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Electromagnetic Field Study

Electromagnetic field synthesis: site assessment methodology.

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Oregon Wave Energy Trust (OWET) is a nonprofit public-private partnership funded by the Oregon Innovation Council. Its mission is to support the responsible development of wave energy in Oregon. OWET emphasizes an inclusive, collaborative model to ensure that Oregon maintains its competitive advantage and maximizes the economic development and environmental potential of this emerging industry. Our work includes stakeholder outreach and education, policy development, environmental assessment, applied research and market development.

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Record of Revisions

Revision	Date	Section and Paragraph	Description of Revision
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1. EXECUTIVE SUMMARY

This report synthesizes the expected ambient Electromagnetic (EM) conditions at a wave energy test site in Reedsport, Oregon with the anticipated EM emissions from wave energy converters (WEC), underwater equipment, and associated cables to estimate the minimum and maximum field conditions as if the site were developed. These predictive results were then used to develop sensory instrumentation and spatial considerations to enable the specification of adequate and affordable methodologies that ensure a scientifically valid approach to assessing EM field conditions at the site, both before and after development. The results of this synthesis have been described to provide an extensible methodology to evaluate other potential wave energy sites in Oregon—inclusive of longer-term monitoring needs.

This study was commissioned with the goal of superimposing estimated WEC and power cable signatures onto expected ambient EM conditions at a specific site, and in so doing, identify the necessary measurement and instrumentation requirements to obtain repeatable and reliable EM measurements.

2. INTRODUCTION

2.1 Purpose

This study was commissioned to form the basic methodology for site-specific assessments of wave energy projects in the near-shore environment on the Oregon coast. This report is designed to articulate measurement and assessment requirements based on existing conditions at the site, with anticipated EM signatures from wave energy equipment superimposed on those conditions. From that, instrumentation requirements are stated to identify a robust methodology to characterize and monitor the site before and after development.

2.2 Background

This contains the culmination of several related topical reports on the subject of near-shore EMF generation from natural and man-made sources, and superimposes the results to establish instrumentation requirements for reliable and repeatable wave energy site assessment methodologies. This report is a building block to establish fundamental measurement and instrumentation requirements.

2.3 Report Organization

This report contains ten primary sections and two supporting appendices. The first two sections contain the executive summary and introduction, and provide the project motivation and background. The methodology for how the results were derived is described in Section 3, followed by development of the site assessment protocol (Section 4). Sections 5 through 9 describe the application of the protocol to the proposed Reedsport site. Section 10 summarizes the basic protocol. Appendix A contains an acronym list. Appendix B presents predicted EM fields from a representative AC power cable.

3. METHODOLOGY

This analysis was created by merging technical results from five other companion reports to establish the technical basis for measurement methods and instrumentation requirements for a robust site assessment protocol. These reports address the following major topical areas:

1. Literature survey for known or anticipated biological sensitivity to EM fields (EMF) in the marine environment;
2. Estimation of existing ambient EMF conditions in Oregon's near-shore environment;
3. Prediction of EMF generated by wave energy converters;
4. Prediction of EMF generated by electrical power export cables;
5. Summary of existing commercially available EM techniques used to assess underwater EM fields.

From these resources, a measurement and site assessment protocol was outlined, followed by application of the protocol to the Reedsport site. The protocol was established by first estimating the minimum and maximum expected EM fields in the region before and after the introduction of energized wave energy conversion equipment into the environment. Next, source level and propagation models or measurements were postulated, followed by synthesis of existing conditions, EM sources, and instrumentation capabilities to identify site-specific recommended measurement setup parameters.

4. SITE ASSESSMENT

Effective measurement of both ambient conditions and those conditions with energized power equipment will require high quality instruments with a broad dynamic range. Some of the dynamic range requirements could be mitigated by analyzing the proposed installation design, assessing emitted output of wave energy devices prior to installation, and then identifying placement of instruments in strategic locations to assess EM field conditions with a minimum instrumentation suite. The following generic protocol is recommended to ensure that both minimum and maximum conditions may be assessed, but with a minimal use of instrumentation to achieve the measurement goals.

4.1 Site Assessment – Measurement Planning

Effective measurement of any quantity involves determination of the quantities to be measured, and to the degree possible, control of the measurement environment. Field measurements pose additional constraints not possible in a laboratory setting. However, thoughtful analysis of the measurement environment, field conditions, instrument capabilities and limitations, and expected values to be measured together can ensure valid measurements, and yet minimize the instrumentation and support requirements.

4.1.1 Signature Assessment – Existing Conditions

The first step in creating a robust measurement environment is to review existing ambient conditions, including dominant wave, tidal, and coastal current conditions, and to identify any unique biological considerations—these two factors will establish the noise floor requirements for the instruments. Few, if any, EM field measurements have been made along the Oregon coast and no known measurements have been made in potential wave energy sites. A complicating factor is due to the widely dynamic ocean conditions in the near-shore regime, which create a wide span of EM conditions, and in particular, widely varied electric fields. However, using the companion documentation as guidance, together with any data obtained in similar coastal conditions, the existing ambient conditions may be estimated or modeled. As part of this analysis, use of data from buoy observations or other instrumentation placed to assess wave or current conditions over time should be consulted to establish dominant hydrodynamic conditions. Another consideration for instrumentation is if any species sensitivities are known for the area. For example, if a particular species is known to exist in the region, and furthermore, the species has been demonstrated to exhibit a given sensitivity, this data should be included to ensure the minimum noise floor of the measurement instrumentation.

4.1.2 Signature Assessment – Source Strength and Analysis

The second step is to evaluate the expected source levels of proposed equipment and cables to be introduced into the site. This knowledge will set the maximum levels to be measured, and thus set the dynamic range requirements. Furthermore, source information and expected emission levels will be used to establish the site layout to ensure that maximum, worst-case conditions may be assessed and monitored.

Several methods are available to predict the source levels for power generation and transmission equipment. The preferred method is to explicitly measure the output of wave energy converters, cables, and associated hardware, such as sub-sea pods and junction housings. Such measurements may be made in a terrestrial, test-stand environment to the required degree of precision. Within this context, the magnetic field output is the primary factor to be assessed in a terrestrial environment for two reasons:

1. Magnetic emissions by power generation devices are largely unaffected by the presence of seawater, and thus, in-air measurements under controlled conditions may be used as a proxy for operational in-water conditions; and
2. Electric fields generated by power generating devices and cables can be easily mitigated by the use of shielding and metallic Faraday cages around such equipment to strongly attenuate the signals before they are able to emanate into the surrounding environment.

While induced electric fields will undoubtedly be created near cables and generators, such fields are primarily a result of induction due to the magnetic fields emitted, and not by direct emission of electric fields from the generators themselves.

A second method for source prediction is to apply the models provided in the companion reports to estimate the source levels emanated by each type of device (WEC, power cable, sub-sea pod, etc.) using fundamental models. This method is less preferred than to measure device output in a test-stand environment. In the absence of test data, this approach should provide valid results to within an order of magnitude. Over time, such modeling can be compared to the explicit measurement of devices with the goal of modifying the models to match the empirical data. As the models improve, they will reduce the need to make explicit output measurements. As wave energy installations become more complex, validated models will be required to assess multi-device fields to evaluate the interaction of various power generation components. In short, this step should involve direct measurement of single cables and devices under controlled conditions, with results compared to single source models for the purpose of validating and improving the single source models. Results of validated single source models can then be extended to model complex, multi-device fields.

As part of this analysis, it is essential to identify the type of source (*e.g.* point source, dipole radiator, line source, etc.) and establish the expected propagation behavior (*e.g.* loss vs. distance) away from each source. Depending on source type, EM fields generally decay as function range, r, away from a source, usually to the second or third power, $1/r^2$ or $1/r^3$. So while sources would be expected to be strong at high levels of power generation, generated fields would also dissipate relatively quickly with distance. This step could employ models developed in companion reports to describe propagation behavior, or actual measurements could be made in a single-device environment to validate models.

4.1.3 Signature Synthesis

Once source levels and propagation behavior have been established, the next step involves analysis of the planned site layout to estimate worst-case conditions at various locations within and adjacent to the site—in the context of existing ambient EM field conditions. The expected arrangement of WECs and power cables is assumed to be related to specific site conditions to optimize power produced, as well as accommodate required navigational, environmental, or engineering needs not related to generation or propagation of EM fields. Therefore, once the source and propagation model have been analyzed, the specific propose site layout should be analyzed with regard to expected EM field generation superimposed on background conditions and geological or bathymetric features. Magnetic and electric fields are vector quantities, and thus the combination of multiple sources will add and subtract depending on the characteristics of the sources themselves, as well as their arrangement with respect to one another, as well as their orientation to the predominant hydrodynamic and bathymetric conditions of the site. By way of example, cables emanating a magnetic field will produce stronger electric fields when oriented parallel to the predominant wave directions or tidal flows, than the same field oriented perpendicular to the predominant wave conditions.

The output of this step is to identify expected magnitude and locations of anticipated "hot spots" as a result of the installation superimposed together with local conditions. This will identify locations of desirable instrumentation placement to establish areas of worst-case field strength.

4.1.4 Measurement Design

Once the site layout has been established and worst-case field conditions estimated, instrumentation requirements, and arrangement may be constructed. Specific achievable instrument specifications (*e.g.* noise floor, dynamic range, etc.) have been identified in this report (see Section 6). These specifications, together with the planned site layout and estimated EM field conditions, will identify areas of suitable placement of sensors. Sensors should be placed sufficiently close to worst-case fields, but not so close to overload the sensors themselves. It is recommended to place a sensor suite at a local control point to provide the relative contribution to EM fields as a result of localized conditions. This location should be sufficiently far from the site to avoid contamination of data by power generation sources, but sufficiently close to ensure that dominant conditions are representative of the site being assessed. Detailed analyses would establish this expected distance, but based on the expected strength and loss factors described herein; this distance should be on the order of 1 km or more.

Another consideration in the measurement design is the propagation factors associated with EM fields. Since fields drop away quickly from the source due to the logarithmic behavior of EM field propagation, errors in distance from source to sensor will greatly affect source level measurement accuracy. Sensors should therefore be placed in a tightly controllable and well-known distance from each source or otherwise placed at distances for which moderate errors in distance do not substantially affect the measured results. For example, at a distance of 1 meter, an error of 10 cm (10%) would have the same impact as a 10-meter error at 100-meter distance.

To ease logistical concerns for instrument placement and recovery, instruments should therefore be located somewhat away from source hot spots, but with sufficient resolution to capture emitted EM fields at that distance—generally within tens or hundreds of meters.

In summary, the primary output of this step is to identify instrument locations that will assess worst-case areas, but allow use of reasonably low-cost instrumentation.

4.2 Site Assessment – Logistics and Operational Considerations

Consideration should be made for related activities that could affect the quality and timeliness of the acquired data. While these factors may not be directly related to the measurement and signature assessment, and are not mandated as part of the measurement protocol itself, such factors are nonetheless critical to the overall effectiveness of site assessment, inclusive of such activities of calibrating and fielding instruments, supporting maintenance and repair of instruments, as well as collection of data on a more-or-less routine basis.

Due to the dynamic nature of the environmental site conditions, including weather, the measurement methodology needs to be robust with respect to such conditions to ensure that instruments and hence, the data, can reliably acquire and report measured conditions. For this reason, the instrumentation should be readily deployable, recoverable, and should also not require undue maintenance or repair cycles. Furthermore, the ideal instrumentation package would involve the use of local resources to deploy and recover such instrumentation using readily available equipment and methods—and not require sophisticated equipment, vessels, or installation/recovery methods. Therefore, it is strongly recommended that instruments be integrated to allow surface deployment by modest fishing vessels of opportunity or available research platforms (or WEC support vessels once the site has been built.)

From a safety and logistics standpoint, it is best to arrange the placement of instruments away from WEC cables and devices to avoid damage or entanglement during operation, installation, or recovery. Due to the nature of electric field measurements in particular, it is necessary to position sensors in a rigid-location on the ocean floor. Thus, use of a single clump-type anchor with rigidly affixed orthogonal sensors is the preferred approach. Synchronicity among measurement channels is likewise important to enable vector summation of the measured fields.

The natural outcome of this requirement is to co-locate instrumentation and data acquisition equipment for each measurement point.

Instrument power is another consideration that will have an impact on the total cost of measurement and monitoring. The best-case instrument is battery powered to eliminate potential external field sources that might contaminate the data. Although, for long monitoring periods in excess of several day or weeks, battery-powered instruments may be problematic. In this scenario, the instrument would be lowered to the sea floor, and equipped with an external release device, *e.g.* acoustic release or timed burn-wire, that would float a messenger buoy at the conclusion of the data measurement period for recovery of the device to a support vessel. The long-term viability of this approach is not known, since there are unknown outcomes for sediment transport or wave activity that could otherwise move, bury, or damage the instrument during the measurement period—compounded by the fact that instrument health would be difficult to ascertain in near real-time.

Cabled power and data telemetry links would be ideal for longer-term monitoring conditions, *e.g.* after the site has been installed, but may not be feasible for initial ambient monitoring. Thus, a hybrid approach may be possible, wherein surface battery sources could be used to provide ease of access and replenishment from a support vessel, and a sub-surface cable run to power the anchored instrument. This would provide a cost-effective methodology, and with prudent application of local methods (*e.g.* commercial crab pot and buoy maintenance) provide the means for long-term data collection with a minimum of support. Such an approach could enable EMF monitoring with other types of environmental monitoring data collection using a shared infrastructure.

The specific protocol for instrumentation logistics and support is not critical to the measurement of data, but is stated herein to ensure that such considerations are made during the measurement planning stage.

4.3 Site Assessment Risks

As noted in the previous section, a number of risks should be considered as part of the measurement design. The primary risk is that to the collected data itself, which is the essential benefit of the measurement itself. The data will need to be collected, analyzed, and correlated with operational conditions and biological and environmental observations to create the overall effects of the site. Thus, data assurance is critical. Because the near-shore oceanic environment is harsh and relatively unforgiving, consideration should be made to the instrument design to enable robust data storage and/or telemetry of the data to a secure location. The preferred method would be to obtain data in near real-time, *e.g.* over a cabled or RF link to a shore location, which would enable real-time comparison of data to existing conditions, as well as an up-to-date monitor for data quality.

Another consideration is the risk to loss of the instrument due to extreme weather conditions, or by other means, such as by theft or vandalism. EM instruments and related data acquisition devices are not inexpensive, and routine replacement of instruments is simply unaffordable. Therefore, some consideration should be made to first identify the most affordable instrumentation suite as practical, as well as providing identification and recovery features that would enable tracking or recovery of such equipment (and any stored data) if it were to break loose, lose its mooring, or other postulated scenario. Routine or real-time monitoring of the instrument health is strongly desirable, although loss of such instrumentation is entirely possible due to the aforementioned causes, in spite of routine monitoring or preventive measures.

5. REEDSPORT SITE – SIGNATURE SYNTHESIS

There is a generally accepted process to address effectively the potential impact of WEC development on an existing ecology and the species within that area. The process starts with an assessment of the baseline conditions at potential sites, followed by an evaluation of the potential impacts to the flora and fauna of species that may be affected. Then the task is to monitor the site during and after development to observe and quantify the effects realized. The methodology outlined within this report follows that same approach. We first establish the existing EM conditions at the site and determine the requirements to assess conditions after development. While measurements of the site are important, it is logical to link the EM field estimates and measured signatures with observation of the environment. Thus, it is presumed that these measurements would be used in conjunction with biological observations to characterize both the normal occurring ambient environment, as well as to assess the impact of changing EM conditions from development.

5.1 Minimum EM Conditions

Minimum EM conditions are expected to occur in the near-shore environment during periods of calm weather, since the movement of electrically conductive seawater in the presence of the Earth’s magnetic field causes much of the ambient noise there. Normally occurring wave activity, tides, coastal currents, and internal waves are expected to dominate the electric fields in the near-shore areas, whereas naturally occurring magnetic sources, including the Earth’s magnetic field contribute to low-frequency ambient conditions. It is recognized that the conductive seawater will naturally act as a filter to atmospheric and terrestrial EM sources. Thus, in the absence of locally generated, naturally occurring EM fields, EM fields in the sea will generally be lower, even substantially so, when compared to atmospheric or terrestrial conditions—with deep ocean conditions the quietest of all. It should be noted that there is a dearth of near-shore EM marine measured data. This fact together with the certain knowledge that this marine regime is dynamic with respect to currents, weather and wave conditions, and other geological and atmospheric factors ensures that EM fields will vary widely over the course of time, with time-scales from seconds, to hours, days, weeks, or even longer. Instrumentation therefore must have sufficient dynamic range and noise floor performance to characterize the minimum and maximum conditions—ideally without requiring a multitude of different sensors to achieve the span of expected observations.

Operating wave energy converters and power cables are expected to create EM fields that may exceed existing conditions within some distance of the devices and cables—especially at power generation frequencies such as 60 Hz and harmonics of 60 Hz. Further, it is expected that the presence of magnetic fields generated by energized cables and devices could also locally affect EM field conditions due to ocean wave, tide, and other current conditions that will move the conductive seawater through such fields, thereby inducing electric fields in the immediate vicinity of the power generation and transmission equipment. Methods to assess the site after the introduction of energized equipment then must be adequate to measure stronger fields, but also have sufficient resolution to assess minimal ambient noise conditions.

From the companion reports and modeling, the following natural conditions are expected at the Reedsport site:

1. The minimum estimated electric fields generated by wave motion are expected to be approximately 6 μV/m, and will be observed at frequencies around 0.3 Hz. The minimum induced magnetic fields due to wave motion should be observed over the same frequency regime with an amplitude on the order of 0.02 nT. The minimum levels will occur at the ocean floor.
2. Electric fields generated by tidal motion and coastal currents will likely be present the majority of the time. When the currents are absent, so is their contribution to the electric field.
3. Man-made sources of EM noise may be observed in measured ambient noise data. It is difficult to estimate the potential range of magnitude from man-made sources on the existing ambient conditions at the site. Man-made sources are expected to exhibit discrete frequencies at 60 Hz and higher order harmonics of 60 Hz.

Further, from the limited EM sensitivity data available for marine species, it is estimated that some the most sensitive of species have known electric field sensitivity on the order of 1 nV/m (generally elasmobranches). Less is known about the magnetic sensitivity of marine species, but some species have been reported as being sensitive to 12,000 nT, and some benthic species sensitive to fields of a few mT (milli-Tesla).

Measured deep ocean conditions are known to be quieter than shallower conditions. Thus, biological sensitivity of species coupled with deep ocean conditions will generally set the minimum noise threshold to be measured.

This means that the minimum sensitivity for near-shore measurements should be 1 nV/m or better over the regime of 1 Hz or greater, and a sensitivity of 10 to 100 nV/m at lower frequencies to capture the fields generated by ocean waves. Magnetic field instrumentation should be capable of measuring levels of 10 nT to assess the direct measurement of fields associated with the most sensitive of certain known marine species as well as the induced levels due to wave motion—although existing technology should be capable of sensing AC magnetic fields in the pT (pico-Tesla) regime. Generation of electric fields at wave sites will likely be dominated by induced E-fields (as compared with direct emission of electric fields, which can be largely shielded by metallic shields or hulls of wave energy equipment and cables). Furthermore, it is simpler to assess magnetic field conditions than it is electric field conditions. Thus, the acquisition of low-noise magnetic field conditions would be useful to compare with measured electric field conditions for the purpose of correlating results, and the potential to use magnetic measurements as a surrogate for electric field estimates—but only so far as magnetic field conditions can be measured.

5.2 Maximum EM Conditions

The maximum EM conditions at the site will depend on two primary factors. First, maximum electric field conditions will be noted during periods of large waves, with highest levels at the sea surface and in the surf zone. Second, maximum conditions will be observed near energized wave energy converters and associated cables and equipment, including sub-sea pods or other power conversion or aggregation devices.

5.2.1 Existing Maximum EM Conditions

At Reedsport, the following naturally occurring maximum conditions are expected for AC electric and magnetic fields:

1. Estimated maximum electric fields generated by wave motion are expected to range to 216 µV/m, and are expected nominally in the 0.04 Hz regime. Maximum induced magnetic fields due to wave motion should be observed over the same frequency regime, with magnitudes up to 0.54 nT or more.
2. Maximum electric fields generated by tidal motion are expected to be 33 µV/m, and the maximum magnetic fields as a result of tidal sources are expected to be .08 nT.
3. Coastal currents are expected to generate electric fields up to 22 µV/m, although higher values may be observed, with potential values up to 44 µV/m during extreme current flows. The corresponding estimated magnetic field values for these conditions would be 0.06 nT to 0.12 nT.

For reference, the intensity of the Earth's magnetic field (essentially DC) is approximately 52.2 µT at the Reedsport site.

5.2.2 Maximum EM Conditions from Wave Energy Conversion Equipment

In order to estimate the expected maximum conditions due to the presence of energized wave energy conversion equipment, several assumptions are made to establish the modeled baseline conditions for the Reedsport site. Emission of EM fields from WECs and associated hardware will depend on a variety of factors, including specific design of the equipment, cables, the use of Faraday screens in cables and metallic hulls on WECs and housings, etc. For the purposes of this analysis, a number of conditions were identified to quantify the expected effects due to anticipated operating conditions of the proposed Reedsport facility. Such conditions may be modified to obtain a more refined result, but for estimating purposes to characterize the instrumentation and expected source levels the following assumptions are noted:

1. The Ocean Power Technologies' PB150 PowerBuoy® is the modeled WEC, with a stated maximum rated peak output of 150 kW[1]. For the purposes of this analysis, it is assumed that each PB150 is operating at the peak rated output. The output voltage of the PB150 is not stated other than "low voltage," thus an output voltage of 600 volts

[1] http://www.oceanpowertechnologies.com/pb150.htm

(AC) line-to-line is assumed. The buoy is constructed of a steel hull, which is assumed to fully enclose all power generating equipment.

2. No details were available for the internal design of the PB150 electrical generator or the technology and arrangement of the sub-sea pod. However, with some basic assumptions, rough order-of-magnitude estimates can be made, at least in relative proportion to cable emission estimates. Of course, this approach yields crude estimates of the source level from an assumed WEC. (Specific estimates will depend on the design details for a given type of converter.) The assumed values for PB150 power take-off unit are:
    a. AC generator, 3 phase type, wired in delta configuration, operating at 60 Hz
    b. Characteristic coil size 0.5 meter diameter
    c. 1000 turns per pole
3. Based on the information available on OPT's web-site describing the proposed Reedsport project[2], ten such PB150 buoys will be connected to an adjacent sub-sea pod (Underwater Substation Pod™, or USP)[3] located on the seafloor. The USP will aggregate the 1.5 MW output of ten buoys, step the voltage up to medium voltage (15 kV line-to-line is assumed for this analysis), and export electrical power to shore on a single, assumed to be armored three-phase, trefoil AC cable design. It is assumed that the hull of the USP is steel, and fully encloses all electrical power aggregation and conversion equipment.
4. Each PB150 is assumed to be operating at a maximum power output level during a moderately heavy sea-state. The highest sea conditions are typically in the winter at the site location, thus the mean wave height and associated wave period are assumed. It is critical to note that this may not be representative of the efficiency of the PB150. It is merely an assumed condition to synthesize an estimated baseline condition.

[2] http://www.oceanpowertechnologies.com/reedsport.htm

[3] http://www.oceanpowertechnologies.com/pod.htm

5. All electrical cables are assumed AC 3-phase cables, with a single steel armor layer. The emitted electric fields are assumed to be perfectly shielded.

5.2.3 Model Development – Power Cable

The power cables were modeled using an existing submarine cable EMF modeling program developed by ENS Consulting (see Appendix B). Assuming a three-phase AC cable with a single layer of armor, normalized field strength values were estimated for a given phase current of one amp. For the case at hand however, it was necessary to scale the results from a nominal one-amp condition to the expected electrical current conditions of the cables. Two calculations were made: one for the nominal 600 VAC cable for each PB150 back to the aggregation device, and a second for the nominal 15 kVAC cable from the sub-sea pod to the shore facility. Assuming 150 kW output, each phase would produce 50 kW, ignoring power factor and efficiency.

600 VAC Cable:

Phase current: 50 kW / 600 V = 83 A (line current = √3 x phase current, or 144 A)

Using the modeled results, and scaling by a factor of 83:1 to account for the phase current, the expected magnetic field strength at 60 Hz would be 68 nT at a distance of 1 meter, and 2 nT at 10 meters. The induced electric field at 60 Hz is estimated at 39 μV/m at a distance of 1 meter, and 3 μV/m at 10 meters.

15 kVAC Cable:

Phase current: 500 kW / 15,000 V = 33 A (line current = √3 x phase current, or 58 A)

Since the emitted magnetic field is directly proportional to electric current through the cable, it is expected that the 600 VAC cables to each individual WEC would produce higher magnetic fields than the shore cable at 15 kV.

5.2.4 Model Development – Wave Energy Converter

In the case of the PB150 to pod cable, which is assumed to operate at 600VAC (three phase), the power generated by each phase is 50 kW, resulting in a phase current of 83 amperes

(50,000 kW/600 V), or a line current of 144 amps (phase current times $\sqrt{3}$). Using the magnetic loop coil point source model from the companion report on predicted WEC EMF signatures, the magnetic field strength due to radiation from a single magnetic loop coil is given by:

$$B(r) = \frac{\mu_0 \mu_r I dA}{2\pi r^3} \qquad 9)$$

where: μ_0 = permeability of free space ($4\pi \times 10^{-7}$ N/A^2)

μ_r = relative permeability of medium (~1 for non ferromagnetic materials)

I = current in amperes

dA = loop area = πa^2 (m^2) and a = loop radius (m)

For the assumed case of 83 amps, loop radius of 0.25 m (.5 m diameter), the 60 Hz magnetic output for each generator loop is roughly estimated to be 3 µT at range of 1 meter from the source. Assuming 1,000 loops in each winding, the total the total maximum magnetic field 1 meter from generating unit of the assumed PB150 WEC operating a full capacity is estimated to be 1,000 times greater, or 3 mT. Moving away from the generator, the field strength will drop off as the cube of distance (r), or $1/r^3$. At a distance 10 meters from the generator, the magnetic field would be estimated as 1/1000th of the 1evel observed at 1 meter, or 3 µT (at 60 Hz), and 3 nT at a distance of 100 meters. This result ignores any cancellation of the magnetic field of the three phases of the generator, but for purposes of estimation, is adequate to establish the baseline model.

An electric field is induced in the surrounding seawater due to the changing magnetic field at 60 Hz. The induced electric field can be estimated from the relationships provided in the companion report:

$$E(r) = \frac{Z I_0 dA \beta'}{4\pi r^2}$$

where $$Z = \sqrt{\frac{\mu_0 \mu_r}{\varepsilon_0 \varepsilon_r}} = \sqrt{\frac{\mu_0 \times 1}{\varepsilon_0 \times 81}} = 41.86\Omega$$

$$\beta' = \text{phase constant} = \frac{\omega}{v_p} \text{ (radians per meter)}$$

and v_p = phase velocity (m/sec)

$\omega = 2\pi f$

Thus, for the magnetic field introduced by the single coil, a corresponding electric field 1 meter from the source would be estimated to have a magnitude of 68 µV/m at 60 Hz. For the assumed 1,000 coil generator operating at peak capacity, the estimated maximum electric field would be 68 mV/m at 60 Hz at a distance of 1 meter. The electric field drops as the square of distance, thus expected levels at 10 meters would be 68 µV/m, and 68 nV/m at 100 meters.

5.2.5 Model Development – Sub-Sea Pod

The model for the 10-input/1-output sub-sea pod was developed as an extension of the single WEC generator using the method of superposition. It was assumed that the magnetic field strength produced by the PB150 generator would create a similar magnetic field in the sub-sea pod for each generator attached—for a total of ten generators. For this to be the case, each terminating cable would be terminated into a matching transformer, the voltage stepped up to the assumed 15 kV for export over the shore cable. Further, assuming that each of 10 generators are mounted closely together, and operate in phase with one-another (synchronized), the worst-case magnetic field would simply be the mathematical sum of ten simultaneously operating generators. In practice, this may not be the case due to physical mounting considerations; this approach yields a conservative estimate. Thus, a fully populated sub-sea pod operating at 150 kW per buoy (1.5 MW total) would be expected to produce a magnetic field of 32 mT at a distance of 1 meter from the magnetic centroid of the pod, or 32 µT at a distance of 10 meters. The corresponding electric field at 1 meter would be expected to be 680 mV/m at 60 Hz, and 680 µV/m at 10 meters.

5.3 Signature Synthesis

Using relatively crude estimates of WEC output, it is evident that at least at power frequencies (*e.g*. 60 Hz) emitted magnetic fields from the energized equipment would likely exceed the local ambient conditions. With the assumed PB150 arrangement described above, the maximum magnetic fields created would most likely occur near the sub-sea pod, and may produce levels up to 32 mT within 1 meter of the pod centroid, and create an induced magnetic field of 680 mV/m. The strength of these fields drop off rapidly with distance, although with sufficiently sensitive instrumentation, may be detectable at a range of hundreds of meters, perhaps as far as 1 km, depending on existing ambient conditions at the time of measurement.

6. INSTRUMENTATION – REEDSPORT SITE

As described in the previous section, minimum and maximum EM field estimations were made for existing ambient conditions, as well as significant contributors for an assumed wave energy converter implementation. While specific values are only estimated, the results serve to inform the magnitude of the quantities to be measured, and therefore, the salient features of the required instrumentation and their placement can be stated.

6.1 Magnetic Sensors

Both magnetic and electric field sensors will be required to assess the EM field conditions at the site directly. The existing magnetic fields, especially in the low-frequency AC regime common to wave and current conditions, will be very low, perhaps at the limit of the noise floor of existing commercial equipment. However, with the introduction of electrical generating equipment into the environment, magnetic signatures at power generation frequencies should be readily apparent within tens of meters of the dominant sources (sub-sea pod and generators). Line sources, such as cables, would also produce magnetic fields, but not nearly so strong as those created by concentrated generating units due to the lack of the multiplicative effect of coils in each generator and/or transformer presumed to be used in each WEC design.

The minimum ambient levels to be measured by magnetic field sensors would be expected to be 10 nT from a biological perspective, but pT resolution would provide the best basis for establishing the existing magnetic field ambient conditions. Thus, magnetic sensors should have a noise floor of less than 1 pT per root Hz (<1 pT/$\sqrt{\text{Hz}}$), with lower values recommended if existing technology could support such measurements.

The maximum magnetic source levels would be expected near power generation equipment, including the PB150 buoys and the sub-sea pod, as to a lesser extent, the AC power cables. Magnetic instrumentation capable of measuring ambient magnetic conditions (very quiet) may easily be overloaded if placed adjacent to power equipment. Thus, some separation distance would be required to re-use the same equipment for both applications. Pre-assessment of actual equipment magnetic signatures should be made to identify specific placement distances in-situ, but it is sufficient to note that ambient measurement equipment could be used to measure magnetic sources if maximum conditions for instrument sensitivity could be made *a priori*. As an alternative strategy, it may be feasible, even desirable, to use less sensitive magnetic sensors to conduct localized monitoring of energized power equipment, primarily due to the capital expense of the sensors. However, this would limit the ability to re-use such sensors for ambient noise assessments, since low sensitivity sensors are simply not capable of making high-resolution ambient measurements without unnecessarily limiting the low-noise conditions in existing EM fields.

6.2 Electric Field Sensors

Ambient electric field noise conditions in the marine environment will be driven by motional noise of the water moving the Earth's magnetic field, with highest levels observed near the ocean surface during periods of largest waves. Minimum conditions at wave frequencies are expected to be on the order of a few microvolts per meter. Certain biological observations of sharks and skates have demonstrated that weak electric fields on the order of 1 nV/m could be detected by these species. Therefore, the limiting measurement factor for electric field ambient conditions would be driven by biological observation requirements, that is, to enable measurements down to 1 nV/m resolution, assuming a root Hz noise bandwidth (*e.g.* 1 nV/m per √Hz noise floor).

The emitted electric fields will not likely be directly measurable from the cables or devices themselves, except perhaps within very close proximity, *i.e.* less than a few meters. However, induced electric fields will be apparent in the proximity of magnetic fields. Thus, it will be important to place electric field instrumentation in the same area as the magnetic sensors to correlate the relative relationship between the magnetic field strength and the induced electric field strength.

6.3 Dynamic Range

The dynamic range of an instrument is defined as the span of values, from the lowest to highest value, that the instrument is capable of measuring. Dynamic range is often expressed in decibels (dB) to define the ratio of values an instrument is capable of sensing. The dynamic range of instrumentation is not limitless. In the case of both marine magnetic and electric field conditions, the required dynamic range to assess the full suite of expected conditions is very high. Within the frequency range of interest to wave energy sites along Oregon's coast, existing ambient conditions for magnetic field strength would be expected to range from 40 pT to 52 μT, or over 6 orders of magnitude. This requirement would necessitate that an instrument have approximately 122 dB of dynamic range to sense the minimum and maximum values. Electric field requirements are slightly higher, with minimum and maximum values of approximately 1 nV/m to over 216 μV/m, or 107 dB minimum dynamic range. The base instrumentation should therefore be able to measure the full dynamic range of the magnetic and electric field signals present, including some margin for possible outlying conditions.

The dynamic range required for energized equipment grows even more, since the maximum levels emitted or induced by such equipment would likely produce higher levels than would be observed in the natural environment. Maximum magnetic levels would be expected as high as 32 mT in close proximity to energized equipment, or another three orders of magnitude greater than existing ambient conditions at that same location. Electric fields could be as high as 680 mV/m adjacent to energized equipment, or another three to four orders of magnitude higher than ambient conditions. Fortunately, these fields drop off rapidly moving away from the equipment, and thus placement of sensors could somewhat reduce instrumentation dynamic range requirements. Although instrument dynamic range should be maximized to what is reasonably achievable to enable maximum flexibility in assessing both existing ambient conditions and conditions near energized power generation equipment.

6.4 Frequency Range

Instrumentation should be capable of sensing power generation frequencies directly, as well as frequencies of known EM forcing functions in the natural environment, predominantly ocean wave spectra, or other related naturally occurring phenomena over the same span, including atmospheric and terrestrial effects. This requirement would enable interpretation of the data such that comparison of conditions involving energized wave energy equipment could be made directly with existing natural conditions at the site. AC power generation equipment would be expected to generate 60 Hz narrowband tones, although higher order harmonics due to harmonic distortion of the power waveforms may also be present. Some sub-harmonics may also be present, such as 30 Hz due to the presence of rotating power generation equipment. The presence of AC magnetic fields could also induce electric fields at frequencies in addition to power harmonics due to the relative interaction of the surrounding seawater moving in the emitted magnetic fields. These frequencies would be observed at dominant frequencies observed in the near-shore environment, generally due to wave motion, tidal and coastal currents, and internal ocean waves. Electric fields may be present at DC due to potential galvanic currents or stray currents due to the presence of metal in the seawater, e.g. due to corrosion of steel. Electric field sensors capable of detecting DC potentials could sense these fields.

6.5 Other Instrumentation Considerations

In addition to EM sensors, auxiliary sensors could be used to assist in the interpretation of the acquired EM data. Magnetic and electric fields produce not only magnitude (strength), but also direction (a vector quantity). Simply reporting the strength of a field does not fully document field conditions, but it would also be important to know something about direction. For example, the Earth's magnetic field near Reedsport is largely vertical, and wave motion is dominant from the West. Induced electric fields are created by the cross-product of magnetic and water velocity fields, thus are induced at right-angles to the Earth's magnetic fields and the incoming wave velocity direction. Therefore, it is important for instrumentation to have the ability to segregate direction, that is, vector quantities in three orthogonal directions (*i.e.* x, y, and z). With this data, the total intensity would be measured as the vector sum of each directional value, and directional data would be assessed to fully understand the mechanics of how EM fields are induced, and how existing ambient fields behave in this environment. Therefore, the position of the sensors is important over any measurement period. This could be accomplished by some means of rigidly placing the sensor on the ocean bottom in a known orientation, or some means of equipping the instrument with an orientation sensor would be desirable. The former could be accomplished by the use of divers or remotely operated vehicles (ROVs), both of which may be expensive or not possible due to operational considerations. Alternatively, an orientation sensor module, such as a compass with pitch and roll features could accomplish the same and be provisioned with the instrument itself for data recording and interpretation.

Another form of instrumentation that could be helpful in the interpretation of data would be a three-dimensional current sensor that records the wave and current conditions that exist at the time of data measurement. Because electric fields are strongly related to water flow conditions, knowledge of the 3-D water velocity field could be used to validate electric field measurements.

6.6 Calibration

Instrumentation should be calibrated with known sources before data measurement periods to ensure the validity of acquired data. A companion report describes recommended calibration methods for EM instrumentation suitable for this environment. Calibration of the instrumentation should be independent of location, thus generic methodologies are described therein. All measurements need to use calibrated instruments, with calibrations conducted with equipment traceable to NIST[4] standards.

[4] National Institute of Standards and Technology, http://www.nist.gov/index.html

7. MEASUREMENT DESIGN – REEDSPORT SITE

As previously described, the highest EM fields are expected in the vicinity of the sub-sea pod, and other sources including the WECs and low-voltage power cables from each WEC to the sub-sea pod will also contribute to the EM fields at the site. The ideal measurement layout for this site would position the EM suite within the expected propagation range of the sub-sea pod, but at a distance to avoid overloading the sensors. While the geometry will depend on the specific instruments chosen, this distance should be no closer than 10 meters, but could be as far away as 100 meters. WECs and low-voltage (600VAC) power cables would be presumed to be located seaward of the pod, thus positioning of the sensor suite should be made in the vicinity of the "middle" or near the two-dimensional centroid of the field, but within the prescribed distance to the pod. Arrangement of the sensor suite in this manner will ensure acquisition of the worst-case field conditions of the multi-device site.

The best methodology to select the worst case location is to first establish the source levels of each contributor (e.g. pod, high-voltage cable, low-voltage cables, and WECs), and then, using MATLAB or other numerical visualization tool, superimpose sources to predict the most energetic locations of the proposed site. Once this site has been determined, the instrument should not only be placed within the estimated "hot-spot," but the location of the instrument and power generation equipment should be well documented to enable interpretation of the data.

A second, more distant, instrument location should likewise be identified, primarily to determine how existing conditions vary over time away from the energize equipment—*e.g.* a control site. This site should be up to 1 km or more away from the site, and should also be positioned in a similar hydrodynamic field, e.g. similar depth and bottom contour, and exposed to similar wave, current, and tidal conditions.

Another critical aspect of measurement design is the temporal assessment of electrical power output conditions of each device. Most importantly, the electrical current produced by each device is an important determinant in the magnetic output of each. For each device, the phase current should be measured, recorded, and stored in a format that could be correlated to measured EM field data. This data is essential to the long-term understanding of the EM field effects, and once sufficient information is obtained to use measured current and applied voltage to validate models, this method could potentially be used to predict fields at a multitude of points within a site—which could be verified on a spot-check basis by actual EM measurements. Correlation of measured electrical factors is critical to the understanding of EM field generation and emission! Furthermore, such sensing and recording of electrical parameters should not be limited simply to the overall output of the shore cable. The output of each WEC is essential to understand localized effects.

8. LOGISTICS AND OPERATIONAL SUPPORT – REEDSPORT SITE

Reedsport, Oregon and the surrounding area are home to a variety of marine resources, including fishing vessels and a modest industrial base that could support installation and maintenance of EM instrumentation. Instrumentation design should accommodate local resources to enable the lowest possible logistical support costs. It is assumed that knowledgeable engineering staff will be required to set up and deploy the instrument in conjunction with local marine resources to ensure the best possible odds for success. Once a wave site is installed, it is presumed that routine maintenance of EM instrumentation could be made with on-site resources. Other logistical support issues identified in Section 4.2 would apply to the Reedsport site.

9. RISKS – REEDSPORT SITE

No unique or undue risks have been identified for the Reedsport site. The site itself is located away from the mouth of the Umpqua River, and the bottom conditions at the site are relatively benign—modest slope, no major rock outcroppings or sources of current shear are anticipated. Therefore, typical risks for EM instrumentation at this site would be similar to those identified in Section 4.3. Long-term deployment of an instrument package should follow proper notification of the U.S. Coast Guard, as well as formal notification to local mariners using standard protocols for navigational issues or hazards.

10. SUMMARY

This study was commissioned with the goal of establishing a measurement protocol for conducting site assessments for electromagnetic field conditions, both for existing ambient conditions, and for sites where wave power generation equipment has been deployed. The methodology was established in a generic sense, and then specific conditions were analyzed for the Reedsport site as a demonstration on the basic application of the protocol.

The basic protocol follows the primary topical, sequential approach:

1. Estimation or measurement of minimum and maximum EM fields in the existing environment. Measurements should be made unless existing data or related data from similar sites could be used as the basis of estimate for a given location.
2. Prediction of source levels and propagation of EM fields produced by wave energy power generation equipment, including WECs, cables, and sub-sea pods or junction housings. This stage includes direct assessment of energized devices in a controlled environments and then application or modified source modes tailored for each type of source.
3. Synthesis of existing conditions and predicted power generation signatures to establish the range of values to be measured and thus create a site-specific measurement plan inclusive of instrumentation requirements.
4. Identification of suitable instrumentation for the measurement scenario, including consideration for logistics support, risks, and data quality needs. This stage includes instrument calibration using NIST-traceable resources.

APPENDIX A – ACRONYMS

ASW	anti-submarine warfare
B-field	magnetic field
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research Into The Environment
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
Hz	Hertz, cycles per second
MKS	meter-kilogram-second
MMS	Minerals Management Service
NIST	National Institute of Standards and Technology
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
SI	International System of Units
SIO	Scripps Institute of Oceanography
UK	United Kingdom
WA	Washington
WEC	Wave Energy Converter

APPENDIX B – NORMALIZED EMF EMISSIONS FROM MODELED ARMORED AC SUBMARINE CABLE

PARAMETER	Value	Units
Step ratio	5000.00	N/A
Outside diameter of cable	6.00	cm
Wall thickness of outer jacket	0.00	cm
Conductivity of jacket	0.00	mho/cm
Permittivity of jacket	2.30	dimensionless
Conductivity of sea/seabed if buried	0.01500	mho/cm
Permittivity of sea/seabed if buried	34.00	dimensionless
Resistivity of steel wires	26.40	micro-ohm.cm
Permeability of steel wires	204.86	dimensionless
Thickness of steel wires	0.50	cm
Power Frequency	60.00	Hz
Skin depth	53.05	m
***Equivalent RMS** Current*	0.19	Amps
Earths field	0	uT
RMS PHASE CURRENT	1.00	Amps
Burial Depth	1	m

ARMOR PROPERTIES (INTERSTICES AIR FILLED)		
No inner wires	*30*	-
No outer wires	*0*	-
Inner wire dia	*5*	*mm*
Outer wire dia	*0*	*mm*
Core diameter	*50*	*mm*
Wire resistivity	*18*	*µohm.cm*
Wire permeability	*300*	-
Volume ratio (wire to void)	*0.68*	*µohm.cm*
Equivalent Resistivity	*26.40*	*µohm.cm*
Equivalent Permeability	*204.86*	-

Input horizontal distances from cable axis (m)
0.06
0.5
1
2
5
10
20
30

Click here with your rat to start calculation

Height from seabed (m)	0

Distance from cable (m)	*Max B Field (uTesla)*	*Max E Field (V/m)*	*Peak B Field (nT)*	*Peak E field (uV/m)*
0.06	0.00164	7.12E-07	1.64	0.71192
0.50	0.00131	6.24E-07	1.31	0.62435
1.00	0.00082	4.69E-07	0.82	0.46944
2.00	0.00032	2.67E-07	0.32	0.26720
5.00	0.00006	9.42E-08	0.06	0.09415
10.00	0.00002	3.88E-08	0.02	0.03878
20.00	0.00000	1.50E-08	0.00	0.01500
30.00	0.00000	7.81E-09	0.00	0.00781