OregonWaveEnergy TRUST

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Assessment of Underwater Noise Generated by Wave Energy Devices

Prepared by JASCO Applied Sciences on behalf of Oregon Wave Energy Trust

Oregon Wave Energy Trust (OWET) – with members from fishing and environmental groups, industry and government – is a nonprofit public-private partnership funded by the Oregon Innovation Council in 2007. Its mission is to serve as a connector for all stakeholders involved in wave energy project development – from research and development to early stage community engagement and final deployment and energy generation – positioning Oregon as the North America leader in this nascent industry and delivering its full economic and environmental potential for the state. OWET's goal is to have ocean wave energy producing 2 megawatts of power – enough to power about 800 homes – by 2010 and 500 megawatts of power by 2025.

Assessment of Underwater Noise Generated by Wave Energy Devices

Submitted to:
Oregon Wave Energy Trust

Authors:
Melanie Austin
Nicole Chorney
James Ferguson
Del Leary
Caitlin O'Neill
Holly Sneddon

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JASCO Applied Sciences
Suite 2101, 4464 Markham St.
Victoria, BC, V8Z 7X8, Canada
Phone: +1.250.483.3300
Fax: +1.250.483.3301
www.jasco.com

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1. Introduction

Energy harnessed from wave motion is a promising candidate as a clean renewable energy source. The Oregon coast is a key location for Wave Energy Converter (WEC) technology in North America due to the state's abundant access to ocean wave resources and its coastline transmission capacity. Additionally, the research facilities at Oregon State University (OSU) are ideal to act as a WEC test bed for research and development. A summary of the wave energy potential and the work that has been carried out to date at OSU has been published (Brekken et al, 2009).

The potential for creating underwater noise disturbance is one environmental impact that must be accounted for by wave energy developers to meet the needs of regulatory agencies. This review study has been conducted to provide a concise knowledge base of the expected underwater noise conditions in the near shore environment in regions of the Oregon coast where wave energy projects could be developed and to present an overview of noise measurement methodologies that would be suitable for the effective regulatory assessment of potential acoustic impacts. This report is intended as a reference to be used by wave energy developers in the specification and selection of approaches to underwater noise measurement that would be acceptable to regulatory bodies, consistent with the state of the industry and cost effective to implement.

In an attempt to address some of the uncertainties surrounding these types of environmental noise assessment studies, this report provides information on the expected existing ambient noise conditions, the sound propagation characteristics of the environment, and the expected sources of noise associated with various types of wave energy devices. Guidelines detailing specific noise measurement studies are provided, along with a listing of several commercially available devices that are suitable for performing these measurements.

Section 2 of this report provides an overview of the factors that contribute to ambient noise in near-shore environments. As part of this study a literature review was conducted to identify any available measurements of ambient noise along the Oregon coast, but no relevant data were found in published research. To address at least partially this knowledge gap, the latter part of Section 2 provides an overview of the characteristics of the Oregon coast that influence the ambient noise environment and thus helps define a basis for future studies.

Section 3 provides on overview of the various types of currently available WEC devices suitable for use in the Oregon coastal environment and lists the potential sources of noise associated with the construction, operation and decommissioning phases for these devices.

A framework for a comprehensive noise assessment program is detailed in Section 4 of this report with a description of specific measurement programs that are recommended to meet regulatory needs. The types of equipment suitable for performing these noise assessment measurement programs are detailed in Section 5.

As a complement to the above, an indicative sound propagation modeling study was conducted to provide an introduction to an estimation tool that is becoming the standard in noise impact assessments for regulatory approval. Section 6 of this report presents transmission loss estimates at three sample sites along the Oregon coast that are suitable for wave energy installations and are representative of a range of propagation conditions that can be found along the coast. These results provide an indication of the rate at which sound levels can be expected to decay as a function of distance from potential WEC development sites in the Oregon coastal environment.

2. Ambient Noise Characterization

2.1. Ambient Noise in the Coastal Ocean

Ambient noise is defined as “the composite noise from all sources in a given environment excluding noise inherent in the measuring equipment and platform” (Bradley 1996). The overall ambient noise in an environment includes sound from natural and anthropogenic sources, and varies with time and location. Ambient noise levels for a given location depend in part on the typical weather conditions of the region such as wind, waves and precipitation, as these factors all influence underwater noise. Natural occurrences such as seismic activity and turbulence from tidal currents similarly contribute to the ambient noise of an environment, as does biological noise including marine mammal vocalizations. Common anthropogenic sources that contribute to the ambient noise environment include vessel activity and industrial operations such as pile driving, seismic surveys, offshore drilling etc.

Ambient noise *spectral levels* (sound levels resolved in a range of frequency bands) differ between deep and shallow water environments, and the levels in coastal water, bays and harbors are subject to large variations (Urick, 1975). Oregon’s near-shore area, with bottom depths up to approximately 60 m, is classified as a shallow water environment – generally defined as water less than 200 m deep (Richardson et al., 1995).

The National Research Council (2003) published a report containing a thorough overview of the various issues to be considered when introducing noise into a marine environment. A chart of adapted Wenz curves reproduced from this report, describing the predicted ambient noise from weather, shipping, and other potential sources of noise, is given in Figure 1. In the remainder of this section the features of the Oregon coastal environment will be interpreted in terms of these curves in an attempt to provide a general estimate of the anticipated ambient noise levels in the absence of published measurements. However, given the variability of shallow water ambient noise levels with location and time, accurate levels at a specific location can be determined only through a dedicated baseline ambient measurement study (see Section 4.2 of this report). Ambient noise levels have been measured at deep water sites throughout the Northeast Pacific but this review focuses solely on the near-shore coastal environment.

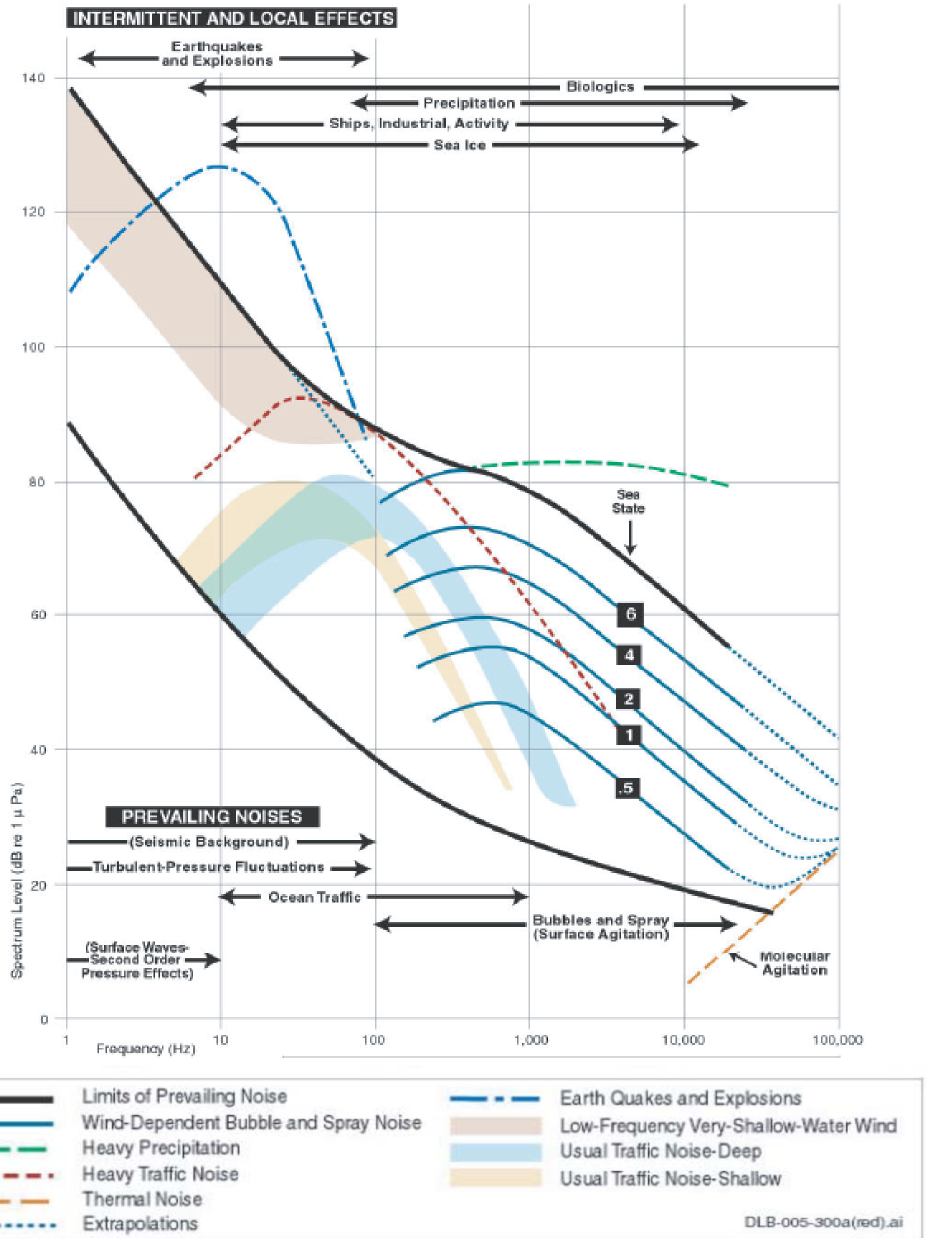

Figure 1 Adapted Wenz curves describing pressure spectral density levels of marine ambient noise from weather, wind, geologic activity, and commercial shipping. (Adapted from Wenz, 1962, reproduced from report of National Research Council, 2003)

2.2. Expected Ambient Noise Conditions for Oregon Coastal Waters

Underwater ambient noise measurements for Oregon's near-shore zone were unavailable from any publicly accessible reference at the time of writing. However, as seen above, shallow water noise generally originates mainly from features such as weather conditions, shipping or industrial activity, and vocalizations of marine mammals. Ambient noise characteristics for the Oregon coastal environment can be inferred from consideration of each of these parameters. This sub-section describes the features of the Oregon coast environment that are acoustically relevant and attempts to qualify the expected ambient noise in broad frequency ranges.

Wave noise

Underwater noise levels along the coast of the Pacific Northwest are considered to fluctuate with changes in wave height (Oregon State University, 2006). The National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center maintains weather data for several marine buoys and land based stations along the Oregon coast. To provide a general overview of wind and wave conditions across the coast, the NOAA data were reviewed over a four year period between 2005 and 2008 for three National Data Center Buoy Stations distributed along the length of the Oregon coast. Plots of the average winds speeds and wave heights at these three stations are provided in Appendix A. Generally, these recordings indicate that the wave height correlates approximately with the wind speed and that these two quantities are higher in the winter months. The plots show that the average significant wave height can vary throughout the year between 1.5m in the summer months to up to 3m or more in the winter. Allan and Komar (2006) have indicated that average significant wave heights along the Oregon cost are roughly between 2 and 3 meters. These conditions correspond to sea state 5 on the Beaufort scale. Therefore, referring to Figure 1, the wave induced contribution to ambient noise spectral levels in the Oregon coastal environment can be expected to lie in the range bounded by the solid blue curves labelled 4 and 6 in the chart.

Biological noise

The Oregon near shore marine environment is home to several species of marine mammals including pinnipeds such as seals and sea lions and cetaceans such as blue, fin, and gray whales. The waters are also home to a wide assortment of fish and invertebrate species. This variety of marine animals indicates that biologic noise can expected to contribute to the ambient noise field over a wide range of frequencies but the associated sound levels cannot be quantified from the limited information that was obtained through this review study.

Shipping noise

The "OCS Alternative Energy and Alternate Use Programmatic EIS" report prepared by the U.S. Department of Interior, Minerals Management Service (2007) describes the underwater acoustic environment of the Pacific Region including the Oregon/Washington OCS Planning Area, which encompasses waters beyond State jurisdiction out to about 200 nautical miles. The report states that commercial shipping, one of the largest sources of anthropogenic sound in the ocean, is expected to increase and continue to be a major contributor to ambient noise within the region. In addition, ports along the Columbia River accessed via Pacific shipping lanes were ranked among the top U.S. ports of call in recent years. Ambient noise levels in the Northeast Pacific are also impacted by commercial and recreational fishing.

Ports related noise

Several large ports such as the Oregon International Port of Coos Bay, the Port of Newport and the Port of Astoria are found along the Oregon coast. International shipping and regional-scale fishing fleets make regular use of these ports. Large vessels generally emit lower frequency noise than smaller ones. The noise characteristics associated with a particular area, therefore, could be generally described based on the numbers and types of vessels dwelling in the region. While the infrastructure of Oregon's ports has been described in reports such as the EPRI Survey and Characterization of Potential Offshore Wave Energy Sites in Oregon (EPRI, 2004), and some web sites document the types of vessels transiting within the near-shore zone at certain locations, there is no one source available that provides comprehensive transit statistics for a broad range of vessel types. The EPA (1999) reported transit statistics for numerous commercial vessels for the Port of Portland, the Port of Coos Bay and the Port of Astoria, showing tugs to have the highest incidence at all locations. Approximately 1700 commercial ships entered the Columbia River in 2003 (FERC, 2007), and 1740 in 2006 (NorthernStar Energy and Bradwood Landing, 2007). Although recreational use is not generally described, ports such as the Port of Depoe Bay and the Port of Alsea would be examples of locations where only small vessels would be found based on the infrastructure available. Referring to the Wenz curves in Figure 1, ambient levels in the frequency band between 10 Hz and 1 kHz can be expected to contain a contribution from shipping noise at levels bounded by the beige shaded area and the red dashed line (associated with usual to heavy vessel traffic in shallow water).

3. Noise Associated with Wave Energy Conversion Devices

Comprehensive environmental assessments examining potential impacts associated with WEC devices should include an assessment of any potential underwater noise impacts. To date, no public studies have been completed to assess the noise impacts due to the installation, operation, or decommissioning of these devices. Furthermore, no known acoustic field measurements are available to quantify the noise generated by any WEC devices. An effort to collect such data is currently being undertaken as the WEAM (Wave Energy Acoustic Monitoring) project by the Wave Energy Centre in Portugal. Their group has recently completed an extensive review of the literature pertaining to noise assessments on several different devices (Patricio et al, 2009a).

It is generally presumed that the environmental impact from noise generated by WEC devices will be minimal; some reviews, however, are more cautious as to the level of impact these devices will have (Patricio et al, 2009b) particularly for installations with many devices in place. Without field measurements, sound source levels for WEC devices can only be inferred by considering the noise associated with their operational components. Their acoustic signatures will be composed of noise from things such as turbines, generators, hydraulic components (such as pumps and valves), as well as other moving parts such as hinges and actuators. Secondary noises caused by external factors are difficult to predict but could include the noise of water waves hitting the device, vibration of mooring cables, and cavitation (the formation and subsequent implosion of decompression bubbles in a volume of water subjected to rapid displacement).

In the absence of any measured acoustic data, an overview of four classes of WEC devices suitable for use along the Oregon Coast, covering the probable noise sources associated with each technology, is presented in this section. This review examines the underwater noise potentially generated during the installation, operation and decommissioning phases.

The device classes presented in this section are categorized as point absorbers, attenuators, terminators or oscillating water column devices, and over-topping devices. Each class differs in their operational principles and their orientation relative to the direction of the wave motion. The examples provided here for each class of WEC devices are limited to models that either have passed field trials or are in advanced prototype stages; in other words, designs that as of this writing are purely conceptual are not considered.

3.1. Categories of WEC Devices

3.1.1. Point Absorbers

Point absorbers utilize a mechanism consisting of two components: one immobile, either weighted or moored to the seafloor, and the other following the wave motion. The relative motion at a single point on the device is used for energy conversion. Point absorber devices generally fall into one of three groups: simple point absorber (where the floating component moves vertically relative to the base), oscillating wave surge converter (where the floating component moves transversely as well as vertically), and submerged pressure differential (where the floating component is submerged). Examples of point absorbers are the PowerBuoy™ (shown in Figure 2 below) developed by Ocean Power Technologies (OPT), the AquaBuOY™ WEC developed by AquaEnergy Group Ltd., and the Archimedes Waveswing.

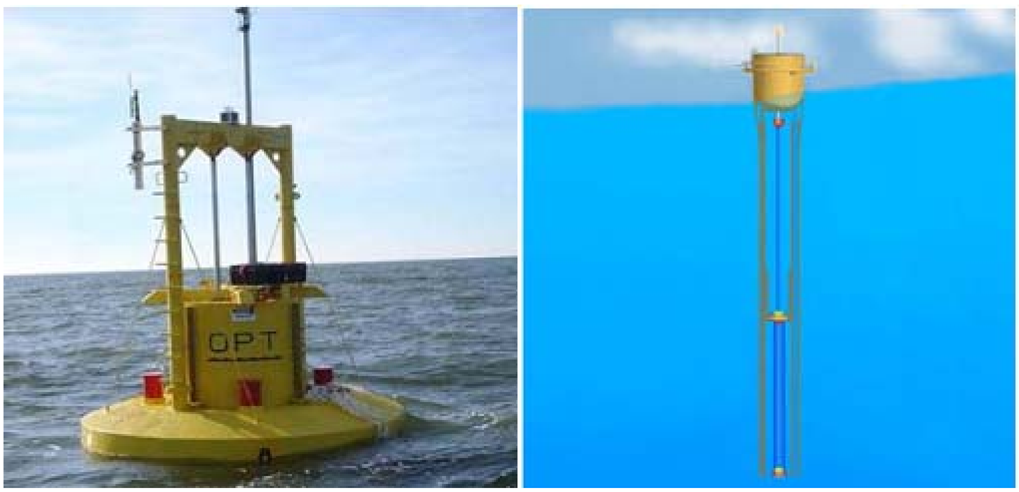

Figure 2. The PowerBuoy, a point source absorber developed by Ocean Power Technologies (New Jersey).

OPT is currently planning a deployment of their PowerBuoy, with an initial power generation of 150 kW, near Reedsport, Oregon. The initial phase with deployment of a single PowerBuoy is expected to be ready for implementation in 2010. OPT were awarded $2 million by the US DOE in 2008 in support of this project, and Pacific Northwest Generating Cooperative (PNGC) agreed to partial funding in 2007. OPT is also developing the first utility-grade underwater substation, or pod, for wave power. The pod will serve as the collection point for the energy generated by multiple PowerBuoys to be transmitted ashore and is intended for use in the Reedsport, Oregon wave farm and the UK Wave Hub wave farm. A larger project involving OPT may also occur in Coos Bay following the Reedsport Project.

Any potential noise emissions associated with the installation of point absorber devices would depend on the mooring technique used. Drilling or pile-driving could be required to moor the fixed component of the device to the seafloor. Any piles or fasteners, however, are not likely to be large in dimension and would require far less intensive percussive piling than would be required, for example, to install the large tower foundations associated with wind turbines. Suction piling could also be used, with a significantly lower associated noise. Large anchors are another option for bottom mooring and would likely require powerful tugs for their deployment.

The sound from the tugs, originating from their power train and from cavitation at the propeller blades, would be the most prominent noise source in this case and would be a temporary and short term activity.

Noise associated with the operation of point absorbers would mainly be created by the energy conversion mechanism, which would vary by device design. The mechanisms involved could include turbines, electrical generators, hydraulic or electromechanical energy converters, pumps, valves etc. The noise from these components would likely be continuous and may contain tonal (single or narrow band frequency) features, with most of the sound energy at frequencies less than a few kilohertz (Patricio et al, 2009a). The nature and intensity of this noise should be comparable to that emitted by machinery on board typical vessels (Marine Minerals Management Service, 2007). Any external mechanical noise associated with these devices would arise from vibrating mooring lines and the motion of the device at the surface and would likely be of low level, comparable to underwater sound emissions typically associated with large ocean buoys. A single point absorber device is not likely to cause significant noise impact at longer ranges; a full regulatory assessment, however, would have to consider the additive effect for groups of devices in simultaneous operation since a typical production installation could involve the deployment of tens or hundreds of point absorbers.

Decommissioning of these point absorber devices would require the use of vessels to retrieve the mooring infrastructure and the devices themselves. These activities would be expected to be comparable, from a noise perspective, to the installation phase minus any piling or drilling activities.

3.1.2. Attenuators

Attenuators consist of long multi-segmented floating structures orientated parallel to the wave travel direction. As surface waves pass, the attenuators flex at the segment joints and the mechanical energy is harnessed via hydraulic pumps or other converters. Attenuators float on the surface and therefore have minimal installation requirements, generally requiring only a tethered mooring. The attenuator design, incidentally, can also be adapted to pressurize water for desalinization (e.g. McCabe wave pump by Hydam Technology).

An example of an attenuator WEC unit, the Pelamis, is shown in Figure 3. This device, named after the Greek word for sea snake, consists of 4 tubular sections with actuating hinges between the segments. The P-750 total device length of is 150 m with a tubular diameter of 4.63 m. The most recent design of the Pelamis device is 180 m in length. Several sites have been targeted for evaluation: Hawaii, Oregon, California, Massachusetts, and Maine (Minerals Management Service, 2006).

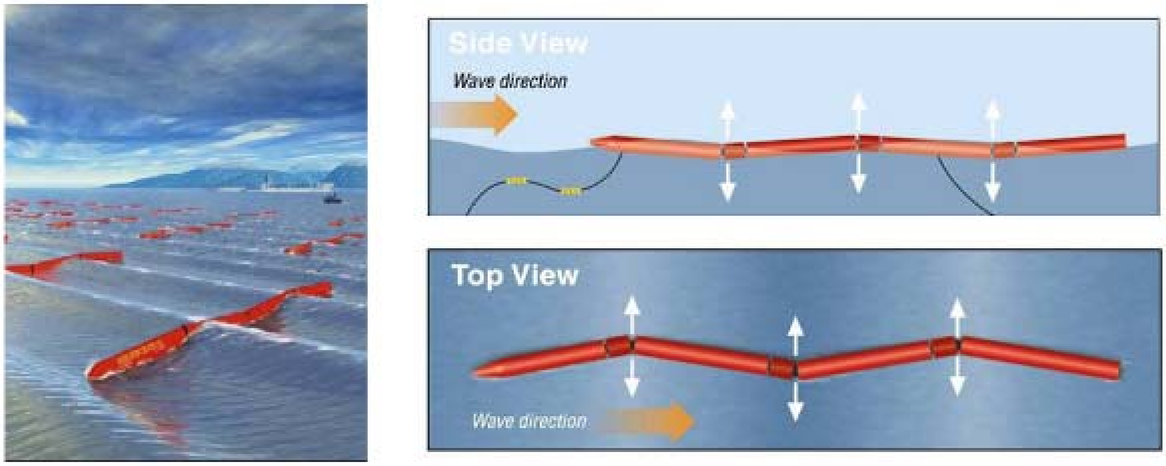

Figure 3. The Pelamis, an attenuator developed by Pelamis Wave Power (formally Ocean Power Delivery, Scotland)

Noise associated with the installation and decommissioning phases for these attenuator devices would be due to the vessels required to deploy/recover the mooring anchors and the devices themselves. The vessels involved would likely include tugs, barges as well as smaller crew vessels and support vessels.

The noise associated with the operation of these devices would include the noise from the hydraulic pumps or other energy converter mechanism, as well as mechanical noise that may arise from the motion at the hinges and from the water interacting with the device at the surface. The hinging noise could likely be kept at low levels through appropriate device design.

3.1.3. Terminators or Oscillating Water Column

Terminator devices, also known as Oscillating Water Column devices (Figure 4), are positioned perpendicular to the wave motion, and are typically installed on or near shore. Some terminator variants are floating versions designed for offshore platforms. Typically, a subsurface opening feeds into a vertical compression chamber, in which the water surface oscillates with the wave action, forcing air out and across a turbine. An oscillating water column device is being proposed for installation in Oregon's coastal waters within Douglas County.

Figure 4. An oscillating water column device, developed by Oceanlinx (formerly Energetech, Australia)

The installation of these terminator devices onshore would create general construction type noise at or near to the shoreline that might couple into the water. Small vessels may also be involved n this activity, but their presence would likely be limited and of short duration and their operating speed, which is generally associated with noise level, would tend to be very low. Similar types of noise could be expected to be associated with the decommissioning of these devices.

The main source of operational noise associated with terminator or oscillating water column devices is the noise from the air being expelled through the turbine. This noise is generated in air, and it is possible for it to couple into the water as well. Another source of underwater sound associated with these devices is the low frequency noise of the waves impinging on the structure.

3.1.4. Overtopping Devices

Overtopping devices consist of elevated reservoirs that are filled by waves spilling over a ramp and empty back into the ocean below through a drain. The potential difference creates a head pressure across the outlet that forces water through hydro turbines or other conversion devices. Overtopping devices have been built in either fixed onshore (or near shore) or floating varieties. The Wave Dragon™ (designed by Wave Dragon, Wales & Denmark, see Figure 5) has proven to be effective with a 7 MW demonstration project off the coast of Wales; much larger systems are potentially feasible since overtopping devices need not be in resonance with the wave as is the case with point absorbing or attenuator devices.

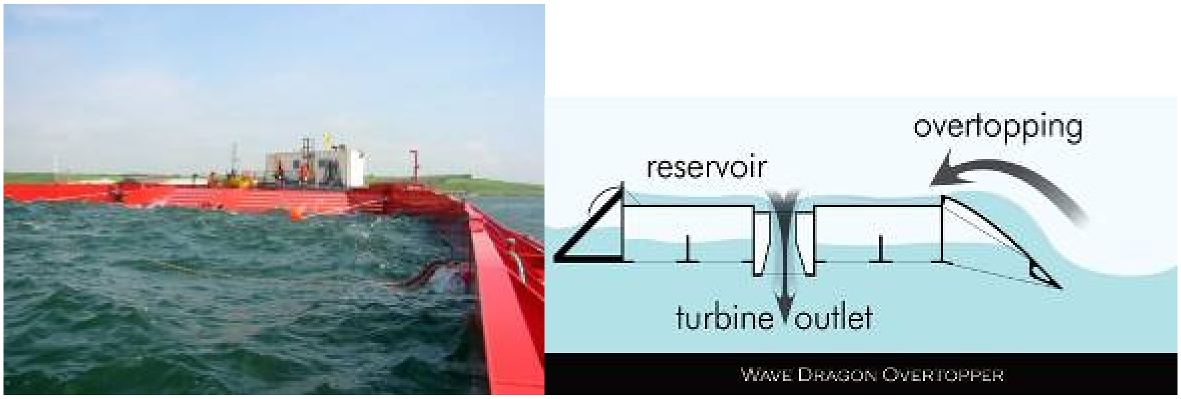

Figure 5. Wave Dragon (from Wave Dragon, Denmark).

Similar to the terminator devices, general construction and small vessel noise could be associated with the installation and decommissioning of over-topping devices.

Operational noise emitted from overtopping devices would be mainly generated by the waves impinging on the device and the flow and mechanical noise from the turbine outlet.

Additional sources of underwater sound both temporary and ongoing for all WEC device classes in a full scale wave farm development would include the noise associated with the construction and operation of energy collection hubs linking arrays of individual devices, the recurrent noise from service and maintenance vessels, and the noise associated with the cable laying activities.

A table of current WEC devices and their respective manufacturers is provided in Appendix B of this report. Additional information on current WEC devices and manufacturers can be found at: http://peswiki.com/energy/Directory:Ocean_Wave_Energy.

4. Noise Assessment Program Framework

Underwater noise can potentially impact the behaviour of marine animals or even cause them temporary or permanent hearing damage. Behaviourally, anthropogenic noise can disturb marine animals by masking communications or by causing avoidance reactions and thus disrupting normal movement patterns. Physically, noise can cause direct injury or changes in sensitivity in the animals' auditory systems. Marine animals exhibit species-dependent differences in hearing abilities and thus exhibit different responses to anthropogenic noise. Their susceptibility to noise depends on the intensity and spectral composition of the noise. The type and level of impact are also dependent on the temporal nature of the noise itself – that is, whether the noise consists of single pulse, multiple-pulse, or non-pulsed (continuous) sounds [Southall et al., 2007].

The Oregon Department of Fish and Wildlife has identified the following marine mammals, found in the Oregon near shore marine environment, to be in need of special management: California sea lion (*Zalophus califonianus*), Stellar sea lion (*Eumetopias jubatus*), Northern elephant seal (*Mirounga angustirostris*), Pacific harbour seal (*Phoca vitulina*), gray whale (*Eschrichtius robustus*) and harbor porpoise (*Phocoena phocoena*).

A common and targeted species of concern in the area along the Oregon coast is the gray whale. These whales have an estimated population of 18,000 and follow a long migration path from Alaska in the summer to Baja California, Mexico during the winter. A previous OWET funded study concluded that areas proposed for wave energy development projects along the Oregon coastline may interfere with migrating gray whales (Lagerquist and Mate, 2009). Data collected that tracked the paths taken by several tagged whales is illustrated in Figure 6.

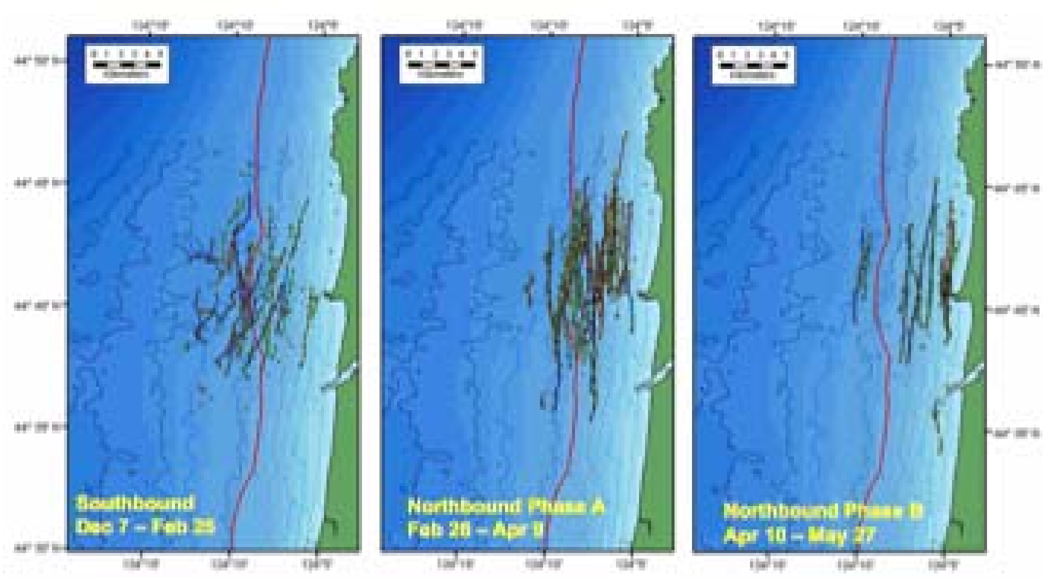

Figure 6. Tracklines of gray whales sighted during the southbound, northbound-A, and northbound-B migration phases 2007/2008. The red line indicates the Oregon territorial sea boundary (3 nautical miles offshore).

Federal and state environmental agencies (e.g., National Marine Fisheries Service) have shown increased awareness of the potential impacts of noise in the marine environment and the need for responsible noise management. In 2007, the Minerals Management Service (MMS) of the U.S.

Department of the Interior (USDOI) produced an Alternative Energy and Alternate Use programmatic Environmental Impact Statement (EIS) that examined a number of potential environmental consequences of various alternative energy technologies. The EIS indicates that there is the potential for noise impacts that may be associated with the construction, operation and decommissioning of wave energy installations.

Guidelines, regulations and permitting restrictions are well defined for several marine industrial activities including offshore oil and gas exploration, development and production as well as marine pile driving. Since wave energy development is a relatively new field, such guidelines and permitting details have not yet been formulated to the same extent. An adaptive management approach would allow regulatory agencies to establish appropriate guidelines and requirements for the wave energy industry as more information on potential impacts is gathered. To satisfy regulatory concerns the permitting requirements for the deployment of wave energy devices will require an assessment of the noise associated with the devices.

A series of noise assessment tools are presented in this section that would assist wave energy developers in meeting the expected assessment requirements. A comprehensive noise assessment should include each of the following aspects:

a. Characterization of noise emitted by sound sources
b. Characterization of existing ambient noise conditions
c. Characterization of sound propagation in the local environment
d. Identification of sensitive receptors
e. Field verification measurements

This section provides conceptual guidelines for a predictive modelling approach and two types of measurement studies that in combination would provide the information needed to address each of the aspects listed above. The subsections that follow show how a predictive modelling study largely addresses point (c) in the list above, a baseline ambient noise measurement study satisfies points (b) and (d), and a source characterization measurement study addresses points (a) and (e) while also providing ground truth information for (c).

Little information currently exists regarding the aspects listed above. While the costs and effort associated with conducting all of the above studies would seem burdensome for a single wave energy developer, particularly at the pilot project stage, there is an opportunity in this nascent field for developers in Oregon to work collaboratively to fill in the current data gaps and share the knowledge among members of the industry for the common benefit of subsequent permitting applications.

4.1. Propagation Modelling Studies

Numerical algorithms can be used to model the physical laws defining propagation of sound in underwater environments. The models compute transmission loss (that is, the decay of sound levels as the sound spreads away from a source) as a function of frequency over a grid of points covering the region of interest in both planar extent and depth, taking into account topographic and environmental properties that influence the sound distribution. These estimated transmission loss values are combined with the estimated or measured spectral sound levels emitted from a source to calculate received sound levels at each of the model grid points. From the estimates of received sound level it is possible to compute impact distances or zones for specific threshold levels associated with potential behavioural influence or injury.

The sound propagation modelling results are commonly presented graphically as sound level isopleth contours overlaid on GIS maps, and unless a specific depth holds particular significance for a species (for example, a bottom dwelling animal) the map contours are drawn to follow the maximum estimated level over the full water column. The frequency-dependent model results can be presented as simple broadband levels (all spectral components summed together) or can be scaled to provide frequency-weighted levels that account for the hearing acuity profiles of specific marine animals. This allows to estimate sound levels as they would be perceived by particular animals and to forecast species specific potential zones of impact.

An indicative sound propagation modelling study is presented in Section 6 of this report.

4.2. Baseline Ambient Noise Measurements

4.2.1. Purpose

An ambient noise study helps quantify potential noise impacts of a planned WEC installation in two ways. First, the measurements provide a baseline against which to compare future changes to the acoustic environment (not necessarily related to the development in question). Secondly, prior to installation the estimated noise footprints surrounding WEC devices can be compared to baseline levels to determine the extent to which any new noise is likely to be detected above ambient levels. This information is used to establish zones of potential impact. Ambient noise measurements can additionally be reviewed for the presence of marine mammal vocalizations, which can be used to infer relative abundance and distribution of marine mammals near the planned WEC location.

To perform a baseline study, several underwater sound recorders would be deployed over the area of interest before installation of WEC devices to measure existing ambient noise conditions. These receivers would also remain in place or be redeployed following installation to measure the potentially affected acoustic environment. The measurements obtained before and after installation would be compared to identify any changes in the acoustic landscape and, through analysis of vocalizations, any possible effect on the distribution of known marine mammal populations. The baseline study is not necessarily targeted at the specific noise generated from the WEC devices, but rather at assessing how their deployment and presence has affected acoustically the surrounding area.

4.2.2. Methods

A baseline ambient noise recording should be at least 24 hours in duration. However, a long term baseline study lasting up to a year is strongly recommended to capture both daily and seasonal variability in the ambient noise field. Variations in weather conditions can greatly influence ambient noise levels, although if the target location experiences little annual variability in weather conditions, approximations could be made to shorten the duration of the ambient noise measurement. The temporal extent of a baseline study is also determined by the interest in capturing any seasonal cycles in marine mammal migration or feeding behaviours as well as fluctuations in vessel traffic levels (such as variability according to fishing season).

At a minimum, a single acoustic recorder would be deployed near a proposed WEC installation site to measure baseline ambient noise conditions at the source location. It is recommended that at least one additional recorder be placed in a ‘control’ location some distance away to allow a comparison of the ambient noise variability post-installation of the device. The separation between the source and control locations should be sufficient to ensure that the expected acoustic emission from the installed WEC would not reach the latter at any significant level; this can be determined by estimating the transmission loss of the environment over the separation distance either using rule of thumb spreading loss calculations or preferably through a modeling study as discussed in Section 6.

4.2.3. Equipment

Devices for baseline sound measurement must have sufficient autonomy and be suitably rugged to withstand long-term ocean deployments. Baseline ambient noise data are often collected using ocean bottom hydrophone (OBH) recorders, like the unit pictured in Figure 7. These systems are designed to carry out autonomous recording for extended durations. The continuous deployment time of OBH units is limited by the power supply (battery life) and data storage capacity, and under most circumstances it can be prolonged by programming a duty cycle in which the OBH records data in periodic intervals separated by standby time. For example, setting a recording time of ten minutes every hour or some similar ratio would adequately sample the fluctuations in ambient noise throughout the day while significantly prolonging the time before the data storage medium reaches capacity or the power supply is depleted.

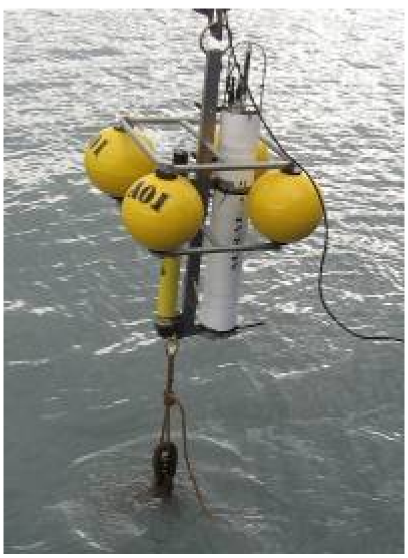

Figure 7. An OBH system, consisting of a hydrophone recording system and an acoustic release, with floats and anchor.

The analog acoustic signal from hydrophones should be digitized and recorded with the highest possible sample rate compatible with storage autonomy requirements. The base standard for modern commercially available digital recording systems is to sample at 48 kHz with 24-bit resolution. Sampling theory states that the highest signal frequency that can be recovered from digitized data is equal to ½ of the sample rate. Therefore, these specifications give a frequency bandwidth up to 24 kHz with a dynamic range greater than 16 million (2^{24}) discrete values in amplitude. The measurable frequency range also depends on the response of the specific hydrophone used in the OBH device, which is often the limiting factor.

Several commercially available underwater sound recording systems that are suitable for baselne ambient noise studies are described in Section 5 of this report.

4.2.4. Analysis

Baseline data obtained with OBH recorders can be analyzed in various ways to yield metrics suitable for noise assessment. By segregating sound pressure levels into various frequency bandwidths (Figure 8a) or visually representing frequency distribution in a spectrogram (Figure 8b), various dominant sources (e.g., vessels or marine mammals) can be detected and potentially classified. Measurements over extended periods allow the statistical characterization of ambient noise level fluctuations. Percentile plots indicating the statistical spread of the ambient noise levels as a function of frequency are also commonly reported.

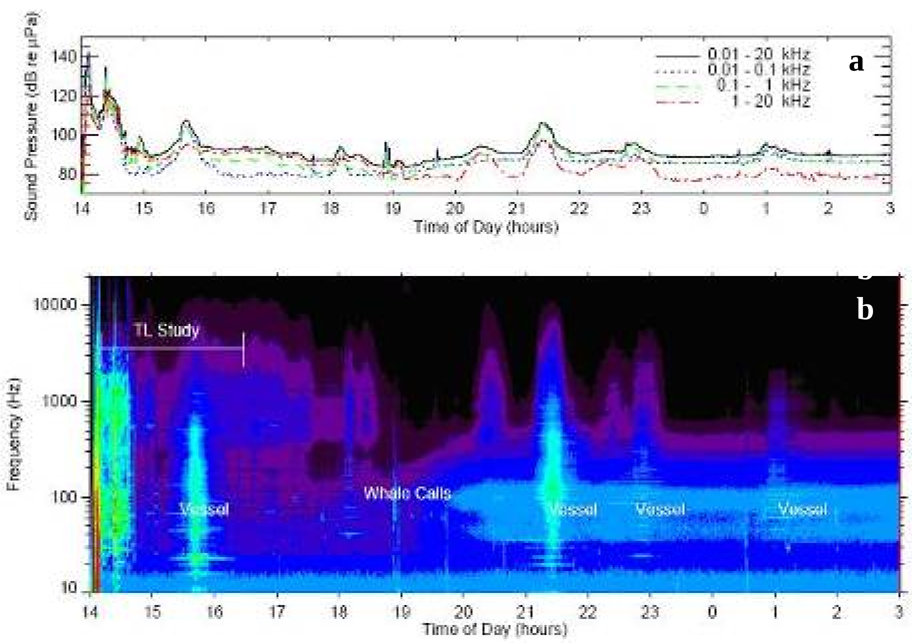

Figure 8. Example of (a) sound pressure in each decade frequency band and the corresponding (b) spectrogram,. This spectrogram capures transmission loss study broadcasts, baleen whale calls, and several passing vessels over a 13 hour period.

4.2.5. Presentation of Results and Reporting

The presentation of analyzed baseline data should provide an overall indication of the ambient noise level at the site as well as evidencing any temporal and spatial variability. If possible the reporting should identify specific acoustic sources contributing to the background, such as marine mammal vocalizations or pre-existing industrial noise including vessel activity (see Figure 8b). Since ambient noise levels frequently depend on prevailing weather conditions, it is useful to present comparative plots showing on a common time axis noise level and recorded wind speed or wave height data which may be obtained from meteorological ocean buoys in the relevant geographic area.

The detection and classification of marine mammal vocalizations is often of particular value to understanding the ecosystem that the noise might affect. The count of detected vocalizations over an advancing time window yields a time history of the vocalization density over the recording period. Figure 9 shows an example of this type of data collected on a distributed grid of receivers over an extended time period, presented as a bubble plot where the size of each circle represents the number of detected vocalizations. For a more limited program involving a single recorder or a small grouping of them, a simple bar plot display showing density of detections as a function of time may be a more appropriate form of presentation.

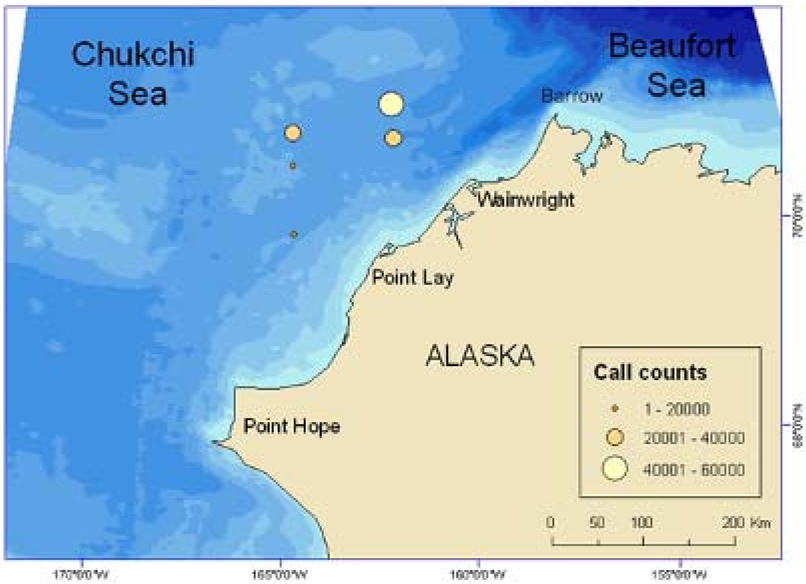

Figure 9. Bubble plot superimposed on a geophysical map to represent the density over a period of time of vocalizations for a particular species.

4.2.6. Case study

JASCO Applied Sciences (JASCO) recently conducted ambient noise measurements as part of an environmental assessment for the development of a large scale offshore wind farm. This case study provides an example of the kind of baseline characterization study that should be carried out prior to installation of WEC devices. The study involved deploying three ocean bottom hydrophone (OBH) recorders to measure ambient noise levels over a one year period in the planned wind farm grid area. The focus of this study was to characterize the existing ambient noise levels, to detect killer whale vocalizations and humpback singing/foraging sounds, and to quantify the presence of vessel traffic in the project area. The three autonomous OBH systems were equipped with AURAL underwater recorders (Multi-Electronique; see Appendix C.3 for specifications for this system) sensitive to frequencies between approximately 6 Hz and 16 kHz. The data were recorded at a sample rate of 32 kHz and 16-bit resolution and stored on an internal hard drive. The OBH devices were deployed on the seabed using anchor weights attached to an acoustically triggered release system fir retrieval. A specimen of the type of OBH devices deployed was shown earlier in Figure 7.

One OBH system was placed inside the planned wind farm grid boundary; the other two were deployed 20 km north and south of the center location in an arrangement parallel to the coast line to serve as controls. The recorder's duty cycle was set to 20% (recording for 13 minutes out of every hour) giving a maximum recording time per deployment of 4 months before the hard drive was filled. The OBHs were recovered every 4 months and immediately redeployed following extraction of the acquired data and replacement of the battery pack. The reporting of this baseline study included statistical summaries of the seasonal baseline ambient noise measurements, an analysis of the correlation of ambient noise with the recorded wind speed at the site, a tally of detected vessel passes to provide an indication of the level of vessel traffic in the area, and a summary of the detection, classification and tallying of marine mammal vocalizations to show the seasonal presence of particular marine mammal species in the study area.

The baseline assessment just described included the recommendation that the year-long ambient study be repeated after the installation of the wind farm, using the same receiver locations, to document any changes to the acoustic environment.

4.3. *Source Characterization Measurements*

4.3.1. *Purpose*

The intensity and frequency content of sound emitted by a WEC device are best characterized through direct acoustic measurements on a full scale unit deployed in the ocean environment, since measurements performed in a wave energy test tank would easily be contaminated by reverberation. The source level information thus obtained can then be used as input for sound propagation models to establish zones of potential impact (see Section 4.1 above).

Sound source characterization measurements obtained *in situ* also provide a means to validate any predictive acoustic modeling based on estimated sound source levels and to ensure that a specific unit is not generating any uncharacteristic and excessive noise due to malfunction or deployment issues.

This section provides guidelines targeted to the measurement of noise levels from operating WEC devices, but the same approach applies to measuring the noise from construction activities during device installation.

4.3.2. *Equipment*

This type of measurement can be done either from a small measurement vessel with a surface deployed hydrophone connected to a digital recorder on board, or using an autonomous subsea recording device that is tethered to a mooring point or resting on the seafloor. Given that the measurements should be obtained while the WEC device is in full operation, and therefore while sea conditions are not calm, the use of an autonomous recorder is especially recommended for measurements of noise from WEC devices as wave motion can easily degrade measurements performed from a vessel.

The recording equipment must be calibrated in the field immediately before the study to ensure accuracy, since a source characterization measurement is intended to yield absolute acoustic levels rather than a comparison of acoustic conditions as in the case of baseline studies. The analog acoustic signal from a hydrophone should be digitized and recorded with the highest possible sample rate and resolution, as discussed earlier in Section 4.2.3. It is not anticipated that WEC devices will generate noise at frequencies much higher than a few kilohertz (Patricio et al, 2009a) so a sample rate as low as 16 kHz would be acceptable for these measurements unless other noise sources associated with construction must be characterized.

4.3.3. *Methods*

Sound levels should be recorded at a number of measurement points located at a selection of ranges from the operating WEC device. It is recommended that measurements be obtained at the closest range to the device that is logistically feasible (though no closer than a few device sizes to avoid near-field effects where the source cannot be considered point-like) and at several longer ranges out to a suggested maximum of approximately 5 km. The accuracy of the source level estimate will be improved by collecting data at many different measurement ranges, although clearly the number of measurement locations will be limited by the available units if autonomous recorders are used to perform the measurement in a single deployment (generally the preferred approach). Acoustic source characterization can be performed with reasonable accuracy based on measurements at a single recording position, but a standard of three to five measurement ranges is preferred. It is critical to correlate the measured data with range from the WEC device; accurate GPS coordinates of the source and the recorder stations must be logged to determine the separation ranges. If a WEC installation consists of a network of multiple devices the measurement ranges should be calculated from the centroid of the device field and the setback of the recorders should be adequately increased based on the overall extent of the field.

If feasible, measurements should also be obtained along several radial orientations around the device to investigate the directionality of the sound emission. Directional measurements are likely less important for devices such as point absorbers, which being vertical structures can be expected to radiate noise omnidirectionally in a horizontal plane, than for WEC systems such as attenuators, terminators and over-topping devices as described in Section 3.1.

The duration of the recording at each measurement range should be sufficient for a statistical analysis of the natural fluctuation of the device's sound signature. Ideally the measurements should be made under various WEC operating conditions and sea states, which strengthens the argument for use of autonomous recorders since these units can readily be deployed for an extended time period. The measured data should be correlated in time with operational status and power output of the WEC device (e.g. turbines idle, generating at full power etc) and with logs of local weather and sea state to fully characterize the variations of the noise levels. A minimum recording period of 24 hours using autonomous recorders is recommended.

4.3.4. *Analysis and Presentation of Results*

The measured data should be processed to provide root-mean-squared received levels, for the various recorded operating conditions of the WEC device, as a function of measurement range and of frequency. Spectral levels are commonly binned into 1/3-octave frequency bands for analysis. Source level estimates in 1/3-octave bands are computed by adding to the received levels the estimated transmission loss for the environment, which can be estimated by fitting an approximate spreading loss equation to the measured data, or through numerical modeling (see Section 6) if only one or two measurement ranges are available. This yields spectral levels normalized to a nominal measurement distance of 1m from an idealized point-like source, which is the standard way of expressing the intrinsic loudness of an acoustic emitter. In reporting the results of the characterization, the spectral and broadband source levels should be tabulated or presented graphically in relation to relevant operating conditions of the WEC system to provide a comprehensive description of the potential range of noise emission level under different regimes and/or external conditions.

5. Acoustic Measurement Devices

This section begins by providing under individual headings a high-level overview of available underwater acoustic measurement and recording technologies that could be used to carry out the baseline ambient and source characterization studies described in previous parts of the report. It then presents a list of selected devices for which a detailed specifications profile is provided in an Appendix. This information does not represent an endorsement of any particular manufacturer or product but rather is intended to assist in the process of evaluating for suitable use the wide variety of devices available on the market.

5.1. Acoustic Tags

Acoustic recording tags are the smallest of all the acoustic measurement devices, which allows them to be easily fastened (usually with barbs or hooks) to marine mammals or installed on underwater equipment. They are most commonly used to record the acoustic environment of an animal in tandem with physiological or behavioral information. Acoustic recording tags can also be a component of multi-purpose underwater recording or observing systems. The small size of acoustic tags limits their battery power and recording capacity, usually limiting their operational autonomy to the order of a few tens of hours. They also tend to be less accurate or precisely calibrated than more substantial sound monitoring instrumentation. Being designed for applications in which device loss is a fairly common occurrence, acoustic tags are the least expensive of all underwater acoustic recording devices.

5.2. Autonomous Systems

Autonomous recording systems record acoustic data internally on digital storage media and are commonly used for long term baseline ambient noise characterization studies due to their long operational autonomy and their multitude of recording options. They can record continuously or in duty-cycle mode at numerous sampling rates and frequency bandwidths and may also record other variables such as depth (pressure) and temperature. The precise sensor calibration and high quality of data recording of these units, combined with their ease of deployment, makes them quite suitable for subsea applications such as measuring the acoustic transmission loss properties of an environment, determining ambient noise levels, characterizing anthropogenic sound sources and detecting marine mammal vocalizations. These systems can be deployed on various kinds of moorings or directly on the seafloor, either independently or in combination with other recording devices.

5.3. Cabled Systems

Cabled systems are a network of instruments deployed on the seafloor that are connected via cable to a marine or onshore receiving station. These systems allow real-time monitoring and remote recording, and therefore are primarily used for very long term ambient data collection and for construction and operational noise monitoring where immediate mitigation decisions may have to be made in response to received levels. Often cabled systems form part of an extensive experimental network connected to a large archival data storage system. The **V**ictoria **E**xperimental **N**etwork **U**nder the **S**ea (VENUS) project is an example of a cabled system that hosts a hydrophone array for acoustic monitoring along with video cameras and many other underwater scientific instruments, all linked to a data network via an underwater power and fiber optic cable. While the costs and effort associated with installing a cabled hydrophone network would make it an unwarranted undertaking for a single wave energy developer, a collaboration of developers or organizations might consider either installing such a system for long-term acoustic monitoring purposes or investigating the possibility of obtaining access to data from existing cabled networks.

5.4. Radio Telemetry Systems

Radio telemetry systems provide real-time monitoring, which is primarily used for time-critical construction and operational noise monitoring. They are more complex and therefore more expensive than similarly featured autonomous systems, especially factoring in the added cost of a marine or terrestrial receiving station (or access to a satellite uplink). Internal data recording capabilities are sometime provided in conjunction with the radio telemetry, usually for the purpose of acquiring full-waveform archival data at a higher sampling rate and resolution than could possibly be transmitted wirelessly. Because of the additional power required by the radio transmitter, telemetric systems cannot operate on an equivalent battery supply for as long as internally recording systems. The acoustic frequency bandwidth of these systems is also limited since the data must be transmitted through the modulation bounds of radio or satellite channels; in some systems the issue is circumvented by computing various signal metrics directly on board the deployed system and only telemetring the results.

5.5. Detailed Specifications of Selected Devices

Descriptions of several commercially available measurement systems are provided in Appendix C to this report. The descriptions are based on information obtained from the manufacturers' websites and/or marketing information, and in some case through direct contact with vendors or manufacturers. The systems described include the following:

- Advanced Multi-channel Acoustic Recorder (AMAR)
- Autonomous Underwater Acoustic Recorder (AUAR)
- Autonomous Underwater Recorder for Acoustic Listening Model 2 (AURAL – M2)
- Acousonde
- C-Pod/T-Pod
- Directional Autonomous Seafloor Acoustic Recorder (DASAR)
- DTAG
- Ecological Acoustic Recorder (EAR)
- High-frequency Acoustic Recording Package (HARP / ARP)
- Pop-Up
- Passive Acoustic Listener (PAL)
- Programmable Underwater Acoustic Recorder (RASP)
- Remote Underwater Digital Acoustic Recorders (RUDAR, µRUDAR and MiniRUDAR)
- SRB-16 Autonomous Recording Buoy

6. Indicative Modelling Study

This section provides results from an indicative modelling study undertaken to investigate the sound propagation properties off the Oregon coast at three representative sites. The modelling was performed using JASCO's proprietary Marine Operations Noise Model (MONM). The modelling locations were selected from proposed wave energy conversion (WEC) device installation sites and were chosen to reflect the diverse topographic and geo-acoustic properties encountered along the Oregon coast. The selection criteria were as follows:

- Sites should be located in regions already identified as having potential for wave energy devices installation.
- Sites should exhibit substantial differences in environmental parameters (i.e. the results from the three model runs should be qualitatively different).
- Sites should allow for a source location in 50m water depth within 3 nm from shore (but at least 1.5 nm away from shore).

The modeling grid boundaries at the three representative sites are depicted with green boxes on the map in Figure 10. The sites are located near Oceanside in Tillamook County, near Depoe Bay in Lincoln County and near Jewitt Island in Douglas County; their coordinates are listed in Table 1. The three modelling regions have distinct sound propagation characteristics due to differences in their geo-acoustic properties as will be explained in Section 6.2.

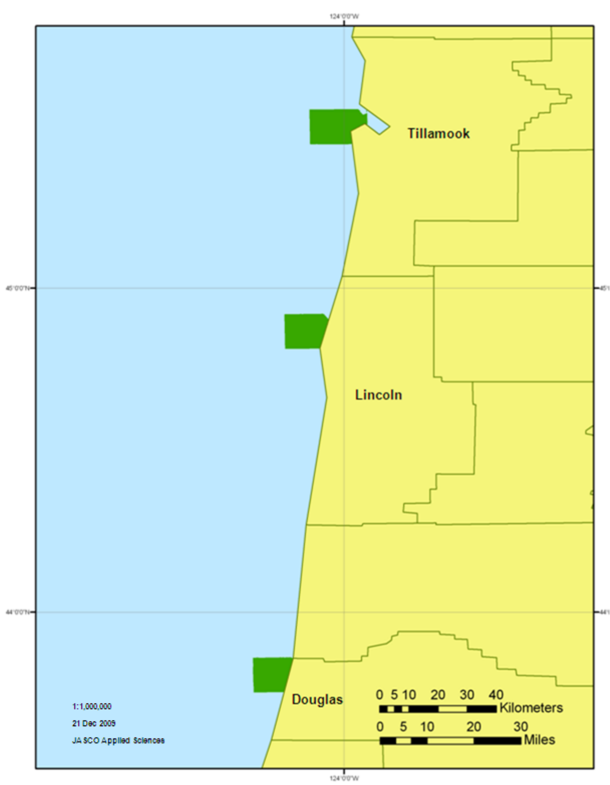

Figure 10 Sites selected for representative transmission loss modelling.

Table 1. Coordinates of WEC device sites used for model scenarios.

Site (County)	Latitude	Longitude
Oceanside (Tillimook)	45°33’04” N	124°15’35” W
Depot Bay (Lincoln)	44°52’17” N	124°23’34” W
Jewitt Island (Douglas)	43°42’26” N	124°28’25” W

In the context of a noise impact assessment study the propagation modeling results would be combined with spectral source level data for a specific WEC device or construction activity to estimate the acoustic footprint at any relevant levels. For this indicative study, on the other hand, no source levels were introduced and the results represent a generalized propagation footprint for a hypothetical source with uniformly distributed intensity at all modeled frequencies.

6.1. MONM Description

MONM is a computer software application that computes transmission loss for arbitrary three-dimensional (3-D), range-varying acoustic environments using a parabolic equation solution to the acoustic wave equation. The parabolic equation code in MONM is based on the U.S. Naval Research Laboratory’s Range-dependent Acoustic Model or RAM (Collins, 1993), which has been extensively benchmarked for accuracy and is widely employed in the underwater acoustics community. MONM computes acoustic fields in 3-D by modelling transmission loss along evenly spaced radial traverses covering a 360 º swath from the source (so-called N×2-D modelling). The modelling takes into account a number of environmental parameters including bathymetry, sound speed profile in the water column and geoacoustic properties of the seafloor. This approach has been validated against experimental data and has proven to be highly accurate for predicting noise levels in the vicinity of industrial operations (Hannay and Racca, 2005).

For the indicative study presented here a 50m range step was used in the spatial sampling of the acoustic environment along model traverses. Frequency dependence of the sound propagation characteristics was treated by computing acoustic transmission loss at the center frequencies of 1/3-octave bands between 10 Hz and 2 kHz. Received sound pressure levels would normally be computed by applying the frequency-dependent transmission loss estimates to the corresponding 1/3-octave band source levels and summing across bands to obtain broadband values, but as mentioned earlier an indicative result was obtained here by merely assuming a flat spectrum source and summing the transmission loss estimates.

6.2. Oregon Coastal Environment

The primary factors affecting sound propagation in a coastal environment are bathymetry, geo-acoustic properties of the ocean floor, and depth dependent variations in the speed of sound in water. The continental shelf extends from the Oregon coastline well past the region of interest for this modelling study. The ocean floor in this region generally consists of a sedimentary layer of either sand or gravel above a basaltic basement. In some locations, however, the basalt pushes up through the sediment to form protruding rocks while in other places there is no sedimentary layer at all – just a basalt seafloor. Within 10 km of the shoreline, in the areas considered in this study, the water depth does not exceed 200 m. This is to be expected, as the continental shelf deepens only gently seaward until it hits the continental slope. A map of the bathymetry along the Oregon coast is shown in Figure 11.

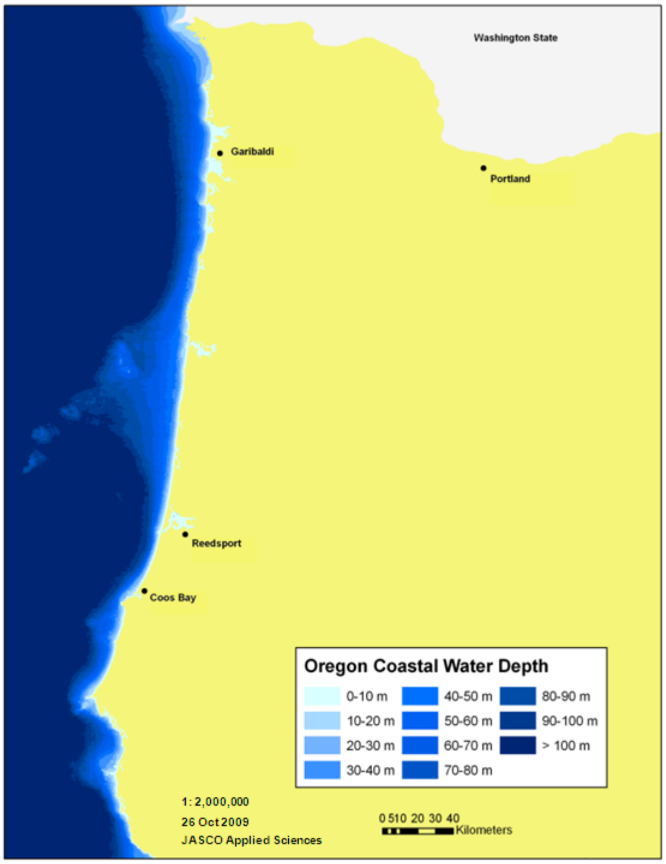

Figure 11. Oregon coastal bathymetry.

Referring to data from the Pacific Coast Oregon Observing System or PaCOOS, found on-line at http://pacoos.coas.oregonstate.edu/), the geo-acoustic parameters were defined at each modeling location. The northernmost model site (in Tillamook County) was classified to consist of a gravel layer overlaying basalt, the central model site (in Lincoln County) was described as exposed basalt, and the southern model site (in Douglas county) was classified as a layer of sand overlying basalt. The respective geo-acoustic parameters are shown in the tables that follow.

Table 2. Geoacoustic profile parameters used for modelling at Tillamook county.

Material	z(m)	c_p (m/s)	ρ (g/cm^3)	α_p (dB/λ)	C_s (m/s)	α_s (dB/λ)
Gravel	0	1579	1.54	0.330	311	5.38
	200	1779	1.69	0.265		
	400	1979	1.83	0.200		
Basalt	400	3700	2.20	0.111		
	>2500	5300	2.70	0.159		

Table 3. Geoacoustic profile parameters used for modelling at Lincoln county.

Material	z(m)	c_p (m/s)	ρ (g/cm^3)	α_p (dB/λ)	C_s (m/s)	α_s (dB/λ)
Basalt	0	3500	2.10	0.105	600	0.097
	>2500	5300	2.70	0.159		

Table 4. Geoacoustic profile parameters used for modelling at Douglas county.

Material	z(m)	c_p (m/s)	ρ (g/cm^3)	α_p (dB/λ)	C_s (m/s)	α_s (dB/λ)
Sand	0	1800	1.80	0.540	509	6.72
	400	2200	2.10	0.330		
Basalt	400	3700	2.20	0.111		
	>2500	5300	2.70	0.159		

Water sound speed profile data used in this modelling study were obtained from the Generalized Digital Environmental Model Variable Resolution (GDEM - V) database published by the U.S. Naval Oceanographic Office, which contains globally gridded ocean temperature and salinity profile data for each month of the year. The database has specialized extraction routines that use this information to compute sound speeds to various depths for any user-specified month and geographic location (Naval Oceanographic Office 2003). Sound speed profiles were computed using GDEM - V for the months of January and July at each modeling location, and were found to exhibit only minor variation from site to site but a distinct seasonal difference. Figure 12 shows the speed of sound as a function of depth for the summer and winter profiles. The winter sound speed profile is upward refracting, meaning that it causes sound to be defected upward as it propagates through the water. Since this condition generally results in less attenuation of sound at the seafloor interface, it was used as a precautionary modeling parameter.

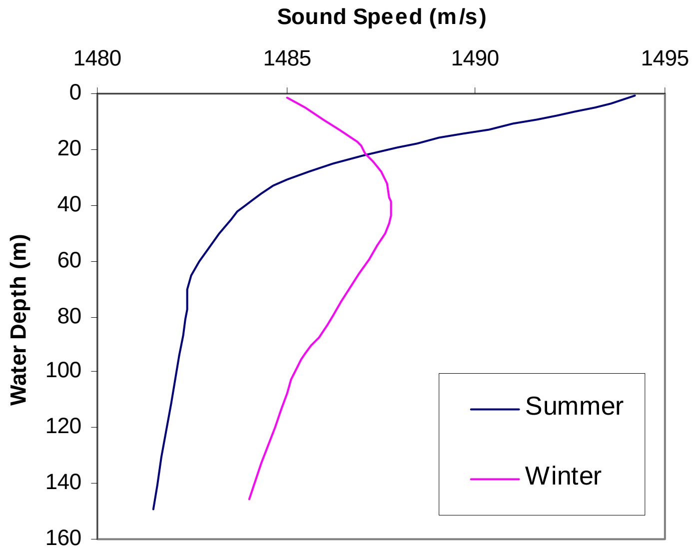

Figure 12 Winter and summer sound speed profiles for the Oregon Coast. The winter profile was used to generate the model results shown below.

6.3. Results

Frequency specific transmission loss estimates from MONM were summed across frequency bands from 10 Hz to 2 kHz, assuming a flat source spectrum, to yield idealized broadband transmission loss values which were then contoured and rendered as thematic maps. These contours are precautionary in that they follow the locus of minimum transmission loss (i.e. maximum sound propagation) over all depths. The maps in Figure 13 through Figure 15 present the idealized transmission loss contours for the three modeled sites. The contours denote the amount (in dB) by which acoustic pressure levels would decay as sound spreads away from the source location at the center of the contours.

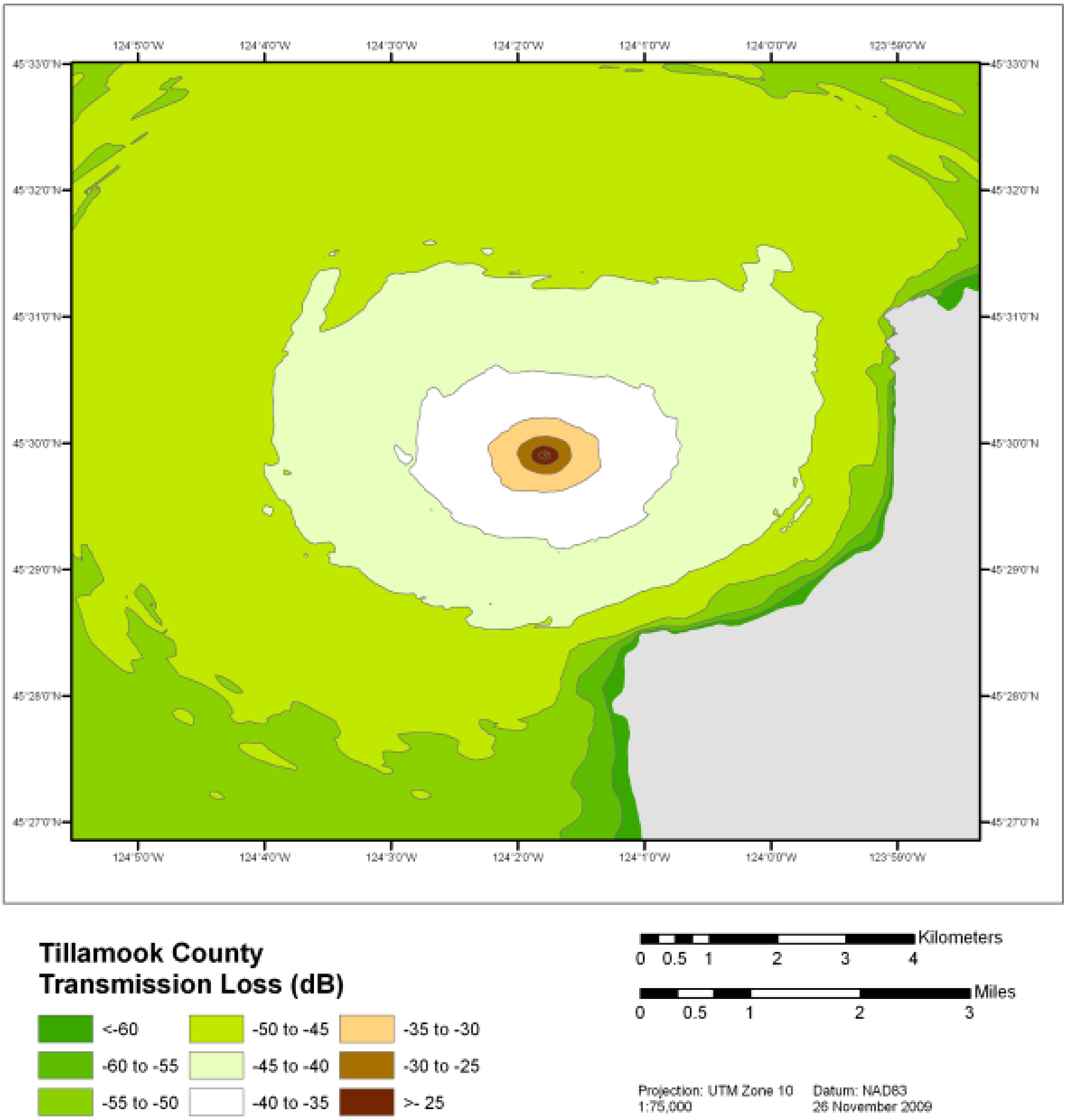

Figure 13. Transmission loss contours at a hypothetical wave energy development site for Tillamook County. The seafloor for this site consists of a gravel layer overlying basalt.

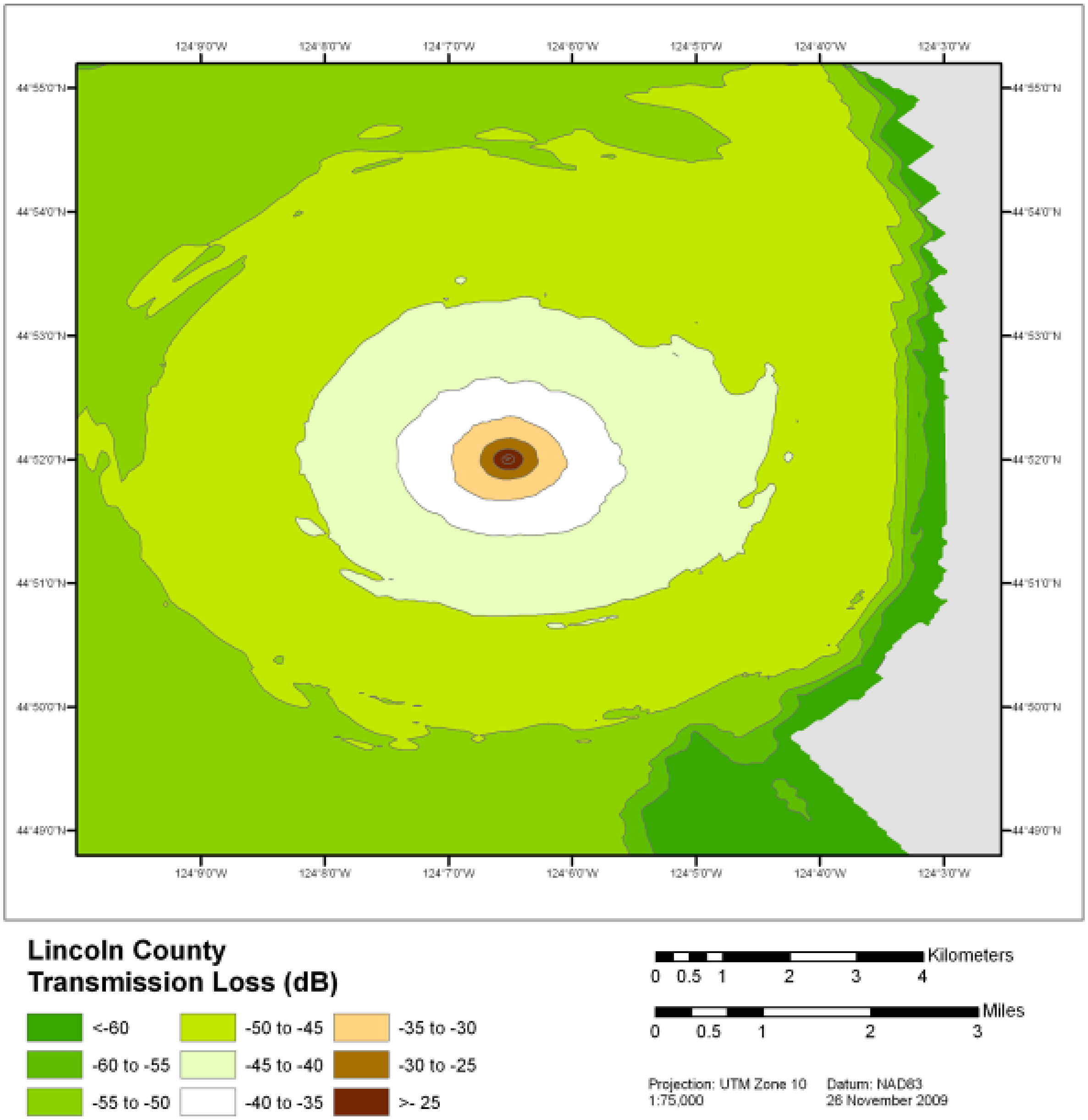

Figure 14. Transmission loss contours at a hypothetical wave energy development site for Lincoln County. The seafloor at this site consists of basalt with no overlying sediment.

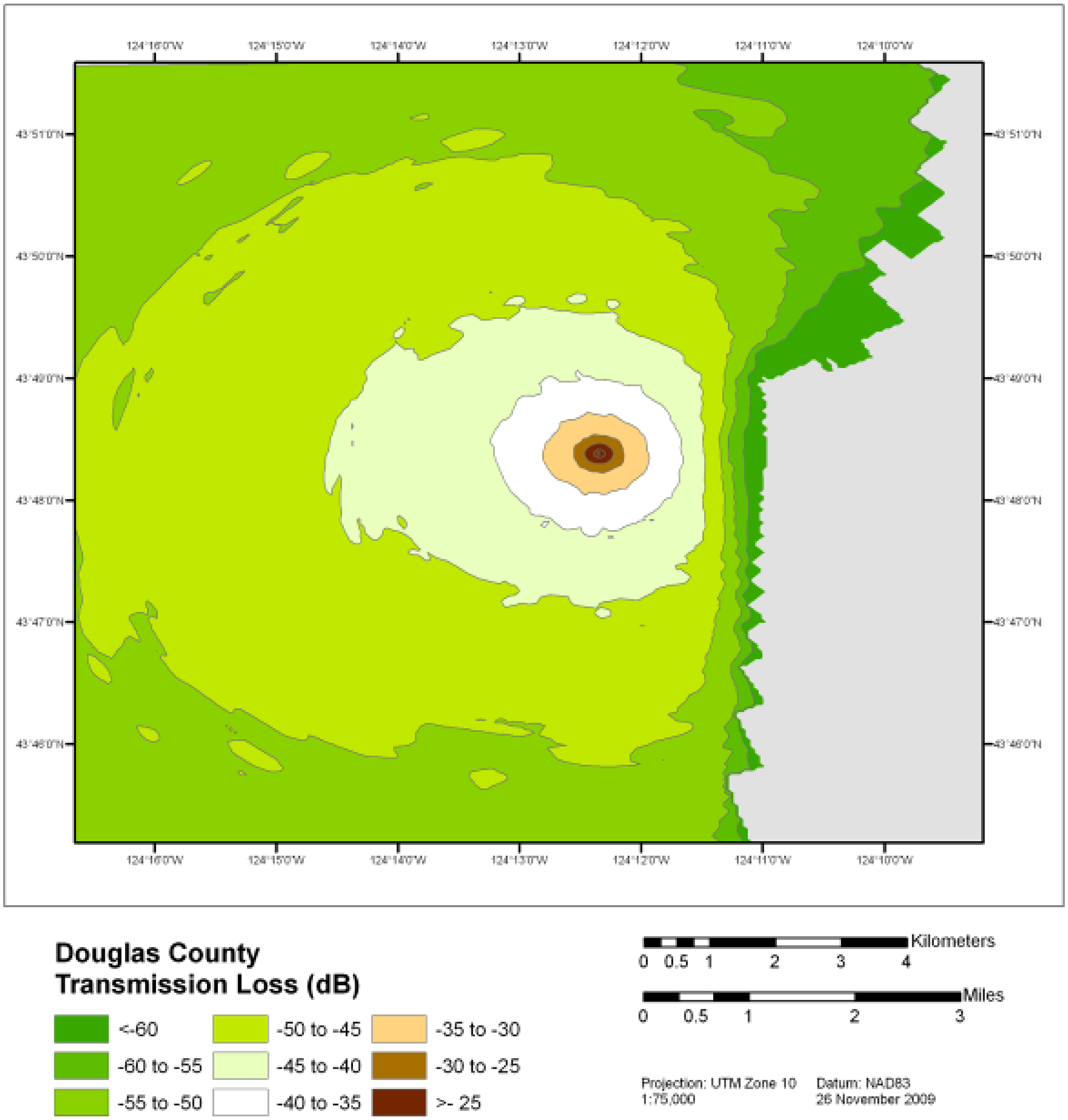

Figure 15. Transmission loss contours at a hypothetical wave energy development site for Douglas County. The seafloor at this site consists of sandy sediment overlying basalt.

At ranges close to the source (the center of the inner contours) the sound levels decrease slightly more quickly for the sandy seafloor compared to the gravel or the basalt seafloor compositions. This is intuitively expected since a sandy layer tends to be more sound absorbing than gravel or basalt. At longer ranges however, and particularly in the offshore direction, greater transmission loss is observed at the Lincoln County site (basalt seafloor) than at the other two sites. This cannot be explained purely in terms of geo-acoustic properties and points to the fact that the local bathymetry at the site also strongly influences the propagation characteristics. Indeed for sound propagation toward shore the bathymetry alone causes the rapid increase in transmission loss.

The idealized broadband transmission loss maps, while indicative to some extent of the influence of the propagation environment on the results, do not evidence the relevance of the frequency content of sound on its propagation. To examine the frequency dependence of the transmission loss at each location, contour plots indicating transmission loss levels as a function of frequency and of range along a single radial from each source location toward the offshore (westward) are shown in Figure 16 below. From these plots it can be seen that transmission loss is markedly lower for frequencies above 100 Hz up to the 2 kHz upper bound of the modeling. That means that noise from WEC installations that lies in that frequency range will spread further away from the source than will the lower frequency components.

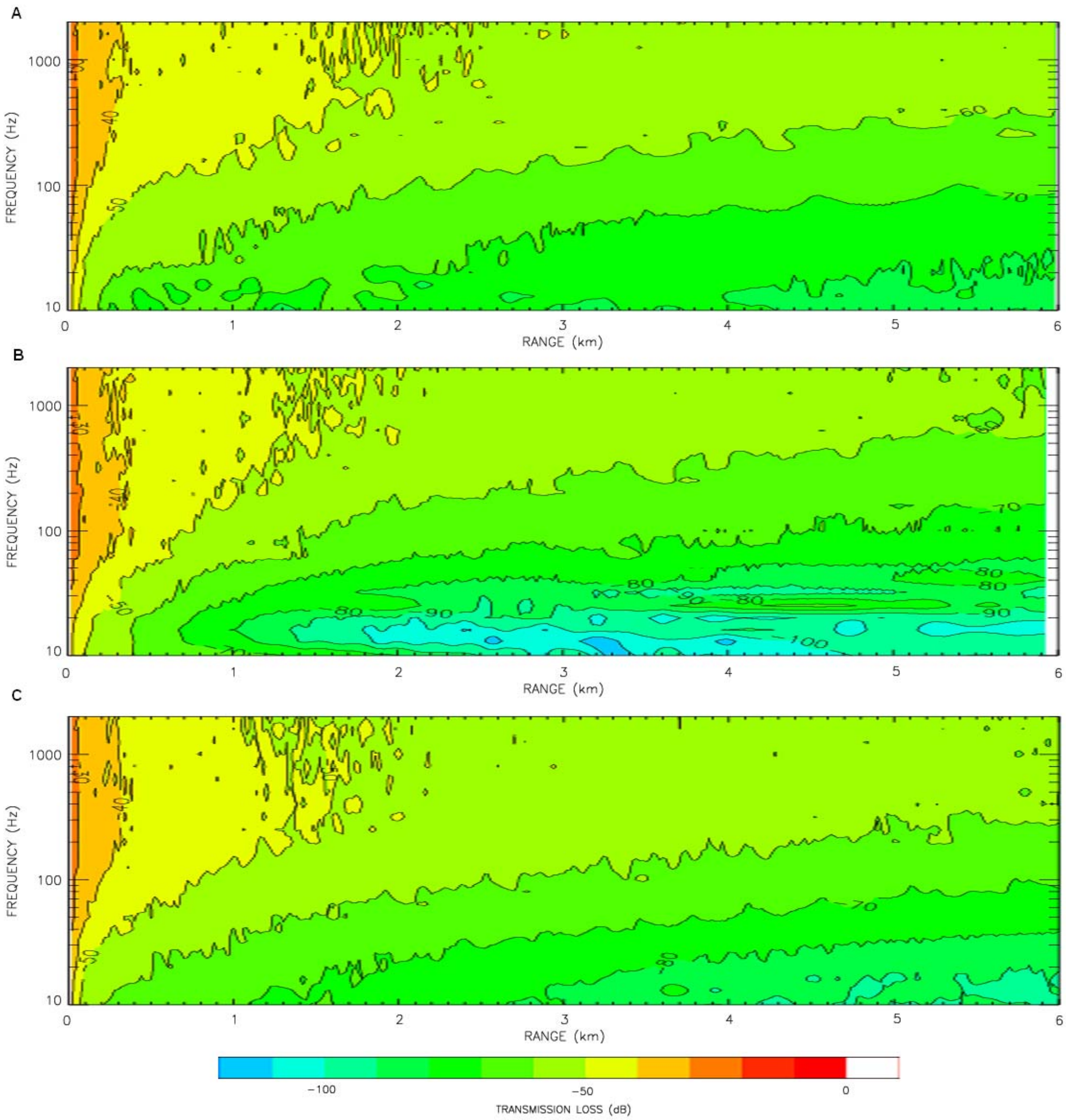

Figure 16. Contour plots of tranmission loss versus range and frequency for a due west seaward profile for A) Tillamook, B) Lincoln, and C) Douglas.

7. Summary

This report is intended to provide wave energy developers in Oregon with fundamental information on the principles, methods and equipment involved in conducting environmental noise assessments related to the permitting of their projects. As part of assembling a knowledge base, a literature review study about ambient noise conditions along the Oregon coast was undertaken without any success in identifying measured data for the near-shore environment. In its place a characterizations of the components of the environment that contribute to the overall ambient noise field was provided in the report.

Potential sources of noise associated with various classes of wave energy conversion devices were discussed and a summary table listing the currently known wave energy devices have been provided, followed by an overview of noise assessment studies that should assist wave energy developers in specifying a thorough noise assessment program for regulatory review, including guidelines for baseline ambient and source characterization measurement studies.

A review of the various types of acoustic measurement systems currently available and suitable for use in conducting the aforementioned assessment studies has been provided, including detailed specifications listings for several devices in current use.

To complete the overview of noise assessment approaches, the results of a representative sound propagation modelling study have been presented showing transmission loss contour maps at three representative WEC development candidate sites along the Oregon coast that exhibit diverse topographic and geo-acoustic properties.

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Appendix A. Average Wind Speed and Wave Height for the Oregon Coast

Monthly averaged wind speed and wave height data at three locations along the Oregon coast are provided below. These data are averaged over a four year period between 2005 and 2008. The data were collected at the following marine NDBC Stations (shown north to south):

- 46029 Col River Bar, 46°8'37" N, 124°30'37" W, 135.3 m water depth,Figure 17.
- 46050 Stonewall Banks, 44°38’28" N, 124°30’0" W, 123 m water depth, Figure 18
- 46015 Port Orford, 42°44'48" N, 124°49'24" W, 422.6 m water depth, Figure 19.

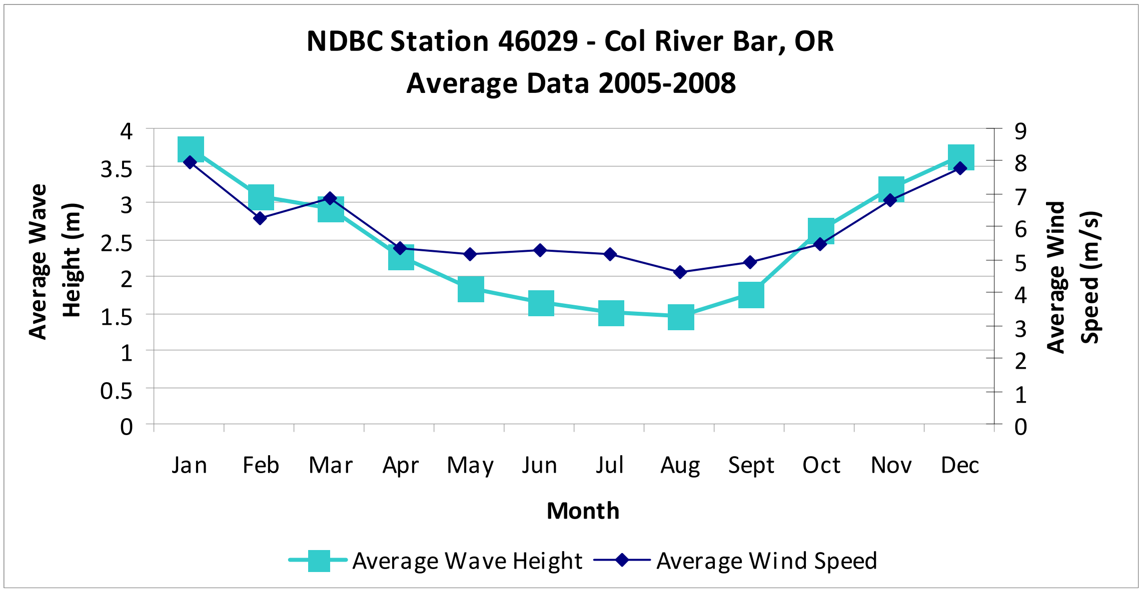

Figure 17: Average wind speed (m/s) and wave height (m) between 2005 and 2008 for NDBC Station 46029 – Col River Bar, OR. Some data is lacking for 2005-2006. Data obtained from NOAA National Data Buoy Center.

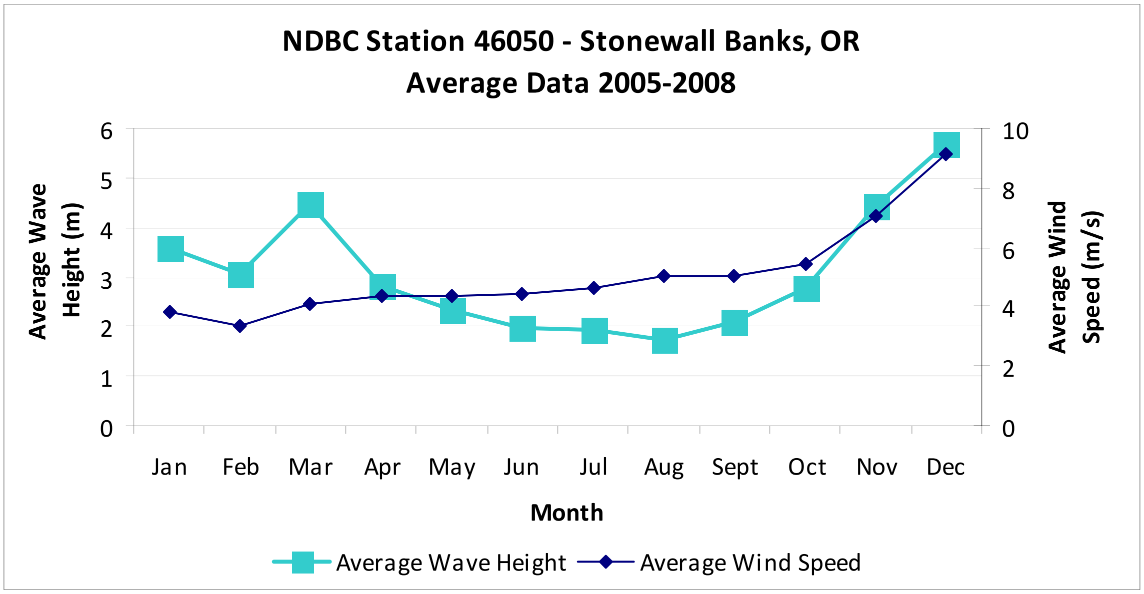

Figure 18. Average wind speed (m/s) and wave height (m) between 2005 and 2008 for NDBC Station 46050 – Stonewall Banks, OR. Some data is lacking for 2005-2006. Data obtained from NOAA National Data Buoy Center.

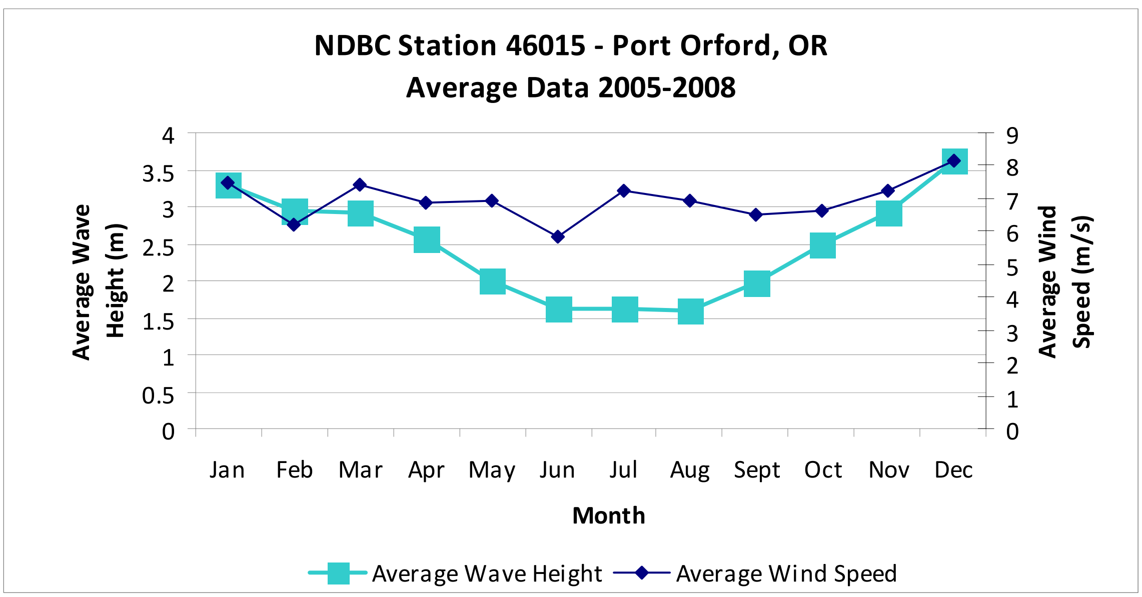

Figure 19. Average wind speed (m/s) and wave height (m) between 2005 and 2008 for NDBC Station 46015 – Port Orford, OR. Some data is lacking for 2005-2006. Data obtained from NOAA National Data Buoy Center.

Appendix B. Available Wave Energy Conversion Devices

Table 5. Available wave energy conversion (WEC) devices by type and manufacturer.

Manufacturer	Address	Country	Device
Point Source Absorbers			
Finavera Renewables http://www.Aquaenergygroup.com admin@AquaEnergyGroup.com	595 Burrard St., Suite 3113 3 Bentall Ctre, PO Box 49071 Vancouver, BC V7X 1G4	Canada	AquaBuOY
Independent Natural Resources Inc. http://www.Inri.us seadog@inri.us	7466 Washington Ave. S. Eden Prairie, MN 55344	United States	SeaDog (Point source absorber/ terminator)
Ocean Power Technologies http://www.oceanpowertechnologies.com info@oceanpowertech.com	1590 Reed Rd. Pennington, NJ 08534 Warwick Innovation Centre Gallows Hill, Warwick CV34 6UW	United States United Kingdom	PowerBuoy
Ocean Wave Energy Company http://www.owec.com foerd@owec.com	20 Burnside St. Bristol, RI 02809-2004	United States	Ocean Wave Energy Converter
AWS Ocean Energy Ltd. http://www.waveswing.com info@awsocean.com	13 Henderson Rd. Longman Industrial Estate Inverness, IV1 1SN	United Kingdom	Archimedes Waveswing
WaveBob Ltd. http://www.wavebob.com	H3, Maynooth Business Campus Maynooth, Co. Kildare. 420 Chinquapin Round Rd. Suite I, Annapolis, MD 21401	Ireland United States	Wavebob
AW-Energy Oy http://www.aw-energy.com info@aw-energy.com	Kolamiilunkuja 6 FI-01730 Vantaa	Finland	WaveRoller
Attenuators			
Hydam http://www.wave-power.com	1 Bishops Court New St. Killarney Co Kerry	Ireland	McCabe Wave Pump (no update found)
Pelamis Wave Power Ltd. **http://www.pelamiswave.com** **enquiries@pelamiswave.com**	31 Bath Rd., Leith Edinburgh EH6 7AH	Scotland, UK	Pelamis
Terminators			
Oceanlinx Ltd. http://www.oceanlinx.com	PO Box 116 Botany, NSW 1455 Portland House, Stag Place London, SW1E 5RS	Australia United Kingdom	OWC device
Float http://www.floatinc.com projects1@floatinc.com	4903 Morena Boulevard, Ste. 1213, San Diego, CA 92117	United States	Pneumatic Stabilized Platform
OreCON Ltd. http://www.orecon.com sue@ashley-pr.co.uk	2 Dreason, Bodmin Rd. Bodmin, Cornwall, PL30 4BG	United Kingdom	Multi Resonant Chamber (MRC)
Voith Hydro Wavegen Ltd. http://www.wavegen.co.uk enquiries@wavegen.com	13a Harbour Rd. Inverness, IV1 1SY	United Kingdom	Coastal and Offshore OWC

Overtopping Device			
Wave Dragon http://www.wavedragon.net info@wavedragon.net	Blegdamsvej 4 DK-2200 Copenhagen N	Denmark	Wave Dragon

Appendix C. Commercially Available Acoustic Recording Systems

This section describes a selection of acoustic recording systems currently available.

C.1. Advanced Multi-channel Acoustic Recorder (AMAR)

JASCO Applied Sciences' Advanced Multi-Channel Acoustic Recorder (AMAR) is designed to meet demands for an ultra-low power multi-channel digital measurement system capable of sound recording at high sample rates and 24 bit resolution in harsh environmental conditions. A picture of the AMAR is shown in Figure 20 and its specifications are shown in Table 6. The AMAR can be equipped with various omni-directional hydrophones, with sensitivities ranging from -201 dB re 1 μPa to -160 dB re 1 μPa and a maximum recording bandwidth of 64 kHz. A directional hydrophone is also available with sensitivity of -140 dB re 1 μPa and a bandwidth of 100 Hz to 2 kHz, and other hydrophones are available on request. The AMAR system features eight 24-bit channels with > 108 dB dynamic range; each channel can be sampled at rates selectable from 8 kHz to 128 kHz. A single 16-bit high speed channel can sample at selectable rates from 128 kHz to 1 MHz with approximately 80 dB of dynamic range. The AMAR can record in either continuous or duty cycle modes and can host up to 2 TB of on-board solid-state memory. Its low power and high storage capacity allow an autonomy of 48 days of continuous single-channel recording at a rate of 32 kHz using a power pack of 48 alkaline batteries. AMARs operate at temperatures from -5° C to 50° C. The standard depth limit for AMAR units is 400 m, but specialized versions can operate at greater depths. More information can be found at http://www.jasco.com.

Figure 20. JASCO Applied Sciences' standard Advanced Multi-Channel Acoustic Recorder (AMAR).

Table 6. Specifications of the Advanced Multi-Channel Acoustic Recorder (AMAR).

Frequency range	8 channels of up to 64 kHz (24 bits/sample); or 1 channel of 64 kHz to 500 kHz (16 bits/sample)
Sampling frequency	8 channels of 500 Hz to 128 kHz (24 bits/sample); or 1 channel of 128 kHz to 1 MHz (16 bits/sample)
Sampling resolution	8 channels of 24 bits/sample (500 Hz to 128 kHz); or 1 channel of 16 bits/sample (128 kHz to 1 MHz)
Data format	WAV formatted recordings
Autonomy	Continuous or duty cycle recording.
Data storage capacity	16x120 GB = 2 TB or expandable to more
Power supply	18 or 48 (alkaline or lithium) D-cell batteries (for omni-directional hydrophone), or 66 alkaline D-cell batteries (for directional hydrophone).
Depth Limit	400 m standard, greater by request.

C.2. Autonomous Underwater Acoustic Recorder (AUAR)

The Pacific Oceanological Institute (POI) designed and manufactured the Autonomous Underwater Acoustic Recorder (AUAR) to listen to the western gray whale. The AUAR records acoustic data in the frequency range from 1 Hz to 15 kHz on an internal 160 GB hard disk drive (Table 7). Sampling frequencies up to 100 kHz are available with a sampling resolution of 16 bits/sample with a potential dynamic range of 96 dB. The recorder is also available with a radio-telemetry unit, adding the ability to perform real-time monitoring. During real-time monitoring acoustic data in the frequency range from 10 Hz to 5 kHz is transmitted to a land or marine receiver. The AUAR's power supply provides 18 days of continuous recording with transmission, or 30 days without transmission. For more information contact POI at rutenko@poi.dvo.ru. Reference: Borisov, S.V., D.G. Kovzel, A.N. Rutenko, and V.G. Uschipovsky (2008).

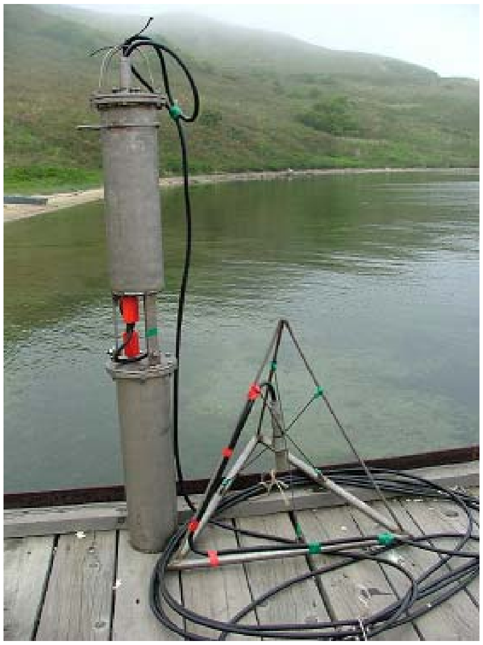

Figure 21. POI's Autonomous Underwater Acoustic Recorder (AUAR).

Table 7. Specifications of the Autonomous Underwater Acoustic Recorder (AUAR).

Frequency range	1 Hz to 15 kHz
Sampling frequency	Up to 100 kHz
Sampling resolution	16 bits/sample
Data format	Not available
Autonomy	Continuous recording and real-time radio transmitting.
Data storage capacity	160 GB hard disk drive
Power supply	Three sealed gel batteries with a capacity of 115 Ah
Depth Limit	Maximum tested depth of 50 m

C.3. Autonomous Underwater Recorder for Acoustic Listening Model 2 (AURAL – M2)

Multi-Électronique designed and built an autonomous underwater digitalized sound recording system called the Autonomous Underwater Recorder for Acoustic Listening Model 2 (AURAL-M2), shown in Figure 22. Along with acoustic recordings, it can also record temperature and pressure. The AURAL-M2 records acoustic data in the frequency range from 5 Hz to 16384 Hz in the format of WAV files (Table 8). It is able to sample frequencies up to 32768 Hz with a sampling resolution of 16 bits/sample. The data are stored on a 2.5 inch internal hard disk drive with 160 GB capacity or greater. A built-in adjustable amplifier allows for selectable gain settings of 16, 18, 20 or 22 dB. The AURAL operates at temperatures from 32° F to 104° F (0° C to 40° C) at depths less than 984 ft (300 m). The AURAL-M2 power supply consists of standard "D" size alkaline batteries with three sizes available: 16-, 64- and 128-batteries. Other power supply options are available on demand. There are two programmable recording modes on the AURAL, continuous and duty cycle, both available with a delay start option. Depending on the recording settings and battery size, AURALs can record for up to a year. More information can be found at: www.multi-electronique.com/pages/auralm2en.htm.

Figure 22. Multi-Électronique's Autonomous Underwater Recorder for Acoustic Listening Model 2 (AURAL-M2).

Table 8. Specifications of the Autonomous Underwater Recorder for Acoustic Listening Model 2 (AURAL – M2)

Frequency range	5 Hz to 16384 Hz
Sampling frequency	256 Hz to 32768 Hz
Sampling resolution	16 bits/sample
Data format	WAV files
Autonomy	Continuous or duty cycle recording.
Data storage capacity	2.5 inches Hard Disk Drive 160 GB or more
Power supply	12V DC nominal, Standard Size "D" Alkaline Batteries
Depth Limit	300 m

C.4. Acousonde

The Acousonde™ is made by Acoustimetrics, which is a brand of Greeneridge Sciences, Inc. It is a miniature, self-contained, autonomous acoustic/ultrasonic recorder designed for underwater applications. It combines two hydrophones, sensors for attitude, orientation, depth and temperature, a digital recorder, and a field-replaceable battery in a single, self-contained instrument, as shown in Figure 23. Applications of the Acousonde include: acoustic/behavioural recording tags for marine wildlife, highly portable acoustic field recorders, autonomous seafloor sound monitors, long-baseline acoustic arrays, acoustic and attitude/orientation recorders for underwater vehicles, and temporary attitude/orientation monitors for towed cables. The Acousonde can be attached to a free-ranging subject with suction cups or other means, or it can be applied as an autonomous recorder suspended from a cable, placed on the seafloor, or housed in a robotic or remotely-operated vehicle. The Acousonde is equipped with two hydrophone channels with hydrophone sensitivities of -201 dB (low-power channel) and -204 dB (high-frequency channel). Unfortunately the system is not able to perform simultaneous samplings from both hydrophones. With hydrophones attached to both channels the A/D converter "ping-pongs" between the two hydrophones; this decreases the per-channel sampling rate for each of the two channels to one-half of the A/D master sampling rate. The Acousonde can be programmed to record on a duty-cycle or to perform continuous recording, both with the option of setting a delayed start time. The system also has two user-selectable acoustic gain settings: 0 dB and 20 dB. The Acousonde can record for 42 hours at a sampling rate of 26kHz and operate at depths up to 3000 m. Specifications of the Acousonde are shown in Table 9. More information can be found at: www.acousonde.com.

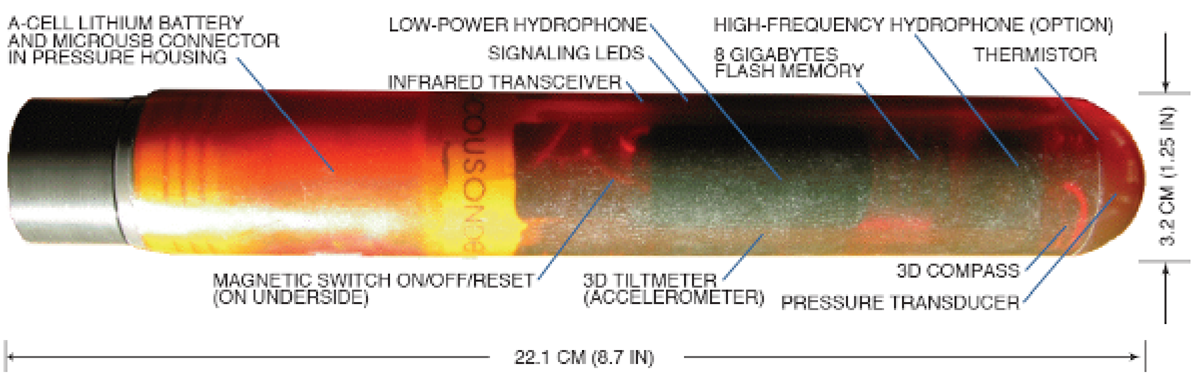

Figure 23. A picture of the properties and dimensions of the Acousonde™.

Table 9. Specifications of the Acousonde™.

Frequency range	12.5 Hz to 9285 Hz
Sampling frequency	232 kHz
Sampling resolution	16 bits/sample
Data format	MT format
Autonomy	Continuous or duty cycle recording.
Data storage capacity	8 GB flash memory
Power supply	Single A-cell lithium battery
Depth Limit	3000 m

C.5. C-POD / T-POD

Chelonia Limited manufactures the T-POD and C-POD. The T-POD is now out of production and has been superseded by the C-POD. These systems are used to detect and log the occurrence of high-frequency cetacean clicks. Both systems use digital waveform characterisation to detect cetacean clicks and log the time, centre frequency, intensity, and bandwidth of each click. The C-POD, shown in Figure 24, detects clicks in wider frequency bands than the T-POD, resulting in a much wider range of data to advance species identification. Dedicated PC software identifies and classifies trains of clicks within the logged data. The process of click-train recognition filters out non-cetacean clicks and gives reliable data on the presence of the animals and some indication of their behaviour. The omni-directional hydrophone on the C-POD detects frequencies from 20 kHz to 160 kHz with a sampling resolution of 8 bits/sample (Table 10). The C-POD also records attitude (i.e. the angle from vertical in which the unit is oriented) and temperature every minute. A C-POD can record up to 4 months of data using 8 D-cell alkaline batteries. More information can be found at: www.chelonia.co.uk/about_the_cpod.htm.

Figure 24. A picture of the C-POD.

Table 10. Specifications of the C-POD.

Frequency range	20 kHz to 160 kHz
Sampling frequency	N/A
Sampling resolution	8 bits/sample
Data format	Not available
Autonomy	Continuous.
Data storage capacity	removable Secure Digital (SD) memory card
Power supply	8 or 10 alkaline D-cells
Depth Limit	100 m (maximum to be determined).

C.6. Directional Autonomous Seafloor Acoustic Recorder (DASAR)

Greeneridge Sciences Inc developed the Directional Autonomous Seafloor Acoustic Recorder (DASAR), shown in Figure 25. It is a directional underwater digital acoustic recorder that was primarily designed to monitor the movement and distribution of vocalizing marine animals. The system was designed for deployments in arctic waters and features a low profile to resist motion in water currents and is ocean bottom mounted to avoid entanglement with ice flows while deployed on the seafloor. Each system contains a directional sensor in the form of a three-axis geophone and an omni-drectional flexural pressure transducer. The directional sensor allows the horizontal directions for received sounds to computed through appropriate post-processing. The four data channels (two horizontal, one vertical, and one omni-) are each sampled at 1000 Hz with a resolution of 16-bits/sample (Table 11). The sample rate supports a data bandwidth of 450 Hz. An internal 40 GB hard drive will store acoustic data from 60 days' continuous operation. More information can be found at: http://www.greeneridge.com/technology.html

Figure 25. Photograph of a Directional Autonomous Seafloor Acoustic Recorder (DASAR) on deck after retrieval.

Table 11. Specifications of the Directional Autonomous Seafloor Acoustic Recorder (DASAR).

Frequency range	20 Hz to 500 Hz
Sampling frequency	1000 samples/sec
Sampling resolution	16 bits/sample
Data format	Not available
Autonomy	Continuous recording.
Data storage capacity	40 GB 2.5 inches Hard Disk Drive
Power supply	D-cell batteries
Depth Limit	50 m

C.7. DTAG

The Digital Acoustic Recording Tag (DTAG) was developed by Mark Johnson and Peter Tyack at the Woods Hole Oceanographic Institution to monitor the behavior of marine mammals and their response to sound. It is attached to a marine mammal by means of suction cups and weighs only 0.7 lbs (300 g) in air. The DTAG, shown in Figure 26, contains a large array of solid-state memory and records continuously from a built-in hydrophone and suite of sensors. The sensors include a temperature sensor, a pressure sensor to record depth, and accelerometers and a three-axis magnetometer to record the unit's 3-dimensional orientation (pitch, roll and heading). The temperature, depth and orientation are recorded at a sampling rate of 50 Hz. The hydrophone system measures 12-bit acoustic data at sampling rates from 48 kHz to 192 kHz (Table 12). The maximum acoustic frequency that the system can record is 96 kHz. The DTAG can hold 6.6 GB of data, is powered with a rechargeable battery, and can record continuously for up to 24 hours at depths less than 2000 m. Reference: Johnson, M. P. and P. L. Tyack (2003).

Figure 26. A picture of an assembled Digital Acoustic Recording Tag (DTAG) with casing and suction cups.

Table 12. Specifications of the Digital Acoustic Recording Tag (DTAG).

Frequency range	24 kHz to 96 kHz
Sampling frequency	48 kHz to 192 kHz
Sampling resolution	12 bits/sample
Data format	Not available
Autonomy	Continuous recording.
Data storage capacity	6.6 GB
Power supply	Rechargeable battery
Depth Limit	2000 m

C.8. Ecological Acoustic Recorder (EAR)

The Ecological Acoustic Recorder (EAR), shown in Figure 27, was developed jointly between the Hawaii Institute of Marine Biology (HIMB), the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Ecosystem Division (CRED), and Oceanwide Science Institute (OSI). It is a digital, low power underwater acoustic recording system designed for long-term monitoring of natural and anthropogenic sounds between 20 Hz and 30 kHz (Table 13). There are three types of EARs: a diver-deployed shallow water (0 m to 36 m) version, a bottom moored deep water version deployed complete with an acoustic release suitable to depths less than 500 m, and an extra-deep version deployed with an acoustic release suitable to depths less than 1000 m. The EAR records acoustic data from a hydrophone with a sensitivity of -193.5 dB re 1V/1µPa at sampling frequencies up to 64 kHz with a resolution of 16 bits/sample . Raw binary files are written to an internal 160 GB hard disk drive. There are two event detectors on the EAR's custom-designed circuit that can optionally be used as a trigger to initiate recording. A "wideband" event detector monitors the energy in the frequency band from 20 Hz to 20 kHz, while a "high frequency" detector monitors the energy in the band from 10 kHz to 20 kHz. The event detectors can be used in conjunction with a programmable duty cycle recording schedule or not at all. The EAR can also be programmed to begin recording either immediately when powered on, or at a programmable future date and time. Shallow water EARs can be deployed for one year or longer, depending on the number of batteries included and the selected recording schedule. The duration of deep EAR deployments are limited by the batteries of the acoustic releases. More information can be found at : www.oceanwidescience.org/docs/EAR.htm.

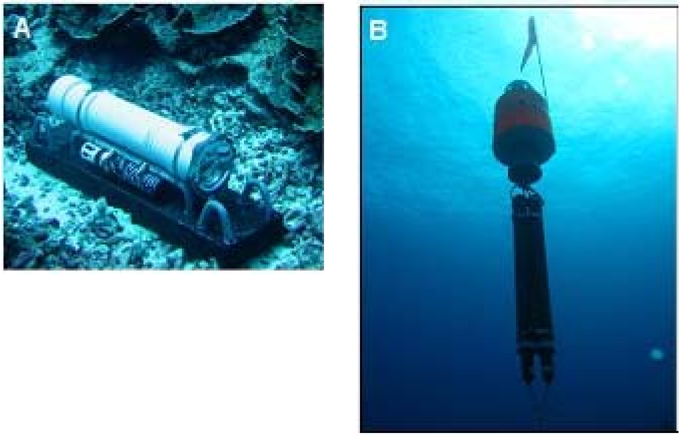

Figure 27. Pictures of (A) a deployed shallow EAR attached to anchor and (B) a deployed deep EAR with paired acoustic releases.

Table 13. Specifications of the Ecological Acoustic Recorder (EAR).

Frequency range	20 Hz to 30 kHz
Sampling frequency	Up to 64 kHz
Sampling resolution	16 bits/sample
Data format	Raw binary files
Autonomy	Duty cycle and/or event detector.
Data storage capacity	160 GB hard disk
Power supply	Seven high capacity D-cell alkaline batteries serially wired to provide 20500 mA h of current at 10.5 V
Depth Limit	1000 m

C.9. High-frequency Acoustic Recording Package (HARP / ARP)

The High-frequency Acoustic Recording Package (HARP) was developed for broad band, long-term marine mammal monitoring by the Scripps Whale Acoustic Lab at Scripps Institution of Oceanography. It can record frequencies between 10 Hz to 100 kHz at 8 different sampling rates from 2 kHz to 200 kHz with a resolution of 16 bits/sample (Table 14). The HARP is able to record continuously or in a programmable duty cycle mode. 16 120 GB hard disk drives generate 1.92 TB of storage, allowing 54 days of continuous recording at a sampling frequency of 200 kHz or approximately one year of continuous recording at 30 kHz. The HARP is equipped with a hydrophone with a sensitivity with more than -120 dB re 1V/µPa. HARP can be deployed to depths less than 6600 m as a mooring or as a seafloor package, as shown in Figure 28. More information can be found at: http://cetus.ucsd.edu/technologies_Main.html.

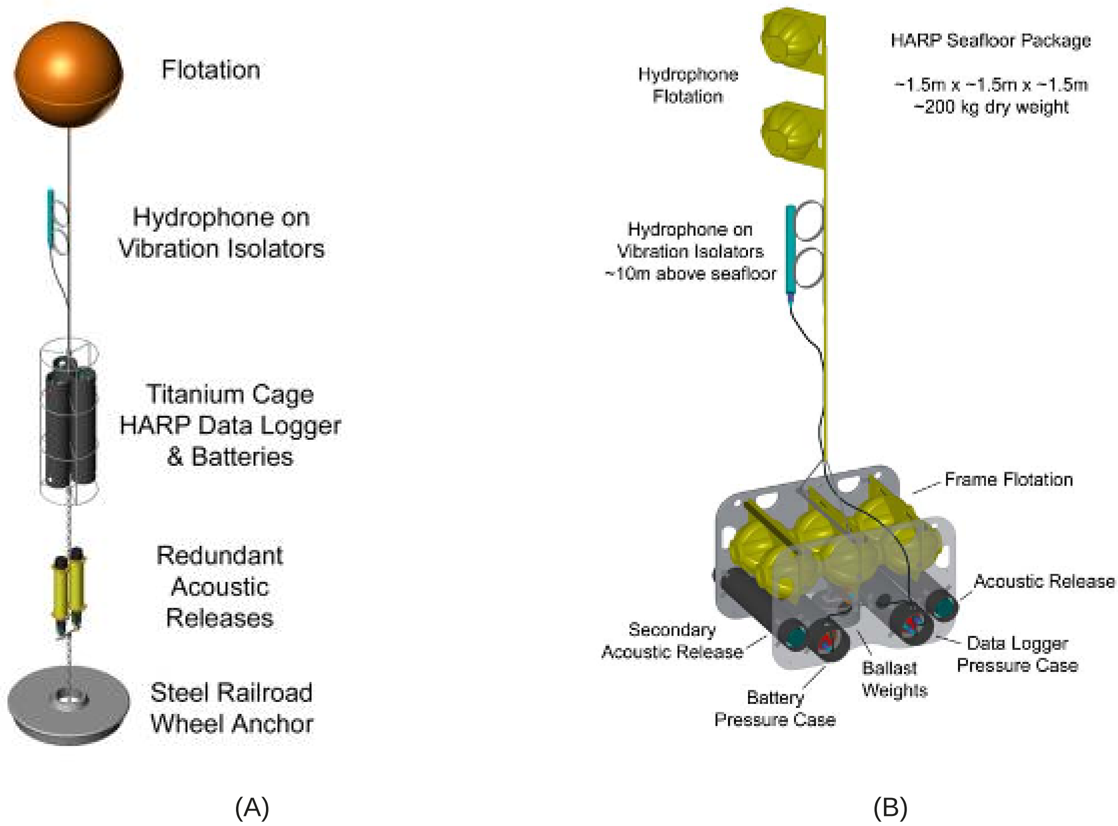

Figure 28. (A) The mooring design and (B) seafloor package design of the High-frequency Acoustic Recording Package (HARP) developed by the Scripps Whale Acoustic Lab at Scripps Institution of Oceanography.

Table 14. Specifications of the High-frequency Acoustic Recording Package (HARP).

Frequency range	10 Hz to 100 kHz
Sampling frequency	2 kHz to 200 kHz
Sampling resolution	16 bits/sample
Data format	XWAV, which is similar to a WAV formatted file but with additional information in an expanded header.
Autonomy	Continuous or duty cycle recording.
Data storage capacity	16x120 GB hard disk drives = 1.92 TB
Power supply	192 D-size alkaline batteries in 4 sub-packs (in the HARP Seafloor Package)
Depth Limit	6600 m

C.10. Pop-Up

The Bioacoustics Research Program at Cornell University developed an autonomous acoustic recording device, called a Pop-Up, for deployment on the ocean floor. The device, shown in Figure 29, includes a microprocessor, hard disk for data storage, acoustic communications circuitry, and batteries, all sealed in a single 17 inch (48 cm) glass sphere. An external hydrophone, with a sensitivity of -165 dB re 1V/1μPa, is connected to the internal electronics through a waterproof connector. The Pop-Up can record continuously, or can be programmed to record in duty-cycle mode for longer deployments. The system measures acoustic data at sampling rates from 1 kHz to 64 kHz and records in the frequency range of 10 Hz to 32 kHz on its internal 120 GB hard disk drive. The Pop-Up can be deployed at depths up to 6000 m and can continuously record for 24 days at a sampling rate of 12 kHz. Specifications of the Pop-Up are shown in Table 15. More information can be found at: www.birds.cornell.edu/brp/hardware/pop-ups.

Figure 29. A picture of the Pop-Up, developed by the Bioacoustics Research Program at Cornell University.

Table 15. Specifications of the Pop-Up.

Frequency range	10 Hz to 32 kHz
Sampling frequency	1 kHz to 64 kHz
Sampling resolution	12 bits/sample
Data format	Binary
Autonomy	Continuous or duty-cycle recording
Data storage capacity	120 GB hard disc drive
Power supply	Alkaline batteries
Depth Limit	6000 m

C.11. Passive Acoustic Listener (PAL)

The Applied Physics Laboratory at the University of Washington developed the Passive Acoustic Listener (PAL). The PAL is an autonomous acoustic recorder designed to be attached to ocean moorings. As shown in Figure 30, the PAL is a cylindrical instrument 30 inches (76 cm) long by 6 inches (15 cm) in diameter with a hydrophone extending from one end. It is typically mounted in a cage to avoid damage by possible fishing lines. The system has a sensitivity of -160 dB re 1 V/µPa and it records frequencies between 200 Hz and 50 kHz. The programmable duty-cycle mode of the PAL allows for deployments up to 1 year. The depth limit of the PAL has not been calculated, but it has successfully recorded data at a depth of 100 m. Specifications of the PAL are shown in Table 16. Reference: Jones, C.D. and M.A. Wolfson (2006). More information can be found at: www.apl.washington.edu/projects/haro_strait/Haro_Acoustic_Environment.htm#_4.1_Passive_Aquatic

Figure 30. A picture of the Passive Acoustic Listener (PAL), developed by the Applied Physics Laboratory at the University of Washington.

Table 16. Specifications of the Passive Acoustic Listener (PAL).

Frequency range	200 Hz and 50 kHz
Sampling frequency	Up to 100 kHz
Sampling resolution	Not available
Data format	Custom format: time series of spectral levels
Autonomy	Duty-cycle recording.
Data storage capacity	2 GB flash memory card
Power supply	3 stacks of 10 alkaline D-cell batteries
Depth Limit	At least 100 m

C.12. Programmable Underwater Acoustic Recorder (RASP)

The Programmable Underwater Acoustic Recorder (Registratore Acustico Subacqueo Programmabile, RASP, Figure 31) produced by NAUTA Ricerca e Consulenza Scientifica (Milano, Italy) was designed for acoustic monitoring in a simple design that is easily deployed. The system is capable of short deployments of days or weeks, depending on recording scheme. The RASP utilizes an M-Audio MicroTrack II recorder with a Sensor Technology SQ26 hydrophone with sensitivity -169 dB re 1V/1µPa. It includes a custom timer control board offering up to 10 hours time delay. The RASP can be deployed to depths of up to 500 m (1640 ft). More information can be found at: www.nauta-rcs.it/Instruments/RASP/NAUTA_RASP_UK.htm.

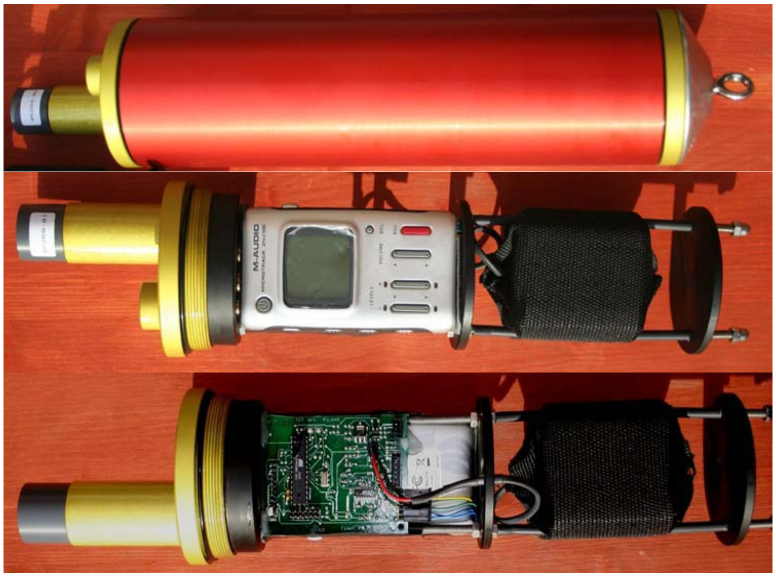

Figure 31. NAUTA's Programmable Underwater Acoustic Recorder (Registratore Acustico Subacqueo Programmabile, RASP), showing the (top) aluminum housing, (middle) recorder, and (bottom) timer control board.

Table 17. Specifications of the Programmable Underwater Acoustic Recorder (RASP).

Frequency range	Up to 48 kHz
Sampling frequency	Up to 96 kHz WAV, or 48 kHz MP3
Sampling resolution	24-bit
Data format	16 or 24-bit WAV or 96–320 kbps MP3
Autonomy	Programmable timer, 10 hr time delay
Data storage capacity	64 GB, CompactFlash
Power supply	NiMH batteries, fast rechargeable
Depth Limit	500 m

C.13. Remote Underwater Digital Acoustic Recorders (RUDAR, µRUDAR and MiniRUDAR)

CETACEAN RESEARCH TECHNOLOGY (Seattle, WA) offers three versions of their Remote Underwater Digital Acoustic Recorder (RUDAR): the standard RUDAR for 2 to 3 week deployments, the (soon to be available) MiniRUDAR for 80 to 90 hr deployments, and the micro RUDAR (µRUDAR) for 10.5 hr deployments. More information can be found at: http://aww.cetaceanresearch.com/hydrophone-systems/rudar/index.html.

C.13.1. Standard RUDAR

CETACEAN RESEARCH TECHNOLOGY's RUDAR (Figure 32) is a long-term autonomous recorder. The first conceptual RUDAR prototype was completed in early January 2002, and custom-built RUDARs are now available for purchase. The standard RUDAR can be deployed for 2 to 3 weeks, and longer deployments are possible with an additional pressure housing dedicated to batteries. The RUDAR is outfitted with a CETACEAN RESEARCH C55 hydrophone, rated to a depth of 460 m, or with a custom-made hydrophone for depths of up to about 1000 m. The

RUDAR utilizes the core data acquisition and processing components of the ST1400ENV Mobile Data Recorder & Sound Level Monitor with a proprietary internal hard drive. It has an embedded Linux operating system and offers flexible recording scheme programmability. Sample rates up to 96 kHz are selectable over a wide frequency range, providing a recording bandwidth of up to 48 kHz.

Figure 32. 3D rendering of CETACEAN RESEARCH TECHNOLOGY's Remote Underwater Digital Acoustic Recorder (RUDAR).

Table 18. Specifications of the Standard RUDAR.

Frequency range	Up to 48 kHz
Sampling frequency	Up to 96 kHz
Sampling resolution	24-bit, continuous
Data format	WAV, 1 to 4 channels
Autonomy	Yes. And can be controlled remotely when above water.
Data storage capacity	500 GB, or upgrade to 1 TB
Power supply	Alkaline or rechargeable NiMH, depending on desired lifetime
Depth Limit	460 m (up to 1000 m with custom built hydrophone)

C.13.2. Micro RUDAR (µRUDAR)

CETACEAN RESEARCH TECHNOLOGY's µRUDAR (Figure 33) is a smaller version of the RUDAR for short deployments, at about one tenth the price. The µRUDAR has a recording time of about 10.5 hrs and is rated to a depth of 250 m. It utilizes a Sensor Technology SQ26-06 hydrophone, with a frequency bandwidth of 30 kHz, and an M-Audio MicroTrack II digital recorder. The recorder offers sampling frequencies up to 96 kHz at 16 or 24-bit resolution (1 or 2 channels), with a storage capacity of 16 GB (CompactFlash or Microdrive). The µRUDAR records a series of 2 GB WAV files until the power supply is depleted.

Figure 33. CETACEAN RESEARCH TECHNOLOGY's micro Remote Underwater Digital Acoustic Recorder (μRUDAR).

Table 19. Specifications of the Micro RUDAR.

Frequency range	0.030 to 30 kHz
Sampling frequency	Up to 96 kHz WAV, or 48 kHz MP3
Sampling resolution	16 or 24-bit WAV, or 96–320 kbps MP3
Data format	2-channel WAV, or MP3
Autonomy	No
Data storage capacity	16 GB
Power supply	Rechargeable Li-ion battery, ~10.5 hrs recording time
Depth Limit	250 m (820 ft)

C.13.3. MiniRUDAR

By late January 2010, CETACEAN RESEARCH will also be offering a MiniRUDAR, similar to the μRUDAR, but capable of a longer recording time of 80 to 90 hrs (3–4 days).

C.14. SRB-16 Autonomous Recording Buoy

The SRB-16 (Figure 34) is a short-deployment autonomous recording system developed and manufactured by High Tech, Inc. (Gulfport, MS). It consists of three components: a multi-channel array of deep-water, high-sensitivity hydrophones connected to an electronics buoy and vertically or horizontally mounted to the seafloor; an electronics buoy housing a telemetry link, data recorder, power supply, and associated circuitry; and a shipboard interface to individually control up to 64 buoy systems.

Figure 34. High Tech, Inc.'s SRB-16 Autonomous Recording Buoy.

The SRB-16 can operate at depths of up to 3000 m, with a continuous operational running time of 72 hours and a standby mode of up to 15 days. It is configured remotely, from up to >10km away, via a 24 W radio-frequency telemetry link, with an RS-232 navigation interface, setting the number of hydrophone channels, hydrophone channel gain (0, 12, 24, 36, or 48 dB) and standby duration. A faster RF link sends status information and sample data traces from the SRB-16 back to the ship. Up to 5 GB of hydrophone array data are recorded on Exabyte 8500 tape in digital format on 1 to 16 channels. The system frequency bandwidth is tailored to the customer's application, with a dynamic range of at least 132 dB. The SRB-16 is temperature-rated for operation at 0 to 40°C and storage at -40 to 85°C. More information can be found at http://home.att.net/~hightechinc/taab.html#SRB-16.

Table 20. Specifications of the SRB-16 Autonomous Recording Buoy.

Frequency range	Built to suit
Sampling frequency	Built to suit
Sampling resolution	24-bit, 1 to 16 channels
Data format	Exabyte 8500 digital tape
Autonomy	Configured remotely via RF telemetry link, up to 7 mi away, 15 days standby mode
Data storage capacity	5 GB
Power supply	Internal battery pack - 72 hrs continuous operation
Depth Limit	10,000 ft (3049 m)