 13:30 on the 28th July 2010 (inner site 2) and 09:30 on the 29th July 2010 (south SSB).

Boat deployments took place on the 27th July 2010 between 9:54-12:58, 28th July 2010 between 11:29-14:36 and 29th July 2010 between 10:07-11:24. During these periods, the engines and generator of the *Flamborough Light* were switched off so as to reduce contribution to background noise levels.

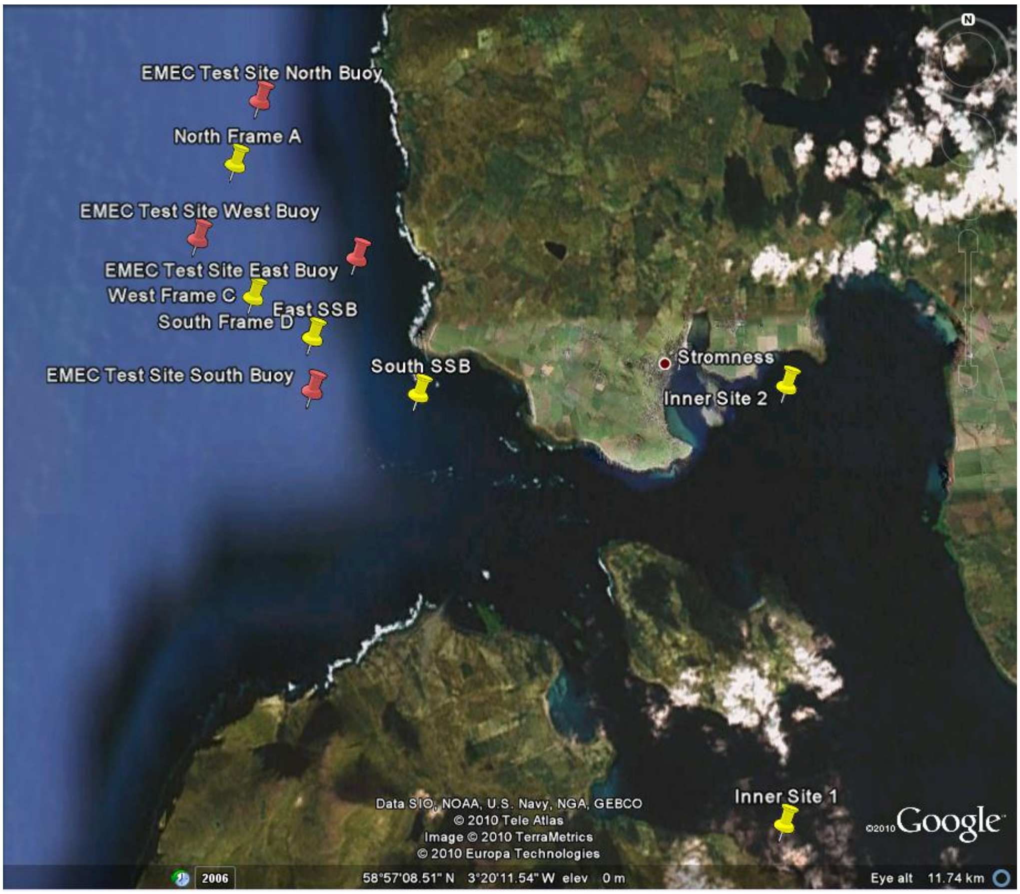

Figure 2-6: EMEC trial buoy locations (Note that data collection was carried out before the buoyage was amended in 2011 to mark the additional northern-most cable).

2.3 DATA FORMAT

All frame and SSB data were saved in uncompressed .wav file format at a sample rate of 96 kHz in 24-bit format. Over 30 hours of acoustic data was recorded on frame C and 5 hours on frame A from the Billia Croo site. All hydrophones in terms of noise performance and bandwidth where directly applicable to the appropriate bandwidth of the data acquisition systems used. Data was collected in band 10 Hz – 200 kHz covering all know marine species hearing responses.

3 DATA PROCESSING

3.1 INTRODUCTION

The overall aim of the measurements is to provide information on levels and variation both temporal and spatial for baseline noise across the EMEC wave site.

- Variation of sound level with frequency
- Identification of dominant sound sources
- Absolute levels of underwater sound at measurements sites

The subsequent analysis of collected data was carried out using bespoke data analysis routines following where applicable recognize standards. Optimised processing routines within packages such as MATLAB and LABVIEW were used to achieve these aims.

Data were collected in the form of continuous lossless sound recordings. All system hydrophone sensitivities and electronic gains were fully calibrated both before and after deployment and where possible *in situ* calibration tones will be used. Recording systems were synchronized to GPS accuracy before deployment and re-checked after retrieval.

3.2 ANALYSIS:

Various spectral analysis techniques were used to provide time-frequency analysis both for long term data trends and analysis of short term ‘event’ signals. In the case of data sets of long duration long term spectral averaging (LTSA) was used. In this case linear FFT analysis was performed and the resulting spectra averaged over 60 second periods. For longer data sets the averaging window was extended to 10 minutes. Data within that period was spectrally averaged using a Welch average technique. These data then formed linear time versus frequency plots.

In addition, averaged third octave band (TOB) power and third octave band constant percentage bandwidth (CPB) analysis were processed averaged across sequence of up to 10 minutes made up of consecutive 1 s time windows. The Constant Percentage Bandwidth (CPB) analysis may be viewed as the equivalent to spectral density commonly used in literature for description of ambient noise. All results given are either for specific frequency bands or a combined frequency versus time plots. All absolute level plots will be corrected for system sensitivities and windowing functions used.

In specific cases, narrow band linear Fourier analysis was used to identify low frequency tonal components. The combination of narrow band analysis and Third Octave Bands provides insight into different signal properties for example broader band noise can be better represented across a large frequency range using Third Octave Bands however strong narrow band tonal components would not be as well represented using this approach. In this case narrow band analysis would provide more information on the acoustic signal generated. This process may be particularly relevant to effects of noise on fish species.

The long term spectral averaging was carried out first and used to identify time variant / stable noise characteristics and interesting specific noise events. These events were then analysed in turn using either power spectral density, spectral level or third octave bands analysis and correlated where possible with known device status, weather conditions *etc.*, (figure 3.1).

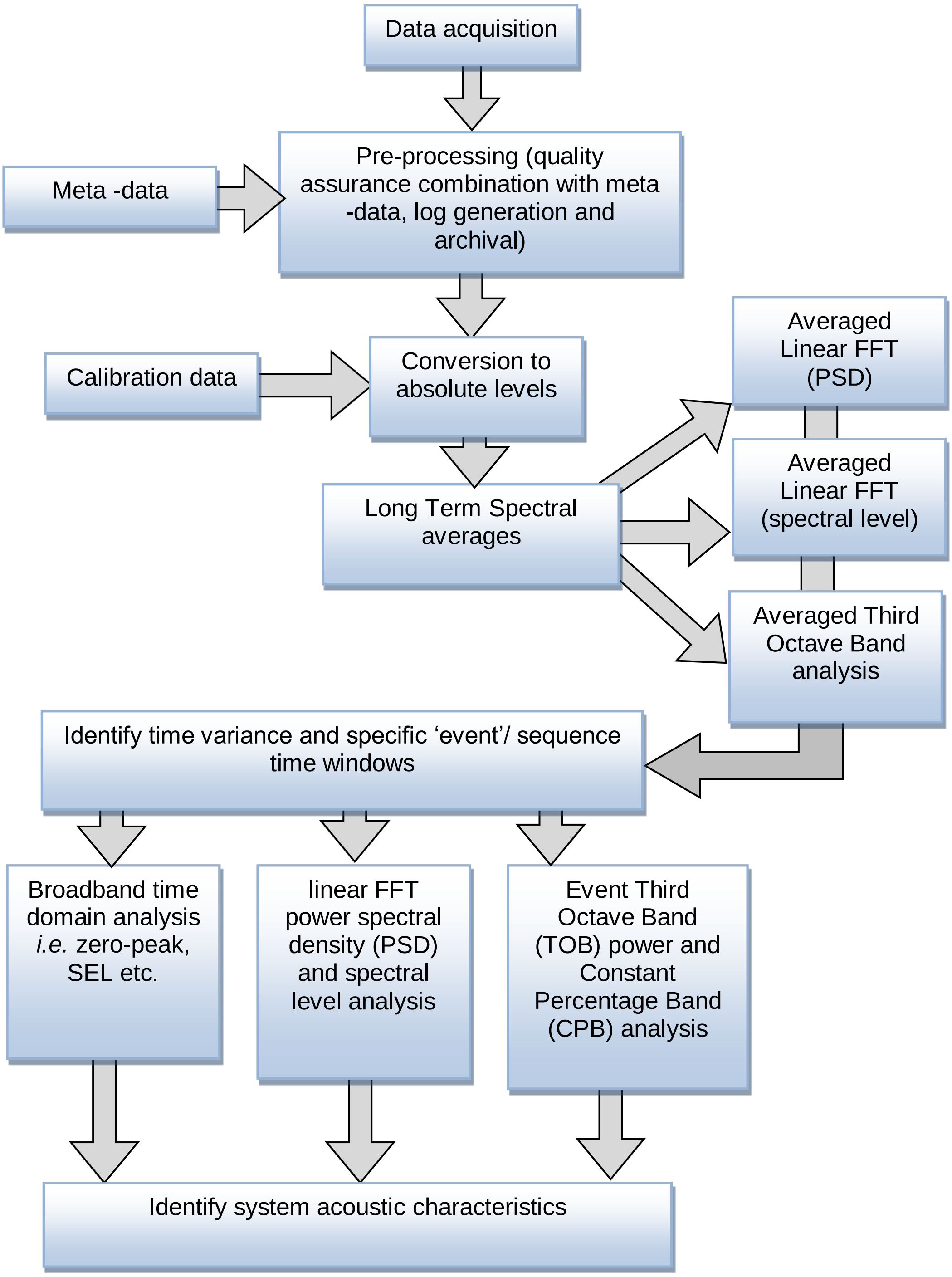

Figure 3-1: Proposed data analysis process

4 RESULTS

4.1 MEASUREMENT SUMMARY

Data from the main study site were collected from the deployment of three frames (A, C and D) positioned at the north, west and south of the site, respectively. Data were collected starting 26th July 2010 AM for around 30 hours for frame C, 5 hours for frame A. Figures 4.1 and 4.2 shows the Long Term Spectral Average (LTSA) of frame A and C's recorded data. In addition to this, data were collected from Sub-Surface Buoy (SSB) deployments within the site at east (27th July 2010 AM) and south (29th July 2010 AM) positions, for around 3 hours. A summary of all measurement made is provided in table 4-1[3].

Name	Deployment period (UTC + 1)	Location (lat./Lon. WGS84)	Water depth (m)	Description
West Frame	12:57 26th July – 19:16 27th July	N58.96348 W3.39761 (Billia Croo)	~ 55m	Bottom mounted frame
North Frame	14:48 26th July – 17:35 26th July	N58.98447 W3.39761 (Billia Croo)	~57 m	Bottom mounted frame
East SSB deployment	10:16 27th July – 13:02 27th July	N58.96357 W3.38370 (Billia Croo)	~ 34 m	Sub-surface buoy deployment
Boat drift measurement (1)	11:07 27th July – 11:28 27th July	N58.98296 W3.37528 (Billia Croo)	~30 m	Broadband boat based measurement
CTD deployment (1)	11:41 27th July	N58.97145 W3.38253 (Billia Croo)	~47 m	
Boat drift measurement (2)	12:43 27th July – 12:58 27th July	N58.97132 W3.37855 (Billia Croo)	~34 m	Broadband boat based measurement
CTD deployment (2)	13:21 27th July	N58.90767 W3.26721 (Inner site 1)	~25 m	
Inner site 1 SSB deployment	09:44 28th July – 12:45 28th July	N58.90503 W3.27415 (Inner site 1)	~25 m	Sub-surface buoy deployment
Boat drift measurement (3)	11:29 28th July – 12:05 28th July	N58.90484 W3.26814 (inner site 1)	~25 m	Broadband boat based measurement
Inner site 2 SSB deployment	13:39 28th July – 14:56 28th July	N58.95674 W3.35895 (Inner site 2)	~10 - 15 m	Sub-surface buoy deployment
CTD deployment (3)	12:14 28th July	N58.90429 W3.25765 (Inner site 2)	~10 - 15 m	
Boat drift measurement (4)	13:56 28th July – 14:36 28th July	N58.95718 W3.27195 (Inner site 2)	~10 - 15 m	Broadband boat based measurement
CTD deployment (4)	14:41 28th July	N58.95636 W3.27359 (Inner site 2)	~10 - 15 m	
South SSB deployment	09:36 29th July – 12:38 29th July	N58.95674 W3.35895 (Billia Croo)	~12 m	Sub-surface buoy deployment
Boat drift measurement (5)	10:07 29th July – 10:17 29th July	N58.95645 W3.38210 (South cardinal)	~37 m	Broadband boat based measurement
Boat drift measurement (6)	11:14 29th July – 11:24 29th July	N58.95550 W3.35537 (south SSB)	~12 m	Broadband boat based measurement

Table 4-1 Measurement summary baseline noise measurement 26-29th July 2010

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[3] All times reported in this report are based on BST (UTC +1). GPS positions are in decimalized degrees using WGS84 datum

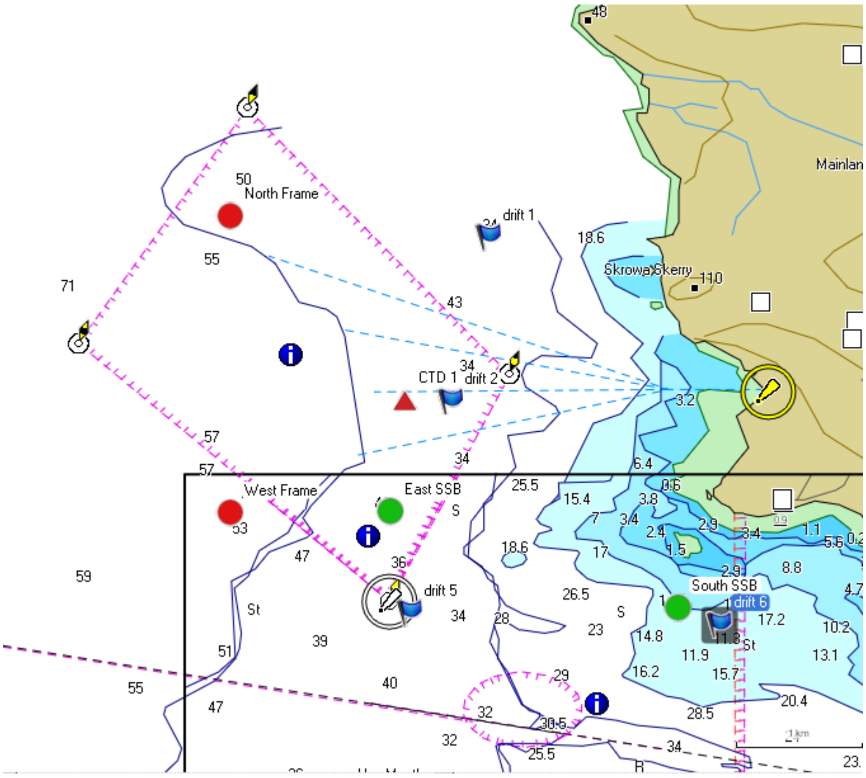


Figure 4-1: Measurements sites Billia Croo (July 2010). (Red circles frame deployments, green circles sub-surface buoy deployments, blue flag boat based drift deployments, red triangles CTD deployments).

Note: Shortly after the baseline measurements an additional cable and mooring position was added to North west of site (not shown on chart above) at 58° 59.5N & 003° 25.330W in approximately 70 m of water.

4.2 LONG TERM RECORDER ANALYSIS

West frame (Billia Croo)

Figure 4-2 shows a 30 hour long term spectral averaged sequence recorded at the west frame site from midday on 26th July 2010. The data shows an initial quieter period directly after deployments indicated by marker C1. A gradual increase in noise levels was then observed after about 3 hours with a further increase at around 9 hours shown by marker C4. These levels are then relatively constant at slightly lower levels for remainder of the 30 hour sequence.

A significant potential contribution to the background noise level at the main study site were likely due to the presence of the Sovereign, a cable-laying ship operating within the site during the July 2010 measurements, figure 4.2. To allow assessment of the potential general background levels, levels of both during quieter Sovereign activity and at two inner sites were also analysed. In addition data from two measurement periods without CS Sovereign present were processed including data from May 2011.

Figure 4-2: The cable laying ship the CS Sovereign at the Billia Croo wave test site

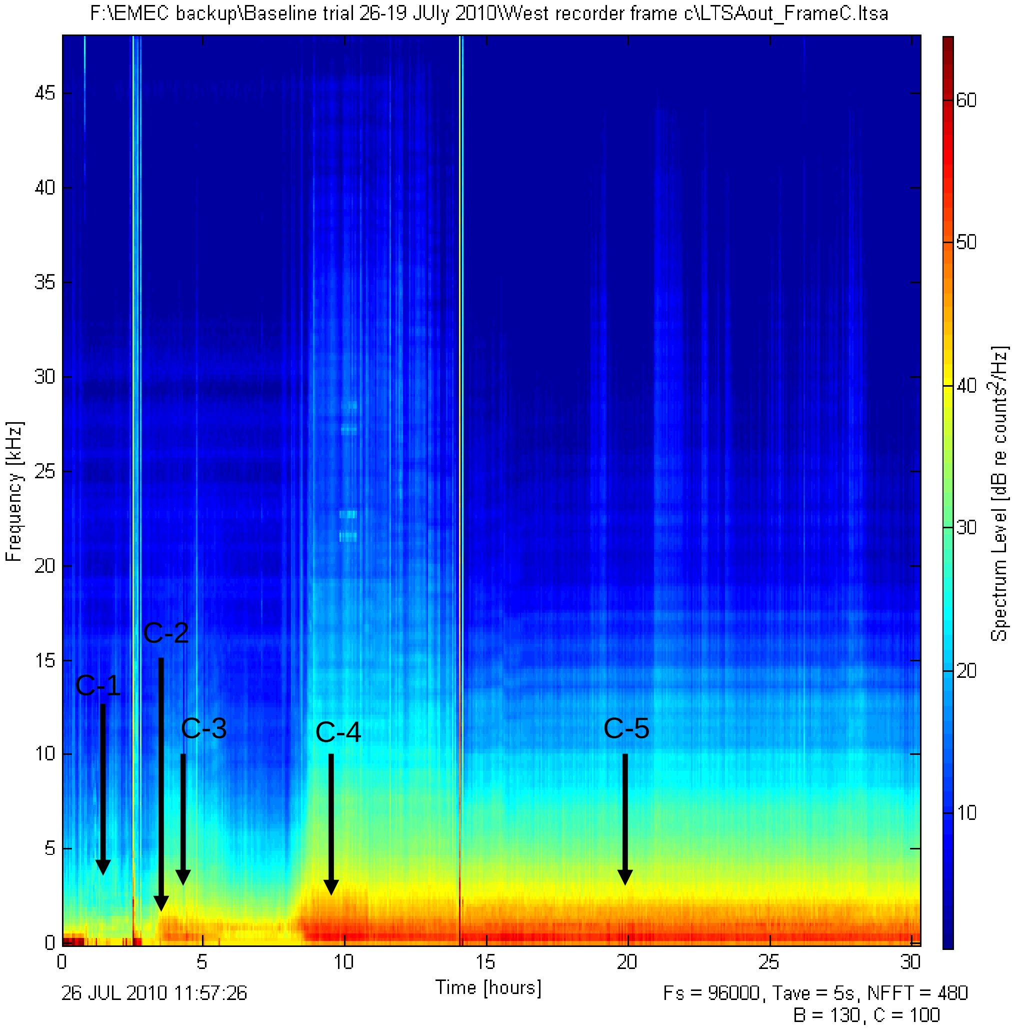
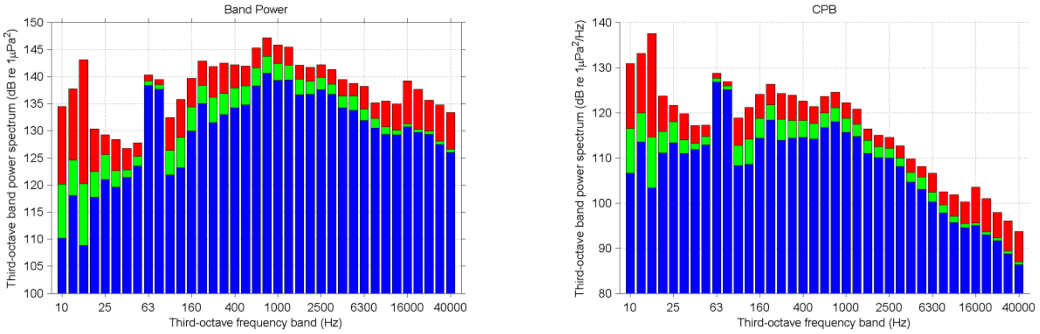


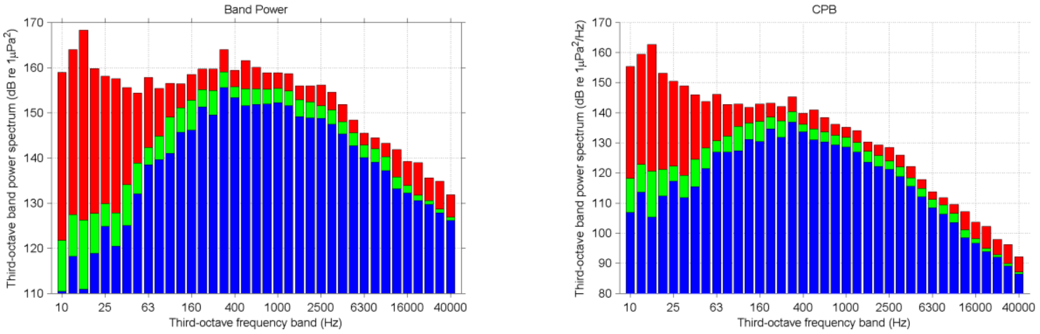
Figure 4-3- Long Term Spectral Average (LTSA) for frame C (west).

The LTSA was generated using the Triton software developed by the Marine Physical Laboratory are UCSD, San Diego. Data from consecutive long term wav files are concatenated and long term spectral trends provided. Relative amplitude levels shown on the z-axis colour bar are dB relative to counts^2/Hz, where counts are the numeric resolution of the data acquisition system used. For example, for a 16 bit system the full dynamic range of the analogue to digital converters used in volts corresponds to a range of ± 32,768 (2^{15}) counts .



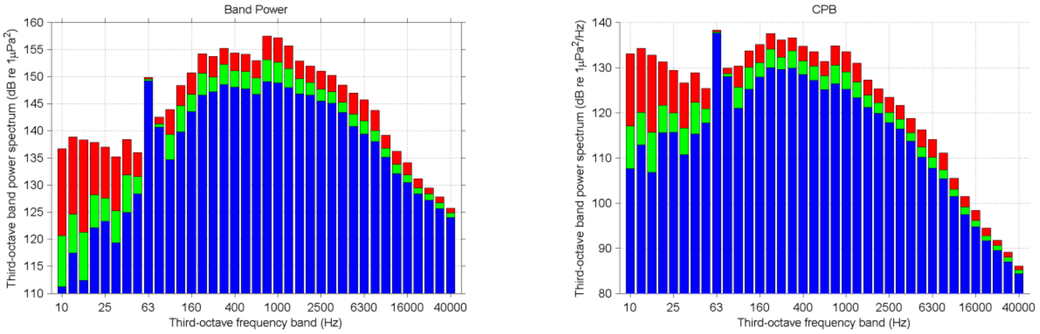
Averaged TOB power data for a 10 minute sequence (C1) data Frame C (West) start 14:12 26th July 2010 TOB power
(a)

Averaged CPB data for a 10 minute sequence (C1) Frame C (West) start 14:12 26th July 2010
(b)



Averaged TOB power data for a 10 minute sequence (C2) data Frame C (West) start 16:28 26th July 2010 TOB power
(c)

Averaged CPB data for a 10 minute sequence (C2) Frame C (West) start 16:28 26th July 2010
(d)



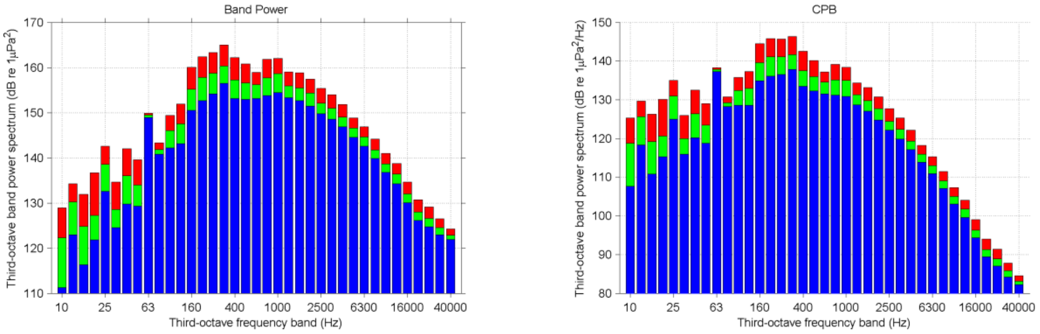
Averaged TOB power data for a 10 minute sequence (C3) data Frame C (West) start 17:00 26th July 2010 TOB power
(e)

Averaged CPB data for a 10 minute sequence (C3) Frame C (West) start 17:00 26th July 2010
(f)

Figure 4-4 a-f: West frame. Third Octave Band (TOB) power and constant percentage bandwidth (CPB) power in third octave bands. 10 minute averaged maximum (red), mean (green) and minimum (blue) data integrated over consecutive a 1s period across entire 10 minute sequence.

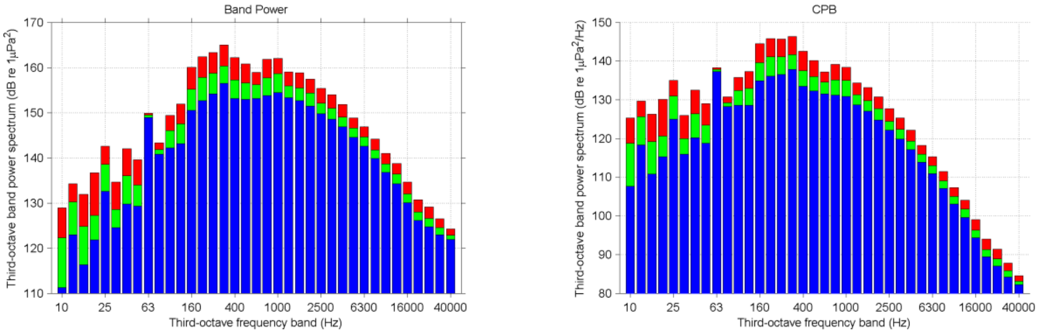
Figure 4.4 (a-f) shows data for averaged data integrated across consecutive 1 second blocks over a 10 minute period for the west frame at sequence times C1-C3 shown in figure 4.2. data shows significant increases in levels both in third octave band power (TOB) and constant percentage bandwidth power (CPB) over time.

Figure 4.5 (a-d) shows additional averaged levels across a 10 minute window at 22:00 on the 27th July 2010 and 09:00 on the 28th July 2010 labeled sequence C4 and C5 in figure 4.2 respectively.



Averaged TOB power data for a 10 minute sequence (C4) data Frame C (West) start 22:00 27th July 2010 TOB power
(a)

Averaged CPB data for a 10 minute sequence (C4) Frame C (West) start 22:00 27th July 2010
(b)



Averaged TOB power data for a 10 minute sequence (C5) data Frame C (West) start 09:00 27th July 2010 TOB power
(c)

Averaged CPB data for a 10 minute sequence (C5) Frame C (West) start 17:00 27th July 2010
(d)

Figure 4-5 (a-d): West frame. Third Octave Band (TOB) power and constant percentage bandwidth (CPB) power in third octave bands. 10 minute averaged maximum (red), mean (green) and minimum (blue) data integrated over consecutive a 1s period across entire 10 minute sequence.

North frame (Billia Croo)

Figures 4.2 and 4.4 can be directly compared with data from the north frame shown in figures 4.6 and 4.7. Where sequences A1- A3 (figure 4.6) were taken at identical times to sequence C1-C3 analysed from the west frame data. In general levels in the bands 100 Hz – 1 kHz are similar across the two sites, with slight variation between the two. All sequences are for a 10 minute sequence of averaged 1 second consecutive time windows.

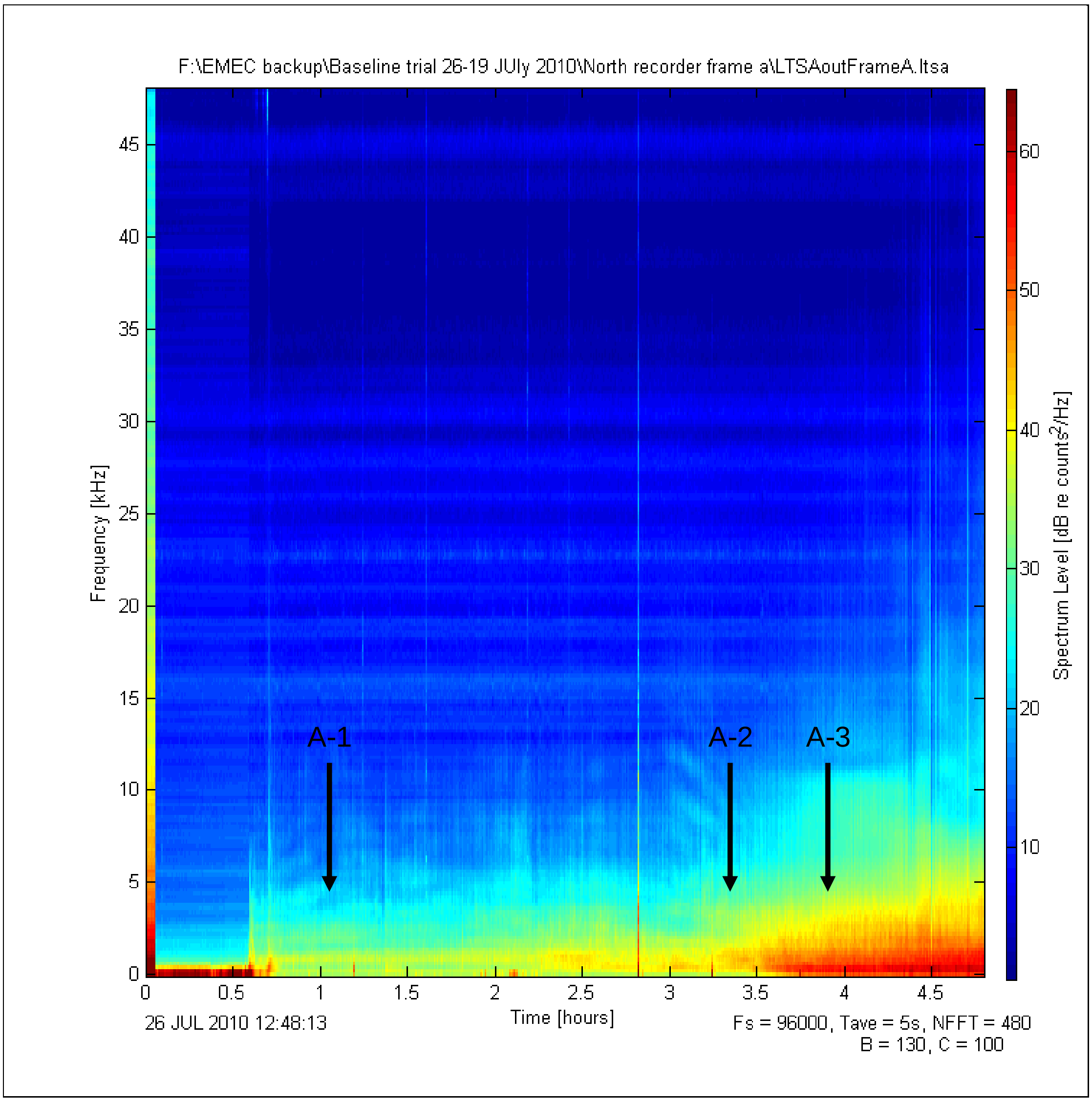
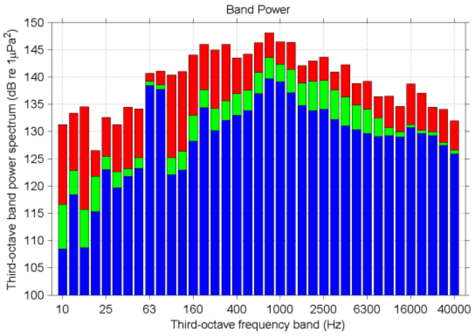
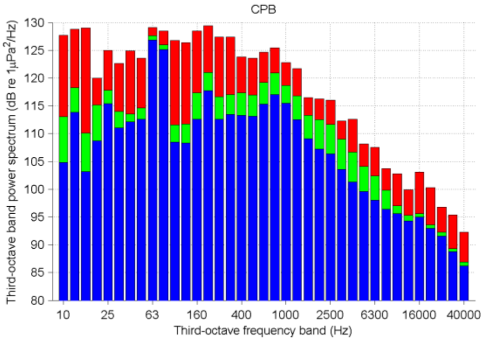


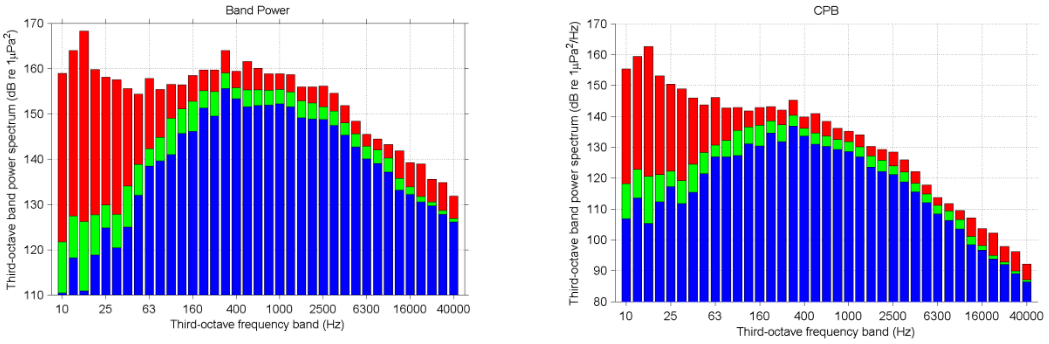
Figure 4-6: Long Term Spectral Average (LTSA) for frame A (north).



Averaged TOB power data for a 10 minute sequence (A1) data Frame A (North) start 14:12 26th July 2010 TOB power (a)

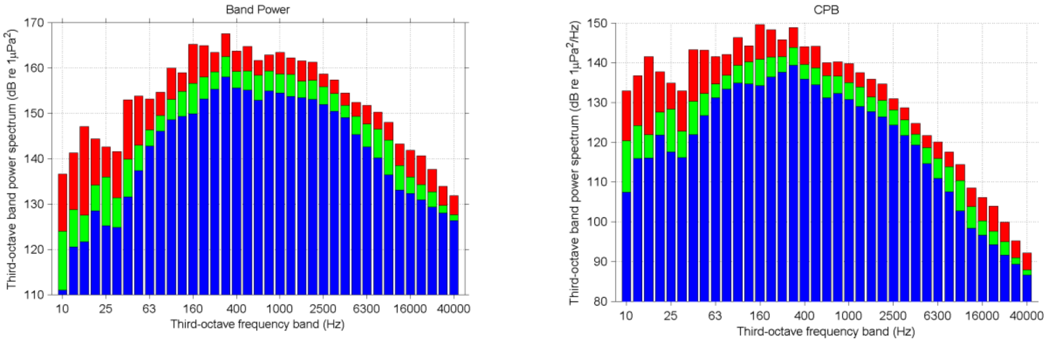


Averaged CPB data for a 10 minute sequence (A1) Frame A (North) start 14:12 26th July 2010 (b)



Averaged TOB power data for a 10 minute sequence (A2) data Frame A (North) start 16:28 26th July 2010 TOB power
(c)

Averaged CPB data for a 10 minute sequence (A2) Frame A (North) start 16:28 26th July 2010
(d)



Averaged TOB power data for a 10 minute sequence (A3) data Frame A (North) start 17:00 26th July 2010 TOB power
(e)

Averaged CPB data for a 10 minute sequence (A3) Frame A (North) start 17:00 26th July 2010
(f)

Figure 4-7 a-f: North frame A. Third octave band (TOB) power and constant percentage bandwidth (CPB) power in third octave bands. 10 minute averaged maximum (red), mean (green) and minimum(blue) data integrated over consecutive a 1s period across entire 10 minute sequence.

<u>East and south sub-surface buoy deployments</u>

Figures 4.8 and 4.9 show the long term spectral average for the east and south sub-surface deployments respectively. Further analysis is included in the following sections. In the case of the East SSB deployment system was in the water at around 10:47 27th July 2010 and the south position SSB system at 09:56 29th July 2010.

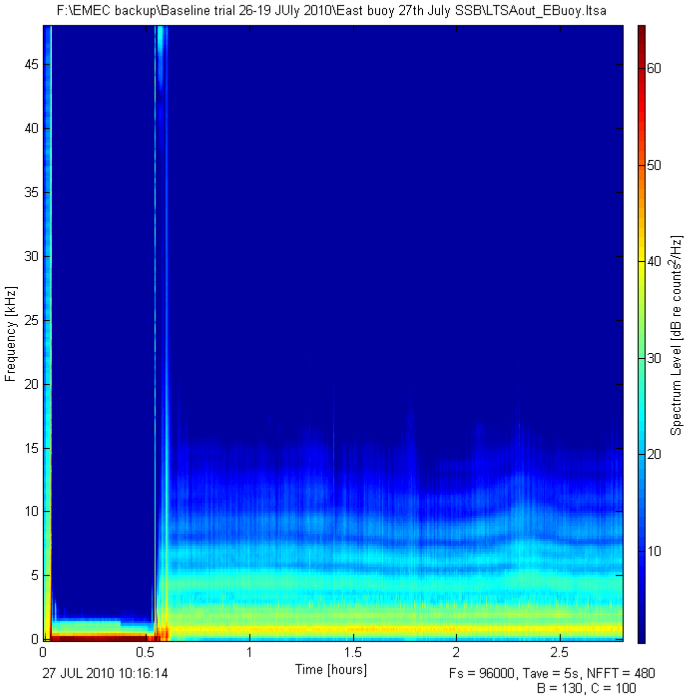


Figure 4-8: Long Term Spectral Average (LTSA) for sub-surface buoy system (south). 10:16 27th July 2010 Billia Croo site.

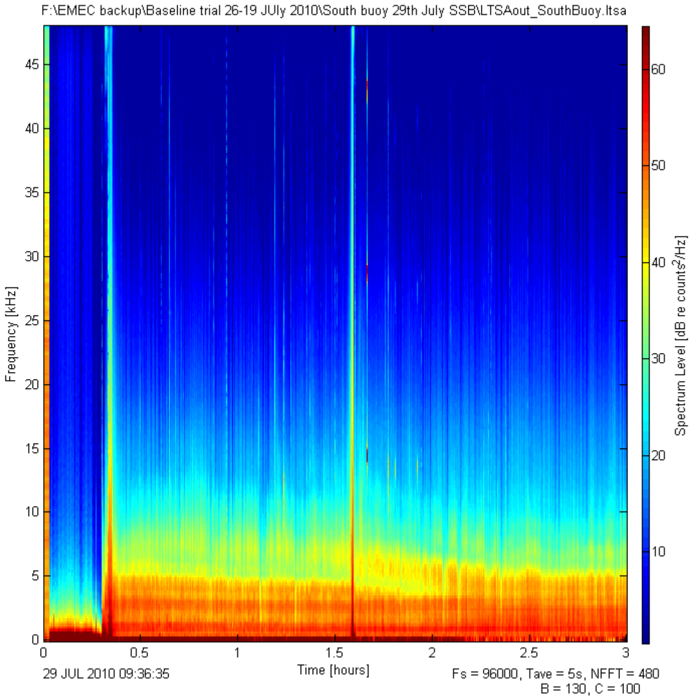


Figure 4-9: Long Term Spectral Average (LTSA) for sub-surface buoy system (east). 10:56 29th July 2010 Billia Croo site.

4.3 SPATIAL AND TEMPORAL VARIATION ACROSS EMEC BILLIA CROO SITE

Time period comparison 1: 26th July 2010 14:00-15:10 (North and West Frames)

This time period was selected as a within-site relatively 'quiet period' to compare data from north frames A and west frame C. Figure 4.10 indicates the period on each frame's LTSA plot using a white arrow.

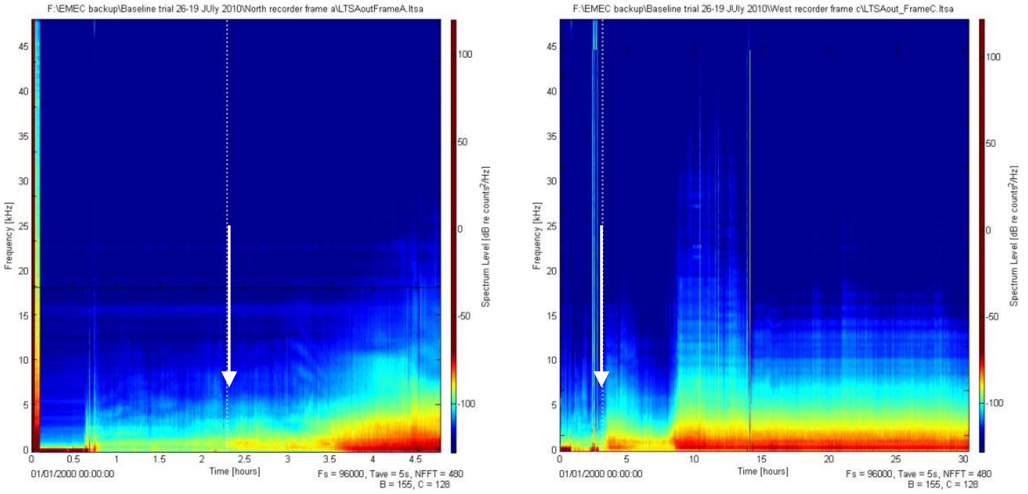


Figure 4-10: Indicating time period comparison 1 (white arrow) on the LTSA plot of north frames A (left) and west frame C (right). 26th July 2010 14:00-15:10

Figure 4.11 and 4.12 show comparison of the average CPB analysis for both North and West frames during period 14:15-14:25 respectively. Data are averaged across consecutive 1 second intervals across entire 10 minute sequence. The red circles indicate mean levels across 10 minutes and the bars ± 1 standard deviation. Both sites show very similar noise profiles during this period with strong noise components in the 63 and 80 Hz TOB band with mean peak levels of around 127 dB re 1 µPa^2 Hz^{-1} and CPB levels of around 120 dB re 1 µPa^2 Hz^{-1} at 800 Hz.

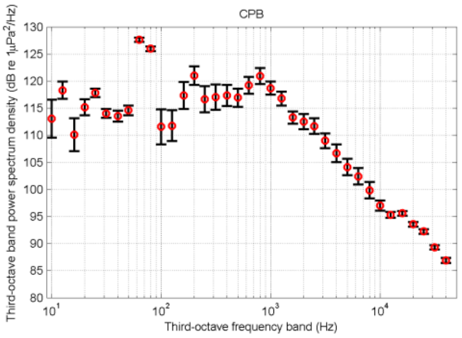


Figure 4-11: 10 minute averaged data (14:15-14:25 26th July 2010) North Frame Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive

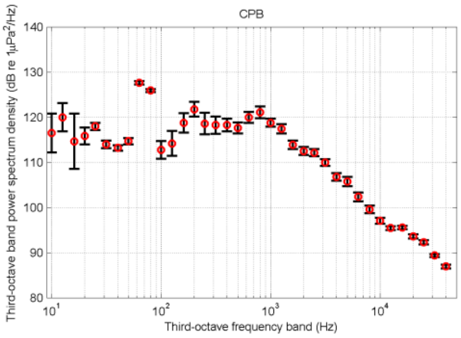


Figure 4-12: 10 minute averaged data (14:15-14:25 26th July 2010) West Frame Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive

across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

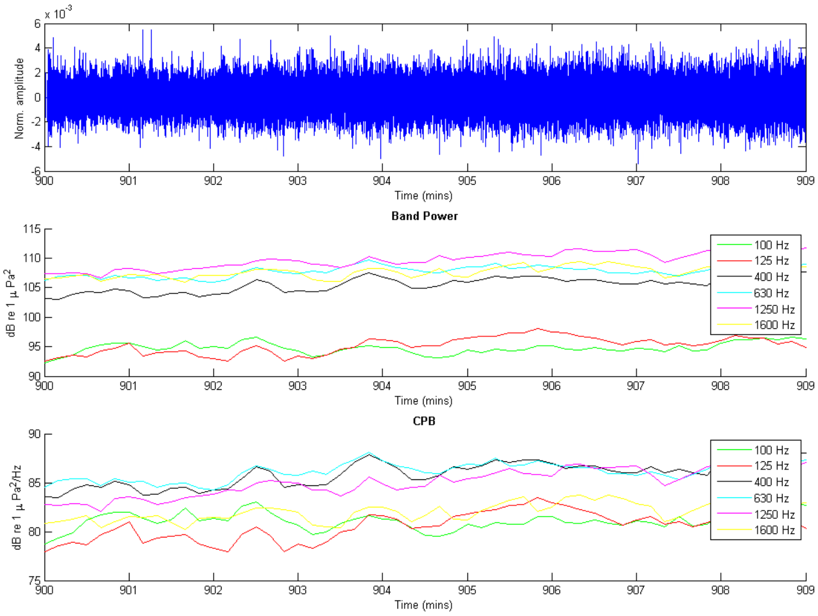


Figure 4-13: Plots demonstrating the variation in third octave frequency over the course of time period comparison 1 (North frame A) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

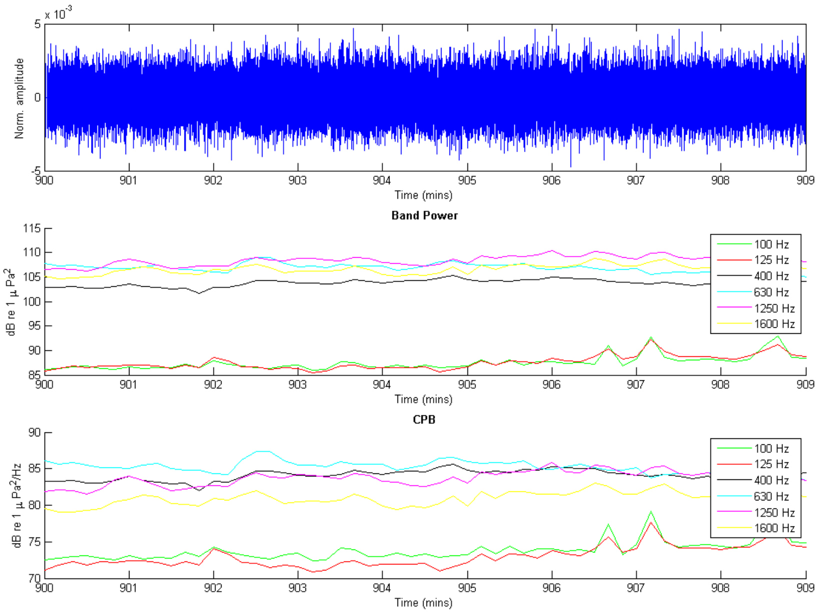


Figure 4-14: Plots demonstrating the variation in third octave frequency over the course of time period comparison 1 (West frame C) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

The variation in time in TOB power and CPB for specific bands across 10 minute sequence for the North and West frames is shown in figures 4.13 and 4.14 respectively. Third Octave Band Power (TOB) analysis is integrated over a period of consecutive 10 s time windows across the entire 10 minute sequence. The specific frequencies chosen were 100, 400, 630, 1250 and 1600 Hz. Analysis of all third octave band across the full measurement spectrum are given later however these frequencies were chosen to look at relative stability across most dominate part of spectrum. Both plots in figures 4.13 and 4.14 show a CPB spectral density between 70-90 dB re 1 µPa^2 Hz^{-1} for most frequencies. In both cases, the lower frequencies 100 and 125 Hz generally had a lower spectral density than the higher frequencies throughout.

Time period comparison 2: 26th July 2010 17:00-17:20 (North and West Frames)

This time period was selected with increasing noise compared to previous analysis. Figures 4.15 a-b indicate the period on both the North and West frame's LTSA plots respectively. The simultaneous analysis period on both frames is shown by the white dotted line/arrow.

As previously figure 4.16 and 4.17 show the averaged data (starting at 17:00 26th July 2010) for both North and west frames respectively. Figures show the Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows for a 10 minute sequence. Red circles mean values, bars ± 1 standard deviation.

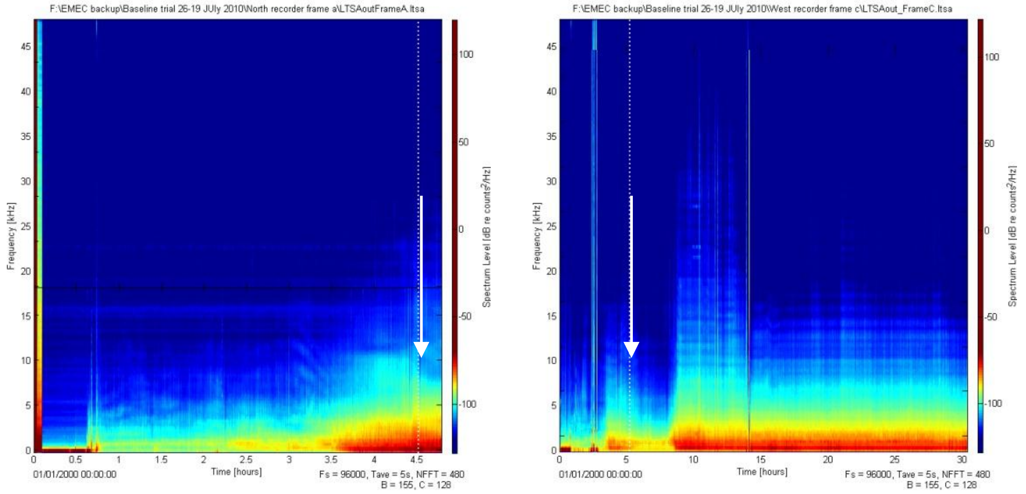


Figure 4-15: Time period comparison 2 (white dotted line) on the LTSA plot of North frames A (left 4-15a) and C (right 4-15b). 26th July 2010 17:00-17:20

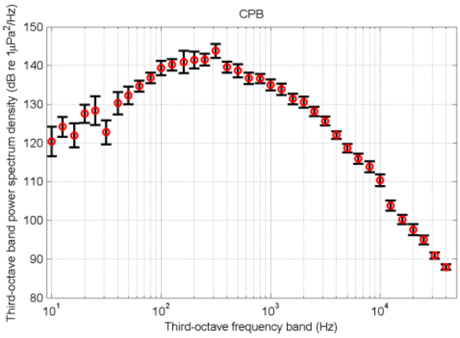


*Figure 4-16: 10 minute averaged data (*17:00 – 17:10 26th July 2010*) North Frame Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.*

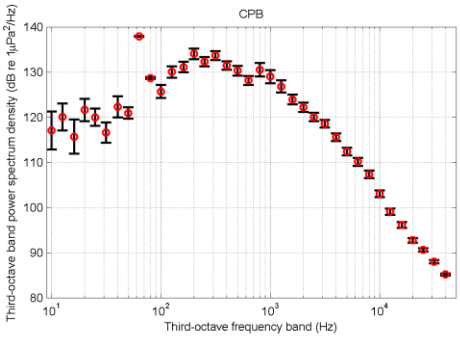


*Figure 4-17: 10 minute averaged data (*17:00 – 17:10 *27th July 2010) West Frame Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation*

Compared to the previous analysis period approximately 2.5 hours earlier general levels are generally higher with, in the case of the north frame, around 20 dB increases at 800 Hz, and a lower increase at the west site. The presence of strong components in the 63 Hz band however are also increased at the west site from around 127-137 dB re 1 μPa^2 Hz^{-1}. The presence of these components is not evident above generally elevated levels at the North site.

For each frame, the 10 minute segment was taken and again TOB analysis run at 10 second intervals, integrated over a period of 10 s. Figures 4.18 and 4.19 show the TOB band power and TOB CPB over the course of the segment for selected frequencies.

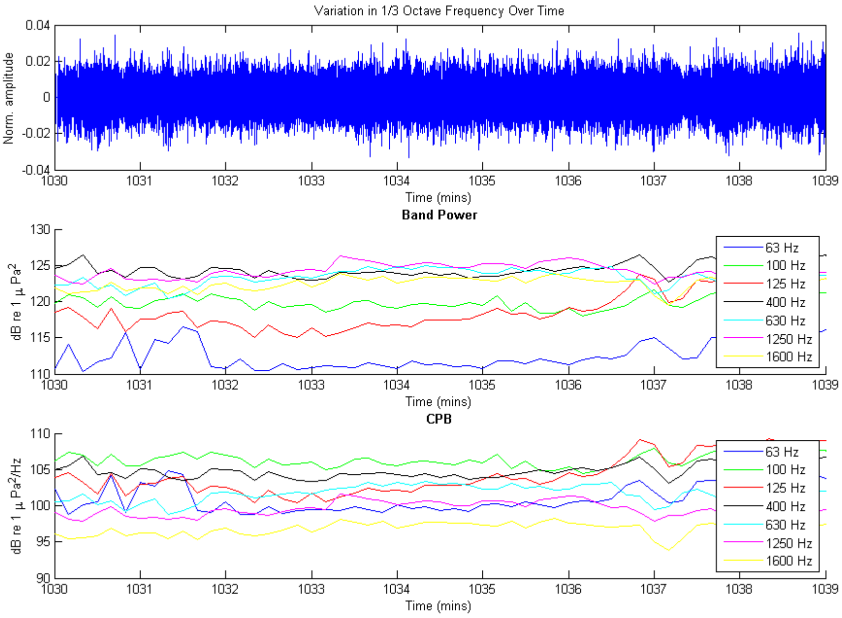


Figure 4-18: Variation in third octave frequency over the course of time period comparison 2 (frame A) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

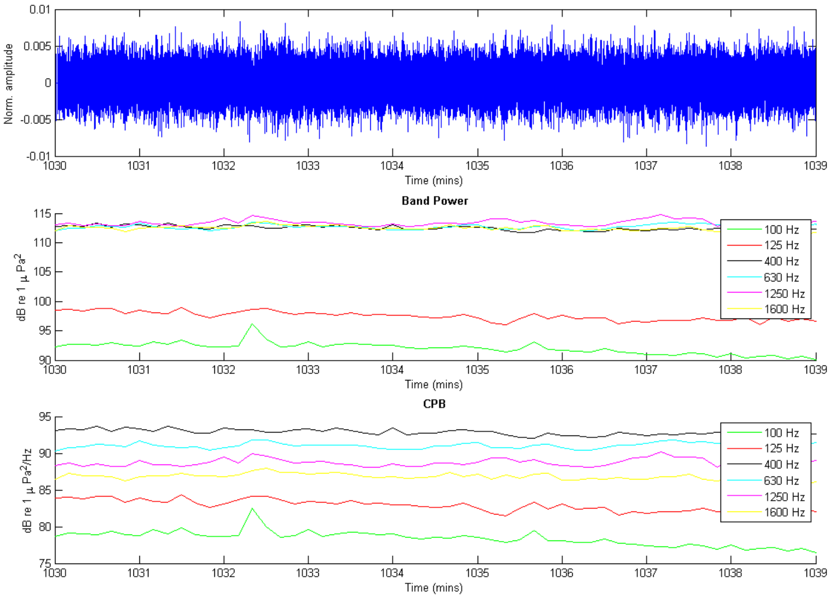


Figure 4-19: variation in third octave frequency over the course of time period comparison 2 (frame C) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

For the west frame results appeared similar to the previous comparison, with CPB spectral densities between around 85-95 dB re 1 µPa^2 Hz^{-1} for most frequencies, excluding the 63 Hz band. However, the results for North frame appeared markedly different, with CPB spectral densities between around 95-110 dB re 1 µPa^2 Hz^{-1} for all frequencies, including 63 Hz.

Time period comparison 3: 27th July 2010 11:00-11:30 (West / east and boat based buoy systems (drift 1))

This time period was selected as a within-site relative with higher noise levels to compare data from frame C (west) and the SSB deployment (east). Figure 4.20 indicates the periods on each LTSA plots for both frames respectively.

Figures 4.21 and 4.22 show the relative CPB analysis for both the west and north frame site for an identical periods shown in figure 4.20. In general levels in the 1 kHz band approximately 10 -15 dB lower at the northern site.

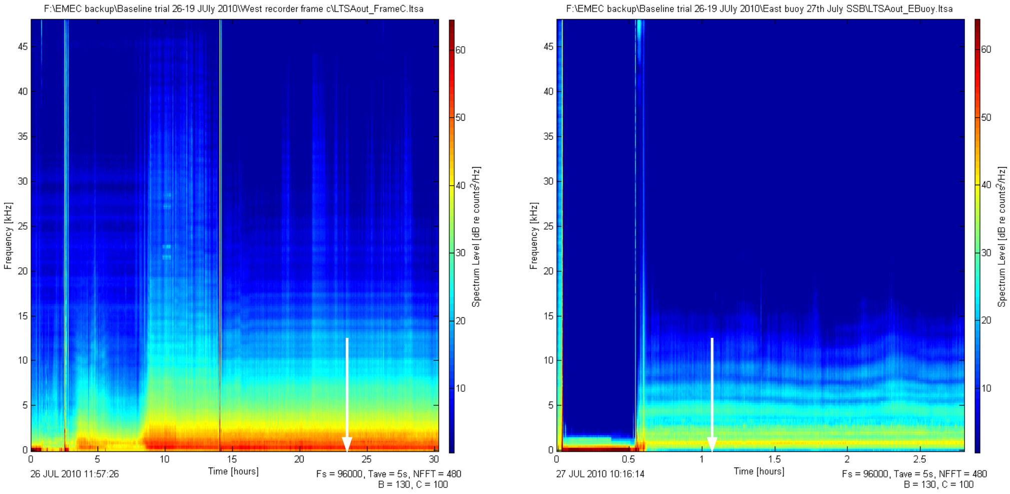


Figure 4-20:Time period comparison 3 (white arrow) on the LTSA plot of frame C (left) and the east buoy system (EBS) (right).

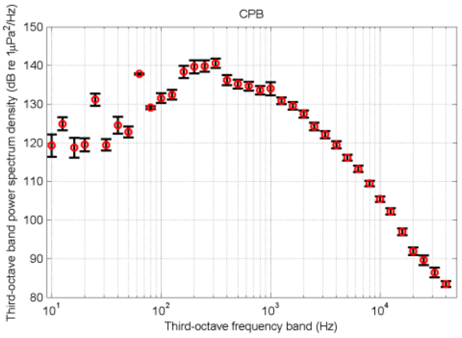


Figure 4-21: 10 minute averaged data (11:19-11:29 27th July 2010) West Frame Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

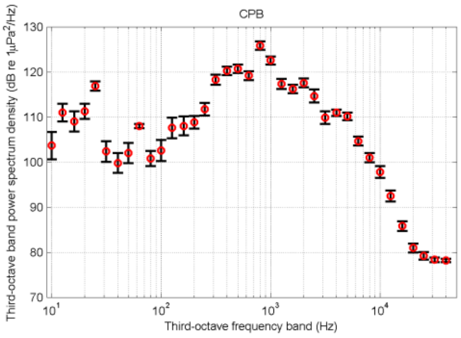


Figure 4-22: 10 minute averaged data (11:19-11:29 27th July 2010) east buoy system (EBS) Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

For each data set, the 10 minute segment was again taken and TOB analysis run at 1 minute intervals, integrated over a period of 10 s. Plots were again produced of the TOB band power and TOB CPB over the course of the segment for selected frequencies, as shown in Figures 4.23 (West frame C) and 4.24 (east SSB).

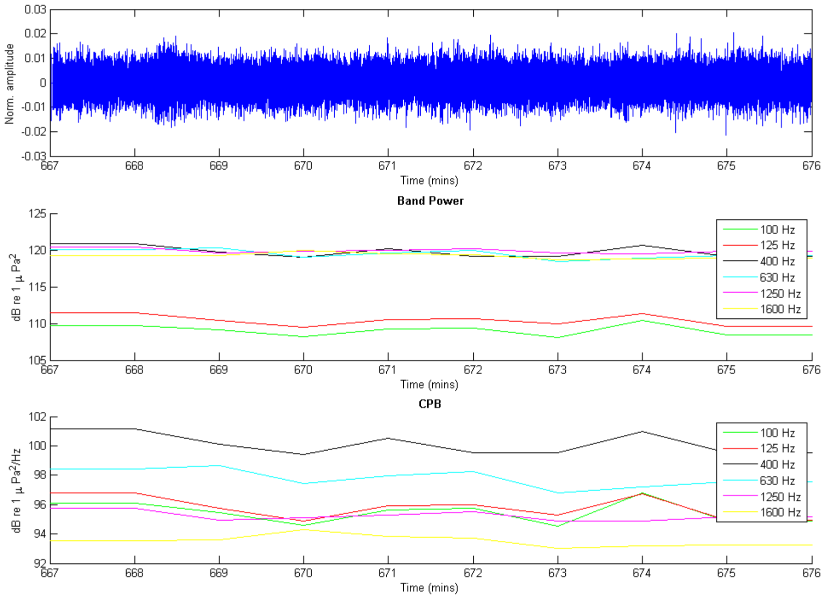


Figure 4-23: Variation in third octave frequency over the course of time period comparison 3 (frame C) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

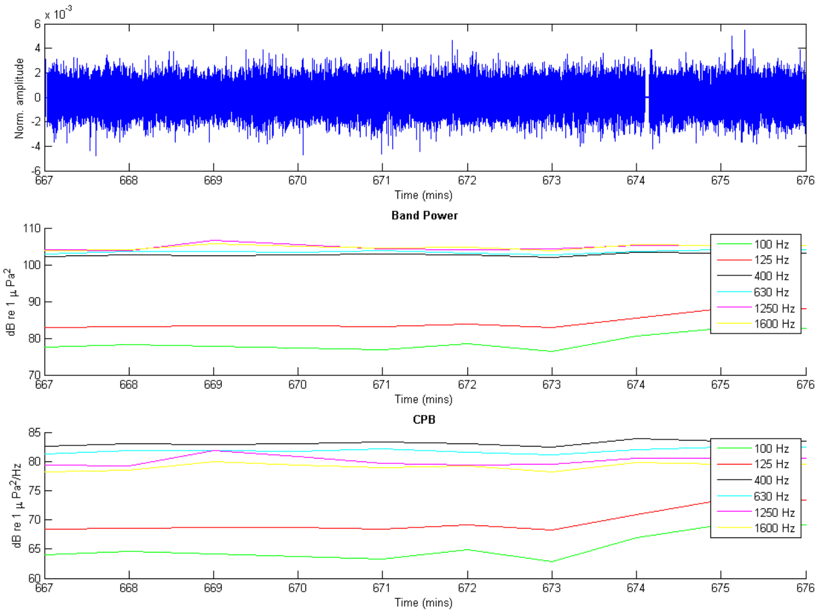
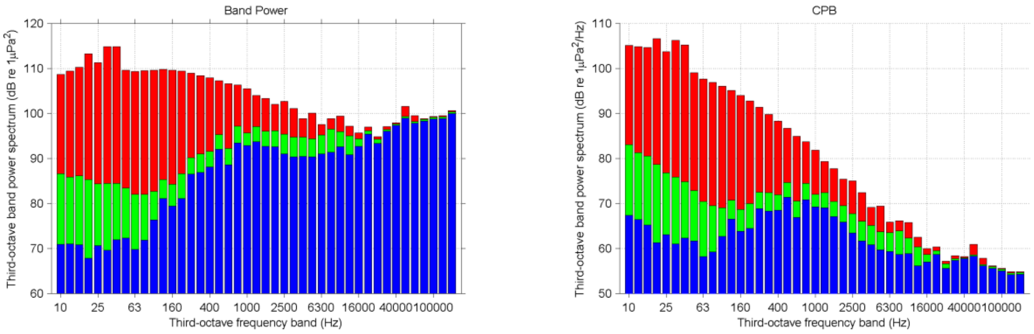


Figure 4-24: Variation in third octave frequency over the course of time period comparison 3 (east SSB) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

For the west frame C, CPB spectral densities appear elevated for most frequencies, between 93-101 dB re 1 μPa^2 Hz^{-1} (around 6-8 dB re 1 μPa^2 Hz^{-1} higher than frame C time period comparison 2). The east SSB data demonstrated levels 18-31 dB re 1 μPa^2 Hz^{-1} lower than west frame C data, with CPB spectral densities between around 62-83 dB re 1 µPa^2 Hz^{-1}. The 100 and 125 Hz bands had lower spectral densities than the higher frequencies, although conversely the data for west frame C had now indicated the lowest spectral densities for higher frequencies 1250 and 1600 Hz. In addition simultaneous broadband (10Hz – 150 kHz) boat based measurements were made during this period. Figures 4.25 a & b) show the average TOB power and CPB levels across a 10 minute sequence. Figures 4.26 show the equivalent mean and standard deviation analysis for CPB level at bands with centre-frequencies of 10 Hz – 125 kHz.



Averaged TOB power data for a 10 minute sequence boat drifting measurement start 11:19 27th July 2010 TOB power (a)

Averaged CPB data for a 10 minute sequence (boat drifting measurement start 11:19 26th July 2010 (b)

Figure 4-25 a-b: boat drifting measurement (drift 1) Third Octave Band (TOB) power and constant percentage bandwidth (CPB) power in third octave bands. Averaged maximum (red), mean (green) and minimum (blue) data integrated over consecutive a 1s period across entire sequence.

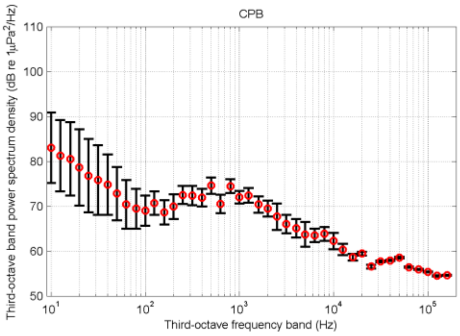
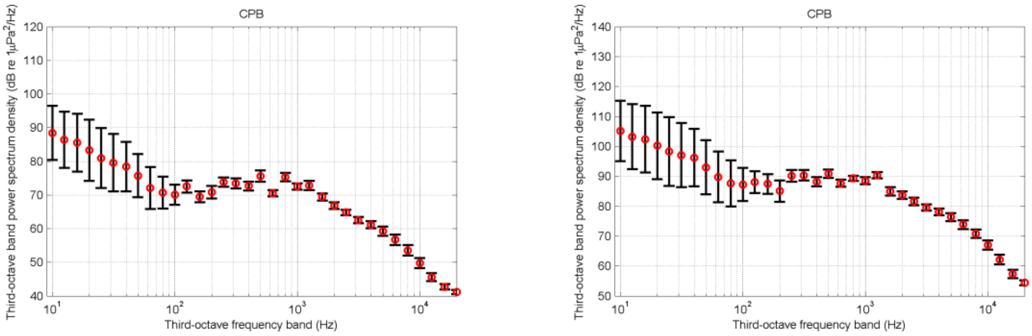


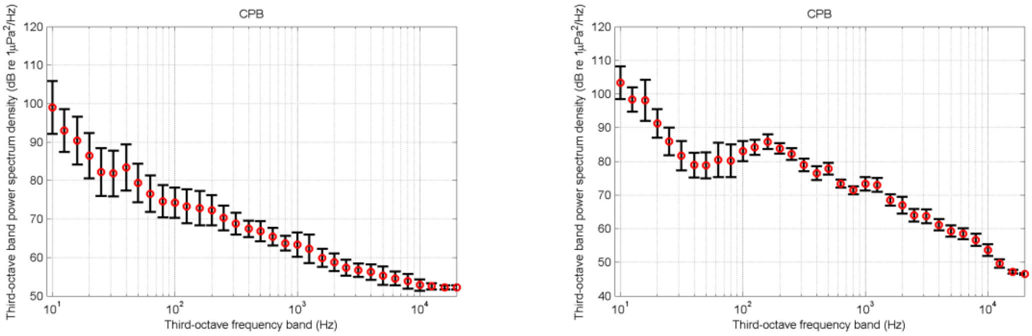
Figure 4-26: boat drifting measurement (drift 1). averaged data (11:19 27th July 2010) Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

Figures 4.27 a-d) shows the variation in broadband TOB data taken for 10 minute sequence during drift 1 (northerly site) between 11:19 and 11:24 and between 12:44 and 12:54 the 27th July on a drift 2 site near the east cardinal buoy.



11:19 27th July 2010 (drift 1)
(a)

11.24 27th July 2010 (drift 1)
(b)



12:44 27th July 2010 (drift 2)
(c)

12:54 27th July 2010 (drift 2)
(d)

Figure 4-27 a-d: boat based measurement (drift 1 11:19 & 11:24) and (drift 2 12:44 and 12:54) averaged data (27th July 2010). Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

Note analysis of the max and minimum data across 1 second intervals for the drift 2 sequence at 12:54 shows the presence of occasional strong components in the 63 Hz centred band similar to that observed on the north and west frames. The band power analysis shown in figure 4.28 shows the average maximum value (per 1 second integration) above surrounding levels at 63 Hz. The mean value however does not show any strong deviation from surrounding bands suggesting a regular but intermittent component in this band resulting in higher maximum values.

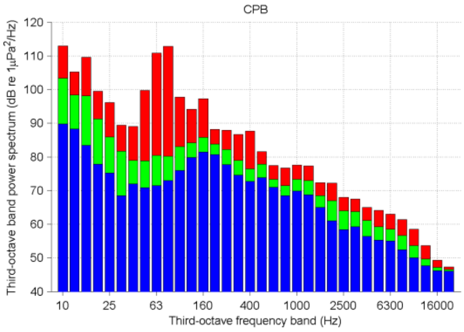


Figure 4-28: TOB power drift 2 deployment. Averaged maximum (red), mean (green) and minimum (blue) data integrated over consecutive a 1s period across entire sequence.

Time period comparison 4: 29th July 2010 10:07-11:14 (Boat based and South buoy systems)

Figure 4.29 shows the long term spectral average (LTSA) for the South buoy deployment. Figures 4.30 4.33 show respectively the TOB power CPB power for a 10 minute sequence at 10:07 and again at 11:14 processed as described previously. Both show significant levels in bands up to 20 kHz; a slight increase in general levels was observed in the later sequence. CPD levels of around 140 dB re 1 µPa^2 Hz^{-1} are seen in the 1 kHz third octave band. In parallel, boat based drift measurements were made drift 5 at the south cardinal and drift 6 close to the South SSB deployment shown in figures 4.34 and 4.35.

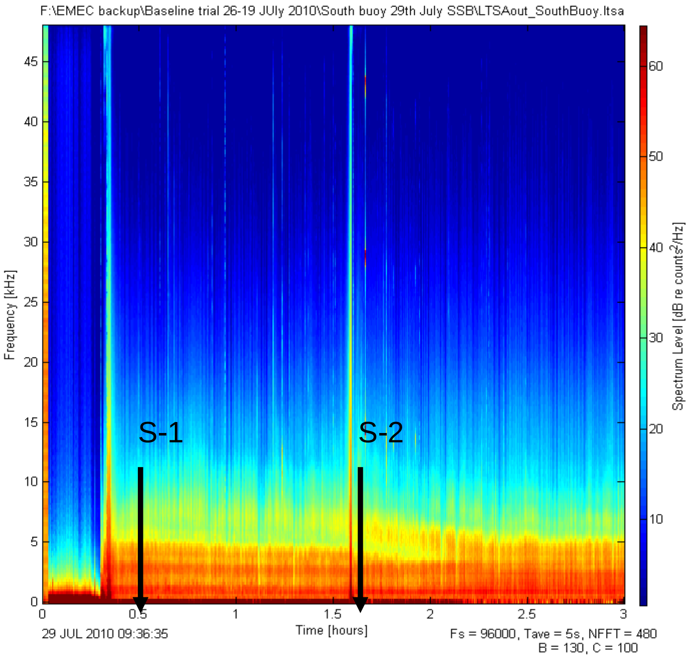
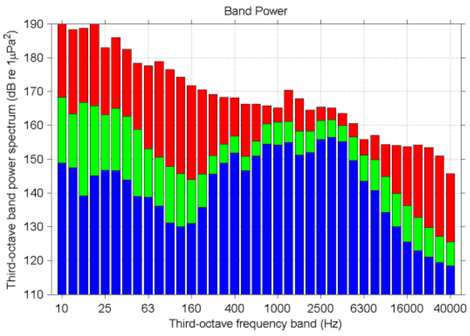


Figure 4-29: LTSA for sub-surface buoy (SSB) deployment on 29th July 2010 at the Billia Croo site (south).

Sequence S-1 time 10:07 29th July 2010



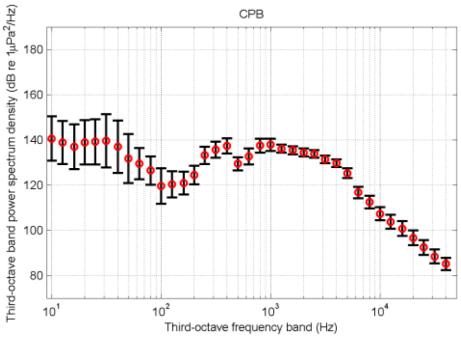


Figure 4-30: Averaged TOB power data for a 10 minute sequence South sub-surface buoy system 10:07 29th July 2010. Averaged maximum (red), mean (green) and minimum(blue)

Figure 4-31: 10 minute averaged data (10:17 29th July 2010) south buoy system (SSB) Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

Sequence S-2 time 11:14 29th July 2010

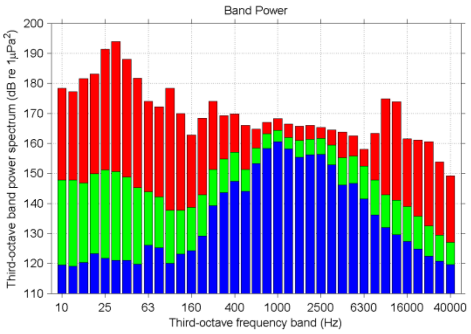


Figure 4-32: Averaged TOB power data for a 10 minute sequence South sub-surface buoy system 11:14 29th July 2010. Averaged maximum (red), mean (green) and minimum(blue)

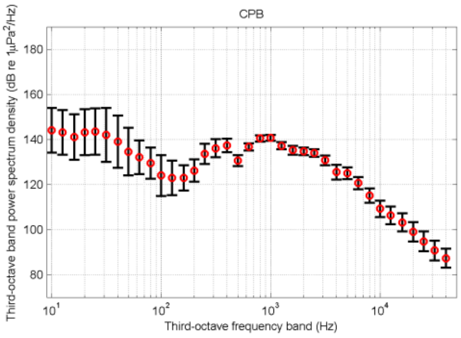


Figure 4-33: 10 minute averaged data (11:14 29th July 2010) south buoy system (SSB) Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

Figures 4.34 and 4.35 show the equivalent boat based measurements made at positions drift 5 and drift 6 respectively. At the south buoy position, only a slight increase is observed in the a general level between the two time sequences, however levels are significantly lower at the drift 5 position (south cardinal) with levels around 140 dB re 1 μPa^2 Hz^{-1} at the south buoy site compared to around 90 dB re 1 μPa^2 Hz^{-1} in the 1 kHz band for the 10 minute sequence S-1 at the south cardinal. Levels are even lower at around 60 dB at 11:14 (sequence S-2).

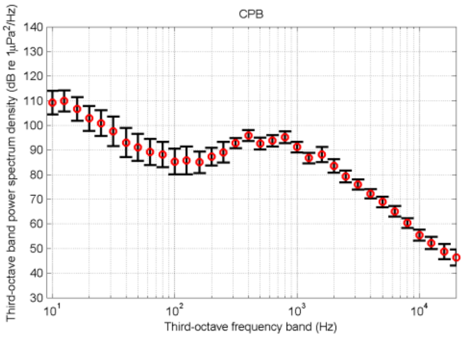


Figure 4-34: Averaged data (10:07 29th July 2010) Boat based deployment (drift 5) Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

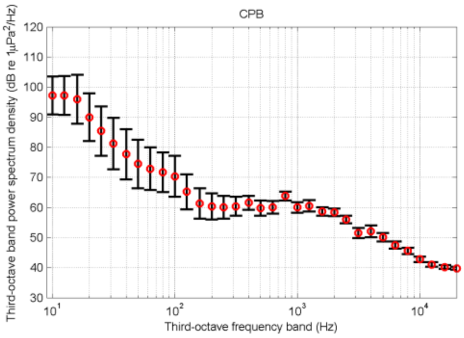


Figure 4-35: Averaged data (11:14 29th July 2010) Boat based deployment (drift 6) Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

4.4 INNER SITE MEASUREMENTS:

On the 28th July, measurements were made at two inner most sheltered sites. Site 1 south of Graemsay and site 2 in the western part of the Bay of Navershaw. Comparison with Billia Croo data was made with both long term spectral averaged data and boat based measurements. Figure 4.36 shows both site deployments.

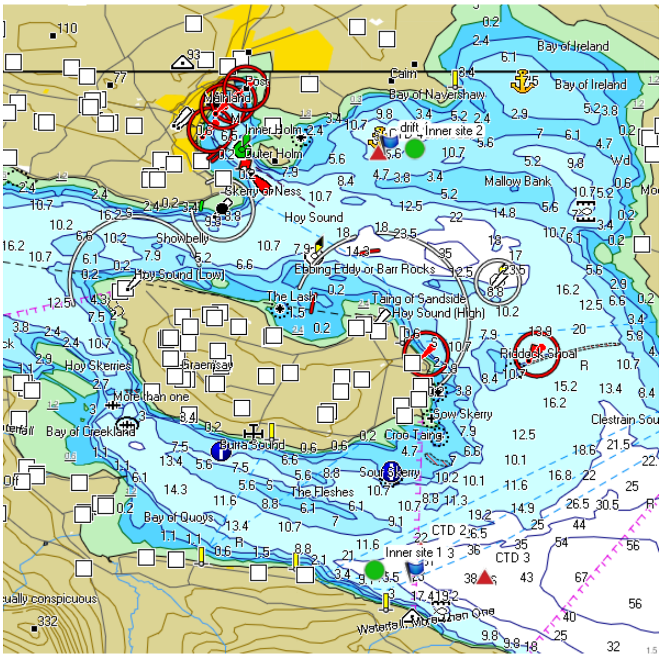


Figure 4-36: Inner site 1 and site 2 measurement position. (Red circles frame deployments, green circles sub-surface buoy deployments, blue flag boat based drift deployments, red triangles CTD deployments).

Figures 4.37 show the long term spectral average data for both sites analysis showed significant ship traffic across the measurement period including periods of relative ‘quiet’ then periods of higher noise levels due to passing shipping.

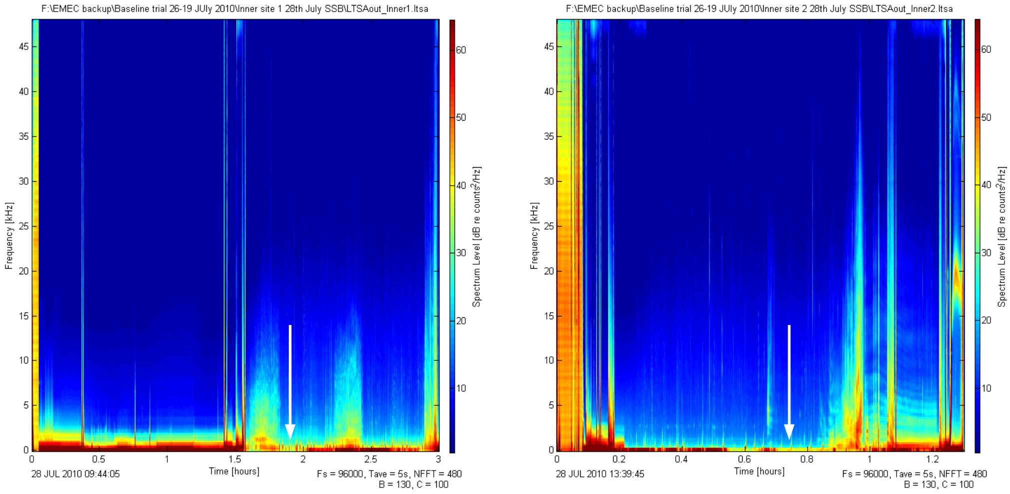


Figure 4-37: Site comparison 1 (white arrow) on the LTSA plot of the inner 1 SSB (left) and the inner 2 SSB (right).

Site comparison 1: Inner site 1 (28th July 2010 AM) vs. inner site 2 (28th July 2010 PM). The two ‘quieter’ periods were compared to obtain relative background levels using data from the inner 1 SSB and inner 2 SSB. A white arrow on figure 4.37 depicts the time periods chosen on each LTSA plot. For each data set, the 10 minute segment was taken and TOB analysis run at 1 minute intervals, integrated over a period of 10 s. Plots were again produced of the TOB band power and TOB CPB over the course of the segment for selected frequencies, figures 4.38 (inner 1) and 4.39 (inner 2). Both show, even in this relatively quiet period, significant variation in TOB levels over the 10 minute sequence both in time domain and TOB analysis across the sequence, with variation as high as 20 dB over a period of 20 s.

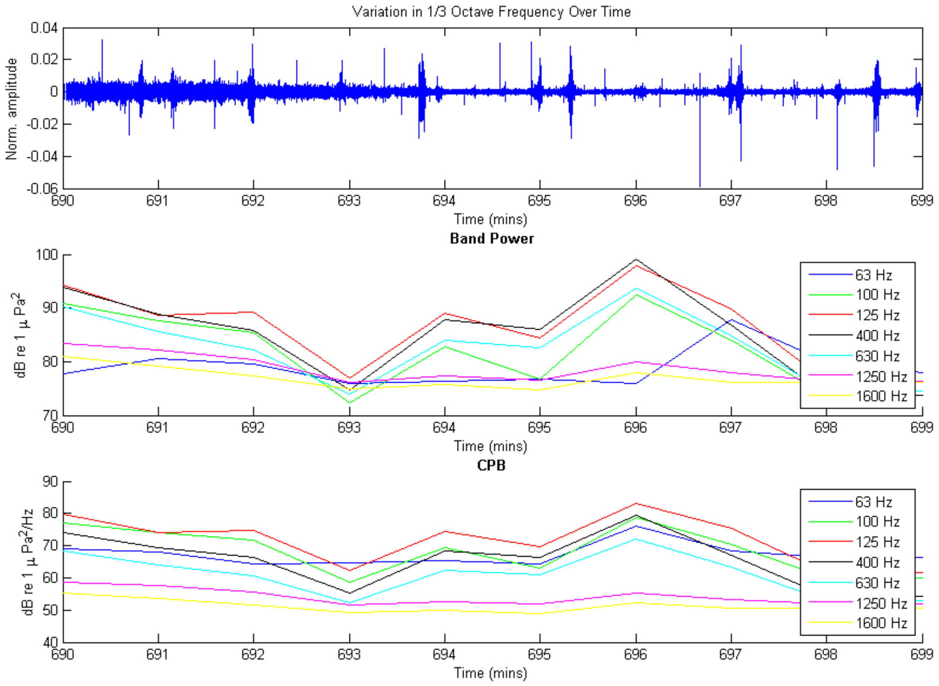


Figure 4-38: Variation in third octave frequency over the course of site comparison 1 (inner 1) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

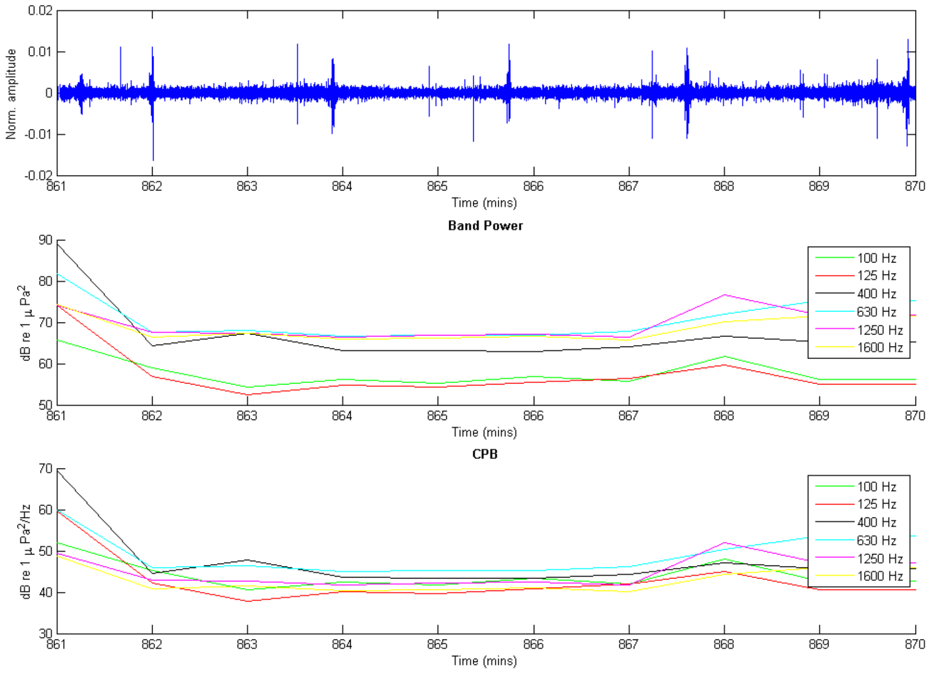


Figure 4-39: Variation in third octave frequency over the course of site comparison 1 (inner 2) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

Overall, the CPB spectral density for inner site 1 ranged between around 45-85 dB re 1 µPa^2 Hz^{-1}, while for inner site 2 the range was around 10 dB lower at 35-70 dB re 1 µPa^2 Hz^{-1}. Site 1 demonstrated the lowest levels for the higher frequency bands 1250 and 1600 Hz.

Figures 4.40 a-d) shows the CPB power for the broadband boat based measurements at times 11:29 (inner site 1), 11:55 (inner site 1), 14:05 (inner site 2) and 14:15 (inner site 2) on the 28th July 2010. Figure 4.40 a) inner site at 11:29 shows a more stable period with lower standard deviation particularly at higher frequencies. This can be compared with significantly lower average levels (20-30 dB) seen 25 minutes later shown at the inner 1 site, Figure 4.40 b). Higher variation is seen across all frequency bands most likely due to the variation in local traffic over time. Figure 4.40 c and d again show similar variation both in general level and in standard deviation across the integration period to that seen at the first inner site with variation of around 20 dB seen within the 10 minutes sequence.

Comparing a relative ‘quiet’ segment of data (time period 1) from frame C (Figure 4.3) to the inner site sequences (figure 4.37) indicated CPB spectral densities were overall around 18 dB re 1 µPa^2 Hz^{-1} lower, on average, at the inner sites compared to at the frame C location. Of all the frequency bands assessed, the 100 and 125 Hz bands were roughly 10 dB re 1 µPa^2 Hz^{-1} lower than the other bands at west frame C site.

Comparing a relative ‘noisier’ sequence (time period 3) of data from frame C (Figure 4.3) to the inner site segments (figure 4.37) indicated CPB spectral densities were overall around 37 dB re 1 µPa^2 Hz^{-1} lower, on average, at the inner sites compared to the same time period on the west frame C. At the west C site, the 400 and 630 Hz bands appeared elevated as compared to the other frequencies, which was not observed at the inner sites.

Comparing a relative ‘noisier’ sequence of data from the east SSB (figure 4.9) to the inner site segments (figures 4.37) indicated CPB spectral densities were overall around 15 dB re 1 μPa^2 Hz^{-1} lower, on average, at the inner sites compares with the east SSB data.

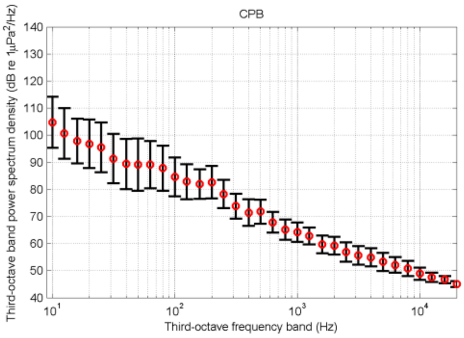


Figure 4-40 (a): Averaged data (11:29 28th July 2010) Boat based deployment at inner site 1. Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

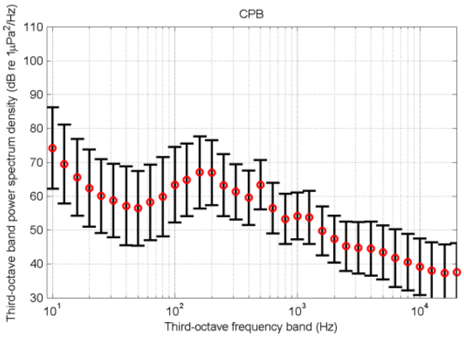


Figure 4-40 (b): Averaged data (11:55 28th July 2010) Boat based deployment at inner site 1. Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

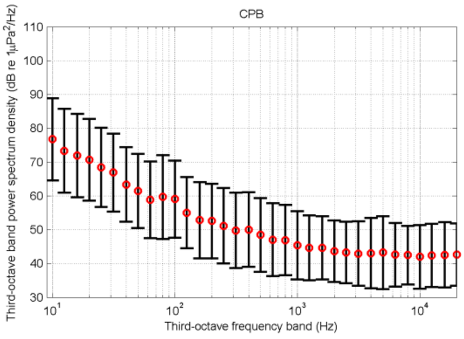


Figure 4-40 (c): Averaged data (14:05 28th July 2010) Boat based deployment at inner site 2. Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

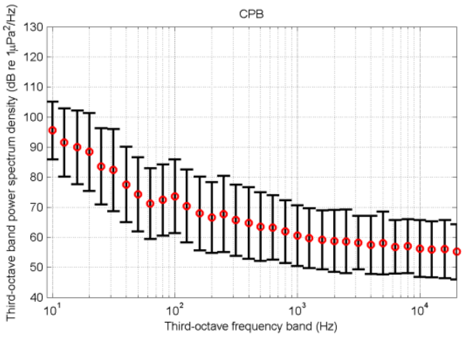


Figure 4-40 (d): Averaged data (14:15 28th July 2010) Boat based deployment at inner site 2. Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

4.5 SHORT TERM TEMPORAL VARIATION

Several events were identified within the data set for further analysis; from the frame C recorded data and south SSB data. West frame C events are indicated on the LTSA plot in Figure 4.3, and for the south SSB in Figure 4.10.

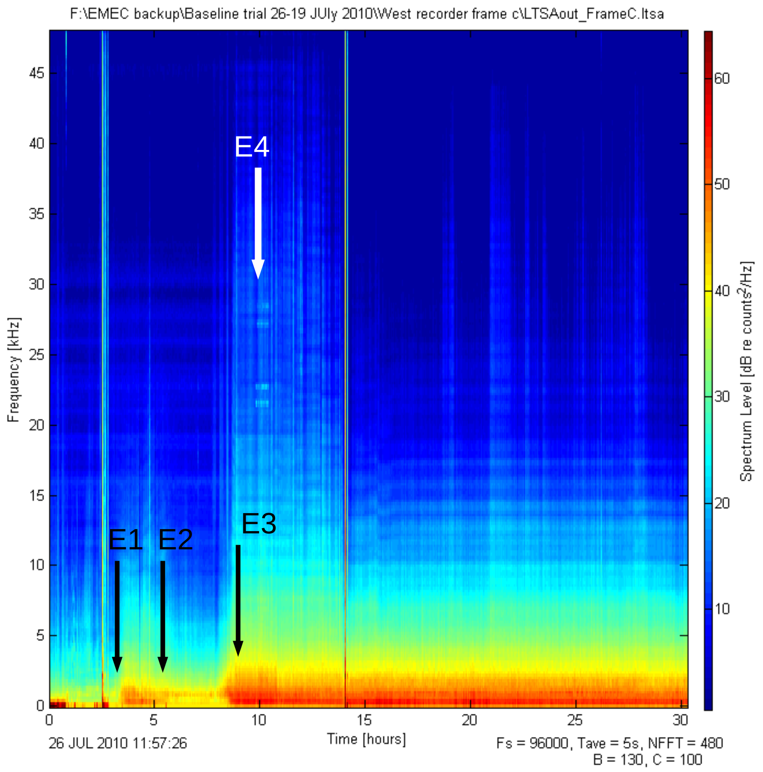


Figure 4-41: Specific events from the frame C data set indicated on the LTSA by white arrows.

Event 1: 26 July 2010 15:27-15:37 noise level increase

During this period the noise level, particularly at lower frequencies, appeared to increase (see figure 4.41). Figures 4.42 show the TOB analysis for the 10 minute segment run at 1 minute intervals, integrated over a period of 10 s, for the corresponding data segment recorded at frame A (north) and C (west).

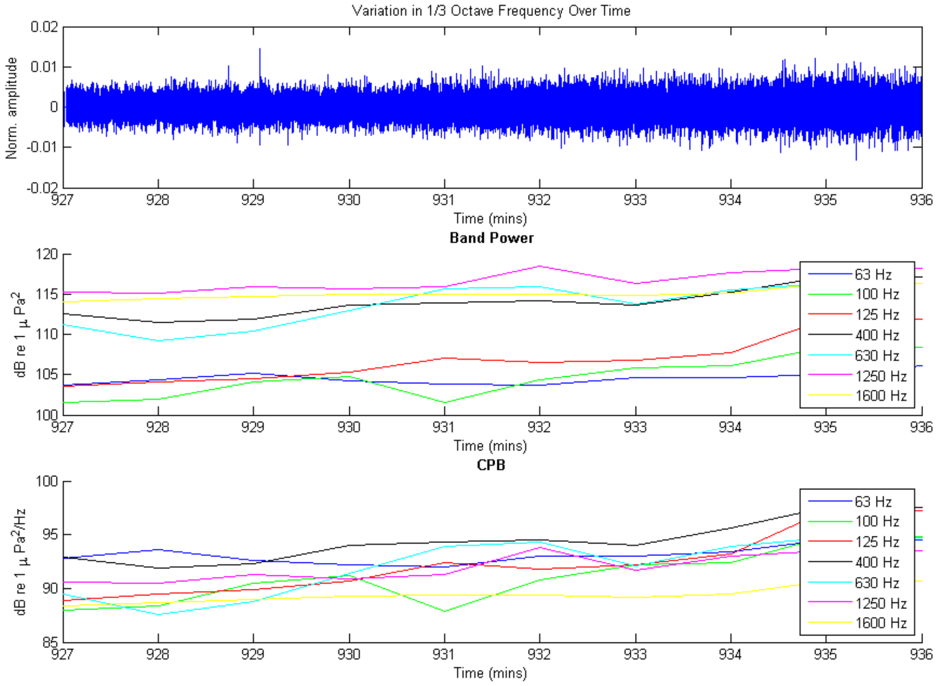


Figure 4-42: Variation in third octave frequency over the course of event 1 (frame A) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

During this event, the CPB spectral density appeared to increase over time for the frequencies assessed. At frame A the overall level was recorded to rise from 88-93 dB re 1 μPa^2 Hz^{-1} to 91-98 dB re 1 μPa^2 Hz^{-1} (mean +4 dB increase), while at frame C the level rose from 76-92 dB re 1 μPa^2 Hz^{-1} to 86-96 dB re 1 μPa^2 Hz^{-1} (mean +7 dB rise).

Event 2: 26 July 2010 17:27-17:37 noise level change

During this period the noise level, particularly at lower frequencies, appeared to be lower than previously (see Figure 4.41). Figure 4.43 shows the TOB analysis for the 10 minute segment run at 1 minute intervals, integrated over a period of 10 s, for the corresponding data segment recorded at frame A (north) and C (west).

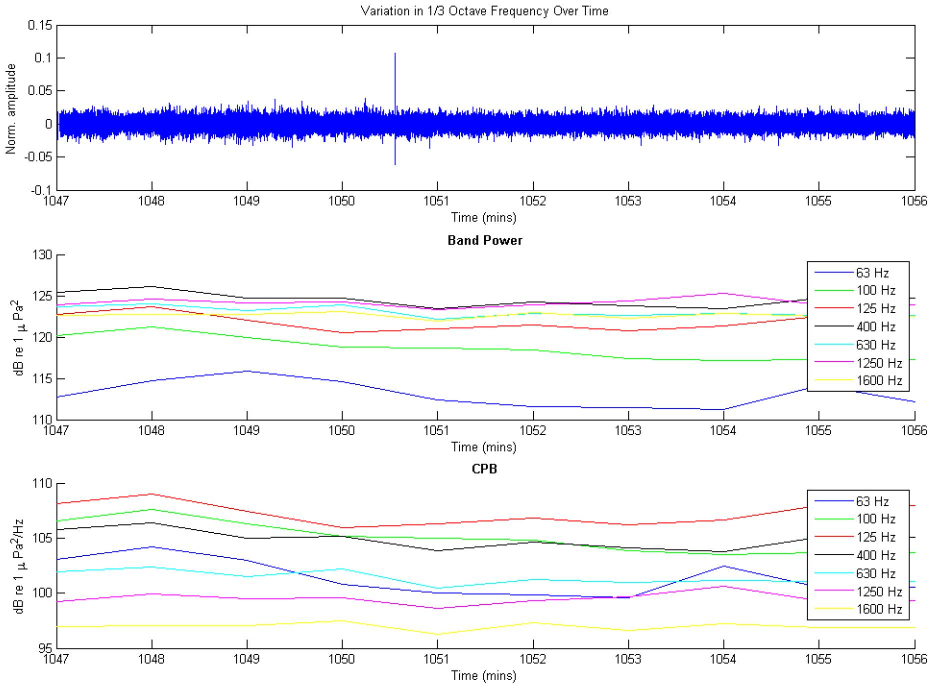


Figure 4-43: Plots demonstrating the variation in third octave frequency over the course of event 2 (frame A) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

During this event, the CPB spectral density appeared to remain roughly constant over time for the frequencies assessed. At frame A the overall level was recorded at 97-108 dB re 1 μPa^2 Hz^{-1}, while at frame C the level (excluding the 63 Hz band) was recorded at 76-91 dB re 1 μPa^2 Hz^{-1}. Interestingly, this on average was still around 23 dB higher for frame A and 4 dB higher for frame C than the 'quiet' period levels of time comparison 1.

Event 3: 26 July 2010 20:21-20:41 noise level increase

During this period the noise level, particularly at lower frequencies, appeared to be higher than previously (see figure 4.41). Figure 4.44 shows the TOB analysis for the 20 minute segment run at 1 minute intervals, integrated over a period of 10 s, for the corresponding data segment recorded at frame C.

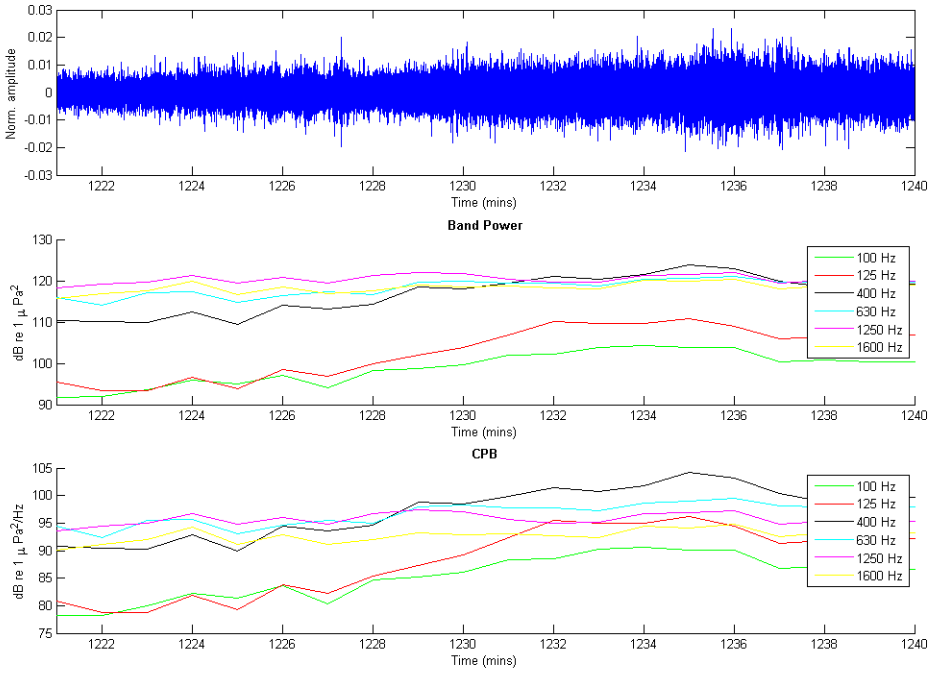


Figure 4-44: Variation in third octave frequency over the course of event 3 (frame C) for selected frequencies (inset). Figure shows time domain of segment (upper), TOB band power (middle) and TOB CPB (lower).

During this event, the CPB spectral density appeared to increase over time for the frequencies assessed. At frame C the overall level (excluding the 63 Hz band) was recorded to rise from 78-94 dB re 1 µPa^2 Hz^{-1} to 87-100 dB re 1 µPa^2 Hz^{-1} (mean +8 dB). Overall, this noise level increase for frame C was similar to that recorded at event 1.

Event 4: 26 July 2010 22:58-23:02 mid- frequency intermittent components

During this period broadband clicking occurred in the higher frequency region of the data, starting at around 6 kHz. Pulses were around 10 ms duration. With the frequency of highest energy of this example at around 6 kHz, with a secondary peak at 11 kHz and high-frequency peaks at 17, 20, 31 and 34 kHz.

4.6 BASELINE MEASUREMENTS 12TH MAY 2011

Additional measurements were made during operational noise measurements conducted between 9-12th May 2011 at the Billia Croo site. On this occasion site weather conditions were significantly better with significant wave heights of average 63 cm and wind speed of 1.3ms^{-1}. On this occasion an operation WEC system under test was deployed on the north of the EMEC site. Measurements were conducted just north of the south cardinal buoy at a range of 2.4 km from the Pelamis system, figure 4.45. In addition to the range data was selected to avoid significant additional contribution from the Pelamis system.

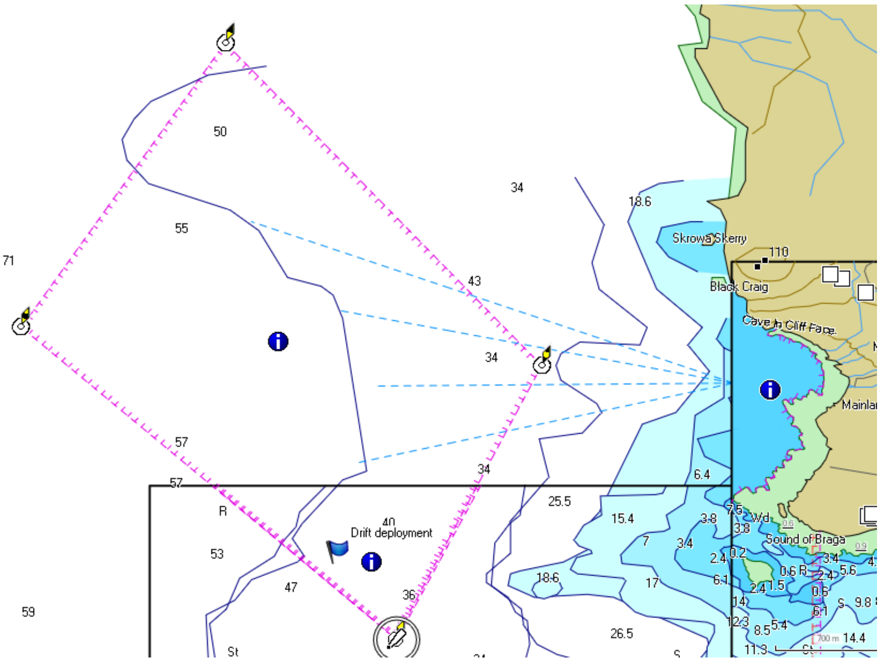


Figure 4-45: Boat based drift deployment 12th May 2011. Position ~ 2.4 km south of Pelamis system.

Data were analysed for a 4 minute, 150 kHz bandwidth sequence to produce averaged data from consecutive 1 second integration periods across the sequence as used with previous analysis. The mean, minimum and maximum third octave band (TOB) power is shown in figure 4-46 and the mean constant percentage bandwidth and ±1 standard deviation is shown in figure 4-47.

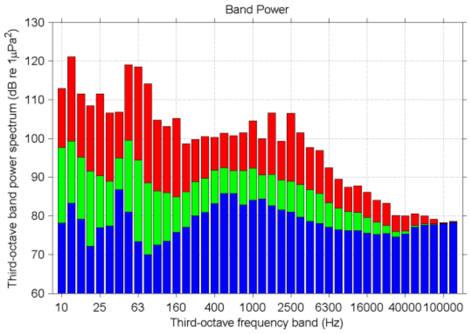


Figure 4-46: Averaged TOB power data (11:58 12th May 2011) Boat based deployment at Billia Croo). Averaged maximum (red), mean (green) and minimum(blue)

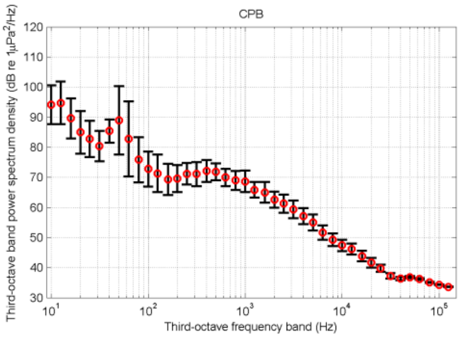


Figure 4-47: Averaged data (11:58 12th May 2011) Boat based deployment at Billia Croo. Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation.

Data show mean CPB levels of around 65 dB re 1 µPa^2 Hz^{-1} in the 1 kHz TOB with levels of around 72 dB re 1 µPa^2 Hz^{-1} in the 500 Hz band. Stronger components can be seen in the 40 and 50 Hz bands. With mean levels around 90 dB re 1 µPa^2 Hz^{-1}. General levels are below 45 dB re 1 µPa^2 Hz^{-1} at frequencies greater than 10 kHz with a standard deviation of around 5 dB for frequencies below 1 kHz. Weather conditions were relatively good with mean significant wave height from wave rider data of 64 cm and wind speeds of 1.3 ms^{-1} corresponding to a sea-state of around 2-3. Wind and wave directions were westerly during measurements[4].

4.7 CTD MEASUREMENTS

Both up and down CTD casts were conducted periodically both at the Billia Croo and the two inner sites. Figure 4-48 shows data from both Billia Croo and Inner site 1 from the 27th July 2010. Both profiles show maximum sound velocity variation of less than 0.5 ms^{-1}. The Billia Croo site has a slight minimum profile around 10 m water depth at Billia Croo with a similar slight minima at 7m depth at inner site 1. The maximum velocity at the surface of around 1499.8 ms^{-1} at Billia Croo and 1500 ms^{-1} at inner site 1. Figure 4-49 shows both up and down sound velocity profile at the inner 2 site taken on the 28th July 2010. In this case the profile is slightly positive with depth with surface values similar to that seen at the other two sites.

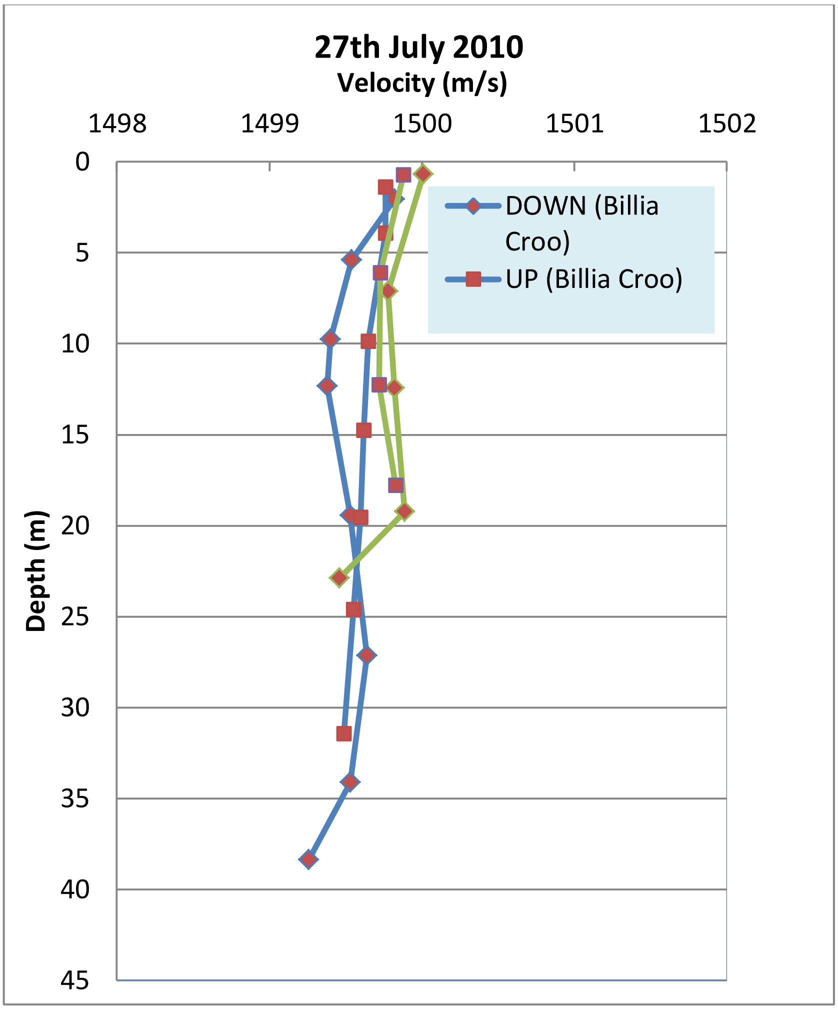


Figure 4-48: CTD profiles 27th July 2010. Billia croo and Inner site 1.

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[4] Metrological and wave rider data provided by EMEC Ltd

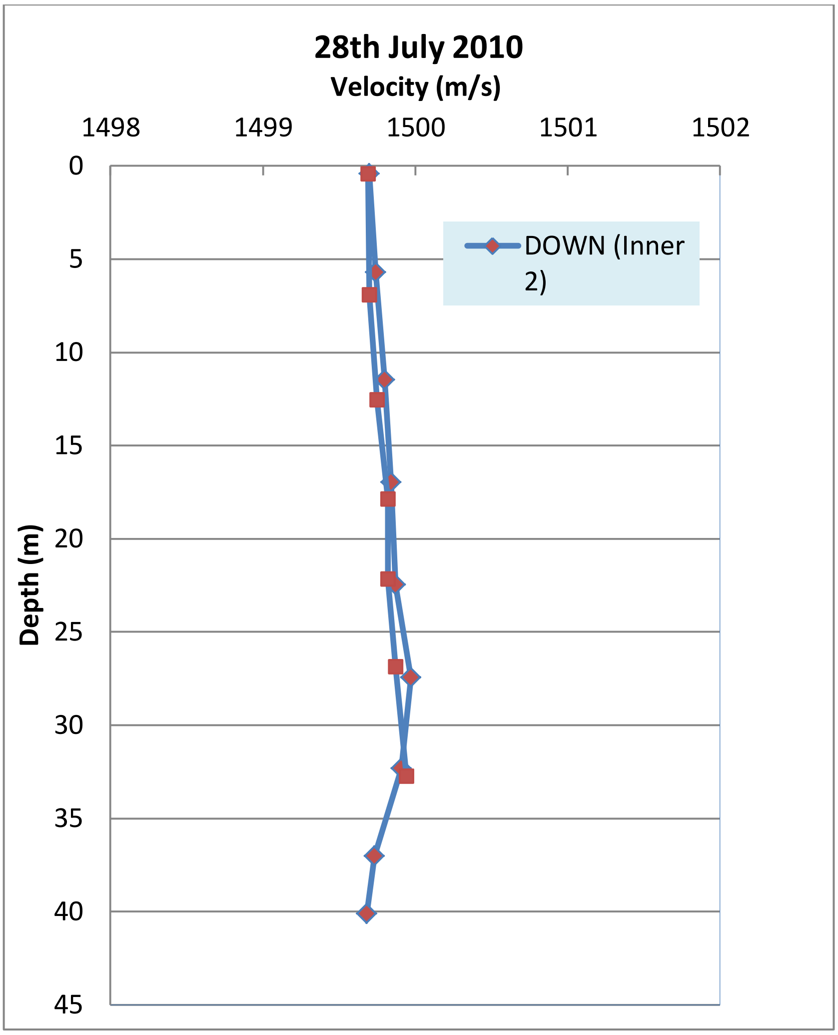


Figure 4-49: CTD profiles 27th July 2010. Inner site 1 & 2.

4.8 WEATHER DATA

Figures 4-50 and 4-51 show significant wave height from wave rider buoys at the EMEC site. Both profiles show significant wave heights during most of the measurement period with variation from 70 to 200 cm across the entire period. The period shortly after deployment of the north and west frames corresponding to the lowest wave height of entire trial period ranging from 70-80 cm. During the 27th July a gradual increase from around 70 cm to greater than 150 cm can be seen. Levels as high as 150 -200 cm were then seen throughout the 28th July and then again 125-200 cm on the 29th. Figure 4-52 shows variation of wind speed across the measurement period with variation ranging from 1-6 ms^{-1} across the entire period, with occasional significant increases across most of the trial period, with the highest consistent wind speeds seen on the 29th July. Sea states ranged from slight (3) on the 26th through to 4-5 later on 27th to 29th.

Wind direction was predominantly north westerly with occasional short term southerly period. The wave direction was relatively stable during the period 26-29th July in range 265°-300 degrees°.

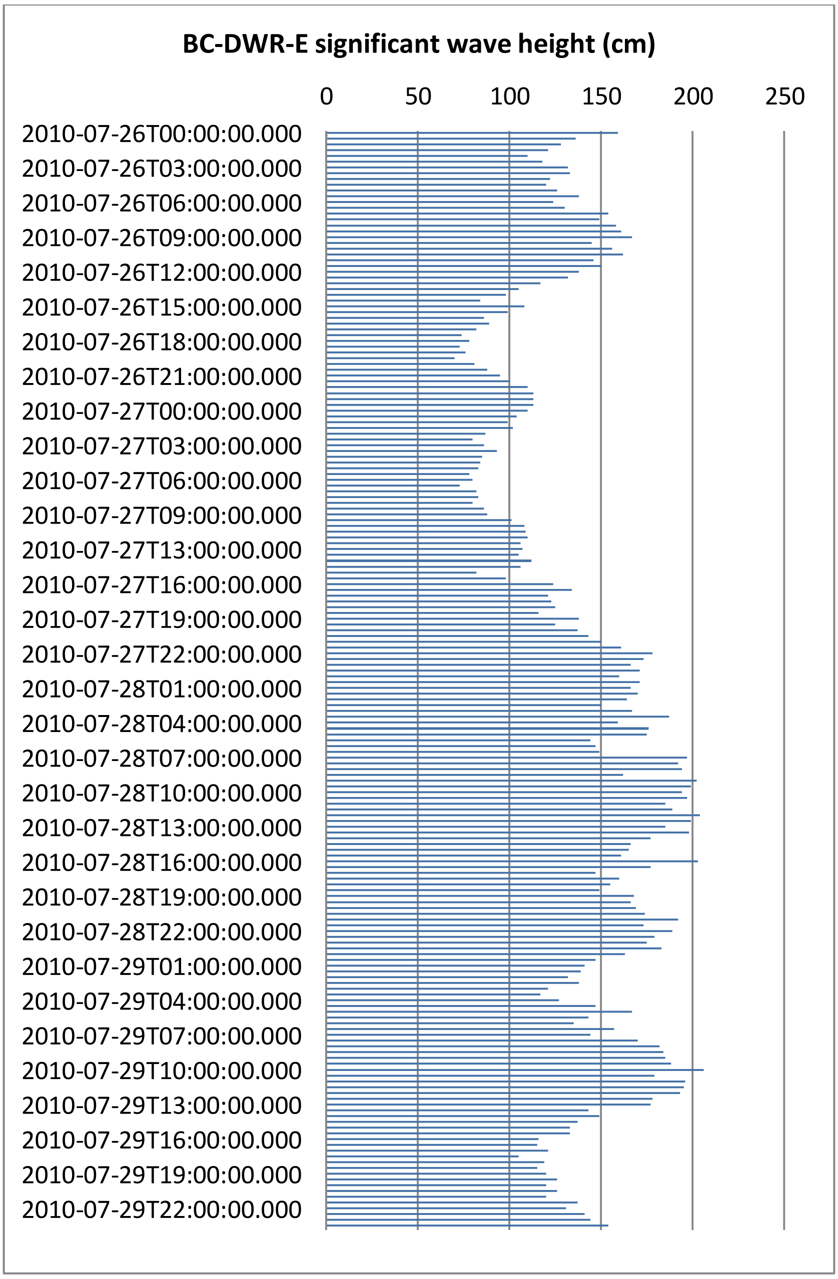


Figure 4-50: Significant wave height 26th-29th July 2010. (wave rider BC-DWR-E) [Data provided by EMEC Ltd.]

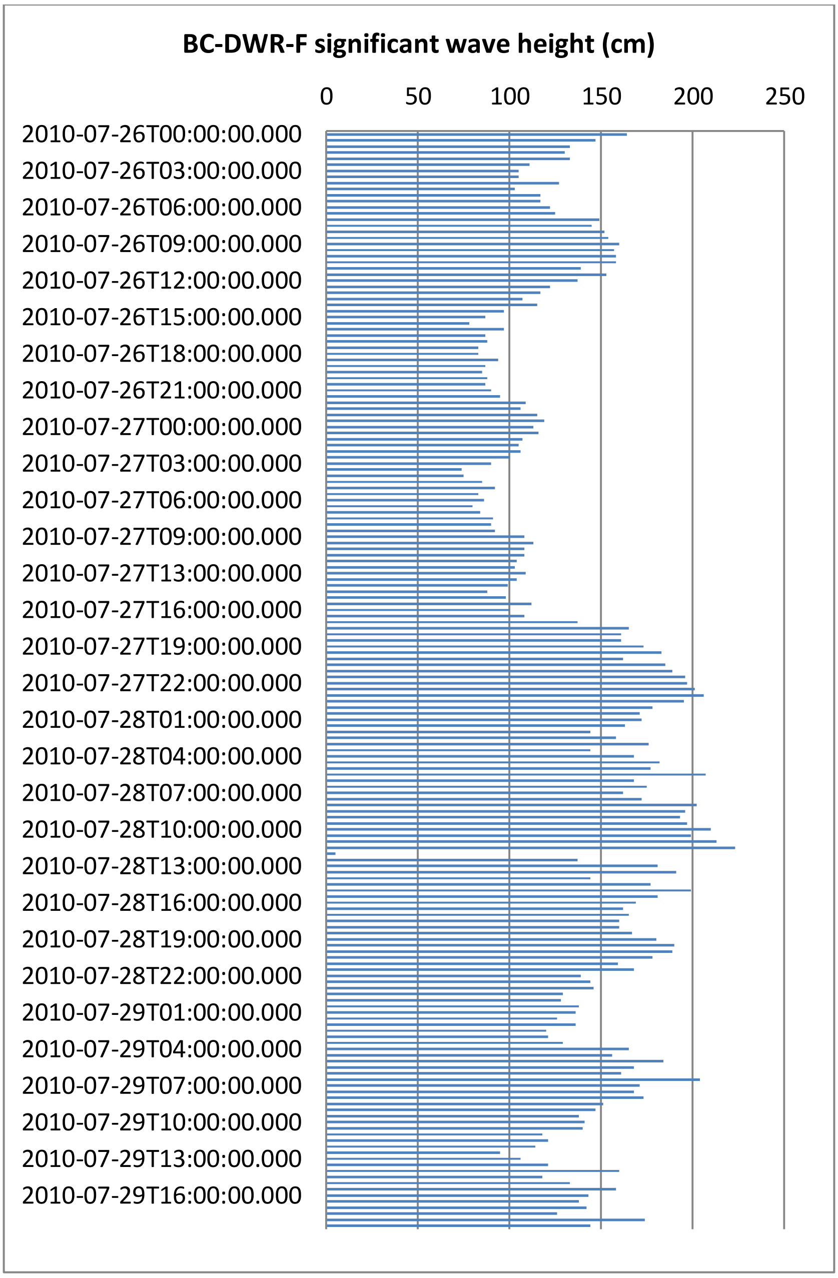


Figure 4-51: Significant wave height 26th-29th July 2010. (wave rider BC-DWR-F) [Data provided by EMEC Ltd.]

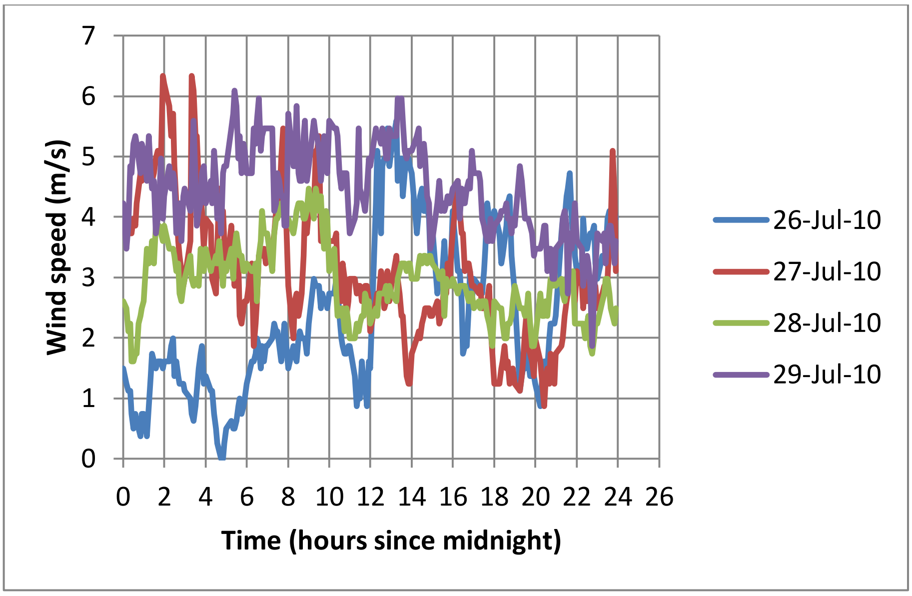


Figure 4-52: Wind speed 26th-29th July 2010.
[Data provided by EMEC Ltd.]

5 SUMMARY

Underwater background noise levels have been measured at the EMEC wave energy convertor test site under differing weather conditions across the full hearing range of all likely marine receptors. The initial noise level assessment was conducted at the EMEC wave energy converter test site at Billia Croo, Orkney between 26thand 29th July 2010. These data were supplemented with additional data collected in June 2010 and during device operational noise trials in May 2011 both at the Billia Croo site. During July 2010, long term autonomous seabed recorders were deployed at sites to the north and west of the site. Additional autonomous sub-surface recorder systems were deployed for various periods at locations on the east and south of the site. Additional measurement was made at two ‘inner’ sites between the island of Hoy and Orkney. Various broadband boat based surveys were also carried out during the entire measurement period.

Analysis of data was carried out in third octave bands to determine third octave band power (TOB) and constant percentage bandwidth power spectral density (CPB). Simultaneous recordings across the sites were made to determine noise levels during the measurement period and comparison made for spatial and temporal variation in levels across the sites surveyed. During a majority of the measurement period the dominant noise source at the wave energy site was due to the presence of the CS Sovereign, a cable laying vessel. Figure 5-1 below shows the long term spectral output at the west recorder site over a 30 hour period.

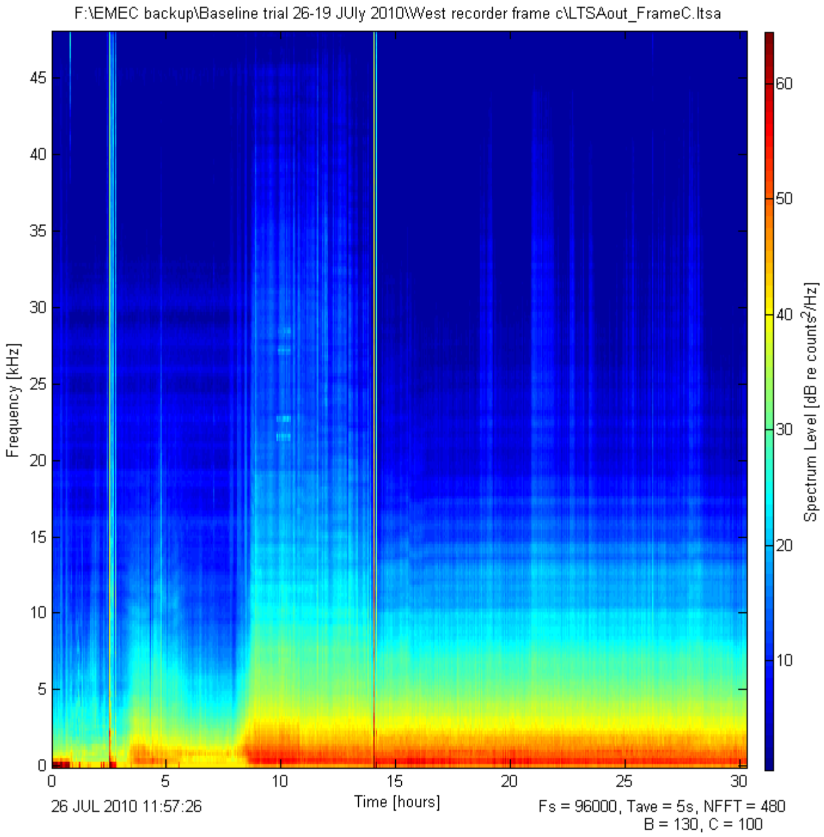
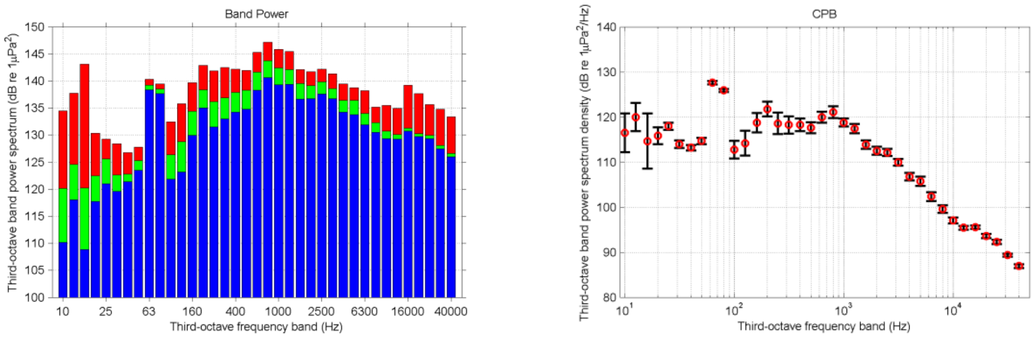


Figure 5-1- Long term spectral average for frame C (west).

These data show significant increase in noise level in band below 10 kHz across the site in a period between 14:00 (figure 5-2) and 22:00 (figure 5-3) on the 26th July 2010. Figures 5-2 and 5-3 show variation in noise levels in the bands from 100 Hz and 1 kHz of around 15-20 dB during the initial measurement period. Lower and higher frequency bands however remain relatively stable over this period.

Averaged maximum (red), mean (green) and minimum(blue)

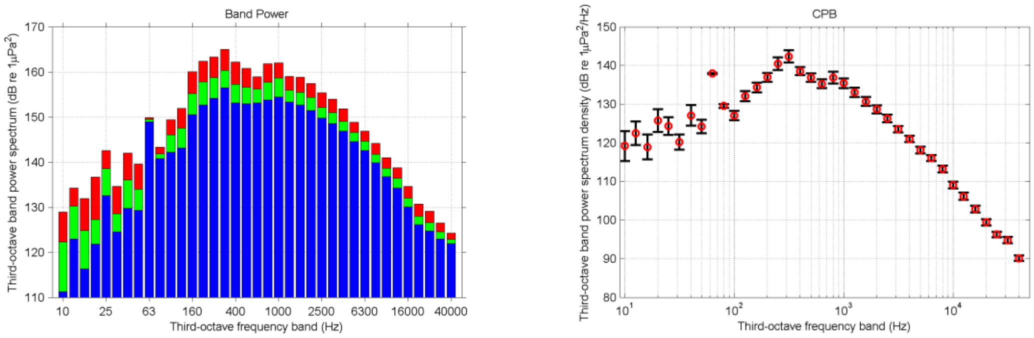
Red circles mean values, bars ± 1 standard deviation.



Averaged TOB power data for a 10 minute sequence (C1) data Frame C (West)

Averaged CPB data for a 10 minute sequence (C1) Frame C (West)

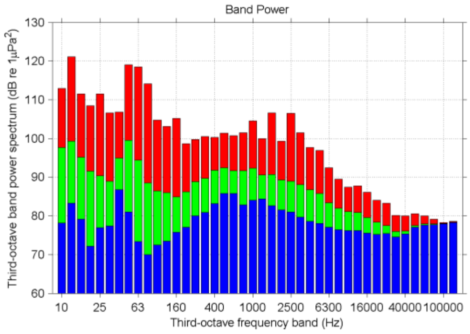
Figure 5-2: West frame 26th July 2010 14:12



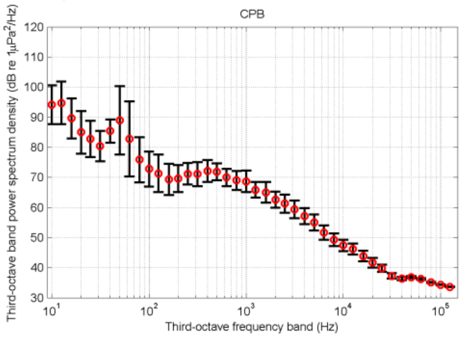
Averaged TOB power data for a 10 minute sequence (C4) data Frame C (West)

Averaged CPB data for a 10 minute sequence (C4) Frame C (West)

Figure 5-3: West Frame 26th July 2010 22:00



Averaged TOB power data (11:58 12th May 2011) Boat based deployment at Billia Croo).



Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows.

Figure 5-4: Boat based deployment 11:58 12th May 2011.

The majority of this contribution in the July 2010 data is likely to be from the presence of the CS Sovereign and changes in its operational status over time. Both periods during the July 2010 trials period can be compared with data from May 2011 (figure 6-4). In this case the CS Sovereign was not present and the site was clear, with the exception of a single wave energy convertor deployed (but not operating) 2.4 km to the north. The May 2011 data shows significantly lower levels across most of the bands. For example, in the case of the 400 Hz band, CPB levels range from 70 dB re 1 μPa^2 Hz^{-1} in 2011 in sea-state (2-3) compared with 115 dB re 1 μPa^2 Hz^{-1} for the quietest period seen in 2010, and as high as 140 dB re 1 μPa^2 Hz^{-1} during the noisier period in a sea state 3 equivalent conditions.

High level components in the 63 Hz third octave were observed in some of the July 2010 Billia Croo data across the site and recording platforms, shown in figures 6-2 and 6-3. High resolution linear spectral analysis showed a strong narrow band 67 Hz tonal component contributing to this level. If present, this component was extremely stable at relatively high levels, however this component was not present in all data sets or consistently in individual data sets. This component was observed occasionally on all systems. Post analysis of systems and difference in design and spatial isolation eliminated electronic interference. The source of this component is unknown and previously not observed in the systems. This component was not observed in the May 2011 data analysed.

The analysis given in this report shows significant variation both temporally and spatially across the Billia Croo site and in comparison with the inner sites, over relatively short periods. The use of 1 second integration periods averaged over a sequence of minutes showed significant variation both in level standard deviation and observed maximum and minimum levels. In the case of the inner site measurements general levels were slightly lower than that observed at the Billia Croo site, however significant variation was observed due to passing ship traffic resulting in levels in excess of that shown in figure 6-4. Additional noise sources were identified at the Billia Croo site independent of components likely from the CS Sovereign, all of which are likely to contribute part of the general sound scape at the Billia Croo site. These include observed examples of mooring noise (chains and unidentified 'squeaks') potentially associated with the cardinal buoys and, in case of July 2010, navigation markers for a second wave energy convertor system (now not present), the regular ferry passage to the south of the wave site, boats operating on site (such as the Flamborough light and the Voe Viking) and weather variations.

The current data show no significant evidence of increased noise levels to the east of the site that can be directly attributed to surf noise. Noise levels to the south of the site were generally higher, potentially due to the proximity of the ferry and boat passage and increased tidal flow and surf noise to east.

Data from the May 2011 measurements are felt to be generally indicative of potential site noise levels under good sea state conditions. These data contain contribution from distant shipping (ferry etc. and wave device at 2.4 km) and associated site mooring noise in these sea-states. Level are, however, likely to be higher and more widely variable with operational vessels such as the Voe Viking and the CS Sovereign on site. Comparison of levels at sea-state 2-3 (slight) and 3-4 (moderate) showed general variation in levels with increasing sea state consistent with published deeper water noise data.

Although very little data currently exists for output characteristics of wave energy converter systems a review in [EMEC, 2011] suggests considerable overlap of the potential frequency range of WEC systems and potential levels for regularly occurring baseline noise levels from a few 10 Hz to 10's kHz. With the baseline noise levels generally higher at lower frequencies but also highly variable dependent on weather conditions, local traffic etc. Similarly WEC system have potential for higher noise levels in higher sea-states due to more energetic motion, higher wave noise (slap, bow waves, etc.) Correspondingly higher noise levels would be expected due to wind driven background noise and surf noise in higher sea states. A significant potential long term contribution to baseline levels is from distant or close by shipping traffic where boat noise for example often contributes significantly to the overall spectrum of a few tens of Hz to a few kHz. It is likely that outputs from some WEC systems could contribute to the general sound scape in similar frequency bands due to small scale (internal) and large scale mechanical motion, gearbox, hydraulic, generator, etc. related noise at larger ranges and components may be individually detectable at shorter ranges.

At higher frequencies (> 10 kHz) noise levels both from weather related sources and boat traffic generally are lower, however the outputs from WEC systems is currently unknown. A number of cetacean species are known to occur in and around the EMEC test site with hearing ranges from a few 100's Hz to greater 150 kHz cover [EMEC, 2011]. The lower frequency bands from a few 100 Hz to a few kHz overlaps with regularly occurring noise sources that these species are likely to encounter as seen in this report.

The generally lower baseline levels at higher frequencies for some cetacean species corresponds with increased hearing sensitivity band associated with echolocation etc. This increased hearing sensitivity and lower ambient levels may allow detection of higher frequency components from WEC systems if they occur. Any higher frequency components however are more likely to be attenuated at shorter ranges due to higher attenuation losses at higher frequencies. Any noise measurement methodology should be designed to consider potential hearing range of marine species and corresponding hearing sensitivity and likely baseline noise levels.

REFERENCES

[EMEC, 2011] “Acoustic Noise Measurement Methodology for the BILLIA CROO European Marine Energy Centre wave energy test site (EMEC): Background Data Review”, Lepper P.A, Harland E., Robinson S.P., Hastie G., & Quick, N., EMEC Report No. EMEC_007_09_01 (2011).

SECTION 4:

MEASUREMENT METHODOLOGY FOR OPERATIONAL NOISE ASSESSMENT OF WEC SYSTEMS

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1. INTRODUCTION

1.1 BACKGROUND TO REPORT

This report has been produced for the European Marine Energy Centre (EMEC) under contract EMEC_007_09 by a consortium led by Loughborough University in partnership with the National Physical Laboratory, Chickerell BioAcoustics and the Sea Mammal Research Unit acting through SMRU Ltd.

The aim of the work undertaken is to provide a methodology appropriate for underwater operational noise assessment of Wave Energy Converter (WEC) systems at the EMEC WEC test site, located off Billia Croo, Mainland, Orkney Islands. It also provides a baseline acoustic characterisation of the site. The project is intended to provide developers with both the baseline acoustic characterisation of the site, and a robust and repeatable methodology for gathering future acoustic data from the site once devices are operational, that will ensure consistency with the baseline site characterisation data made available to them. It is therefore an enabler for developers wishing to characterise the noise signature of their devices.

This report outlines the development of a revised methodology based on output from three earlier phases of work. The first two phases include a review of relevant background data related to the overall project aims including related standards, regulatory impact guidance, likely biological receptors etc. [EMEC, 2011a] and a baseline noise assessment [EMEC, 2011b]. These data providing a baseline for decisions made in the development of the interim measurement methodology [EMEC, 2011c]. In the third phase trials of a proposed interim methodology were conducted on an operational attenuator WEC system in the summer of 2011. Based on lessons learned from all three phases, details of a revised underwater acoustic assessment methodology are given in this report.

The report is organized such that the main body of the report outlines the revised measurement methodology including both the measurement and data analysis proposed. Analysis examples are drawn from the baseline noise survey and from other industries for illustrative purposes.

1.2 THE EUROPEAN MARINE ENERGY CENTRE (EMEC)

The European Marine Energy Centre provides developers of wave and tide energy converter devices with performance testing facilities. It is located in the Orkney Islands off the north of Scotland. It has two principal grid-connected test sites, one for tidal devices and the other for wave devices [EMEC, 2011d], and two non-grid connected nursery sites for smaller-scale testing in more sheltered open water

The main wave energy converter test site is located off Billia Croo on the west side of Mainland, the principal island of the Orkney Islands group. It is to the north of Hoy Mouth, the western entrance to Scapa Flow. This site is very exposed to the west and provides high energy waves to exercise devices under test. Shore side facilities provide cable connections from the test devices through a sub-station at Billia Croo and to the National Grid. There are also support facilities such as weather and oceanographic instrumentation and internet access.

2. UNDERWATER NOISE MEASUREMENT METHODOLOGY

2.1 INTRODUCTION

In May 2011 field trials were conducted to measure underwater acoustic output from a surface attenuator wave energy system at the EMEC Billia Croo wave site. These trials were carried out in order to assess the proposed interim measurement methodology developed for wave energy converter systems as part of contract (EMEC_ITT_007_09). Measurements conducted in 2011 facilitated review and revision of the methodology outlined in this report, based on this experience.

The final methodology developed and proposed for ongoing use has been based on the following work carried out as part of the contract with EMEC Ltd:

- A review of current and developing UK and European guidelines to ensure collected data falls in line with current and possible future requirements of the consenting processes followed by the developers and EMEC.
- Identification of marine receptors likely to be present at the EMEC wave test site and the particular characteristics of sounds that are likely to affect them.
- A review of appropriate current and developing measurement standards and methodologies for the sound output from other marine activities such a shipping, dredging etc.
- Analysis of operational trials using the interim methodology on a WEC system at the Billia Croo site.

The primary aim of the measurement methodology was to provide a robust reproducible methodology for the assessment of acoustic output from wave energy converter (WEC) systems. These systems are undergoing rapid development and already a wide variety of device concepts exist with emerging ones continuing to appear. One key requirement for the development of these systems is assessment of any potential impact that system may have on the marine environment during standard operation. The effects of underwater noise (unwanted, accidental, acoustic energy emissions) have been highlighted as being of particular concern. As such the consideration of operational underwater noise now regularly features in the Environmental Impact Assessment (EIA) process for system development and its characterisation often appears as a condition on licences to deploy.

Any measurement methodology should consider the temporal, spatial and spectral characteristics of a WEC system in terms of ‘received levels’ (RL) within the water column. Acoustic output may vary over time, related to device operational status etc. Similarly, many device concepts may exhibit varying spatial distribution of radiated noise, for example they may radiate sound differently in different directions due to system design and operation, and the sound may cover wide frequency ranges. The proposed methodology includes consideration of device spatial properties (directivity), determination of long term temporal variation related to device operational variations (e.g. changes in significant wave height), and radiated noise over frequency bands of all potential receptors.

The wide variety of WEC device concepts (see, e.g., [EMEC 2011e]) poses particular problems in the assessment of the noise field surrounding a device. In terms of acoustic assessment these system concepts generally fall into two physical categories termed here floating, or water column distributed (i.e. seabed mounted extending to the surface). In the review of current and developing WEC systems a number of key characteristics have been identified and are listed below.

Position

- Floating systems may include moored floating surface-based attenuator systems, point absorbers, floating overtopping systems, etc. These systems convert wave energy at the surface from a variety of directions. Depending on the system it will have varying degrees of motional freedom. Both overtopping systems and attenuators may have relatively complex but 'flexible' mooring configurations which allow them to turn with the dominant wave direction typically across a limited bearing range that may be as much as 180^0. By comparison point absorber systems are often hinged to seabed whilst still allowing motion of floating surface system over a more restricted range.

- Water column distributed systems such as oscillation wave surge converters and potentially point absorber systems, or submerged pressure differential systems, etc, are often hinged to a fixed seabed foundation allowing a more limited range of motion throughout the water column compared to some surface based systems.

Directivity

- A sea surface floating system is likely to have a sound field associated with noise sources close to the surface. These are associated with the device itself or wave interaction such as over-spilling or bow waves. This may vary along the device and be different in different directions. The potential also exists for noise generation associated with the mooring system located throughout the water column.

- The mechanical configuration of many distributed water column systems are often fixed with device motion in a specific orientation for example an oscillating wave surge system. In this case the sound field may vary depending on azimuth bearing from the device. Any directionality is likely however to be fixed relative to the seabed. In the case of point absorbers motion relative to variety of wave directions may be possible allowing wider variation in the horizontal (azimuth plane) sound field.

Operational mode

- Both types of system involve physical mechanical movement or water motion which is translated to electrical energy through a number of possible processes. These processes may generate noise. There may be additional noises peripheral to the energy generation method associated with mechanisms such as wave slap, etc. It is likely that these noises will be dependent on sea state and tidal conditions.

2.2 ASSESSMENT CONSIDERATIONS

A common practice in underwater acoustics is the use of the concept of a 'source level' to describe the acoustic output amplitude of a source. The source level can be used as a source amplitude term in a variety of propagation loss models allowing prediction of the variation in sound level with increasing range from the source. This predictive process is then used for assessment of sound fields in other locations using known source levels and specific propagation loss models (PL) which include information on the local environment. The ability to predict the sound field in a given environment is a common requirement of the current Environmental Impact Assessment (EIA) process. Traditionally, the 'source level' term refers to the acoustic output of a theoretical 'monopole' point source which characterises the source and is independent of the environment (under acoustic free field and far-field conditions). This type of source can then be implemented in a wide variety of propagation modelling techniques allowing the environment (seabed bathymetry, water depth etc.) to be considered. Determination of acoustic source levels and limits are discussed within this report.

The wide variety of WEC device concepts poses a particular challenge in terms of estimation of source levels due to the lack of free-field and far-field conditions during measurements. The systems themselves are acoustically large, and are often either distributed throughout the entire water column in the case of oscillating water column systems, etc, or may have a significant distributed surface presence such as the case of some attenuator systems. Current prototypes may have an overall length of greater than three equivalent water depths. In both cases a wide variety of sources of noise may exist distributed across entire systems and potentially different at different positions on the system.

Due to the above problems, the characterisation of the source in terms of a traditional source level is difficult without detailed knowledge of the position of specific noise source within the system in isolation from other contributing noise sources in the sound field. For example common attenuator systems may contain a series of hydraulic hinged joints between floating sections distributed over 10-100's m. Potential noise from the hinge systems may occur from any of these joints at any time making isolation of the noise source problematic at a recorder system some distance away. At any one moment, a measurement of the sound field made at some distance from the source will potentially contain contributions from a wide variety of distributed sources within the system. The variety of distributed sources on the device will potentially act as a form of distributed array with different sources at different effective ranges. As such, this array will have a complex near-field (an area close to device where interference of signals from different noise sources may provide a complex highly variable sound field, where sound appears to come from a variety of directions). At greater ranges, an array far-field condition may be reached where combined noise components appear to radiate from a single point.

Figure 1 shows a simplified example of complex arrivals for a distributed noise components for a hypothetical attenuator WEC system. In this example relatively large variations in the effective range from source can be seen from various potential noise components across the device. At shorter ranges to any recorder system, the relative effect of the range differences (or range errors due to uncertainty in position) has much larger effect on measured received levels and therefore associated source level estimates. At greater ranges the effect of the range difference will be significantly reduced. The effect of range associated errors is discussed further in section 4.5.

Additionally, energy from any one source is likely to interact with the environment; for example an arrival signal may contain a direct path (a straight line between source and receiver) and numerous multi-paths where energy has been reflected from sea surface and seabed to varying degrees. In many cases the noise source may be at the surface or close to the seabed. Figure 2 shows a hypothetical example of a distributed water column device such as an oscillating wave surge converter. In this case examples of potential multipath arrivals are shown between potential source positions and a recorder system. These multi-paths are likely to be delayed and lower in amplitude (due to longer propagation paths and reflection losses) than the direct path components. However for longer duration signals where the direct path components are still present after arrival of delayed multi-path signals, the potential exists for constructive and destructive interference effects. These may result in complex sound fields with high levels of temporal and spatial variation.

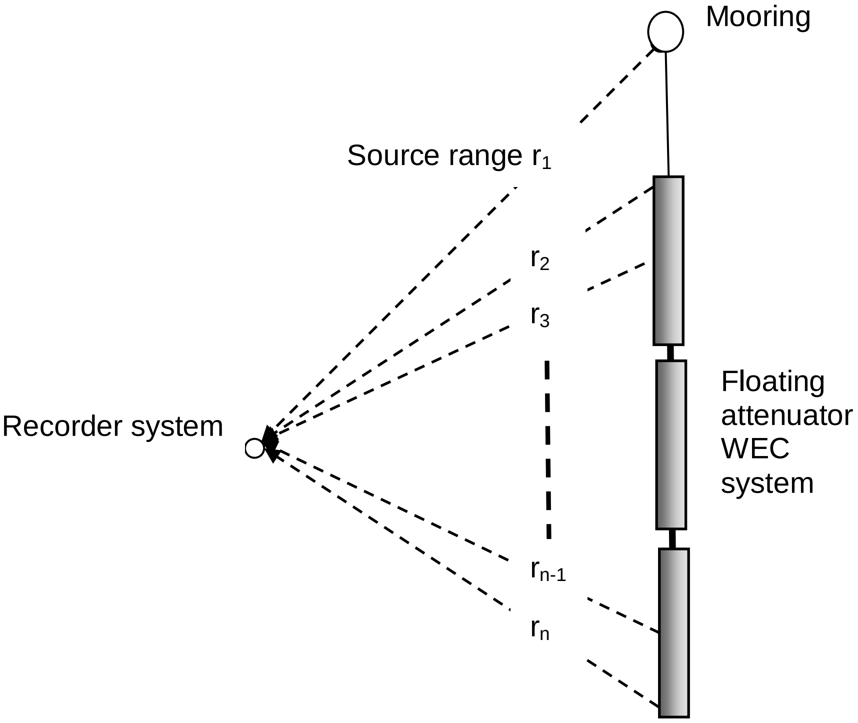

Figure 1: Plan view example of potential complex arrivals for distributed noise components from a floating hypothetical attenuator WEC system.

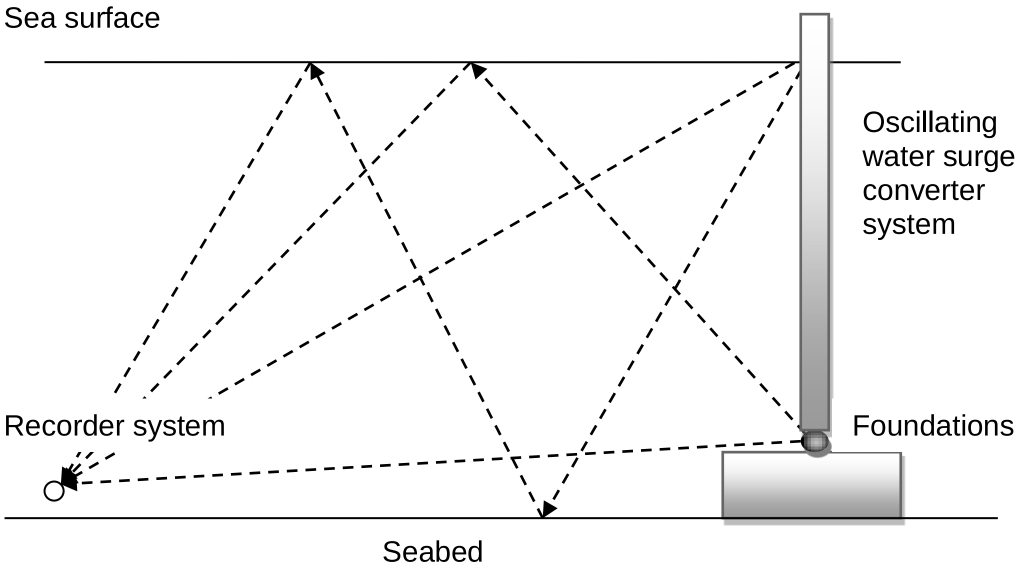

Figure 2: Example of potential multi-paths arrivals from a hypothetical distributed water column system such as an oscillating wave surge WEC system.

The complex combination of signals from a distributed device as shown in Figure 1 and multi-path arrivals in Figure 2, are also seen in other systems such as shipping [ANSI S12.64, 2009] and marine dredging [Robinson et al, 2011a] particularly in shallow water. In these cases, there is additional large scale directional motion of the source in relation to any static recording system. An approach that has been adopted in these cases is to integrate the total received energy (from all noise source components) in a variety of frequency bands usually for a defined angular sector of travel either side of the closest point of approach (CPA).

A similar approach is proposed here, where recorder systems are placed far enough away from the WEC system to allow array far-field arrival of complex (multiple sources distributed across the system), and combination of complex, sea surface and seabed interaction in the surrounding water. A range at which both surface and seabed interactions are well developed and greater than distributed array far-field is termed the 'source far-field' in this report and it related to both the device geometry and distribution and the water depth and bathymetry. In this case, the greater measurement range reduces the relative effect of the spatial distribution of potential noise sources associated with a device and multipath arrival. Numerical modelling approaches may then be used to estimate a theoretical noise source position, i.e. a point at which radiated noise when viewed from a distance in the far-field appears to radiate from.

Due to the considerations above, two measurement configurations are proposed with different measurement configurations for floating WEC systems such as attenuator systems and distributed water column systems such as an oscillating water surge WEC system. The intent however is to capture identical data and allow direct comparison between generation systems. It is likely that systems will show significant variation in acoustic output over time due to different wave / weather conditions and potentially device position depending on configurations. To capture this variation, the recording system should be in place over periods sufficient to capture a range of operational states and / or sample various conditions to provide comprehensive characterisation of the noise field.

3. MEASUREMENT CONFIGURATIONS

3.1 MEASUREMENT CONFIGURATION: FLOATING SURFACE SYSTEMS

Floating surface-based systems may have varying degrees of positional freedom depending on mooring configuration. Some WEC systems may rotate around a fixed mooring position dependent on tide, wave and wind directions to varying degrees, referred to as the watch circle. In the case of larger systems this may result in considerable variation in position over time; in some cases 100’s of meters. This variation and relative range to any recorder systems must be considered in post analysis. In addition, systems may also exhibit considerable directivity. To accommodate this, the use of long term recorder units is proposed. These must have sufficient bandwidth and storage / duty-cycle and noise performance to allow data capture from a variety of operational conditions across the spectral band of interest.

Figure 3 illustrates a plan view of the proposed measurement methodology for (in this example) a surface attenuator system. In this case the system has considerable degrees of positional freedom, allowing movement within the watch circle. The system, however, will generally have preferred orientations determined by the prevailing wave direction and weather conditions. The proposed methodology deploys a number of autonomous long term recorders to capture the sound field data from a range of position possibilities. The recorders should be isolated from the surface to minimise the effects of surface interaction noise and outside of the watch circle to avoid any danger of entanglement as the generation system moves.

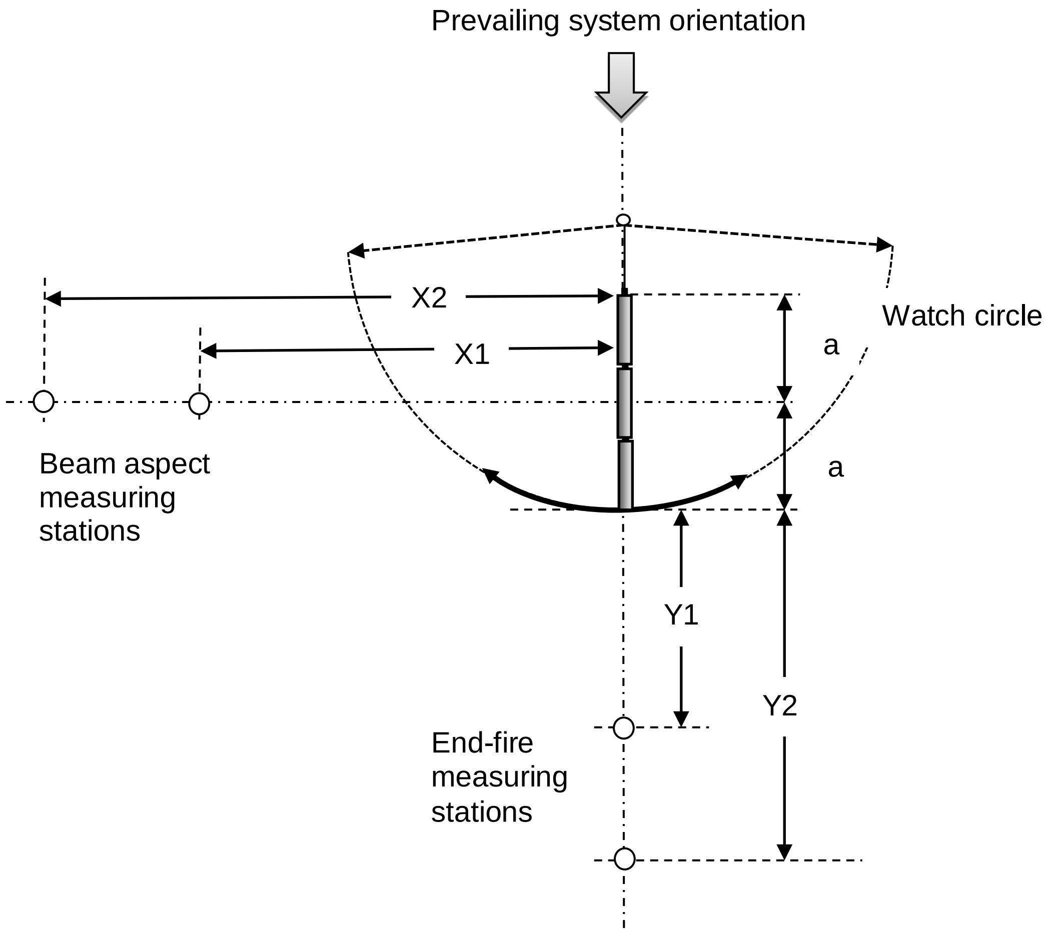

Figure 3: Plan view surface system measurement configuration. The dashed circle line (watch circle) shows trajectory of a moored system and circles indicate proposed positions of recording systems.

Depending on the number of underwater recording units available the recommended choice of locations will be:

Two hydrophone systems:	One beam (X_1) and one end-fire (Y_1) position
Three hydrophones systems:	Two beam (X_1) and (X_2) and one end-fire (Y_1) position
Four hydrophones systems:	Two beam (X_1) and (X_2) and two end-fire (Y_1) and (Y_2) positions

The aim is to measure at least the beam (orthogonal transect from the mid-point of the surface system) and end-fire aspect noise levels with at least one recorder system in each case placed in the device far-field, see discussion section 2.2. In order to better understand source characteristics a determination of the local propagation conditions is also required. If possible two recording system on a single transect from the source is proposed. This will allow estimation of the propagation loss between the two and therefore estimate uncertainty associated with source function estimates, discussed further in section 4.5.

It is anticipated that the device will not always lie along the anticipated radial of the watch circle as shown in Figure 3 and will swing depending on the tidal state, wave and wind strength and direction. This movement will potentially allow the fine detail of the radiation pattern to be explored. The recording system should be placed as far as possible (X_1, X_2, Y_1 and Y_2) in the 'source far-field'; however, this needs to be balanced against avoidance of contamination from other nearby sources and maintaining sufficient signal to noise to allow device acoustic analysis. The greater ranges will reduce the effect of uncertainty in position and range estimates, i.e. at shorter ranges small variations in range or position estimates may result in large variation in received levels as well as avoiding device near-field effects from a distributed source.

To determine both positional and range estimates it is essential that the system developer make available the actual location(s) and operational state of the generation system during the measurement periods.

Due to the highly dynamic state likely at a WEC device location the use of bottom mounted recorder systems with receivers close to the seabed as shown in figure 2, is recommended. Surfaced buoyed systems or boat based deployments may suffer from parasitic noise due to wave motion and in the case of boat based deployments increased platform self-noise. Bottom moored but vertically distributed system throughout the water column have also been used on the wave test site successfully; however, they may suffer from greater positional variation due to tidal flow and therefore increased uncertainty in source term estimates. Systems closer to the seabed may also suffer less from unwanted flow noise.

There is a possibility that device noise levels may be too low to be heard above the background levels. Under these circumstances the hydrophone units may need to be redeployed within the watch circle. This could be achieved by using a deployment method that has no surface presence and will require the use of acoustic releases. However, moving the measuring hydrophone too close to the sound source may also put it into the device near field, making source level estimation difficult.

3.2 MEASUREMENT CONFIGURATION: DISTRIBUTED WATER COLUMN WEC SYSTEMS

A majority of current water column distributed systems are fixed or hinged at the sea bed to a fixed foundation and although there may be moving parts, they will move within relatively predictable and small volumes. In the case of many wave surge converters mechanical motion of the device is in a fixed direction potentially leading to variation in radiated sound field in different azimuthal directions from the source. As with the surface based systems a series of at least two long term recording systems based on orthogonal transects around the system is proposed with additional systems added at varying ranges on the same transects to improve source term estimates.

As discussed in section 2, recorder systems should be placed sufficiently far into the source far-field to avoid near-field effects. Factors such as water depth, device size configuration and noise levels will lead to a choice of offset distances X_1, X_2, Y_1 Y_2 and Y_3 as depicted in Figure 4. Each of the hydrophone positions should have at least one hydrophone placed close to the seabed. In the case of a wave energy converter system, for example, potential varying noise sources exist throughout the water column, i.e., wave noise at surface, hydraulic pumps at base of system, etc. These distributed sources and seabed and sea surface multi-paths will result in complex arrivals and therefore measured received levels. At shorter ranges these fields may be highly variable for relatively short positional or range variations. At greater ranges the combined effect of distributed source and multipath arrivals shows less spatial variability as the relative ratio of the source distribution and the range increases.

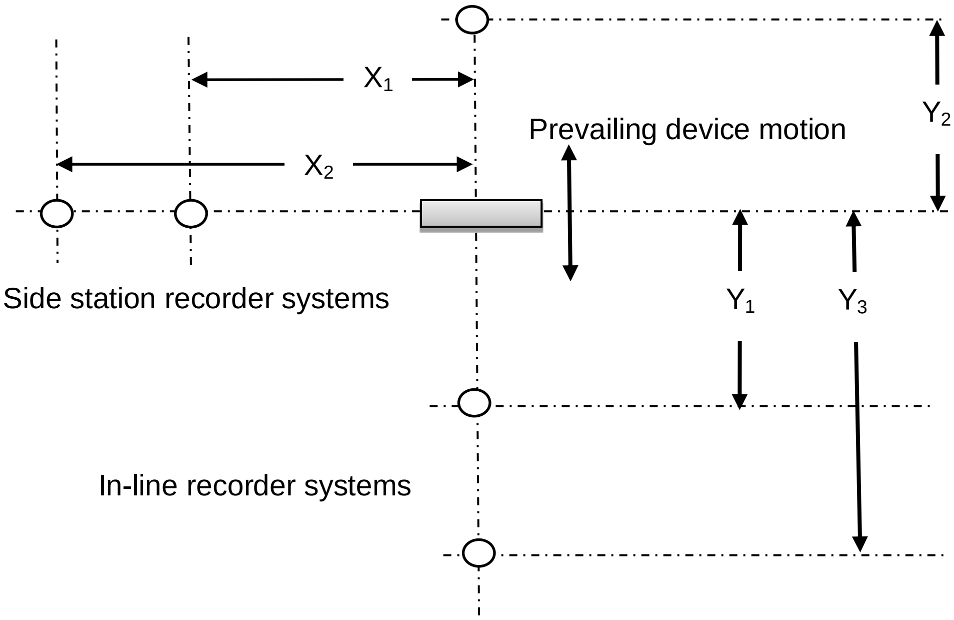

Figure 4: Water column distributed system measurement configuration.

Depending on the number of underwater recording units available the recommended choices of configurations are:

Two hydrophone systems:	One side (X_1) and one in-line (Y_1) position
Three hydrophones systems:	One side position (X_1) and one either side of device on in-line position where (Y_1) and (Y_2) are identical ranges.
Four hydrophones systems:	Two side positions (X_1) and (X_2) and two in-line position at different ranges (Y_1) and (Y_3).
Five hydrophones systems:	Two side positions (X_1) and (X_2) two in-line position at different ranges (Y_1) and (Y_3) and one opposite in-line position (Y_2).

The use of recorders on two orthogonal transects allows estimation of variation in radiated energy in these directions. The use of secondary recorder systems on the same transect at different ranges can be used in conjunction with propagation loss modelling to estimate source terms to a higher degree of certainty. This certainty level will be lower if only a single recording system is used on a given transect. A potential process of source term estimation is discussed further in section 4.5 of this report. In the case of an oscillating wave surge converter system, a difference may also occur between front and back of the inline direction. In this case the use of equally spaced recorders either side of the systems is suggested, allowing direct comparison of front and back radiated energy under similar propagation loss conditions. With five systems, the use of both front and back and two orthogonal transects with two recorders on each is recommended.

The definition of a fixed range at which all systems were measured was considered. For example, this approach has been adopted for marine piling for offshore windfarm construction in German waters, where received levels were observed at 750 m from the source [Harland *et al,* 2011]. This has a number of advantages as general comparison of received levels made at a particular range may be made for devices in similar environments, i.e. water depth, bathymetry profile, sediment type etc. However, systems having, for example, equal source amplitude, will potentially have higher or lower received levels at a fixed distance dependant on the specific environment. In this case, detailed propagation loss modelling would have to be used to compare estimated source terms. In general terms, the wide variety of WEC design concepts, and therefore potential noise outputs and variation in deployment environments, makes definition of a fixed recorder range problematic. This is particularly so for surface WEC systems with a high degree of positional freedom, such as some attenuator designs. However the use of fixed ranges for example X_1 and Y_1 should generally be encouraged across the industry. The ultimate choice of these recorder deployment ranges, however, is constrained by device noise and background levels, water depth and device size and potential degrees of freedom.

3.3 RECORDING DURATION AND BANDWIDTH

Consideration of all potential receptors suggest that species range from low frequency animals such as larger whales and fish species up to smaller *odontoceti* such as the harbour porpoise [EMEC, 2011a]. These and many other marine species have combined hearing capabilities ranging from a few tens of Hertz up to around 150 kHz. In consideration of environmental impact, potential noise generated across the entirety of this frequency band should be considered. In shallow water environments typical of WEC systems such as that at Billia Croo however, low frequency sound propagates poorly due the wavelength of the signal being large compared to the water depth. This propagation effect is referred to as low frequency cut-off [Urick, 1988 and Jensen *et al,* 2000].

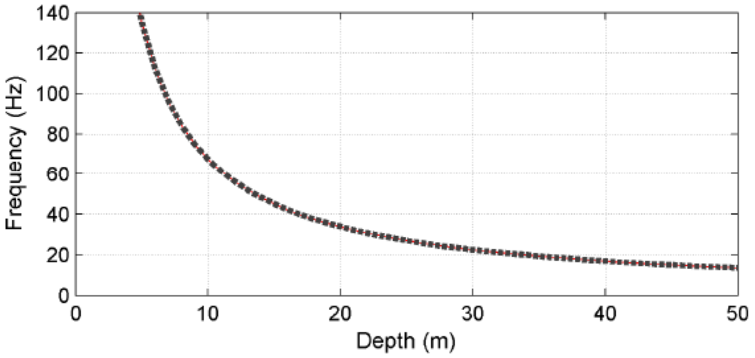

Figure 5: Low frequency cut off in shallow water for a seabed sound speed of 1805 ms^{-1} and water sound speed of 1503 ms^{-1}
[Urick, 1983 and Jensen et al, 2000, *Robinson et al, 2011]*

Figure 5 shows low frequency cut off versus depth. At the water depths common at the Billia Croo wave test site, this cut-off will occur for frequencies below around 15 Hz, and for components below around 35 Hz at water depth of 20 m. Similarly, very high frequency will also propagate poorly due, in this case, to increased absorption in the water column; for example, energy at 150 kHz is attenuated approximately by 20 dB per km in addition to spreading losses compared to 0.05 dB per km at 1 kHz [Urick, 1983]. These higher levels of sound attenuation means that energy in these high and low frequency bands will only radiate relatively short distances from source. Any measurements of device noise in these bands will be likely to need to be made relatively close to the source to allow detection above background levels.

Long term recording systems

These systems allow data to be collected over multiple tidal cycles and varying wind and wave conditions. They will also allow data to be collected under high sea state conditions when manned data collection would not be possible. However current technology is potentially limited in bandwidth and storage capacity. Autonomous recorder systems are now available working with bandwidths from a few 10's Hz to greater than 100 kHz; however, these systems are often limited by storage capacity, bandwidth and battery life. For example: at 24 kHz bandwidth, a single channel recorder system will have around 4 days of continuous record time using 32 GB storage media. By comparison, at a bandwidth of 192 kHz suitable to cover all potential receptor frequencies, the same storage capacity will allow just over 6 hours continuous recording. An approach used by some autonomous recorders is the use of a duty-cycled recording schedule. Systems will make timed periodic recordings, for example 10 minutes every hour at a variety of bandwidths. These capabilities are usually programmable, allowing extension of the total deployment time within the same bandwidth total storage limits.

In the case of wideband recordings careful consideration of recorder system noise performance should be made. Typical background levels in the absence of device noise may show as much as a 60 dB difference between frequencies below 1 kHz compared to lower level, higher frequency components above 100 kHz. In these cases consideration of both system self-noise and dynamic range must be made across the whole band of interest. An approach used on some systems is the use of dual-band systems with different gain / transducer settings across different bands re-ordered in parallel. Another technique is the use of weighted filter functions in conditioning filters allowing lower frequency / higher amplitude signals to be suppressed. Both these techniques can improve use of the system dynamic range and, in the case of dual band systems, improve overall band noise performance.

Note: There is currently a rapid development of autonomous recording systems allowing longer and wider band recording, and it is likely that as newer recorder systems come on to the market, the capability of longer term deployments at wider bandwidths will increase.

Another potential methodology is the use of cabled fixed wideband hydrophone systems. Where possible, a hydrophone system could be fitted in the vicinity of WEC devices as part of the device instrumentation package, potentially using existing shore links to provide data transfer and power. Extended timelines of radiated noise can be obtained at the frequency bands of interest. This would allow the detailed device characterisation to be placed in the context of the extended timelines and operational modes. Existing WEC systems have already implemented cabled hydrophone systems with the role of providing device conditioning monitoring; these systems' role could be extended to allow high quality long term acoustic output monitoring. The introduction of stand-alone cabled systems is usually cost prohibitive, however integration with existing shore links may make this technique more viable in future developments.

Snap-shot survey techniques

An alternate approach to obtaining wide-band data capture is the use of snapshot surveys in conjunction with long term recorder system deployments. At frequencies above 100 kHz current autonomous recording systems are relatively limited in terms of storage and bandwidth compromises for longer term sampling. However, broadband systems may be deployed from boat-based or drifting drone surveys for short periods in parallel with longer term recorder system deployments. Boat-based surveys offer the advantage of use of higher quality electronic capture with improved noise performance compared to many autonomous recording systems. For example bandwidths of hundreds of kHz can be achieved using 16-24 bit resolutions.

The use of sampled (snap-shot) drifting hydrophone (from drones and or drifting boat surveys) in conjunction with a long term bottomed deployments along the lines is felt to be the most favourable approach to acoustic field assessment based on current available technologies and economic limits. This provides a cost effective compromise of short term broadband measurements to the context of the extended dataset from long term bottom recorders, capturing longer term variations in device operational status.

3.4 CALIBRATION AND QUALITY CONTROL

All systems should be calibrated traceable to national or international standards. In the case of underwater acoustic transducers, these systems vary over time based on use, depth, etc., and performance may no longer match factory-delivered values. Wherever possible, hydrophones / electronic data acquisition systems should be regularly calibrated across all frequencies of interest. The full transfer functions of all systems, including hydrophones, data acquisition systems (DAQs), etc., should be included in post analysis of received level estimates. For in-situ calibration and quality assurance (at deployment / retrieval), a portable calibration system such as a Brüel & Kjær hydrophone calibrator (piston phone) can be used to test full system performance (hydrophone and DAQ systems) directly before and after deployment, greatly enhancing confidence in overall system performance.

3.5 NON-ACOUSTIC DATA

In addition to the above acoustic measurements as much as possible of the following data also needs to be collected while recording acoustic data:

- Accurate positioning (GPS, DPGS) of all recorders and sound sources
- Weather conditions, wave height, period and direction, rainfall, wind speed and direction, tidal state, etc.
- Shipping movements (AIS) within acoustic range of the test site
- Sound velocity profiles (carried out periodically)
- Geotechnical surveying (bathymetry and sediment types)
- Device status (position, operational mode etc.)

4. POST PROCESSING

4.1 DATA PROCESSING

The overall aim of the measurements is to provide information on the following device characteristics.

- Variation of sound level with frequency
- Variation of sound level with bearing
- Variation of sound level with wave height
- Attempt to identify dominant sound sources
- Absolute levels of sound put into the water

Assessment of these properties is likely to play an important role in current and future environmental impact processes. In addition data collected should, wherever possible, allow assessment of source terms to enable potential future modelling exercises to take place. Such modelling would utilise known source characteristics and environmental characteristics to produce estimates of environment-dependent propagation losses and sound fields at future development sites.

Data collected will ideally be in the form of continuous (or suitably duty-cycled) long term sound recordings of sufficient bandwidth. All system hydrophone sensitivities and electronic gains should be calibrated both before and after deployment and, where possible, *in situ* calibration tones used. Recording systems should be synchronized to GPS accuracy before deployment and re-checked after retrieval. Data should be stored in a lossless format such as 'wav' file format.

4.2 BROADBAND DATA ANALYSIS

The primary intention, as outlined above, is to provide data suitable for sound field estimation or received levels at specific points surrounding the WEC device. The Joint Natural Conservation Committee currently suggests in its draft guidelines [JNCC, 2010a, 2010b] the use of physiological damage criteria such as that outlined by the Marine Mammal Noise Exposure group [Southall *et al,* 2007] for impact on marine mammals in English and Welsh waters, with similar guidelines likely to be developed for Scottish waters. These include assessment of peak (maximum zero-to-maximum positive or maximum zero-to-negative excursion) in dB re 1µPa and Sound Exposure Level (SEL) dB re 1 $\mu Pa^2 s$. In the case of SEL it may be used both for short-term transients and for more stable exposure signals. In either case the integration period and bandwidth should be stated. For transient or pulse-like signals a 90% energy criterion is proposed and for more stable SEL measurements 1 second integration will be used along lines suggested by Madsen, [Madsen, 2005]. Additional commonly used metrics for impact criteria include Root Mean Square (RMS) sound pressure levels where again bandwidth and integration period must be stated [Madsen, 2005]. The latter metric is used commonly in the scientific literature for description of received levels in relation to behaviour response from various marine species.

Figure 6a-b shows an example of a SEL energy estimate using a 90% energy criteria for a transient pulse; in this case a pulse from a single pile driving hammer strike. All three of the above metrics zero-peak, SEL and RMS are time domain descriptions of total energy or maximum level across a specific frequency band at a specific point in the sound field.

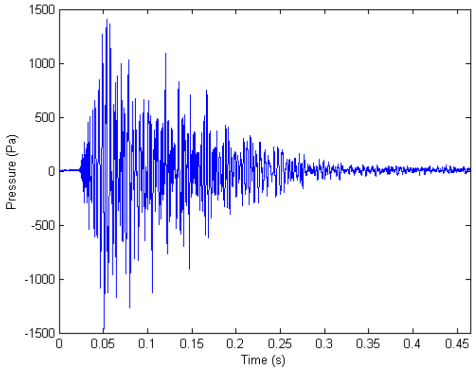

Figure 6a: Time domain plot of a single hammer strike from a marine piling event shown in Pa. [Robinson et al, 2007].

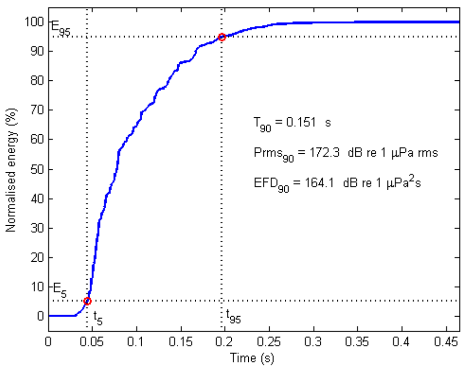

Figure 6b: Equivalent 90% energy estimate for a Sound Exposure Level (SEL) for a single marine piling transient signal. [Lepper et al, 2009].

Note: A common term in underwater acoustics literature is Sound Pressure Level (SPL). This term unfortunately often undergoes a number of varying and confusing interpretations and its definition is not universally agreed. In context of this report SPL is taken to be the broadband RMS equivalent value of a signal. However the use of RMS sound pressure level as defined by Madsen is used to avoid potential ambiguities [Madsen, 2005].

4.3 SPECTRAL-TEMPORAL ANALYSIS:

Various spectral analysis techniques are proposed; these are chosen to provide time-frequency analysis both for long term data trends and analysis of short term ‘event’ signals.

Linear and third octave band spectral analysis

In the case of data sets of longer than24 hours duration, long term spectral averaging (LTSA) is proposed. This analysis can be useful for determining long term noise level trends and identification of specific device operational models and changes in operational status as well as overall data quality. Figure 7 shows an example of long term spectral averaged data taken from the baseline survey data for a 30 hour period from a seabed autonomous recorder system. In this case noise levels have a significant and varying contribution from changes in onsite activities unrelated to any WEC systems operation. Using this approach specific events or device operational modes can be identified and more detailed analysis carried out. This approach also allows assessment of slowly varying longer term trends in acoustic output for example those associated with slow changing (over periods of hours) significant wave heights and directions.

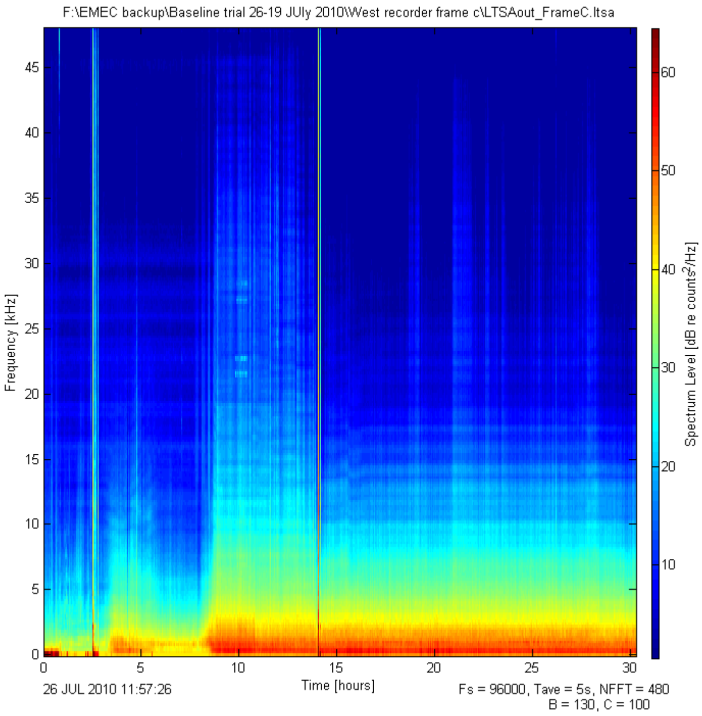

Figure 7: Long term spectral averaged (LTSA) data for a 30 hour period reordered during baseline survey in 2010. Data normalized to system dynamic range [Lepper et al, 2011a].

Specific event analysis can be carried out using linear FFT analysis allowing assessment of frequency time distribution. In this case appropriate integration periods should be used dependant on signal type. All frequencies should be appropriately calibrated. For strong tonal components, levels should be quoted as RMS sound pressure level in dB re 1µPa. In the case of broadband noise levels the use of power spectral density (PSD) may be appropriate using units of RMS sound pressure level in dB re 1µPa^2/Hz. Data within that period may be spectrally averaged using techniques such as Welch averaging to reduce variance and reveal underlying average values. In all of these cases the integration band, sample rate, window functions, overlaps functions, etc. should be stated with presented data.

Another useful approach is the use of third octave band analysis. In this case the RMS energy is calculated over a fixed integration period in a specific band, with lower bandwidths at lower frequencies. For a defined integration period of, for example, 1 second these levels can then be considered the equivalent SEL value in that band over a 1 second interval as discussed in previous section. The use of third octave bands has advantage of description of relatively wide bandwidths with relatively few numbers for example data covering the band 10 Hz to 150 kHz can be defined by around 41 values compared to an equivalent 128 point linear FFT. As with linear Fourier analysis it is useful to quote both band level in dB re 1µPa i.e. absolute level in that band as well as frequency normalized data in form of a constant percentage bandwidth (CPB). These data are the equivalent of the power spectral density in that band with units dB re 1µPa^2/Hz. In the case of analysis of very low frequencies the use of integration periods of 40 s may be required to improve low frequency accuracy. Third octave band analysis is useful in source level definition where broadband propagation loss modelling may be required. In this case, single frequency models are run at each of the band centre frequencies and range-averaging or frequency-averaging is used to obtain propagation loss values which are representative of the average losses across the entire band. This process is widely used for broadband propagation modelling and source term definition where individual bands are propagated back to a source then combined into a broadband source term. Using this approach is often considerably less computationally intensive compared to equivalent broadband time domain modelling techniques.

Note: In both linear Fourier analysis and third octave band analysis all integration periods, sample rates, window functions, overlap parameters, etc. used must be stated with presented data.

Short term average data

Acoustic output from WEC systems may exhibit large scale rapidly changing variations due to complex system interactions from a wide variety of potential noise sources within the systems. These acoustic 'events' may be analysed individually and where appropriate characteristics of these events described in isolation. In some cases a specific event may occur periodically / intermittently but with uncorrelated periods or duty cycles. To assess an average state or mean 'acoustic noise output' of a system a longer term integrations periods may be used. Data can be assessed over defined integration period appropriate to bandwidth and resolution requirements both for techniques such as linear spectral analysis or third octave band analysis. These data can then be averaged across longer periods (minutes) to obtain an average assessment of noise output across that period. The period itself potentially contain a wide variety of complex noise events, some continuous some intermittent or periodic. Figure 8a and 8b show examples of an averaged TOB analysis over a 10 minute integration period. Individual TOB analysis was performed over consecutive 1 second windows with a 0 % overlap.

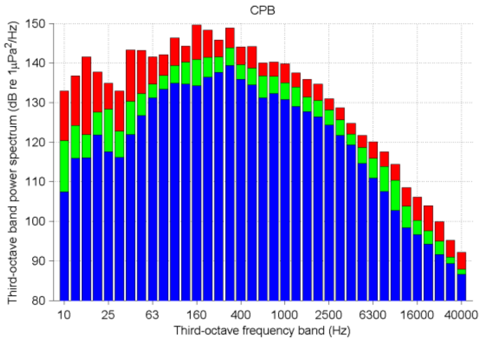

Figure 8a: 10 minute averaged Constant Percentage Bandwidth (CPB) power across third octave bands averaged maximum (red), mean (green) and minimum(blue) data integrated over consecutive a 1s periods. [Lepper et al, 2011a]

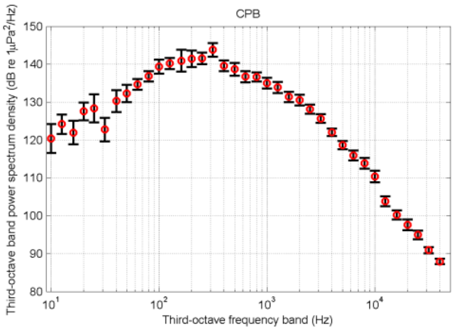

Figure 8b: 10 minute averaged data Constant Percentage Bandwidth (CPB) power across third octave bands integrated across consecutive across 1 s windows. Red circles mean values, bars ± 1 standard deviation. [Lepper et al, 2011a]

The output in Figure 8a shows the average of the mean, maximum and minimum observed values for each 1 second interval across the 10 minute period for each third octave band. Figure 8b shows the identical data with in this case with mean data with bars indicating ± 1 standard deviation in output. This approach allows assessment of short term average acoustic state of a system allowing capture of both continuous and short time variant or intermittent signals. These data can then be used to compare acoustic output of other data taken before or later to allow assessment of longer term (hours) changes in device operational status etc. Both plot types are useful conveying average, maximum and minimum values and distribution of variance in the form of standard deviation. In the example shown in figure 8, the maximum values at lower frequency for example may be greater than 10 dB higher than the mean value over a 10 minute period however these events occur relatively infrequently with a standard deviation of around 2-3 dB for the same band. More detailed analysis of the variation in time in the 10 minute window can also be made for specific frequencies or bands. Figure 9 shows an example data for a 10 minute period integrated across consecutive 10 second intervals. In this case the variation over time in individual bands can be observed of the 10 minute analysis window.

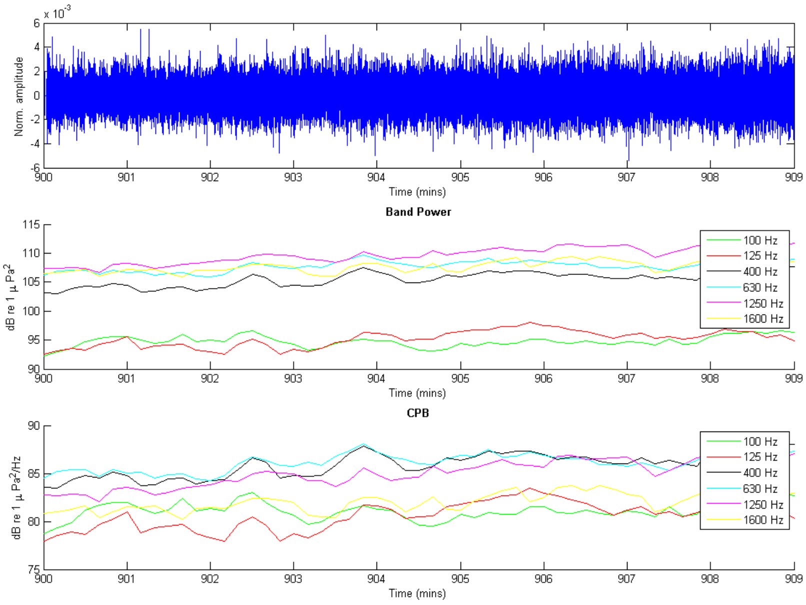

Figure 9: Variation in third octave frequency over the course of time period comparison 1 (frame A) for selected frequencies (inset). Plots show time domain of segment (upper), TOB band power (middle) and TOB CPB (lower). Integration period 1 second, 0% overlap, [Lepper et al, 2011].

4.4 DATA PROCESSING METHODOLOGY

The flow chart shown in figure 10 outlines the proposed data analysis methodology. The long term spectral averaging allows identification of time variant / stable noise characteristics, specific noise events and long term trends in acoustic levels. Specific events will then be analysed in turn using either power spectral density, spectral level or third octave bands analysis and correlated where possible with known device status, weather conditions, *etc.* Using these data and propagation loss modelling, source characteristics can then be estimated.

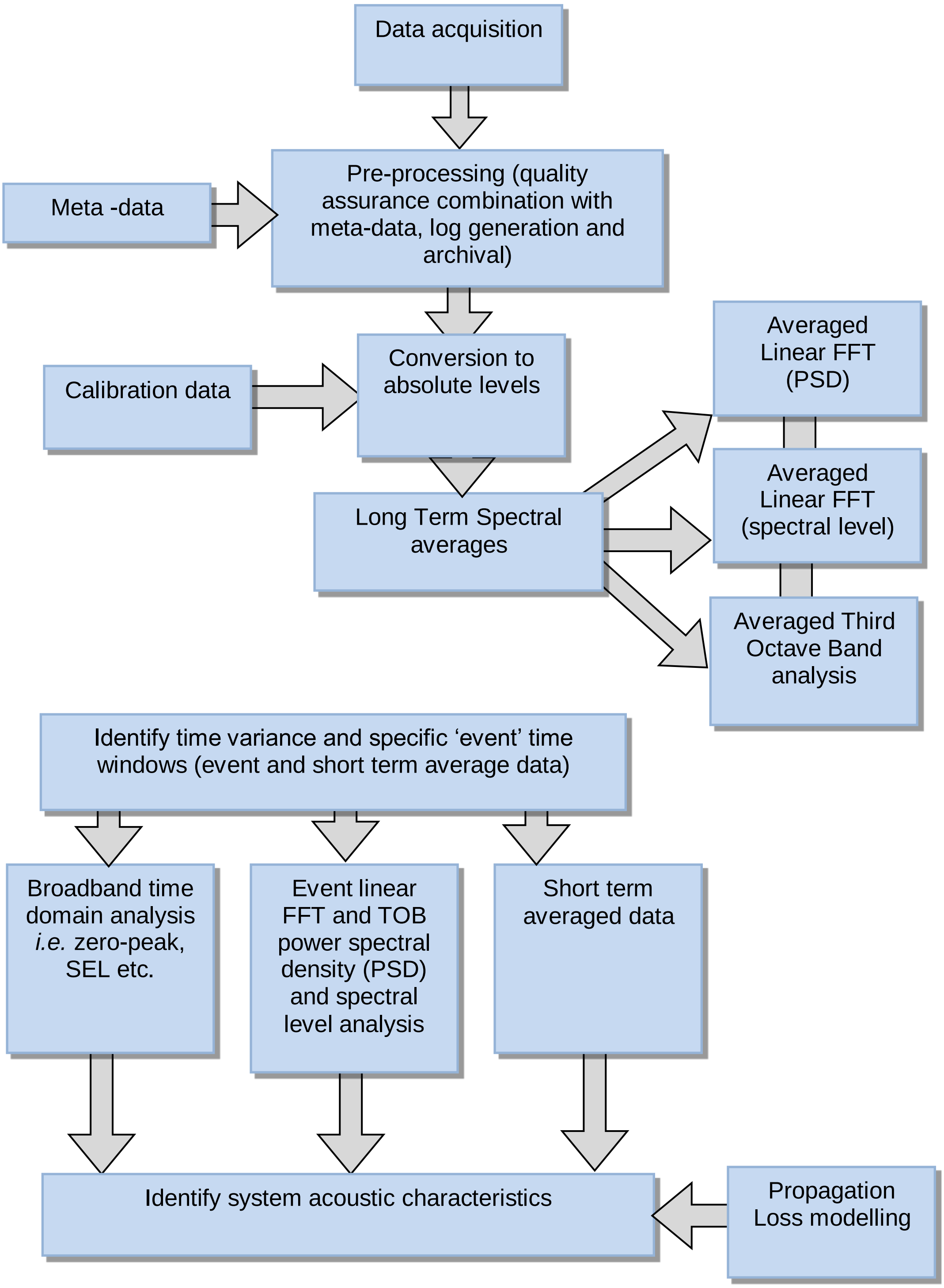

Figure 10: Data analysis process

4.5 SOURCE TERM ESTIMATES

To be useful for predictions of noise levels in other locations, it is often desirable to be able to determine some description of the source in terms of the source output amplitude which is a characteristic of the source but independent of the local environment (water depth, etc). This is most commonly done by estimating the source level. To do this, received levels are measured at some distance from the source and then 'propagated back' to a nominal position 1 metre from the acoustic centre of the source using an appropriate propagation loss modelling technique. The propagation models range from simple spreading laws to more sophisticated numerical modelling approaches such as ray-path, normal model, parabolic equation, wavenumber integration etc., [Jensen, 1994]. The later examples taking into account both direct and multi-path interactions (sea surface and seabed reflections). Many of these approaches operate in the frequency domain and are run for single frequencies. The loss experienced by wider band responses may be run for a series of adjacent individual bands where the average propagation loss in that band is used. These band values and band losses which can then be recombined to generate a broadband received level.

As discussed in section 2 the geometric nature of propagation loss means much higher loss variations are observed at shorter ranges compared with longer ranges.

Using an extreme example of a free-field spherical spreading loss profile can be described using a simple geometric spreading equation.

$$\text{Free field propagation loss (PL)} = 20*\log_{10}(\text{range}) + \alpha(\text{range}) \qquad (1)$$

Where range is in meters and α is the attenuation coefficient of absorption in dB/m.

Comparison of propagation loss between 20 to 30 m from a source assuming free-field loss profiles is around 3.5 dB higher. However for the same distance of 10 m at a range of 1 km, i.e. 1000 to 1010 m, the difference in transmission loss is around 0.0864 dB. Therefore, uncertainties in source range at closer ranges may lead to significant variation in propagation loss estimate, and therefore equivalent source level estimate, due to the larger fractional errors in the range estimates. The degree of effect of range uncertainty becomes reduced at greater ranges, as shown in the example above. This becomes particularly important for distributed sources such a large surface attenuator or a water column distributed system such as a oscillating wave surge converter systems due to the distribution of potential sources along a device. This distribution resulting in uncertainty in position and therefore range estimates, i.e. a ±10 m positional error for a recorder nominally 20 m from source, could be + 3.5 dB or – 6 dB; however, the same ± 10 m range error would be negligible for a system placed 1 km away from the device. Due to the potential uncertainty of the relative position of a noise source in distributed system measurements should ideally be made as far from the source as possible. This is illustrated in figure 11 where the relative proportional difference in range from r_1 and r_2 reduces at greater ranges from the source.

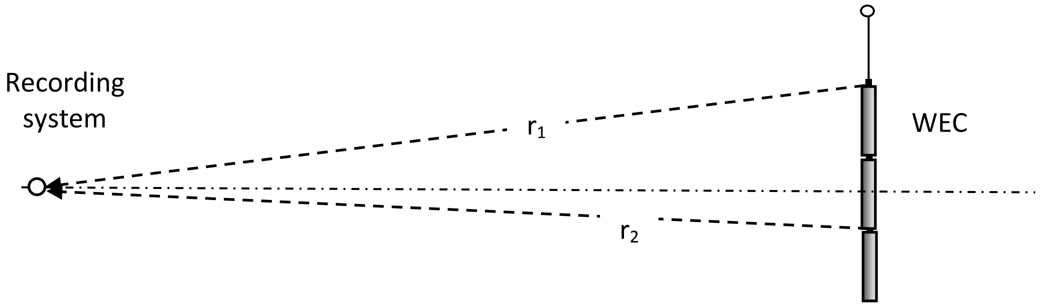

Figure 11: Range estimate variation due to distributed noise source across a WEC system

In practice however the maximum range for deployment will be limited by overall noise levels, back ground noise, contamination from other noise sources and uncertainties in modelling processes. Similar arguments can also be applied to vertically distributed systems such as oscillating wave surge converter systems.

To increase confidence in propagation loss estimates the use of several receivers on a single transect from the source is proposed. Figure 12 shows an example of two measured data points taken from seabed mounted recorders for a marine dredging operation [Robinson *et al,* 2011]. The closer point around 70 m from the source at the closest point of approach (CPA) and the further at 475 m from the source at CPA in 29 meters of water depth. The dashed line shows output of a propagation loss model estimate for a 100 Hz signal. Although the propagation loss in the water depth is relatively complex, measured data 'fits' relatively well within the measurement variation bars to the loss profile. A least-squares fitting process to minimise residual fitting error is then used to determine overall loss profile position within the measured data. This profile can then be traced back to an equivalent infinitely small mono-pole source [Urick, 1983]. This process can then be repeated for a range of frequency band for example third octave bands with individual loss profiles. These loss profiles are then combined with band received level data to obtain third octave band source terms for an equivalent mono-pole source for each band. These data may then be used in future modelling processes to re-propagate each TOB in a particular environment.

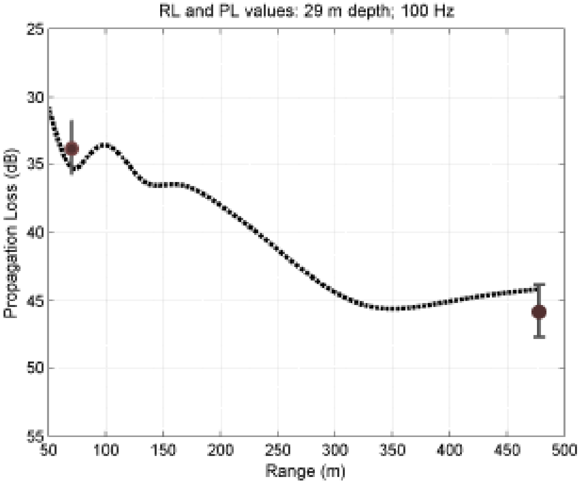

Figure 12: measured received level data (circles show mean and bars variance) and propagation loss model (dashed lines) for a marine dredging operation in 29 m of water [Robinson et al, 2011].

Using this process the uncertainty in range estimate due to uncertainty in the location of multiple sources in a distributed device can be tested. These data can then be used to estimate error variation in source level estimate. If the exact position of a noise source is known then direct estimation of source terms may be made using similar modelling techniques. As discussed above the greater range from source to receiver the lesser the effect of the distributed source. Using this approach a theoretical source term is obtained at an infinitely small mono-pole within or close to the systems. This term is then a far-field concept to allow prediction of received levels in the far-field of the device in similar or different environments. Caution should be used in interpretation of modelled results close (within the near-field) of a device. To do this detailed assessment of all potential sources within a device would have to be made. If using any complex modelling processes the use of sound velocity profiles taken across the site is also important to assess overall propagation conditions. Collection of regular and spatially diverse CTD profiles across the site is recommended to allow determination of propagation conditions and improve modelling accuracy.

5. CONCLUSIONS

A revised acoustic underwater noise measurement methodology has been proposed for a variety of wave energy converter (WEC) devices that may be present at the EMEC site. These include surface based systems and water column distributed systems. This methodology is based on device characteristics, potential receptors, site characteristics and likely regulatory requirements. Data is drawn from a review baseline noise survey and field-trials conducted on a surface attenuator system at the EMEC Billia Croo site in 2011. In addition, a review of measurement methodologies used in other industries was conducted.

In the case of relatively large scale systems (either on surface or distributed through the water column) in relatively shallow water, sound propagation is likely to be complicated, including strong spatial variation due to the distributed nature of potential noise sources in the device and surface and seabed interactions. The use of long term recording systems placed in the devices / environment far-field designed to assess long term variance in acoustic output due to device operation status, weather, tidal conditions *etc.* is therefore proposed, wherever feasible. Multiple measurement configurations are proposed to allow data capture for the two key device concept types. Ideally, multiple recording systems would be deployed at different ranges on transects for the device to allow assessment of local propagation loss conditions, and therefore estimate 'at source' absolute levels. In addition, multiple aspects angles of the systems will be measured simultaneously to assess potential directivities of the source.

It is identified that long term recordings at the complete hearing bandwidth of all potential receptors (~150 kHz) is often a limited compromise of bandwidth versus record time. However, it is anticipated that the majority of signals of interest will be for frequencies up to low to mid 10's of kHz, because higher frequencies will be more highly attenuated with range due to increased absorption and will not propagate as far. Several commercially available recording systems exist that can be used to make continuous recordings at these lower bandwidths for periods of days to allow assessment of long term operational and environmental noise variation. It was also felt important to sample at higher bandwidth (up to 150 kHz) at regular intervals. In this case two technical solutions are proposed - these include bottom mounted high-bandwidth recorders with a suitable duty cycle and/or the use of wide bandwidth 'drifting snap-shot techniques'. Either solution can be used simultaneously with a longer term recording system to augment long term data sets with sampled wideband data. This provides a cost effective compromise of system bandwidth and recording duration.

Equipment specifications for acoustic measurements should include:

Long term surveys:
Autonomous underwater acoustic logger systems with sufficient bandwidth of 10's Hz to greater than 20 kHz, dynamic range [EMEC, 2011b] and noise performance for survey

periods from days to weeks to capture long term variation in system output due to varying operation status in response to changes in weather and wave conditions etc. System may be suitably duty cycled to optimise bandwidth and record time. All system responses should be fully calibrated to traceable standards regularly (ideally just before and after survey) across full frequency spectrum of interest. The use of piston-phone field calibration systems just before and after survey deployments would be recommended. Digital data capture ideally performed at 16-24 bit resolution.

Snap-shot surveys:
Equipment for deployment from boat based surveys should again have sufficient bandwidth, dynamic range and noise performance. At least one system (hydrophone and data capture) should be deployed with bandwidth sufficient to capture high frequency spectrum up to 150 kHz (upper hearing range of marine species of interest [EMEC, 2011a]). A combination of both low noise hydrophones, for example a RESON 4032, and wider band hydrophones such as RESON 4014, deployed simultaneously, provides a good compromise of bandwidth and noise performance. Data capture (digitization) should ideally be performed using high specification systems such as National Instruments, Pulse etc. with sufficient bandwidth, dynamic range, bit-resolution (16-24) and noise performance. Again, all systems (hydrophones and data acquisition systems) should be calibrated across full frequency spectrum of interest ideally just before and after surveys.

Many WEC devices have the potential for complicated noise characteristics within the water column. This complexity comes from multiple on-system components behaving differently to each other at different times and with different operational phases of the overall system. Where appropriate analysis of specific noise events may be conducted, addition analysis of short term averaged data is proposed for periods of around 10 minutes. These data may contain a wide variety of shorter term events, the average of these seen as indicative of the device in that operational state at that time. Comparison of these short term averages under different operational conditions (significant wave height etc.) allows assessment of overall systems noise under different conditions. A data processing protocol is outlined based on likely signal types and data requirements for system noise assessment. This is designed to provide a comprehensive analysis of the system acoustic output both spectrally, temporally and spatially in a variety of operational modes.

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7. GLOSSARY

AIS	Automatic Identification Systems
ANSI	American National Standards Institute

CBA	Chickerell BioAcoustics
CPA	Closest Point of Approach
CPB	Constant Percentage Bandwidth
CTD	Conductivity, Temperature, Density
DGPS	Differential Global Positioning System
EIA	Environmental Impact assessment
EMEC	European Marine Energy Centre
FFT	Fast Fourier Transform
GPS	Global Positioning System
JNCC	Joint Nature Conservation Committee
LU	Loughborough University
NPL	National Physical Laboratory
PSD	Power Spectral density (units dB re 1 $\mu Pa^2/Hz$)
RL	Received Level
RMS	Root Mean Square (units dB re 1 µPa)
SEL	Sound Exposure Level (units dB re 1 $\mu Pa^2 s$)
SPL	RMS Sound Pressure Level (units dB re 1 µPa)
SMRU	Sea Mammal Research Unit, St Andrews, Scotland
SMRU Ltd	A company set up to make the expertise of SMRU (the Sea Mammal Research Unit at St Andrews University) available to industry, their advisors and Regulators to address challenges related to environmental regulations concerning marine mammals.
WEC	Wave Energy Converter
Zero-peak	Maximum signal amplitude positive or negative from the at rest zero mean position.

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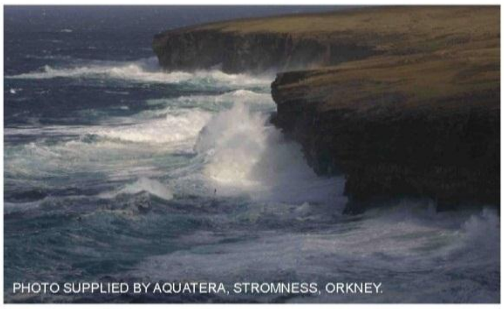
9. ANNEX A:

A summary report of acoustic data obtained and data analysis from operational noise field trials conducted on a WEC system at the Billia Croo site in May 2011. Report title “Summary of operational underwater noise from a Pelamis WEC system at the EMEC wave energy test site May 2011: Comparison of Pelamis system operational and baseline noise measurements”



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