



Electromagnetic Field Study

Executive Summary

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This work was funded by the Oregon Wave Energy Trust (OWET). OWET was funded in part with Oregon State Lottery Funds administered by the Oregon Business Development Department. It is one of six Oregon Innovation Council initiatives supporting job creation and long-term economic growth.

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.

1. EXECUTIVE SUMMARY

The Oregon Wave Energy Trust (OWET) commissioned this study to develop protocols and methods to achieve affordable, reliable, and repeatable electromagnetic (EM) measurements in the near-shore environment. The study was conducted in several stages, with a number of technical reports provided at each stage to document and describe findings. A synopsis of each technical report is provided herein.

1.1 Objective and Results

The major objective of this project was to demonstrate an ability to achieve affordable, reliable, repeatable EMF measurement protocols in support of wave and tidal energy technology development and deployment. As such, this report was prepared to describe the prototype instrumentation fabricated with affordable and available components, calibration results to provide the basis for repeatability, and a data summary of the ambient background and energized power cable measurements conducted during at-sea measurement deployments. Thus, the team designed and constructed an instrument to demonstrate that available components could be assembled to achieve basic measurement objectives. The instrument was deployed in-situ at two different near-shore marine environments, and acquired EM field data near an operating submarine power cable-of-opportunity to show the efficacy of the system to quantify EM emanations due to the influence of the power cable within the environment. As part of this activity, the instrument was calibrated in a laboratory to ensure a valid and repeatable methodology for measurements. Data acquired clearly showed the presence of strong electric (E-field) and magnetic (B-field) power line frequencies and harmonics (namely 60 Hz, 180 Hz, 300 Hz, and 420 Hz discrete lines) near the power cable.

The affordability, reliability, and repeatability objectives of the study were demonstrated. Modeling, calibration, measurement, and processing protocols and techniques identified within this study serve to advance the science of marine EM measurements in coastal waters, and promote a standardized methodology that is both reliable and repeatable.

1.2 Summary Conclusions and Recommendations

The following summary conclusions and recommendations as a result of this study are made:

1. Substantial published data is lacking on observed effects to marine species from EM fields at power frequencies (60 Hz and harmonics). Application of equipment and techniques documented within this study could easily be adapted to provide repeatable, quantifiable EM field data to ensure that observable conclusions are based on valid data sets.

Recommendation: Conduct additional biological study to better understand and quantify observed effects to biota from man-made EMF. Apply equipment and techniques developed in this study in support this of biological research.

2. Due to the limited scope of the study, the long-term temporal variability of naturally occurring EM fields was not quantified in terms of range or extent. Longer term monitoring or periodic sampling would provide better insight into the naturally occurring environment, as well as that of operating energy generating facilities. Scientific documentation of concurrent conditions over longer time horizons (weeks, months, seasons) will add to the physical understanding, and hence, biological understanding of measured EM fields.

Recommendation: Conduct long-term monitoring with energized cables. As part of monitoring, collect electrical and physical data to correlate measured levels to physical phenomena.

3. Modeling and predictions of E- and B-field strengths in the coastal environment are strongly dependent on local conditions, including the underlying geology. In particular, local conditions substantively affect longer-range propagation of EM fields. The existing modeling framework together with a larger set of physical measurements of in-situ data using technologies demonstrated within this study can account for these phenomena and lead to a better understanding and predictions for impacts to potential wave energy sites.

Recommendation: Evaluate and improve existing modeling capabilities with measured data at wave energy sites. Consider performing this activity while concurrently monitoring energized cables along Oregon's coast.

1.3 Technical Reports

The results provided in this report are the culmination of a series of thirteen studies to investigate methods, protocols, and other significant input parameters for establishing reliable, repeatable, and affordable EM measurements at wave project sites. The following reports were prepared to investigate, analyze, and report on current near-shore EMF knowledge base, to research state-of-the-art and available technologies in measurement approaches and equipment, and prepared to review measurement physics, including sources and modes of EM generation and propagation. Methods were assessed and summarized, with alternatives and recommendations provided to achieve the project objectives. Data for these reports were obtained through literature reviews, market surveys, computational activities, and laboratory and field tests.

- ***Effects of Electromagnetic Fields on Marine Species: A Literature Review, report 0905-00-001.*** This report summarizes the results of a top-level literature survey on the topic of the electromagnetic (EM) effects on marine biota. The primary driver for this survey was to determine the basic state of knowledge on the topic of potential biological effects that EM fields (EMF) may have on marine species, and then to apply that knowledge to identify EMF sensing requirements. A number of species were reported in the literature to be sensitive to EM fields, and could potentially be affected by EM fields created by wave energy devices and cables.
- ***Estimated Ambient Electromagnetic Field Strength in Oregon's Coastal Environment, report 0905-00-002.*** This report describes characteristics of ambient background EM field strength characteristics in Oregon's near-shore marine environment, including estimated results near Reedsport, Oregon. Background levels are a natural by-product of local and global scale activities, including wave motion (wave height, frequency, and direction), bathymetric conditions, coastal and tidal currents, and the Earth's magnetic field strength and direction, and other external factors such as geologic and solar-scale conditions, as well as local weather.
- ***The Prediction of Electromagnetic Fields Generated by Wave Energy Converters, report 0905-00-003.*** This report describes the characteristics of electromagnetic (EM) fields emitted from wave energy converters (WECs) in the marine environment. The basic physical theory was derived from the fundamental laws of electrical current and magnetism using basic analytical magnetic and electric dipole sources, with boundary conditions were applied to determine the local EM field effects. This report presents a basic model for estimating the electromagnetic fields propagating from a point electromagnetic emission source in a homogeneous medium. In practice, the decay of the electric and magnetic fields depends on the nature of the source, and the physical parameters of the surrounding media, e.g. seawater and sediments.

- ***EMF Synthesis: Site Assessment Methodology, report 0905-00-004.*** 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, inclusive of longer-term monitoring needs.
- ***EMF Measurements: Data Acquisition Requirements, report 0905-00-005.*** This report describes the recommended data acquisition requirements for obtaining valid electromagnetic field (EMF) assessments of potential wave energy sites, taking into account various input processes such as ocean wave activity, local bathymetric conditions, coastal and tidal currents, and knowledge of the Earth's magnetic field strength and direction. The provided methodology recommends data acquisition parameters based on the underlying temporal variability, frequency content, and general statistical character of EM fields in the near-shore environment. In particular, this report addresses measurement of EM fields that are a result of, or are directly affected by, wave energy conversion equipment and associated cables.
- ***EMF Measurements: Instrumentation Configuration, report 0905-00-006.*** This report describes specific calibration methods for EM measurement instrumentation using best engineering practices to achieve valid instrumentation calibration results. Calibration of measurement instrumentation is an essential part of the scientific process; calibration results are critical to the full understanding and correct interpretation of the underlying physical phenomena to be sensed. Specific procedures were developed as a result of completed modeling studies, literature and commercial surveys, and recommended measurement solutions. The report describes important factors, calibration methods, and provides test procedures to conduct the calibrations.
- ***The Prediction of Electromagnetic Fields Generated by Submarine Power Cables, report 0905-00-007.*** This report describes the emissive characteristics of electromagnetic (EM) fields from submerged power cables in the marine environment. Expected EM field levels were analyzed and synthesized for a basic homogeneous environment in which energized power cables were superimposed. Basic physical theory was derived from fundamental laws of electrical current and magnetism for a homogeneous environment, and boundary conditions were applied to estimate first-order predictions of local EM field effects from energized cables representative of the subsea power cable industry.

- ***Ambient Electromagnetic Fields in the Nearshore Marine Environment, report 0905-00-008.*** This report describes the ambient background field strength characteristics of electric and magnetic fields in the nearshore marine environment of the continental shelf. The results were prepared by collecting and summarizing existing data on the nearshore electric and magnetic field ambient conditions to serve as a surrogate for the existing conditions suitable for an environmental baseline of wave energy projects on the Oregon coast. It was noted during the literature survey phase that there was a paucity of EMF data available for the coastal environment. Factors describing sources, environment, and temporal character of marine EM fields are stated, and a range expected values is provided.
- ***Trade Study: Commercial Electromagnetic Field Measurement Tools, report 0905-00-009.*** This report describes commercially available methods and instrumentation currently used in marine electromagnetic applications. The report describes state-of-the-art marine electromagnetic (EM) methods within their historical context and identifies the instrumentation necessary to achieve these methods, including those used for geophysical exploration, marine corrosion surveys, locating sub-sea objects such as cables and pipelines, and ship signature measurements.
- ***EMF Measurements: Field Sensor Recommendations, report 0905-00-010.*** This report presents a review of instrumentation and data acquisition requirements for near-shore marine measurements, including a comparison of existing tools and sensors available to conduct such measurements. Recommendations are made for optimal instrumentation configuration suitable for characterization of EM fields in natural conditions and within the presence of energized wave energy power equipment, with a focus on sensors, data acquisition equipment, optional auxiliary sensors to aid in data interpretation, and implementation recommendations.
- ***Summary of Commercial EMF Sensors, report 0905-00-012.*** This report summarizes the results of a market survey for available electric and magnetic field sensors and measurement equipment suitable for the near-shore marine environment. Commercially available sensors and data acquisition hardware are identified, with information provided from public sources of information, manufacturer data sheets, and evidence gathered from users (typically academic researchers) using such equipment for field work or laboratory studies.
- ***Wave Energy Converter Measurement Project Plan, report 0905-00-014.*** This report, together with an available Microsoft Office Project file, describes the preparation and execution of EMF signature assessments of various aspects of a Wave Energy Converter (WEC), including in-air testing, single- and multiple-device testing, as well as associated in-water cabling. This plan may be used to prepare for conducting a signature assessment of a device or multiple devices, and then comparing the result to predicted or modeled expectations. A Microsoft Office Project 2007 plan has been prepared that matches the narrative description for the WEC measurement plan, and includes estimated resources

such as labor hours, generic costs, materials, and other direct costs required to conduct a suite of measurements.

- ***Electromagnetic field measurements: environmental noise report, report 0905-00-015.***
This report describes the configuration and use of a stand-alone EM instrument to demonstrate that available components could be assembled to achieve basic instrumentation objectives for nearshore marine EM measurements. The instrument was deployed in-situ in two different near-shore marine environments, and included acquisition of data near an operating submarine power cable-of-opportunity to show the efficacy of the system to quantify EM emanations due to the influence of the power cable within the environment.

Reports are available from the Oregon Wave Energy Trust, <http://www.oregonwave.org/>.



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Effects of electromagnetic fields on marine species: A literature review.

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1. EXECUTIVE SUMMARY

This report summarizes the results of a top-level literature survey on the topic of the electromagnetic (EM) effects on marine biota. The primary driver for this survey was to determine the basic state of knowledge on the topic of potential biological effects that EM fields (EMF) may have on marine species, and then to apply that knowledge to identify EMF sensing requirements. In particular, specific knowledge was sought on species sensitivity to field strength to electric or magnetic fields and on the frequency range of such sensing sensitivity.

It was noted as a result of the survey (Table 1) that EM sensitivities varied significantly by species. Elasmobranchs (sharks and skates) were noted to have extreme sensitivity to low-frequency AC electric fields, including the area between 1/8th to 8 Hz, but no notation was made for sensitivity to magnetic fields. Telost fish, including salmonids, also have an electric field sensitivity, but one that is orders of magnitude lower (less sensitive) than sharks. Elasmobranchs provide the most stringent requirement for electric field sensing, with some species sensitive to levels as low as 1 nV/m (1×10^{-9} volts/meter).

On the other hand, benthic species and some marine mammals have been observed to be affected to varying degrees by magnetic fields, but not electric fields. Magnetic sensing requirements appear to be driven by eels, which the literature reports as having sensitivities to magnetic fields on the order of a few μ T (1×10^{-6} Tesla). Some benthic species have been shown to be affected by stronger magnetic fields, although there has been little research reported on the subject of certain species native to the Pacific Northwest, including the Dungeness crab.

In summary, a number of species were reported to be sensitive to EM fields, and could potentially be affected by EM fields created by wave energy devices and cables. Thus, instrumentation used to assess the impact of EM fields should provide adequate resolution to allow direct measurement of known sensitivity levels. Furthermore, it would be desirable, but not required, to investigate instrumentation that is capable of measuring levels below the known levels of sensitivity to enable future research on any collected data that may have an observable impact.

2. INTRODUCTION

Oregon's demand for energy continues to increase and the need to develop renewable energy projects remains a high priority for the State. Oregon has been identified as an ideal location for wave energy conversion based primarily on its tremendous wave resource and coastline transmission capacity. However, there are multiple devices, in various stages of development, which convert the power of waves into electricity. Research and development is still required for wave energy to be economically competitive with traditional technologies.

Electromagnetic fields (EMF) originate from both natural and anthropogenic sources. Natural sources include the Earth's magnetic (B) field and different processes (biochemical, physiological, and neurological) within organisms. Marine animals are also exposed to natural EMF caused by sea currents traveling through the geomagnetic field. Anthropogenic sources of EMF emissions in the marine environment include submarine telecommunications (fiber optic and coaxial) and undersea power cables.

Three components of a wave energy conversion project are likely sources of EMF: the wave energy converter (WEC) device itself, the subsea pod, i.e. the power aggregation, control, or conversion housings, and the subsea power transmission cables including the power cable exiting the bottom of each WEC and those cables from the subsea pod to a land-based substation. If part of a WEC design, the enclosed metallic structure of the WEC device and subsea pod designs could potentially serve as Faraday cages, where an enclosure of conducting material results in an electric field shield.

Federal and State agencies, along with other stakeholders have raised the issue of the potential effects of EMF on marine life, including elasmobranchs, including sharks and skates, green sturgeon (*Acipenser medirostris*), salmonids (*Oncorhynchus* species), Dungeness crab (*Cancer magister*), and plankton, with the development of WEC devices and associated infrastructure.

Specific concerns raised suggest that the EMF generated by a WEC project may disrupt migration or cause disorientation of salmon. Recreational and commercial users of the marine environment, such as surfers and fishermen, also suggest that EMF may attract sharks (an electro-sensitive species), and increase the risk of shark attacks in the area. Agency staff are

concerned that a WEC project differs from traditional sources of anthropogenic EMF in the ocean. Instead of a single cable lying on or under the seabed, a proposed WEC project represents multiple devices and associated cables running through the entire water column before running along the seabed to connect with the subsea pod. This configuration would increase the potential level of exposure of EMF to marine species.

This report summarizes the existing literature on the EMF effects on marine species, particularly those present in the Pacific Northwest.

3. METHODOLOGY

Over 50 journal articles, abstracts, and reports were reviewed in the course of this research. The sources of literature and information included:

1. Aquatic Sciences and Fisheries Abstracts;
2. Bio One Abstracts and Indexes;
3. University of Washington library system;
4. Toxnet (Toxicology Data Network); and
5. Internet searches.

To ensure a high probability of identifying relevant literature a wide variety of keyword combinations were used in the search, such as “EMF”, “marine”, “aquatic”, and “effects”; or “submarine”, and “cables.”

4. POTENTIAL EFFECTS OF EMF ON MARINE BIOTA

The transmission of electricity from a WEC device to the onshore facilities may involve either a direct current (DC) or an alternating current (AC). DC is characterized by a constant flow of electrical charge in one direction, from high to low potential, while in AC the magnitude of the charge varies and reverses direction many times per second.

The B-fields from these two types of electrical current interact with matter in different ways. While AC induces electric currents in conductive matter, both interact with magnetic material, such as magnetite-based compasses in organisms (Ohman et al. 2007).

Electric (E) fields are produced by voltage and increase in strength as voltage increases, while magnetic fields are generated by the flow of current and increase in strength as current increases.

EMF consists of both E- and B-fields. The presence of magnetic B-fields can produce a second induced component, a weak electric field, referred to as an induced electric (iE) field. The iE-field is created by the flow of seawater or the movement of organisms through a B-field. The strength of E- and B-fields depends on the magnitude and type of current flowing through the cable and the construction of the cable. In addition, shielding of the cable can reduce or in essence eliminate E-fields. Overall, both E- and B-fields, whether anthropogenic or naturally occurring, rapidly diminish in strength in seawater with increasing distance from the source.

The type and degree of observed EMF effects may depend on the source, location, and characteristics of the anthropogenic source, and the presence, distribution, and behavior of aquatic species relative to this source. Since EMF levels decrease in strength with increased distance from the source, it may be surmised that fields emitted by a submerged or buried submarine cable would have more effect on benthic species and those present at depth than on those occupying the upper portion of the water column. While logical in conclusion, this assumption has not yet been validated in an in-situ environment with EMF measurement and observation.

Organisms that can detect E- or B-fields (i.e., electro-sensitive species) are presumed to do so by either iE-field detection or magnetite-based detection, either attracting or repelling an animal.

Electro-sensitive species detect iE-fields either passively (where the animal senses the iE-fields produced by the interaction between ocean currents with the vertical component of the Earth's magnetic field) or actively (where the animal senses the iE-field it generates by its own interaction in the water with the horizontal component of the Earth's B-field (Paulin 1995, von der Emde 1998)).

Data on the detection of B-fields by marine species is limited. Research shows that electro-sensitive aquatic species have specialized sensory apparatus enabling them to detect electric field strengths as low as 0.5 microvolt per meter ($\mu\text{V}/\text{m}$). These species use their sensory apparatus for prey detection and ocean navigation (McMurray 2007). For example, members of the

elasmobranch family (i.e., sharks, skates, and rays) can sense the weak E-fields that emanate from their prey's muscles and nerves during muscular activities such as respiration and movement (Gill and Kimber 2005).

Magnetosensitive species are thought to be sensitive to the Earth's magnetic fields (Wiltschko and Wiltschko 1995, Kirschvink 1997, Boles and Lohmann 2003, McMurray 2007, Johnsen and Lohmann 2008). While the use of B-fields by marine species is not fully understood and research continues (Lohmann and Johnsen 2000, Boles and Lohmann 2003, Gill et al. 2005), it is suggested that magnetite deposits play an important role in geomagnetic field detection in a relatively large variety of marine species including turtles (Light et al. 1993), salmonids (Quinn 1981, Quinn and Groot 1983, Mann et al. 1988, Yano et al. 1997), elasmobranchs (Walker et al. 2003, Meyer et al. 2005), and whales (Klinowska 1985, Kirschvink et al. 1986), many of which occur in the Pacific Northwest.

4.1 Changes in Embryonic Development and Cellular Processes

The ability to detect E- and B-fields starts in the embryonic and juvenile stages of life for numerous marine species. For example, through controlled experiments it has been shown that B-fields have been found to delay embryonic development in sea urchins and fish (Cameron et al. 1993; Zimmerman et al. 1990, Levin and Ernst 1997). Several studies have found that EM fields alter the development of cells; influence circulation, gas exchange, and development of embryos; and alter orientation.

Research on sea urchins showed that 10 μ T to 0.1 T (100 Gauss [G] to 1,000G) static B-fields are able to cause a delay in the mitotic cycle of early urchin embryos. These fields also increase greatly the incidence of exogastrulation, a mental abnormality in sea urchins (Levin and Ernst 1997).

Furthermore, barnacle larvae passed between two electrodes emitting a high frequency AC EMF, caused significant cell damage to the larvae and caused the larvae to retract their antennae, interfering with settlement (Leya et al. 1999).

However, in a study involving chum salmon (*O. keta*), Prentice et al. (1998) found no increase in the percentage of egg production/female, fertilization rates, larval mortality or deformity rates, or overall survival in the EMF-exposed fish.

Formicki and Perkowski (1998) exposed embryos of rainbow trout (*O. mykiss*), a common resident of Oregon, in different development stages to the influence of constant, low B-fields: 5 μ T and 10 μ T (50 G and 100 G, respectively). An increased oxygen uptake in embryos influenced by the field activity (as compared to those, which develop in a geomagnetic field) was observed. Researchers also noted the effect of a B-field on the breathing process of embryos was more pronounced in periods of advanced morphogenesis.

In addition, Formicki and Winnicki (1998) exposed brown trout (*Salmo trutta*) and rainbow trout to similar constant, low level magnetic B-fields (0 to 13 mG [0 G to 0.013 G, respectively]) to the aforementioned study. Results showed this exposure slowed the embryonic development of both species. Furthermore, in this same study, Formicki and Winnicki found B-fields also induced change in the circulation of embryos and larvae of pike (*Esox lucius*) and carp (*Cyprinus carpio*), as well as in the embryos of brown trout. Formicki and Winnicki concluded that while intensity of breathing processes increase in a magnetic field, they concluded it was dependent on the stage of embryonic development and was especially manifested in the period of an advanced organogenesis.

In another study, embryos of rainbow trout and brown trout exhibited a sense of direction both in natural and artificially created B-field (Tanski et al. 2005). In a controlled experiment, fish embryos in artificially generated 0.5, 1.0, 2.0, and 4.0 μ T (5, 10, 20, and 40 G, respectively) horizontal B-fields, superimposed on the geomagnetic field were compared to the orientation in the Earth's B-field (i.e., the control). The artificially generated constant B-fields were found to induce significantly stronger orientation responses in embryos, compared to those elicited by the geomagnetic field alone.

However, additional research on pike embryo failed to show changes in locomotive responses to varying B-fields (Winnicki et al. 2004).

4.2 Benthic Species

There is little information on benthic species' sensitivity to magnetic fields. No studies on B- or E-field impacts to Dungeness crab, an important commercial and recreational fishery in Oregon, have been conducted. However, several studies have examined the effects and use of B- and E-fields on crustaceans of similar size and the same order (i.e., Decapoda).

In addition to other cues, such as hydrodynamics and visual stimuli, spiny lobster (*P. argus*) also uses the Earth's magnetic field to orient (Boles and Lohmann 2003). Lohmann et al. (1995) used B-fields to demonstrate that spiny lobster altered their course when subjected to a horizontal magnetic pole reversal in a controlled experiment. However, even under the influence of anthropogenic fields, no negative impacts have been observed in crustacean. For example, no ill effects were detected in western rock lobster (*Panulirus cygnus*) after electromagnetic tags, emitting a 31 kHz signal, were attached to them (Jernakoff 1987).

Furthermore, when the blue mussel (*Mytilus edulis*), along with North Sea prawn (*Crangon crangon*), round crab (*Rhithropanopeus harrisi*), and flounder (*Plathichthys flesus*), were all exposed to a static B-field of 3.7 μ T (37 G) for several weeks, no differences in survival between experimental and control animals was detected (Bochert and Zettler 2004).

However, an investigation on the blue mussel did show effects of B-fields on biochemical parameters (Aristharkhov et al., 1988). Changes in B-field action of 5.8, 8, and 80 μ T (58, 80, 800 G, respectively) lead to a 20% decrease in hydration and a 15% decrease in amine nitrogen values, regardless of the induction value.

4.3 Teleost (Bony) Fish Species

Eels exhibited some sensitivity to EMF (Centre for Marine and Coastal Studies (CMACS) 2003). Magnetosensitivity of the Japanese eel (*A. japonica*) was examined in laboratory conditions (Nishi et al. 2004). This species was exposed to B-fields ranging from 12,663 to 192,473 nT (0.12663G to 0.192473 G). After 10 to 40 conditioning runs, all the eels exhibited a significant conditioned response (i.e. slowing of the heartbeat) to a 192,473 nT (0.192473 G) B-field. Researchers concluded that the Japanese eel is magnetosensitive.

However, other species of eels have not exhibited the same responses as the Japanese eel. Westerberg and Begout-Anras (2000) investigated the orientation of silver eels (*Anguilla anguilla*) in the presence of a submarine high voltage, DC power cable. Approximately 60% of the eels crossed the cable, enabling researchers to conclude the cable did not act as a barrier to this species' migration path, although they did concede that further investigation is required. Westerberg (1999) reported similar results after investigating elver (a young stage in the eel life cycle) movement under laboratory conditions. Furthermore, Westerberg and Lagenfelt (2008) found that swimming speed of silver eels was not significantly lowered around AC cables, although more research into eel behavior during passage over the cable is required.

There are a variety of salmonid stocks that pass offshore of Oregon. Threatened or endangered stocks (listed under the Endangered Species Act of 1973) are of particular interest and include southern Oregon/northern California Coast Coho salmon (*O. kitsch*), Oregon Coast Coho salmon, Lower Columbia River Coho salmon, Lower Columbia River Chinook salmon (*O. tshawytscha*), Upper Columbia River spring-run Chinook salmon, Snake River spring/summer-run Chinook salmon, and Snake River fall-run Chinook salmon. Furthermore, steelhead (*O. mykiss*) and cutthroat trout (*O. clarkia*) originating from the Umpqua River also pass offshore of Oregon. Research suggests salmonid species may be influenced by anthropogenic E-fields, but there is limited support for the influence on B-fields.

Marino and Becker (1977) reported that the heart rate of salmon and eels may become elevated when the fish are exposed to E-field strengths of 0.007 to 0.07 V/m. The "first response", shuddering of gills and fins, is exhibited when the fish are exposed to fields of 0.5 to 7.5 V/m and the anode reaction (i.e., the fish swims towards an electrically charged anode) occurs at field strengths ranging from 0.025 V/m to 15 V/m. Harmful effects on the fish, such as electro-narcosis or paralysis occur only at field strengths of 15 V/m or more (Balayev 1980, and Balayev and Fursa 1980).

There are several potential mechanisms that Pacific salmon use for navigation, including orienting to the Earth's magnetic field, utilizing a celestial compass, and using the odor of their natal stream to migrate back to their original spawning grounds (Quinn et al. 1981, Quinn and Groot 1983, Groot and Margolis 1998). Crystals of magnetite have been found in four species of

Pacific salmon, though not in sockeye salmon (*O. nerka*; Mann et al. 1988, Walker et al. 1988). These magnetite crystals are believed to serve as a compass that orients to the Earth's magnetic field.

Quinn and Brannon (1982) conclude that while salmon can apparently detect B-fields, their behavior is likely governed by multiple stimuli as demonstrated by the ineffectiveness of artificial B-field stimuli. Supporting this, Yano et al. (1997) found no observable effect on the horizontal and vertical movements of adult chum salmon that had been fitted with a tag that generated an artificial B-field around the head of each fish. Furthermore, research conducted by Ueda et al. (1998) on adult sockeye salmon suggests that, rather than magnetoreception, this species relies on visual cues to locate natal stream and on olfactory cues to reach its natal spawning channel. Blockage of magnetic sense had no effect on the ability of the fish to locate their natal stream.

4.4 Elasmobranchs

Elasmobranchs, such as sturgeons, sharks, skates, and rays utilize natural EM fields in their daily lives and, as a result, are at a higher risk of influence from anthropogenic EMF sources than non-electrosensitive species. These species receive electrical information about the positions of their prey, the drift of ocean currents, and their magnetic compass headings.

In general, elasmobranchs experience sensitivity to E-fields between 5×10^{-7} to 10^{-3} V/m. At this level, these species are generally attracted to the source; however, at $1 \mu\text{V}/\text{cm}$ or greater, elasmobranchs typically avoid the source (Kalmijn 1982, Gill and Taylor 2002). However, there are discrepancies between the findings of Gill and Taylor (2002) and Kalmijn (1982) on the lower threshold for elasmobranchs sensitivity to E-fields. Gill and Taylor report this threshold at 5×10^{-7} V/m, while Kalmijn reports it to be 5×10^{-9} V/m.

Although they are members of one of the oldest classes of bony fishes, the skeleton of sturgeons is composed mostly of cartilage. Hence, they are discussed under "Elasmobranchs." Sturgeons are weakly electric fish that can utilize electroreceptor senses, as well as others, to locate prey. While no research has been conducted on sturgeon species found in Oregon, research on sturgeon has been conducted in Europe. Research found that the behavior of the sterlet sturgeon

(*Acipenser ruthenus*) and the Russian sturgeon (*A. gueldenstaedtii*) varies in the presence of different E-field frequencies and intensities (Basov 1999). At 1.0 to 4.0 hertz (Hz) at 0.2 to 3.0 $\mu\text{V}/\text{cm}$, response was searching for the source and active foraging; at 50 Hz at 0.2 to 0.5 $\mu\text{V}/\text{cm}$, response was searching for source; and at 50 Hz at 0.6 $\mu\text{V}/\text{cm}$ or greater, response was avoidance of the source.

Sharks typically detect an EM field between the frequencies of 1/8 and 8 Hz. Turning at a constant speed allows shark exploration of the ambient E-field. Acceleration without turning allows exploration of magnetic heading (Kalmijin 2000). This allows sharks to navigate using the Earth's B-field (Walker et al. 2003).

Research has shown responses by skates in a similar frequency range as sharks. The skate, *Raja clavata*, exhibited cardiac responses to uniform square-wave fields of 5 Hz at voltage gradients of 0.01 $\mu\text{V}/\text{cm}$; and at a voltage gradient of 10^{-6} V/m, their respiratory rhythms were also affected (Kalmijin 1966). At 4×10^{-5} V/m, with a 5 Hz square-wave, research showed a slowing down of the heartbeat (Kalmijin 1966).

Elasmobranchs attacking submarine cables has been observed (Marra 1989). In 1982, off the coast of Massachusetts, an experiment determined the sensitivity of dogfish (*Mustelus canis*), stingray (*Urolophus halleri*), and blue shark (*P. glauca*) to E-fields. Each species attacked the E-field sources (Kalmijn 1982). In the case of the dogfish, the E-fields were produced by a current of 8 μA DC passed between two electrodes that were 2 centimeters (cm) apart. Larger dogfish initiated 44 out of 112 attacks from 30 cm and farther, where fields measured less than or equal to 0.010 $\mu\text{V}/\text{cm}$. In 15 of the responses, the distances were in excess of 38 cm where the field measured 5 $\mu\text{V}/\text{m}$. For the blue shark a direct current of 8 μA DC was applied to one dipole at a time, producing a full-space field half as strong as the half-space field used for the larger dogfish. In one instance, four to five blue sharks (6 to 8 feet long) repeatedly circled the apparatus and attacked the electrodes 31 times. In training experiments, stingrays showed the ability to orient relative to uniform electric fields similar to those produced by ocean currents.

This aggressive reaction may be age-specific. Naïve neonatal bonnet head sharks (*Sphyrna tiburo*) less than twenty-four hours post-parturition failed to demonstrate a positive feeding

response to prey-simulating weak E-fields, whereas vigorous biting at the electrodes was observed in all sharks greater than thirty two hours post-parturition (Kaijura 2003).

With regards to B-fields, a CMACS (2003) discussion indicated that the strength of the B-fields emitted by submerged AC cables are substantially lower than those associated with the Earth's geomagnetic field. Therefore, they may be undetectable to magneto-sensitive species, such as elasmobranchs, that are attuned to naturally occurring B-field strengths. It should be noted that the Earth's geomagnetic field is essentially DC, and the comparison made in the CMACS report was noted at AC power frequencies (e.g. 50 Hz), thus caution should be employed when describing the relative strength of a EM field at different frequencies.

4.5 Turtles

Several species of sea turtles undergo transoceanic migration; however, limited research has been conducted on these species and their use of magnetic "maps" (Lohmann et al. 2001, Lohmann et al. 2004). What research that has been conducted suggests several species of turtle use the earth's B-fields for migration. Lohmann and Lohmann (1996) noted that Kemps ridley's turtle (*Lepidochelys kempi*), green sea turtle (*Chelonia mydas*), and loggerheads (*Caretta caretta*) all utilize the Earth B-fields, although, the use of these fields is not necessary for these species. Green sea turtle's magnetic cues were found to not be essential for adult females to navigate 2,000 kilometers from Ascension Island to Brazil (Papi, et al., 2000).

4.6 Marine Mammals

Whales and dolphins form a useful "magnetic map" which allows them to travel in areas of low magnetic intensity and gradient ("magnetic valleys" or "magnetic peaks"; Walker et al. 2003).

Many whale and dolphin species are sensitive to stranding when Earth's B-field has a total intensity variation of less than 0.5mG (5×10^{-4} G). Species that are significantly statistically sensitive include common dolphin (*Delphinus delphis*), Risso's dolphin (*Grampus griseus*), Atlantic white-sided dolphin (*Lagenorhynchus acutus*), finwhale (*Balaenoptera physalus*), and long-finned pilot whale (*Globicephala malaena*) (Kirschvink et al. 1986).

Live strandings of toothed and baleen whales have also been correlated with local geomagnetic anomalies (Kirschvink et al. 1986). It has been suggested that some cetacean species use

geomagnetic cues to navigate accurately over long-distances of open ocean that do not have geological features for orientation. Valburg (2005) suggested that while sharks are unlikely to be impacted by low electric fields immediately around submarine electric cables, shifts in EMF have been significantly correlated to whale strandings.

5. CONCLUSIONS

For WEC devices and their associated infrastructure, the influence of EMF on marine organisms must be closely examined as EMF may have positive or negative implications for a marine organism within the nearby vicinity. (See Table 1 for a summary of observed EM sensitivities found within the literature.)

Varying reactions were observed at an embryo development, depending on species. Research has shown that B-fields delay embryonic development in sea urchins and fish, while several studies have found EM fields alter the development of cells; influence circulation, gas exchange, and development of embryos; and alter orientation. However, eggs of certain species, such as chum salmon, when exposed to EMF appeared to have no effect on the development or survival of salmon zygotes.

Some aquatic species, including spiny lobster and loggerhead turtle, utilize the Earth's geomagnetic field for navigation and positioning (Lohmann et al. 2001; Boles and Lohmann 2003). In addition, benthic species such as skates, rays, and dogfish use electroreception as their principal sense for locating food.

More open water (pelagic) species, such as salmon, may encounter E-fields near the seabed but spend significant time hunting in the water column. Overall, the potential for an impact is considered highest for species that depend on electric cues to detect benthic prey.

For B-fields, certain teleost fish species, including salmonids and eels, are understood to use the Earth's B-field to provide orientation during migrations. If they perceive a different B-field to the Earth's field, there is potential for them to become disorientated. However, experimental evidence is inconclusive regarding whether or not migrating salmon are affected by anthropogenic B-field levels similar in strength to the Earth's geomagnetic field (Quinn 1981).

Therefore, depending on the magnitude and persistence of the confounding B-field the impact could be a trivial temporary change in swimming direction or a more serious delay to the migration.

While some elasmobranch species can detect and respond to E-fields that are within the range induced by submerged power cables, no studies were found describing whether such EMF levels affect the behavior of elasmobranchs under field conditions.

There is a significant lack of research into the potential impacts of EMF to sea turtles and marine mammals. Sea turtles do not appear to be as sensitive to EMF as marine mammals. Statistical evidence suggests that marine mammals are susceptible to stranding as a result of increased levels of EMF.

Table 1 – Summary of Electromagnetic Field Impacts to Marine Species

Species	Tested For	B-Field	E-Field	Frequency	Effect	Reference
Benthic Species						
North Sea prawn (<i>Crangon crangon</i>) round crab (<i>Rhithropanopeus harrisi</i>) Blue mussel (<i>Mytilus edulis</i>)	Survival	3.7mT (37G)	--	--	No detection	Bochert and Zettler (2004)
Blue mussel (<i>Mytilus edulis</i>)	Biochemical parameters	5.8, 8, and 80 mT (58, 80, 800 G)	--	--	20% decrease in hydration and a 15% decrease in amine nitrogen values	Aristharkhov et al., (1988)
Sea urchins	Developmental abnormalities	10 mT – 0.1 T (100G - 1000G)	--	--	Delayed mitotic cycle of early embryos and great increase in the incidence of exogastrulation	Levin and Ernst (1997)
Teleost Fish						
Flounder (<i>Plathichthys flesus</i>)	Survival	3.7mT (37G)	--	--	No detection	Bochert and Zettler (2004)
Salmonids (general)	Bradycardia	--	7 μ V/cm to 70 μ V/cm	--	Elevated heart rate	Marino and Becker (1977)
	First Response	--	0.5 to 7.5 V/m	--	Shuddering of gills and fins	Marino and Becker (1977)
	Anode reaction	--	0.025 V/m to 15 V/m	--	Swims towards an electrically charged anode	Marino and Becker (1977)
	Electro-narcosis or Paralysis	--	15 V/m	--	Electro-narcosis or Paralysis	Balayev (1980), Balayev and Fursa (1980)
Eels (general)	Bradycardia	--	7 to 70 μ V/cm (0.007 to 0.07 V/m)	--	Elevated heart rate	Marino & Becker (1977)

Species	Tested For	B-Field	E-Field	Frequency	Effect	Reference
	First Response	--	0.5 to 7.5 V/m	--	Shuddering of gills and fins	Marino & Becker (1977)
	Anode reaction	--	25 μ V/m (0.025 V/m) to 15 V/m	--	Swims towards an electrically charged anode	Marino & Becker (1977)
	Electro-narcosis or Paralysis	--	15 V/m	--	Electro-narcosis or Paralysis	Balayev (1980), Balayev & Fursa (1980)
Silver eels (<i>Anguilla anguilla</i>)	Migration	Same order of magnitude as the Earth's geomagnetic field at a distance of 10m	--	--	Approximately 60% crossed the cable	Westerberg & Begout-Anras (2004)
Japanese eel (<i>Anguilla japonica</i>)	Magneto-sensitivity	12,663 nT (0.12663G) to 192,473 nT (0.192473 G)	--	--	Exhibited significant conditioned response	Nishi et al. (2004)
Elasmobranchs						
Sharks (general)	AC current sensitivity	All	All	1/8 Hz and 8 Hz	Effects basic function	Kalmijn (2000b), Walker et al. (2003)
Blue shark (<i>P. glauca</i>)	Sensitivity to electric fields	--	A full-space field half as strong as the half-space field used for the larger dogfish	--	Repeated circling and attacked apparatus.	Kalmijn (1982)
Small dogfish (<i>Mustelus canis</i>)	Sensitivity to electric fields	--	<0.021 μ V/cm	--	Attacked from 18 cm or more away from the source	Kalmijn (1982)
Large dogfish	Sensitivity to electric fields	--	5 nV/m	--	Attacked from 38 cm or more away from source	Kalmijn (1982)
Skates (general)	Cardiac response	--	1 x 10 ⁻⁹ V/m	5 Hz (uniform square wave)	Cardiac responses	Kalmijn (1966)

Species	Tested For	B-Field	E-Field	Frequency	Effect	Reference
Skates (<i>Raja clavata</i>)	Respiratory and cardiac responses	--	10^{-6} V/m	5 Hz (uniform square wave)	Respiratory and cardiac rhythms are affected	Kalmijn (1966)
	Cardiac response	--	4×10^{-5} V/m	5 Hz (uniform square wave)	Slowing down of the heart beat	Kalmijn (1966)
Stingray (general)	Orientation	--	Similar to those produced by ocean currents $< 5\text{nV/m}$ (5×10^{-9} V/m)	--	Ability to orient relative to uniform electric fields similar to those produced by ocean currents	Kalmijn (1982)
Turtles						
Green sea turtle (<i>Chelonia mydas</i>)	Navigation	Variable	--	--	No detection	Papi et al., 2000
Marine Mammals						
Whales and dolphins (general)	Navigation	Earth's magnetic field $\pm 0.5\text{mG}$	--	--	Use of magnetic maps to travel in areas of low magnetic intensity and gradient	Walker et al. (2003)
Common Dolphin (<i>Delphinus delphis</i>) Risso's dolphin (<i>Grampus griseus</i>) Atlantic white-sided dolphin (<i>Lagenorhynchus acutus</i>) Finwhale (<i>Balaenoptera physalus</i>) Long-finned pilot whale (<i>Globicephala malaena</i>)	Sensitivity to stranding	Earth's magnetic field $\pm 0.5\text{mG}$	--	--	Significantly statistically sensitive to stranding	Kirschvink et al. (1986)

APPENDIX A – CONVERSION FACTORS

Magnetic (B-field) Units:

1 Tesla, T = 10,000 Gauss, G

100 microTesla, μT = 1 Gauss, G

1 milliGauss, mG = 1×10^{-3} G = 1×10^{-7} T = .1 μT = 100 nT

1 milliTesla, mT = 1×10^{-3} T

1 microTesla = 1×10^{-6} T

1 nanoTesla, nT = 1×10^{-9} T

1 picoTesla, pT = 1×10^{-12} T

1 femtoTesla, fT = 1×10^{-15} T

For reference, the approximate strength of the Earth's magnetic field near Reedsport, OR is 52 μT (.52 G)

Electric (E-field) Units:

1 volt/cm = 100 V/m

1 millivolt/cm, mV/cm = .1 V/m

1 microvolt/cm, $\mu\text{V}/\text{cm}$ = .1 mV/m = 100 $\mu\text{V}/\text{m}$

1 nanovolt/cm, nV/cm = .1 $\mu\text{V}/\text{m}$ = 100 nV/m

1 millivolt/meter, mV/m = 1×10^{-3} V/m

1 microvolt/meter, $\mu\text{V}/\text{m}$ = 1×10^{-6} V/m

1 nanovolt/meter, nV/m = 1×10^{-9} V/m

1 picovolt/meter, pV/m = 1×10^{-12} V/m

APPENDIX B – ACRONYMS

AC	alternating current
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
DC	direct current
DoI	Department of Interior
E & E	Ecology and Environment, Inc.
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
G	Gauss
Hz	Hertz, cycles per second
iE-field	induced electric field
μ T	micro-Tesla
μ V/cm	microvolt per centimeter
μ V/m	microvolt per meter
MKS	meter-kilogram-second
MMS	Minerals Management Service
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

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Electromagnetic Field Study

Estimated ambient electromagnetic field strength in Oregon's coastal environment.

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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.

Record of Revisions

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

This report describes the estimated ambient (or background) field strength characteristics of the electric and magnetic fields in Oregon's near-shore marine environment, focusing on the coastal area near Reedsport, Oregon. The results may be adjusted for other Oregon coastal locations, subject to one's knowledge of the natural conditions there, including wave activity (wave height, frequency, and direction), bathymetric conditions, coastal and tidal currents, and the Earth's magnetic field strength and direction.

This study was commissioned with the goal of estimating the ambient EM fields along the Oregon coast. The results support the design and specification of instrumentation to assess the potential impacts of anthropogenic electromagnetic (EM) fields from wave energy development. The reader is reminded that the results provided in this report are theoretical. They have not been correlated with field measurements.

A number of external factors contribute to the ambient EM fields along the coast, including geologic and solar-scale conditions, as well as local weather. Thus, the results herein are estimated within the stated assumptions, and cover a broad range of values, within which the measured values would be expected to lie. Specific natural factors affecting ambient EM noise are addressed in a companion report,¹ which states that:

1. EMF levels are highly dependent on physical location;
2. For a given location, EMF levels are highly variable;
3. EMF levels near the shore environment are likely higher than those observed in the deep ocean environment;
4. The distance scale for changes to the EMF field is dependent on individual forcing functions, and may range from meters to thousands of kilometers.

For the Reedsport test site, this analysis concludes that:

1. The estimated electric fields generated by wave motion are expected to range from 6 to 216 $\mu\text{V/m}$, and will be observed between 0.04 and 0.3 Hz. The maximum induced magnetic fields due to wave motion should be observed over the same frequency regime, and should be observed with magnitudes ranging from 0.02 to 0.54 nT.

¹ Slater, M., Schultz, A. (2010). Ambient electromagnetic fields in the nearshore marine environment. Oregon Wave Energy Trust.

2. The maximum electric fields generated by tidal motion are expected to be $33 \mu\text{V/m}$, and the maximum magnetic fields because of tidal sources are expected to be 0.08 nT .
3. Coastal currents are expected to generate electric fields up to $22 \mu\text{V/m}$, although higher values may be observed, with potential values in extreme current flows of up to $44 \mu\text{V/m}$. The corresponding estimated magnetic field values for these conditions would be 0.06 nT to 0.12 nT .
4. Man-made sources of EM noise may be observed in measured ambient noise data. It is difficult to estimate the potential range of magnitude 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 , e.g. 120 Hz , 180 Hz , etc.

2. INTRODUCTION

2.1 Purpose

This report estimates the ambient (or background) electromagnetic (EM) field strength near Reedsport, Oregon. This estimate establishes the basis for the design and specification of EM measurement instrumentation capable of measuring the expected ambient fields. The report presents a simple model that predicts the electric and magnetic fields produced by localized marine sources near the shore. The results of this model establish the sensitivity requirements for the measurement equipment.

2.2 Background

This report describes local estimates for a specific location and builds on the results of companion reports on EM fields in the shallow water marine environment. The focus is on the development of EM effects from localized marine-based sources and does not address non-marine sources of naturally occurring EM fields such as those due to geomagnetic or solar influences. In the measurement scenario, however, the resultant EM fields represent the superposition of atmospheric and terrestrial sources that may propagate into the marine environment on the additive effects of marine-based sources.

2.3 Report Organization

This report has nine sections and three supporting appendices. The first two sections contain the executive summary and introduction, which provides the project motivation and background. Section 3 presents the methodology for how the results were derived, followed by a description of the theory used to estimate EM fields (Section 4). Sections 5, 6, and 7 provide estimates of the EM field magnitudes induced by three marine-based forcing functions – wave action, tidal flow, and coastal current. Section 8 discusses the frequency content of marine-based EM sources. The report conclusions are stated in Section 9. Appendix A describes the application of Ampere's law concerning the estimation of induced magnetic fields from naturally occurring electric fields. Appendix B is an acronym list. Appendix C contains the bibliography.

3. METHODOLOGY

The results stated in this report were derived by first identifying and describing the physical theory of each known factor that contributes to the generation of magnetic and electric fields, then listing the estimated range of values for each factor in or near the area of interest. For example, two primary factors affecting the generation of electric fields in the ocean are the movement (velocity) of seawater as a conductive medium and the local strength of the Earth's magnetic field. Next, these factors were combined to estimate field strength values and superimposed on other naturally occurring sources of EM fields. The results were then summarized to provide the estimated range of values.

4. THEORY

The motion of electrically conductive seawater, which moves due to naturally occurring, physical oceanic processes, induces ambient EM noise in the marine environment. Regardless of the process, any motion of seawater in the Earth's magnetic field induces electric voltage potentials, which creates an impressed electrical current. Surface waves, tidal flows, internal waves from flow over bottom features, and coastal ocean currents cause water to move in the coastal environment. The impressed electrical current creates weak magnetic influences. Similarly, changes in the prevailing magnetic field induce changes in the electric field. Magnetic storms, electrical storms, and solar events (e.g. solar flares) represent common changes in the prevailing magnetic field.

4.1 Electric and Magnetic Fields Induced by Sea Motion

When a conducting fluid such as seawater flows through the Earth's magnetic field, an electric field is generated in the seawater, as shown schematically in Figure 1.

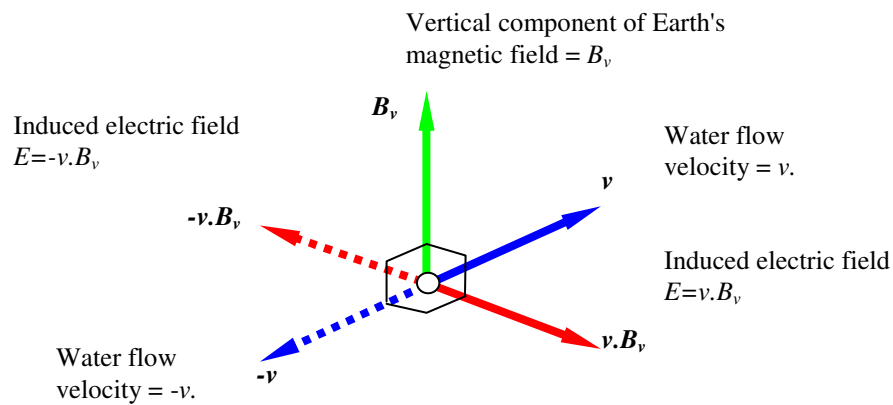


Figure 1 – Vector Diagram for Induced Electric Field

The force imparted to a charge moving at velocity v is the vector sum of the magnetic and electric forces, which is given by the Lorentz equation:

$$F = q(\vec{E} + \vec{B} \times \vec{v}) \quad 1)$$

where $q = \text{charge (C)}$

\vec{E} = applied electric field (V/m)

\vec{B} = applied magnetic field (T)

\vec{v} = velocity (m/sec)

Referring to Figure 1, the magnetic force is given by:

$$F_{mag} = q(\vec{B}_v \times \vec{v}) = q|B_v||v|\sin(\theta) \quad 2)$$

where: \vec{B}_v = vertical component of earth's field (~ 50 μ T)

θ = angle between flow velocity and magnetic field (90 deg)

Equation 2) can be rearranged to give the magnitude of the electric field induced by the fluid motion:

$$\frac{F_{mag}}{q} = E_{ind} = B_v v \quad 3)$$

The electric field generated will be mutually perpendicular to both the velocity and magnetic field vectors as shown in Figure 1.

A magnetic field will also be produced, which is described by Maxwell's fourth equation (Ampere-Maxwell Law):

$$\vec{\nabla} \times \vec{B} = \mu_0 \left(\vec{J} + \epsilon_0 \frac{d\vec{E}}{dt} \right) \quad 4)$$

where μ_0 = permeability of free space ($4\pi \times 10^{-7}$ N/A²)

ϵ_0 = permittivity of free space (8.85×10^{-12} F/m)

\vec{J} = current density (A/m²)

This equation shows that the induced magnetic field has two components, one from the current, or flow of charge, and the other from the rate of change of the electric field with time. Thus, an oscillating electric field produces a magnetic field and similarly, an oscillating magnetic field produces an electric field (Faraday's Law).

As described in the companion report, the induced electric field can be estimated using the conversion factor of .514 V/m/knot/T (volts per meter per knot per tesla). The expected location of the wave energy converter test ground is near Reedsport, Oregon, (lat / long = 43.754780°N, -124.233214°W) and the horizontal and vertical components of the earth's magnetic field at this location are 21.37 and 47.58 μ T (see Figure 2), with a total magnetic intensity of 52.2 μ T. Thus, with a uniform flow of 1 meter per second in this area, a maximum steady state electric field of 52.2 μ V/m would be expected.

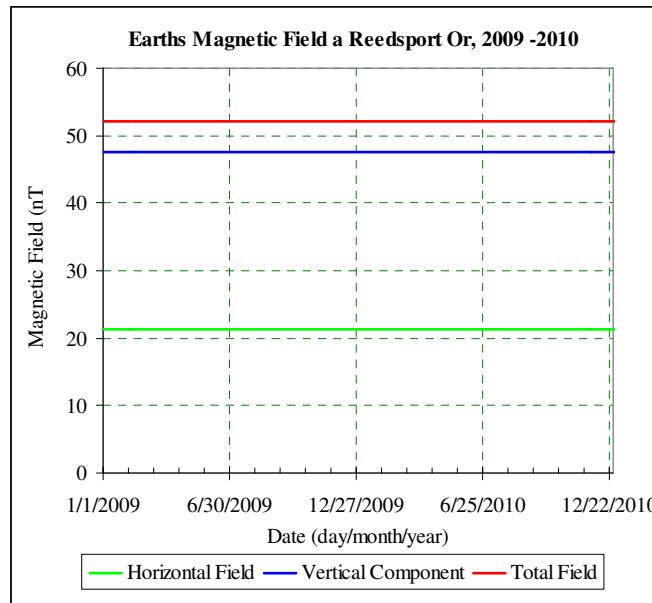


Figure 2 – Earth's Magnetic Field at Reedsport, OR from from 2009 to 2010

Location Lat/Long 43.754780°N, - 124.233214°W

Source: <http://www.ngdc.noaa.gov/geomag/magfield.shtml>

4.2 Mechanics of Progressive Ocean Surface Waves

The surface motion of the sea in the open ocean is described as a progressive wave, where energy, but not matter, is transferred from one location to another. The surface waves result from the wind interacting with the sea surface. The period and height of surface waves depend on the wind speed, the duration of the wind, and the distance (fetch) over which the wind blows.

In deep water, the wave motion at the surface is sinusoidal and the 'particle motion' beneath the wave is circular, with the orbit diameter decreasing with distance from the surface (see Figure 3). The orbit diameter decays to near zero at a depth equal to half of the wavelength at the surface. As the wave moves into shallower water, the wave orbits begin to interfere with the seabed, the wavelength shortens, and the wave height increases producing a wave in the form of a trochoid. The wave orbits now become elliptic where the vertical axis decreases in magnitude with depth, resulting in just linear displacement at the seabed.

If the depth is greater than one-half of the wavelength of the corresponding deep-water wave, then the wave is considered a deep-water wave. Similarly, the shallow water condition prevails if the depth is less than one-twentieth of the deep-water wavelength. If the depth is between these limits, then an 'intermediate' situation occurs. If either the deep or shallow water condition occurs, then approximations can be applied to simplify the equations. However, this will not be possible for the intermediate depth case and the complete equations must be used.

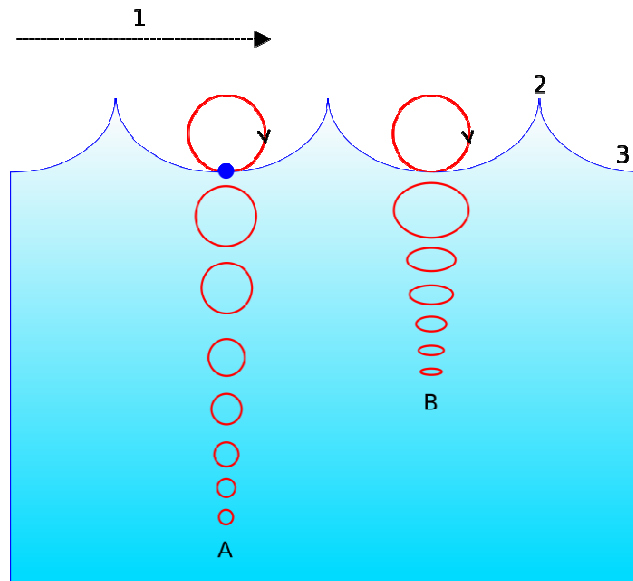


Figure 3 – Elliptical Motion of Surface Gravity Waves As a Function of Depth

Source: http://commons.wikimedia.org/wiki/File:Wave_motion-i18n.svg, public domain

In deep water, the surface wave profile is sinusoidal, with a period T_p and the corresponding wavelength in deep water is given by:

$$\lambda_{deep} = \frac{gT_p^2}{2\pi} \quad 5)$$

where: g = acceleration due to gravity (9.806 m/s²)

The deep-water 'wave number' is defined by:

$$k_{deep} = \frac{2\pi}{\lambda_{deep}} \quad 6)$$

The wave dispersion (ω) is defined by:

$$\omega = \sqrt{gk \tanh(kd)} \quad 7)$$

In deep water, $\tanh(kd) \rightarrow 1$, thus $\omega \rightarrow 2\pi f$, which is commonly known as the angular wave frequency.

The phase velocity (V_p) of the wave is given by:

$$V_p = \frac{\omega}{k} = \sqrt{\frac{g\lambda}{2\pi} \tanh(kd)} = \frac{1}{k} \sqrt{gk \tanh(kd)} \quad 8)$$

The group velocity (V_g) is given by:

$$V_g = \frac{\partial \omega}{\partial k} = \frac{\partial}{\partial k} \left(\sqrt{gk \tanh(kd)} \right) \quad 9)$$

Evaluating this differential yields:

$$V_g = \frac{1}{2\omega} \left(\frac{\omega^2}{k} + gkd(1 - \tanh(kd)^2) \right)$$

which reduces to
$$V_g = \frac{V_p}{2} \left(1 + \frac{gkd}{V_p} (1 - \tanh(kd)^2) \right) \quad 10)$$

From equation 10) it is observed that in deep water, the hyperbolic term tends to unity and the group velocity tends to half of the phase velocity.

The maximum vertical and horizontal components of the water particle velocity are then, as a function of depth:

$$v_{vert} = \frac{H\omega}{2} \frac{\sinh(k(d-z))}{\sinh(kz)} \quad (11)$$

$$v_{horiz} = \frac{H\omega}{2} \frac{\cosh(k(d-z))}{\sinh(kz)} \quad (12)$$

where z = distance from surface

As a deep-water wave passes into shallow water, the wave height increases, but the total energy of the wave (kinetic + potential energy) remains near constant. The energy of a wave can be shown to be dependent on the square of the wave height; therefore, the local wave height (H_{local}) as the wave approaches shore can be approximated using:

$$H_{local} = \sqrt{H_{deep}^2 \frac{V_{deep}}{V_{local}}} \quad (13)$$

where H_{deep} = wave height in deep water

V_{deep} = phase velocity in deep water

V_{local} = local phase velocity

As a wave comes ashore its height increases until the wave breaks, which occurs when the wave height exceeds approximately 78% of the local water depth.

All equations required to determine the electromagnetic fields induced at the seabed, or any other depth, by surface waves have now been defined. However, numeric iteration is required to determine the local wavelength as the deep-water wave moves into shallower water. An alternative approach is to use an approximation that gives the local wavelength as a function of the prevailing depth, as developed by Fenton and McKee (1990). This expression is:

$$\lambda_{local} = \lambda_{deep} \cdot \left(\tanh \left(\frac{\omega_{deep}^2 \cdot d_{local}}{g} \right)^{\frac{3}{4}} \right)^{\frac{2}{3}} \quad 15)$$

In the next section, these relationships are used to estimate the maximum EM fields in this environment.

5. ESTIMATED EM FIELDS INDUCED BY SURFACE WAVE MOTION

One of the most dominant factors in the generation of naturally occurring EM fields in the near-shore environment is wave activity, which creates motion in the sea, and hence, induces an EM field in the presence of the Earth's magnetic field. Ocean surface waves produce elliptical water particle motion in shallow water, with the greatest velocities in the horizontal direction along the direction of wave propagation. Motion is greatest at the ocean surface, and diminishes towards the bottom. Therefore, since the highest velocities are near the ocean surface, the highest values of electric field strength will likewise occur at the surface. The values are reduced as wave activity diminishes away from the ocean surface, towards the bottom. The resultant EM field occurs at the wave frequency, which provides an electric field spectrum over the same regime as the wave motion itself.

As a means to estimate the resultant EM field at Reedsport, measured joint distributions of significant wave height vs. period were examined at a nearby buoy location considered representative of the Reedsport site (Station 46229 - UMPQUA OFFSHORE, OR (139), located at 43.769 N 124.551 W)². Data from this buoy were modeled as a surrogate for wave conditions at the Reedsport site, with corrections made for shallow and intermediate water depth conditions. Using the mathematical relationships developed in Section 4.2, maximum water velocities were estimated as a function of wave conditions and water depth, from which maximum induced electric and magnetic field magnitudes were computed.

From equations (11) and (12) it is evident that water particle motion due to wave motion is maximum at the sea surface, and diminishes at deeper depths. The resulting EM fields are directly proportional to wave height, but inversely proportional to wave period. Thus, the ratio of wave height to wave period dictates the overall magnitude of the induced EM field due to surface waves. In Figure 4, the estimated horizontal component of water velocity is shown as a function of depth, using the average significant wave height and wave period for 2009 at the Reedsport site using data from Station 46229 site corrected for the estimated water depth at the

² <http://cdip.ucsd.edu/?nav=historic&sub=data&stn=139&stream=p1&xitem=product34&xyrmo=200912&xwait=2>

site of 56 m^3 . The maximum horizontal velocity occurs at the surface (0.67 m/s), and minimum occurs at the bottom (0.18 m/s). The same wave in 28 meters of water (half the depth) produces a horizontal velocity at the surface of 0.79 m/s, and 0.46 m/s at the bottom. As the wave moves shoreward into shallower water, the horizontal velocity increases in magnitude—thus increasing the magnitude of the induced electric and magnetic fields. Furthermore, as wave size increases, the magnitudes likewise increase. Using data from the maximum daily wave at Station 46229 from May 2007 through December 2009⁴, wave height of 17.37 meters, and a period of 18 seconds, the estimated horizontal velocity at the surface was 4.1 m/s.

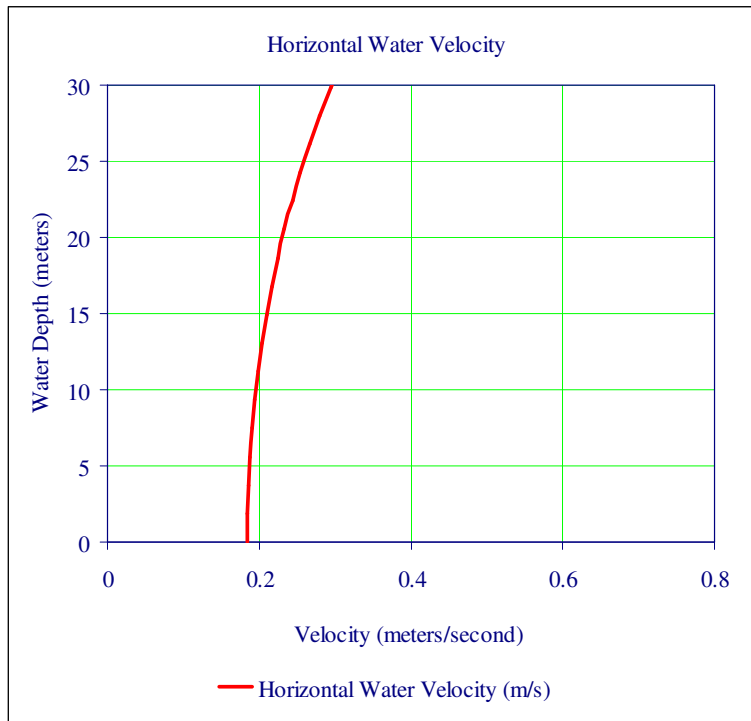


Figure 4 – Horizontal Component of Water Velocity as Function of Depth
 $H_s = 2.25\text{m}$, $T_p = 11\text{s}$, $d = 56\text{m}$

Once the water velocity is known, the maximum electric field magnitude can be computed. The maximum electric field occurs at the water surface, and is computed as the product of maximum water velocity and the strength of the earth's magnetic field at the site ($52.2 \mu\text{T}$). For the maximum daily wave described above, the expected peak electric field produced is estimated at

³ <http://cdip.ucsd.edu/?nav=historic&sub=data&stn=139&stream=p1&xyrmo=200912&xitem=product35>

⁴ <http://cdip.ucsd.edu/?nav=historic&sub=data&stn=139&stream=p1&xyrmo=200912&xitem=product33>

216 $\mu\text{V/m}$ at the surfaces, and 147 $\mu\text{V/m}$ at the sea bottom. Using the 2009 average wave data ($H_s = 2.25\text{m}$, $T_p = 11.01\text{s}$, depth = 56m), an electric field of 35 $\mu\text{V/m}$ is estimated at the surface.

Once the electric fields are known, the induced magnetic field can also be computed once the conductivity of the surrounding seawater is known by application of Ampere's law (See Appendix A). Assuming that the conductivity of the seawater at the site is 4 S/m (siemens per meter), an electric field of 216 $\mu\text{V/m}$ at the surface from the daily maximum wave will induce a magnetic field of 0.54nT. Using the more typical average wave data from 2009 ($H_s = 2.25\text{m}$, $T_p = 11.01\text{s}$, depth = 56m), the induced magnetic field at the surface is estimated at 0.09 nT.

Table 1 – Estimated EM Fields at Reedsport Site for Selected Wave Conditions

Condition	Wave Height, H_s (meters)	Wave Period, T_p (seconds)	Maximum Induced E-field ($\mu\text{V/m}$)	Maximum Induced B-field (nT)
2009 Minimum Wave	0.49	15.38	6.4	0.02
2009 Maximum Wave	10.77	25.00	127	0.32
2009 Mean Wave	2.25	11.01	35	0.09
2007-2009 Maximum Daily Wave	17.37	18.00	216	0.54
Assumptions: Water depth: 56 m Water conductivity: 4 S/m Earth's magnetic field strength 52.2 μT Maximum field magnitude is at sea surface Data source: http://cdip.ucsd.edu/?nav=historic&sub=data&stn=139&stream=p1&xyrmo=200912&xitem=stn_home				

From Table 1, it is concluded that the maximum prevailing electric field at the sea surface due to wave motion at the Reedsport site will vary between 6 and 216 $\mu\text{V/m}$, and the corresponding maximum induced magnetic field will vary from 0.02 to 0.54 nT (20 to 540 pT).

The maximum amplitudes observed for induced electric fields due to wave motion are computed as the product of the magnitude of the water velocity and magnetic field vectors. Direction is important, since the electric field is mathematically defined as the cross-product between the water velocity field and the magnetic field.

Near Reedsport, the earth's magnetic field is largely vertical, and the dominant wave direction is from the west. The resultant dominant electric field would be produced in the horizontal plane, that is, more-or-less parallel to the ocean surface. Data from Station 46229 reported that the dominant direction for waves at this site were from the west (270 degrees), with over one-third

of all waves in 2009 arriving from that direction⁵. Wave periods at that same location in 2009 ranged from a maximum of 25 seconds to a minimum of 3.45 seconds. Significant wave heights over this same time ranged from 0.49 meters to 10.77 meters. It should be noted that significant wave height and wave periods do not represent the worst-case conditions, but instead represent a statistical representation of that condition of the highest one-third of waves during the observation period.

⁵ <http://cdip.ucsd.edu/?nav=historic&sub=data&stn=139&stream=p1>

6. ESTIMATED EM FIELDS INDUCED BY TIDAL MOTION

Tidal flows produce bulk movement of seawater, which induces EM fields in the sea in the same manner as surface waves, albeit at a much longer period (hours, not seconds). Depending on location, tides may be either diurnal (1 tide/day) or semidiurnal (2 tides/day). The Reedsport area experiences a semidiurnal tide, with a maximum tidal swing of approximately 3 meters. Reviewing December 2009 tide tables for the Umpqua River Entrance, 58 tidal cycles from December 1 through December 31 are expected, with an average period of 12.42 hours⁶. Using the same wave theory as developed above for surface waves, the expected maximum velocity, and thus the EM field values can be estimated. With a basic period for the semidiurnal tide is 12.42 hours, which implies a deep-water wavelength that is much greater than the depth of the oceans; so tide waves are always shallow water waves.

Table 2 – Estimated EM Fields at Reedsport Site for Maximum Tidal Conditions

Parameter	Value	Units
Depth	56	m
Wave period	12.42	hours
Maximum wave height (tide)	3.0	m
Maximum horizontal velocity	0.63	m/s
Maximum electric field	33	μV/m
Maximum magnetic field	0.08	nT

This demonstrates that the maximum fields generated by the tide at the Reedsport will be lower than the typical maximum surface wave contribution, but not substantially so. Since these are estimated current conditions based on theory, specific current measurements near the test site could be used to improve the estimates made here.

⁶ <http://www.winchesterbayfishing.net/tides.htm>

7. ESTIMATED EM FIELDS INDUCED BY COASTAL CURRENTS

Another source of seawater motion is coastal currents. One such observation is that of the measured ocean surface currents near the Reedsport site, which are available online. While surface current observations do not fully describe the sub-surface coastal current “corkscrew” conditions along the coast, they do serve to estimate the maximum electric and magnetic field conditions on the ocean surface because of such currents. There may be cases where internal waves could produce substantial velocities, and thus induce significant EM fields, although no specific data were found to quantify these for the Reedsport site. It would be useful to analyze any current measurements made near Reedsport to determine the maximum surface velocities as that data is collected and becomes available.

A review of the coastal surface currents near Reedsport indicated that currents can vary in magnitude and direction over a period of hours or days. Daily averaged surface current data from 1 December to 26 December 2009 at a location within 4 miles of the Reedsport site (124.30233W, 43.78352N) varied significantly over the course of the month. Primary velocity vectors varied in strength and direction daily, although the along-coast velocities appeared to be stronger than the cross-coast velocities⁷. In December 2009, a maximum daily velocity of 43 cm/s (0.43 m/s) was observed on December 16, resulting in an estimated electric field magnitude of approximately 22.4 $\mu\text{V/m}$, and corresponding magnetic field strength of 0.056 nT. cursory review of other coastal sites over the same time period indicated that occasional surface velocities can exceed 80 cm/s (0.8 m/s), thus producing a maximum estimated electric field of 42 $\mu\text{V/m}$, and maximum estimated magnetic field of 0.1 nT.

⁷ <http://bragg.oce.orst.edu/>

8. FREQUENCY SPECTRUM OF OCEAN INDUCED EM FIELDS

Various sources of oceanic electromagnetic fields will create EM noise over a relatively broad frequency spectrum. Surface waves are expected to be the dominant source of EM fields at the Reedsport site. While single wavelengths were modeled here for simplicity, in practice, the spectral content of wave action in general is not at all monotonic, and will create diffuse spectra over the observed range of values. Because the earth's magnetic field is very slowly changing, it can be considered essentially constant with regard to induced frequency content. Thus, EM energy developed by marine sources such as surface waves will exhibit the same frequencies as are observed in the wave spectra itself. In the Reedsport area, the typical minimum and maximum wave periods observed range from 3.5 seconds to 25 seconds, which will span the 0.04 to 0.3 Hz regime, and will occasionally cause noise above and below these values due to the random processes involved.

The tides are caused by the gravitational influence of the moon and sun upon the oceans. The magnitude of the tide is therefore dependent on the astronomical motion of the moon and sun. The wave amplitude (tide range) as a function of time can be described by a summation of various sinusoidal functions that relate to the lunar and solar motion. As described in Section 6, the typical tidal period at Reedsport is approximately 12.42 hours (2.2×10^{-5} Hz). Coastal currents would create noise at even lower in frequencies, since there is no regular hourly or daily pattern that is readily discerned in the data. It would be expected that periods of days or weeks would result, creating EM noise in the regime of 10^{-5} Hz (daily) to 10^{-6} Hz (weekly) regime.

Figure 5 graphically depicts the estimated ambient electric field values in the Reedsport, Oregon ocean environment. Results in the crosshatched areas represent maximum expected values. The grey line on the chart represents the minimum expected measurable levels based on current electric field measurement technologies available. The chart in the figure was derived from a deep-ocean model (Keys 2003) and due to the complex motions of the near-shore environment, both the electric and magnetic field noise levels are expected to be substantially higher than deep ocean levels. Above approximately 10 Hz (periods less than approximately 10^{-1} seconds), it will be difficult to fully characterize existing ambient electric field conditions below the physical

limits of the measurement instrumentation, nominally below approximately 1 nV/m. It is important to note that this measurement threshold is also at the lowest expected limit of sensitivity for the most sensitive of marine species, thus lower level measurements may not provide much additional information.

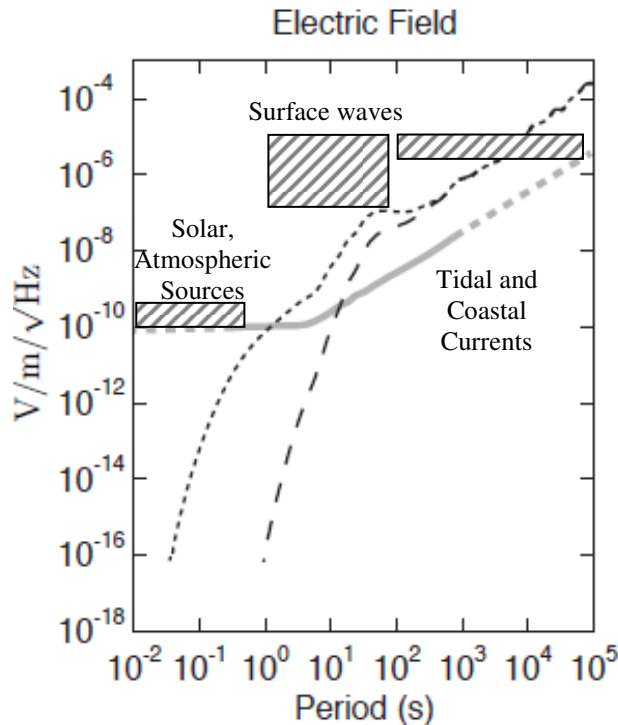


Figure 5 – Estimated Electric Field Range of Values at Reedsport, OR

Man-made sources of EM fields may be observed in the ambient noise data. In North America, 60 Hz sources are commonplace, and are tied to earth ground at virtually “everywhere” there is development. The resistive character of the Earth’s crust will undoubtedly allow 60 Hz and other electrical power frequencies to propagate into nearby areas, including the near-shore marine environment. The specific magnitude of this noise is difficult, if not impossible to estimate, thus it will need to be determined by conducting actual measurements at the site. It is expected that a 60 Hz narrowband tone will be detected in the ambient noise spectra at the Reedsport site. In addition, harmonics of 60 Hz may also be observed, such as 120 Hz, 180 Hz, and higher order harmonics. At least one electric field measurement in the near-shore environment in Europe revealed strong 50 Hz power line frequencies, including detection of an electric commuter train operating at a distance (Dalberg 2001).

9. CONCLUSIONS

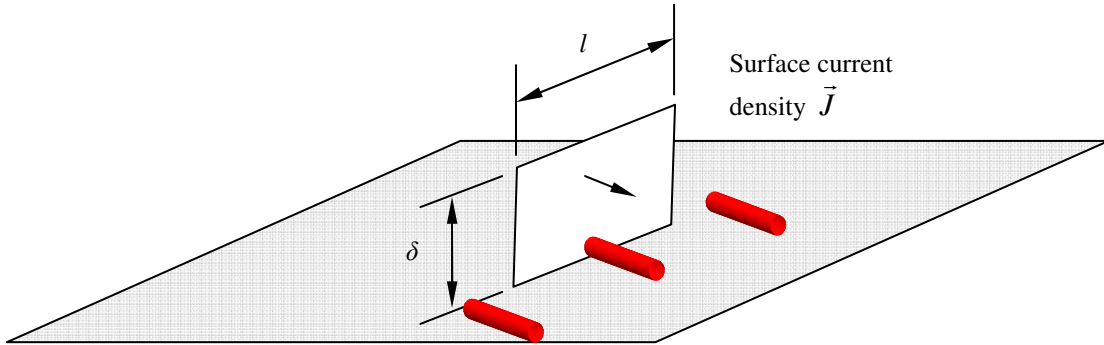
This study was commissioned with the goal of estimating the existing electric and magnetic field strength levels near the Reedsport, OR wave energy test site. This estimate of levels is one input factor to the requirements specification of EM sensors required to characterize the site.

Based on this analysis it is concluded that at the Reedsport test site:

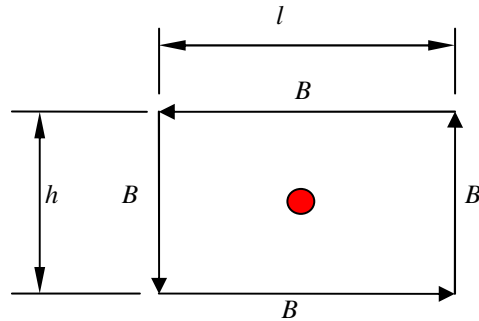
1. The estimated electric fields generated by wave motion are expected to range from 6 to 216 $\mu\text{V/m}$, and will be observed between 0.04 and 0.3 Hz. The maximum induced magnetic fields due to wave motion should be observed over the same frequency regime, and should be observed with magnitudes ranging from 0.02 to 0.54 nT. The maximum values are expected at the sea surface, and will diminish at deep depths towards the bottom. However, wave induced EM fields will nonetheless be detectable at the ocean bottom at the test site.
2. The maximum electric fields generated by tidal motion are expected to be 33 $\mu\text{V/m}$, and the maximum magnetic fields because of tidal sources are expected to be 0.08 nT.
3. Coastal currents are expected to generate electric fields up to 22 $\mu\text{V/m}$, although higher values may be observed, with potential values in extreme current flows of up to 44 $\mu\text{V/m}$. The corresponding estimated magnetic field values for these conditions would be 0.06 nT to 0.12 nT.
4. Man-made sources of EM noise may be observed in measured ambient noise data. It is difficult to estimate the potential range of magnitude 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, e.g. 120 Hz, 180 Hz, etc.

The methods used in this report could be extended to estimate EM noise levels at other locations along Oregon's coast subject to local knowledge of wave, water current, and magnetic field conditions. Furthermore, the comparison of measured values to the natural conditions would be useful in refining the level of precision of estimated results for this site and others.

APPENDIX A – DETERMINATION OF THE INDUCED MAGNETIC FIELD BY APPLICATION OF AMPERE’S LAW



The ‘ordinary’ current density \vec{J} is given by $\vec{J} = \frac{I}{\delta}$ with units of A/m². Consider the current density to be equivalent to many parallel conductors as shown above. The *surface* current density is given by $\vec{J}_s = \vec{J}l$ and has units of A/m.



Applying Ampere’s Law to the rectangular current loop gives:

$$\oint \vec{B}dl = \int_{\text{TOP}} \vec{B}dl + \int_{\text{BOTTOM}} \vec{B}dl + \int_{\text{SIDES}} \vec{B}dl = \vec{B}l + \vec{B}l + 0 = \mu_0 I = \mu_0 \vec{J}_s l$$

Thus
$$\vec{B} = \frac{\mu_0 \vec{J}_s}{2}$$

APPENDIX B – 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
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

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Electromagnetic Field Study

The prediction of electromagnetic fields generated by wave energy converters.

Prepared by
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on behalf of Oregon Wave Energy Trust

This work was funded by the Oregon Wave Energy Trust (OWET). OWET was funded in part with Oregon State Lottery Funds administered by the Oregon Business Development Department. It is one of six Oregon Innovation Council initiatives supporting job creation and long-term economic growth.

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1. EXECUTIVE SUMMARY

This report describes the characteristics of electromagnetic (EM) fields emitted from wave energy converters (WECs) in the marine environment. This study was commissioned with the goal of analyzing and synthesizing the expected EM field levels near energized wave energy converters in the coastal environment.

The basic physical theory was derived from the fundamental laws of electrical current and magnetism. Then, boundary conditions were applied to determine the local EM field effects. This report focuses on the EM field from WECs. A companion report discusses the EM fields generated by energized submarine power cables in the coastal marine environment.

This report presents a basic model for estimating the electromagnetic fields propagating from a point electromagnetic emission source. The model shows that the electric and magnetic fields in the sea decrease rapidly with distance from the source in the presence of a homogenous environment. The decay of the electric and magnetic fields depends on the nature of the source, and the physical parameters of the surrounding media, e.g. seawater and sediments.

2. INTRODUCTION

2.1 Purpose

This report estimates the localized EM field strengths created by energized wave energy converters. The purpose is to define the analytic methods for predicting the EM fields (EMF) produced by these devices. Therefore, the report focuses on identifying the range of values of EM signals created by wave energy converters in the near-shore marine environment.

2.2 Background

The Oregon Wave Energy Trust (OWET) was formed in 2007 to coordinate the development of power generation from offshore wave energy with the objective of generating 500 MW along the Oregon coast by 2025. The generated power will be transmitted to shore using subsea power cables to enable local or national distribution. The transmission of high power along such cables will induce both electric and magnetic fields into the sea. These EM fields may disturb marine species such as sharks and rays, which are sensitive to them. Together with the estimated or measured ambient EMF noise conditions, predictive results from this report can be used to estimate the environmental effects of placing such EM fields into the near shore environment.

2.3 Report Organization

This report contains several sections and supporting appendices. The first section contains the executive summary. The introduction (Section 2) describes the project's purpose, motivation, and background. Section 3 presents the methodology of analysis, followed by descriptions of the basic theories in Section 4. Section 5 presents the development of magnetic and electric field point source models. Section 6 provides overall conclusions. Appendix A contains a glossary of mathematical symbols, Appendix B provides an acronym list, and Appendix C contains reference materials.

3. METHODOLOGY

Two primary analytical models were developed to describe EM emissions from wave energy converters: (1) magnetic dipole, and (2) electric dipole. This approach is consistent with the controlled source magnetic and electric field models used in the geological community to analyze the upper structure of the earth's crust for oil exploration and scientific discovery.

While these models may not cover every possible type of wave energy converter, they do demonstrate the methodology to create analytical models that predict the range and magnitude of EMF values from an energized device. Further, they provide a basic toolset from which one can create variations to or adaptations of the initial model.

Readers are reminded that the modeled predictions for this work assume a simplified model, including the relatively homogeneity of the water and substrate conditions. Research into EMF generation and propagation, has demonstrated that a variety of factors, such as topographic, bathymetric, and geologic conditions, contribute to the natural generation and propagation of EM fields, particularly for the near shore environment. However, these conditions are not mathematically described herein. Thus, caution is urged when applying these predictive results to a specific environment.

4. BASIC THEORY

The basic theory for the development of an electromagnetic source, provided in a companion report, is replicated here for ease of reference.¹ Two fundamental relationships describe the magnetic and electric fields generated by an electrical conductor in a given medium. To simplify the analysis, the relative permeability (μ_r) and relative permittivity (ϵ_r) of the media are assumed constant. The magnetic field (B) as a function of distance (r) from the center of a conductor carrying a current I , can be derived from Ampere's Law:²

$$B(r) = \frac{I\mu_0\mu_r}{2\pi r} \quad 1)$$

Where I = current in amps
 μ_0 = permeability of free space ($4\pi \times 10^{-7}$ N/A²)
 μ_r = relative permeability of medium (~1 for non ferromagnetic materials)

Similarly, the electric field surrounding a line charge can be derived from Gauss's Law:^{3,4}

$$E(r) = \frac{q}{2\pi r\epsilon_0\epsilon_r} \quad 2)$$

Where q = charge/unit length (coulomb/m)
 ϵ_0 = permittivity of free space (8.66×10^{-12} F/m)
 ϵ_r = relative permittivity of material surrounding line charge (1 for air)

¹ Slater, M., Schultz, A. (2010). The prediction of electromagnetic fields generated by submarine power cables. Oregon Wave Energy Trust

² <http://farside.ph.utexas.edu/teaching/316/lectures/node75.html>

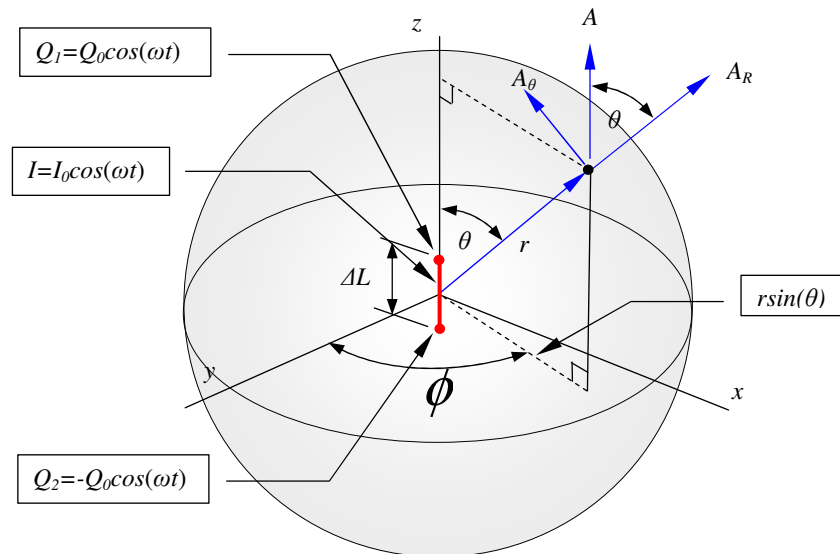
³ http://en.wikipedia.org/wiki/Gauss's_law

⁴ http://35.9.69.219/home/modules/pdf_modules/m133.pdf

5. EM FIELDS INDUCED IN THE SEA BY A POINT SOURCE

This discussion assumes that the power generation unit for each WEC will be housed within a surface or near-surface expression, or buoy, which will produce electromagnetic emissions that may propagate into the sea. The section develops and describes the application of basic theory to the problem of assessing the magnitude of the electric and magnetic fields induced in the sea from a point source of electromagnetic energy.

A convenient method for charactering the fields from a point source is to consider the generator as an electric dipole as shown in Figure 1.



- $Q_1, Q_2,$ and Q = charge (Coulombs)
- $\omega = 2\pi f$ (radians/s)
- t = time (s)
- ΔL = length of dipole (m)
- I, I_0 = Current (A)

Figure 1 – Hertzian or Electric Dipole Model

The derivation of the electric and magnetic fields produced from a Hertzian Dipole (Ida 2004) is summarized below.

The magnetic potential ($A(r)$) at point P is given by:

$$A(r) = \hat{z} \frac{\mu_0 \mu_r I_0 \Delta L}{4\pi r} \exp(-i\beta' r) \quad 3)$$

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

And $v_p = \text{phase velocity (m/sec)}$

$\hat{z} = \text{unit vector in } z$

In spherical coordinates, the components of the magnetic potential are:

$$A_r = A_z \cos(\theta) = \frac{\mu_0 \mu_r I_0 \Delta L \cos(\theta)}{4\pi r} \exp(-i\beta' r)$$

$$A_\theta = A_z \sin(\theta) = \frac{\mu_0 \mu_r I_0 \Delta L \sin(\theta)}{4\pi r} \exp(-i\beta' r)$$

Therefore, the magnetic vector potential is given by:

$$A(r, \theta) = \hat{r} \frac{\mu_0 \mu_r I_0 \Delta L \cos(\theta)}{4\pi r} \exp(-i\beta' r) - \hat{\theta} \frac{\mu_0 \mu_r I_0 \Delta L \sin(\theta)}{4\pi r} \exp(-i\beta' r) \quad 4)$$

where $\hat{\theta} = \text{unit vector in } \theta$

$\hat{r} = \text{unit vector in } r$

The magnetic field B can now be determined using:

$$B(r, \theta) = \nabla \times A(r, \theta) = \hat{\phi} \frac{\mu_0 \mu_r I_0 \Delta L \sin(\theta)}{4\pi} \left[\frac{i\beta'}{r} + \frac{1}{r^2} \right] \exp(-i\beta' r)$$

$$B(r, \theta) = \hat{\phi} \frac{\mu_0 \mu_r I_0 \beta'^2 \Delta L \sin(\theta)}{4\pi} \left[\frac{1}{\beta' r} + \frac{1}{(\beta' r)^2} \right] \exp(-i\beta' r) \quad 5)$$

where $\hat{\phi} = \text{unit vector in } \phi$

The power frequency will be 60 Hz, which equates to a wavelength (λ) of 5000 km, which is much greater than the radii of interest (i.e. 0 to 1 km). Therefore, a near field approximation (i.e. $r < \lambda/1000$) for the maximum magnetic field, can be applied to equation 5), which gives:

$$B(r) = \frac{\mu_0 \mu_r I_0 \Delta L}{4\pi r^2} \quad (6)$$

An expression for the electric field can be derived from equation 5) using Maxwell's (1873) equations, which gives:

$$E(r, \theta) = \frac{c^2}{i\omega} \nabla \times B(r, \theta) = -\hat{r} \frac{ZI_0 \Delta L \beta'^2 \exp(-i\beta' r) \cos(\theta)}{2\pi} \left[\frac{1}{(i\beta' r)^2} + \frac{1}{(i\beta' r)^3} \right] \\ - \hat{\theta} \frac{ZI_0 \Delta L \beta'^2 \exp(-i\beta' r) \sin(\theta)}{4\pi} \left[\frac{1}{i\beta' r} + \frac{1}{(i\beta' r)^2} + \frac{1}{(i\beta' r)^3} \right]$$

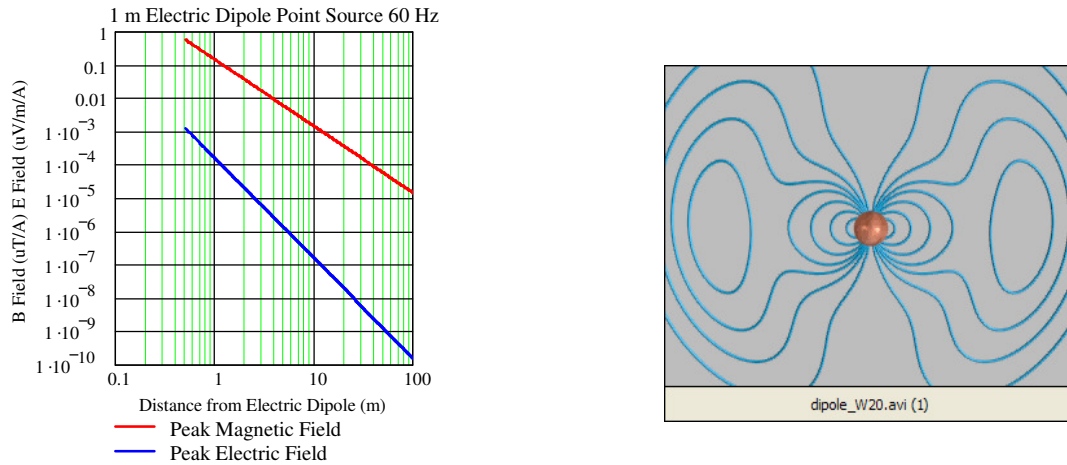
The maximum E field occurs when $\theta = 0$, and a near field approximation (i.e. $r < \lambda/1000$) can be adopted, which gives:

$$E(r) = -\frac{ZI_0 \Delta L}{2\pi \beta' (ir)^3} \quad (7)$$

Where Z is the characteristic impedance of the sea:

$$Z = \sqrt{\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r}} = \sqrt{\frac{\mu_0 \times 1}{\epsilon_0 \times 81}} = 41.86 \Omega$$

A plot of the peak electric and magnetic fields as a function of distance from a dipole length of 1 m, presuming that no shielding surrounds the energy source, is shown in Figure 2.



**Figure 2 – Normalized Magnetic and Electric Fields vs. Distance from Electric Dipole
 Dipole length = 1 m. Frequency = 60 Hz. Current $I_0 = 1A$**

A magnetic dipole could also be considered as the emission source rather than an electric dipole. The fields for this case are (Ida, 2004):

$$E_{\phi} = \frac{Z\beta'^3 I_0 dA \sin(\theta) \exp(-i\beta' r)}{2\pi} \left[\frac{i}{\beta' r} + \frac{1}{(\beta' r)^2} \right]$$

$$B_r = \frac{i\beta'^3 \mu_0 \mu_r I_0 dA \cos(\theta) \exp(-i\beta' r)}{2\pi} \left[\frac{1}{(\beta' r)^2} - \frac{i}{(\beta' r)^3} \right]$$

$$B_{\theta} = \frac{i\beta'^3 \mu_0 \mu_r I_0 dA \sin(\theta) \exp(-i\beta' r)}{4\pi} \left[\frac{i}{\beta' r} + \frac{1}{(\beta' r)^2} - \frac{i}{(\beta' r)^3} \right]$$

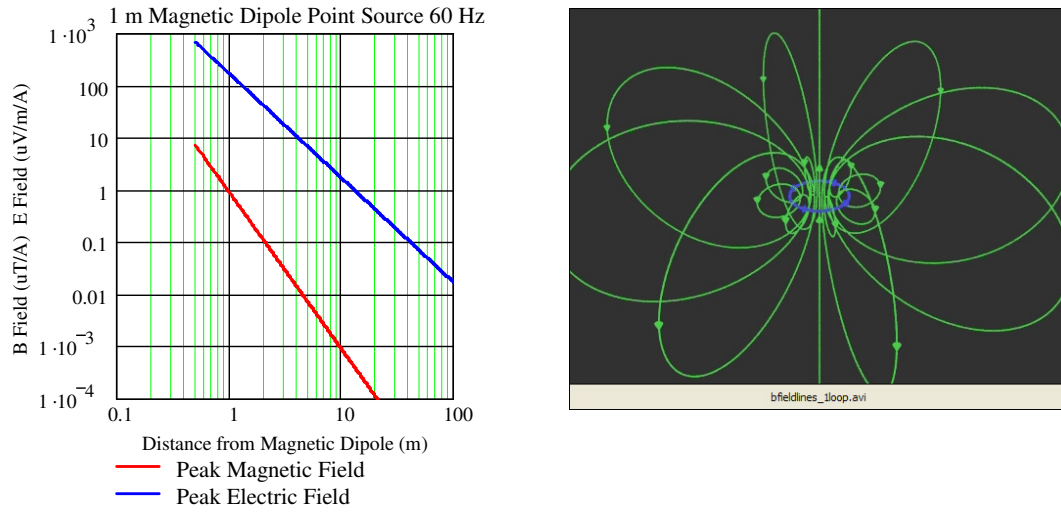
The corresponding near field approximations (i.e. $r < \lambda/1000$) for the maximum magnetic and electric fields are:

$$E(r) = \frac{ZI_0 dA \beta'}{4\pi r^2} \tag{8}$$

$$B(r) = \frac{\mu_0 \mu_r I_0 dA}{2\pi r^3} \tag{9}$$

Where $dA = \text{loop area} = \pi a^2 \text{ (m}^2\text{)}$ and $a = \text{loop radius (m)}$

The peak fields for a 1 m radius current loop, again with no shielding around the source, are shown in Figure 3.



**Figure 3 – Normalized Magnetic and Electric Fields vs. Distance from Magnetic Dipole
Dipole diameter = 1 m. Frequency = 60 Hz. Current = 1A**

6. CONCLUSIONS

This report presents models for predicting the electromagnetic fields produced by wave energy converters. The models are based on fundamental physical laws.

The basic model presented estimates the electromagnetic fields propagating from a point electromagnetic emission source. The model shows that the electric and magnetic fields in the sea decrease rapidly with distance from the source. The decay of the electric and magnetic fields depends on the nature of the source (i.e. electric or magnetic):

For a magnetic dipole source: $E \propto \frac{1}{R^2}$ and $B \propto \frac{1}{R^3}$

For an electric dipole source: $E \propto \frac{1}{R^3}$ and $B \propto \frac{1}{R^2}$

The normalized magneto-hydrodynamic electric field produced when seawater moves through the earth's magnetic field is approximately 0.515 V/m/knot/T. Changing magnetic fields in the presence of a conductor creates induced electric field effects, and furthermore, motion of a magnetic field within a conductor (e.g. seawater) for induced electric field effects, it is given that energized wave energy converters will most likely form induced electric field effects. Primary factors affecting the induced electric field near each WEC will be related to relative speed of motion between the device and surrounding seawater, as well as the strength of the magnetic field produced by the power generation unit on board the device.

APPENDIX A – GLOSSARY OF SYMBOLS

$\alpha, \beta, \theta, \phi$	Angle	radians
a	Current loop radius	m
A	Magnetic vector potential	$\text{Wb}\cdot\text{m}^{-1}$ or $\text{T}\cdot\text{m}$
B	Magnetic Field	Tesla
β'	Phase constant	$\text{radian}\cdot\text{sec}^{-1}$
C', C	Transmission line capacitance	$\text{F}\cdot\text{m}^{-1}$
dA	Area of current loop	m^2
δ	Skin depth	m
E	Electric field	$\text{V}\cdot\text{m}^{-1}$
ϵ_0	Permittivity of free space	$8.66 \times 10^{-12} \text{ F}\cdot\text{m}^{-1}$
ϵ_r	Relative permittivity	
f	Power frequency	Hz
G'	Transmission line conductance	$\text{S}\cdot\text{m}^{-1}$
h	Depth	m
I	Current	Amperes
l	Length	m
L'	Transmission line inductance	$\text{H}\cdot\text{m}^{-1}$
λ	wavelength	m
μ_0	Permeability of free space	$4\pi \times 10^{-7} \text{ N}\cdot\text{Amp}^{-2}$
μ_r	Relative permeability	
v_p	Phase velocity	$\text{m}\cdot\text{sec}^{-1}$
v	Sea water flow velocity	$\text{m}\cdot\text{sec}^{-1}$
Q	Charge	coulomb
q	Charge/unit length	$\text{coulomb}\cdot\text{m}^{-1}$
r	Radial distance	m
R'	Transmission line resistance	$\Omega\cdot\text{m}^{-1}$
R_1, R_2, R, R_C	Radii	m
ρ	Resistivity	$\Omega\cdot\text{m}$

σ	Conductivity	$\text{S}\cdot\text{m}^{-1}$
$\hat{\theta}$	Unit vector in θ	
V	Potential	volts
v	Volume fraction	
ω	angular frequency	$\text{radians}\cdot\text{sec}^{-1}$
x, y, z	Cartesian coordinates	m
Z	Impedance	Ω
Z'	Transmission line impedance	Ω
\hat{z}	Unit vector in z	

APPENDIX B – ACRONYMS

ASW	anti-submarine warfare
B-field	magnetic field
BWEA	British Wind Energy Association
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research Into The Environment
DECC	Department for Energy and Climate Change
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
FEA	Finite Element Analysis
Hz	Hertz, cycles per second
MHD	magneto hydrodynamic
MHz	megahertz
MKS	meter-kilogram-second
MMS	Minerals Management Service
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
RMS	Root Mean Square
SI	International System of Units
SIO	Scripps Institute of Oceanography
THz	terahertz
UK	United Kingdom
WA	Washington
WEC	Wave Energy Converter

APPENDIX C – BIBLIOGRAPHY

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Electromagnetic Field Study

Electromagnetic field synthesis: site assessment methodology.

Prepared by
Michael Slater, Science Applications International Corp.
Dr. Adam Schultz, consultant
Richard Jones, ENS Consulting
on behalf of Oregon Wave Energy Trust

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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 $\mu\text{V/m}$, 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 $\mu\text{V/m}$, 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 $\mu\text{V/m}$, 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 $\mu\text{V/m}$, although higher values may be observed, with potential values up to 44 $\mu\text{V/m}$ 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 kW¹. 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 project², 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:

$$\text{Phase current: } 50 \text{ kW} / 600 \text{ V} = 83 \text{ A (line current} = \sqrt{3} \times \text{phase current, or } 144 \text{ A)}$$

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 $\mu\text{V/m}$ at a distance of 1 meter, and 3 $\mu\text{V/m}$ at 10 meters.

15 kVAC Cable:

$$\text{Phase current: } 500 \text{ kW} / 15,000 \text{ V} = 33 \text{ A (line current} = \sqrt{3} \times \text{phase current, or } 58 \text{ A)}$$

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:

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

where:

μ_0 = permeability of free space ($4\pi \times 10^{-7}$ N/A²)

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

I = current in amperes

dA = loop area = πa^2 (m²) 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 μ T 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 $1/1000^{\text{th}}$ of the level observed at 1 meter, or 3 μ T (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:

$$E(r) = \frac{ZI_0 dA \beta'}{4\pi r^2}$$

where

$$Z = \sqrt{\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r}} = \sqrt{\frac{\mu_0 \times 1}{\epsilon_0 \times 81}} = 41.86 \Omega$$

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

and

$$v_p = \text{phase velocity (m/sec)}$$

$$\omega = 2\pi f$$

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 $\mu\text{V/m}$ 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 $\mu\text{V/m}$, 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 $\mu\text{V/m}$ 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 ($<1 \text{ pT}/\sqrt{\text{Hz}}$), 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 $\sqrt{\text{Hz}}$ 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 μ T, 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 μ V/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 NIST⁴ 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:

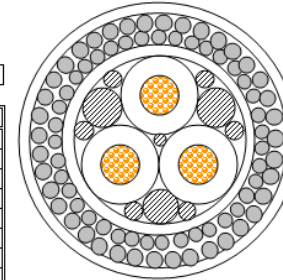
1. Estimation or measurement of minimum and maximum EM fields in the existing environment. Measurements should be made unless existing data or related data from similar sites could be used as the basis of estimate for a given location.
2. Prediction of source levels and propagation of EM fields produced 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

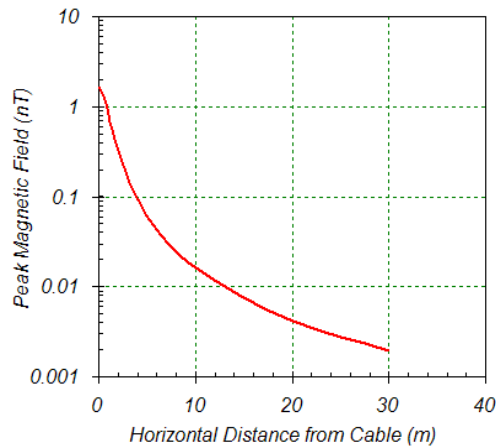
ASW	anti-submarine warfare
B-field	magnetic field
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research Into The Environment
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact 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

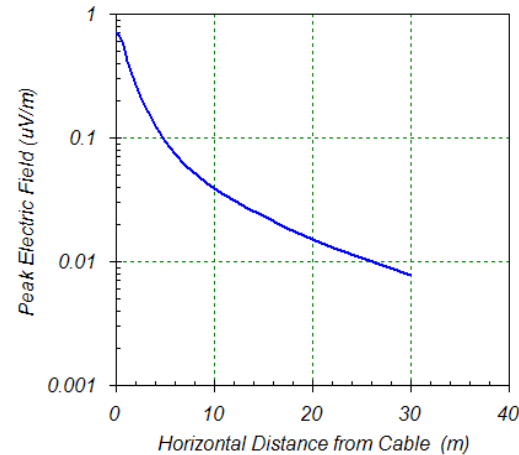
PARAMETER	Value	Units	ARMOR PROPERTIES (INTERSTICES AIR FILLED)			Input horizontal distances from cable axis (m)
Step ratio	5000.00	N/A	No inner wires	30	-	
Outside diameter of cable	6.00	cm	No outer wires	0	-	
Wall thickness of outer jacket	0.00	cm	Inner wire dia	5	mm	0.06
Conductivity of jacket	0.00	mho/cm	Outer wire dia	0	mm	0.5
Permittivity of jacket	2.30	dimensionless	Core diameter	50	mm	1
Conductivity of sea/seabed if buried	0.01500	mho/cm	Wire resistivity	18	$\mu\text{ohm.cm}$	2
Permittivity of sea/seabed if buried	34.00	dimensionless	Wire permeability	300	-	5
Resistivity of steel wires	26.40	micro-ohm.cm	Volume ratio (wire to void)	0.68	$\mu\text{ohm.cm}$	10
Permeability of steel wires	204.86	dimensionless	Equivalent Resistivity	26.40	$\mu\text{ohm.cm}$	20
Thickness of steel wires	0.50	cm	Equivalent Permeability	204.86	-	30
Power Frequency	60.00	Hz	<input type="button" value="Click here with your ratio to start calculation"/>			
Skin depth	53.05	m				
Equivalent RMS Current	0.19	Amps	Height from seabed (m)	0		
Earths field	0	uT				
RMS PHASE CURRENT	1.00	Amps				
Burial Depth	1	m				
Distance from cable (m)	Max B Field (μTesla)	Max E Field (V/m)	Peak B Field (nT)	Peak E field ($\mu\text{V/m}$)		
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		



Magnetic Field vs. Horizontal Distance from Cable



Electric Field vs. Horizontal Distance from Cable





Electromagnetic Field Study

Electromagnetic field measurements: data acquisition requirements.

Prepared by
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on behalf of Oregon Wave Energy Trust

This work was funded by the Oregon Wave Energy Trust (OWET). OWET was funded in part with Oregon State Lottery Funds administered by the Oregon Business Development Department. It is one of six Oregon Innovation Council initiatives supporting job creation and long-term economic growth.

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.

Record of Revisions

Revision	Date	Section and Paragraph	Description of Revision
Original	September 2010	All	Initial Release

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1. EXECUTIVE SUMMARY

This report describes the recommended data acquisition requirements for obtaining valid electromagnetic field (EMF) assessments of potential wave energy sites in Oregon's near-shore marine environment and focuses on the proposed Reedsport site in particular. The results of this report may be used to determine data acquisition requirements for other wave energy sites, so long as the fundamental processes that comprise the electromagnetic spectrum in a given region are comparable to those in the Reedsport site. These processes include ocean wave activity, local bathymetric conditions, coastal and tidal currents, and knowledge of the Earth's magnetic field strength and direction. In general, this methodology should nominally apply to sites along the Oregon coast, with little or no adaptation.

This study was prepared with the goal of establishing data acquisition requirements based on the underlying temporal variability, frequency content, and general statistical character of EM fields in the near-shore environment. In particular, this report addresses measurement of EM fields that are a result of, or are directly affected by, wave energy conversion equipment and associated cables.

In many ways, the existing EMF environment in the near-shore region varies widely in time, and over location due to the predominant local wave and weather conditions, as well as other geologic and atmospheric factors. The addition of man-made EMF to this environment will serve to increase the potential range of values that could be observed in this environment. Thus, consideration of measurement statistics is important to the assessment and quantification of EM fields.

2. INTRODUCTION

2.1 Purpose

This report describes the factors affecting the statistical variables of natural and proposed anthropogenic sources at wave energy sites. The purpose of the report is to define the minimum data acquisition requirements to ensure that statistically valid results are used for scientific observation because of the potential changes in environmental conditions due the introduction of wave energy conversion equipment into the environment.

2.2 Background

This report describes the anticipated statistical variability at the Reedsport, Oregon site. However, it is of a sufficiently generalized nature to apply to other wave energy sites in Oregon's coastal area. This same approach could also be extended to other potential wave sites, so long as the underlying factors affecting statistics of a given site are modified accordingly.

2.3 Report Organization

This report contains five sections and one appendix. The first section contains the executive summary. The introduction, Section 2, provides the project motivation and background. The methodology for how the results were derived is described in Section 3, followed by a description of recommended data analysis (Section 4) and data acquisition (Section 5) techniques for site assessments. Appendix A contains the acronym list.

3. METHODOLOGY

The results stated in this report were derived by first identifying and describing the physical factors that contribute to the components of naturally occurring and EM fields, with allocations for the expected introduction of EM sources from wave energy converters and cabling that could be introduced into the environment. Statistical methods were derived by adopting scientifically accepted methods in other areas of data acquisition and measurement; such as are commonly used in signal processing and acquisition applications.

4. DATA ANALYSIS TECHNIQUES

The generally accepted technical approach to acquiring and analyzing time-sampled data is based on Fourier analysis, whereas data sets can be represented as a form of energy distribution of a signal over a given time period. The spectral concept is based on Fourier's work that essentially states that many functions can be described over a given interval as an infinite sum of sine and cosine functions and reasonably represented as a spectrum. However, in the application of Fourier analysis to EM fields in the ocean, it must first be established that time-sampled EMF data meets basic suitability criteria for Fourier analysis. While a rigorous analysis could be made for the mathematical properties of the signal itself, it is generally sufficient to know that the signal being analyzed is time-invariant, that is, it is relatively stable over the period being measured, and that sharp discontinuities or abrupt changes to the signal do not occur. Such is the case for the marine environment, where the dominant signals in the sea are indeed slowly changing, driven by oceanic waves, tidal currents, or other geologic scale events. Thus, for the purposes of EMF data analysis, it is a most logical activity to apply Fourier analysis as one primary means of decomposing the resulting spectra into narrow bands for which a suitable interpretation can be applied.

The use of Fourier analysis has dominated signal analysis for decades, and continues to be one of the most effective toolsets for quantifying and understanding time-sampled data, including observations of natural phenomena. In order to use Fourier processing on a data set, it is first necessary to sample the real data under sufficient conditions to enable subsequent analyses. The underlying assumption with Fourier analysis is that uniformly time-sampled data is available for processing. Uniform time sampling is routine in today's digital world, where use of the Discrete Fourier Transform (DFT) and the Fast Fourier Transform (FFT), a special case of the DFT, are commonplace. For example, the National Data Buoy Center uses FFT processing to analyze wave buoy data¹ statistically.

¹ <http://www.ndbc.noaa.gov/wave.shtml>

5. DATA SAMPLING REQUIREMENTS

A number of important parameters are required to fully characterize and specify the data acquisition requirements. The following sections describe each of these parameters more fully, and provide recommended conditions for each.

5.1 Sampling Rate

The Nyquist–Shannon sampling theorem states that if a function $F(t)$ contains no frequencies greater than or equal to y Hertz, then the function can be completely determined from a uniform series of points spaced $1/2 y$ seconds apart. Another way to re-state the theorem is to say that sampling of a real signal with a series of uniformly spaced samples in time will completely represent the signal if the signal bandwidth is less than one-half the sampling rate, $f_s/2$, where f_s is the sampling frequency. Therefore, the time-sampled data should be sampled at a minimum rate to ensure that the highest frequency of interest is less than $f_s/2$.

A minimum data-sampling rate of 1 kHz is recommended for EMF sensors, which will allow reconstruction of signals containing frequencies up to 500 Hz. A sampling rate of 1 kHz would allow characterization of AC power cables operating at a power frequency of 60 Hz to be monitored and enable characterization of the power frequency harmonics up to the eighth harmonic (480 Hz).

5.2 Data Filtering

One primary issue associated with data sampling and Fourier analysis is the phenomenon of aliasing, which involves the creation of false artifacts in the band of interest from signals outside the band of interest. There is a fundamental assumption in Fourier analysis that the signal of interest be band-limited, that is, it is assumed to not have any energy above a certain frequency, namely the sampling frequency (f_s) by which the original time-sampled data set is created. If adequate steps are not taken during the sampling process, energy above the sampling frequency will be falsely translated into the band of interest, which then becomes part of the spectrum of interest, and will not be discernable from it. Since the acquired signal from real EM fields are truly not band-limited, and will undoubtedly contain frequency content above the sampling

frequency, it is a certainty that aliasing could be a factor in EM field analysis. The most common means to overcome the problem of aliasing is to introduce a filter during the data sampling process to attenuate unwanted signals to the point that they effectively do not appear in the measurement band of interest. All EM data sampling should employ anti-aliasing filtering as part of the sampling process.

5.3 Sampling Duration

Sampling duration is another important factor in the interpretation of acquired data. Not to be confused with sampling rate, that is, how far apart in time (usually fractions of a second) each uniformly spaced sample is made as described in the preceding section, sampling duration is a measure of how long an observation period is required to fully represent the signal of interest. For a truly stationary, time-invariant signal that persists for an infinitely long period, sampling duration is not critically important, since the signal being analyzed simply does not change over that time. The simple answer is to sample continuously over a long period, thus ensuring that all events over the period are captured. This is the most conservative approach, but it comes at the practical expense of storage space and battery life. Consideration should be made for understanding the underlying signals of interest, and the phenomena that creates the signal in the first place. By way of example, many physical activities that contribute to the generation of EM fields are represented on a number of time scales. Ocean waves are a dominant contributor to EM fields in the near-shore environment. Typical wind-driven wave and swell activities occur between 0.05 and 1 Hz, or conversely, over periods of 1 – 20 seconds or more. However, wave conditions along Oregon's coast are frequently dominated by distant storms, wherein large swells traverse the ocean and crash on Oregon's beaches. Wave conditions can typically occur over a period of hours or days without any substantial change. Thus, continuous measurement would undoubtedly produce very similar results from hour to hour.

The longest period ocean waves measured near Reedsport typically do not exceed 25 seconds. The measurement of a series of such long-period waves over time should capture approximately tens of cycles to ensure a robust statistical data set, although longer periods would be preferred. For example, the capture of ten each waves, nominally 25 seconds in duration, would require 250 seconds of measurement. Increasing the measurement period to 20 or 30 minutes would provide

a robust set of data from which to form a reasonable statistical representation of EM fields generated by ocean wave activity. The Coastal Data Information Program (CDIP) at the Scripps Institution of Oceanography computes ocean wave spectral parameters using 26 to 30 minute data measurement periods². For the typical long-period, 25-second waves observed on the Oregon coast, 30-minute recordings would represent approximately 72 waves, from which statistically significant parameters are derived and reported by CDIP.

Other long period phenomena, including tides and coastal currents, can persist for hours or days. In order to effectively capture changes these variables, measurements should be made to fully encompass at least one full period of each measured phenomenon. Longer sampling periods will serve to reduce the random noise in the data, which will emphasize measured events and minimize the effects of noise on the resulting spectra. It should be noted that in a time-sampled signal, random spectral noise is reduced by the square root of the number of samples acquired. Thus, thus within reason, more samples of a signal provide a better data set than do fewer samples.

² <http://cdip.ucsd.edu/?nav=documents&sub=index&xitem=waves>

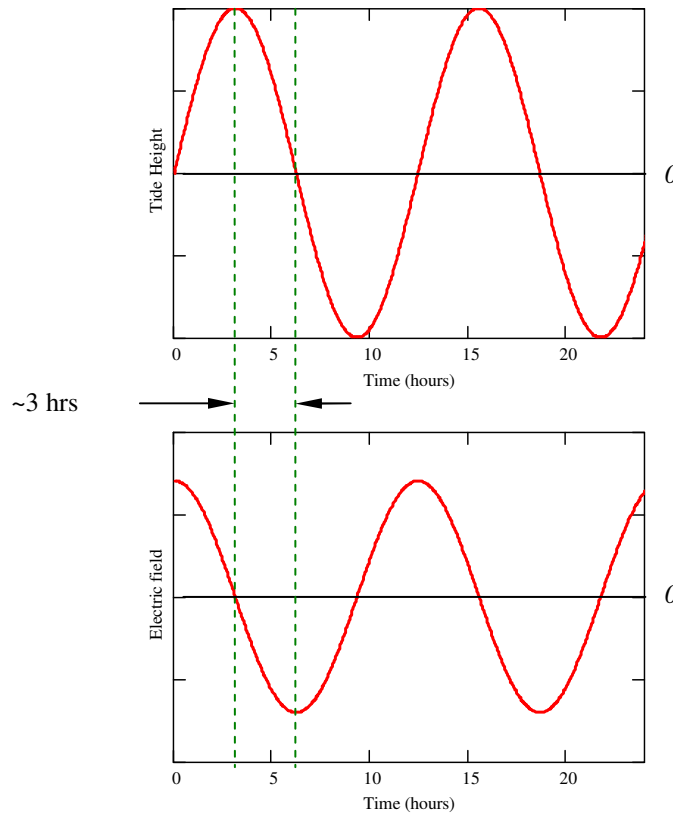


Figure 1 – Typical Tidal Time Series

The highest frequency in the spectral distribution of the tidal flow is approximately 2.3×10^{-5} Hz (e.g., one diurnal, nominal 12-hour period, see Figure 1). Application of the Nyquist–Shannon sampling theorem implies that the sinusoidal form of the tide induced fields can be reconstructed if the sample period is less than $\frac{1}{2 \times 2.3 \times 10^{-5} \text{ Hz}} = 6$ hours (i.e. the Nyquist rate). Therefore, an appropriate period for sampling the sensors is a quarter of the tide period, or approximately every three hours.

Higher frequency phenomena, including man-made sources of EM noise from wave energy equipment will produce much higher frequencies (e.g. 60 Hz and harmonics), and would therefore not be the limiting factor for sampling duration requirements.

5.4 Sampling Periodicity

Over periods of weeks and months, average wave conditions have been shown to change drastically with the seasons, with modest activity in the summer months, and very energetic

conditions in the winter. Figure 2 shows ten-year average wave periods for NDBC Station 46050, located to the west of Newport, Oregon. In the long term, it is recommended that measurements be made over the course of the seasons to ensure that a broad range of minimum and maximum conditions is assessed.

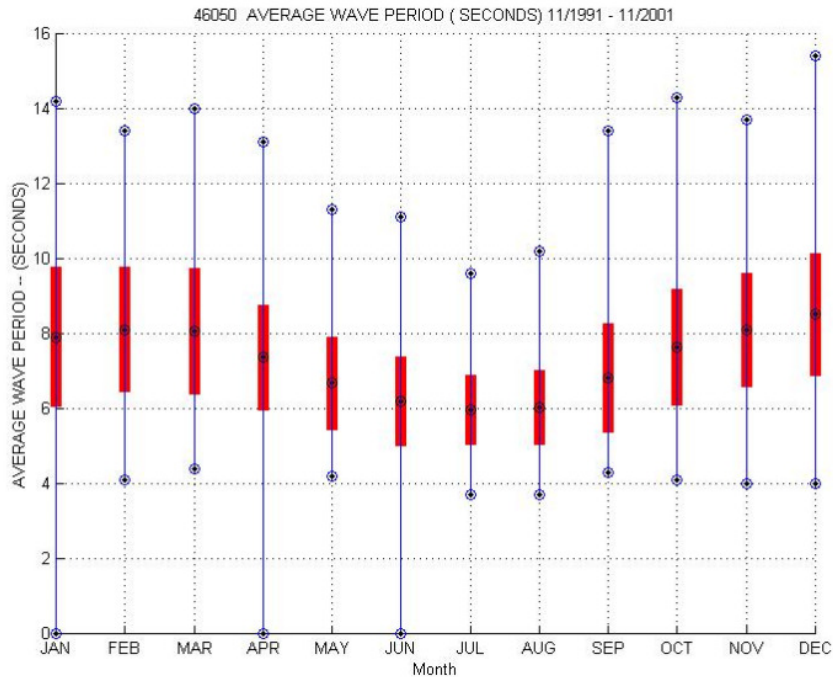


Figure 2 – Average Wave Period, NDBC Station 46050, Nov 1991 to Nov 2001

Initially, it is recommended to sample continuously as much as possible to capture time-cycles that may not yet be fully understood. While some segments of the ambient noise spectra may be well understood (*e.g.* due to wave cycles), others may be less understood, and continuous data sampling, if practical, should be considered to assist in the identification of unknown sources of naturally occurring EM conditions.

As an alternate to the continuous sampling approach, longer-term monitoring could benefit from periodic sampling, such as several minutes each hour or 30-minute periods every three hours. This technique would provide periodic snapshots in time to directly capture higher frequency events, while allowing periodic sampling for the analysis of longer-term events such as tidal cycles and coastal or surface currents. This hybrid approach could be adopted to sample higher frequency content for shorter periods, coupled with periodic gaps in measurement to conserve storage space and battery power without a significant loss in the ability to observe long period

events (hours, days, or weeks). Decimation techniques of the time-sampled data can reduce the processing load for acquired data, while still providing the necessary low-frequency spectral resolution.

5.5 Spectral Processing and Presentation

Most EM data reported in literature is presented in spectrum level, that is to say, with a nominal 1 Hz bandwidth, *e.g.* spectrum levels per “root Hz.” This approach is strongly recommended for EM site characterization results, which provides a standardized bandwidth to enable repeatable comparisons of a given site over time, and to compare results from site to site. DFT processing parameters should be selected to enable nominal 1 Hz bandwidth reporting directly. Alternative processing can be made to enable a much finer bandwidth resolution for long-period phenomena, with optional power summation methods applied to report 1 Hz bandwidths. Finer spectral results would be required for very long period phenomena, including tidal and coastal current observation periods. Above 1 Hz however, spectrum levels should be computed directly. Regardless of processing methodology, all EM data should be presented in the recommended frequency resolution to enable direct comparison of results.

APPENDIX A – ACRONYMS

ASW	anti-submarine warfare
B-field	magnetic field
CA	California
CDIP	Coastal Data Information Program
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research into the Environment
DFT	Discrete Fourier Transform
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
FFT	Fast Fourier Transform
KHz	Kilohertz, thousand cycles per second
Hz	Hertz, cycles per second
MKS	meter-kilogram-second
MMS	Minerals Management Service
NDBC	National Data Buoy Center
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 Institution of Oceanography
UK	United Kingdom
WA	Washington
WEC	Wave Energy Converter



Electromagnetic Field Study

Electromagnetic field measurements: instrumentation configuration.

Prepared by
Michael Slater, Science Applications International Corp.
on behalf of Oregon Wave Energy Trust

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Record of Revisions

Revision	Date	Section and Paragraph	Description of Revision
Original	September 2010	All	Initial Release

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1. EXECUTIVE SUMMARY

This report provides specific calibration methods for EM measurement instrumentation using best engineering practices to achieve valid instrumentation calibration results. Calibration of measurement instrumentation is an essential part of the scientific process; calibration results are critical to the full understanding and correct interpretation of the underlying physical phenomena to be sensed. Specific procedures were developed as a result of completed modeling studies, literature and commercial surveys, and recommended measurement solutions. This report describes important factors, calibration methods, and provides test procedures to conduct the calibrations. Test equipment set up and calibration test procedures to validate proper sensor calibration in a controlled laboratory site (e.g. bench-top) are provided.

2. INTRODUCTION

As described in companion reports, there are large dynamic range considerations for EM data acquisition challenges when considering the span of possible values ranging from a quiescent ambient environment compared with a region adjacent to power generation equipment. The technical approach outlined in this report addresses dynamic range requirements, and includes steps to ensure that the instrument is capable of spanning the recommended dynamic range within the frequency span of interest.

2.1 Purpose

This report was prepared to assimilate results of modeling studies, literature and commercial surveys, and recommended measurement techniques and sensors, and then to apply those results to the development of procedures to calibrate the instruments for use in the ocean environment. Thus, this report describes important factors, calibration methods, and provides test procedures and test forms to conduct the calibrations.

2.2 Report Organization

This report contains six primary sections, and includes supporting appendices. The first sections contain the executive summary and introduction, and provide the project background. The methodology for how the results were prepared is presented in Section 3. Section 4 briefly

discusses calibration theory, while Section 5 provides top-level sensor calibration factors, and identifies the general methods and technical issues associated with obtaining valid calibrations and resulting measurements. A brief summary is made in Section 6. Appendix A contains an acronym list, and Appendix B contains detailed test procedures and data log forms to be used for the calibration and characterization of sensor instrumentation. A bibliography of sources is provided in Appendix C.

3. METHODOLOGY

This report addresses set up and calibration test procedures to validate proper sensor calibration in controlled laboratory conditions (*e.g.* bench-top), and in-situ field observations in a marine environment. Specific procedures are explained in Appendix B.

4. THEORY OF CALIBRATION

Calibration of measurement instrumentation is an essential part of the scientific process, results of which are critical to fully understand and correctly interpret the underlying physical phenomena being observed. Calibration requires deliberate care and attention to detail, which can be enhanced with the use of procedures to ensure repeatable processes are identified to obtain and maintain calibrated results to a high degree of confidence.

In general, calibration of instruments should be done under controlled conditions, most typically in a low-noise environment to ensure high signal-to-noise conditions in the calibration process. It is assumed that test equipment, including meters, scopes, or other tools used during the calibration process have themselves been calibrated to the precision required following standards traceable to the National Institute of Standards and Technology (NIST). For scientific quality measurements, it is generally accepted best practice to ensure calibration of test equipment by a third party, usually an independent calibration laboratory, instead of relying on manufacturer's claims of accuracy.

The general approach to instrument calibration is based on comparison of a measured value against a known value. Using a known signal level as an input factor to a device under test, the output is measured, accounting for signal losses or gains along the way, and compared to the

input signal. Once calibration factors have been determined, they are applied to the raw output signal to ensure that results have been corrected to the degree of precision possible with the calibration test setup.

For the purposes of EM sensor calibration for field assessments, it is not necessary to obtain absolute precision during the calibration process, since field measurements themselves will introduce errors substantially larger than the calibration of a multitude of sensor types. For example, if a measurement scenario involves a range calculation to correct for source level, errors in distance are much more difficult to ascertain underwater compared with the expected degree of error of the electrical sensitivity of the sensor itself. Therefore, it is recommended to attempt to achieve the best possible calibration of EM sensors possible, but there is no strong argument to achieve calibration accuracy better than ~1%. For comparison, a 1% error in a measured value contributes approximately less than 0.1 dB in measurement error of the final result. Measurement accuracy will ultimately be controlled by measurement geometry, range accuracy, propagation anomalies—and not by the basic accuracy or calibration of the instrument itself. In the EMF measurement environment, differences of 3 to 6 dB may be considered significant.

5. CALIBRATION SETUP

As previously described, careful design and setup of the calibration environment is essential to obtaining valid calibration results, and hence, quality field measurements. Basic setup guidance is provided in the following sections for instrumentation calibration to achieve useful calibration results. Where appropriate, additional tests have been identified to ensure instrument performance over the range of expected use.

5.1 Electric Field Instrumentation Calibration

A number of critical technical evaluation factors are required during the electric field instrumentation calibration procedure. These factors apply regardless of instrumentation selected. Thorough characterization of the instrument performance only need be conducted once, until a change is made to the configuration, such as replacement of a component or sensor. Once the characterization has been done, a routine verification of sensor transfer function and

basic functionality should be ideally performed and documented prior to each deployment of the instrument to ensure the best possible integrity in the measured results.

The following requirements, re-stated below from the sensor requirements recommendation phase, are the fundamental specifications essential for a minimally acceptable instrument package, and should be validated during the calibration process.

1. Frequency response: .01 Hz to 1 kHz
2. Dynamic range: ≥ 120 dB
3. Noise floor: ≤ 1 nV/m $\sqrt{\text{Hz}}$ @ 1 Hz

In addition to top-level critical factors, the following technical and functional factors are important determinants during the calibration process.

4. Transfer function: conversion factor from digital counts to sensed voltage
5. Linearity error as a function of input, expressed in dB
6. Maximum Input Level Input signal clipping level expressed in volts or dBV
7. Repeatability error as function of repeated tests, expressed in dB
8. Output Verification – Data Storage
9. In-Situ Observation

Procedures for verification of all factors, including test equipment setup, calibration methods, and data forms are provided in Appendix B.

5.1.1 Test Set-up

This specific procedure has been prepared to calibrate the specific instrumentation recommended, but the procedures and data forms could be modified to suit equivalent instrumentation following the same protocol. The basic philosophy to calibration is to introduce a signal into the front end of the equipment, measure the signal with a calibrated meter, and compare the results with the instrument output. This process is conducted over the desired frequency range of interest of the sensor to determine the calibration factor (transfer function) from sensor input voltage to digital output. In general, the transfer function will be a frequency

dependent “curve”, and may depend on system gain or other configuration changes. Using this same basic test setup, a series of tests are required to characterize and calibrate the system. Appendix B contains the full calibration test procedure.

5.1.2 In-Situ Observation

Once all boards have been fully characterized and calibrated, operational tests should be conducted in relatively benign, real-world marine environment. The purpose of this observation is to ensure that the instrument functions properly and provides reasonable levels for the given environmental conditions. This stage will not have specific results by which to compare, and is intended solely as a functional operational step to gain confidence in the instrument prior to ocean deployment.

5.1.3 In-Situ Source Verification

As an optional step, the electric field instrumentation can be functionally verified in-situ by creating an artificial electric field using a dipole source. Subseption Ltd. offers a commercial electric dipole source instrument capable of generating electric dipoles of up to 10 A-m.¹ Alternatively, a source could be fabricated with marine rated single conductor cable and electrodes, and energized with a suitable signal source capable of driving the source in a low impedance environment, coupled with a calibrated multimeter to measure the amount of current driven through the source. The key element of this step is to estimate the electric field produced by the dipole source using models described in companion reports, and then compare the model to measured results.

It is important to note that this is not a precise method for calibration, and is intended only as a means to verify the functionality of the measurement system. Too many uncertainties exist in the measurement environment to consider this as a precise means of calibration. Sources of error include including source imperfections, range errors, propagation conditions, measured conductivity of the seawater and substrate, and potential movement of seawater that could contaminate the measurements.

¹ <http://www.subseption.com/downloads/sensor-electricfield.pdf>

5.2 Magnetic Field Sensor Calibration

Similar to the electric field sensor calibration, several critical technical factors are required for adequate magnetic sensor calibration, and should be completed for any sensor selected for EM field measurements. Calibration of magnetic field sensors should be made periodically to ensure validity of measurements. At a minimum, sensors should have their basic transfer function verified prior to each deployment, or if changes to measured values vary unexpectedly. Calibration of sensors is straightforward. The basic magnetic calibration sensor factors required for a minimally acceptable instrument package are stated as follows:

1. Frequency response: .01 Hz to 1 kHz
2. Dynamic range: ≥ 120 dB
3. Noise floor: ≤ 1 pT $\sqrt{\text{Hz}}$ @ 1 Hz

In addition to top-level critical factors, the following technical and functional factors are important determinants during the calibration process. Because recommended sensors are analog output, digital recording and storage factors are not identified—but do apply once connected to suitable recording equipment (see related discussion in Section 5.3)

4. Transfer function: analog conversion factor from field input to sensed output.
5. Linearity error as a function of input, expressed in dB
6. Maximum Input Level Input signal clipping level expressed in Tesla
7. Repeatability error as function of repeated tests, expressed in dB
8. In-Situ Observation

5.2.1 Test Set-up

The primary methodology to conduct a magnetic sensor calibration is analogous to that used for many types of sensing equipment: expose a sensor to a known signal, measure the sensor response to that signal, and document the deviations from expected values. For magnetic sensors, there is no means available to simply connect a source to test equipment and measure results directly. However, using knowledge of the inextricable link between magnetic fields and

electrical currents, a straightforward means of calibration can be created using a coil of wire of known dimensions.

The magnitude of a magnetic field inside a solenoid is given in units of Tesla by:

$$B = \mu_0 n I$$

where $\mu_0 = 4\pi \times 10^{-7}$ magnetic permeability of air, expressed in henries/meter

n = number of turns per unit length of coil in units of meters⁻¹

I = electrical current in coil, in amperes

Alternatively,

$$B = \mu_0 \frac{NI}{L}$$

where N = number of turns in coil

L = length of coil in meters

since $n = \frac{N}{L}$

Thus, calibration of magnetic field sensors will require construction of a suitable coil, the dimensions of which will depend on the basic instrument sensitivity and the physical size of the sensor. For the recommended Zonge Engineering ANT-5 product, the instrument has a basic sensitivity of 100mV/nT in the passband. The number of turns for a suitable calibration coil will depend on the maximum field the sensor can sense without overloading the input, the amount of current required in the coil to create that level, and furthermore, the availability of the test equipment to measure the calibration current to the resolution required. A second factor involves the physical length of the sensors. Since solenoid coils are known to have non-linear effects near the ends of the coil, it is important to ensure that the coil is many times longer than the sensor. The Zonge ANT-5 magnetic sensor is approximately 18 inches in length, thus a coil length of 12

feet is recommended (8x sensor length). Based on the availability of a 6.5 digit calibrated voltmeter and the basic instrument sensitivity, between 100 and 300 coils are estimated to provide a reasonable range of values over the frequency range of interest. For purposes of calibration of the prototype instrument a 12 foot coil (12" diameter) was constructed of 144 wraps, or 1" per wrap. Use of precision resistors and voltage divider circuitry may be required to match the dynamic range of a given instrument.

A suitable means to place the sensor in the center of the coil will also need to be arranged. It should be noted that the use of ferromagnetic materials shall be avoided in the construction of the coil to avoid creating magnetic anomalies during calibration. Appendix B contains the full calibration test procedure.

5.2.2 In-Situ Observation

Magnetic fields behave in the ocean in a manner nearly identical to that in the atmosphere due to the relative permeability of air and water. Therefore, in-situ observations of magnetic sensors may be made on dry-land as a purely functional operational test to ensure proper operation of the instrument prior to ocean deployment. However, other than simulated source tests outlined in the next section, no specific tests are prescribed.

5.2.3 In-Situ Source Verification

Once the sensors and data acquisition boards have been characterized and calibrated, operational tests should be completed in the proximity of energized cables with known cable cross-sectional details and electrical current known. Using magnetic field emission models, the magnetic field can be estimated and compared to measured values from the calibrated sensors. Results should be compared. If possible, the cable should use a frequency other than typical power line frequencies or harmonics to ensure that no contamination of the signal is made. For example, a frequency of 55 Hz or 65 Hz would be similar to 60 Hz, but with sufficient frequency separation to avoid confusing the output.

As with the electric field source verification tests, cable simulation tests are not a precise calibration method. Therefore, care should be taken to use cable simulation tests as a means for

equipment verification, and not as a substitute for the coil calibration procedure provided in the appendix.

5.3 Data Acquisition Instrumentation

All sensors will be digitized and recorded using a multi-channel, high-fidelity analog-to-digital converter system with individual single-channel data acquisition boards. The test procedure for this is the same as used for the electric field electronics calibration (Appendix B.)

5.4 Calibration of Auxiliary Sensors

Other sensors important to the data interpretation and reporting of EM signatures should be calibrated prior to use. Specific procedures are not provided herein due to the relative simplicity of the instrument types. Suggestions for calibration verification methods for these sensors are provided below.

Compass: Affix the compass and an independent compass, ideally a calibrated compass or a high quality hand-held compass, to a non-ferrous horizontal turntable. Swing the compass in a 360° circle, record compass output and reference compass output each 10°. Chart results and look for anomalies greater than 1 degree. Investigate sources of errors.

Orientation sensor: Affix the attitude/orientation sensor to lift table, and mount a protractor to the lift table. Raise the sensor in 5° increments, and record sensor output. Compare measured results to protractor. Rotate the sensor by 90 degrees, and repeat. Chart results and investigate any anomalies greater than approximately 2.5 degrees.

Depth sensor: Compare output with calibrated pressure gauge, or affix the pressure sensor to a weighted line of known length. Suspend the sensor on the line in salt-water to a known depth, and compare results with pressure sensor output.

6. CALIBRATION SUMMARY

This report describes the essential elements of EM sensor calibration and in-situ observation to ensure proper operation of the recommended instruments, and verification of the accuracy of the sensor output. Specific recommended procedures are contained with this report to characterize

specific EM instruments, and with sufficient explanations provided to extend these results to EM site assessments using equivalent EM sensors.

APPENDIX A – ACRONYMS

1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
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
fT	femto Tesla
Hz	Hertz, cycles per second
kHz	kilo Hertz
μ T	micro Tesla
μ V	micro volts
mHz	milli Hertz
mT	milli Tesla
mV	milli volts
MKS	meter-kilogram-second
MMS	Minerals Management Service
NIST	National Institute of Standards and Technology
nT	nano Tesla
nV	nano volts
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
pT	pico Tesla
SEMC	Seafloor Electromagnetic Methods Consortium
SI	International System of Units
SIO	Scripps Institute of Oceanography
UK	United Kingdom
US	United States
WA	Washington
WEC	Wave Energy Converter

APPENDIX B – TEST PROCEDURES

Electric Field Sensor Electronics Calibration Procedure

DESCRIPTION: The purpose of this procedure is to perform instrument characterization and calibration of the Zonge Engineering Zeus III data acquisition board for use with the electric field electrodes.

TOOL LIST: The following tools are required to conduct this procedure.

Item	Make/Model Used	Serial Number	CAL Date
Programmable Signal generator, AC/DC			
Precision AC/DC Voltmeter, 6.5 digit*			
Variable DC Power Supply, 6-16 VDC			
Various BNC test leads, adapters, cables			
Electro-static discharge (ESD) work station			
* Must be calibrated			

TEST PROCEDURE:

1. Set up the test equipment as shown in Figure 1.
2. Connect a programmable AC/DC source and precision voltmeter to the instrument as shown.
3. Replace the probes in the circuit by substitution of the probes with a precision termination resistor of the equivalent value as the probes. If possible measure probe resistance in seawater solution at spacing of 1 meter. Expected value is between 2 and 10 ohms. Record equivalent resistance value: _____ ohms

Warning: Excessive exposure to DC current can cause polarization of the electrodes. Use caution when measuring DC resistance of electrodes using multimeters, and to not connect probes to meter for more than a few seconds. For each measurement taken, reverse probes and repeat for same duration.

4. Configure the electronics board to acquire signal data at 0 dB gain, 1 kHz sampling rate.
5. Energize the source with a sine wave at 100 Hz, output voltage of 1 Vrms. Adjust source output to achieve 1 Vrms across termination resistor as measured by the precision voltmeter.
6. Record data for 10 seconds.

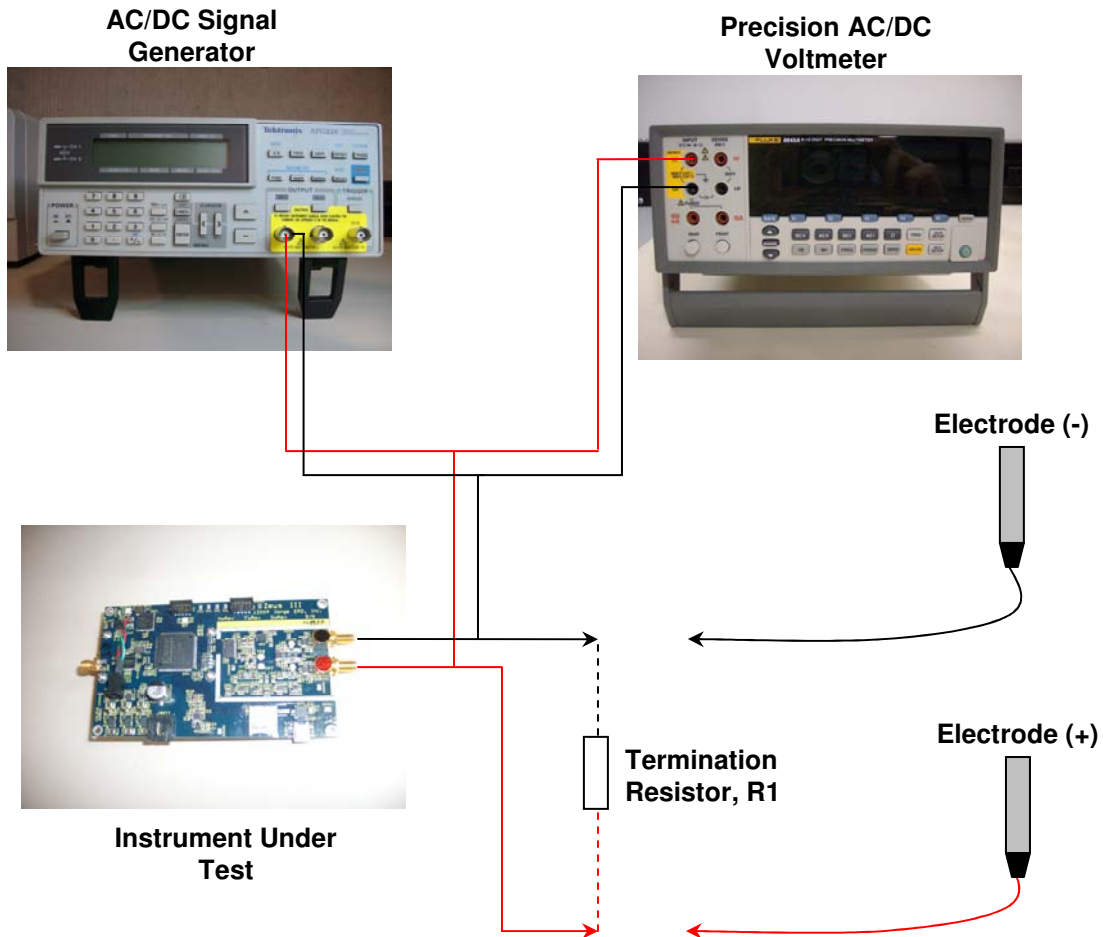


Figure 1 – Test Setup Schematic For Instrument Calibration

7. Stop recording, retrieve data file and compare recorded results to precision voltmeter. Ensure proper operation of recording system and storage of acquired data.
8. Complete Data Form for all values.

Table 1 – Instrument Calibration Data Log

Unit Serial Number: _____ Date: _____
 Termination Resistance (ohms): _____ Calibrated by: _____
 Input Gain (dB): _____
 Sampling Rate (Hz): _____
 Nominal Source Output (Vrms): _____

Frequency ^{Note1, 2} (Hz)	Source Output Level (volts)	Measured Output (counts)	Measured Output (volts)	Transfer Function (dB) ^{Note2}
DC				
.01				
.1				
1				
10				
100				
400				

Note 1: If frequency response is not flat (<.25 dB) between values, log values at intermediate frequencies sufficient to document smooth transfer function shape.

Note 2: Transfer function is computed as: $20 \cdot \text{Log}_{10} \frac{\text{MeasuredOutput}}{\text{SourceOutput}}$

Note 3: for AC values, ensure recording time for each frequency provides time-bandwidth product greater than unity. Example: Record data for >100 seconds at .01 Hz.

9. Compute transfer function at each frequency.
10. Repeat step 8 for all gain values. Reduce source level at each gain stage to obtain nominal 1 Vrms recorded output. Log results in data forms.
11. Subtract gain from transfer function, and chart all transfer function curves.
12. Compare error and identify anomalies in linearity.
13. At gain of 0 dB gain setting, and 100 Hz source frequency, adjust source input level in steps of 0.1 Vrms. Record data for 10 seconds. Increase source level until manufacturer specification for maximum input level is exceeded. Fill in table. Stop procedure when clipping is noted in recorded data, or when output is no longer linear. This is the maximum operating input level.

Table 2 – Linearity Data Log

Frequency ^{Note 1, 2} (Hz)	Source Output Level (volts)	Measured Output (counts)	Measured Output (volts)	Linear? (Y/N)
100	1			
100	1.1			
100	1.2			
100	1.3			
100	1.4			
100	1.5			
100	1.6			
100	1.7			
100	1.8			
100	1.9			
100	2.0			
100	2.1			
100	2.2			

14. Remove board from test set up. Short electrode (+) and electrode (-) leads together. Configure board for 1 kHz sampling rate, and 0 dB gain. Record data for 5 minutes.
15. Compute FFT of resulting spectrum into 1 Hz bandwidth using uniform (boxcar) windowing. Compute RMS average spectra. Chart results. This result is noise floor in per root Hz bandwidth at 0 dB gain setting.
16. Repeat step 14 and using mid-gain and maximum gain settings. Record gain. Chart results.
 - a. Mid – gain setting (dB): _____
 - b. Maximum gain setting (dB): _____
17. Turn power off to board. Reconnect to Figure 1 test setup. Repeat steps 1 through 8. Overlay results to determine repeatability of transfer function. Identify errors in excess of .25 dB.
18. Provide photographs, sketches, of test setup and test environment.
19. Log unusual results or explanations to deviations to the test procedure.
20. End of procedure.

Magnetometer Calibration Procedure

DESCRIPTION: The purpose of this procedure is to perform magnetometer characterization and calibration.

TOOL LIST: The following tools are required to conduct this procedure.

Item	Make/Model Used	Serial Number	CAL Date
Programmable Signal generator, AC/DC			
Precision AC/DC Voltmeter, 6.5 digit*			
Various BNC test leads, adapters, cables			
Calibration coil			
Data acquisition board*			
* Must be calibrated			

TEST PROCEDURE:

1. Set up the test equipment as shown in Figure 2.
2. Connect a programmable AC/DC source and precision voltmeter to the calibration coil as shown.
3. Place a precision resistor in series with the coil. Select the value of the resistor to reflect the desired strength of the magnetic field to be created. Record calibration resistor value: _____ ohms
4. Voltage output may be measured using the precision voltmeter, or by use of a calibrated data acquisition board. If the data acquisition board is used, configure the electronics board to acquire signal data at 0 dB gain, 1 kHz sampling rate.
5. Energize the coil to create a field of approximately 10 nT using a sine wave at 100 Hz. This should produce a nominal output of the ANT-5 sensor of 1 Vrms. Adjust source output to achieve the proper current in the coil to achieve the required field strength.
6. Using data acquisition board configured for 0 dB gain, 1 kHz sampling rate, record data for 10 seconds. Stop recording, retrieve data file and compare recorded results to precision voltmeter. Ensure proper operation of recording system and storage of acquired data.

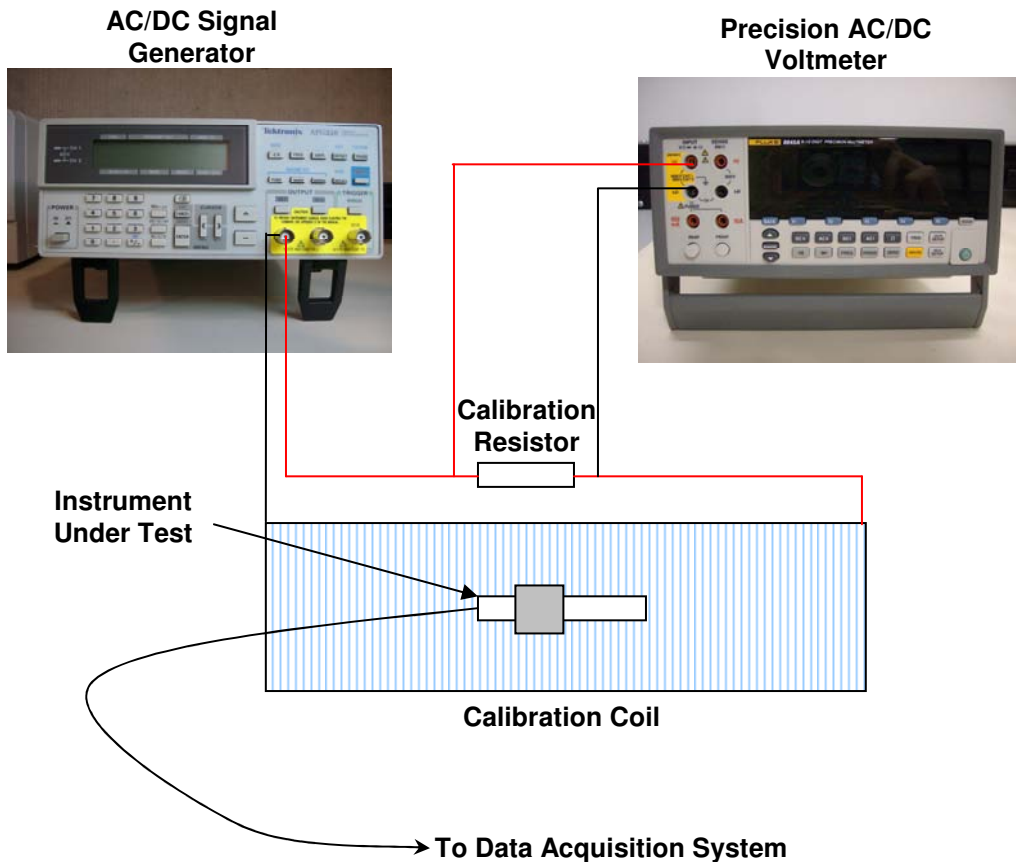


Figure 2 – Test Setup Schematic For Instrument Calibration

7. Complete Data Form for all values.

Table 3 – Magnetometer Calibration Data Log

Unit Serial Number: _____ Date: _____
 Termination Resistance (ohms): _____ Calibrated by: _____
 Input Gain (dB): _____
 Sampling Rate (Hz): _____
 Nominal Source Output (Vrms): _____

Frequency ^{Note1, 2} (Hz)	Source Output Level (volts)	Computed Coil Output (nT)	Measured Output (nT) (100mV/1nT)	Transfer Function (dB) ^{Note2}
.01				
.1				
1				
10				
100				
400				

Note 1: If frequency response is not flat (<.25 dB) between values, log values at intermediate frequencies sufficient to document smooth transfer function shape.

Note 2: Transfer function is computed as: $20 \cdot \text{Log}_{10} \frac{\text{MeasuredOutput}}{\text{ComputedOutput}}$

Note 3: Ensure recording time for each frequency provides time-bandwidth product greater than unity. Example: Record data for >100 seconds at .01 Hz.

8. Compute transfer function at each frequency.
9. Repeat step 8 for all gain values. Reduce source level at each gain stage to obtain nominal 1 Vrms recorded output. Log results in data forms.
10. Subtract gain from transfer function, and chart all transfer function curves.
11. Compare error and identify anomalies in linearity.
12. At gain of 0 dB gain setting, and 100 Hz source frequency, adjust coil output in steps of 1 nT. Record data for 10 seconds. Increase source level until manufacturer specification for maximum input level is exceeded. Fill in table. Stop procedure when clipping is noted in recorded data, or when output is no longer linear. This is the maximum operating input level.

Table 4 – Magnetometer Linearity Data Log

Frequency ^{Note1,} 2 (Hz)	Source Output Level (volts)	Computed Coil Output (nT)	Measured Output (nT) (100mV/1nT)	Linear? (Y/N)
100		10 nT		
100		11 nT		
100		12 nT		
100		13 nT		
100		14 nT		
100		15 nT		
100		16 nT		
100		17 nT		
100		18 nT		
100		19 nT		
100		20 nT		
100		21 nT		
100		22 nT		

13. Move electrode and data acquisition board to electrically quiet location to minimize effect of low-frequency magnetic fields. Outdoors away from buildings, power lines, and other influences as much as possible. Record data for 5 minutes.
14. Compute FFT of resulting spectrum into 1 Hz bandwidth using uniform (boxcar) windowing. Compute RMS average spectra. Chart results. This result is noise floor in per root Hz bandwidth at 0 dB gain setting.
15. Repeat step 14 and using mid-gain and maximum gain settings. Record gain. Chart results.
 - a. Mid – gain setting (dB): _____ Ensure that data is not clipped, e.g. < 2 volt output.
 - b. Maximum gain setting (dB): _____ Ensure that data is not clipped, e.g. < 2 volt output.
16. Turn power off to board. Reconnect to Figure 1 test setup. Repeat steps 1 through 8. Overlay results to determine repeatability of transfer function. Identify errors in excess of .25 dB.
17. Provide photographs, sketches, of test setup and test environment.
18. Log unusual results or explanations to deviations to the test procedure.
19. End of procedure.

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Electromagnetic Field Study

The prediction of electromagnetic fields generated by submarine power cables.

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Record of Revisions

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

This report describes the emissive characteristics of electromagnetic (EM) fields from submerged power cables in the marine environment. This study was commissioned with the goal of analyzing and synthesizing the expected EM field levels near energized power cables and wave energy conversion devices in the coastal environment.

The basic physical theory was derived from fundamental laws of electrical current and magnetism. Then, the boundary conditions were applied to determine the local EM field effects from energized cables that were representative of the subsea cable industry. First, a model was derived to predict the electromagnetic fields produced by DC monopole and bipole power cables. Next, a transmission line model was developed to quickly and accurately determine the electromagnetic fields surrounding an AC cable as a function of distance from the cable using the cable construction, the power frequency, and phase current. The AC model was developed for both single phase and trefoil three phase cables, with either individual phase shields, or with a single shield that encompasses all three phases. The model was verified using Finite Element Analysis. The model successfully predicted the fields measured and recorded in a baseline assessment of EMF for an offshore wind farm [1]. Therefore, a transmission line model will reasonably predict the fields generated around specific cable designs being considered for subsea power transmission.

Finally, this work has shown that accurate measurements of the fields adjacent to power cables requires knowledge of the location of the sensors relative to the cable as the fields decrease rapidly with distance from the cables.

2. INTRODUCTION

2.1 Purpose

This report estimates the localized electromagnetic field (EMF) strength values created by energized submarine power cables. The purpose of this report is to define analytic methods for predicting the electric and magnetic fields produced by DC cables (single and bipole) and AC cables (single and three phase), and then to predict the effect of cable burial on these fields. The focus of this report is to identify the expected range of values of electromagnetic signals created by submerged power cables in the near shore marine environment, and compare the expected results to those found in other literature on the subject.

2.2 Background

The Oregon Wave Energy Trust (OWET) was formed in 2007 to coordinate the development of power generation from offshore wave energy with the objective of generating 500 MW along the Oregon coast by 2025. The generated power will be transmitted to shore using subsea power cables to enable local or national distribution. The transmission of high power along such cables will induce both electric and magnetic fields into the sea, which may disturb marine species such as sharks and rays, which are sensitive to electromagnetic fields. Together with estimated or measured ambient EMF noise conditions, predictive results from this report can be used to estimate the environmental effects of placing such EM fields in the near shore environment.

2.3 Report Organization

This report has ten topical sections and five supporting appendices. The first three sections contain the executive summary, the introduction, which describes the project motivation and background, and a survey of prior work on this subject. Section 4 describes the methodology of analysis. The fundamental physical theories outlined in Section 5 serve as the basis for understanding the subsequent modeling analysis. Sections 6 (DC) and 7 (AC) present the development of models for various cable types. The use of these models applied to the special condition of buried cable is given in Section 8. Section 9 compares the modeled results to actual measurements made of a submarine cable crossing in the UK. Overall conclusions are presented in Section 10. Appendix A contains a glossary of mathematical symbols used in this report,

Appendix B provides an acronym list. Appendix C describes the physical phenomenon of skin depth. Physical details of the cables described in Section 9 are shown in Appendix D. Appendix E contains the bibliography of references.

3. PRIOR ART

Collaborative Offshore Wind Research into the Environment (COWRIE), Ltd is a registered charity in the UK governed by a Board of Directors drawn from The Crown Estate, the Department for Energy and Climate Change (DECC), and the British Wind Energy Association (BWEA). The purpose of the organization is to advance and improve the understanding and knowledge of potential environmental impacts of offshore wind farm development in UK waters.

COWRIE commissioned a study of the electromagnetic fields generated by submarine power cables, which was undertaken by the Centre for Marine and Coastal Studies (CMACS, 2003). This work used Finite Element Analysis (FEA) to predict the electromagnetic fields around a cable, which required little understanding of the underlying physical process, and generation of a new model for each cable, or environment, to be analyzed. Although attractive field plots can be produced with commercially available FEA software, this approach can be cumbersome and perhaps unnecessary, as analytic solutions are possible. Further, the electric field in the seawater, or seabed, was not determined directly from the FEA analysis, but derived from the predicted magnetic field. However, the equations presented by CMACS for calculating the electric field in this way appear to be incorrect. The COWRIE report states that the electric and magnetic fields are related by the following expression:

$$E = 2\pi f B$$

Where:

E = electric field (V/m)

f = power frequency (Hz)

B = magnetic field (tesla)

The dimensions, or units, of this equation do not balance, unless the E field has units of V/m^2 rather than V/m , resulting in what appears to be an anomaly in the mathematical development. Otherwise, the report is a good starting point on the subject and is the original work from which the current undertaking was initiated.

4. METHODOLOGY

Two primary cable types were modeled using basic electromagnetic theories: direct current (DC) and alternating current (AC) cables. First, a single conductor cable was analyzed, from which other conditions were derived. Next, two distinct DC cable models were considered. The first was a single DC cable with a seawater return path of the type commonly used in the telecommunications industry. The second was a two-conductor or bi-pole cable, with positive voltage on one conductor, and a return path on the other. Three types of AC cable were modeled. The first was a simple two-conductor cable using a single phase of alternating current. Two variants of a three conductor (trefoil) cable were analyzed, one with individually shielded conductors, and the other with an overall shield surrounding the trefoil cable bundle.

While these models may not cover every possible combination of cable type encountered, they do demonstrate the capability to create analytical models that predict the range of magnitude of EMF values of an energized cable. Further, they provide a basic toolset from which additional variations could be created, subject to the imagination of cable designers. For each development, assumptions are stated, and mathematical expressions provided as the primary technical descriptor of the analyses.

Readers are reminded that the modeled predictions for this work assume a simplified model, including the relatively homogeneity of the water and substrate conditions. Research into EMF generation and propagation has demonstrated that a variety of factors, such as topographic, bathymetric, and geologic conditions, contribute to the natural generation and propagation of EM fields, particularly for the near-shore environment. However, these conditions are not mathematically described herein. Thus, caution is urged when applying these predictive results to a specific environment.

5. BASIC THEORY

Two fundamental relationships describe the magnetic and electric fields generated by an electrical conductor in a given medium. To simplify the analysis, it is assumed that the relative permeability (μ_r) and relative permittivity (ϵ_r) of the media are constant. The magnetic field (B) as a function of distance (r) from the center of a conductor carrying a current I , can be derived from Ampere's Law:¹

$$B(r) = \frac{I\mu_0\mu_r}{2\pi r} \quad 1)$$

Where I = current in amps
 μ_0 = permeability of free space ($4\pi \times 10^{-7}$ N/A²)
 μ_r = relative permeability of medium (~1 for non ferromagnetic materials)

Similarly, the electric field surrounding a line charge can be derived from Gauss's Law:^{2,3}

$$E(r) = \frac{q}{2\pi r\epsilon_0\epsilon_r} \quad 2)$$

Where q = charge/unit length (coulomb/m)
 ϵ_0 = permittivity of free space (8.66×10^{-12} F/m)
 ϵ_r = relative permittivity of material surrounding line charge (1 for air)

¹ <http://farside.ph.utexas.edu/teaching/316/lectures/node75.html>

² http://en.wikipedia.org/wiki/Gauss's_law

³ http://35.9.69.219/home/modules/pdf_modules/m133.pdf

6. DIRECT CURRENT CABLES

This section describes simple analytic models for determining the magnitude of the electric and magnetic fields produced by single and bipole DC submarine cables.

6.1 Single Conductor DC Cable

Consider an unshielded DC conductor insulated with polyethylene, carrying a current I amps at a voltage V_C volts, with the cable immersed in seawater (see Figure 1).

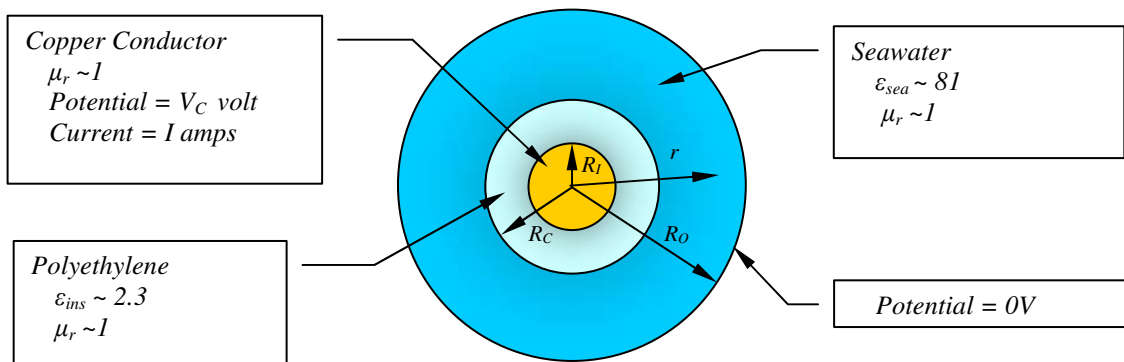


Figure 1 – Model for a Single DC Conductor in the Sea

The highest electric fields can be expected to reside within the dielectric with the lowest permittivity, which in all practical cases will be the cable insulation. To determine the electric field within the sea, the potential at the interface between the cable insulation and seawater must first be determined using the classical capacitor divider equation.

$$V_{SEA} = \frac{V_C C_{INS}}{C_{INS} + C_{SEA}} \quad 3)$$

Where

C_{INS} = Capacitance of the cable insulation (F/m)

C_{SEA} = Capacitance of the sea (F/m)

These capacitances are determined using the well-known equations for coaxial conductors.

$$C_{INS} = \frac{2\pi\epsilon_0\epsilon_{INS}}{\ln\left(\frac{R_C}{R_I}\right)} \quad \text{and} \quad C_{SEA} = \frac{2\pi\epsilon_0\epsilon_{SEA}}{\ln\left(\frac{R_O}{R_C}\right)}$$

Where ϵ_0 = permittivity of free space ($4\pi \times 10^{-7}$ N/A²)
 R_C , R_I , R_O , ϵ_{INS} , and ϵ_{SEA} are as defined in **Figure 1** ^{4,5}

The electric fields within the sea and cable insulation are coaxial fields, which are given by equations 4) and 5) respectively:

$$E_{SEA}(r) = \frac{V_{SEA}}{r \ln\left(\frac{R_O}{R_C}\right)} \quad \text{where } r > R_C \quad 4)$$

$$E_{INS}(r) = \frac{V_C}{r \ln\left(\frac{R_C}{R_O}\right)} \quad \text{where } R_I < r < R_C \quad 5)$$

The maximum magnetic field around the cable is given by:

$$B(r) = \frac{I\mu_0\mu_r}{2\pi r} + B_{earth} \quad 6)$$

Where μ_r = permeability of medium (= 1 for seawater and polymers)
 B_{earth} = 50 μ T (typically between 30 and 60 μ T) ⁶

The resulting electric and magnetic fields for an arbitrary cable design detailed in Table 1, have been calculated for a normalized line current of 1 A and potential of 1 V, and the results are shown in Figure 2 and Figure 3.

⁴ http://www.kayelaby.npl.co.uk/general_physics/2_6/2_6_5.html

⁵ http://www.kayelaby.npl.co.uk/general_physics/2_6/2_6_6.html

⁶ http://en.wikipedia.org/wiki/Earth's_magnetic_field#Field_characteristics

Table 1 – Properties of an Arbitrary Unshielded DC Cable

Parameter	Value
Conductor diameter (mm)	50
Insulation Diameter (mm)	100
Permittivity of insulation	2.3
Permittivity of sea	81
Max DC Current (A)	1000
Conductor resistance (ohm)	1

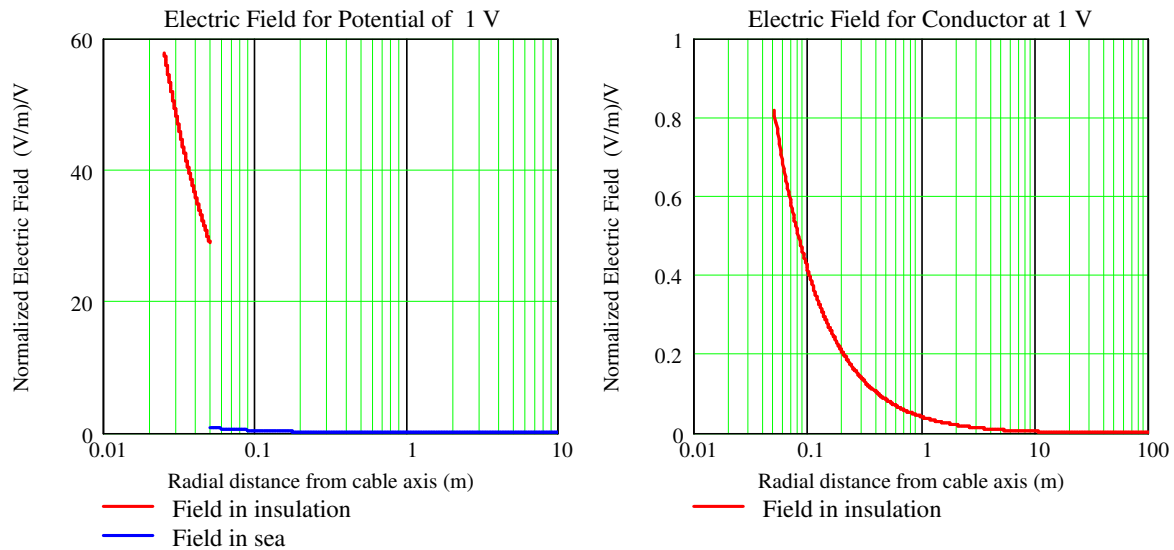


Figure 2 – Normalized Electric Field Generated by Potential of 1V on Conductor

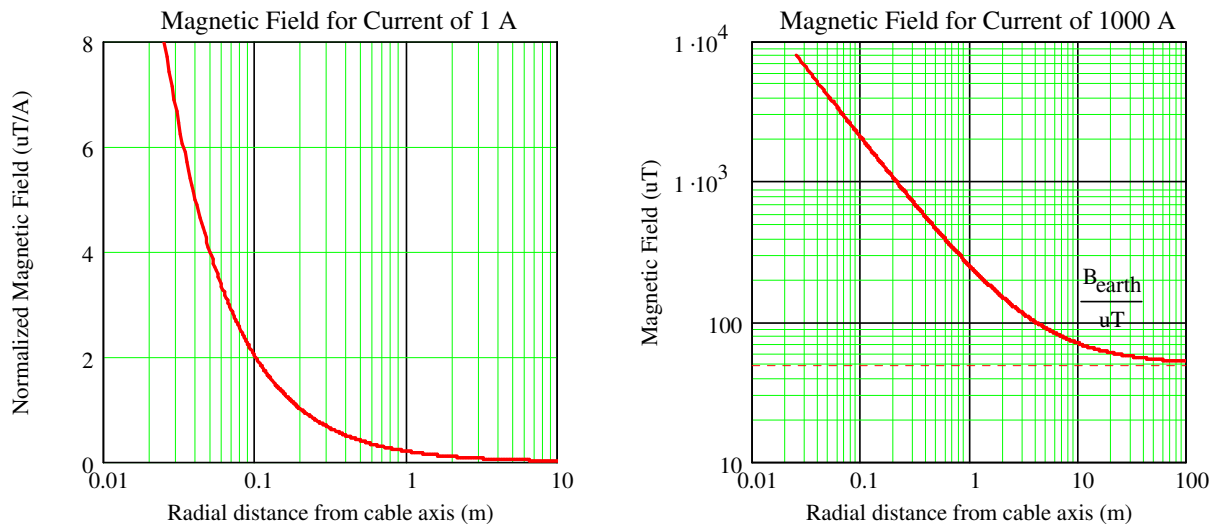


Figure 3 – Normalized B Field and Absolute B Field for a Current of 1000 A

If a perfectly grounded metallic shield is applied over the insulation, then the electric field will be contained solely within the insulation. However, the magnetic field in the sea will not be attenuated by the shield, as the magnetic field is time invariant (i.e. DC conditions).

If this magnetic field is induced in *flowing* seawater, then an electric field will be induced in the sea by magneto-hydrodynamic (MHD) generation (Figure 4), and the maximum electric field is given by:

$$E_{MHD}(r) = B(r)v$$

Where

v = water flow velocity (m/s)

$B(r)$ = peak magnetic field at a distance r from cable (T)

Substitution into equation 1) gives:

$$E_{MHD}(r) = B(r)v = \frac{I\mu_0\mu_r}{2\pi r}v \quad 7)$$

This MHD induced electric field is additive to the electric field generated by seawater moving through the earth's magnetic field, therefore the maximum electric field is given by:

$$E_{\max}(r) = (B(r) + B_{earth})v = \left(\frac{I\mu_0\mu_r}{2\pi r} + B_{earth} \right)v \quad 8)$$

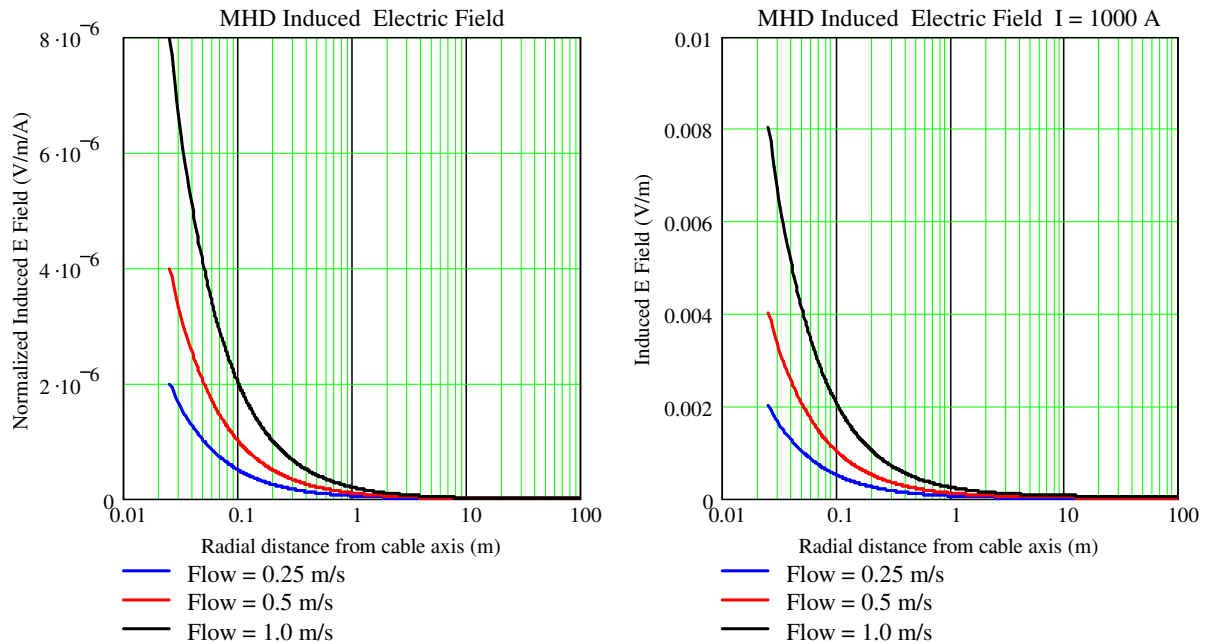


Figure 4 – MHD Electric Fields Generated in Sea by Seawater Flow Across Cable

6.2 Single DC Conductor, Sea-Earth Return

If a single DC power cable is adopted, then the circuit must be completed via the sea using an anode and cathode. High electric fields can occur in the sea close to an electrode from current convergence at the electrode and the electrode resistance. Consider the power transmission system as seen in Figure 5.

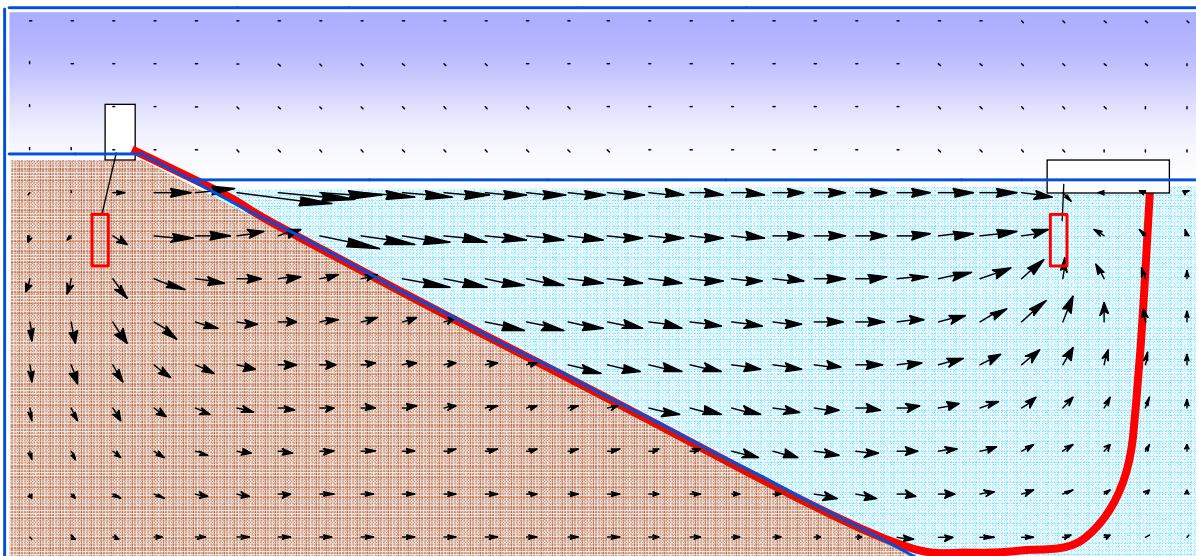


Figure 5 – Schematic of Single Cable DC Power Transmission

The anode of the system is usually located on land and consists of multiple electrodes embedded in coke breeze to give a low electrode resistance. If the cathode is a cylinder, then the resistance of the electrode to the sea (also referred to as the electrode resistance) can be calculated as follows:

If only one end of the cylindrical cathode is exposed to the sea, then the electrode resistance (R_{cath}) is given by the following surface integral:

$$\begin{aligned}
 R_{cath} &= \int_{r_0}^{r_1} \frac{\rho}{2\pi r l + \pi r^2} dr = \frac{\rho}{2\pi l} [\ln(r) - \ln(l+r)]_{r_0}^{r_1} \\
 &= \frac{\rho}{2\pi l} \ln\left(\frac{r_1(2l+r_0)}{r_0(2l+r_1)}\right)
 \end{aligned} \tag{9)$$

where:

- l = length of electrode (m)
- r_0 = radius of electrode (m)
- ρ = resistivity of seawater (~ 0.25 Ω .m)
- r_1 = distance from electrode axis (m)

If $r_1 \gg l$ equation 5) reduces to:

$$R_{cath} = \frac{\rho}{2\pi l} \left[\ln\left(\frac{2l+r_0}{r_0}\right) \right] = \frac{\rho}{2\pi l} \left[\ln\left(\frac{4l}{d} + 1\right) \right] \tag{10)$$

Where

- d = diameter of electrode (m)

It should be noted that if the distance between the two remote electrodes is greater than 100 times the radius or length of the electrodes (actual case for a sea ground return), then the resistance of the electrolyte (*i.e.* the sea resistance) is very small and may be neglected.

The electrode resistance as a function of length is shown in Figure 6 for various electrode diameters and a typical seawater resistivity of 0.25 ohm·m. From this graph it is seen that if the cathode diameter is 6 inches, then it must be ≥ 1.5 m long to give a resistance to the sea of ≤ 0.1 ohms

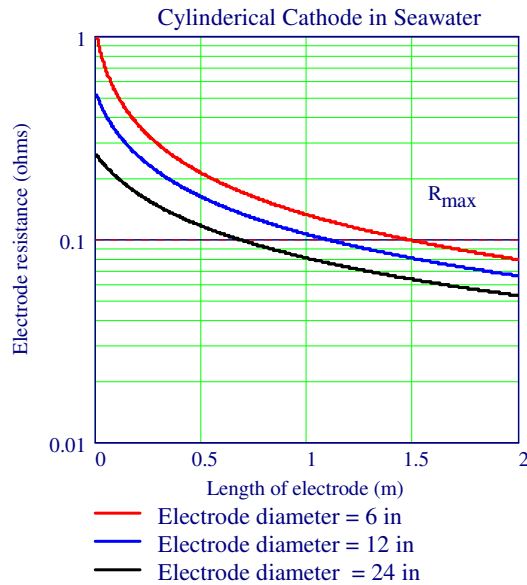


Figure 6 – Cathode Resistance vs. Length of Cylindrical Electrode

The potential, and electric field as a function of distance can now be calculated and the results for a 0.1 m diameter cathode that is 1 m long, are plotted in Figure 7.

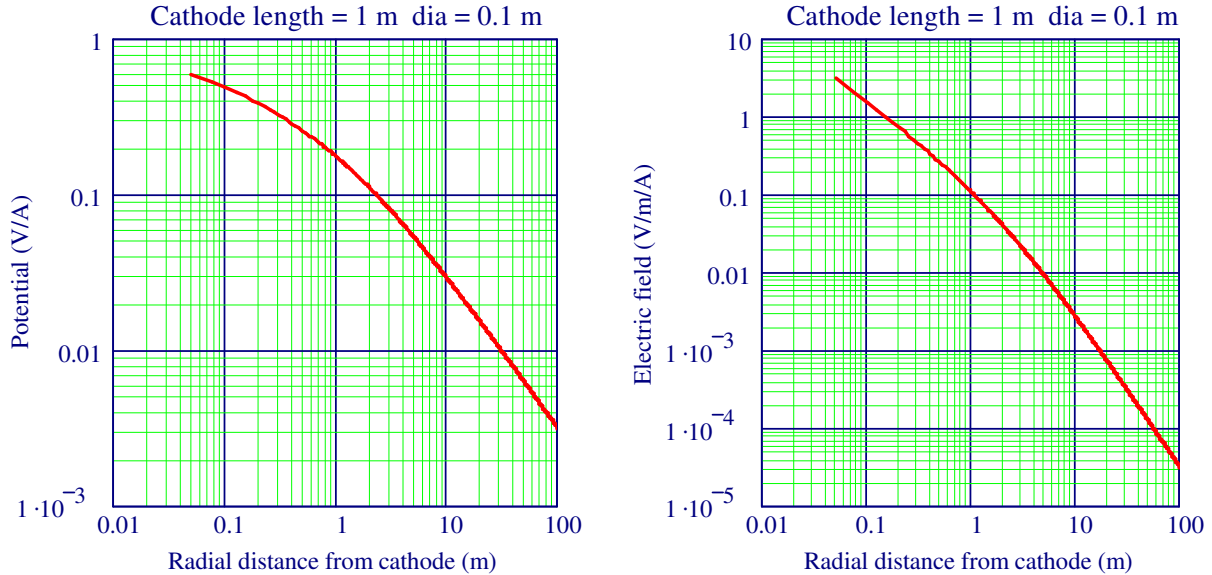


Figure 7 – Potential and Electric Field vs. Distance from Sea Cathode Normalized for 1 A Current

6.3 DC Bipole Cable

The preferred method for subsea DC power transmission is to use a ‘bipole’ cable consisting of two cables; one carrying positive current and the other negative (Figure 8). This has the

advantage that high electric fields in the sea associated with sea electrodes are avoided, and a degree of electric and magnetic field cancellation results.

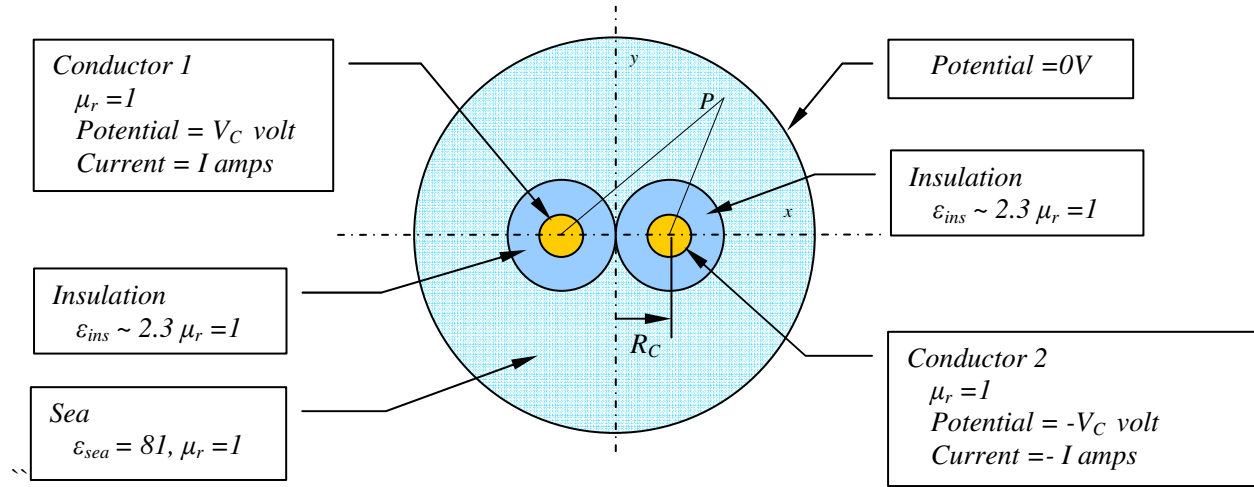


Figure 8 – Unshielded Bipole Cable

The fields surrounding the bipole cable can be determined by superposition of the fields generated by two single cables as follows. Consider the point P in Figure 9, which shows the E and B fields from each individual cable. These vectors can be resolved into the x and y planes and the resultant E and B fields derived as a function of the radius R and angle θ around the cable. To enable the calculations, the distances R_1 , R_2 , angles α , and β were determined as functions of r and θ by simple trigonometry. It can be shown that:

$$R_1(\theta, r) = \sqrt{R_C^2 + r^2 - 2R_C r \cos(\theta)}$$

$$R_2(\theta, r) = \sqrt{R_C^2 + r^2 + 2R_C r \cos(\theta)}$$

$$\alpha(\theta, r) = \arcsin \left[\frac{r \sin(\theta)}{R_2(\theta, r)} \right]$$

$$\beta(\theta, r) = \pi - \arcsin \left[\frac{r \sin(\theta)}{R_1(\theta, r)} \right]$$

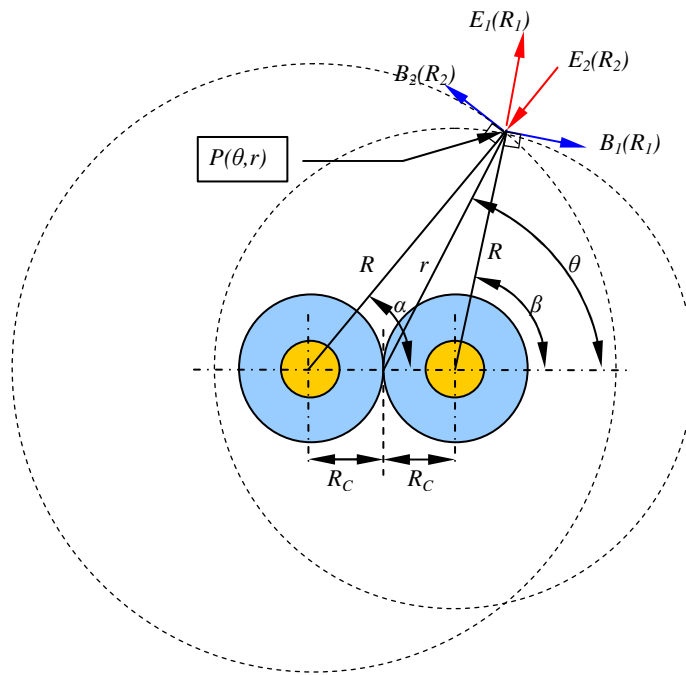


Figure 9 – Components of Electric and Magnetic Fields

From Figure 9, it is apparent that the maximum electric and magnetic fields in the sea occur when $\theta = 0$ or 180° , and the minimum fields occur when $\theta = 90$ and 270° where the fields tend to cancel. The magnetic and electric fields surrounding the cable have been calculated as a function of angle around the bipole, for various radii from the cable axis (Figure 10).

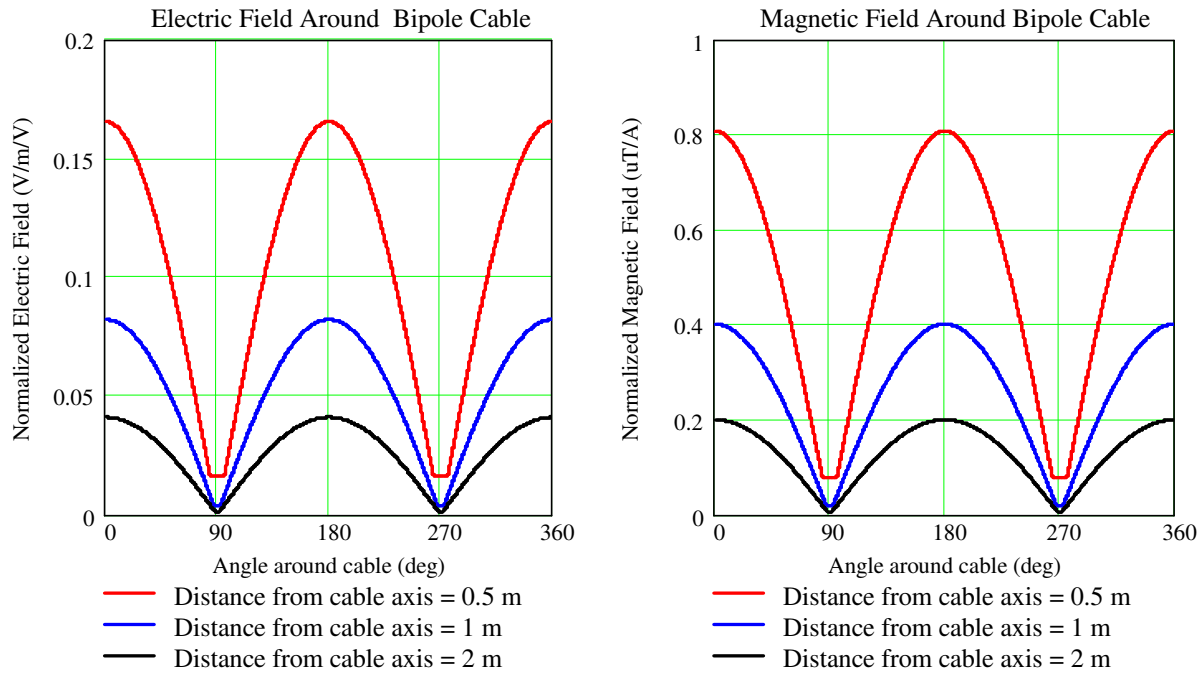


Figure 10 – Normalized E and B Fields around an Ideal Unshielded DC Bipole Cable

Therefore, the *peak* electric field as a function of distance from the cable axis (r) is given by:

$$E_{SEA}(r) = \frac{2V_C C_{INS}}{r \ln\left(\frac{R_O}{R_C}\right) \cdot (C_{INS} + C_{SEA})} \quad \text{where } r > R_C \quad (11)$$

Similarly, the maximum B field can be determined using:

$$B_{SEA}(r) = \frac{I \mu_0 \mu_r}{\pi \cdot r} \quad (12)$$

The normalized electric and magnetic fields as a function of distance from the cable axis are shown in Figure 11, together with the plots for a single DC cable, which demonstrates the degree of field cancellation.

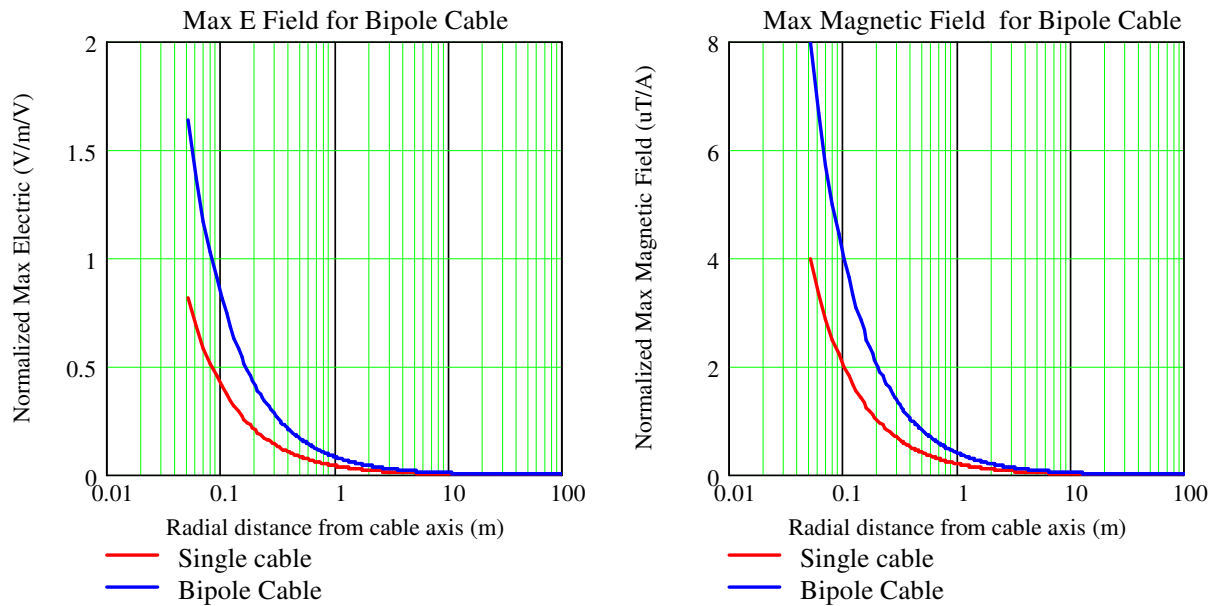
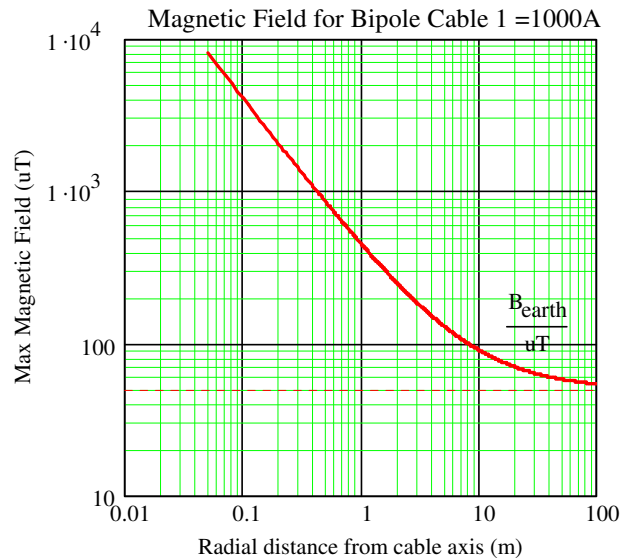


Figure 11 – Maximum E and B Fields vs. Distance from Unshielded DC Bipole Cable

The maximum magnetic field around a bipole DC cable is given by:

$$B_{SEA}(r) = \frac{I\mu_0\mu_r}{\pi.r} + B_{earth} \quad 13)$$

The maximum magnetic field for a current of 1000 amps is shown in Figure 12.



**Figure 12 – Maximum Absolute B Field vs. Distance from an Unshielded Bipole Cable
 I = 1000 A. Earth’s Field assumed to be 50 μT**

7. ALTERNATING CURRENT CABLES

The preceding section considered the electromagnetic fields induced in seawater from DC power cables. However, the DC model is not applicable to AC cables, as the impedance of the seawater “return path” must now be considered as alternating fields are propagating into the sea. Further, with a DC power cable in stagnant water, a perfect metallic shield reduces the electric field in the sea to zero, but this is not the case with an AC cable, as there is a time variant (sinusoidal) magnetic field in the seawater, which produces an *induced* electric field in the sea.

7.1 Transmission Line Model

The magnetic and electric fields surrounding an AC power cable can be calculated directly using the concept of a radial transmission line model. Such a transmission line comprises of concentric shells that are thin compared to both the conductor radius and the skin depth (see Appendix C) of a plane wave propagating into the sea (Figure 13).

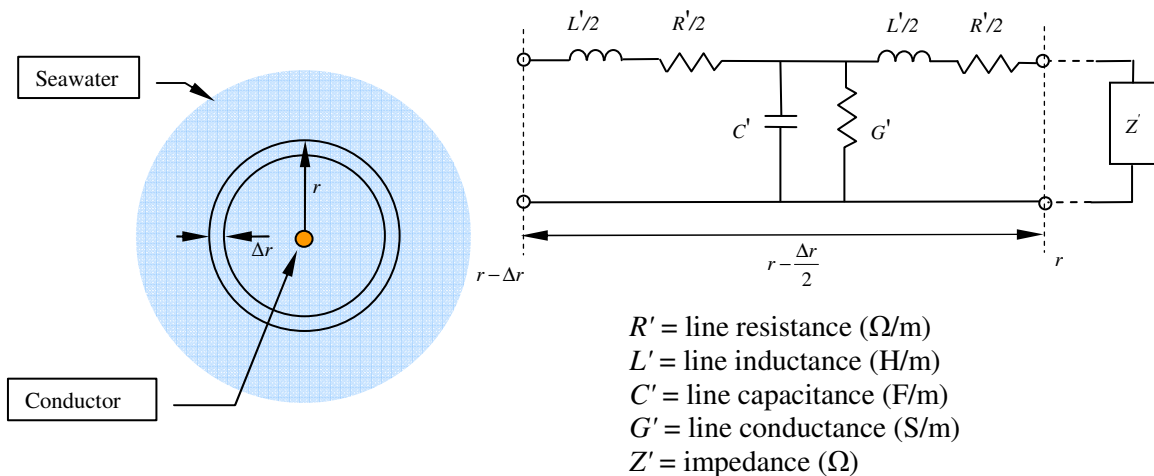


Figure 13 – Radial Transmission Line Concept and Equivalent Circuit

The propagation across *each* shell is defined by near constant parameters at a specific radius. These parameters are the resistance, inductance, conductance, and capacitance of the shell between its inner and outer radii and are used to define the distributed transmission line as seen in Figure 13.

To simplify and provide a realistic boundary condition, the maximum radius for the calculation is selected as 10 times the skin depth over which a plane wave will be attenuated by 10 nepers (-86 dB)

With a 60 Hz power frequency, the skin depth is approximately 32 m in seawater, so the termination impedance can be equated to zero (*i.e.* short circuit) at a radius of approximately 320 m with an error of < 0.005 %.

The input impedance of the line at a specific radius, which relates the voltage (*i.e.* the electric field) to the current (*i.e.* the magnetic field), can now be calculated. If a current of 1 Amp is applied at the line termination, then the current (I_0) required at the input of the line (*i.e.* at the cable surface) to generate the 1 Amp at the termination can be determined. The current at this radius per amp applied at the cable surface, is given by $1/I_0$. The current at the cable surface is the return current in the effective outer conductor of the cable (*i.e.* the sea), and is the same as the current in the inner conductor of the cable. In the practical case, the conductor will be insulated and there may be an external metallic shield or armor wires. In this case, the model comprises of transmission lines in tandem and the line parameters change accordingly.

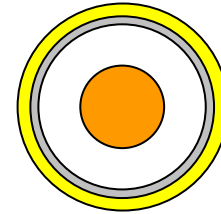
The required calculations are solved by a Visual Basic macro, previously developed by ENS Consulting, for location of submarine telecommunication cables with a 25 Hz toning signal. The cable construction, power frequency, and distances from the cable are entered into the worksheet, then the program calculates and plots the electric and magnetic fields as a function of radial distance from the cable axis.

7.2 Single Phase AC Cable

Consider an arbitrary single phase shielded cable with the properties detailed in Table 2.

Table 2 – Arbitrary Single Phase Shielded AC Cable

Parameter	Value
Wall thickness of Shield (cm)	0.2
Shield Permeability (steel)	300
Resistivity of shield ($\mu\text{ohm.cm}$)	18
Permittivity of outer jacket	2.3
Wall thickness of outer jacket (cm)	0.5
Conductivity of outer jacket (mho/cm)	1×10^{-12}
Permittivity of sea	81
Conductivity of sea (mho/cm)	0.04
Cable diameter (cm)	11.4



The calculated peak electric and magnetic fields as a function of distance from the cable axis and normalized for a current of 1 amp, are seen in Figure 14.

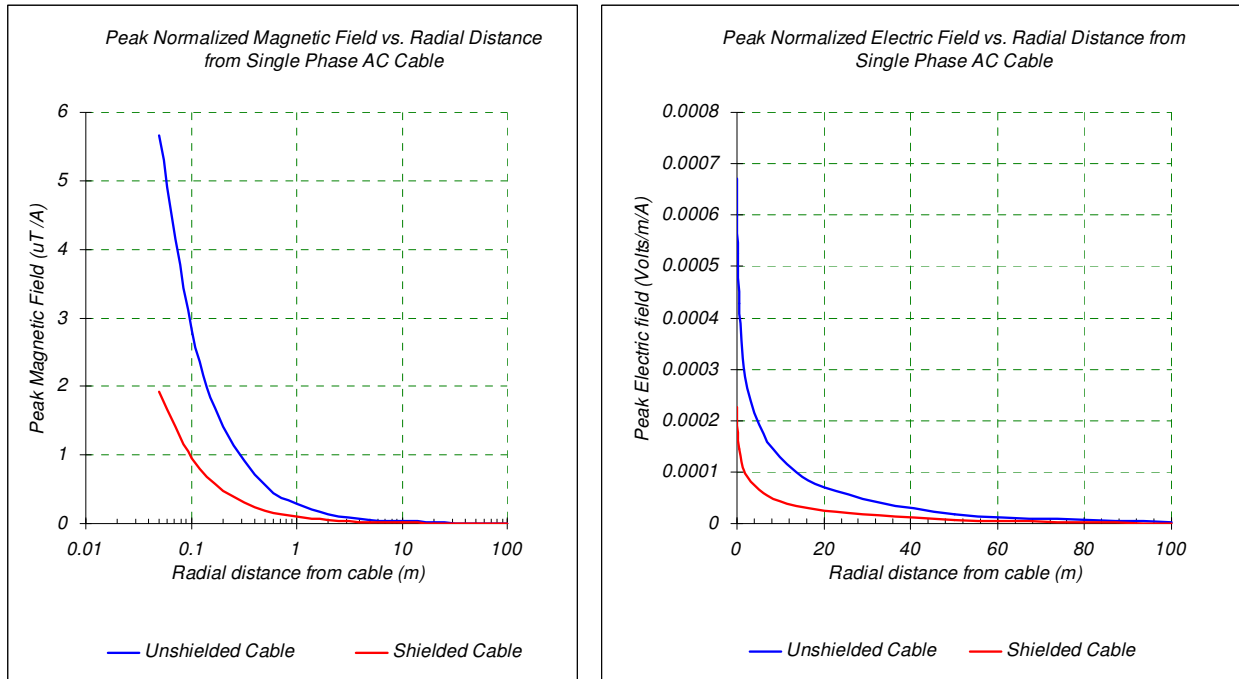
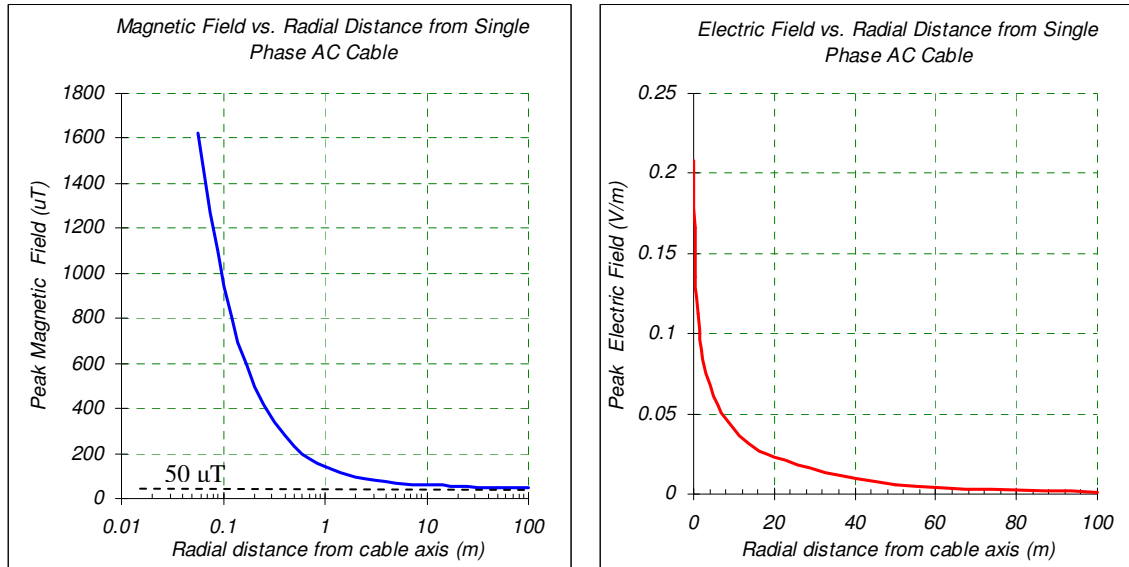


Figure 14 – Normalized Peak E and B Fields around an Arbitrary Single Phase AC cable Frequency = 60 Hz

From Figure 14, it is observed that the shield reduces both the electric and magnetic fields, but the electric field in the sea does not reduce to zero, as occurs with a shielded DC cable, as this electric field is induced by the magnetic field.

The magnetic field is additive to the earth’s magnetic field which results in magnetic field “ripple” at the power frequency over the background magnetic field. The peak electric and

magnetic fields as a function of distance from a single-phase cable carrying 1000 A (RMS) at 60 Hz are shown in Figure 15.



**Figure 15 – Peak E and B Fields around an Arbitrary Single Phase AC Cable
 Current = 1000 A. Frequency = 60 Hz. Earth’s Field = 50 µT (assumed)**

To validate the transmission line model, a Finite Element Analysis (FEA) of the shielded cable detailed above was undertaken using Ansoft Maxwell 2D™. The peak electric and magnetic fields predicted by the transmission line model and FEA, as a function of distance from the cable axis, are summarized in Table 3. Good agreement between the two methods is observed, but the FEA model tends to underestimate the electric field and overestimate the magnetic field, if the outer boundary is positioned too close to the cable.

**Table 3 – Comparison between FEA and Transmission Line Model Single Phase Cable
 Current= 1 A (RMS) Frequency = 60 Hz**

Distance from cable axis (m)	Peak B field by FEA (µT)	Peak B field from X-line Model (µT)	Peak E field by FEA (V/m)	Peak E field from X-line Model (V/m)
0.1	0.9460	0.95663	0.0001908	0.000202
0.2	0.4800	0.47831	0.0001658	0.000178
0.5	0.1910	0.19128	0.0001325	0.000145
1	0.0966	0.09559	0.0001077	0.000121
2	0.0482	0.04769	0.0000825	0.000096
5	0.0192	0.01881	0.0000495	0.000065
10	0.0096	0.00900	0.0000247	0.000043

The electric and magnetic field at a specific distance from the cable is a function of the power frequency, and these characteristics are shown in Figure 16 for various distances from the cable.

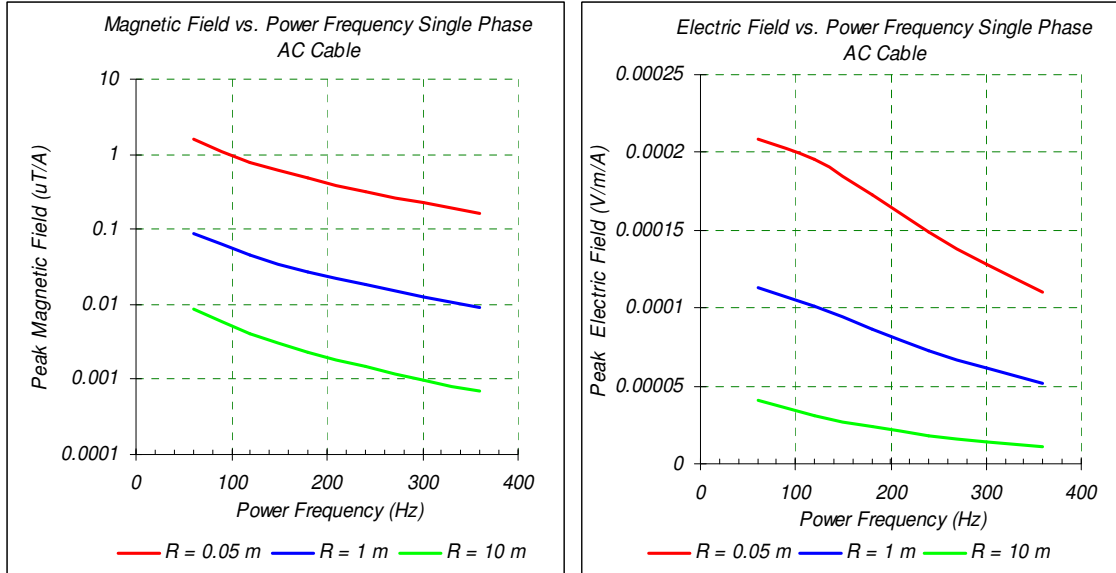


Figure 16 – Normalized E and B Fields vs. Power Frequency for Single Phase Cable

7.3 Individually Shielded Triaxial AC Cable

The most common cable type of subsea 3-phase power transmission is the triaxial, or trefoil cable, where three conductors are laid up in the form of an equilateral triangle.

It is possible to determine the electric and magnetic fields surrounding such a cable by superposition of the fields calculated for a single conductor as previously done for the DC bipole cable. Consider the triaxial cable shown in Figure 17, with each conductor being individually shielded, as specified in Table 2.

In a balanced line the phase currents are 120 degrees out of phase, thus the maximum field rotates around the cable axis with time, shown in Figure 18.

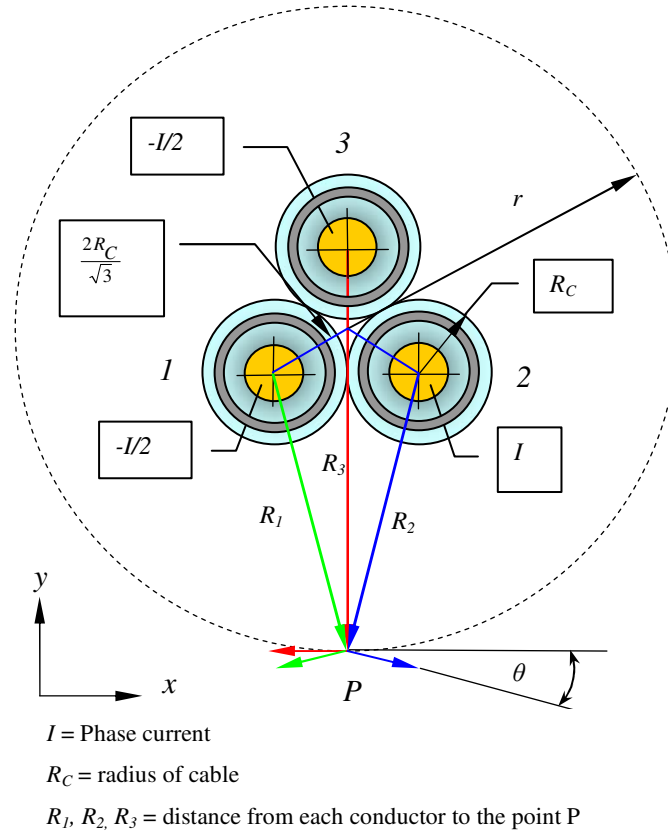


Figure 17 – Vector Diagram for B fields around a Three Phase Triaxial AC Cable Each Phase Individually Shielded

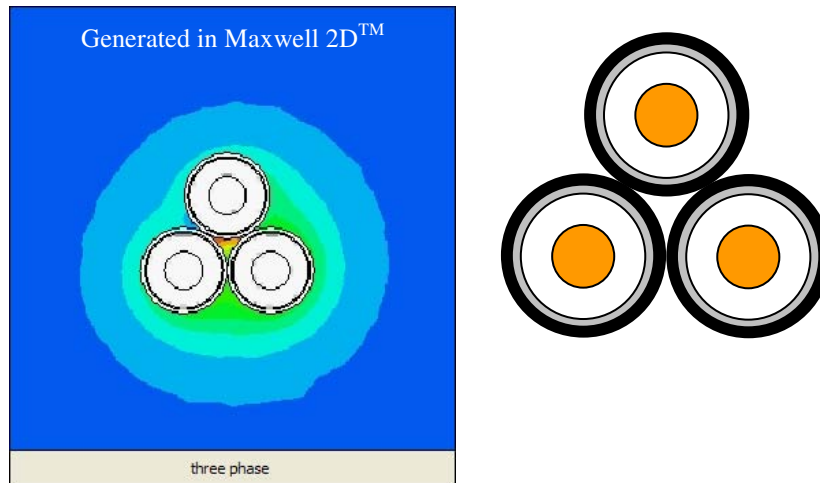


Figure 18 – Magnetic Field Visualization for Individual Shielded Trefoil AC Cable

The values of R_1 and R_2 , as shown in Figure 17, were determined using the cosine rule, which yields:

$$R_1(r) = R_2(r) = \sqrt{r^2 + \frac{4R_C^2}{3} - \frac{2R_C r}{\sqrt{3}}}$$

$$R_3(r) = r + \frac{2R_C}{\sqrt{3}}$$

The angle θ in Figure 17, is given by:

$$\theta(r) = \arcsin\left[\frac{R_C}{R_1(r)}\right]$$

Where $\theta(r)$ is in radians

The components of the magnetic field around the 3-phase cable are determined by vector summation of the B fields from each conductor.

$$B_y(r) = \frac{3B_{1,2}(r) \sin(\theta(r))}{2}$$

$$B_x(r) = \frac{B_{1,2}(r) \cos(\theta(r)) - B_3(r)}{2}$$

Where $B_{1,2}(r)$ = Magnetic field from conductor 1 or 2 (T)

$B_3(r)$ = Magnetic field from conductor 3 (T)

Similarly, the components of the E field were determined to be

$$E_x(r) = \frac{E_{1,2}(r) \sin(\theta(r))}{2}$$

$$E_y(r) = \frac{\cos(\theta(r))\{E_{1,2}(r) - E_3(r)\}}{2}$$

Where $E_{1,2}(r)$ = Electric field from conductor 1 or 2 (V/m)

$E_3(r)$ = Electric field from conductor 3 (V/m)

The resultant fields are given by

$$E(r) = \sqrt{E_x(r) + E_y(r)}$$

$$B(r) = \sqrt{B_x(r) + B_y(r)}$$

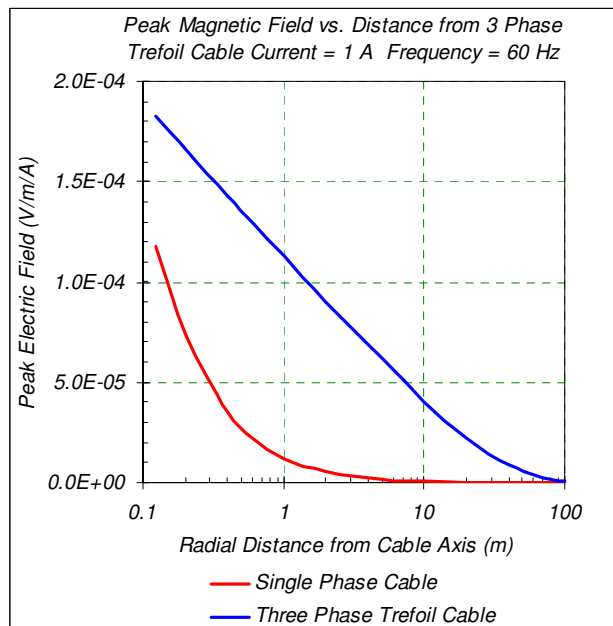
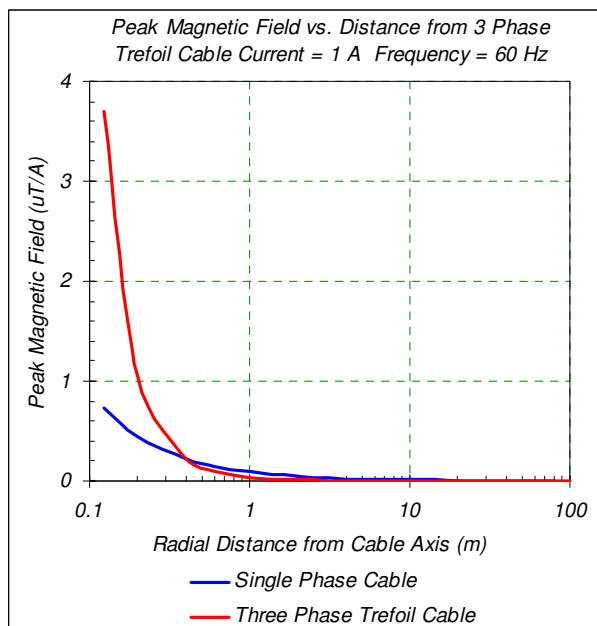
Finally, the peak electric and magnetic fields generated by the phase currents are:

$$E_{peak}(r) = k\sqrt{E_x(r) + E_y(r)}$$

$$B_{peak}(r) = k\sqrt{B_x(r) + B_y(r)}$$

Where $k(r) = 2\sqrt{3}$

The maximum fields around the ideal triaxial cable are shown in Figure 19, together with those calculated for the ideal single-phase cable, and it is observed that both the electric and magnetic fields are reduced with the triaxial cable compared to the single-phase cable for distances greater than 0.4 m from the cable axis. However, less than 0.4 m from the axis, the 3-phase cable generates magnetic fields that are higher those produced at the same distance from a single-phase cable carrying the same current.



**Figure 19 – Electric and Magnetic Fields vs. Distance from Axis of Triaxial cable
Each Phase Individually Shielded**

To validate the transmission line model for the three phase trefoil cable, the cable was analyzed using Ansoft Maxwell 2D™ and the resulting magnetic potential plot is shown in Figure 20.

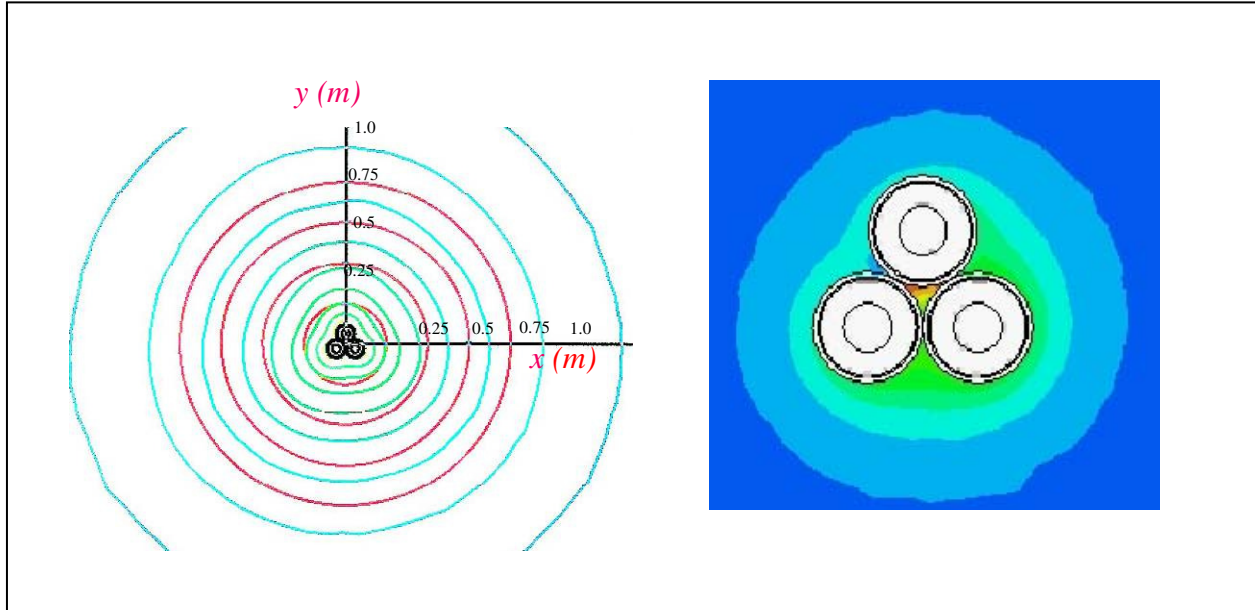


Figure 20 – Magnetic Potential and Field Plots for 3 Phase Trefoil Cable

From Figure 20 it is apparent that the magnetic field becomes near circular for radii greater than 0.5 m from the cable axis, thus close agreement between the TLM and FEA model is expected beyond 0.5 m from the cable. Figure 21 shows the magnetic field along the y-axis in Figure 20, which gives the maximum fields, together with the maximum magnetic fields predicted with the transmission line model.

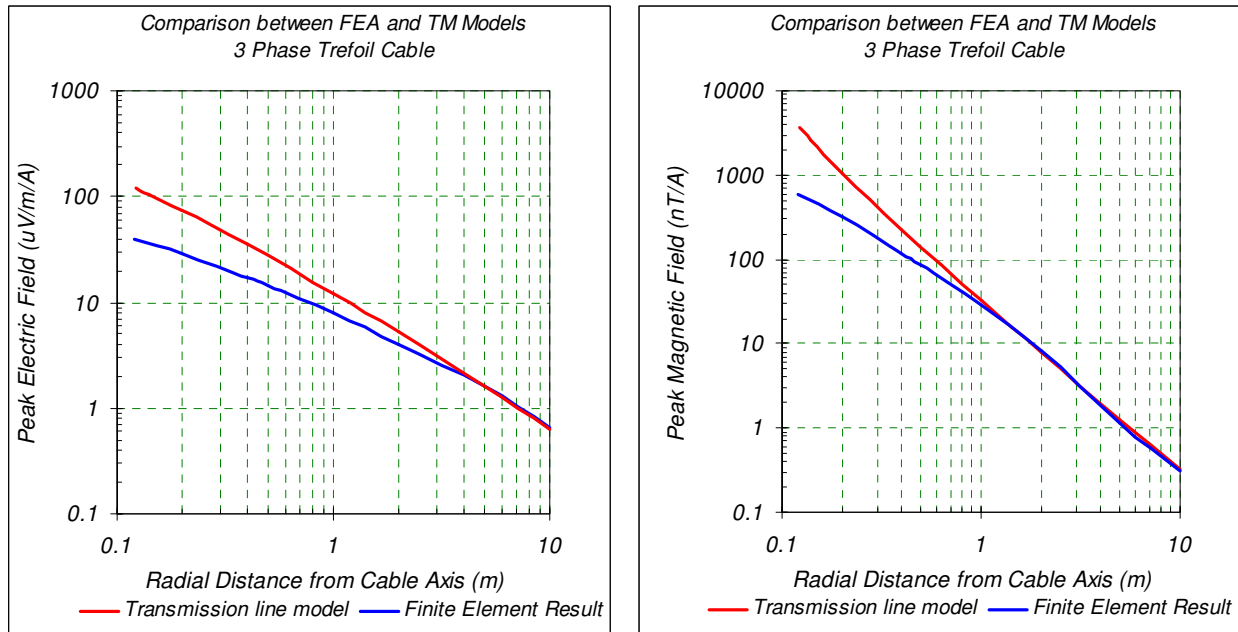


Figure 21 – Normalized E and B Fields by FEA and TLM vs. Distance from Trefoil Cable

Figure 21 demonstrates excellent agreement between the two models for distances greater 1 m from the cable axis and the TLM is conservative in predicting the fields for distances less than 1 m from the cable. The transmission line model for the individually shielded trefoil 3-phase cable is therefore justified.

7.4 Triaxial AC Cable with a Common Outer Shield

Another type of three-phase cable construction is to apply an outer shield, or armor layer, that encompasses all three conductors and examples of this design are shown schematically in Figure 22.

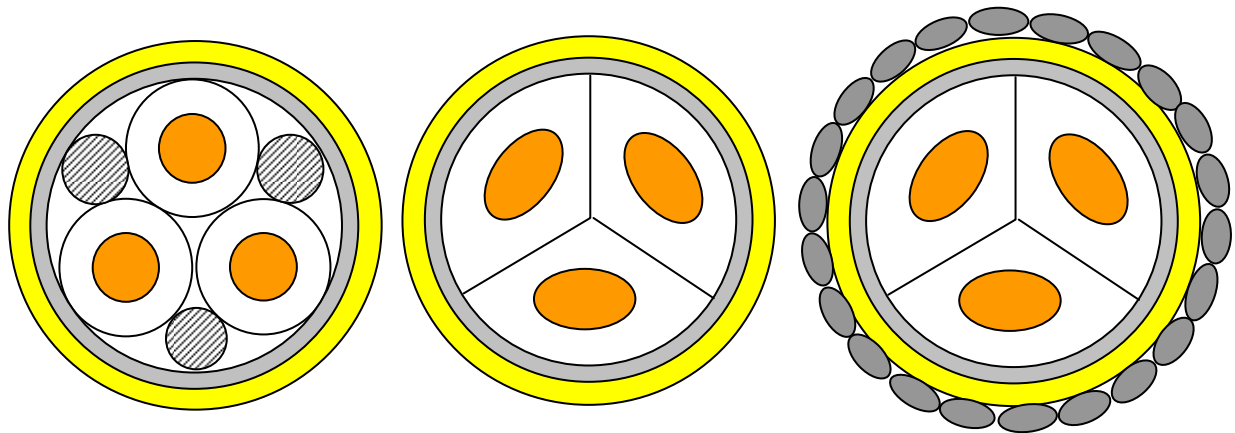


Figure 22 – Schematics of Outer Shielded and Armored Triaxial Cables

The fields external to these cables will be more uniform compared to those surrounding an unshielded trefoil cable (Figure 20) due to the presence of the nominally annular metallic outer conductor (see Figure 23).

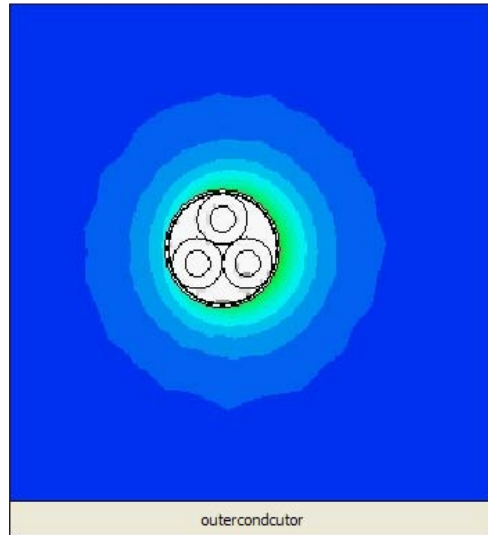


Figure 23 – FEA Visualization of Magnetic Field around Trefoil Cable with Common Outer Armor

To predict the fields around this type of cable using the transmission line model, an effective current must be defined from the phase currents of the three-phase cable as follows:

$$I_{EFF} = \frac{I_{RMS}}{3\sqrt{3}}$$

Where I_{RMS} = RMS phase current of power cable

The normalized fields using the analytic and finite element methods are shown in Figure 24, where excellent correlation of the two methods is again apparent.

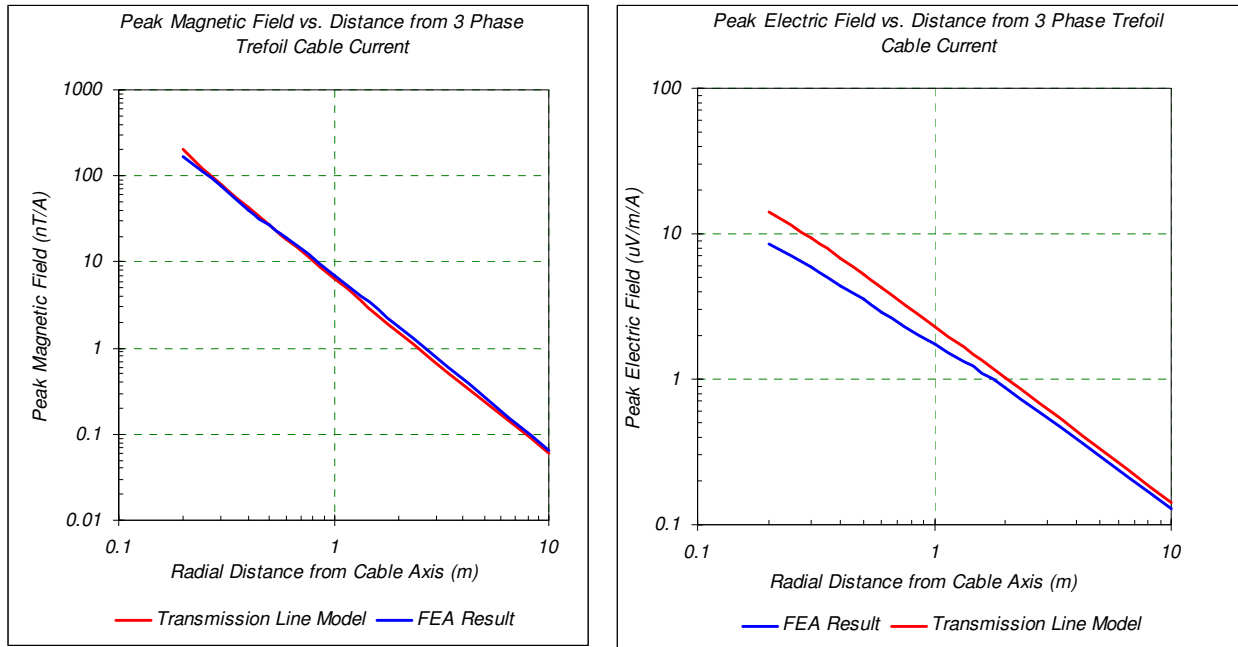


Figure 24 – Normalized Electric and Magnetic Fields vs. Distance from 3 Phase Cable with a Single Outer Shield

8. EFFECT OF CABLE BURIAL

To provide additional protection from external aggression in shallow water, submarine cables are usually buried below the natural seabed to a depth of approximately 1 m. Therefore, the effect of the cable being surrounded by seabed sediments, rather than seawater, on the electric and magnetic fields will now be considered.

The magnetic permeability of the seabed and seawater are approximately unity, as both are non-ferromagnetic, thus burial of the cable into the seabed will not change the magnetic field surrounding the cable.

The electric field external to the cable is dependent on the relative permittivity and conductivity of the medium surrounding the cable.

To determine the effective permittivity of the seabed sediment consider the simplified model where the sand or silt particles are considered as spheres of radius r_s located at the center of cubes of seawater of side r_s , positioned to form a regular lattice as seen in Figure 25.

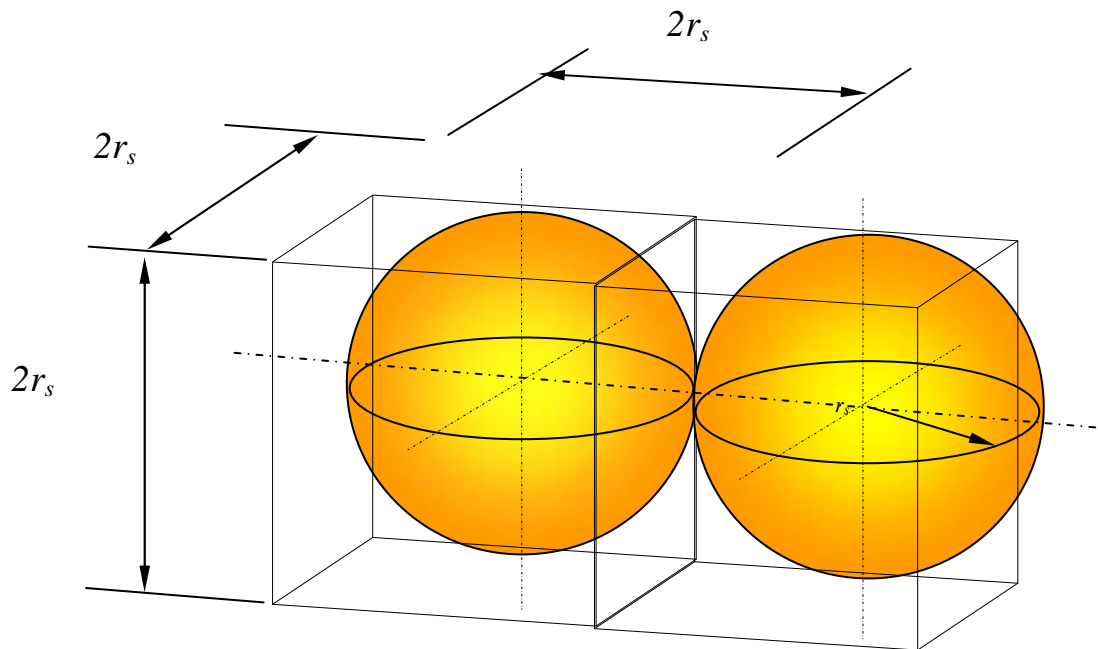


Figure 25 – Model for Determining the Permittivity and Conductivity of Seabed Sediments

From Figure 25, the volume fraction (v) of the sand particles is given by:

$$v = \frac{4\pi r_s^3}{3(2r_s)^3} = \frac{\pi}{6} = 0.524 \quad 9)$$

The volume fraction of sand in the seabed sediment can also be defined by:

$$v = \frac{\rho_{seabed} - \rho_{seawater}}{\rho_{sand} - \rho_{seawater}} \quad 10)$$

Where

ρ_{seabed} = density of seabed (kg/m^3)

$\rho_{seawater}$ = density of seawater (typically 1025 – 1030 kg/m^3)

ρ_{sand} = density of dry sediment (kg/m^3)

The density of silica based seabed sediments is typically 1600 kg/m^3 , and the density of silica sand is typically 2100 kg/m^3 . Substitution of these values gives a volume fraction of 0.53, which is very similar to that of the regular lattice, and justifies the adoption of the model in Figure 25

Two equations for determining the effective permittivity of a mixture of materials a function of the solid fraction, as arranged in Figure 25, are the Maxwell-Garnett and Bruggeman models (Jylhä and Sihvola, 2007):

$$\varepsilon_{bed}(v) = \varepsilon_w \left[1 + 3v \left(\frac{\varepsilon_s - \varepsilon_w}{\varepsilon_s + 2\varepsilon_w - v(\varepsilon_s - \varepsilon_w)} \right) \right] \quad (\text{Maxwell-Garnett}) \quad 11)$$

$$\frac{\varepsilon_s - \varepsilon_{bed}}{\varepsilon_s + 2\varepsilon_{bed}} v + \frac{\varepsilon_w - \varepsilon_{bed}}{\varepsilon_w + 2\varepsilon_{bed}} (1 - v) = 0 \quad (\text{Bruggeman}) \quad 12)$$

Where

ε_w = Permittivity of seawater (81)

ε_s = Permittivity of solid material (5 for silica)

Similarly, the conductivity of the seabed can be determined using:

$$\sigma(v) = \sigma_w \left[1 + 3v \left(\frac{\sigma_s - \sigma_w}{\sigma_s + 2\sigma_w - v(\sigma_s - \sigma_w)} \right) \right] \quad (13)$$

$$\frac{\sigma_s - \sigma_{bed}}{\sigma_s + 2\sigma_{bed}} v + \frac{\sigma_w - \sigma_{bed}}{\sigma_w + \sigma_{bed}} (1 - v) = 0 \quad (14)$$

Where

σ_w = Conductivity of seawater (4 S/m)

σ_s = Conductivity of solid material ($\sim 10^{-10}$ S/m for silica).

The calculated permittivity and conductivity of the seabed using the two mixing models is shown in Figure 26.

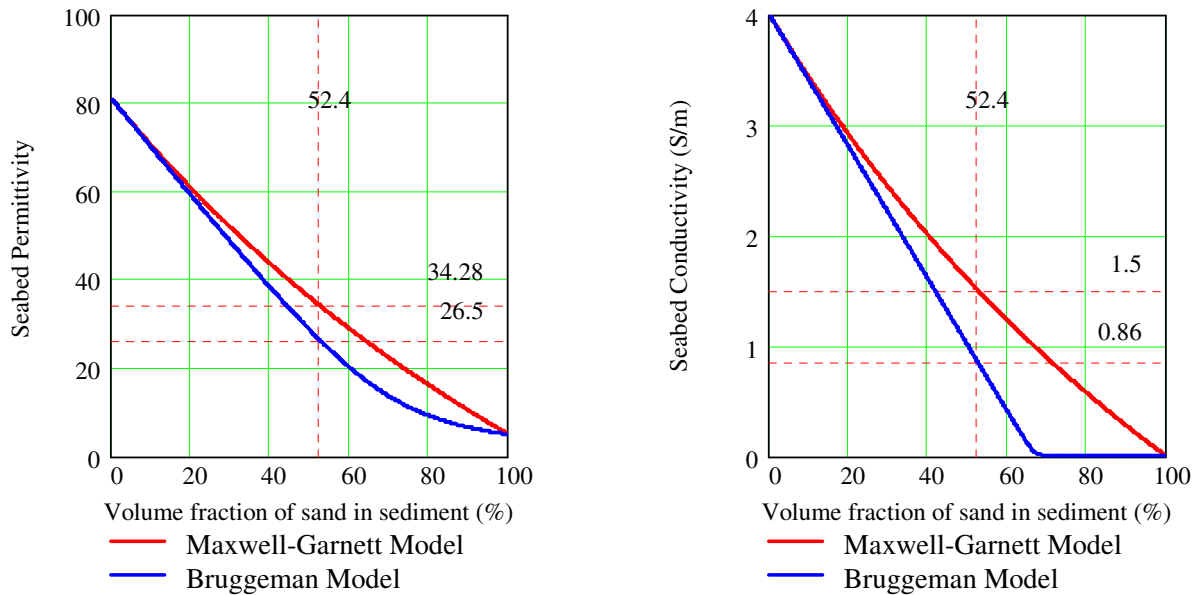


Figure 26 – Effective Permittivity and Conductivity of the Sea Bed

In practice, the actual value of permittivity or conductivity will lay between those predicted by the two models. Therefore, for a solid fraction of 0.524, the effective conductivity is expected to be between 0.86 and 1.5 S/m, and the permittivity will be between 26 and 34.

Consider a single-phase cable buried below the seabed as shown in the simplified model in Figure 27.

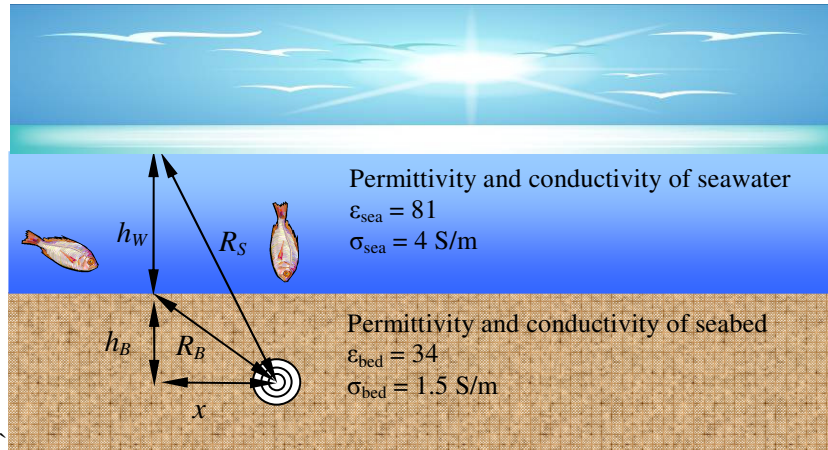


Figure 27 – Cable Burial Model

The radial distances from the cable to the seabed and the surface of the sea as a function of distance from the cable in the x direction are given by:

$$R_B(x) = \sqrt{x^2 + h_B^2} \quad \text{and} \quad R_S(x) = \sqrt{x^2 + (h_B + h_W)^2} \quad 15)$$

The highest fields occur at the interface with the seabed, due to the lower permittivity of the seabed sediments. This is demonstrated in Figure 28, which shows the fields at the seabed and sea surface as a function of the perpendicular distance (x) from the cable for a burial depth of 1m and a water depth of 50 m.

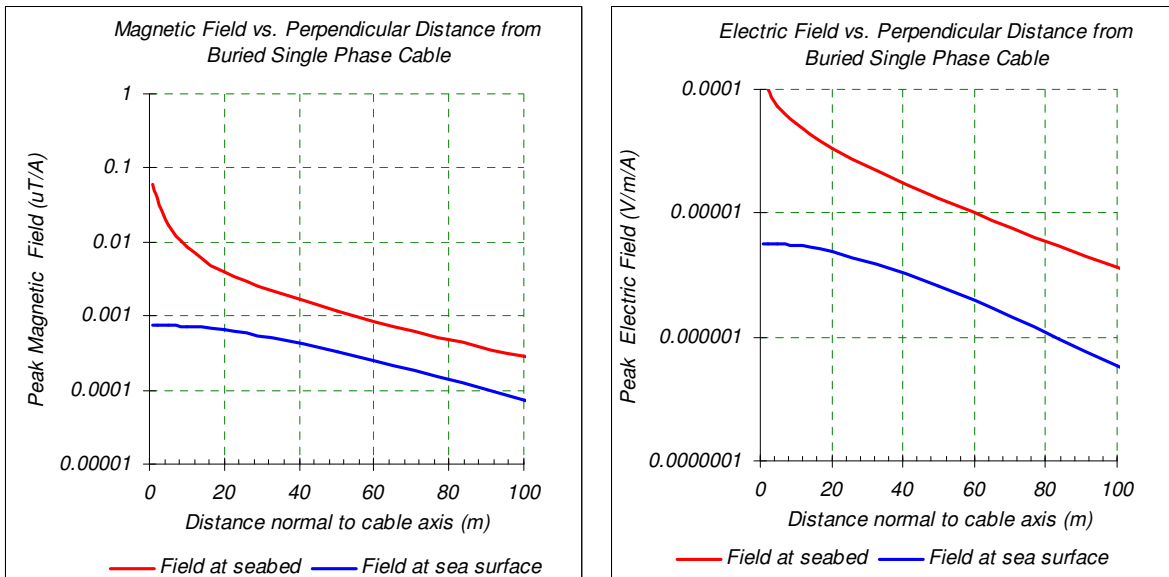


Figure 28 – Normalized Magnetic and Electric fields for a Buried Single Phase Cable
 Water Depth = 50 m. Burial depth = 1 m. $\epsilon_{sea} = 81$ $\epsilon_{seabed} = 34$ $\sigma_{sea} = 4$ S/m $\sigma_{seabed} = 1$ S/m

9. COMPARISON OF PREDICTED FIELDS WITH MEASUREMENT

The COWRIE report detailed the magnetic and electric field measurements made on two 3-phase power cables, which cross the River Clwyd near the Foryd Bridge (see Figure 29).

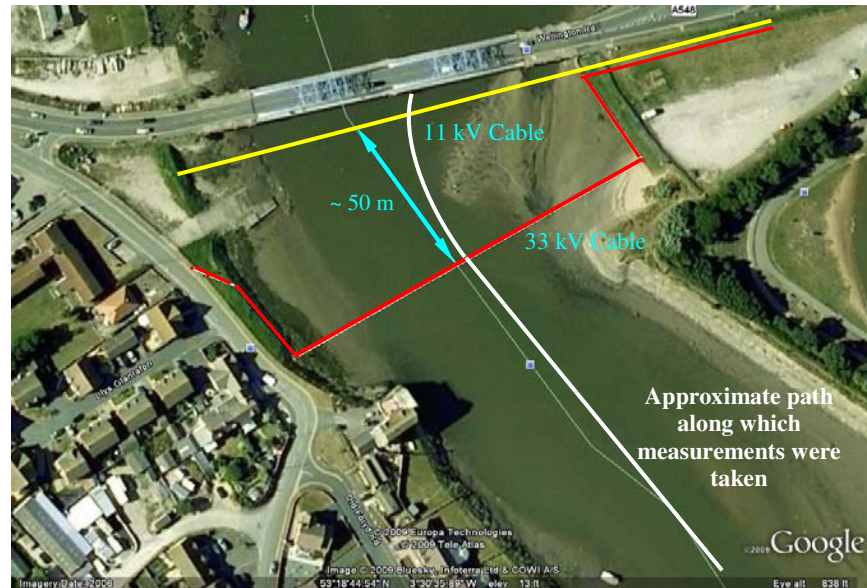


Figure 29 – Location of Power Cables across River Clwyd

It was found that the electric field was $>70 \mu\text{V/m}$ irrespective of where the measurement was made, but no reason for this was presented in the report. If the river flow was 3 knots, which is certainly plausible, a ‘background’ electric field of $>70 \mu\text{V/m}$ would be produced by magneto-hydrodynamic generation, which could account for the electric field being $>70 \mu\text{V/m}$.

The COWRIE report did not detail the cable construction particularly well, but did reference the 33 kV cable and 11 kV cables as conforming to BS 6480 and EATS 09-12 respectively. These specifications are given in Appendix D for reference, and have been used to define the cable dimensions required for the analysis.

The cables were reported as buried in the riverbed by approximately 1 m, and the sensors were deployed approximately 1.5 m below the water surface. Unfortunately, the water depth was not reported, but literature surveys indicate a water depth of two or three meters in this location (US Navy, 1917). The predicted performance, using the transmission line model described herein,

and the actual measurements for the two cables are shown in Figure 30, which shows very good correlation between theory and reality.

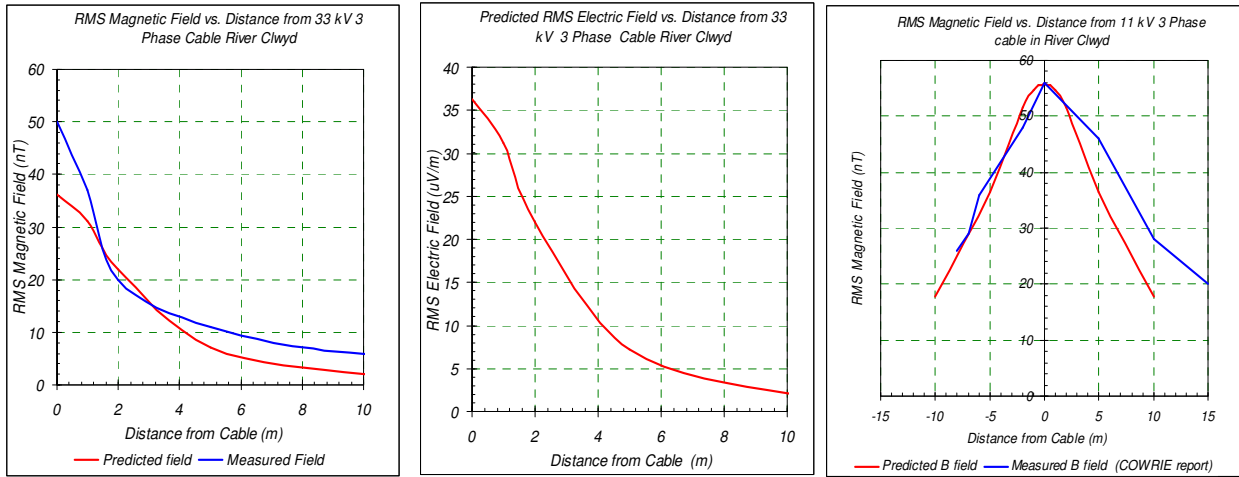


Figure 30 – Predicted and Actual Field Measurements on 33 and 11 kV 3 Phase Cable across the River Clwyd

10. CONCLUSIONS

This report has presented models for predicting the electromagnetic fields produced by DC monopole and bipole power cables that are based on fundamental physical laws.

A transmission line model was developed to enable the electromagnetic fields surrounding an AC cable as a function of distance from the cable, to be quickly and accurately determined from the cable construction, the power frequency, and phase current. The model was developed for both single phase and trefoil three phase cables, with either individual phase shields, or with a single shield that encompasses all three phases. The model has been verified using Finite Element Analysis, and has accurately predicted the fields recorded during 2002, from a pair of 3 phase cables that cross the River Clwyd. It is concluded that the transmission line model will reasonably predict the fields generated around specific cable designs being considered for subsea power transmission.

This work has also shown that if sea trials are to be undertaken to measure the fields adjacent to power cables, the actual location of the sensors relative to the cable must be known as the fields decrease rapidly in close proximity to the cables. Caution should be exercised when extrapolating these analytical results for a specific site; simplifying assumptions made for the homogeneity of the surrounding medium (e.g. seawater or underlying geology) may affect the accuracy as one moves away from the vicinity of the electrical cable source unless such features are incorporated into the calculations.

The normalized magneto-hydrodynamic electric field produced when seawater moves through the earth's magnetic field is approximately 0.515 V/m/knot/T , and will change 'polarity' with flow reversal (i.e. tidal effects). This field is additive to the electric field produced by the current flow in the cable, therefore, when developing systems for measuring the E-field adjacent to a power cable, methods for accounting for this 'background' field must be defined.

APPENDIX A – GLOSSARY OF SYMBOLS

$\alpha, \beta, \theta, \phi$	Angle	radians
a	Current loop radius	m
A	Magnetic vector potential	$\text{Wb}\cdot\text{m}^{-1}$ or $\text{T}\cdot\text{m}$
B	Magnetic Field	Tesla
β'	Phase constant	$\text{radian}\cdot\text{sec}^{-1}$
C', C	Transmission line capacitance	$\text{F}\cdot\text{m}^{-1}$
dA	Area of current loop	m^2
δ	Skin depth	m
E	Electric field	$\text{V}\cdot\text{m}^{-1}$
ϵ_0	Permittivity of free space	$8.66 \times 10^{-12} \text{ F}\cdot\text{m}^{-1}$
ϵ_r	Relative permittivity	
f	Power frequency	Hz
G'	Transmission line conductance	$\text{S}\cdot\text{m}^{-1}$
h	Depth	m
I	Current	Amperes
l	Length	m
L'	Transmission line inductance	$\text{H}\cdot\text{m}^{-1}$
λ	wavelength	m
μ_0	Permeability of free space	$4\pi \times 10^{-7} \text{ N}\cdot\text{Amp}^{-2}$
μ_r	Relative permeability	
v_p	Phase velocity	$\text{m}\cdot\text{sec}^{-1}$
v	Sea water flow velocity	$\text{m}\cdot\text{sec}^{-1}$
Q	Charge	coulomb
q	Charge/unit length	$\text{coulomb}\cdot\text{m}^{-1}$

r	Radial distance	m
R'	Transmission line resistance	$\Omega \cdot \text{m}^{-1}$
R_1, R_2, R, R_C	Radii	m
ρ	Resistivity	$\Omega \cdot \text{m}$
σ	Conductivity	$\text{S} \cdot \text{m}^{-1}$
$\hat{\theta}$	Unit vector in θ	
V	Potential	volts
v	Volume fraction	
ω	angular frequency	$\text{radians} \cdot \text{sec}^{-1}$
x, y, z	Cartesian coordinates	m
Z	Impedance	Ω
Z'	Transmission line impedance	Ω
\hat{z}	Unit vector in z	

APPENDIX B – ACRONYMS

ASW	anti-submarine warfare
B-field	magnetic field
BWEA	British Wind Energy Association
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research Into The Environment
DECC	Department for Energy and Climate Change
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
FEA	Finite Element Analysis
Hz	Hertz, cycles per second
MHD	magneto hydrodynamic
MHz	megahertz
MKS	meter-kilogram-second
MMS	Minerals Management Service
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
RMS	Root Mean Square
SI	International System of Units
SIO	Scripps Institute of Oceanography
THz	terahertz
UK	United Kingdom
WA	Washington

APPENDIX C – SKIN DEPTH

The skin depth describes the extent that an electromagnetic wave penetrates into a material, and is defined as the distance at which the amplitude of the incident wave is attenuated to $1/e$ of the initial value. A mirror is an example of this effect, where the light is reflected from the surface of a metalized coating and energy is also absorbed into the material. The incident wavelength (energy) propagates into the metallic coating, decaying exponentially with penetration distance. The visible spectrum ranges from 400 to 800 THz, and the skin depth for silver varies from 0.07 to 0.1 nm over this frequency band. Therefore, the E and B fields of the incident wavelengths, which penetrate into the silver coating, decay to near zero within a nanometer of the surface.

Similarly, if an AC current is passed through a conductor, the current density will be highest at the conductor surface, and decay with distance toward the center of the conductor. The skin depth of copper at 60 Hz is approximately 8.5 mm, so ~63 % of the current flows within 8.5 mm of the conductor surface. Therefore, a copper bus bar with a radius > 10 mm is essentially ‘wasting’ copper.

The generalized equation for the skin depth as a function of frequency ($\delta(f)$) can be derived from Maxwell’s (1873) equations, and is:

$$\delta(f) = \frac{1}{\omega(f)} \sqrt{\frac{2}{\mu_r \mu_0 \epsilon_r \epsilon_0}} \left[\sqrt{1 + \left(\frac{\sigma}{\omega(f) \epsilon_r \epsilon_0} \right)^2} - 1 \right]^{-\frac{1}{2}} \quad \text{A1)}$$

Where

$\omega(f)$ = angular frequency = $2\pi f$

μ_r = relative permeability of material

μ_0 = permeability of free space ($4\pi \times 10^{-7}$ N·Amp⁻²)

ϵ_r = relative permittivity of material

ϵ_0 = permittivity of free space (8.854×10^{-12} Farad/m)

σ = conductivity of material (S/m)

If $\frac{\sigma}{\omega(f) \epsilon_r \epsilon_0} \gg 1$, then equation A1) reduces to:

$$\delta(f) = \sqrt{\frac{2}{\omega(f)\mu_r\mu_0\sigma}} \quad \text{A2)}$$

Equation A2) is the used to calculate the skin depth as a function of frequency for good conductors such as metals or seawater. However, as the frequency increases, equation A2) will no longer be valid, and the high frequency approximation must then be used, which is:

$$\delta = \frac{2}{\sigma} \sqrt{\frac{\epsilon_r\epsilon_0}{\mu_r\mu_0}} \quad \text{A3)}$$

It should be noted that the high frequency approximation is independent of frequency, and the maximum frequency for which the *low* frequency approximation is valid is given by:

$$f_{\max} = \frac{\sigma}{4\pi\epsilon_r\epsilon_0} \quad \text{A4)}$$

Using equation A4), the low frequency approximation is valid for copper for frequencies up to approximately 5×10^5 THz, whereas with sea water, the low frequency approximation is valid up to approximately 400 MHz.

The skin depth vs. frequency for copper, seawater, and freshwater using Equation A1, are shown in Figure A1, which is also annotated with the approximation regimes given above.

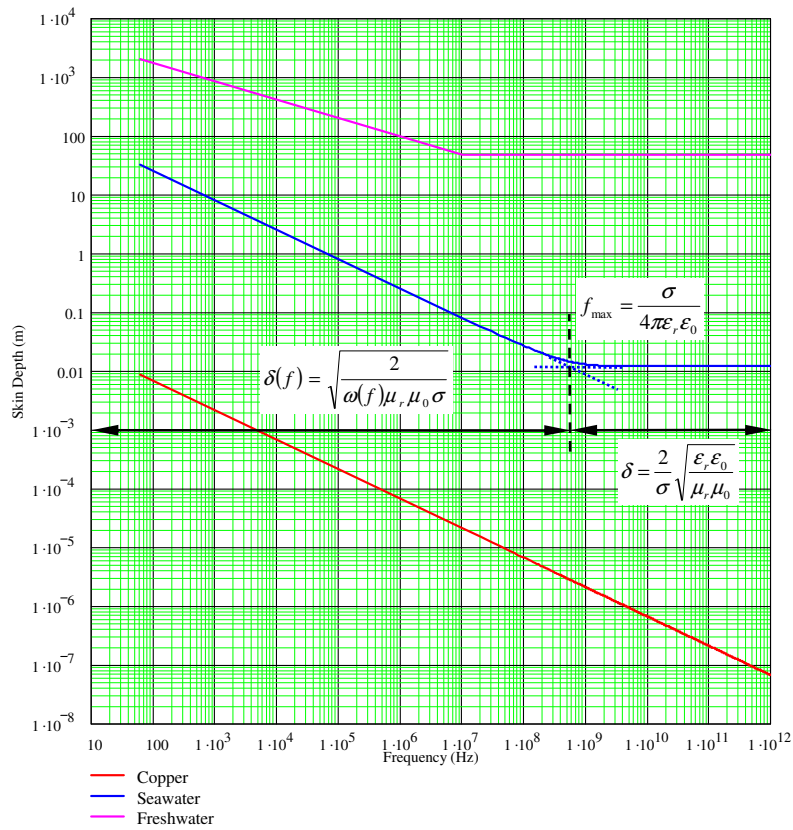


Figure A-1 – Skin depth vs. Frequency for Various Materials

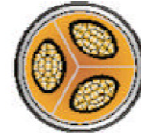
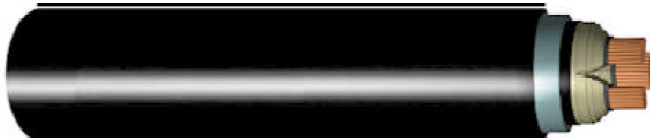
The power frequency will probably be 50 or 60 Hz, justifying the low frequency approximation, which was used in the transmission line model for predicting the electric and magnetic fields surrounding an AC submarine power cable.

The skin depth in seawater at 60 Hz is ~ 32.5 m, and at this distance from the cable, the electric and magnetic fields will have attenuated by 1 neper (8.6 dB) from their values at the cable surface.

APPENDIX D – CABLE TYPES USED IN COWRIE REPORT





**PAPER LEAD 3C
 19/33kV
 COPPER
 H Type**



APPLICATION In urban networks for primary supply to underground residential distribution substations. Main feeders to commercial and industrial projects. The lead sheath provides an earth fault capacity adequate for many installations although it is fixed, and usually less than the equivalent XLPE copper wire screened cable. Each core is screened with metallised paper to distribute electrical stresses evenly through the paper insulation.	STANDARD	AS 1026:1992 BS 6480:1988
	VOLTAGE	19000/33000V
	CONDUCTOR	Shaped Compacted Annealed Copper
	INSULATION	Mass Impregnated (Non Draining) Paper
	SHEATH	PVC, 4V-75 or MDPE
	MAX. OPERATING TEMP.	65 °C

Conductor		Overall Diameter		Approximate Mass		Minimum Bending Radius	
mm ²	(No./mm)	Minimum mm	Maximum mm	MDPE kg/km	PVC kg/km	Installed mm	During Installation mm
50	19 strands	60.2	64.5	8900	9000	1160	1930
70	19 strands	62.5	66.9	10000	10200	1200	2010
95	19 strands	65.0	69.3	11300	11500	1250	2080
120	19 strands	67.7	72.2	12800	13000	1300	2160
150	19 strands	68.9	73.3	13900	14200	1320	2200
185	37 strands	72.6	77.0	16000	16200	1390	2310
240	37 strands	77.0	81.6	18600	19000	1470	2450
300	37 strands	81.2	85.9	21400	21700	1550	2580

Lengths and packing can be supplied to customer's requirements.
 For glanding details, contact your local service centre.
 Bending radii to BS6480

Nominal Area mm ²	CURRENT RATING (a)		ELECTRICAL CHARACTERISTICS						
	Buried Direct 	Buried In Ducts 	Max. DC Resistance @ 20°C ohm/km	Max. AC Resistance @ 65°C ohm/km	Inductance mH/km	Equivalent Star Reactance ohm/km	Capacitance µF/km	3 Phase Voltage Drop mV/A.m	1 Sec Fault Rating (b) 3 Phase Symmetrical kA
50	169	148	0.387	0.456	0.403	0.127	0.230	0.82	5.7
70	204	178	0.268	0.316	0.350	0.110	0.280	0.58	7.9
95	242	211	0.193	0.235	0.328	0.103	0.318	0.44	10.7
120	275	240	0.153	0.181	0.315	0.099	0.346	0.36	13.6
150	311	271	0.124	0.147	0.301	0.095	0.384	0.30	16.9
185	349	305	0.099	0.118	0.292	0.092	0.418	0.26	20.9
240	401	350	0.075	0.090	0.280	0.088	0.464	0.22	27.1
300	451	393	0.060	0.073	0.272	0.085	0.507	0.19	33.9

(a)- Based on 65°C maximum conductor temperature, burial depth of 0.8m, soil temperature of 15°C and thermal resistivity of 1.2°Cm/W.

(b)- For fault durations other than one second, divide the appropriate given value by the square root of the required time (in seconds).

Conductor fault ratings are based on an initial temperature of 65°C and a final temperature of 150°C.

CONDUCTOR			LEAD ALLOY SHEATH				
Nominal Area	Nominal Depth	Min. Insulation Between Conductor and Sheath	Minimum Thickness	Diameter over sheath		Nominal Area	1 Sec Fault Rating (c)
mm ²	mm	mm	mm	Minimum mm	Maximum mm	mm ²	kA
50	8.1	7.3	2.2	56.0	59.8	403	12.2
70	7.4	7.3	2.3	58.1	62.1	438	13.3
95	8.7	7.1	2.4	60.4	64.3	474	14.4
120	9.7	7.1	2.5	62.9	66.9	514	15.6
150	10.7	6.8	2.6	63.9	67.8	541	16.4
185	12.1	6.8	2.7	67.4	71.3	592	18.0
240	13.8	6.8	2.8	71.6	75.6	653	19.8
300	15.5	6.8	2.9	75.6	79.7	714	21.6

(c)- For fault durations other than one second, divide the appropriate given value by the square root of the required time (in seconds).

Sheath fault ratings are based on an initial temperature of 55°C and a final temperature of 250°C.

UTILITY CABLES

MEDIUM VOLTAGE

6350/11000V

EATS 09-12 (11kV Screened) PICAS Cable

CABLE CHARACTERISTICS



WWW.CABLEJOINTS.CO.UK
THORNE & DERRICK UK
TEL 0044 191 490 1547 FAX 0044 477 5371
TEL 0044 117 977 4647 FAX 0044 977 5582
WWW.THORNEANDDERRICK.CO.UK

CABLE DESCRIPTION

1.CONDUCTOR

Compact sector shaped stranded aluminium conductor complying with BS6360 Class 2.

2.CONDUCTOR SCREEN

Semi-conducting carbon paper tapes.

3.INSULATION

Layers of paper tapes applied helically and mass impregnated with non-draining insulating compound (MIND)

5.INSULATION SCREEN

Semi-conducting carbon tapes applied in combination with metallised paper tapes over the core insulation. Core identification, Outer carbon papers printed with white numbers 1, 2 and 3.

4 & 6.LAYING UP

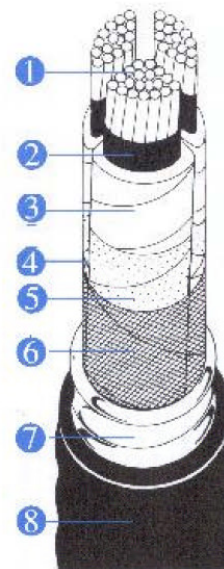
Three cores laid up with paper fillers and bound with copper woven fabric tape.

7.ALUMINIUM SHEATH

Extruded corrugated aluminium sheath with bitumen coating.

8.CABLE SERVING

Extruded red polyvinyl chloride (PVC) is supplied as standard.



Formerly Pirelli Cables

UTILITY CABLES

MEDIUM VOLTAGE

6350/11000V

**EATS 09-12 (11kV Screened) PICAS
 Cable**

Constructional Data

Nominal cross-sectional area mm ²	Minimum thickness of insulation between conductor and screen mm	Approximate thickness of aluminium sheath mm	Minimum average thickness of oversheath mm	Approximate diameter overall mm
95	2.8	1.2	2.5	49.0
185	2.8	1.6	2.8	60.7
300	2.8	2.0	3.2	72.5

Installation Data

Nominal cross-sectional area mm ²	Approximate cable weight Kg/m	Minimum bending radius mm	Nominal internal diameter of ducts mm
95	3.4	600	100
185	5.2	750	100
300	7.5	900	125

Electrical Data

Nominal cross-sectional area mm ²	Maximum DC resistance of phase conductors at 20°C Ohms/km	Maximum AC resistance of conductors at 65°C Ohms/km	Approximate reactance at 50Hz Ohms/km	Approximate capacitance pF/km
95	0.320	0.384	0.087	0.600
185	0.164	0.198	0.081	0.810
300	0.100	0.122	0.077	0.100

Ratings Data

Nominal cross-sectional area mm ²	Current Ratings		
	Laid direct in ground Amps	Drawn into ducts Amps	Laid in air Amps
95	205	170	200
185	295	250	305
300	380	325	410

Current Rating Conditions:

Ground Temperature 15°C
 Depth of Burial 0.8m
 Ambient temperature (air) 25°C
 Thermal Resistance of Soil 1.2°C m/W

APPENDIX E – BIBLIOGRAPHY

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Electromagnetic Field Study

Ambient electromagnetic fields in the nearshore marine environment.

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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.

Record of Revisions

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1. EXECUTIVE SUMMARY

This report describes the ambient background field strength characteristics of electric and magnetic fields in the nearshore marine environment of the continental shelf. This study was commissioned with the goal of collecting and summarizing existing data on the nearshore electric and magnetic field ambient conditions to serve as a surrogate for the existing conditions suitable for an environmental baseline of wave energy projects on the Oregon coast.

It was noted during the literature survey phase that there was a paucity of EMF data available for the coastal environment. Particularly lacking were data sets describing EM fields in the nearshore zone most suitable to wave energy development. However, although actual measured data is lacking, substantial theories have been developed over the past several decades of study in the deep ocean environment, motivated primarily by geophysical research and economic considerations (*e.g.* oil exploration). As a result, a number of expected characteristics of ambient EM fields along the coastal margins can be drawn:

1. A number of different sources of nearshore EM fields exist in theory, including man-made noise, but are predominately comprised of naturally occurring phenomena
2. EMF levels are highly dependent on physical location
3. For a given location, EMF levels can significantly change over time and can be highly variable
4. EMF levels in the nearshore environment are likely higher than those observed in the deep ocean environment
5. The distance scale for changes to the EM field are dependent on individual forcing functions, and may range from meters to thousands of kilometers

Acquisition of measured electric and magnetic field data in the nearshore environment would serve to validate and refine existing theories based on deep ocean research, and extend the level of knowledge across the continental margin.

2. INTRODUCTION

2.1 Purpose

This report describes the ambient background field strength characteristics of electric and magnetic fields in the nearshore marine environment of the continental shelf. The purpose of the report is to summarize existing knowledge about ambient EM conditions along the Oregon coast, and in particular, those areas that may be best suited for energy extraction from ocean waves. The focus of this report is to identify the expected range of values of electromagnetic fields (EMF) of interest to the ocean wave energy community and related stakeholders.

2.2 Background

The introduction or alteration of electromagnetic fields in the near shore ocean environment could affect the behavior of sensitive marine organisms, including elasmobranchs (e.g. sharks and rays), salmonids, Dungeness crab, and other important marine species. Little is known about the potential for submarine power cables or power generating devices to affect such species. Thus, the effect of EMF on marine life is a key issue regarding the development of wave energy projects. Regulatory agencies are likely to favor a conservative approach when quantifying the impact of EMF on the environment. Furthermore, the use of any adaptive management approach requires the use of the best available science to inform the decision making process for natural resource management. Thus, this study is the first step in collecting and analyzing information about existing EMF conditions on the continental shelf, including the identification of factors that affect EMF generation and propagation in the nearshore marine environment.

2.3 Report Organization

This report contains six sections and three supporting appendices. The first section contains the executive summary. Section 2, the introduction, provides the project motivation and background. The methodology in Section 3 describes how the report was prepared. Section 4 orients the reader to the terms and values used to describe EM fields. Next, the report results are summarized in Section 5. Conclusions are stated in Section 6. Appendix A contains a glossary of terms used within the report. Appendix B is an acronym list. Appendix C contains the bibliography of references.

3. METHODOLOGY

The first step in preparing this report was to conduct a literature survey of related work in the continental shelf marine environment, and most importantly, work directly related to the nearshore environment or on the continental margins. The primary objectives in seeking applicable citations was to enable the evaluation of EMF conditions along the Oregon coast, identify factors affecting the strength of EM fields in this environment, and identify any sources of meaningful EM signature measurements along the Oregon coast. Once relevant papers and publications were obtained, they were analyzed, correlated, and summarized for this report.

4. UNITS OF MEASURE

An electromagnetic field is comprised of electrically charged objects, and is considered one of the fundamental forces of nature. In general, EM field is comprised of both electric field (E-field) and magnetic (B-field) components, although it is possible to have one without the other and vice versa. For example, an electrostatic field can be created by applying a voltage to a cable, but a corresponding magnetic field may not be created unless the electric field is changing with respect to time, or if current is flowing in the cable. A moving magnetic field creates an electric field, and a moving electric field creates a magnetic field¹.

Electric field strength is often stated in terms of a voltage gradient over distance, *e.g.* volts per meter (V/m) in SI MKS units. One volt per meter is equivalent to one Newton per coulomb (force per unit charge)², but the units of V/m provides a more intuitive unit of measure. Magnetic (B-field) fields are measured using units of Tesla³ (preferred SI units), or alternatively, units of gauss in the CGS system, wherein 10,000 gauss equals 1 Tesla. The use of the unit Webers per square meter, numerically identically to Tesla, is obsolete, although this form does appear in older literature. In practice, electric and magnetic field strength values are very small

¹ http://en.wikipedia.org/wiki/Electromagnetic_field

² http://en.wikipedia.org/wiki/Electric_field

³ http://en.wikipedia.org/wiki/Magnetic_field

compared to the basic unit of measure. Thus, metric prefixes are often encountered. Table 1 shows commonly used metric prefixes in the wave energy industry.

Units of power spectral density (PSD) are also commonly shown in the literature. It is critical to the fundamental understanding of field strength to indicate the bandwidth in question for a given measurement. For example, PSD measurements of electric fields are often depicted in units of $(V/m)^2/Hz$ (volts per meter squared per hertz), or voltage gradients shown as $V/m/\sqrt{Hz}$ (volts per meter per root hertz). This “bandwidth” factor is especially important to the understanding of measured field strength magnitudes and how they compare to threshold sensitivity limits for biological species of concern. Due to the large number of references in the literature to geo- and solar-scale events, data is often shown in terms of the period of a signal, compared with the frequency of a signal. The period of a signal is simply the inverse of the frequency, given by the following relationship: signal period, T, (seconds), is equal to 1/frequency (frequency in hertz (Hz), or cycles per second). Thus, a signal with a period of 10 seconds has a frequency of 0.1 Hz. The 60 Hz AC power fundamental frequency has a period of $1/60^{th}$ of a second.

Table 1 – Commonly Used Metric Prefixes

Prefix	Multiplier	Notation	Descriptor
tera, T	1,000,000,000,000	10^{12}	trillion
giga, G	1,000,000,000	10^9	billion
mega, M	1,000,000	10^6	million
kilo, k	1,000	10^3	thousand
milli, m	.001	10^{-3}	thousandth
micro, μ	.000,001	10^{-6}	millionth
nano, n	.000,000,001	10^{-9}	billionth
pico, p	.000,000,000,001	10^{-12}	trillionth
femto, f	.000,000,000,000,001	10^{-15}	quadrillionth
Source: http://www.simetric.co.uk/siprefix.htm			

5. SUMMARY OF RESULTS

This section describes the results found in a non-exhaustive literature survey, and summarizes the findings for the degree of available data, the factors affecting EM fields, and the limitations to the existing database of literature.

5.1 Sources of Information

The preponderance of information available on marine EM fields is derived from two primary fields: (1) geophysical studies to better understand the Earth's geologic structure, inclusive of sub-sea oil exploration, and (2) sub-sea environmental and propagation analyses to optimize exploitation of the EM spectrum for the purpose of coastal defense, namely anti-submarine warfare (ASW). Thus, primary contributions to the field of sub-sea EM have been dominated by those associated with naval laboratories or universities associated with the development of geophysical (including oil exploration), oceanographic, and ASW techniques. It is not surprising that one of the primary sources of information on the subject is the *Journal of Geophysical Research*, published by the American Geophysical Union⁴, supplemented by other related geophysical and oceanography publications. The field of study is sufficiently young, having roots dating to the late 1960s, that many of the original researchers are still in practice, although the recent passing of several pioneers has been noteworthy within the community. Classified sources of Navy documents were not considered for this study.

Other areas of study include the use of control techniques for galvanic corrosion of ship hulls, piping, and metallic marine structures, underwater communications, and other means of sensing marine variables using EM techniques. Minimal information was found on the subject of EMF with respect to submarine power cables or wave energy converters. The noteworthy "COWRIE" report (CMACS 2003) was helpful on a variety of topics, but relatively silent on useful background EMF conditions by either reference or measurement. Further, the EMF levels described in that reference did not describe frequency extent, and made the fundamental error of comparing field strength values at different frequencies (*e.g.* 50 Hz cable frequency vs. the Earth's magnetic field at quasi-DC). Whereas this analysis may be appropriate for measurements of an energized cable, it is unsuitable for estimating existing baseline conditions fundamental to the scientific process within an adaptive management approach. Disappointingly, recently published environmental impact reports for significant submarine power cable projects (URS 2006, DoI-MMS 2009) did not provide any additional insight on the subject of background EMF levels in the marine environment.

⁴ <http://www.agu.org/journals/jgr/>

Dalberg (2001) described a nearshore experiment in which the ambient electric field was measured off the coast of Sweden in shallow water near a harbor. While the ambient noise field in Oregon cannot be assumed to similar in amplitude character, this citation does provide insight into the possible span of values in at least one near-shore locale.

In summary, the best sources of information on background magnetic and electric field strength in the marine environment were found in the geophysical literature. The majority of data from such sources focused on the deep ocean environment. The paucity of ambient EMF data in the nearshore environment was apparent. However, sufficient information was located to draw the general characteristics of the EMF environment and identify factors affecting the magnitude of the EM fields.

5.2 Sources of EMF Noise in the Ocean (Natural and Man-made)

Sources of EMF background noise are varied and cover a broad frequency spectrum. Between 10^{-3} and 10^3 Hz, the primary frequency spectrum of interest to wave energy stakeholders, sources include various geo- and solar-related phenomenon as well as certain man-made sources. Table 2 identifies the dominant sources in this frequency regime that may be encountered in the continental margins, derived from Scripps (1990), Chave, Constable, and Edwards (1991), and Dalberg (2001).

Table 2 – Dominant Sources of Electromagnetic Noise in the Shallow Marine Environment

Potential Source	Typical Frequency Range (Hz)	Comment
Internal ocean waves, currents	variable	tidal action, local currents, gyre, and ocean fronts; solitons
Ionosphere and Magnetosphere Pulsations	0.002 – 1 Hz	Driven by solar wind
Bottom Boundary Layer Turbulence	0.01 – 0.1 Hz	turbulence due to local sub-sea geology
Surface Gravity Waves	0.05 – 1 Hz	Wind driven waves and swell
Microseisms	0.1 – 0.3 Hz	Caused by interference of surface gravity wave trains
Rayleigh Waves	0.1 – 1 Hz	Waves on ocean bottom due to seismic activity
Earth-Ionosphere Cavity Resonances	7 – 80 Hz	Schumann Resonances induced by worldwide lightning, including 7.83, 14.3, 20.8, 27.3 and 33.8 Hz ⁵
Man-made	30 – 1,000 Hz	Electrical power generating equipment, including sub-harmonics

In general, the amplitude of naturally occurring electromagnetic fields increases with decreasing frequency, and is driven by solar and geo-processes such as ionospheric sources. A number of measurements below 1 Hz have been made in the deep ocean environment, but noise floor limitations of instrumentation often precludes measurement of the electromagnetic spectrum in quiescent deep ocean conditions above approximately 1 Hz. As of 1990 (Scripps 1990), no known measurements had been conducted in shallow water, and therefore much of what is understood about EM behavior in shallow water has been based on theoretical analyses.

5.3 Character of Ambient EMF in the Nearshore Environment

For the purposes of this report, the definition of nearshore environment is adopted from the Oregon Department of Fish and Wildlife (ODFW 2006), which defined the nearshore region as that area between the shoreline and the 30-fathom depth contour (approximately 180 feet of depth). This region is desirable for wave energy extraction due to the energy of incoming waves, and the proximity to shore for power export.

⁵ http://en.wikipedia.org/wiki/Schumann_resonances

It is clear that the nearshore environment exhibits a number of EM characteristics not seen in the deep ocean. Differences between the deep ocean and continental margin environments that affect EMF characteristics are driven by water currents, wave action, proximity of the bottom to the ocean surface, and the underlying geologic structure. A number of observations are made in the literature that pertains to EMF sources on the continental margin (Scripps, 1990; Chave, Constable, and Edwards, 1991; Dalberg, 2001; and Cox, Filloux, and Larsen, 1971):

1. Depending on the geophysical structure of the area, man-made signals from shore or nearby cities can propagate through the seafloor and become an important source of noise in the nearshore environment.
2. The ocean is always moving. Thus, EM fields are continually being generated by the interaction of the conductive seawater moving through the Earth's naturally occurring magnetic field. Local bathymetry, ocean currents, wave action, and weather produce complex water velocities in the continental margins and induce local turbulence, and thus create largely unpredictable EM field conditions that change over time. Internal ocean wave structure on the shelf is highly variable, and does not exhibit steady-state fluctuations as is often observed in the deep ocean.
3. Soliton waves or transient "wave packets" due to non-linear internal waves from intersecting tidal actions and ocean currents are known to be present in shallow water, and their magnitude is expected to be high due to the velocity at which they move.
4. Frequencies and magnitudes of naturally generated fields due to water motion are highly dependent on local conditions of bathymetry, weather, and geologic substrate. Natural geo- and solar-driven sources of EM fields are also highly non-stationary, and exhibit a strong dependence on physical location. A coastal effect is described in which the sloping geology in the continental shelf can impart strong electrical fields normal to the coastline.
5. Compared with the deep ocean environment, where the water depth provides a low-pass filtering from surface EM effects, the EM background noise from the surface is less shielded, and thus, noise in the continental margins is expected to be higher than that observed in the deep ocean.

Along the Oregon coast, including locations near the proposed Ocean Power Technologies (OPT) site near Reedsport, a number of physical parameters are present that serve to increase ambient EM field levels when compared to the deep ocean environment. The addition of local water flow due to rivers and runoff in an estuarine environment, or surface wave conditions from tidal action, swell, and surf serve to further add to EM fields in the nearshore environment that would not otherwise be present in the deep ocean data set.

5.4 Magnitude of Ambient EMF in Nearshore Environment

No specific citations were identified that described the amplitude of EM fields along the nearshore boundary on the Oregon coast. However, a number of citations provided a reasonable range of values in the deep ocean environment, an area known to be quieter than the nearshore environment. In Key (2003), magnetic and electric field spectra were modeled to show the range of amplitudes expected on the ocean surface and deep ocean. (Figure 1). While these figures do not explicitly define the range of values for the more energetic nearshore regime, it is nonetheless instructive to examine estimated values for comparative purposes. Consider the case of magnetic field amplitude. In the left hand figure, the solid line depicts amplitudes expected on the ocean surface. Over the range of 0.001 Hz to 100 Hz, amplitudes of the magnetic field range from 10^{-8} to 10^{-12} , or 4 orders of magnitude. Contrast this with the black dashed lines, showing results for two different deep ocean models. At a minimum, an amplitude change exceeding twelve orders of magnitude is expected from the surface to the deep ocean. Also shown on this chart is a grey line depicting an achievable sensor noise floor (*e.g.* 100fT at 1 Hz, or 10^{-13} T/ $\sqrt{\text{Hz}}$) for magnetic instrumentation, showing the lower limit for which measurements could reasonably be obtained.

Similarly, the chart on the right shows estimated electric field levels in the deep ocean environment. Near frequencies of 1 Hz, the expected electric field could vary between 10^{-10} and 10^{-16} V/m/ $\sqrt{\text{Hz}}$, whereas the electrode noise floor of a typical low-noise electric field sensor is 0.1nV/m at 1 Hz (10^{-10} V/m/ $\sqrt{\text{Hz}}$). This, it would be difficult to make measurements above 1 Hz for noise fields below 0.1nV/m. In comparison, levels observed in the nearshore environment along the Swedish coast (Dalberg, 2001) varied between 8 and 56 nV/m at 1 Hz. This supports the notion that nearshore amplitudes of at least the electric field spectrum can be substantially noisier than those observed in the deep ocean environment.

It is expected that surface gravity wave motion will provide a significant source of naturally occurring electrical field energy within the regime of approximately 1 to 30 second periods (0.03 to 1 Hz) due to the electromagnetic induction effect. As explained by Faraday's law of induction, an electrical field is induced into a conductive medium while moving through a

magnetic field⁶. In general, an electrical voltage is present in flowing seawater due to the Earth's magnetic field. Furthermore, the magnitude of the induced electrical field in seawater between two electrodes is equal to the magnitude of the magnetic field through which a wave is moving multiplied by the average velocity of the water (Fristedt 2002). The induced electrical voltage is directly proportional to the water velocity, since the Earth's magnetic field can be considered constant.

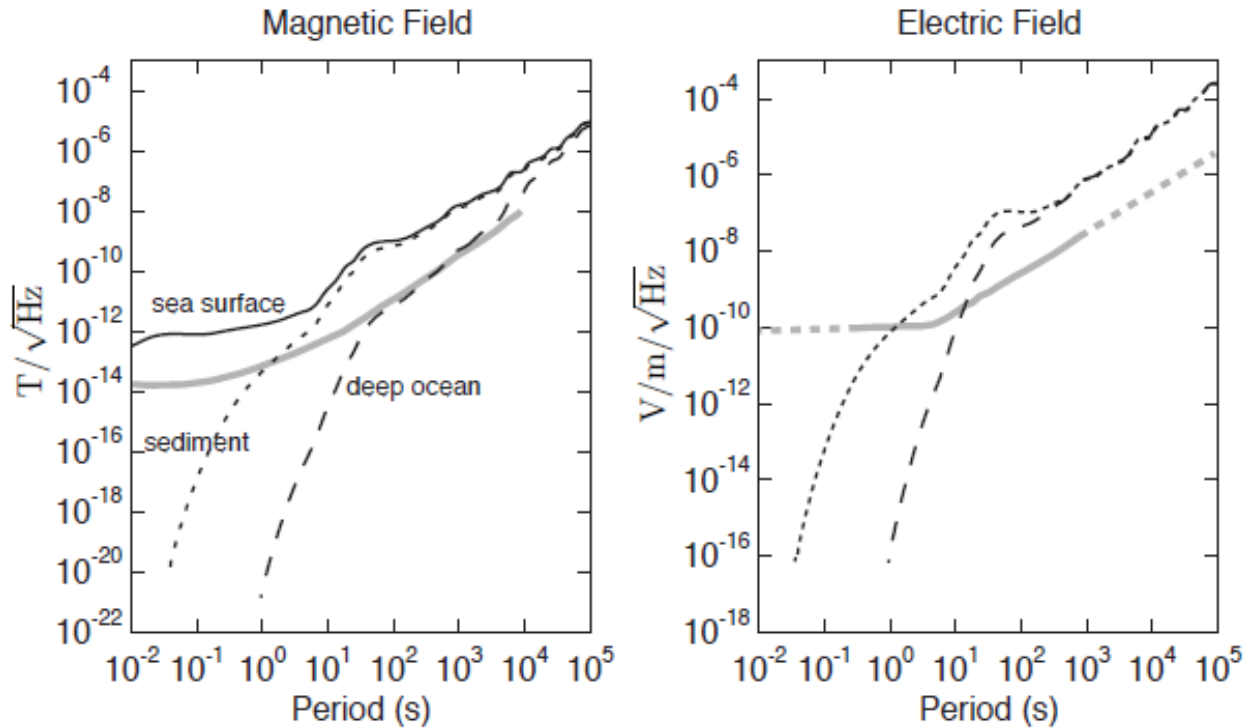


Figure 1 – Representative Modeled Magnetic and Electric Field Spectra in Ocean Environment, from Key (2003).

Measured data acquired during the COWRIE-sponsored investigation do not add clarity to the possible levels of background noise in the EMF, primarily due to the selection of sensors employed for the field testing. The electric field probe reported a maximum sensitivity of 420nV/m (10^{-6} V/m), or approximately 10,000 times less sensitive than instruments designed to measure the deep ocean environment. The magnetic field sensor had a maximum sensitivity of 0.5nT ($\sim 10^{-9}$ T), or nearly 100,000 times less sensitive than deep ocean magnetometers. While the sensitivity values exhibited by these sensors may be appropriate for assessing the field

⁶ Mathematically speaking, induced electric field potential, a vector quantity (E), is related by cross product of the water velocity vector (v) and magnetic field, also a vector quantity (B), by: $\vec{E} = \vec{v} \times \vec{B}$

strength immediately adjacent to an energized cable, they lack sensitivity to assess existing baseline background conditions in the nearshore environment.

The preceding discussion offers modeled results and a momentary snapshot of an actual measurement in Sweden. In the general case, however, nearshore magnetic and electric fields are non-stationary, and vary with a multitude of input factors. For example, increased solar activity will increase the amplitude of the spectrum; more energetic ocean waves due to passing storms will increase the EM field strength near the higher waves. Nearshore ambient EMF conditions are highly variable in time and in location, and levels vary due to changing oceanographic and weather conditions.

5.5 Implications for Nearshore Marine EMF Measurements

The existing database for nearshore ambient EMF conditions is lacking, but theory predicts behavior that provides insight into the problem of quantifying the range of EMF levels in the nearshore environment. In practice, it has been demonstrated that EMF levels in the nearshore environment can, and do, exceed amplitudes measured in the deep ocean in the regime of 1 Hz and above. Sensor noise floor notwithstanding, it should be a straightforward matter from a data acquisition perspective to acquire suitable ambient noise measurements in the nearshore environment using instrumentation with specifications suitable for the deep ocean—at least below 1 Hz. Less is known about the expected environmental background conditions for electric and magnetic fields above 1 Hz, which may pose an instrumentation challenge.

Up to this point, the focus has been on the minimum observable levels in the ocean environment. Of perhaps equal importance to the discussion is consideration for the maximum ambient levels that might be observed. No known data exists that describes the maximum expected magnetic or electric field levels in the nearshore environment; perhaps use of in-air potentials adjacent to the in-water environment could form a worst-case proxy as a rough-order-of-magnitude estimate for instrumentation design. Clearly, some level of study is required in this area to fully inform the instrumentation design parameters for conducting full-scale EMF measurements in the nearshore marine environment. Such analyses are beyond the scope of this report.

6. CONCLUSIONS

This study was commissioned with the goal of collecting and summarizing existing data on the nearshore electric and magnetic field ambient conditions to serve as a surrogate for the existing conditions suitable for an environmental baseline of wave energy projects on the Oregon coast. During the literature survey, it became apparent that the existing data set for nearshore EMF data, and in particular electric field data, was essentially nonexistent. However, extensive examples were found in literature citing deep ocean conditions based on oceanographic and geophysical research that could be used as the “best-case” proxy to estimate absolute minimum conditions expected on the continental margins.

Although actual measured data is lacking, substantial theories have been developed over the past several decades of study in the deep ocean environment, bolstered by terrestrial and atmospheric understanding of how solar and atmospheric conditions contribute to naturally occurring EMF. Motivated primarily by geophysical research and economic considerations (*e.g.* oil exploration) deep ocean research in EMF has served to inform expectations for the nearshore environment.

The following conclusions can be drawn from the literature with respect to the nearshore environment on the subject of electromagnetic background levels:

1. Very little data EMF data exists for the nearshore marine environment. No published electric field data could be found for the Oregon coast
2. A number of different sources of nearshore EM fields exist in theory, including man-made noise, but is predominately comprised of naturally occurring phenomena
3. EMF levels are highly dependent on physical location
4. For a given location, EMF levels can significantly change over time and can be highly variable. Typical sources affecting amplitudes include, but are not limited to
 - a. Wave motions, including long-wavelength swells and shorter period surface waves, usually driven by wind or distant storm activity
 - b. Internal oceanic waves or fronts, usually driven by tides or nearby estuarial flows
 - c. Solar activity
 - d. Turbulence due to varied oceanic flow over varied bottom bathymetric conditions;
 - e. Man-made sources, including electrical power generating facilities or electrically based transportation

5. EMF levels in the nearshore environment are likely higher than those observed in the deep ocean environment
6. The scale for changes to the EMF field is dependent on individual forcing functions. For example, tidal flows can produce fields that extend for many kilometers or tens of kilometers, solar changes can affect scale on the order of hundreds or thousands of kilometers, and surface gravity waves can affect fields on the scale of meters or tens of meters.

In conclusion, additional data is required to quantify existing baseline conditions. A number of theories exist, generally based on deep ocean knowledge, that describe possible naturally occurring nearshore mechanisms that create EM fields. Measured data would significantly increase the understanding of these theories, and serve to refine our understanding.

APPENDIX A – GLOSSARY OF TERMS

The following terms are defined to assist in the understanding of their use within this report. To the greatest extent possible, definitions are stated directly from the quoted sources.

Adaptive Management

Type of natural resource management in which decisions are made as part of an ongoing science-based process. Adaptive management involves testing, monitoring, and evaluating applied strategies, and incorporating new knowledge into management approaches that are based on scientific findings and the needs of society. Results are used to modify management policy, strategies, and practices. (Source: Federal Register 65, no. 202, October 18, 2000, p. 62571)

Continental Margin

The continental slope connects the continental shelf and the oceanic crust. (See Figure A1 below.) It begins at the continental shelf break, or where the bottom sharply drops off into a steep slope. It usually begins at 430 feet (130 meters) depth and can be up to 20 km wide. The continental slope, which is still considered part of the continent, together with the continental shelf is called the continental margin. It does not include the continental rise.

(Source: <http://www.onr.navy.mil/Focus/ocean/regions/oceanfloor2.htm>)

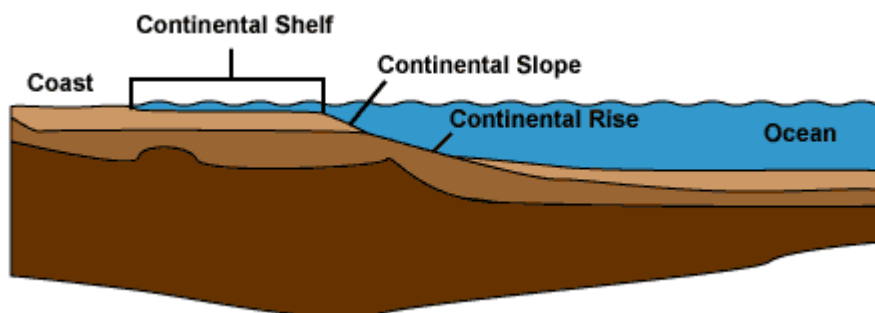


Figure A1 – Ocean Regions

Continental Shelf

Surrounding nearly all continents is a shallow extension of that landmass known as the continental shelf. This shelf is relatively shallow, tens of meters deep compared to the thousands of meters deep in the open ocean, and extends outward to the continental slope where the deep ocean truly begins.

(Source: <http://www.onr.navy.mil/Focus/ocean/regions/oceanfloor2.htm>)

Nearshore

Oregon's nearshore ocean is defined, for the purpose of the Nearshore Strategy, as the area from the coastal high-tide line offshore to the 30-fathom (approximately 180 feet or 55 meter) depth contour.

(Source: http://www.dfw.state.or.us/MRP/nearshore/species_habitats.asp)

Outer Continental Shelf (OCS)

The OCS consists of the submerged lands, subsoil, and seabed, lying between the seaward extent of the States' jurisdiction and the seaward extent of Federal jurisdiction. The continental shelf is the gently sloping undersea plain between a continent and the deep ocean. (Source: <http://www.gomr.mms.gov/homepg/whoismms/whatsocs.html>)

APPENDIX B – 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
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

APPENDIX C – BIBLIOGRAPHY

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Electromagnetic Field Study

Trade study: commercial electromagnetic field measurement tools.

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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.

Record of Revisions

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1. EXECUTIVE SUMMARY

This report describes commercially available methods and instrumentation currently used in a multitude of marine electromagnetic applications. The report describes state-of-the-art marine electromagnetic (EM) methods within their historical context and identifies the instrumentation necessary to achieve these methods.

A number of EM methods are used in the ocean today. Most sophisticated equipment is used for geophysical exploration, motivated by oil exploration and by the quest for knowledge of the Earth's structure. Practical techniques for conducting marine corrosion surveys and locating sub-sea objects such as cables and pipelines are common, with companies offering tools and services for hire. Techniques and equipment for ship signature measurement offer promising capabilities that are suitable for electromagnetic field (EMF) assessments of wave energy sites. While some techniques used in the marine environment have been successfully adapted from terrestrial methods of measurement, not all such techniques are applicable for marine applications.

In the last few decades, developments in low-cost, high-performance electronics have enabled a more widespread application of critical technologies important to the use of EM studies in the ocean. Both electric field and magnetic signatures in the ocean environment require extremely low noise conditions in instrumentation, and techniques are often focused on the development of methods to minimize the impact that noise, motion, or other external factors may have on the quality of the measurements. As a result, there are instruments and techniques commercially available that are capable of assessing near-shore EM signatures with a high degree of resolution. However, the affordability of such instruments off-the-shelf has yet to be determined.

2. INTRODUCTION

2.1 Purpose

This report summarizes commercially available techniques to assess underwater EM fields, including those techniques that use EM fields to assess physical phenomena, but may not assess the EM field itself. Mention is made of terrestrial technologies, with brief descriptions of the

technique, and the limitations for extensibility of the techniques to the sub-sea environment. The focus of this report is on the methodologies and techniques currently used, *e.g.*, a description of the state-of-the-art in subsea measurements; this report does not describe specific sensors, which are the subject of a companion report.¹

2.2 Background

Electromagnetic techniques have been used underwater for decades, for a multitude of purposes. Tools have been used over the years with varying degrees of success to locate conductive or magnetic objects (sunken ships, cables), to explore for oil and gas, to assess the structure of the Earth's geology or other physical features, and to detect military threats, such as submarines, mines, or underwater vehicles. This report identifies the use of EMF tools in their historical context, and describes the current state-of-the-art for commercially available technologies.

2.3 Report Organization

This report contains six sections and three supporting appendices. The first section contains the executive summary. Section 2, the introduction, provides the project motivation and background. Next, the analytical approach is described (Section 3), followed by a description of fundamental instruments (Section 4) as background for the methods listed. Section 5 describes commercially used electromagnetic techniques available today in a variety of marine EM applications. Finally, Section 6 presents the report conclusions. Appendix A contains a glossary of terms used within the report. Appendix B provides an acronym list. Appendix C contains the bibliography of references.

3. APPROACH

Using publicly available sources, known marine electromagnetic methods and techniques were surveyed. Sources included published research papers and dissertations, measurement standards, environmental reports and documentation, personal communications with researchers, vendors or suppliers of electromagnetic products and services, and the Internet. Current industry best practices were sought. The historical context was also investigated where appropriate to

¹ Slater, M., Schultz, A. (2010). Summary of commercial electromagnetic field sensors for the marine environment. Oregon Wave Energy Trust.

understand the development continuum of instruments and methods from primitive origins to the state-of-the-art.

4. ELECTROMAGNETIC TOOLS: PHYSICS-BASED INSTRUMENTS

4.1 Early Discoveries

In 1820, Hans Christian Ørsted developed an electromagnetic instrument that showed that electric and magnetic fields were directly related. Ørsted was the first to prove this finding, and with follow-on work, he proved that a changing electric current flowing in a conductor produces a magnetic field. Soon after Ørsted's findings, Ampere conducted a set of experiments and showed that a coil of wire carrying a current behaves like an ordinary magnet, and mathematically derived Ampere's law. Later, he developed an instrument to measure the flow of electricity, and contributed to the development of the galvanometer, also developed in 1820, by Schweigger. The galvanometer was comprised of a coil of wire wrapped around a graduated compass. This combination of works, completed less than 200 years ago, were the genesis for discovering the relationship between electricity and magnetism, and inventing crude instrumentation for the measurement of such phenomenon. Additional contributions to the field in the 1800's, including those by Faraday and Maxwell, increased our level of knowledge in both the theory of how electromagnetic phenomena are described, as well as practical information, such as Faraday's observation that a changing magnetic field also produces an electric field.²

4.1 Modern Adaptations – Magnetometers

Today, the relationship between electricity and magnetism is well understood, such that electromagnetic fields comprised of electrically charged objects are considered one of the fundamental forces of nature. It is important to note that EM fields are comprised of both electric field (E-field) and magnetic (B-field) components, although it is possible to have one without the other and vice versa. A moving magnetic field creates an electric field and a moving electric field creates a magnetic field.³ While early experimenters found the relationship between electric potential and magnetism, modern instrumentation often uses separate and

² http://en.wikipedia.org/wiki/Timeline_of_electromagnetism

³ http://en.wikipedia.org/wiki/Electromagnetic_field

distinct properties of each field type to observe physical phenomena. Thus, electric field sensors and magnetic field sensors are often not used together.

In the simplest sense, the earliest instruments focused on the measurement of magnetic fields. In particular, most early instruments measured magnetic field direction. As magnetic instrumentation became more sophisticated, tools such as magnetometers and gradiometers were developed to measure the strength of magnetic fields, the rate of change of such fields, and field direction. A magnetometer is used to measure the intensity or strength of a magnetic field, while a gradiometer measures the rate-of-change, or the gradient, of a magnetic field.^{4,5} Measurements of the Earth's magnetic field have been made for over 100 years using magnetometers in a photographic technique called magnetogram.⁶ Perhaps useful for slow changes to the Earth's magnetic field, the progress of science and technology provided more convenient techniques and instrumentation to assess magnetic fields. Today, a variety of measurement instruments and techniques are used to measure the strength and direction of magnetic fields. Table 1 briefly highlights several types of magnetometers used today, and identifies the range of uses for each.

More frequently, a gradiometer is built simply by using two magnetometers, by which the difference in output signal between two magnetometers provides a measurement of the magnetic gradient between the two magnetometers. Gradiometers, in particular, are commonly used to locate submerged objects, or to assess anomalies in the Earth's gravitational field, wherein the rate of change is the quantity of interest, instead of the field strength, or magnitude of an EM field—for which a magnetometer is used.

⁴ <http://www.merriam-webster.com/dictionary/magnetometer>

⁵ <http://www.merriam-webster.com/dictionary/gradiometer>

⁶ <http://www.ctsystems.eu/support/history-mag.html>

Table 1 – Types of Magnetometers

Magnetometer Type	Level of Complexity	Achievable Noise Performance [†]	Uses
Hall effect	Low	Poor	Industrial applications, automotive
Rotating coil	Moderate	Poor	Obsolete, not commonly used
Induction Coil	Low	50 fT/√Hz	AC only, widely used
Fluxgate	Moderate	3 fT/√Hz	Used in geophysics
Magnetoresistive	Moderate	4nT/√Hz	Integrated circuit
Proton precession	High	100 pT/√Hz	Used in geophysics
Cesium vapor	High	4 pT/√Hz	Used in geophysics
Spin-exchange relaxation-free (SERF) atomic	Extremely high	1 fT/√Hz	Under development
Superconducting quantum interference devices (SQUID)	Extremely high	3 fT/√Hz	Under development
Sources: http://en.wikipedia.org/wiki/Magnetometer http://www.tumanski.x.pl/coil.pdf http://www.ssec.honeywell.com/magnetic/datasheets/hmc2003.pdf [†] Best case noise floor described in literature, caution should be used for specific instruments to verify actual performance			

4.2 Electric Field Probes

Simple, handheld or “free body” meters are commonly used to measure terrestrial (in air) electric field potentials wherein the voltage potential is measured between two plates. Another type of meter used in terrestrial applications is the ground-reference meter, which measures the potential between an in-air probe and ground potential. This meter is a bit more challenging than the free-body meter (which provides a relative reading at a point in space), since a known ground condition must be established to obtain meaningful measurements. The use of free-body meters for conducting atmospheric electric field surveys is described in IEEE Std 644-1994 (R2008).

Terrestrial meters operate on the principle that electric fields occur in the presence of a dielectric (non-conductive) medium, namely air. A high-impedance voltmeter is connected to each probe, and the electric field potential is measured directly. This condition is starkly different than is encountered in the ocean, where probes are surrounded by a conductive medium—seawater—and thus an electric field cannot be sensed in the same manner as in air. There are no electric field survey standards for making electric field measurements in seawater. In fact, the

propagation of electric fields in the sea is enhanced by the presence of dielectric materials above (atmosphere) and below (resistive rock, or perhaps oil or gas reservoirs). Although within the seawater itself, electric potentials attenuate very quickly with distance from the source. Adaptation of terrestrial electric field meters to the sub-sea case is also not feasible. Most free body meters have a sensitivity range of perhaps 1 volt/meter to thousands of volts per meter, and are useful for quantifying electric fields in the presence of overhead power lines or power generating equipment. In the ocean, techniques in the use of electric potentials range in the microvolt/meter range and below—a billion or more times smaller than terrestrial hand-held meters are able to measure.

In his seminal paper, Webb (1985) described the design, construction, and testing of an oceanic electric field potential system. Using then state-of-the-art electronics and silver-silver chloride electrodes, Webb's team successfully demonstrated that valid electric field measurements could be made in the ocean at very low levels (on the order of sub-nanovolt resolution) over long distances (~1/2 to 1 km). This development effort, funded by the Office of Naval Research, described the “early years” and was the nucleus around which additional development followed to improve electric sensing technologies in the ocean. One issue of note in this work was the limiting factor of the probes themselves, which set the minimum level of noise for the system.

Two major types of electric field probes are used in the ocean. In practice, the electric fields to be measured are of such a low level that electrical noise emitted by probes can occlude the desired quantity to be measured. Therefore, extensive efforts are made to design and fabricate probes from materials that are very low in noise, to make the resistance between the probe and the surrounding seawater as low as is reasonably possible. The phenomenon of galvanic corrosion currents in dissimilar metals can be orders of magnitude higher than the quantity to be measured. Care must be taken to select materials that do not exhibit this phenomenon. Because the seawater is conductive, use of a resistive probe is feasible. Silver-silver chloride (Ag-AgCl) electrodes are commonly used in sub-sea electric field measurements. Ag-AgCl electrodes, which exhibit reasonable noise levels, are relatively straightforward to manufacture. Other chemical formulations, such as lead-lead chloride may also be suitable and provide adequate performance, but silver chloride probes currently dominate the commercial market.

Commercially, Ag-AgCl electrodes are frequently fabricated using silver rod or wire coated with silver chloride, housed within a plastic tube filled with an electrolytic solution and a porous plug to enable ion exchange with the surrounding seawater. This results in a chemical reaction that increases the surface potential of the probes due to an increase concentration of chloride ions. Commercial reference electrodes consist of a plastic tube electrode body. Two such probes are connected to a voltmeter, which senses the electric field potential between them (Dalberg 2001)⁷. Ultimately, silver-silver chloride probes are limited by their Johnson noise due to the resistance of the probes themselves, ranging between $100 \text{ pV}/\sqrt{\text{Hz}}$ and $1 \text{ nV}/\sqrt{\text{Hz}}$ for a source resistance of a few ohms.⁸

More recently, Crona and Brage (1997) designed and demonstrated the feasibility of carbon fiber electrodes. The primary driver for use of carbon fiber electrodes is the speed at which the probes can provide valid data. Often, metallic or other electrode types (*e.g.* zinc) can require up to one-week stabilization time prior to obtaining valid measurements. Carbon fiber electrodes have been shown to provide useful data within fifteen minutes of deployment, and thus solve some of the practical issues with the use of metallic resistive electrodes. However, considerable DC sensitivity is given up when compared to conventional silver-silver chloride electrodes. Carbon fiber electrodes are commercially available, and are especially favorable for military applications where rapid use of electrodes is a highly desirable trait.

A newer approach to use capacitively coupled probes has shown promise. At least one company states that system noise performance for their probes exceeds that of silver-silver chloride electrodes in the controlled EM source frequency regime.⁹ These probes do not directly contact seawater, but are instead electrically isolated from the surrounding seawater by an insulating dielectric layer, such as an epoxy or metal oxide material. These probes respond to changes in the electric field via changes in the polarization of the electrode surface due to the local flux density, creating an equal and opposite charge on the measurement instrumentation. Because capacitive probes are not connected directly to the seawater, they do not suffer from corrosion

⁷ http://en.wikipedia.org/wiki/Silver_chloride_electrode

⁸ Keithly Low Level Measurement Handbook

⁹ <http://www.quasarusa.com/geo/technology.html>

problems over time, which can become an issue with resistive electrodes. The principle of operation for these probes and an overall electric field measurement system is described in a recent (2008) US patent application. While this probe technology was developed and funded under a Navy small business research program, there are some limited licensing rights available.¹⁰

4.3 Electric Field Sensor Technology Limitations

In spite of several recent innovations in the field, measurement of underwater electric potential suffers from limitations in the sensing technologies, system noise floor primarily. Physical limits on the amount of noise from the probe itself or the sensing electronics set the limits for measurement. One way to overcome this limitation is to widely space the electric field electrodes. In Webb et al. (1985), a spacing of 1,000 meters was used, thus providing a net improvement in sensitivity by 1000 times compared to a nominal 1-meter spacing. This spacing may be acceptable for oil exploration or perhaps a military need, but is simply impractical for near-shore measurements.

The input noise of the sensing electronics provides a limiting case. For conventional electronics, a noise floor of approximately $1 \text{ nV}/\sqrt{\text{Hz}}$ can be achieved without using exotic materials. In the mid 1970's, during the early days of sub-sea e-field electronics development, commercially available laboratory-grade low-noise preamplifiers had a noise floor measured in microvolts. By shrewd electronics design, Webb's team managed to create a very limited-bandwidth amplifier that achieved a noise floor measured in nano-volts—at least three orders of magnitude than was available only ten years previous. Commercial-off-the-shelf (COTS) low-noise wideband amplifiers are available today with nano-volt input noise figures from at least one company. While expensive, they demonstrate that pre-packaged electronics are available for commercial use as a stock item. Commercially available analog-to-digital conversion (A/D) systems are on the market today provide suitable resolution and noise floor limitations to sense the output of commercial amplifiers.

¹⁰ <http://appft.uspto.gov/netahtml/PTO/srchnum.html>, search term: DN/20080246485

Simply put, noise floor limitations will drive the design and affordability of undersea electric field measurement equipment. Noise floor limits for conventional semi-conductors are reaching theoretical minimums, and thus large improvements in commercial sensing equipment are unlikely. Although, the cost curve should trend downward due to advances in electronics development. It is further expected that an increase in volume production of probes in support of oil exploration and military needs will place downward pressure on prices in the future.

5. COMMERCIAL EM METHODS

The previous section described the basic magnetic and electric tools of the trade, which are based on fundamental physical laws. This section describes the primary uses of the tools identified in the previous section, primarily for commercial applications and areas of research.

5.1 Motivation for Oceanic EM Instrumentation

In Nabighian (1991), Chave, et al. summarized the commonly used EM principles for seafloor exploration, previously thought to be of little value due to the relatively high electrical conductivity of the seawater. Largely unexplored, the seafloor was not imagined to be a potential source of commercial value. However, beginning in the early 1980s, geological discoveries on the seafloor gave rise the need for new and improved methods for seafloor and sub-seafloor exploration. As on land, electromagnetic techniques were employed on the seafloor to map the electrical conductivity, and hence the geologic structure of the seafloor and underlying substrate. Furthermore, interest in prospecting for oil and gas reserves increased in this same period, providing ample economic motivation for advancements in EM methods.

Physically, the conductive seawater acts as a low pass filter for higher frequency EM fields generated in the Earth's ionosphere and magnetosphere. Because of this filtering effect, especially at higher frequencies above a fraction of a hertz, noise levels in the deep ocean are miniscule, in spite of the substantial levels measurable at the sea surface or atmosphere. In the nearshore area, man-made sources of EMF likely produce noise along the continental shelf through areas of low conductivity in the seafloor. In shallower water, EM fields are strongly attenuated above 1 Hz. On the other hand, local geology and generally energetic seawater movement in the near-shore areas due to turbulence, wave activity, and thus could create areas of

intensified electric fields due to interaction of naturally occurring magnetic field of the Earth—and yet yield a minimal sub-sea magnetic effect (Chave et al. in Nabighian, 1991).

Researchers at the Scripps Institute of Oceanography have been at the forefront of development in the area of EMF sensing in the deep ocean. In 1996, the Seafloor Electromagnetic Methods Consortium (SEMC) was formed to develop “electromagnetic methods for the purpose of offshore petroleum exploration.” Members of the consortium contributed to the development of geophysical exploration techniques, such as are described below, and highly sensitive electric and magnetic instrumentation.¹¹ Some member companies within the consortium offer integrated sensors or survey services to the petroleum industry.

The following methods have provided economic and academic benefit for terrestrial and marine exploration. However, it should be noted that none of the methods described herein provide any substantially meaningful benefit to the assessment of the EMF signatures of wave energy conversion (WEC) devices or submarine power cables. More likely, such methods can be used to predict any long-distance effects, if any, from WEC devices or submarine power cables as a man-made EM source that could propagate for some distance through the electrically resistive seafloor. Propagation of EM energy in conductive seawater is easily explained. However, interaction of nearby resistive boundaries, including the sea-surface and sea floor, especially in the unique, electrically constrictive geology in the coastal zone could be measured or at least modeled using these techniques.

5.2 Magnetotelluric Methods

Magnetotelluric (MT) methods are used to map spatial variations of the Earth by measuring naturally occurring EMF at the Earth’s (or seafloor) surface. MT methods were first used terrestrially to study and better understand the Earth’s geophysical or geological structure. Such methods rely on naturally occurring EM excitation functions in the Earth’s ionosphere and magnetosphere, from which the electrical conductivity of the surrounding Earth can be discerned. MT is a popular method for exploration of economically valuable commodities such as oil or minerals, or for groundwater. The magnetotelluric method is used in the subsea

¹¹ <http://marineemlab.ucsd.edu/semc.html>

environment for oil exploration. However, in seawater, due to the low-pass filtering effect of the conductive seawater, a usable upper limit of the MT spectrum is typically 1 Hz.¹² Unlike in terrestrial applications, oceanic use of MT methods require that sensors are located on the seafloor to minimize the effects of motionally induced EM fields due to movement of the conductive seawater with respect to the Earth's magnetic field.

5.3 Audio-Magnetotelluric

Audio-Magnetotelluric (AMT) is a technique that uses higher frequency, *i.e.* radio wave EM energy from 1 to 20 kHz or higher. AMT can provide excellent results for the Earth's structure from a few meters down to several kilometers, an extremely valuable regime for geophysical exploration or prospecting. One major drawback of this method is the presence of a "dead band" between 1 and 5 kHz, which is caused by a lack of a strong naturally occurring source of EM energy in that band. Even so, Chave et al. argues that AMT is not useful even in shallow water due to the rapid attenuation of EM fields above 1 Hz.

5.4 Controlled Source Methods

5.4.1 Controlled Source Magnetotellurics

In standard or natural source MT, naturally occurring variations in the Earth's magnetic field are used for EM observations. In Controlled Source Magnetotellurics (CSMT), the naturally occurring variations are enhanced using man-made sources to increase the available signal strength and bandwidth of the MT analyses. CSMT methods reduce the dependence on naturally occurring sources to excite the Earth's strata, instead using active methods by introducing artificial EM signals and measuring the response. Using this method, both electrical resistivity as well as conductivity can be measured. Regions of higher conductivity can indicate possible sources of conductive sources, such as iron, graphite, or nickel. Because of the ability to control the source waveform, CSMT allows correlation of source and receiver signals and provides a higher degree of coherence between source and receiver than passive MT methods.¹³

¹² <http://en.wikipedia.org/wiki/Magnetotellurics>

¹³ <http://www.osti.gov/bridge/servlets/purl/760306-qYSzci/webviewable/760306.pdf>

5.4.2 Controlled Source Audio-Magnetotellurics

Controlled Source Audio-Magnetotellurics (CSAM) is a highly useful technique for mineral exploration, mining, petroleum, and geothermal resources, hydrogeology and other geotechnical needs. With the use of active sources, the “dead band” described previously can be bridged with excellent results obtained.¹⁴

5.4.3 Controlled Source Electromagnetics

In the marine environment, Controlled Source Electromagnetics (CSEM) has proved to be highly valuable for prospecting for oil reserves. Compared to traditional seismic (acoustic) methods for oil exploration, which relies on the density of the substrate to detect reservoirs of oil, CSEM relies on the conductivity of the substrate by using similar types of signal processing methodologies. The added benefit for CSEM over seismic methods is that only one third of discovered reservoirs using seismic methods produce any oil (many are filled with water). However, with CSEM, the methodology can verify if the contents is oil or water based on the electrical conductivity. As a result, CSEM and related methodologies have been popular for oil exploration.¹⁵

Electromagnetic sources are commonly comprised of vertical or horizontal electric dipoles, magnetic dipoles, or some combination thereof, using the physics of electrical and magnetic properties to assess the Earth’s underlying geologic structure. Different types of sources and sensors, together with their deployed orientation can be used to excite various modes of EM behavior to exploit the physical characteristics of each mode type to investigate different physical properties of the seafloor. Physically important EM modes observed are termed transverse magnetic mode (TM, also toroidal mode in the literature), and transverse electric mode (TE, also seen as poloidal mode, or PM in the literature, indicating that flux lines “point” towards the poles). The meaning of these modes has to do with the orientation angle of the field relative to the boundaries defining regions of differing conductivity. By way of example, a horizontal electric dipole (*e.g.* a power transmission cable with an electrical sea-return path)

¹⁴ <http://www.fugroground.com/products&services/acquisition/ControlledSourceAudioMagnetotellurics.html>

¹⁵ http://www.geoexpro.com/sfiles/52/21/1/file/targeting_deeper_p36.pdf

laying on a flat seafloor excites a TM mode in the vertical direction, and the TE mode in the horizontal direction. Due to the orthogonal properties of electric and magnetic fields, the same result can be generated using a vertical magnetic dipole source. These techniques are used extensively in geophysical research and exploration, and thus a large body of technical knowledge exists for how such sources may affect long-range transmission of EM energy. Such experience is valuable for analyzing and determining the effects that local geology near a wave park will have for a given power cable configuration and wave-energy converter design, and perhaps as importantly, their installed configuration and orientation.

5.5 Direct Current Resistivity

In this method, developed in the early 1900s, direct current is passed between two grounded electrodes, and the resulting voltage potential is measured at another pair of electrodes some distance away to provide some degree of measurement of the resistance of the underlying geology. This method has also been used in seawater, and has been most useful for prospecting for sulfide mineral deposits.

5.6 Magnetometric Resistivity

This oceanic method relies on Ampere's circuital law, and is based on the static electrical potential of a grounded source. In this method, seawater electrodes are placed near the sea surface, and on the ocean bottom, and the resistivity of the seafloor can be measured based on the orthogonal properties of the magnetic field of the source.

5.7 Velocity Measurement Methods Using Electric Potential

Seawater is a reasonably good bulk conductor of electricity due to the presence of sodium and chlorine ions. As such, any movement of seawater in the presence of a magnetic field, including that of the Earth, will generate a weak electric field. This effect was described by von Arx (1950). Although he attributed the theoretical observation to Faraday in an 1832 lecture, wherein Faraday stated:

“Theoretically, it seems a necessary consequence that where water is flowing, there electric currents should be formed....”

Faraday lacked sophisticated equipment to prove this thesis, but by the mid 1900's, von Arx was able to successfully demonstrate the geomagnetic electrokinetograph (GEK), an instrument using two seawater electrodes towed behind a ship at sea to measure ocean currents due to the motion of the conductive seawater in the Earth's magnetic field. More recently, Dr. Tom Sanford, professor of oceanography at the University of Washington, has built upon von Arx's work and created very sophisticated techniques and state-of-the-art instruments using electric potential sensors to assess ocean currents and dynamics of the sea, based on the principle of motionally induced electric effects as a proxy for the velocity of seawater (Sanford 1978). The level of sophistication of Sanford's instrumentation to measure velocity profiles in the sea represents a clear example of the current state-of-the-art in oceanic electric field sensing.¹⁶

5.8 Other Marine EM Methods

On a much simpler scale, commercial tools and techniques are readily available for investigating galvanic corrosion of vessels, offshore platforms (*e.g.* oil rigs), piers, and other metallic objects. EM techniques used for the identification and location of submerged objects, including cables powered or not, sunken ships or pipelines rely on electromagnetic principles. Remotely operated vehicles can be equipped with magnetic or electric field sensors to survey an area for such objects, or for mines or other military applications. In addition, a surface workboat can suspend sensors on a cable, and drag them behind the vessel to survey for similar objects.

5.9 Marine Surveys

For the most part, survey tools are used for the detection problem, that is, to determine the location of an object. They are not frequently used to assess the field strengths of submerged EM sources. For example, cable "toning" is frequently done in the telecommunications cable industry to locate a fault in a submerged cable. A known frequency sine wave, usually 25 Hz, is electrically injected into a cable at a shore facility. A ship then tows an electrode behind the ship, and uses on-board analyzers to determine where the tone is detected, thus indicating the location of the cable fault for repair. The sensitivity of this active instrumentation is generally inadequate to conduct high-resolution surveys to establish baseline conditions. Such

¹⁶ Sanford, personal communication, 2009

instrumentation would be useful in a wave farm, for example, to trace the path of an electrical cable, wherein one end (the dry end) of the cable is available for access on which to inject the sine wave, or to locate a faulted cable, but is not generally extensible to EMF strength measurements. The following sections describe commercial methods for magnetic and electric potential surveys.

5.9.1 Magnetic Field Object Location

One use for the survey-class of tools is in the passive location of submerged objects that locally affect the Earth's magnetic field. One of the primary implementations for this type of technique is the use of gradiometer techniques, which are sensitive to changes in the magnetic field of an object, but are often less capable about measuring the absolute magnitude (strength) of a field.

Sensing electronics found in such instruments often lack spectral processing capabilities or time-sampling storage to discern the character of the source, and thus describe or suggest mitigation steps if an EMF field were detected. One recent EMF cable survey used a commercial cesium vapor magnetic sensor towed back and forth over a high-voltage DC cable. This particular instrument had an excellent noise floor ($4\text{pT}/\sqrt{\text{Hz}}$), but unfortunately lacked the ability to discern vector components or frequency spectra, as it was simply a “total field” instrument.¹⁷ This approach is not unlike the use of a simple handheld free-body electric field meters for use beneath power lines—sufficient for total field strength at a single point, but not adequate to address individual components of the field, nor the capability required to analyze the components of a magnetic field.

This technique could be used effectively for rudimentary assessments of the overall magnetic field strength compared to some reference field, such as the Earth's magnetic strength at some other frequency—providing some level of comparison, but perhaps inadequate for characterization of baseline conditions of an ecosystem.

¹⁷ Basslink Marine Magnetometer Monitoring Program

5.9.2 Electric Potential Corrosion Assessment

Corrosion of metal in seawater, also known as aqueous corrosion, is a common problem in the long-term maintenance of boat hulls, pipelines, and other marine structures. Aqueous corrosion is an electrochemical process. Electrolytic probes are often used to measure the voltage potential between the seawater and a structure to assess the possible rate of corrosion of the structure, or to verify that impressed currents on active cathodic protection systems are effectively operating. One methodology is to ground one probe of a voltmeter, and connect the other to a silver-silver-chloride electrode submerged in seawater adjacent to the structure to be measured. The measured voltage, compared to the reference voltage of the probe, provides an indication of the level of corrosion possible in that vicinity.¹⁸ Such equipment is sensitive in the millivolt region, since this level of voltage is sufficient to induce a corrosive environment for some exposed metals in seawater. Marine corrosion survey techniques use the same type of instruments as are used for more detailed electric field measurements (such as those used for geophysical exploration), but unfortunately, the basic sensitivity of such instruments are approximately one thousand to million times less sensitive (10^{-3} instead of 10^{-9}) than is required to assess expected electric fields in a wave park.

5.10 Ship Signature Measurement

Ships produce magnetic and electric field signatures due to a variety of mechanisms, including galvanic corrosion, or due to the effects of equipment on board, or the movement of the water by the propeller. Measurement and control of underwater electric potential (UEP) and magnetic signatures from ships is therefore important to ensure the safety and security of naval vessels, since influence mines can be triggered by magnetic or UEP sensors. The Naval Surface Warfare Center, Carderock Division (NSWCCD) is the Navy's laboratory responsible for ship electromagnetic signature assessment and control. NSWCCD performs research and development in underwater EM signature measurement systems and sensor technology, including the ultra-low and extremely low frequency bands (DC through 3 kHz)¹⁹, spanning the expected range of values for wave energy devices and submarine power cables. While details of

¹⁸ [http://www.stoprust.com/pdf/5/\(1994\)-Maximizing-the-Value-of-Underwater-CP-Surveys---Jim-Britton-\[Unknown\].pdf](http://www.stoprust.com/pdf/5/(1994)-Maximizing-the-Value-of-Underwater-CP-Surveys---Jim-Britton-[Unknown].pdf)

¹⁹ <http://www.dt.navy.mil/shi-sig/und-ele-sig-tec-div/index.html>

the Navy's EM signature measurement programs are not publicly available, a number of commercial companies offer electric and magnetic field sensor products suitable for underwater ship signature measurement. Such products are readily available, and offer state-of-the-art solutions with extremely low noise, wideband frequency coverage, and a variety of data acquisition performance—well suited to the wave energy conversion device and submarine cable assessment problem.

6. CONCLUSION

This study was commissioned to investigate and summarize commercially available electromagnetic field methods used in the marine environment. A multitude of instrument types and techniques are available for consideration, although not all are suitable for the assessment and monitoring of the EM fields produced by wave energy devices and submarine power cables in the near shore environment.

Several key drivers over the past several decades have encouraged investment into the development of EM instruments and techniques. Although primarily motivated (and funded) by the quest for petroleum reserves or increased security against military foes, commercial tools and techniques currently exist that could support the wave energy industry needs. Furthermore, advancements in electronics have substantially reduced noise levels and data acquisition performance over the past 30 years to enable low-noise measurements near theoretical limits of measurement methodologies without resorting to the exotic.

However, because suitable commercial instruments are targeted to oil exploration and the military, the affordability of suitable instrumentation off-the-shelf in a turnkey manner could be elusive. Some researchers have leveraged the development of commercially available components such as low noise amplifiers, high bit-count A/D electronics, and commercial sensors into affordable packages for specific research uses. Thus, the fundamental building blocks are in place and readily available to assemble affordable, reliable (and mass-produced) instruments using straightforward measurement methods. Specific instrumentation options are the subject of a companion report, which also describes the state-of-the-art in key technologies and components required to achieve affordable and reliable measurements—measurements

suitable to both characterize the near-shore ecosystem with sufficient resolution to identify changes over time, as well as achieve monitoring goals for wave energy developers.

APPENDIX A – GLOSSARY OF TERMS

The following terms are defined to assist in the understanding of their use within this report. To the greatest extent, possible definitions were stated directly from the quoted sources.

Greek prefixes – used to demonstrate orders of magnitude:

Prefix	Symbol	Multiplier
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	P	10^{-12}
femto	F	10^{-15}

Magnetometer – A scientific instrument used to measure the strength and/or direction of the magnetic field near the instrument.²⁰

Magnetotelluric method – An electromagnetic method used to map the spatial variation of the Earth's resistivity by measuring naturally occurring electric and magnetic fields at the Earth's surface.²¹

Telluric current – “Earth” current, or electrical currents moving through the Earth or seafloor²².

²⁰ <http://en.wikipedia.org/wiki/Magnetometer>

²¹ <http://www.glossary.oilfield.slb.com/Display.cfm?Term=magnetotelluric%20method>

²² http://en.wikipedia.org/wiki/Telluric_current

APPENDIX B – ACRONYMS

ASW	anti-submarine warfare
B-field	magnetic field
BWEA	British Wind Energy Association
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research into the Environment
DECC	Department for Energy and Climate Change
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
FEA	Finite Element Analysis
Hz	Hertz, cycles per second
MHD	magneto hydrodynamic
MHz	megahertz
MKS	meter-kilogram-second
MMS	Minerals Management Service
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
RMS	Root Mean Square
SI	International System of Units
SIO	Scripps Institute of Oceanography
THz	terahertz
UK	United Kingdom
WA	Washington
WEC	Wave Energy Converter

APPENDIX C – BIBLIOGRAPHY

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Electromagnetic Field Study

Electromagnetic field measurements: field sensor recommendations.

Prepared by
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on behalf of Oregon Wave Energy Trust

This work was funded by the Oregon Wave Energy Trust (OWET). OWET was funded in part with Oregon State Lottery Funds administered by the Oregon Business Development Department. It is one of six Oregon Innovation Council initiatives supporting job creation and long-term economic growth.

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.

Record of Revisions

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1. EXECUTIVE SUMMARY

This report presents a review of instrumentation and data acquisition requirements for near-shore marine measurements, including a comparison of existing tools and sensors available to conduct such measurements. Recommendations have been made for optimal instrumentation configuration suitable for characterization of EM fields in natural conditions and within the presence of energized wave energy power equipment within the context of the top level project requirements: to achieve methods for reliable, repeatable, and affordable electromagnetic field assessments.

The focus of this report is on the sensors, data acquisition equipment, optional auxiliary sensors to aid in data interpretation, and implementation recommendations. Results from this report may be used to evaluate recommended instruments on a prototype basis, suitable for acquisition of coastal ambient EM conditions and field strength in the proximity of an energized power cable in a marine environment.

2. INTRODUCTION

Measurement of EM data in the marine environment poses substantial acquisition challenges when considering the span of possible conditions ranging from quiescent ambient environments to locations adjacent to energized power generation equipment. The technical approach outlined in this report addresses these concerns by analyzing specifications and identifying instrumentation required to achieve project goals within the stated environment.

2.1 Purpose

This report was prepared to create a suite of recommendations for field sensors suitable to obtain reliable, repeatable, and affordable measurements within a set of expected natural and man-made conditions in the marine environment. The purpose of this report is to assimilate results of modeling studies, literature and commercial surveys, and technical principles to establish and recommend measurement requirements, including identification of suitable instrumentation.

2.2 Report Organization

This report contains six primary sections, and includes supporting appendices. The first sections contain the executive summary and introduction, and provide the project background. The methodology for how the results were derived is described next (Section 3), followed by recommended results for EM sensors associated data acquisition instrumentation (Section 4). Section 5 describes recommended auxiliary instrumentation to aid in the correlation and interpretation of data results. Appendix A contains an acronym list, and Appendix B contains a bibliography of references.

3. METHODOLOGY

Using the results from previous surveys, the first step in this analysis was identification of possible measurement techniques and commercial sensors suitable to achieve project goals. From these results, potential solutions were synthesized and organized to ensure that recommended instruments and techniques would meet data validity and affordability goals. Results from this process culminated in specific instrumentation recommendations, which can be used to assemble, calibrate and field test a prototype instrument suite to demonstrate success of the methodology and instrumentation.

4. SENSORS

Due to the differences in electric and magnetic sensors, each type is separately addressed in the following sections.

4.1 Electric Field Sensors

As described in the companion report on the topic of commercial measurement tools,¹ naturally occurring electric field potentials in the sea are extremely small ($\sim 10^{-9}$ volts/meter), while maximum induced levels next to energized wave energy generators can approach a volt or more. Thus fields to be measured could span nine orders of magnitude (>160 dB in terms of a logarithmic scale). The general measurement philosophy approach for signals with such a

¹ Slater, M., Schultz, A. (2010). Trade study: commercial electromagnetic field measurement tools. Oregon Wave Energy Trust.

dynamic range involves the application of multiple gain stages with multiple channels to acquire data sets that together represent the entire dynamic range of the signal. However, in the absence of energized power equipment the expected dynamic range can be accommodated by a single stage system capable of 120 dB of dynamic range. By observation, wave energy converters, cables, and sub-sea pods represent limited spatial extent; that is, they occupy discrete locations and do not exist “everywhere” as might be expected for generalized ambient noise conditions caused by distributed EM sources within the water column, such as ocean waves, tidal action, the earth’s magnetic field, etc. Since electric fields dissipate away from the source quickly in the sea, it is reasonable to assert that locations and sensing distances can be controlled from a measurement planning scenario, thus reducing the dynamic range requirements for the instruments.

Electric field sensors for ambient noise monitoring should have the following critical minimum technical specifications. Of course, specifications that exceed these values are acceptable; minimum criteria are stated as a means to screen potential solutions to achieve project goals. Electric field sensors shall be capable of three-dimensional measurement to assess vector quantities of the electric field.

1. Frequency response: .01 Hz to 1 kHz
2. Dynamic range: ≥ 120 dB
3. Noise floor: ≤ 1 nV/m $\sqrt{\text{Hz}}$ @ 1 Hz
4. Cost: as low as reasonably achievable

A number of commercial electric field sensors identified in the sensor survey would satisfy ambient noise measurement requirements, and with suitable identification and *a priori* determination of source level from power generation equipment, could also satisfy energized device measurement over the frequency span of interest. Top-of-the-line tri-axial sensors from Polyamp (UMISS), Subsection (Ultra Sensitive), and Ultra-PMES (Compact 3-axis) offer specifications to meet the sensing requirements. Use of the Ultra-PMES sense would require additional analog-to-digital sensing electronics, while the Polyamp and Subsection products are

also available with digital sampling features as part of the product itself. These sensors would achieve the top-level sensing requirements for reliable and repeatable protocols.

Unfortunately, these sensor suites, as well as the ultra-low noise electrodes do not provide the most affordable sensing solution. Acquisition cost for commercial probes sufficient to achieve required noise floor specifications range from several thousand dollars per unit, and up to six units (three pairs) are required for each tri-axial sensor. Coupled with ultra-low noise amplifiers and digital data acquisition equipment, turn-key commercial tri-axial measurement systems were found range from entry level systems on the order of \$30K, with research grade systems available for well over \$100K each. As an alternative, leasing or rental of equipment for temporary site assessment purposes was pursued, although an industry survey did not reveal any lease or rental options for periodic EM field monitoring or measurement sampling by vendors or value added resellers.

Until the introduction of commercial electric field equipment, researchers have historically prepared their own electro-chemical electrodes following “recipes” available in the literature. Webb et al. (1985) described manufacture of silver-silver/chloride electrodes capable of achieving nanovolt performance, and suggested other potential formulations such as lead lead/chloride to achieve acceptable performance levels. Development of the carbon fiber electrodes marketed by Polyamp was first motivated by researchers attempting to improve operational performance over current electrode technologies. However, the relatively high cost of each electrode together with published methods available in the literature prompts the recommendation to investigate the feasibility of fabricating electro-chemical electrodes. This approach was taken by CMACS (2003) for the COWRIE EMF cable study with reasonable results, although reasons this approach was taken were not specifically stated in the report. Because commercial sensors were readily available to achieve excellent noise performance, it is presumed that cost may have been a primary driver. As part of this recommendation, the use of lead-lead/chloride formulations (Pb-PbCl_2) should be considered, since the current cost of silver is at historically high levels. Petiau (2000) offers a number of practical suggestions and methods for lead chloride electrodes.

In addition to the probes, ultra low-noise amplification is required to provide a sufficiently strong signal level to be digitized and recorded. Polyamp offers low noise, high gain analog differential amplifiers (PA3004) ideally suited for pairing with either carbon fiber type or electro-chemical electrodes. Although somewhat expensive to acquire, these amplifiers are currently used by researchers in marine EM instrumentation. Existing low-noise technology exists to achieve the levels of noise performance and bandwidth offered by the Polyamp products, but industry surveys did not reveal any strong competitors. General purpose differential input, low-noise instrumentation amplifiers are available, but could not be easily located with features desirable for turn-key EM instrumentation, including impedance matching, extremely high gain, with optional data telemetry and line-driver solutions. For this reason, the Polyamp products are recommended herein for use as part of a low-noise electric field sensing system.

4.2 Magnetic Field Sensors

Ambient magnetic phenomenon in the marine environment are expected to require a dynamic range in excess of 120 dB, with dynamic range of over 180 dB required from the quietest expected ambient level to levels immediately adjacent to energized power generation equipment. Thus, as was the case with electric field sensors, a single sensor is not capable of measuring the entire span without multiple gain or multiple channel configurations. As noted above, pre-analysis for signal strength of power generators in conjunction with measurement planning for spatial arrangement of sensors within a wave energy device field would mitigate the need for complex sensor suites.

Tri-axial magnetic field sensors for ambient noise measurement should have the following critical minimum technical specifications:

1. Frequency response: .01 Hz to 1 kHz
2. Dynamic range: ≥ 120 dB
3. Noise floor: ≤ 1 pT $\sqrt{\text{Hz}}$ @ 1 Hz
4. Cost: as low as reasonably achievable

Two major types of magnetic field sensors were identified during the commercial sensor survey, both of which offered a reasonable frequency span, but differing noise floor and dynamic range

performance specifications. The ambient background noise in the existing environment is not precisely known, and therefore it is essential from a scientific perspective to first quantify the minimum noise conditions before giving up sensor resolution. Fluxgate magnetic sensors are compact, and although not as quiet as measurement grade induction coil sensors, but offer good price/performance nonetheless. As part of the instrumentation evaluation period, it is recommended to assess the lowest noise ambient EM field conditions in the coastal environment to determine if fluxgate magnetometers are suitable for wave energy site assessments prior to development.

However, taking the most conservative approach initially, use of commercial induction coil magnetometers is recommended for the initial ambient noise assessment. Use of commercial fluxgate magnetometers (e.g. Bartington or Billingsley) should be evaluated only after measurements are made to assess their suitability for future assessments.

Regarding induction coil sensors, KMS Technologies offers a sensor suitable for low frequency measurements, although review of the product indicates that it may require marine packaging modifications prior to placement in the ocean. With an upper frequency range of 500 Hz, this unit is judged to be marginally suitable for initial assessments. Two other commercial options that should be considered for at-sea use are those provided by Phoenix Geophysics (their new MTC-80 sensor) and Zonge Engineering (ANT/4/5/6 series). In both cases, these sensors are well known to the geological survey industry, and would require modest marine packaging. Induction coil sensors produce an analog output, thus a suitable high dynamic range analog-to-digital (A/D) conversion system would be required for data sampling and storage.

4.3 Data Acquisition Instrumentation

In both cases of electric and magnetic field sensors, a high resolution, multi-channel means of sampling and storing the acquired data is required. Commercial analog-to-digital converters (ADC) abound, with 16-bit converters commonplace, and 24-bit converter systems available. ADCs are advertised at a particular resolution, typically 16 bits or 24 bits, although in practice not all bits are effectively available; that is, a number of bits are essentially unusable for data due to noise limitations of the amplification and conversion process. A top-notch 24-bit ADC might offer 19 or 20 bits of dynamic range (<120 dB), which is marginal for EM measurement, unless

amplifier gains can be adjusted to match the range to the widely dynamic environment—difficult at best for existing low-cost autonomously operated systems without incurring the expense of a customized electronics solution. Therefore, to ensure that the full dynamic range of the signal is captured, the basic ADC system should ideally be capable of provide a minimum of 22 bits of useable resolution (>130 dB dynamic range). Functional features required for EM field assessments therefore are comprised of the following minimum requirements:

1. Frequency response: flat, +/- 1 dB, .01 – 1 kHz, with anti-aliasing filter
2. Sampling rate: ≥ 1 kHz
3. Dynamic range: > 130 dB
4. Noise floor: ≤ 1 nV/ $\sqrt{\text{Hz}}$ @ 1 Hz
5. Channel synchronicity: < .001 seconds, all channels

A complicating factor is that many high-quality ADC solutions are limited to two channels (driven by professional audio market which tend to offer high production and high quality, but also frequently offer features not conducive for EM remote measurements), and are not therefore well suited for synchronized multi-channel sampling required for effective post-analysis of stored EM sampled data.

Two systems commercially marketed for EM field assessments were located during the industry survey. The first system offered by Ludwig Systemtechnik is advertised as a three-channel system using 26 bit ADCs. Two potential technical limitations for use of this product for EM assessments include: (1) three channels would simultaneously sample electric fields, or magnetic fields, but would not allow cross-correlation of electric and magnetic signals, and (2) detailed specifications for noise floor, sensitivity, and other parameters could not be located, and requests for data were not returned. The multi-channel Zeus ADC system offered by Zonge Engineering provides a very low-noise analog front-end, and employs 32 bit A/D converters, with a useable dynamic range exceeding 130 dB. The differential input boards can be stacked, thus offering an n-channel configuration. The boards feature an auto-synchronization feature with long-term data logging to commonly available solid state media storage using a standardized data storage format. This solution offers a number of advantages for remote,

autonomous, battery powered data acquisition applications, and is therefore recommended for consideration for marine EM field sensor integration.

5. AUXILIARY INSTRUMENTATION

In addition to the EM sensors, auxiliary sensors are recommended for to aid in the interpretation of the acquired data. These recommendations should be considered optional, but are made to fully inform the instrumentation design process. Recommended sensors are provided below.

5.1 Orientation Sensor

An orientation sensor mounted to the instrument would provide sensor pitch and roll attitude plus magnetic compass direction with respect to the earth, and provide a tool to aid data analysis and interpretation of results. Since the electric field is expected to vary in intensity based on incident wave direction to the earth's magnetic field, knowledge of the instrument orientation is a critical factor as a means to correlate measured electric field vectors with predominate wave data at the time of measurement. Commercial compasses are available in very low power models, and generally have a reasonable accuracy. Ocean Server, Inc.² offers one such model, the OS5000-USD, which is designed to operate from batteries, and outputs standardized format readings into an RS-232 serial port. Coupled with an RS-232 data logger, such as the DataBridge SDR2-CF,³ orientation sensing is recommended to aid in data interpretation.

5.2 Depth Sensor

Wave action is expected to play a significant role in the generation of naturally occurring electric fields. Water velocity due to wave motion is a function of the water depth. A depth sensor would provide independent validation of the depth of the instrument to provide insight to electric field generation during periods of high waves. Furthermore, a pressure based sensor, such as the MSP-340 offered by Measurement Specialties, Inc.⁴ may provide some insight into large waves

² <http://www.oceanserver-store.com/compass.html>

³ <http://www.serialdatalogger.com/Products/Products.shtml>

⁴ <http://www.meas-spec.com/>

as they pass above the instrument, provided the data recording rate is sufficiently high. Depth sensors typically do not provide recording, which would also require a data recording module. The Ocean Server compass identified in Section 5.1 is available with a depth option that could provide sufficient sampling ranges and storage capabilities to enable this recommended option.

5.3 3-D Current Meter

The movement of water current, regardless of source (wave motion, tides, currents, wakes, etc.) will induce electric fields in the sea. Simultaneous measurement of the 3-D current field adjacent to the instrument would provide some means of data interpretation of the electric field for comparative purposes. 3-D current meters are not inexpensive, and rental options may exist for these on a short-term basis. No specific recommendations are made for specific makes or models. In order to be useful for ocean wave frequencies, the unit should have a reasonably high sampling rate, such as 1 Hz or greater.

5.4 Wave Buoy or Surface Radar

As an option, use of a tool to assess wave height, period, and direction would provide the means to conduct cross-correlation analyses between electric field measurements and wave factor forcing functions. The expense of a suitable wave buoy or radar system is certainly beyond the scope from a cost or availability standpoint for this particular study, but eventually should be considered as part of a longer-term wave site monitoring program.

6. SUMMARY

This survey was commissioned to identify affordable EM sensor solutions that can provide repeatable and reliable EMF measurements in the marine environment at potential wave energy sites. The results stated herein were derived from a series of modeling reports, literature searches, and industry surveys to identify existing and predicted noise conditions, and requisite sensor and instrumentation sufficient to characterize EM conditions under various field conditions. Recommendations have been made for specific sensor solutions and design requirements for electric field, magnetic field, and auxiliary sensor configurations to achieve the stated measurement objectives for characterization of wave energy project sites. The results of

this report will be used to develop a prototype EM measurement system to be used to acquire ambient EM signatures along Oregon's coast.

APPENDIX A – ACRONYMS

1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
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
fT	femto Tesla
Hz	Hertz, cycles per second
kHz	kilo Hertz
μ T	micro Tesla
μ V	micro volts
mHz	milli Hertz
mT	milli Tesla
mV	milli volts
MKS	meter-kilogram-second
MMS	Minerals Management Service
nT	nano Tesla
nV	nano volts
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
pT	pico Tesla
SEMC	Seafloor Electromagnetic Methods Consortium
SI	International System of Units
SIO	Scripps Institute of Oceanography
UK	United Kingdom
US	United States
WA	Washington
WEC	Wave Energy Converter

APPENDIX B – BIBLIOGRAPHY

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Electromagnetic Field Study

Summary of commercial electromagnetic field sensors for the marine environment.

Prepared by
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on behalf of Oregon Wave Energy Trust

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1. EXECUTIVE SUMMARY

This report summarizes the results of a market survey for available electric and magnetic field sensors and measurement equipment suitable for the near-shore marine environment. For the most part, commercially available sensors and data acquisition hardware have been identified herein, although specific proprietary and cost information unique to each vendor is not incorporated in the spirit of keeping this a publicly available document. Thus, all sources are generally available from public sources of information, manufacturer data sheets, and evidence gathered from users (typically academic researchers) using such equipment for field work or laboratory studies.

To some degree, a handful of academic institutions have experimented with sub-sea electromagnetic field (EMF) sensors to investigate various physical phenomenon of the earth's structure or oceanic processes. Thus, some sources in this report indicate such availability of an extended knowledge base from which sensor technologies have originated.

It should be noted that there could be vast differences in sensors required to measure EM field strength in the presence of an energized power cable compared to measuring the existing background EM noise in the sub-sea environment. In this report, the estimated suitability of each sensor identified indicates the applicability of each sensor to conduct either power cable assessments, or ambient EMF assessments (or both), as not all sensors provide sufficiently robust specifications to achieve both requirements.

As noted in a companion EMF tools report¹ on the subject of commercial measurement tools and techniques, there are a variety of instrument types available for sensing electric and magnetic fields. This report contains those technologies that are currently available, or could be adapted to, sub-sea use, but does not contain items that are not applicable to the passive measurement of near-shore EM fields.

¹ Slater, M., Schultz, A. (2010). Trade study: commercial electromagnetic field measurement tools. Oregon Wave Energy Trust.

2. INTRODUCTION

2.1 Purpose

This study was commissioned with the goal of identifying affordable EMF instruments capable of providing reliable and repeatable EMF signature assessments for wave energy sites on the Oregon coast. This report describes available electric (E-field) and magnetic (B-field) sensors suitable for use in the near-shore marine environment of the continental shelf. The purpose of the report is to summarize existing known candidate sensors, and in particular, those that would be suitable to conduct repeatable, reliable, and affordable measurements in potential wave energy sites. Thus, the primary focus of this report is on the identification of the available range of EMF sensors on the commercial market.

2.2 Report Organization

This report contains six primary sections, and includes supporting appendices. The first sections contain the executive summary and introduction, and provide the project background. The methodology for how the results were derived is described next (Section 3), followed by results of the commercial instrumentation surveys. Section 4 describes the results of the electric field sensor survey, with salient results tabularized. Section 5 summarizes results of the marine magnetic field sensor survey, and likewise tabularizes results. Concluding remarks are made in Section 6, the Summary. Appendix A contains an acronym list, and Appendix B contains detailed point-of-contact information for significant contributors for source information to the survey results, and which could be called upon for additional product information.

3. METHODOLOGY

The content of this report was gathered from known sources of vendors, suppliers, and researchers using sub-sea EMF sensors. Information was gathered using web-based searches, review of literature, including peer reviewed journals and academic papers, as well as personal contact with researchers and vendors alike. In some cases, specific information has been withheld due to specific proprietary information, including confidential cost information. Sources of information are noted, thus potential users of EM sensing technology should consult

directly with the source to obtain proprietary or detailed cost information outside the scope of this report.

Once information was gathered, it was summarized into two major sections using a tabular format: (1) electric field sensors; and (2) magnetic field sensors. Notations were made for certain products that offer an integrated electric and magnetic field sensor suite. From the available data, each sensor was described, inclusive of advertised or measured technical specifications, contact information for the sensor was provided. The suitability for use of each sensor to achieve OWET goals has been separately assessed in a companion report.²

4. ELECTRIC FIELD SENSORS

As described in the companion report on the topic of commercial measurement tools, electric fields in the sea are extremely small, and are therefore substantially more difficult to detect than equivalent electric fields observed in earth's atmosphere. Marine electric-field sensors are essentially highly sensitive voltmeters that measure the voltage potential between two probes separated by some distance, and the output stated in units of volts per unit distance, commonly volts/meter. Several provide turn-key electric field sensors, although individual components are also available from a few vendors to allow experimentation or integration of components into scientific or commercial instrumentation.

4.1 Integrated Marine Electric-Field Sensors

Several companies were found to offer multi-dimensional (e.g. 1-D, 2-D, and 3-D) marine electric field sensors, with 3-D sensors the predominant offering. In general, such turn-key products were focused on the military or port security markets as intrusion detection or ship signature maintenance tools. All major vendors offered configurable or customizable products, including integration of E-field sensors with magnetic, acoustic, or other types of sensing capabilities. Several suppliers offered a suite of individual components to be used by integrators to build sensors for a particular application. It was interesting to note that many of the suppliers were in Europe (UK, Sweden, Germany, Spain) with few in the U.S.; furthermore, several

² Slater, M., Jones, R., Schultz, A. (2010). Electromagnetic field synthesis: site assessment methodology. Oregon Wave Energy Trust.

suppliers counted the US Navy as among their customer base, indicating the dearth of adequate supply of suitable commercial solutions within the U.S. itself. No effort was made to ascertain classified sources (e.g. military or defense) of information on the use or availability of marine electric field sensors.

From a technical perspective, most advertised products were found to have excellent performance specifications, and used either silver silver/chloride or carbon fiber electrodes, generally arranged on an orthogonal 3-D base with integrated electronics for sensing, amplification, and data storage/telemetry. Figure 1 shows typical commercial sensor packages, with integrated electronics.



Figure 1 – Typical Electric Field Sensor Packages

Images courtesy of Subspecion Ltd., www.subspecion.com

Most sensors had excellent noise floor specifications, typically on the order of 1 nV or less at 1 Hz, and a reasonable frequency response. Table 1 summarizes representative technical specifications for commercial electric field sensors for marine use.

Three companies were judged to be at the forefront of the industry, with offerings for best-in-class product performance, a wide variety of product offerings, and very helpful marketing and technical support was made available via e-mail and telephone: Polyamp AB (Sweden), Subspecion (UK), and Ultra-PMES (UK). Contact information for these companies are provided in Appendix A. Ludwig Systemtechnik, a German company, was located via web-search, and Sociedad Anónima de Electrónica Submarina (SAES, a Spanish firm) was located in the technical literature, but requests for information were not returned from either company, and information available on their respective web-sites was minimal.

Table 1 – Commercial Electric Field Sensors for Marine Use

Manufacturer	Application	Model	Probe Type	Output Format	Sensitivity (V/m)	Frequency Span (Hz)	Noise Floor (nV/√Hz @ 1 Hz)
Information Systems Laboratories, Inc. ^{Note1}	Harbor security, surveillance	MEFSS	Silver silver-chloride	digital	6nV/m @ 1 Hz ^{Note2}	25	6 ^{Note3}
Ludwig Systemtechnik ^{Note4}	Signature measurement	EMMS	Carbon fiber	digital	Unk.	Unk.	Unk.
Polyamp AB ^{Note5}	Signature measurement	UMISS®	Carbon fiber	Digital, serial, optical	< 2 nV/m @ 1 Hz ^{Note6}	.003 >1100	~1
Polyamp AB	Signature measurement	3-300/3-500 ^{Note7}	Carbon fiber	Optional	~ 2 to 3 nV/m @ 1 Hz ^{Note6}	.003 >1100	~1
Subspection ^{Note8}	Signature measurement	Ultra Sensitive	Silver silver-chloride	Analog or digital, optical	<1 nV/m @ 1 Hz ^{Note6}	.001 – 5 .5 – 1000	1
Subspection	Signature measurement ^{Note9}	Portable	Silver silver-chloride	Analog or digital	5 nV/m @ 5 Hz	.005 – 5 1 – 1000	1
Subspection	Ranging, Signature measurement ^{Note9}	Compact	Silver silver-chloride	Analog or digital	<2.5 nV/m @ 1 Hz ^{Note6}	.005 – 5 1 – 1000	2.5
Subspection	Harbor security	Miniature	Silver silver-chloride	Analog or digital	~.1nV/m @ 1 Hz ^{Note10}	.001 – 1000	2.5
Ultra-PMES ^{Note11}	Signature measurement	Compact 3-Axis	Silver silver-chloride	Analog, differential	<2.5 nV/m @ 1 Hz	DC to 3000	<0.5

Notes:

- 1 – http://www.islinc.com/sensor_technology.php
- 2 – specified for 1 m electrode separation
- 3 – estimated from sensor sensitivity at 1 meter electrode separation
- 4 – <http://www.stl-gmbh.de/mediaup/index.php?main=Focus&sub=Signature%20Measurement&lang=en>
- 5 – <http://systems.polyamp.com/products/uep-and-elfe-measurement-system.html>
- 6 – Estimated sensitivity based on noise floor and sensor separation
- 7 – Multiple configurations available
- 8 – <http://www.subspection.com/sensors.html>
- 9 – 3-D sensor, but Z-dimension is computed internally
- 10 – Estimated sensitivity based on noise floor and sensor separation of 20m sensor spacing
- 11 – <http://www.ultra-pmes.com/main.asp?page=http://www.ultra-pmes.com/page/index.asp?pageCatID%3D2>

4.2 Electric-Field Sensor Components

Polyamp AB, Subseption Ltd., and Ultra-PMES all offered E-field probe components suitable for integration into marine probe systems. This section describes the basic types of products offered, with a brief synopsis of each.

4.2.1 Electric-Field Probes

Commercial electric field electrodes are offered by multiple vendors. Ultra-PMES offers traditional silver-silver/chloride electrodes, which are also available with low-noise amplifier electronics to isolate and boost the received electric field signals for suitable data processing and storage.

Polyamp AB offers a carbon fiber electrode, model PA3001, which provides an alternative to traditional chemically-based silver silver/chloride electrodes. The PA3001 electrode uses a patented design intended to minimize issues associated with traditional silver silver/chloride electrodes, such as polarization noise and drift associated with chemical stability of the electrodes due to such factors as temperature and salinity differences. This type of electrode is suitable for rapid deployment scenarios and in high reliability applications, although it is not sensitive at DC and long-period frequencies below approximately 1000 seconds (~1 mHz), when sensor noise begins to dominate the amplifier input.

Commercially available corrosion survey electrodes are available in a silver silver/chloride formulation for use in salt water. These low-cost versions contain an insufficient amount of surface area, and hence have a much higher resistance than instrument grade marine measurement electrodes, resulting in a probe noise floor substantially higher than required for EM measurements. These probes are unsuitable for ambient electric field noise assessments in the marine environment.

4.2.2 Electric-Field Amplifiers

Polyamp AB also offers ultra low-noise preamplifiers for use with electric field probes. These amplifiers have been designed for operation with either carbon fiber or chemically-based electrodes (e.g. silver silver/chloride), have an extremely low noise floor and high gain characteristics over a broad frequency span. Model PA3002 is available for rack-mount

applications, and is suitable for research purposes, while the PA3004 amplifier has a small, compact form factor and is intended for use in field probe systems.

Advances in electronics development have enabled proliferation of extremely low-noise components, including amplifier circuits. Noise levels on the order of microvolts were common to instruments as recently as 30 years ago, but today, specifications are available off the shelf from integrated circuit-based amplifiers that claim noise performance on the order of 1000 times quieter, as low as $1 \text{ nV}/\sqrt{\text{Hz}}$. By way of example, Fempto³ offers a general purpose amplifier, with differential input, high gain, and noise performance on the order of a few nanovolts.

4.2.3 Electric-Field Sources

Subspection Ltd. offers a marine electric dipole field source suitable for in-situ characterization of electric field sensors. This source can produce a controlled AC electric dipole signal in seawater within the span of .1 Hz to 1 kHz, at source levels of .2 to 10 amp-meters.⁴

4.3 Other Technology Sources

An extensive set of technical information on marine electromagnetism is available from the Scripps Institution of Oceanography (SIO) Marine EM laboratory, culminating decades of research in the field of EM methods for petroleum exploration and studies of the earth's upper geologic structure. In 1996, the Seafloor Electromagnetic Methods Consortium (SEMC) was formed, from which research-grade marine EM instrumentation was developed, including the EM receiver.⁵ The SIO EM receiver represents state-of-the-art in marine EM instrumentation, and is suitable for deep ocean exploration. At least one company, Quasar Federal Systems, a listed member of the consortium has produced EM receivers following the basic SIO EM design, which are marketed under the name of Quasar Geophyscial Technologies. The product, the QMax EM3, is marketed as a turn-key integrated EM instrument for oil and gas exploration, although the product was not available for purchase as of mid-2009. Of note is QuasarGeo's electric field electrode, which is described as a capacitively coupled design, most likely akin to

³ FEMTO Messtechnik GmbH, http://www.femto.de/datasheet/DE-DLPVA-100-B_5.pdf

⁴ <http://www.subspection.com/downloads/sensor-electricfield.pdf>

⁵ <http://marineemlab.ucsd.edu/semc.html>

the advantages of the carbon fiber electrode marketed by Polyamp. This sensor is designed to be used in controlled-source EM studies, and is therefore inherently sensitive at AC frequencies. It is possible that this design is not suitable for measuring long-period frequencies nor DC electric fields.

Some academic and research institutions have knowledge of electric-field sensing technology, and have used products and components from vendors listed herein for various research studies. Dr. Tom Sanford, Principal Oceanographer at University of Washington's Applied Physics Laboratory has researched use of motionally-induced electric fields to study ocean currents and turbulence, and has been published on the subject for four decades, including topics on ocean sensing instrumentation.

The Swedish Defence Research Agency (FOI) has also supported development of oceanic instrumentation for use in marine research, and as evidenced in the literature, some Agency sponsored research has demonstrated use of carbon fiber electrodes in academic studies and research activities. It is believed that the technology for the patented carbon fiber electrodes marketed by Polyamp was developed in concert with the Swedish Defence Research Agency, and the technology was also described in published work from Stockholm University by Dr. Tim Fristedt. There is evidence in the literature that Dr. Sanford of APL/UW has worked with Dr. Fristedt and his carbon fiber electrodes with positive results, and it apparent that this technology continues to develop, albeit the developmental community is apparently very small!

5. MAGNETIC FIELD SENSORS

As described in the companion report on commercial marine EMF measurement tools, two types of magnetometers dominate the commercial marketplace: induction coil and fluxgate. Induction coils magnetometers are simple, and their use is commonplace due to their simplicity in manufacture, calibration, and operation, and outstanding noise floor specifications for ultra-low noise measurements. Fluxgate sensors are somewhat complex, but commercial products offer a high degree of integration, and reasonable noise floor specifications for moderately quiet magnetic fields. Proton precession and cesium vapor magnetometers were found to have commercial availability for cable and pipeline detection products, or for location of buried

ferrous objects, but none were found with these technologies suitable for low-noise tri-axial marine measurements.

5.1 Fluxgate Magnetometers

Several vendors offer high quality commercial triaxial fluxgate magnetometers for the marine measurement market. These products appear to be an extension of existing terrestrial sensing equipment that has been repackaged for marine use, since sensors and electronic specifications appear to be common to both suites of products from several vendors. Bartington Instruments, Ltd (UK) and Billingsley Aerospace and Defense (U.S.) both offer high quality triaxial fluxgate magnetometers packaged for marine use. Ultra-PMES also offers a triaxial marine magnetometer for signature measurement and underwater surveillance, although the frequency span was limited. Table 2 lists potential commercial sources for marine magnetic measurement equipment.

5.2 Induction Coil Magnetometers

One company, KMS Technologies was found to offer an induction coil magnetometer for marine use, Model MIC-121, which had very good noise characteristics, although the frequency range was limited to 500 Hz. Visual inspection of the data sheet revealed a DB-9 non-marine connector, thus there is some question whether this unit had been tested in such an environment. However, the MIC-121 was the only induction coil marine magnetometer marked as a marine unit located during the survey. All induction coil magnetometers identified during the survey were uniaxial, thus three sensors would be required for triaxial measurements (e.g. 3-D vector measurements)

Induction coil magnetometers are commonly used in terrestrial geophysical measurement, thus the survey included several commercial magnetic sensors intended for terrestrial use, but that would be potentially suitable for repackaging for sub-sea use. Two companies in particular offer a suite of commercial induction coil magnetometers, both of which offer outstanding noise floor performance. Phoenix Geophysical (Canada) and Zonge Engineering (U.S.) both offer a family of coils suitable to cover a broad range of frequencies. In particular, Phoenix Geophysics offers a Model MTC-80, which provides a broad frequency range, although the noise floor performance

is not stated. Zonge Engineering provides a robust suite of induction coil magnetometers which offer broad frequency coverage, and the lowest noise performance of the commercial products surveyed, with noise floor performance in the 100 to 200 fT/ $\sqrt{\text{Hz}}$ regime.

5.3 Other Magnetic Sensors

A number of commercial products were located that are typically used for marine surveys for object location such as sunken vessels, buried objects, or weapons, and for cable or pipeline surveys. Geometrics Inc., offers their Model G-882 marine survey instrument based on cesium vapor technology, with a reasonably low noise floor $4\text{pT}/\sqrt{\text{Hz}}$, but lacks data acquisition features over a broad frequency range—its primary purpose is that of a magnetic anomaly detector for marine surveys.⁶ Innovatum Ltd⁷ and Teledyne TSS Ltd⁸ offer cable and pipeline tracking solutions, also insufficient for full bandwidth magnetic field measurements.

As described in the electric field sensor previous section, the Marine EM Laboratory at Scripps has a demonstrated knowledge base on the science of conducting geophysical marine magnetotelluric exploration using instruments of their own design. Due to the extremely low noise requirements of MT methods in the deep ocean, Marine EM lab equipment is fabricated using induction coil technology.⁹

⁶ <http://www.geometrics.com/geometrics-products/geometrics-magnetometers/g-882-marine-magnetometer/>

⁷ <http://www.innovatum.co.uk/Products.htm>

⁸ <http://www.tss-international.com/commercial/detection.php>

⁹ <http://marineemlab.ucsd.edu/instruments/magnetometers.html>

Table 2 – Commercial Magnetic Field Sensors for Marine Use

Manufacturer	Application	Model	Probe Type	Output Format	Maximum Sensitivity	Frequency Span (Hz)	Noise Floor (pT/√Hz @ 1 Hz)
Bartington ^{Note1}	Measurement	Mag-03MSS	3-D Fluxgate	Analog	1000 μT	0 – 3000 ^{Note2}	11-20 6-10 <6 ^{Note3}
Billingsley ^{Note4}	Measurement	TFM100G4-UWH /	3-D Fluxgate	Analog	100 μT	0 – 3500	20
Billingsley	Measurement	TFM200G4-UWH	3-D Fluxgate	Analog	200 μT	0 – 3500	20
KMS Technologies ^{Note5}	Measurement	MIC-121	Induction Coil	Analog	125nT ^{Note6}	.0001 – 500	<.5
Phoenix Geophysics ^{Note7}	Measurement ^{Note8}	AMTC-30	Induction Coil	Analog	Unknown	1 – 10000	Unknown
Phoenix Geophysics	Measurement ^{Note8}	MTC-50	Induction Coil	Analog	Unknown	.00002 – 400	Unknown
Phoenix Geophysics	Measurement ^{Note8}	MTC-80	Induction Coil	Analog	Unknown	.0001 – 1000	Unknown
Ultra-PMES ^{Note9}	Surveillance, Measurement	VMAG	3-D Fluxgate	Digital, serial	64 μT	0 – 10	100
Zonge Engineering ^{Note10}	Measurement ^{Note8}	ANT/4	Induction Coil	Analog	100 nT ^{Note11}	.0005 – 1000	.1
Zonge Engineering	Measurement ^{Note8}	ANT/5	Induction Coil	Analog	100 nT ^{Note11}	.25 – 10000	1.2
Zonge Engineering	Measurement ^{Note8}	ANT/6	Induction Coil	Analog	40 nT ^{Note11}	.1 – 10000	.2

Notes:

- 1 – <http://www.bartington.com/products/Mag-03ThreeAxisMagneticfieldsensors.cfm>
- 2 – 0 to 5 kHz bandwidth available
- 3 – Three models available with differing noise floor performance
- 4 – <http://www.magnetometer.com/specs/TFM100G4-UWH%20TFM200G4-UWH%20Spec%20Sheet%20February%202008.pdf>
- 5 – http://www.kmstechnologies.com/Files/KMS_Marine_Induction_Coil_MIC-121_Technical_Specs.pdf
- 6 – Estimated based on maximum output voltage, sensitivity factor, and -20 dB output gain
- 7 – http://www.phoenix-geophysics.com/products/sensors/sensors_specsheets.pdf
- 8 – Ultra-sensitive measurement grade terrestrial model, suitable for geomagnetic measurement and marine packaging
- 9 – <http://www.ultra-pmes.com/main.asp?page=http://www.ultra-pmes.com/page/index.asp?pageCatID%3D2>
- 10 – http://www.zonge.com/PDF_Equipment/Ant-564.pdf
- 11 – Estimated based on maximum estimated output voltage and sensitivity factor

6. SUMMARY

This survey was commissioned with the goal of identifying candidate commercial electric field and magnetic field sensors suitable for high resolution EMF measurement in the marine environment. Suitable sources were located for both sensor types, with multiple vendors capable of providing a broad range of instruments. In the case of electric field sensors, commercial solutions were focused on the military/defense marketplace, with a few products targeted at the oil and gas exploration industry that may be suitable. Magnetic sensors were more varied, likely due to the extensive terrestrial market for geophysical sensors, which are also suitable for sub-sea use.

APPENDIX A – ACRONYMS

1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
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
fT	femto Tesla
Hz	Hertz, cycles per second
kHz	kilo Hertz
μ T	micro Tesla
μ V	micro volts
mHz	milli Hertz
mT	milli Tesla
mV	milli volts
MKS	meter-kilogram-second
MMS	Minerals Management Service
nT	nano Tesla
nV	nano volts
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
pT	pico Tesla
SEMC	Seafloor Electromagnetic Methods Consortium
SI	International System of Units
SIO	Scripps Institute of Oceanography
UK	United Kingdom
US	United States
WA	Washington
WEC	Wave Energy Converter

APPENDIX B – SOURCE INFORMATION

The following individuals provided valuable technical insight and feedback on product queries for both electric field and magnetic field sensors and measurement equipment:

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Electromagnetic Field Study

Wave energy converter measurement project plan.

Prepared by
Michael Slater, Science Applications International Corp.
on behalf of Oregon Wave Energy Trust

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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.

Record of Revisions

Revision	Date	Section and Paragraph	Description of Revision
Original	September 2010	All	Initial Release

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1. EXECUTIVE SUMMARY

This plan describes the preparation and execution of EMF signature assessments of various aspects of a Wave Energy Converter (WEC), including in-air testing, single- and multiple-device testing, as well as associated in-water cabling. This plan was commissioned with the goal of preparing for conducting a signature assessment of a device or multiple devices, and then comparing the result to predicted or modeled expectations.

The basic physical theory for a WEC as a magnetic or electric field source was previously developed in a companion report.¹ This project plan is based on the foundational physical modeling of the WEC as an EMF point source, and how each type of field (electric or magnetic) would be affected by the surrounding seawater environment. Narrative descriptions are provided for each major task phase, including basic measurement requirements and methodologies.

2. INTRODUCTION

2.1 Purpose

This plan provides the basis for estimating the level of effort required to estimate the electromagnetic signature of a WEC, as well as the activities essential for conducting in-situ measurements of a device in seawater. This plan addresses monitoring of one or more devices, e.g. a wave park in the near ocean environment, and could form the scientific basis for analyzing the effects of EM fields on the environment over a longer term period.

A Microsoft Office Project 2007 plan has been prepared that matches the narrative description for the WEC measurement plan, and includes estimated resources such as labor hours, generic costs, materials, and other direct costs required to conduct a suite of measurements. The project plan has been developed in two phases: Phase I includes the initial analysis of the device pre-

¹ Slater, M., Schultz, A., Jones, R. (2010). The prediction of electromagnetic fields generated by wave energy converters. Oregon Wave Energy Trust.

deployment, including in-air tests to validate expected in-water results, and is meant as a planning precursor to the in-water measurement phase. Phase II includes the plan and cost to obtain in-situ measurements of a single device, multiple devices, and furthermore, estimates a postulated long-term monitoring program for a site that could contain multiple devices, e.g. a wave-park.

The project plan is generic in the sense that it could be used as a template for device developers to conduct specific measurements to quantify source level and field strengths. The project plan is intended to be used to estimate the level of effort required to establish the signature of a WEC, and furthermore, to develop an on-going measurement program

2.2 Background

The Oregon Wave Energy Trust (OWET) was formed in 2007 to coordinate the development of power generation from offshore wave energy, and the objective of generating 500 MW along the Oregon coast by 2025. The generated power will be transmitted to shore using subsea power cables to enable local or national distribution. The transmission of high power along such cables will induce both electric and magnetic fields into the sea, which may disturb marine species such as sharks and rays, which are sensitive to electromagnetic fields. Having set forth the theory and instrumentation required to make measurements of a WEC and energized cables in companion reports, this plan can be used as a template tailored to achieve measurement or monitoring objectives of one or more WECs in the near-shore ocean environment.

2.3 Report Organization

This plan contains several topical sections and supporting appendices. The first three sections contain the executive summary and introduction, and describe the project motivation and background, including prior work on the subject. Section 4 addresses project assumptions, although the associated MS Project file contains notes and assumptions. The fifth and sixth sections provide the top-level narrative description of the Project plan. For ease of reference, the work breakdown structure (WBS) of the Project plan match the paragraph numbering scheme in

these two technical sections. Acronyms are presented in Appendix A, and a graphical view of the Project Plan is provided in Appendix B. The full electronic version of this file is available in Microsoft Office Project 2007 format.

3. METHODOLOGY

Based on the companion technical reports on the topics of electromagnetic theory and EMF instrumentation, the project plan was created outlining the steps required to achieve the EM signature of a WEC in a terrestrial environment. These results were then extended to conduct measurements of a single WEC in a seawater environment, which could also be connect to a shore cable or other means to export electrical power from the WEC.

Next, an overall multi-device measurement plan was created to model resources and schedules required to engage in a longer term monitoring program to obtain EM measurements in-situ to assist in the analyses of environmental or other effects due to the introduction of anthropogenic EMF into the near-shore environment. Thus, this plan supports the goal of obtaining scientifically rigorous measured data to correlate with any observations over the same period to achieve adaptive management goals with a high level of confidence.

The project plan is intended to address the issues associated with conducting measurements or establishing a monitoring program, and as such, is designed as a generic template that could be used for a multitude of wave energy projects. The plan could be tailored to specific device types, locations, and project extents, and thus could be scaled as necessary.

4. PROJECT ASSUMPTIONS

As with any plan, assumptions are stated such that change can be made as appropriate to reflect alternative approaches or revised assumptions. Notes are provided for each task activity, and assumptions for cost basis are stated. It should be noted that this is an engineering estimating tool, and should not be misconstrued to be a specific offer for goods or services. Actual costs required to successfully execute this plan will depend on a number of factors, including technical methods and assumptions that may require additional validation; assignment of qualified

personnel resources from one or more organizations; as well as availability of subcontracting hardware or services at the assumed cost rate structure.

4.1 Schedule

A notional chronology is presented, with pre-deployment planning and work-up activities conducted first, followed by in-situ measurements of a single device (and power export cable as an optional task). Next, the single device cost model is extended into a multiple device model, e.g. a modest “wave park”. Finally, ongoing costs are estimated for continuous monitoring of EM conditions at the site, with some modest allocations made for instrumentation repair or refurbishment, as well as routine data reporting. The availability of installed WECs and/or power cables is assumed without delay, although real-world conditions may require a delay between project phases. The template is flexible with this regard, and such delays may be programmed into the plan by introducing specific related tasks.

4.2 Labor Categories

The following major labor categories are assumed. Costs for these categories will depend on specific staff assigned by the performing organization, and may vary widely. Reasonable costs have been assumed in the Project plan on the Resource Sheet, but can be adjusted to suit.

Project Manager – This individual is a senior level person, with experience in operating complex projects with a certainly level of uncertainty. This labor category should be staffed with an experienced project manager to ensure project success. The Project Manager is responsible for overall execution of the project, timeliness of deliverables and periodic reporting, and holds the overall responsibility to operate the project on budget.

Senior Scientist – This labor category is assumed to be staffed by a PhD or similarly qualified individual with extensive domain knowledge on the subject of marine electromagnetic signatures and instrumentation. The Senior Scientist provides the technical know-how to ensure that proposed measurements, including test plans, achieve

scientifically valid results, and works hand-in-hand with the Senior Engineer to devise measurement scenarios, and with the Data Analyst to validate measured signatures.

Senior Engineer – The Senior Engineer is experienced in designing and operating marine data acquisition systems, and is intimately familiar with specification, calibration, and implementation of in-water instrumentation and highly sensitive sensor suites. The Senior Engineer is the technical lead for the project.

Engineer – This labor category is staffed by a degreed lead engineer that is capable of leading a small technical team on specific technical tasks, including mechanical design, marine and ocean engineering aspects of the project. Experience in deployment and recovery of in-water systems is essential.

Data Analyst – The Data Analyst is experienced in data process and spectral analysis, including time-series and Fourier analysis with multiple sensors, and works with the Senior Scientist to process, interpret, and validate the measured data sets.

Budget Analyst – This labor category is staffed with an individual knowledgeable about finance and accounting, and is also knowledgeable about subcontracting and related issues. This person is responsible for maintaining a set of orderly financial books, and works with the Project Manager to publish periodic status reports.

Technician – This individual is skilled in preparing mechanical, electrical, and electronics hardware for field use, and most frequently works under the supervision of the Engineer or Senior Engineer. This position requires knowledge of mechanical and electronics tools, and test and measurement equipment.

Logistics Manager – This position is responsible for organizing procurement, storage, and provision of necessary hardware, consumable items, or services in support of the project, and supports shipping and receipt of materials.

Editor – The editor is skilled in word processing and preparation of graphs, text, and tables to convey technical results in a professional, written format. The Editor works with the technical staff to generate final versions of project deliverables and documentation.

Administrative Support – This role is fulfilled by a person knowledgeable about basic office and support functions, and is capable of organizing and preparing meetings, maintaining schedules, and preparing final documents for issue, and other related duties as required.

4.3 Assumed Costs

Costs provided are meant to be representative of expected costs, including level-of-effort by labor categories, anticipated material and services, but not specific, quoted rates. Prices for materials are approximate based on recent commercial procurements or from on-line sources. Allocations have not been made for fees, general and administrative costs, profit, or other rates that are commonly found in contracting. The cost factors used in this template are intentionally imprecise to allow tailoring of the plan to specific vendor or developer conditions, labor rates and cost structure of the executing organization.

4.4 Equipment and Instrumentation

Measurement of in-water variables to obtain high-resolution, repeatable, scientifically valid results is not a trivial exercise. Based on the research in this overall study, the most cost effective tools have been identified as part of this cost template. Undoubtedly there will be improvements in cost for such instrumentation as time moves ahead, but for now, costs for the instrumentation itself is not insignificant, and represents a sizeable portion of the overall project cost. Where practical, use of lesser equipment or rental gear has been assumed to minimize the overall instrumentation cost.

4.5 Other Costs

Specific costs for travel, equipment rental, vessel services, shipping will vary on a number of conditions, including location, time of year, cost of fuel, transit distances, etc. Therefore, estimated costs are provided as placeholders for more precise quotes at the time of project execution, and are meant to be adequate, but not precise.

5. PHASE I – PRE-DEPLOYMENT ACTIVITIES

This section describes the initial analysis and measurement of a WEC in a pre-deployment state, and includes factors required to make device-specific measurements to quantify source levels and E- and B-field strength measurements prior to deployment. The primary driver for conducting in-air assessments prior to deployment is to validate predicted results with actual measurements in a highly controlled manner, much more so than the ocean environment will enable. Furthermore, this approach allows better separation of factors associated with induced electric fields due to the magnetic field produced by the device interacting with the relative motion of the conductive seawater surrounding the device.

5.1 Signature Estimation

Prior to making in-air measurements, it is beneficial to estimate the expected EM fields produced by an operating device to compare with measured results. The WEC manufacturer will have a detailed knowledge of the physical construction of the device itself, including factors such as the method of power generation, general arrangement of the device with respect to location of the generator(s) and power equipment, method and materials used during fabrication, as well as modeled hydrodynamic motion of the device in a sea-water environment.

Using these factors, together with the predictive theory developed under Task 2A, the developer can estimate the expected magnetic and electrical fields produced by the device under a suite of motion and output conditions. For purposes of analysis, a set of estimations should be made to roughly correlate expected seasonal wave conditions in the location into which the device will be deployed. The primary output of this stage would be a set of minimum and maximum

“envelope” signatures expected, as well as a parametric estimate of electric and magnetic field strength as a function of input wave motion activity.

Of course, each type of device may vary, and it may not be possible to perfectly estimate all factors; the primary goal of this activity is to establish fundamental estimates of the device, which could later be adjusted and used as a proxy for estimating the level of E- or B-field emissions in-situ.

5.2 Test Environment and Instrumentation

Once EM signatures are estimated, it will be necessary to establish a suitable testing environment with suitable, and calibrated instrumentation to assess the WEC signatures.

5.2.1 Test Stand

An in-air test fixture should be specified, built, and tested. It is expected that each developer or WEC manufacturer will have access to a mechanical test rig, e.g. test stand with hydraulic or mechanical actuators that could simulate various wave conditions, or at a minimum, at least monotonic, sinusoidal input conditions. It may also be possible to use a model-scale device, or perhaps use a fresh-water wave tank facility to estimate signatures produced by each device type as a function of input factors. It should be noted that some devices may have already been studied using models or actual test stands, and actual in-air measurements may not be required to adequately characterize a WEC prior to deployment. The essential factor for consideration in this step is to determine if a suitable proxy exists, or yet needs to be established from existing or empirical data to use to compare with actual in-situ measurements to provide the foundational basis for longer term monitoring—the better the proxy, the less uncertainty will remain in the in-situ measurements.

5.2.2 Test Environment

Once the mechanical testing apparatus is determined, it is then necessary to arrange a suitable signature measurement environment and measurement schematic. An ideal such environment is one in which the device under test is not adjacent to major sources of EMF, especially facilities using high amounts of power (large electrical current or voltages), such as near a power substation, under high-tension wires, or near power generation or distribution equipment.

Furthermore, the test site should be isolated as much as possible from the effects of the test equipment itself. For example, if an electric motor is required to mechanically drive the device under test, it would be best to move the motor as far away as possible from the device to avoid contaminating the device signature with that of the electric motor. In many cases, an imperfect environment is what is nominally available at each manufacturer location, and with allocations for known limitations, a suitable measurement set can nonetheless be obtained.

Once the location has been determined, the developer should prepare a measurement schematic showing the test stand, the device under test, and the arrangement of measurement instrumentation on or near the device.

5.2.3 Instrumentation

A number of important factors are critical in conducting rigorous EM measurements in any environment. The first of these is the measurement instrumentation itself, wherein sensor sensitivity, dynamic range, and frequency response drive the quality of the measurement. Using the measurement schematic developed in the previous stage, magnetic and electric field sensors should be identified to provide a reasonably dynamic range and sensitivity for the test environment for all device test conditions. The frequency response of the equipment should be capable of measuring all possible forcing frequencies, including those at typical wave frequency rates (*e.g.* to address waves from 1 second to 30 second periods or greater), as well as typical power frequencies, such as 60 Hz and multiple harmonics due to harmonic distortion or other non-linear effects. Sensors with a coverage from .01 Hz to 500 Hz or more should be adequate; however, if other known frequencies are produced by the device outside of this range, sensors should be used that can encompass all such frequencies. For devices using permanent magnets, magnetic sensors should be sensitive at near-DC frequencies.

All measurement instrumentation should be capable of sampling time series data for correlation and data analysis. Use of “single number” meters that produce average or root-mean-square (RMS) values should be avoided, as they may provide erroneous readings, or may only be tuned to investigate outputs at specific frequencies, *e.g.* 50 Hz or 60 Hz. Furthermore, it is strongly recommended that tri-axial instruments be used to establish magnetic and electric field vectors to fully understand and explain the expected emission pattern from the device under test.

In an ideal sense, it would be beneficial to use the same instrumentation proposed for the in-situ measurements during the in-air measurements. However, due to the high degree of sensitivity of the sensors recommended in the companion reports, it may be necessary to position such sensors at some distance away (tens of meters) away from the device under test to avoid saturating the front-end electronics of the sensors themselves. Specifically for the electric field sensors, it may be possible to use low-cost commercial terrestrial sensors or handheld meters for in-air testing.

It is critical to note that operating in-air and in seawater may likely produce substantially different electric field results (from an absolute magnitude perspective, *e.g.* volts per meter) due to the relative conductivity of seawater (a reasonably good conductor) compared to air (essentially a dielectric substance). Thus, the instrumentation sensitivity used for each case should be examined to ensure the suitability of the device for the measurement activity. It is anticipated that a given electric field produced by a point source in air would be several orders of magnitude higher than the same device in seawater.

In addition to measuring the specific EM fields produced by the device under test, it is strongly recommended to simultaneously measure the electrical output of each device, *e.g.* the voltage and current of each output phase. These measurements can then be correlated to the measured EM fields, and form the basis for an in-situ proxy for long-term monitoring.

5.2.4 Calibration

After the measurement environment has been established, and the instrumentation selected and set-up, it is necessary to validate the instrumentation by performing calibrations and conducting background measurements.

Calibration of the magnetic instrumentation can be done by exposing the instrument to a precisely known magnetic field. The calibration procedure and instrumentation described in a companion report would be one means to conduct such a calibration. In this method, a long coil wire is energized with a known current, thus producing a precise magnetic field. This test would be conducted over the expected frequency range of the instrument (*e.g.* .01 to 500 Hz) and compared to the output of the instrument itself. The linearity of the instrument should also be verified, that is, tests should be conducted at the upper and lower amplitude ranges of the sensor

to ensure that the sensor has the dynamic range and linearity specifications required to provide calibrated outputs at any device output level. Any deviations should be noted, and used to provide corrections to the measured data to ensure absolute values of the measurements.

The electric field sensors may be calibrated by injecting a known electric voltage potential into the front end of the instrument. This is generally done with a laboratory grade voltmeter and arbitrary waveform generator or voltage source capable of generating frequencies over the range of the instrument (e.g. .01 Hz to 500 Hz) to be calibrated. As described above, the calibration should inject known signals over the frequency and dynamic range of the sensor, and any deviations noted to correct the measured data set to set for the absolute value of the measurements.

Once the instrumentation has been calibrated, it is important to conduct background measurements of the device under test prior to energizing the device. This will provide a double-check of the functionality of the instrumentation, and will provide the noise floor of the measurement equipment or test environment, thus establishing the lowest possible levels measurable by the system. Again, time-series data should be collected, and spectral (e.g. Fourier analysis) processing completed to establish the background environmental conditions. Ideally, the background measurements should be conducted in the identical locations from the test stand as would be used while the device under test is energized. This way the effects of the environmental conditions on the instrumentation will be minimized.

The output of this step would be an instrumentation and calibration report documenting the instrumentation suite, along with a background measurement.

5.3 In-Air Measurement and Reporting

After instrumentation setup and calibration, device measurements should be conducted under a variety of operating conditions. At this stage, it is critical to document the specific location, orientation, and operating state of each instrument sensor. Magnetic and electric fields drop off very quickly as a function of distance from an energized device or cable, and thus errors in location can provide substantial variability in the final result. Where possible, position sensors as far as possible from the device under test (meters or tens of meters), but not so far away as to

not detect the signature of the device during operation. Depending on the operating condition, it may be necessary to reposition sensors to optimize the sensor output as a function of WEC operating conditions. All test setup should be fully documented, with the use of sketches, drawings, schematics, photographs, and calculations showing the test environment, location and orientation of instruments, operating conditions, and device input and output conditions.

For each test condition, a spectral analysis (*e.g.* FFT) should be performed, and charts prepared that fully describe the measured EM signatures as a function of WEC operating conditions. Correlations should be made between signatures produced compared with input conditions and electrical power output.

The output of this step would be a signature report providing estimated EM signatures of the WEC device in-air under a range of operating conditions. These results would be used in part to establish the Phase II in-situ measurement schematic and instrumentation set-up required to establish valid in-situ measurements of one or more devices, as well as compare measured to estimated results to establish a predictive proxy for monitoring.

6. PHASE II – IN-SITU MEASUREMENT AND MONITORING

This section describes the in-situ measurement activities of one or more WEC installed in an operational condition offshore. Factors are described to ensure that valid measurements are obtained to quantify source levels and E- and B-field strength measurements in a real-world operating environment. Single device measurements are the first stage of this phase, since results from that activity can be used to superimpose results to create a valid measurement model for multiple-device deployments.

6.1 Single Device In-Situ

Measurement of an operational WEC in-situ is an important step in assessing the overall affect the operational device may have under each operating condition. This stage is a precursor to analyzing multiple device deployments, and will serve to validate in-air measurements and measurement proxies.

6.1.1 Site Characterization

As was done for the test stand case in Phase I, it is necessary to characterize the existing baseline EM conditions of the measurement site to ensure that effects of the local environment, including sub-strata, wave and current conditions, orientation, and potential interfering anthropogenic sources are understood. The near-shore environment is complex with regard to electric and magnetic field generation and propagation from naturally occurring sources, and in some cases, nearby power generating facilities, transmission lines, or industrial sources could produce detectable EM fields that might contaminate WEC signature measurements, or otherwise be attributed to the WEC operation.

In this stage, EM instrumentation is deployed in the planned site to measure existing magnetic and electric field conditions. It is expected that the dominant magnetic source will be very low frequency due to the earth's magnetic field or other naturally occurring sources. The site characterization will also identify any sources of magnetic fields at power frequencies from nearby anthropogenic sources. In addition, the existing electric field can be measured in the absence of the WEC. An energized WEC and power cable is expected to produce a magnetic field in the vicinity of the device and cable, thus the motion of the WEC device in the water column, together with the wave action and coastal and tidal currents will create induced electric fields in the same vicinity. Thus, site characterization will identify existing electric field conditions in the absence of this magnetic field and thus differences can be attributed to the presence of energized WEC equipment or cabling.

Background measurements should be made with very low noise sensing equipment such as is described in the companion reports. Unlike in terrestrial applications, conductivity of the seawater will greatly affect the magnitudes of measured EM fields, and thus, ultra sensitive equipment is required to not restrict analysis of the results, nor obscure exiting conditions. Ideally, the same instruments should be used for the background measurements as is used for the device measurements. This approach will minimize any biases associated with different equipment, and will also provide the necessary resolution for both existing background conditions and operational conditions with an operating WEC.

6.1.2 Instrumentation and Calibration

Recommended in-situ instrumentation is described in companion reports, together with calibration equipment and techniques. Use of such equipment or equivalent is strongly recommended to provide a solid scientific basis for monitoring of the EM conditions for comparison with temporal changes, if any, of this site against other control sites. Based on background measurements and in-air results, instrumentation should be selected for the expected noise environment, dynamic conditions, and frequency range, and a detailed schematic prepared for single-device measurements.

Background measurements should be made with very low noise sensing equipment such as is described in the companion reports. Unlike in terrestrial applications, conductivity of the seawater will greatly affect the magnitudes of measured EM fields, and thus, ultra sensitive equipment is required to not restrict analysis of the results, nor obscure existing conditions. Ideally, the same instruments should be used for the background measurements as is used for the device measurements. This approach is intended to minimize any biases associated with different equipment, and yet provide the necessary resolution for both existing background conditions and operational conditions with an operating WEC.

If an export power cable is involved (compared with a “device only” deployment), separate instrumentation should be positioned near the cable, but away from the WEC to establish the cable contribution to the EM signatures produced.

As was done with the in-air testing, detailed measurement of the output power (voltage and current) should be made to compare with and validate the EM signatures, and more specifically, for potential use as a proxy for longer term monitoring.

6.1.3 Measurement and Reporting

Once background measurements have been made, and the device and cable have been installed, measurements should be made under a variety of operating conditions. Sources of background EM noise vary substantially over time, especially so in the dynamic near-shore environment, thus establishment of the entire range of ambient conditions may not be possible. It is

recommended to acquire ambient noise for as long of a period as possible, although it may be cost effective to establish proxy methods for background ambient conditions using alternative modes of instrumentation, and periodically validated by specific site measurements. This approach is beyond the scope of this research activity, but may be considered as part of a longer monitoring program if periodic in-situ measurements can be made to validate proxy measurements. For example, the background magnetic signature might be measurable at a terrestrial site adjacent to the WEC location, with the provision that no interfering anthropogenic or naturally occurring anomaly interferes with this approach. This approach would be site dependent, but may provide an alternative means to provide long term, but affordable and reliable measurements once the provisional conditions have been assessed. In addition, the dominant source of electric fields in the ocean is due to motion of conductive sea water in relative motion to the earth's magnetic field—thus instruments suitable for measuring water currents in the vicinity of the WEC in conjunction with the magnetic field measurements could provide an affordable means to monitor electric field conditions in the absence of the WEC. These approaches, while possible, should be first analyzed in more detail and validated with calibrated EM field measurements to ensure their validity for long-term monitoring.

As was done in-air, after instrumentation setup and calibration, device measurements should be conducted under a variety of operating conditions. At this stage, it is critical to document the specific location, orientation, and operating state of each instrument sensor. Where possible, sensors should be positioned as far as reasonably possible from the device under test (meters or tens of meters), but not so far away as to not detect the signature of the device during operation with sufficient signal-to-noise to obtain the measurement. Distance is difficult to determine underwater, and motion of the WEC from a known position can greatly affect the measured results. Thus, instrumentation should be placed such that distance can be accurately determined, an independent means to measure range from source to sensor, or sufficient range should be established that movement between source and sensor does not substantially affect the measurement—which may not be possible with low source levels—and should be assessed after the in-air measurement and ambient levels are known.

For each test condition, FFT analyses should be performed, and results summarized that describe the minimum, maximum, and average field strength levels at predominant WEC operating

conditions. To the greatest extent possible, source levels of the WEC and power export cable shall be computed and compared to modeled predictions. Measured output of the power cable should also be analyzed and compared to the EM emissions to establish the degree of correlation between WEC output and EMF generation. This is the fundamental basis for long term monitoring and prediction of multiple device measurement scenarios.

6.2 Multiple-Devices In-Situ

Measurement of multiple devices in-situ will be necessary to establish an adaptive management approach to wave energy facilities. For the most case, the protocol for the multiple device field should follow that outlined for the single device, with the additional requirement that allocations are made to obtain measurements that obtain a fair representation of worst-case effects due to the additive nature of EM signatures from multiple devices.

6.2.1 Site Characterization

As was done for the single device case in Phase II, it is necessary to characterize the existing baseline EM conditions of the measurement site. The same protocol described above for a single device site characterization should be followed for multiple devices, including the use of low noise, high resolution sensors. However, if a site characterization has already been completed for a specific location, it need not be replicated for multiple sites unless a specific condition is noted during the single site characterization that could cause differences in expected values of background conditions, perhaps due to vastly different geologic conditions, or potential proximity to anthropogenic sources. Otherwise, the results of the single device site characterization would most likely be representative for sites for multiple devices. If additional data is required in a location where a WEC is currently operating, it may be feasible to de-energize the WEC to obtain background data without the WEC operating to establish baseline conditions.

6.2.2 Instrumentation and Calibration

Instrumentation and calibration of sensors for use in multiple device measurement should follow the same requirements as stated for single measurement conditions. Additional sensors should be used to fully quantify the EM fields superimposed by multiple devices and/or cables

contributing to the overall EM fields. In particular, sensors should be placed in areas expected to provide the highest observed levels, *e.g.* near the “center” of the WEC field to obtain the worst-case conditions. Again, strict care should be taken to establish the measurement schematic, with the means to accurately determine location and distance from sources and sensors.

6.2.3 Measurement and Reporting

As described for the single device condition, full spectral analyses shall be made for various operating (wave conditions) for the multiple device field to obtain minimum, maximum, and average field strength levels at predominant WEC operating conditions. In particular, testing should indicate the worst-case conditions of the field. Where possible source levels of the WEC and power export cable should be computed and compared to modeled predictions of a multiple device field by superimposing results of single device signatures in a spatial extent. Measured output of the power cables should also be analyzed and compared to the EM emissions to establish the degree of correlation between WEC output and EMF generation.

6.3 Power Export Cables

In-situ measurements of WECs, either single or multiple cases, should include measurements from power cables themselves. Modeling techniques have been furnished in companion reports, and should be followed to predict EM signatures emitted by energized power cables themselves, which will undoubtedly contribute to the overall effects of EMF energy within a site. Instrumentation should be positioned to assess the signature from each cable type, and data should be taken to establish the level of magnetic emission as a function of electrical current in each phase of the cable, and electric field emission as a function of applied voltage to conductors in the cable. This data should be compared to the modeled results for that cable type as a function of applied voltage or current modeled results, and the model adjusted to develop a predictive transfer function for the cable to be used to estimate the emitted EMF. This would be used to estimate the long-term effects of the site. As described for the WEC devices, use of current or applied voltage as a proxy for emitted EM signatures should be periodically validated by actual in-situ measurements.

6.4 On-Going Monitoring In-Situ

In order to support an adaptive management approach with a firm scientific basis, it is essential to collect reliable and accurate EM conditions at WEC sites. As of this writing, few, if any, work has been done in the near-shore environment to persistently measure EMF and simultaneously observe effects. The most scientifically robust approach to this situation is to provide instrumentation within the proximity of the WECs and associated cabling to routinely measure and monitor EM conditions, and to establish expected results and trends due to various wave conditions—including naturally induced electromagnetic phenomena that occurs in the ocean environment. In this protocol, a sufficient number of sensors should be placed within the footprint of the WECs and cabling to measure the EM signatures, but also sufficient to establish the degree to which naturally occurring phenomenon can contribute to the environment. While collection of WEC data is vitally important, it is also critical to understand how naturally occurring phenomenon affects the environment, and thus establish the incremental contribution by the WECs and cables.

On-going monitoring of a single device, or of a collection of WECs in a field should follow the same protocols outlined above. Sensors should be placed in the worst-case location within a WEC field, with data collected, analyzed, and reported on a periodic basis. Electric field measurements require a bottom mounted sensor suite due to the potential for seawater flow to obscure the measurements themselves. Long-term persistence of the sensors mandates a cabled sensor suite to supply power and export data to a shore facility for processing and analysis. Battery powered sensors are feasible in the short term, but persistent monitoring for the long-term case would most likely not be cost effective due to the level of upkeep required to charge and/or change out batteries on a periodic basis. Hybrid solutions with bottom mounted sensors with tethered buoys to provide power may be achievable, although nothing is currently available today for this scenario.

However, because electromagnetism is well understood, and the physical basis for the generation and transmission of electrical energy is likewise well understood, there is substantial motivation to establish alternative methods to accurately measures EM signatures that do not require 100% long-term persistence and maintenance of ultra low-noise, high resolution measurements. This

approach will require early adopters to obtain measurements using sensors to directly measure EM signatures, but over time it may be possible to establish other protocols to obtain EM signature measurements by use of proxy measurements to an acceptable level of precision.

7. PROJECT SUMMARY

In summary, long-term monitoring requires placement and collection of data from one or more bottom mounted sensors. Data should be collected, FFT analyzed, and correlated with wave conditions and WEC output, and periodically published for use within the monitoring community to establish long-term causes and effects, if any, due to the presence of wave power generation equipment. The approach outlined in this project plan develops basic building blocks of a long-term monitoring activity, by first understanding EM sources and source levels of a single device, and then extending the measurements over multiple devices. This plan takes the direct approach to conduct scientifically solid measurements of the resulting EM field and sources.

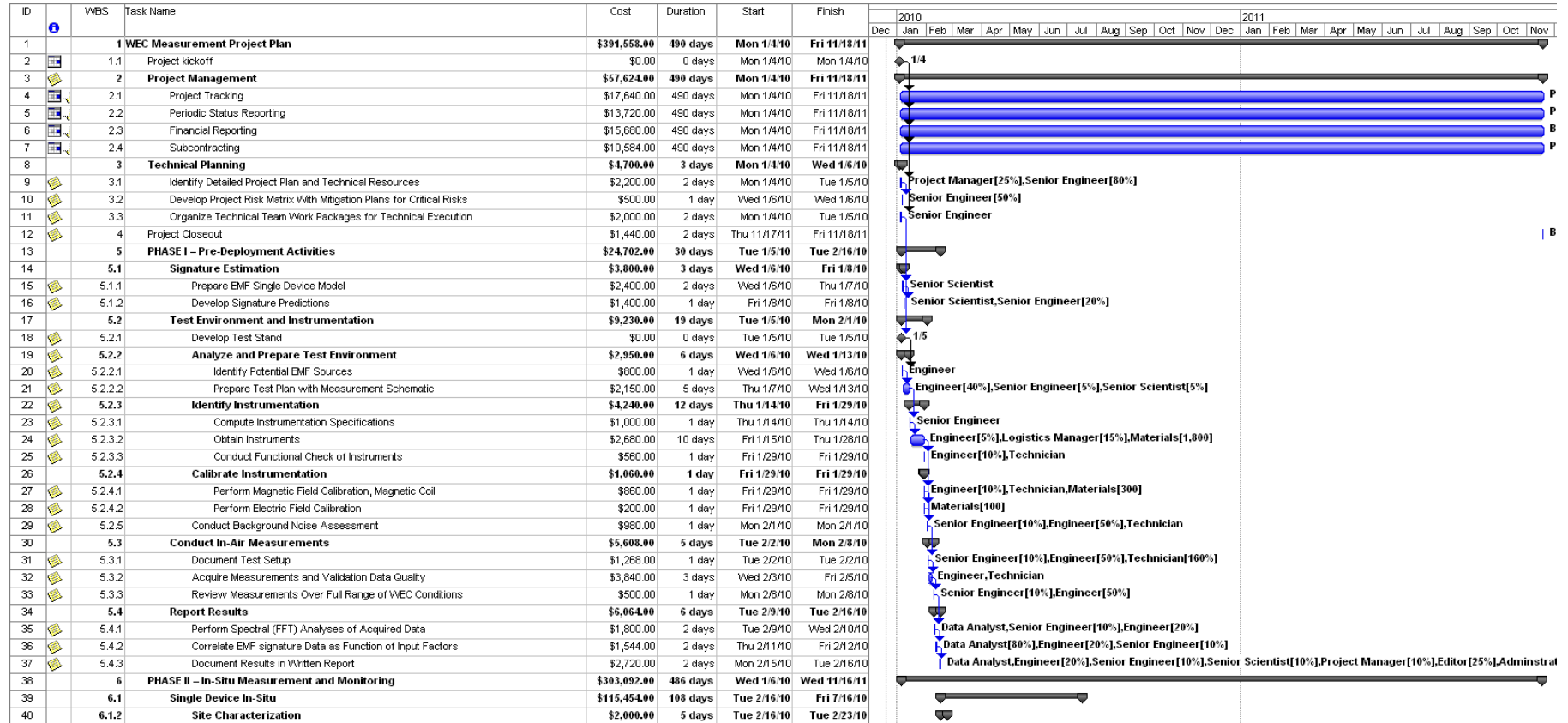
Of course, there may be alternate means to measure EM signatures, and the use of proxies should be investigated as a possible surrogate for around-the-clock measurement in-situ. Over time, direct measurement results correlated with observations of surrogate techniques should reveal if such an approach is feasible.

APPENDIX A – ACRONYMS

ASW	anti-submarine warfare
B-field	magnetic field
BWEA	British Wind Energy Association
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research Into The Environment
DECC	Department for Energy and Climate Change
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
FEA	Finite Element Analysis
FFT	Fast Fourier Transform
Hz	Hertz, cycles per second
MHD	magneto hydrodynamic
MHz	megahertz
MKS	meter-kilogram-second
MMS	Minerals Management Service
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
RMS	Root Mean Square
SI	International System of Units
SIO	Scripps Institute of Oceanography
THz	terahertz
UK	United Kingdom
WA	Washington
WBS	Work Breakdown Structure
WEC	Wave Energy Converter

APPENDIX B – PROJECT PLAN

The full project plan is provided as attachment in Microsoft Office Project 2007 format. The plan is presented herein using a graphical Gantt format for convenience.





Electromagnetic Field Study

Electromagnetic field measurements: environmental noise report.

Prepared by
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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.

Record of Revisions

Revision	Date	Section and Paragraph	Description of Revision
Original	March 2011	All	Initial Release

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1. EXECUTIVE SUMMARY

The Oregon Wave Energy Trust (OWET) commissioned this study to develop protocols and methods to achieve affordable, reliable, and repeatable electromagnetic (EM) measurements in the near-shore environment. This report presents the calibration and measurement results from a prototype EM instrument deployed near a submarine power cable in a representative undersea environment. The data demonstrate that electromagnetic fields (EMF) are indeed present and measureable even from an energized cable of modest electrical capacity. Higher energy cables carrying more electrical current would undoubtedly produce higher EM signatures, which would be observable at greater distances than were measured by the prototype instrument.

As part of this project, the team designed and constructed an instrument to demonstrate that available components could be assembled to achieve basic measurement objectives. The stand-alone EM instrument was comprised of tri-axial electric and magnetic field sensors capable of measuring the relevant bandwidth of interest, and was outfitted with a multi-channel sampling and storage capability to acquire EMF data for processing and analysis. The instrument was deployed in-situ at two different near-shore marine environments, and acquired EM field data near an operating submarine power cable-of-opportunity to show the efficacy of the system to quantify EM emanations due to the influence of the power cable within the environment. As part of this activity, the instrument was calibrated in a laboratory to ensure a valid and repeatable methodology for measurements. Results of the instrument deployments are presented, including analyses of EM spectral processing. Data acquired clearly showed the presence of strong electric (E-field) and magnetic (B-field) power line frequencies and harmonics (namely 60 Hz, 180 Hz, 300 Hz, and 420 Hz discrete lines) near the power cable, which dissipated as the instrument was moved away from the cable, as expected. EM fields created by submarine cables of a commercial capacity (in the megawatt range) would be expected to create much stronger fields than those measured during this study, and would be detected at further distances.

The affordability, reliability, and repeatability objectives of the study were demonstrated. Modeling, calibration, measurement, and processing protocols and techniques identified within this study serve to advance the science of marine EM measurements in coastal waters, and promote a standardized methodology that is both reliable and repeatable.

The following summary conclusions and recommendations are made:

1. Substantial published data is lacking on observed effects to marine species from EM fields at power frequencies (60 Hz and harmonics). Application of equipment and techniques documented within this study could easily be adapted to provide repeatable, quantifiable EM field data to ensure that observable conclusions are based on valid data sets.

Recommendation: Conduct additional biological study to better understand and quantify observed effects to biota from man-made EMF. Apply equipment and techniques developed in this study in support this of biological research.

2. Due to the limited scope of the study, the long-term temporal variability of naturally occurring EM fields was not quantified in terms of range or extent. Longer term monitoring or periodic sampling would provide better insight into the naturally occurring environment, as well as that of operating energy generating facilities. Scientific documentation of concurrent conditions over longer time horizons (weeks, months, seasons) will add to the physical understanding, and hence, biological understanding of measured EM fields.

Recommendation: Conduct long-term monitoring with energized cables. As part of monitoring, collect electrical and physical data to correlate measured levels to physical phenomena.

3. Modeling and predictions of E- and B-field strengths in the coastal environment are strongly dependent on local conditions, including the underlying geology. In particular, local conditions substantively affect longer-range propagation of EM fields. The existing modeling framework together with a larger set of physical measurements of in-situ data using technologies demonstrated within this study can account for these phenomena and lead to a better understanding and predictions for impacts to potential wave energy sites.

Recommendation: Evaluate and improve existing modeling capabilities with measured data at wave energy sites. Consider performing this activity while concurrently monitoring energized cables along Oregon's coast.

2. INTRODUCTION

The major objective of this project was to demonstrate an ability to achieve affordable, reliable, repeatable EMF measurement protocols in support of wave and tidal energy technology development and deployment. As such, this report was prepared to describe the prototype instrumentation fabricated with affordable and available components, calibration results to provide the basis for repeatability, and a data summary of the ambient background and energized power cable measurements conducted during at-sea measurement deployments.

The results provided in this report are the culmination of a series of studies to investigate methods, protocols, and other significant input parameters for establishing reliable, repeatable, and affordable EM measurements at wave project sites. The following reports were prepared to investigate, analyze, and report on current near-shore EMF knowledge base, to research state-of-the-art and available technologies in measurement approaches and equipment, and prepared to review measurement physics, including sources and modes of EM generation and propagation. Methods were assessed and summarized, with alternatives and recommendations provided to achieve the project objectives. Data for these reports were obtained through literature reviews, market surveys, computational activities, and laboratory and field tests.

- Effects of Electromagnetic Fields on Marine Species: A Literature Review, report 0905-00-001
- Estimated Ambient Electromagnetic Field Strength in Oregon's Coastal Environment, report 0905-00-002
- The Prediction of Electromagnetic Fields Generated by Wave Energy Converters, report 0905-00-003
- EMF Synthesis: Site Assessment Methodology, report 0905-00-004
- EMF Measurements: Data Acquisition Requirements, report 0905-00-005
- EMF Measurements: Instrumentation Configuration, report 0905-00-006
- The Prediction of Electromagnetic Fields Generated by Submarine Power Cables, report 0905-00-007
- Ambient Electromagnetic Fields in the Near shore Marine Environment, report 0905-00-008
- Trade Study: Commercial Electromagnetic Field Measurement Tools, report 0905-00-009
- EMF Measurements: Field Sensor Recommendations, report 0905-00-010
- Summary of Commercial EMF Sensors, report 0905-00-012

These reports are available from the Oregon Wave Energy Trust, <http://www.oregonwave.org/>. Results from these studies were combined to prepare the prototype instrument to demonstrate that near-shore EM field measurements could be reliably and affordably obtained at coastal project sites.

2.1 Report Organization

This report contains seven primary sections, and includes supporting appendices. The first sections contain the executive summary and introduction, and provide the project background. Setup of the prototype instrument is described in Section 3. The first deployment is described in Section 4, with the data processing and analysis results from that deployment discussed in section 5. Section 6 describes methods and results from a deployment of the instrument near an energized pipeline in Newport Bay, Oregon. A discussion of the results of the study are provided in Section 8, with conclusions and recommendations presented in Section 9. Appendix A contains an acronym list, and Appendix B contains calibration logs. Reference documents are listed in Appendix C.

2.2 Methodology

A prototype EM probe was constructed to demonstrate that basic, low cost instrumentation could provide affordable, reliable, and repeatable near-shore EM measurements in the marine environment. While available, commercial wideband electric and magnetic field measurement systems are expensive. Further, commercially available magnetic systems generally do not extend up into the kHz frequency range. Thus, the use of magnetic sensors in this study press the current commercial technology above that which is typically available.

As part of this study, a low cost prototype instrument was assembled to demonstrate that such measurements could be obtained with a modest tool. After assembly, the instrument was calibrated in a laboratory, and then deployed to assess the naturally occurring magnetic and electric fields and the emanated electric (E) and magnetic (B) fields from a three-phase AC submarine power cable, and also from an energized submarine pipeline. This report describes the basic instrument and data collection parameters, provides calibration data, and discusses measured results obtained during the demonstration deployments.

3. INSTRUMENTATION SETUP – IN SITU CABLE DEPLOYMENT

The instrument was constructed using available components (see Figure 1) following the recommendations provided in an earlier phase of this study (reference (a)). Tri-axial arrangements of magnetic and electric field sensors were made to obtain orthogonal measurement of B-field and E-field parameters across the frequency range of primary interest, from a few tens of milli-Hz to approximately 500 Hz. The instrument was fully self-contained, with a six-channel high-resolution recording system implemented to receive, sample, and store data for subsequent processing, and a DC battery supply to provide system and sensor power for the duration of the deployment and to avoid any potential AC signal contamination.

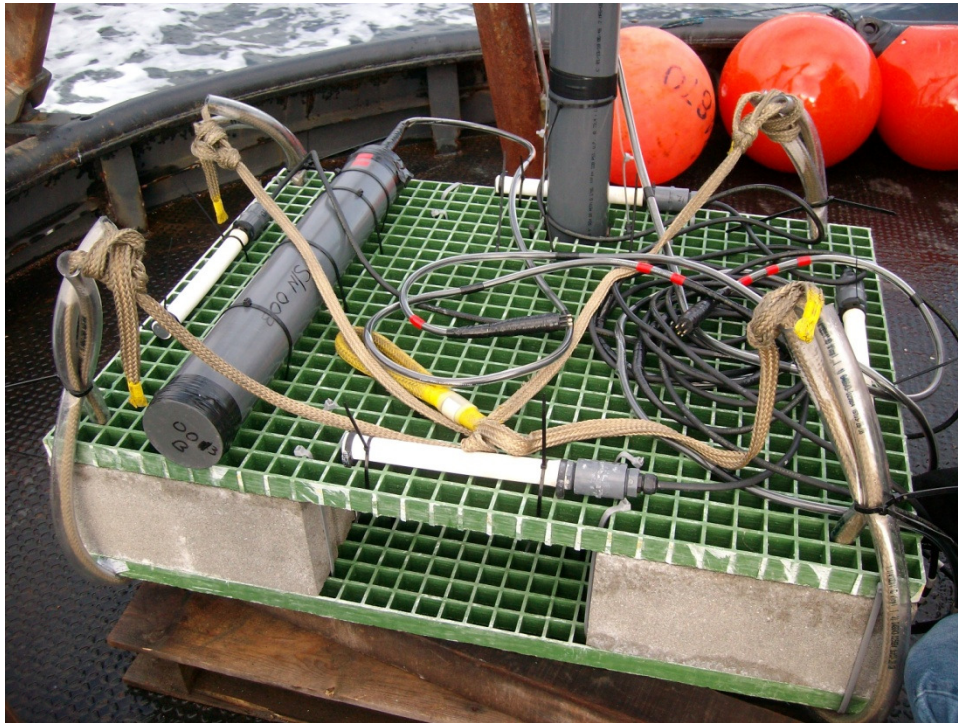


Figure 1 - Prototype instrument on deck of test vessel prior to deployment

Due to the sensitivity of the instruments, wherein motion can induce erroneous measurements by increasing the self-noise level of the instrument, a stable platform was required to minimize movement on of the probe during deployment. Thus, an open platform was fabricated using common construction materials (fiberglass, PVC, concrete, vinyl tubing, plastic cable ties, etc.) to mount the sensors and the instrumentation/battery pack. A deliberate use of non-metallic components minimized possible spurious influence of the recorded data due to the proximity of

electrical or magnetic properties of metallic components. During deployment, the probe platform was lowered to the ocean floor, with a small float attached to mark the instrument for recovery. The overall in-air weight of the instrument was approximately 250 lbs, including concrete weights.

3.1 Magnetic Field Sensors

Induction coil type magnetic sensors were used to sense magnetic fields. Uniaxial ANT-2 antennas from Zonge International, Inc. (Zonge) utilizing a metallic core and an overall length of 18 inches were packaged within pressure vessels constructed from PVC (see Figure 2). The specific design of this particular was well suited to the prototype instrument, which was a result of joint development by Zonge and the Oregon State University (OSU) as part of the National Science Foundation funded National Geoelectromagnetic Facility. Thus, while not completely a commercial component, these sensors were made available to this study via OSU and Zonge in advance of commercial release.



Figure 2 - Uniaxial magnetic field sensor, shown with non-metallic pressure vessel

The probes provided a basic sensitivity of $.1V/nT$ (see Appendix B), and was flat to within 1 dB over the range of 30 Hz to 50 kHz. The low-frequency regime of this sensor rolled off below

30 Hz, with a useable response extending below 1 Hz. Sensors provided a low impedance differential output, and were wired from each sensor output to the data recorder using balanced, shielded cable. During assembly and testing, it was noted that minor movement of the sensors clipped the input of the data recorder (± 2 volts). Differential attenuators (20 dB) were used on the sensor output to limit the output voltage to optimize the available dynamic headroom on the recorder once deployed without clipping the inputs. Pressure vessels were rated for a depth of 250 feet in seawater, and tested in a pressure tank at 130 psi (equivalent to 290 feet of seawater) prior to deployment. Commercial wet-mate pluggable connectors were used to wire the sensors to the recording unit.

3.2 Electric Field Sensors

Low-cost electric field sensors were fabricated in pairs using a lead-lead chloride formulation. The inspiration for the basic electrode design was derived from Webb et al. (reference (b)), who used a silver-silver chloride (Ag-AgCl) sensor chemistry. To keep the sensors affordable, a lead-lead chloride (Pb-PbCl₂) sensor chemistry was adopted for the prototype after Petiau (reference (b)). In our approach, commonly available components were prepared and assembled to achieve very low impedance to seawater, thus reducing the effective sensor noise floor. A diatomaceous earth mixture was prepared to encase the metallic electrodes within a porous sleeve to allow ionic exchange with the surrounding seawater (see Figure 3). This process resulted in probes with a resistance of only a few ohms using electrodes approximately 12 inches in length; electrodes were matched in pairs to minimize DC bias, a known condition common to metallic electrodes. Electrode pairs were cabled to differential inputs of the data recorder.



Figure 3 - Electric field probes and wet-mate interconnect cable

3.3 Data Recorder

Single-channel analog-to-digital recording boards were assembled into a six-channel “stack” to record three each electric field and magnetic field channels (see Figure 4). Each recorder board was configured for a single channel with differential input, and 32 bits of digital resolution provided a wide dynamic range for recording and low system noise floor. The recorder operated as a state machine, and initiated recording upon power-up and synchronization. One board operated as the master, and all boards were synchronized to within one sample to the master board. Sampling rate was set to 1024 samples per second (1024 Hz), providing a useable measurement bandwidth of 512 Hz. Upon deployment, data were synchronized and continuously recorded to microSD formatted memory cards.



Figure 4 - Six-channel data recorder assembly 'stack'

3.4 Calibration

Calibration followed the basic procedure outlined in reference (d), including the use of a 12-foot long, 10" diameter calibration coil with 144 wraps (see Figure 5). Using this coil and a precision resistor, the electrical current passing through the coil was measured with a 6.5 digit calibrated voltmeter. The magnetic field strength within the coil was then computed. The output of each magnetic sensor was measured using a narrowband spectrum analyzer and compared to the manufacturer's specifications for instrument sensitivity. Calibration results are provided in Appendix B for the three magnetic sensors used during the deployment, which shows excellent agreement with the manufacturer's specification over a wide range of frequencies, from 30 Hz to over 50 kHz. A cursory linearity analysis was done showing that the magnetic sensors were flat over the range tested, from 1 nT to over 100 nT, with a useable noise floor of better than 2 pT/ $\sqrt{\text{Hz}}$ at 60 Hz.



Figure 5 - Magnetic sensor undergoing magnetic calibration

Electrical calibration of the data recorder was conducted by injecting a known AC voltage into the front-end of each data recorder channel and measuring the output. A single-frequency sine wave was generated using an arbitrary waveform generator and injected into each channel. Root mean square (RMS) levels were measured using a calibrated voltmeter, which verified that the output was within the manufacturer's specifications.

4. IN-SITU CABLE DEPLOYMENT

After seeking a suitable AC power cable in the oceanic, salt-water environment along the Oregon coast and finding none, a representative cable was located in a controlled Pacific Coast environment, with access provided by a cooperating entity, which provided nominal cable operating parameters during field measurements. The governing agreement between SAIC and the cooperating entity permitted distribution of the experimental results and protected specifics about the entity's operations.

A local test vessel outfitted with an A-frame was contracted to deploy and recover the probe assembly. The probe was shipped to an in-port location, assembled, and staged on the test vessel the day prior to the measurement period. Approximately four hours were required to unpack, assemble, and prepare the probe for data recording. New batteries were fitted, sensors were positioned on the frame, and the sensing and recording equipment was verified to be operational. On the morning of May 28, 2010, the probe was loaded onto the test vessel, which transited to the measurement site.

4.1 Description

After the data recording was started, the test vessel maneuvered to each measurement location and the probe was lowered to the bottom and marked with surface marker buoys. During the measurement period, the test vessel maneuvered away from each probe location to a position greater than 1 km away to minimize any potential interference to the measured data. The probe recorded data continuously during the entire deployment. Measurement locations are shown in Figure 6. Locations were selected to provide a comparable suite of measurement conditions to determine the spatial dependence of the expected EM fields at various distances from an energized cable. Care was taken to stay away from the restricted cable right-of-way to avoid disturbing the cable itself. The closest location was less than 75 meters from the cable itself, and the furthest location was up to one half kilometer (500 meters) away (see Table 1). All measurement positions were located at approximately the same depth (22 to 24 meters of water). Weather conditions during the measurement period were calm. Wave swell amplitude was less than 1 foot, and observed tidal currents were minimal.

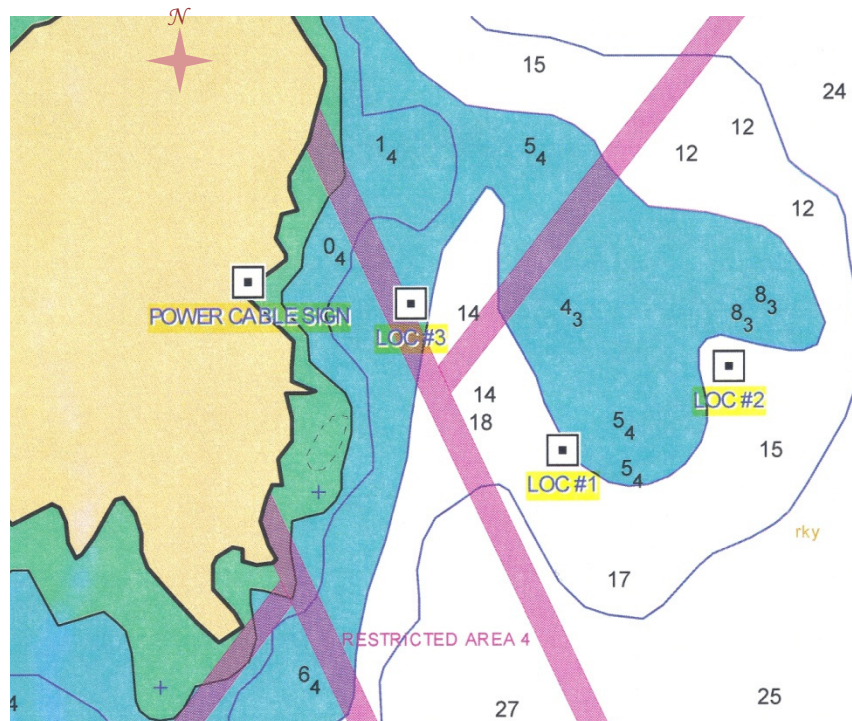


Figure 6 - Sensor locations during deployment

Table 1 - Sensor locations during in-situ cable data collection

Sensor Location	Approximate Distance to Cable (meters)	Water depth (meters)
LOC#1	150 to 200	23
LOC#2	400 to 500	24
LOC#3	50 to 75	22

4.2 Electric Field Sensors

The electric field electrode pairs were mounted to the probe platform on the same orthogonal axes as the magnetic sensors. The spacing varied with each pair, based on the physical dimensions of the probe platform (see Table 2).

Table 2 - E-field electrode spacing

Sensor ID	Orientation	Separation
E1	Horizontal	1.07 meters (42")
E2	Horizontal	.80 meters (31.5")
E3	Vertical	.47 meters (18.6")

4.3 Magnetic Field Sensors

Three induction coil magnetic sensors were encased in PVC pressure vessels and mounted in an orthogonal configuration, two each in the horizontal plane at right angles, and one vertically (see Figure 7). Orthogonal mounting allowed relative comparison of magnetic field strength based on spatial orientation to the energized cable.



Figure 7 - Deployment of probe assembly at in-situ test site



Figure 8 - View of LOC#3 marker buoys looking toward cable landing zone

4.4 Data Acquisition Summary

Six channels were continuously recorded for a period of 4 hours, 53 minutes. Valid data were recorded at each of three locations, with a minimum of one hour at each site. At the end of the recording period, the probe was recovered on deck, and the memory cards removed for processing and analysis. Approximately 330 megabytes of data were recorded for each channel,

with an overall aggregate amount of 2 gigabytes. Files were read and converted into a MATLAB[®] compatible data format.

5. DATA PROCESSING AND ANALYSIS

5.1 Data Processing

Data were recorded on each channel using a 1024 sampling frequency, thus providing a useable frequency bandwidth of 512 Hz. Time series data were calibrated using measured calibration values for each channel, and then high-pass filtered and processed using short-time Fourier transforms to provide spectrum level (1 Hz bandwidth) signatures over the measurement period. Time-frequency spectrograms were computed for each channel over the 4 hour, 53 minute measurement duration to provide a visual representation of the complete recording period. The first thirty-three minutes of each recorded channel represent instrument setup and test vessel maneuvering to the first measurement location. The probe was on deck for this period. It was observed that prior to deployment, relatively high levels of both electric and magnetic fields were recorded which were attributed to sensor motion, and relative proximity to the test vessel equipment, including engines and generator, and electrical circuitry. The set-up and maneuvering period is shown in the approximate period marked from the 0 to 2000 second timescale in the figures.

The recording time of each of three measurement locations is annotated on each figure. Time at Location #1 was 90 minutes, spanning the 2000 to 7388 second timescale. The probe was located from 150 to 200 meters from the energized cable, which was operating at a nominal voltage of 12.7 kV, and carrying between 8 and 10 amperes of AC current during the measurement period.

The second location, marked from nominally 8000 to 12000 seconds, represents approximately 66 minutes, of recording time. The wide, prominent vertical yellow-green bands in Figures 9, 10, and 11 show periods of time during which the probe was recovered from the bottom, and the test vessel maneuvered to the new location and re-deployed the probe on the bottom.

Location #3 represented the closest measurement to the energized AC cable. Data were recorded approximately 70 minutes at this location, at an estimated distance between 50 and 75 meters from the cable. Resulting spectrogram images for each channel presented in Figures 9 through 14, using a logarithmic decibel scale to represent signal amplitude. Recording time begins and the left-hand side of each chart, and progresses to the right-hand side, with the time-scale given in seconds from the beginning of the data recording.

As expected, both electric and magnetic signatures at the fundamental power frequency (line voltage, 60 Hz) and higher order harmonics (180, 300, and 420 Hz) from the energized cable were stronger near the cable, and diminished in amplitude away from it. Theory predicts that the electric field emanates radially from a cable, and is orthogonal to the magnetic field. Thus, strongest electric fields were expected in the horizontal dimension pointing “away” from the cable, and essentially zero parallel to the cable in either the vertical or horizontal orientation. This can be seen in Figures 9 and 10, wherein power frequency harmonics were observed in the horizontal direction (especially at Location #3), and they were notably absent in the vertical direction.

The dominant 60 Hz line in the horizontal dimension was evident at Locations #1 and #3, showing that the field was detected up to 200 meters from the cable. Multiple odd-harmonics of 60 Hz were also seen in at Location #3 (180 Hz, 300 Hz, and 420 Hz) within 75 meters from the cable. The presence of 180 Hz energy and higher order odd harmonics from the cable indicate that the electrical power waveform was not purely sinusoidal, and was likely distorted. A few discrete, time variant frequencies were noted in the data set from an unknown source, which are annotated on the charts.

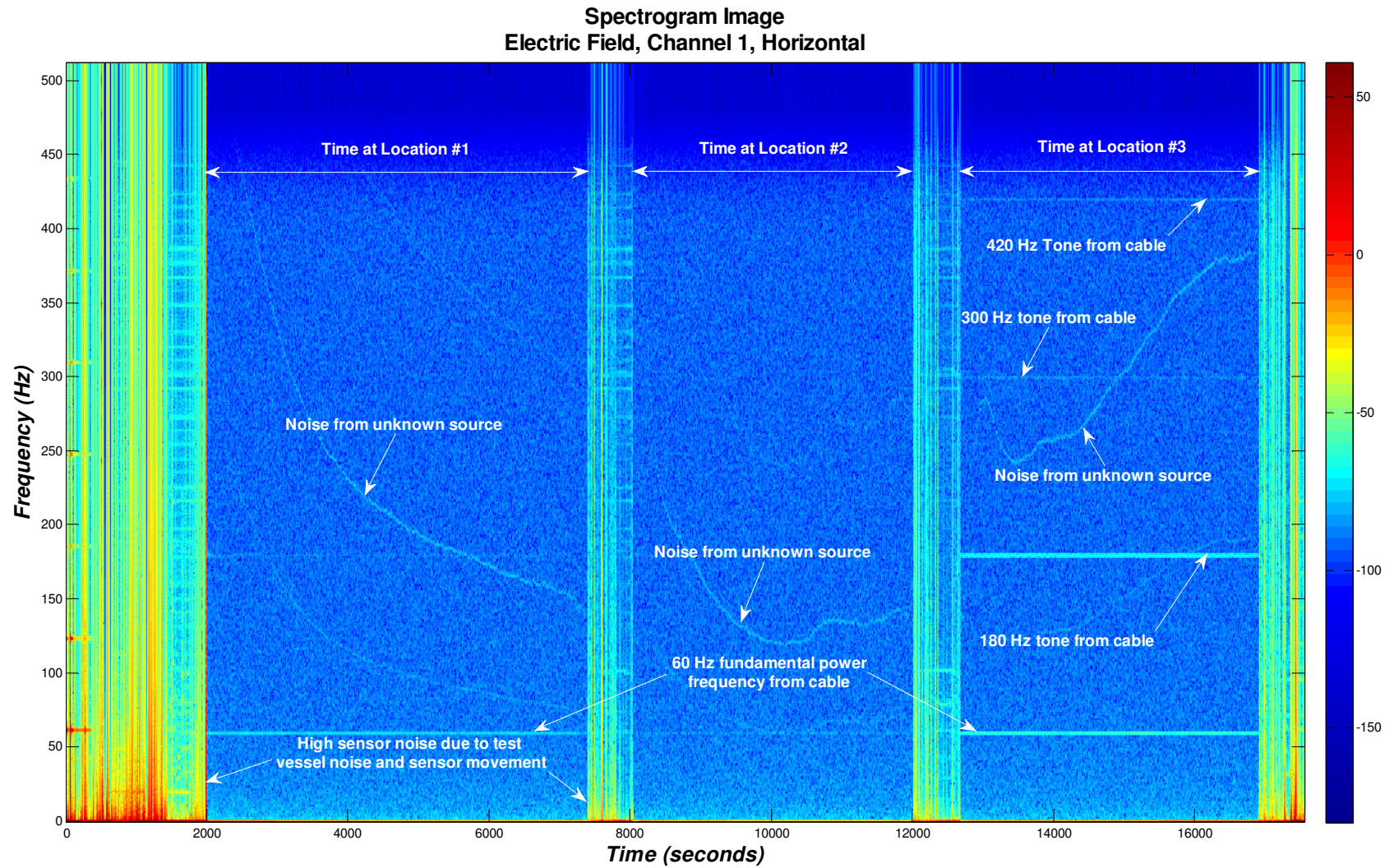


Figure 9 - E-field Spectrogram Image, Sensor E1, Horizontal

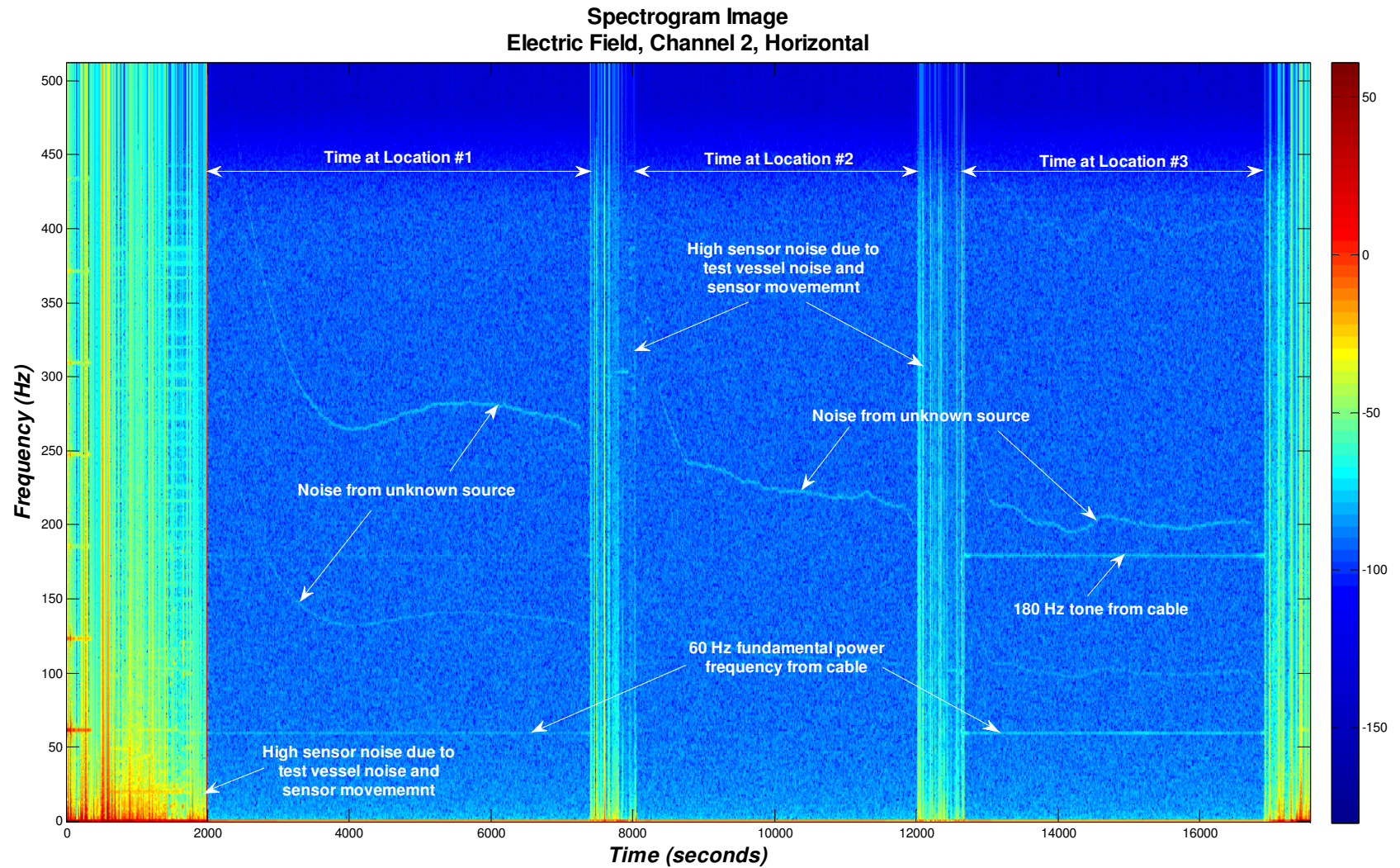


Figure 10 - E-Field Spectrogram Image, Sensor E2, Horizontal

In the vertical direction, the measured electric field was non-descript at all measured locations, and in particular AC power cable harmonics were not readily apparent (see Figure 11) with a nominal continuum level of less than $100 \mu\text{V/m}$. The addition of low-noise preamplifiers would serve to reduce the level of background noise in the measured spectra such that power harmonics might be more easily detected, but it was clear that this dimension was less important for the assessment of power cable frequencies as predicted by electrical field theory. It should be noted that the cable measured was carrying approximately 10 amps of AC current, which would be substantially lower than the level of current expected to be carried by marine energy power export cables, which might range from perhaps 100 amps to over 1000 amps of AC current. Since the induced electric field strength at a given distance from a cable is directly proportional to the current being carried in the cable, it is likely that received levels by the probe near such power cables would provide a much stronger, and thus more detectable signal than those measured during the in-situ tests presented herein.

Figures 12 and 13 show the horizontal magnetic fields observed during the measurement period, and Figure 14 shows the resultant B-field in the vertical dimension. Theory predicts that magnetic fields around a power cable flow around the cable in a circumferential manner, thus in generalized homogeneous environment, an energized cable will product “right-hand-rule” responses to the magnetic field surrounding the cable. All things being equal, no vertical component is expected when directly over an energized cable, and when a cable is crossed, the polarity of the vertical B-field reverses. Likewise, the intensity of the horizontal B-field increases monotonically and symmetrically as the cable is approached from either side. In practice it is unlikely to attain perfectly aligned conditions to achieve theoretical prediction, but in general, predictive theory provides the basis for understanding actual results. So, for any general location in the real world, both vertical and horizontal components to the B-field may be present. In the case of the data obtained during this deployment, sensors were located at some perpendicular distance (greater than 50 meters) from the energized cable, thus the magnitude of the vertical component were expected to be more significant than horizontal components of the B-field vector.

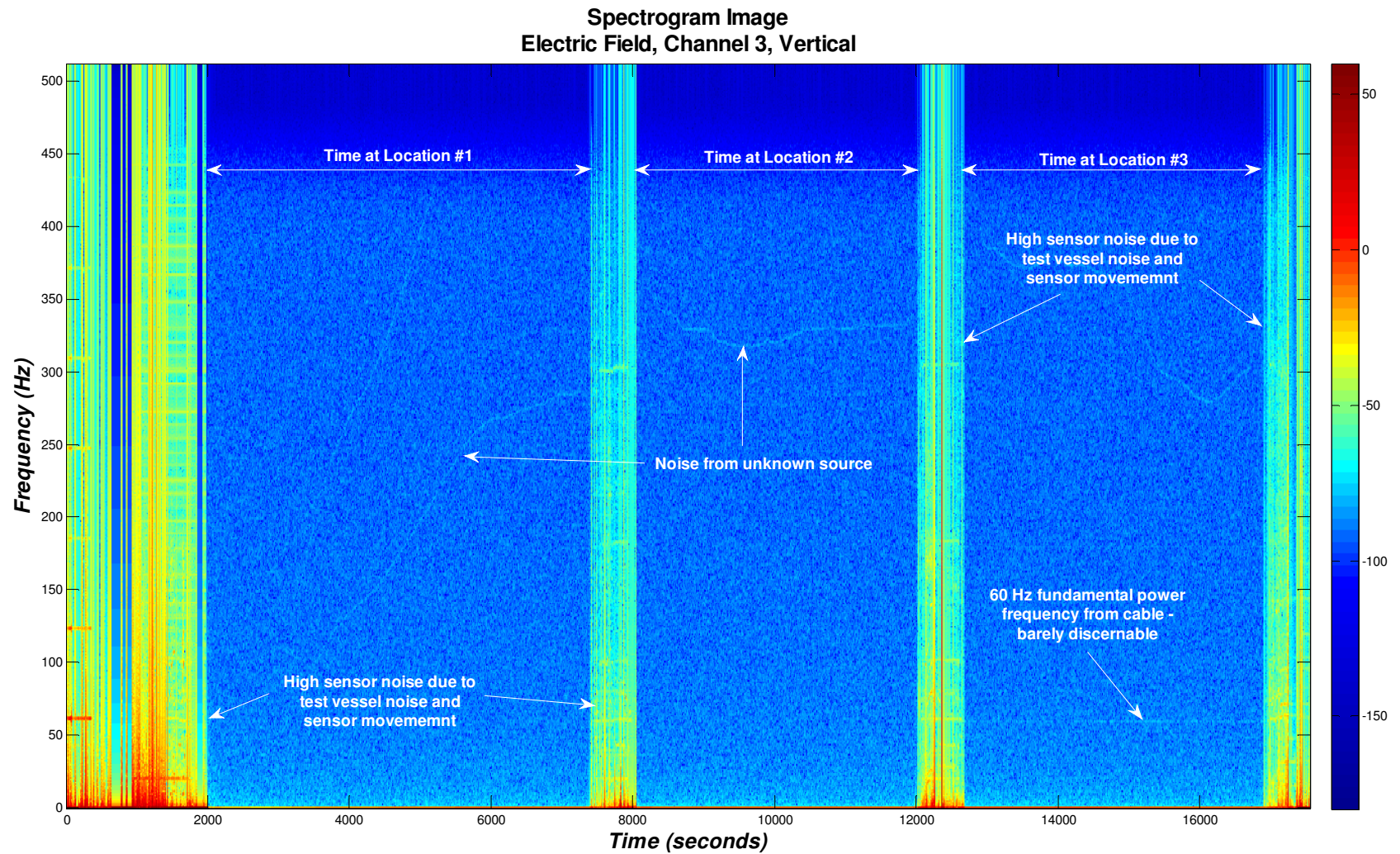


Figure 11 - E-Field Spectrogram Image, Sensor E3, Vertical

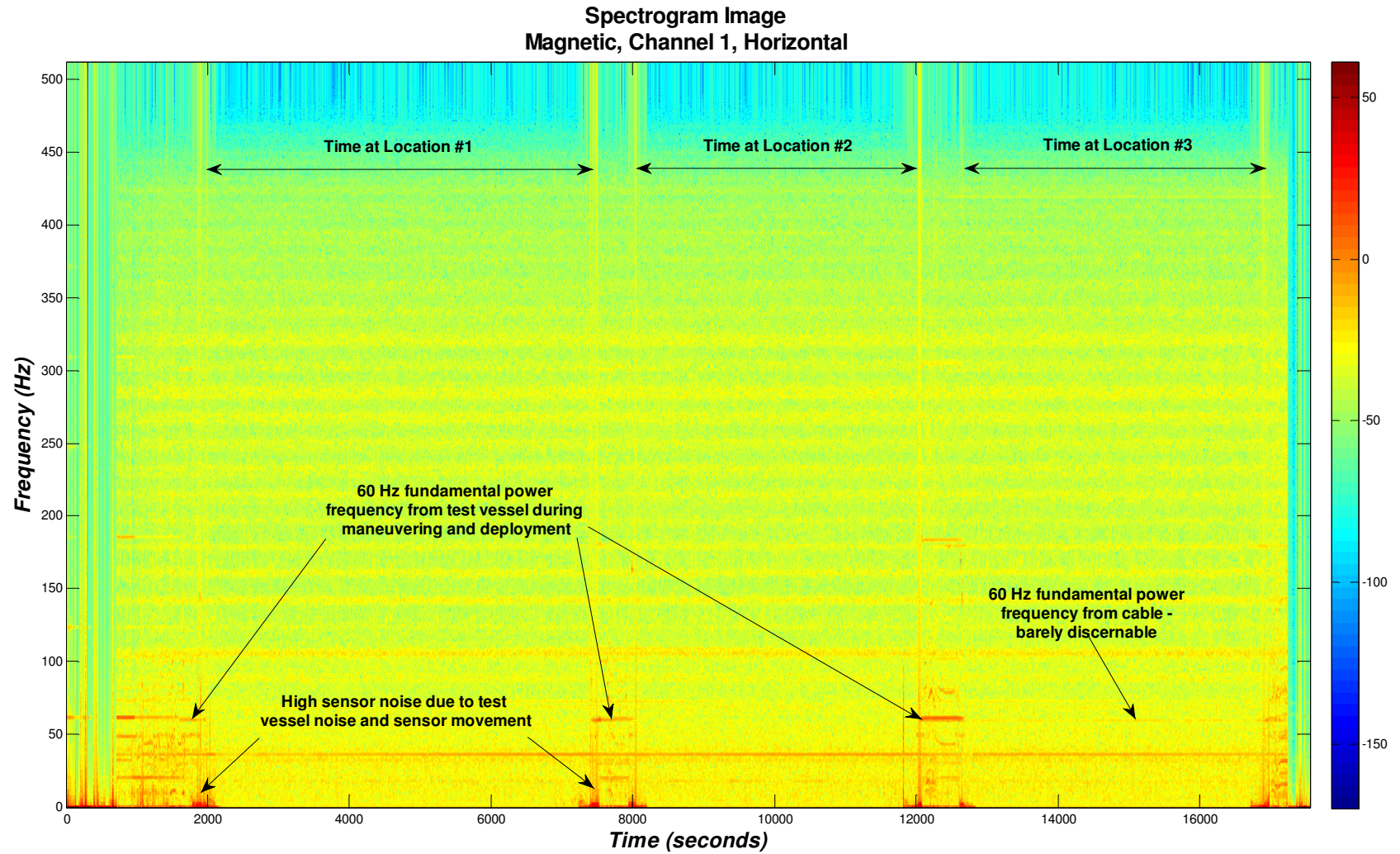


Figure 12 - B-Field Spectrogram Image, Sensor M1, Horizontal

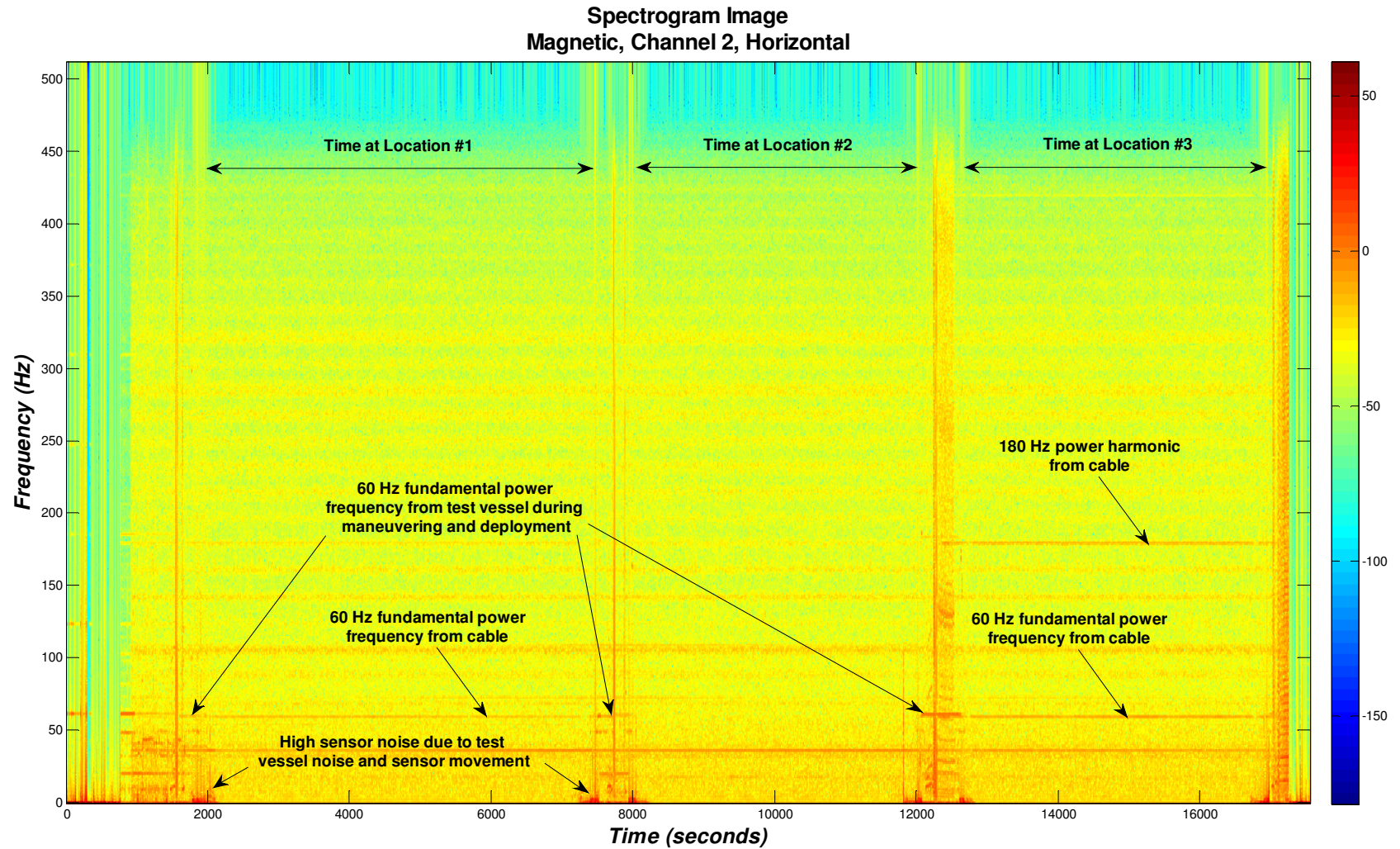


Figure 13 - B-Field Spectrogram Image, Sensor M2, Horizontal

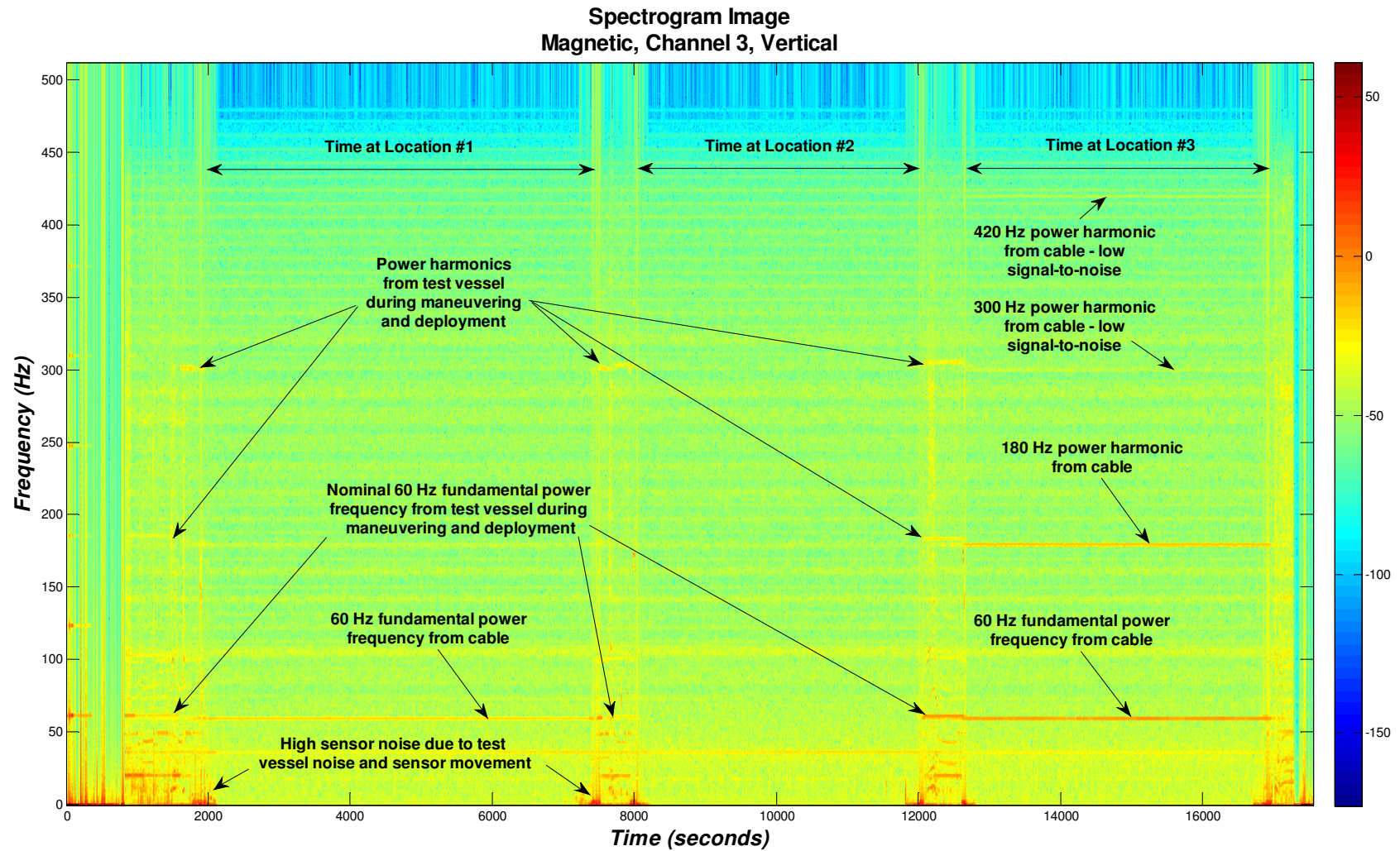


Figure 14 - B-Field Spectrogram Image, Sensor M3, Vertical

This is seen best by comparing Figure 14 (magnetic B-field in the vertical direction) to Figure 12, wherein the odd-harmonic power frequencies at 60, 180, 300, and 420 Hz are strongly evident in the vertical data, and are notably quiet in channel M1 (horizontal) data. Some signals are seen in Channel M2 (also horizontal magnetic) at 60 and 180 Hz, indicating that some magnetic energy was nonetheless detected in this dimension. Transient energy was evident during periods of recovering and repositioning the probe, underscoring the need to have a stable measurement platform to minimize system noise while taking measurements. Magnetic energy is easily induced on the sensors when they are moved with respect to the Earth's magnetic field, which can overload the inputs to these ultra-sensitive devices.

5.2 Spectral Analysis

In addition to time-frequency analysis, narrowband spectra were also computed using one-second integration periods using 1024 point fast-Fourier transforms to provide a 1 Hz equivalent noise bandwidth (spectrum level). Nominal signal-to-noise (SNR) values were computed and logged once per second during the measurement period for all measurement channels. This technique compared the peak tonal amplitudes to the amplitude of the spectral continuum adjacent to each tonal, in terms of a decibel ratio. SNR ratios greater than 10 dB indicate a strong signal not influenced by background (ambient) or system noise floor. SNR between 3 and 10 dB are considered to be influenced by background noise, and thus resultant amplitudes could be affected by local noise. Data with computed SNR values less than 3 dB are not provided, since these values were dominated by local noise affects, and did not represent accurate measured values. Figure 15 shows representative results of the magnetic (B-field) sensor in the vertical orientation (Sensor M3) at 60 Hz. Measurement locations are annotated on the figure. Highest SNR values were noted at location #3, closest to the cable, with typical SNR values greater than 30 dB. High SNR (>18 dB) was also noted at Location #1. Average SNR at location #2 were less than 3 dB, indicating that 60 Hz signals at this location and orientation combination were not substantially present above the background levels. Comparing these results to the visual spectrogram images (see Figure 14), it is evident that 60 Hz was not observed in the vertical direction at Location #2 approximately 500 meters away from the cable.

As expected, both electric and magnetic signatures at the fundamental power frequency (line voltage, 60 Hz) and higher order odd-harmonics (180 Hz (3x 60 Hz), 300 Hz (5x 60 Hz), and 420 Hz (7x 60 Hz)) from the energized cable were stronger near the cable (see representative narrowband spectrum in Figure 16). Signal amplitude diminished in locations away from the cable location.

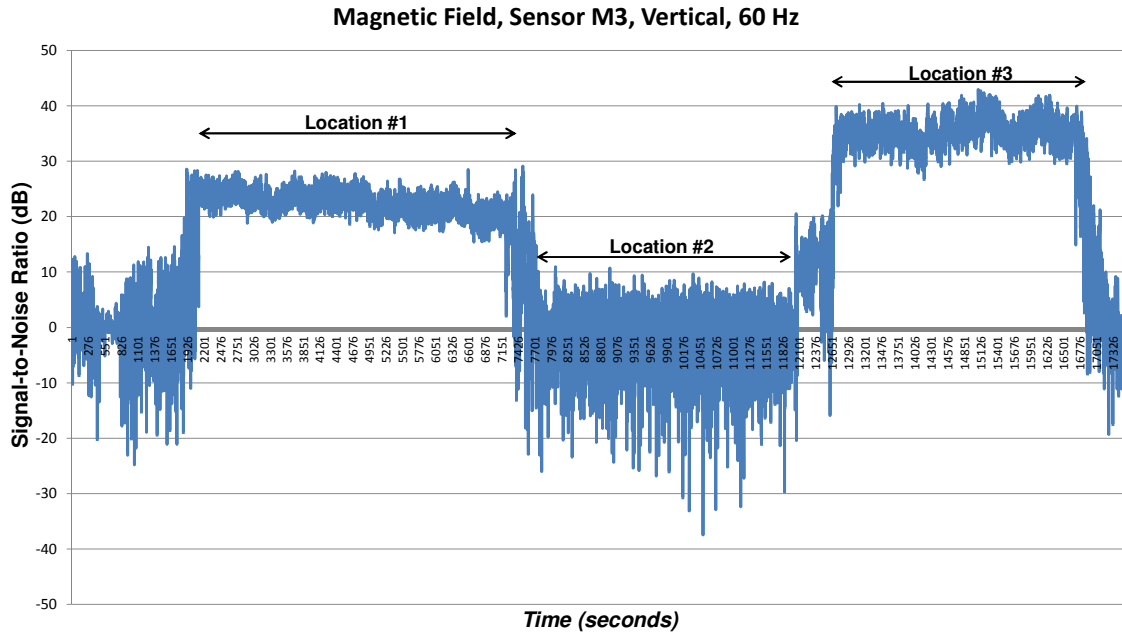


Figure 15 - Representative Signal-to-Noise Analysis, Magnetic Spectra, 60 Hz

Electric field strength at Location #2 were not readily measured using spectral processing, although 60 and 180 Hz tonals at both Locations #1 and #3 were strong, and 300 and 420 Hz tones were also measured at Location #3 within 75 meters of the cable. At distances greater than 50 meters from the cable, maximum E-field levels at 60 Hz were observed at 2 microvolts/meter ($\mu\text{V/m}$) or less. Longer integrations (up to 60 minutes) are possible to reduce the effective noise floor due to processing gain, but this was not analyzed since the 60 Hz power frequency and related harmonics were readily apparent in the data set at a 1 Hz bandwidth (spectrum level).

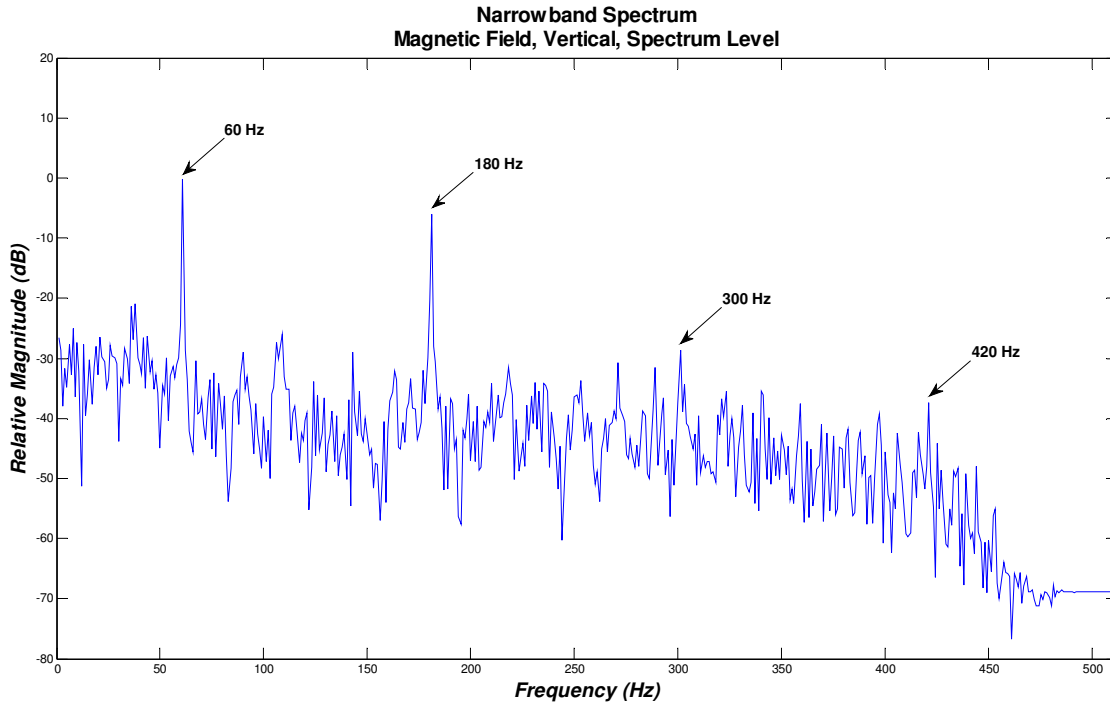


Figure 16 - Representative B-field magnetic spectrum, vertical, 1 Hz bandwidth

Table 3 presents the E-field AC power frequency summary for odd harmonics of 60 Hz at each of three measurement locations.

Table 3 - Electric Field Summary, AC Power Frequencies, Spectrum Level

Frequency (Hz)	Magnitude Location #1 ($\mu\text{V/m}$)	SNR (dB)	Magnitude Location #2 ($\mu\text{V/m}$)	SNR (dB)	Magnitude Location #3 ($\mu\text{V/m}$)	SNR (dB)
60	0.67	8	--	<3	1.98	18
180	0.26	3	--	<3	1.60	19
300	---	<3	--	<3	0.23	3
420	---	<3	--	<3	0.17	3
Approximate distance to AC power cable: Location #1: 150 to 200 meters Location #2: 400 to 500 meters Location #3: 50 to 75 meters Magnitude is computed as vector sum of horizontal and vertical components.						

Table 4 presents the magnetic B-field summary of measured power frequencies. As with the electric field data, field strength was directly related to the distance from the probe to the energized cable, as expected. A relatively weak 180 Hz frequency was measured at Location #2, which was not appreciably above the background level. 60 and 180 Hz magnetic field energy was easily observed at both Locations #1 and #3 (within 200 meters of the cable), with good signal to noise ratios, indicating a significant margin above the background noise levels at those frequencies and locations. Maximum levels were measured at Location #3 at 60 Hz, at 0.13 nT, but no power frequencies were seen at Location #2, which was estimated to be 400 to 500 meters from the energized cable. For reference, the earth’s total magnetic field is approximately 52,000 nT (.000052 Tesla, or .52 Gauss) along the Oregon coast.¹

Table 4 - Magnetic Field Summary, AC Power Frequencies, Spectrum Level

Frequency (Hz)	Magnitude Location #1 (nT)	SNR (dB)	Magnitude Location #2 (nT)	SNR (dB)	Magnitude Location #3 (nT)	SNR (dB)
60	0.04	10	---	<3	0.13	20
180	0.02	12	---	<3	0.07	24
300	---	<3	---	<3	0.01	3
420	---	<3	---	<3	0.01	9
Approximate distance to AC power cable: Location #1: 150 to 200 meters Location #2: 400 to 500 meters Location #3: 50 to 75 meters Magnitude is computed as vector sum of horizontal and vertical components.						

6. ACTIVE SOURCE VERIFICATION DEPLOYMENT

In addition to evaluating the prototype probe for energized and background noise measurements, the probe was deployed in Newport Bay, Oregon in July 2, 2010 to test the probe’s magnetic capability to sense a low-frequency active EM signal on a submerged sewage pipe in the bay. The motivation for the test was to geo-locate the pipeline to in support of planned construction of a new pier in Newport. Although OWET allowed use of the probe as a test-of-opportunity of the

¹ <http://www.ngdc.noaa.gov/geomagmodels/IGRFGrid.jsp>

prototype in an active source scenario, work activities for this test were not funded by OWET. Personnel from OSU (Dr. Adam Schultz and Tristan Peery) and SAIC (Michael Slater) provided technical support during the test period.

6.1 Methodology

A buried and submerged sewage pipe and adjacent metallic conduit was energized with a 256 Hz square wave using a terrestrial geophysical transmitter provided by Zonge. The transmitter was grounded to the pipeline on shore, and a ground electrode was located in a position defining a right angle to the between the ground point and the presumed pipeline direction. The probe was able to detect the transmitted energy at the fundamental frequency of 256 Hz, and using vector properties of the magnetic field sensed by the probe, the magnitude of the vertical magnetic field at various locations could be mapped. The pipeline was buried under approximately 15 meters of sediments in water 15 meters deep.

6.2 Deployment

The probe was staged and assembled near the pier, and then transported to the deck of a small tug outfitted with an A-frame. The data recorders were started, and the tug maneuvered to each location of interest. The probe was lowered to the bottom for a series of nominal five-minute periods, picked up, and moved to the next location.

6.3 Data Analysis

Data acquired during the Newport Bay active source testing were processed using time-frequency analysis in the same manner described for the background data analysis. A spectrogram image of the magnetic sensor in the vertical orientation is shown in Figure 17. Frequency is shown along the left axis, and time (in seconds) runs from left to right. A total span of approximately three hours is shown. Red color in the spectrogram image on the left and right sides represent high signal levels due to sensor motion while the probe was being transported to and from the pier to the measurement site. During the measurement period, the probe was lowered to the bottom in approximately 15 meters of water, and then recovered, moved to the next position, and repeated. Data were acquired continuously throughout this period. A strong signal at 256 Hz due to the source on the pipeline conduit was clearly evident during the measurement period.

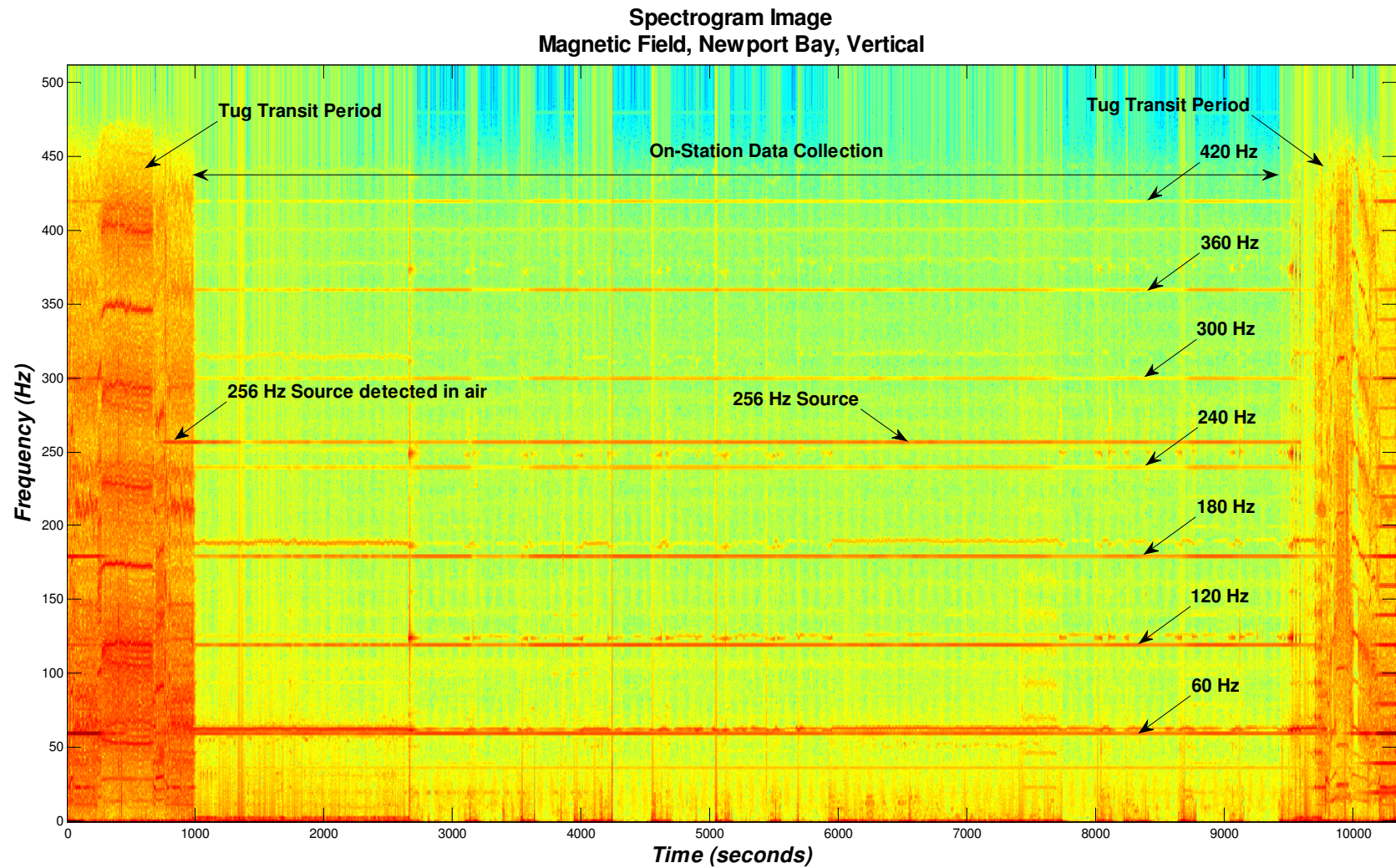


Figure 17 - B-Field Spectrogram Image, Sensor M3, Vertical

A narrowband spectrum (1 Hz bandwidth) was computed at one representative location to demonstrate the ability of the probe to sense and quantify measured signals (see Figure 18). The signal level at 256 Hz had sufficient strength to be observed with the probe in-air on the deck of the tug (see left hand side of chart) prior to placing the probe in the water. From the perspective of calibrated measurements, this observation is not very useful, however, this result does significantly demonstrate that the long-distance propagation of the "air-wave" component of the EM fields can extend the influence of EMFs from the generation source as that energy propagates along the air-sea interface. A similar effect is also possible on the sea-bottom interface due any resistive components of the underlying sub-sea strata, and points to the critical need to consider the specific site geology and physical layout when predicting EM fields in potential wave energy sites. In other words, simplified models with infinitely deep conductive ocean assumptions do not adequately address this affect.

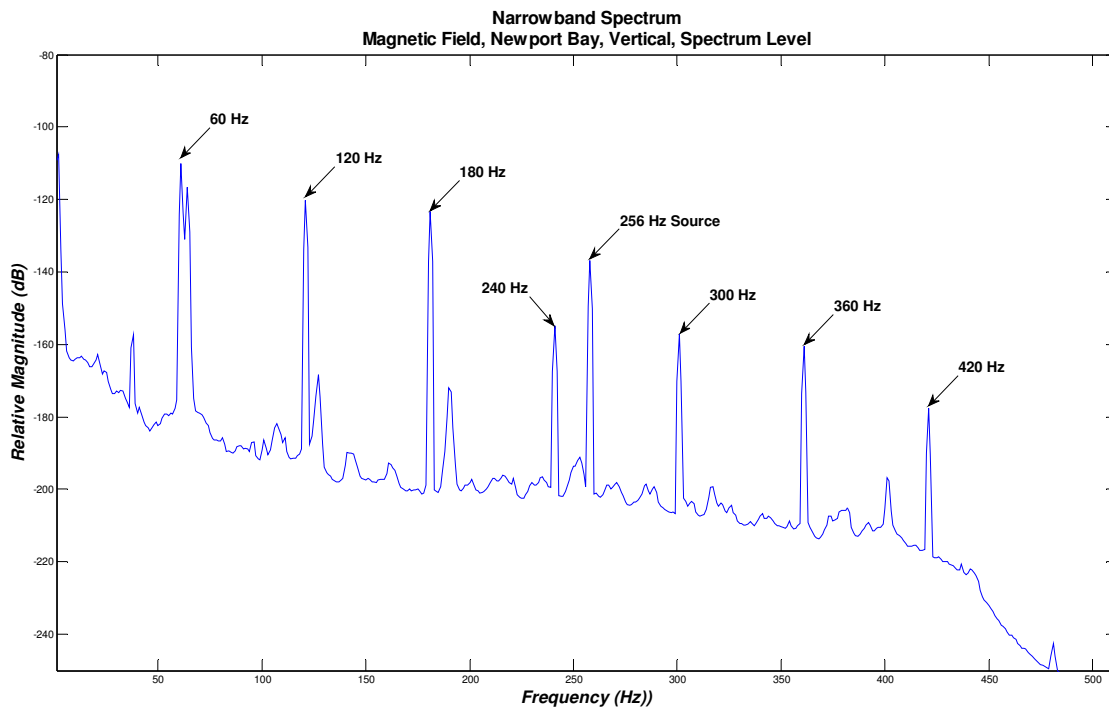


Figure 18 - Representative B-field magnetic spectrum, vertical, 1 Hz bandwidth

Measured levels in the water exhibited over 70 dB of signal-to-noise compared to the background levels. 60 Hz even and odd harmonics were clearly seen in the data from 60 Hz to 420 Hz, and relative signal levels were high relative to the background noise. The specific source for the power frequency signals was not immediately evident, but Newport Bay is a populated area, with a number of nearby commercial sources of power, including distribution lines, that could cause electrical power frequency emanations in the vicinity. It should be noted that similar effects may be observed a potential wave energy sites, especially those located adjacent to populated areas or those with power generation, distribution, or transmission features.

A magnitude-position analysis was prepared to determine the relative magnitude of the field relative to a fixed source as a function of position. Figure 19 shows the results of the vertical dimension of the B-field at 256 Hz. Periods of valid data collected are easily seen as “flat spots” in the chart, which represent periods during which the probe was stable on the bottom of the bay, resulting in a stable measurement of the source magnitude. As the physical location of the probe was changed, changes in magnitude were noted, seen as different relative magnitudes in the figure.

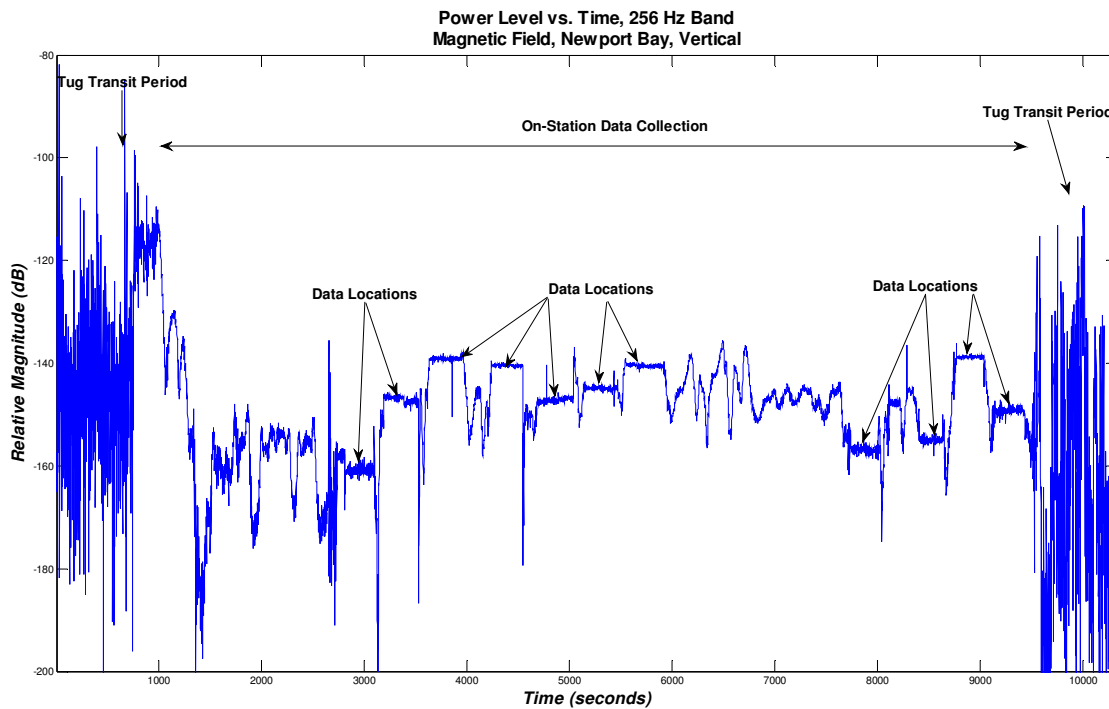


Figure 19 - B-field relative magnitude, vertical, 256 Hz band (1 Hz bandwidth)

7. DATA SUMMARY

The prototype probe effectively demonstrated the ability to sense and record wideband electric and magnetic field data underwater. Furthermore, in the presence of an energized AC submarine power cable, specific signatures emanating from an energized cable were assessed. Data analysis showed that the measurements were able to quantify background and energized cable noise, and that power frequencies could be measured at distances of 150 meters or more, even though the cable-of-opportunity measured was carrying less than 10 amps of current. Practically speaking, submarine power export cables would be carrying 10 to 100 times more electrical current, thus creating EM signatures that would likely be measureable over a larger distance from the cables or WEC devices than observed during the prototype test. Background levels were very low in the absence of power cable noise. Use of extremely low noise preamplifiers in the electric field sensors would be able to further reduce the noise floor of the probe in such cases where an extremely quiet background environment is expected. It was clear from handling of the sensing equipment that stationary probes were required to assess background noise. Motion of electrical field sensors underwater can induce spurious E-fields at the input of the data recorder. In addition, motion of the induction coil style magnetic sensors in the Earth's magnetic field can saturate the coil such that measured data could become clipped and unusable. Any motion by the probe during measurement periods will introduce noise and reduce the ability to sense background levels.

Data acquired in Newport Bay showed that energized sources could be detected and measured. This same data set also showed that 60 Hz noise and higher frequency harmonics (e.g. 120 Hz, 180 Hz, etc.) were prominent, but were due to one or more interfering noise sources, which could pose data interpretation difficulties at potential wave sites adjacent to power generation, distribution, or transmission facilities. That is to say, true background levels at power frequencies may be difficult to assess in populated areas where 60 Hz is somewhat ubiquitous, or if the local underlying geology supports efficient propagation into the surrounding environment.

8. DISCUSSION

Three primary objectives of this study were to demonstrate the reliability, affordability, and repeatability of acquiring EM signatures in the near-shore marine environment. The project's success in achieving these objectives is assessed in the following sections.

8.1 Measurement Reliability

Measurement reliability implies that signatures can be obtained when required, and in a manner that provides valid results. The prototype instrument demonstrated that valid electric and magnetic fields could be accurately assessed over a wide range of frequencies commonly found in the marine environment. On two separate deployments, wideband E- and B-field data were successfully sensed and recorded on multiple high-resolution channels, and the recordings persisted without issue over the planned measurement periods. As part of this demonstration, it was shown that magnetic and electric fields were detected in the vicinity of energized power cables, measured with a reasonable degree of precision as demonstrated by the laboratory calibration results, and accurately monitored over a period of time in multiple locations.

8.2 Measurement Affordability

The prototype probe was assembled using a combination of custom and commercially available equipment and supplies. The recording system and magnetic sensing components were adapted from a terrestrial geophysical application, and packaged to successfully operate in the marine environment at depths of up to 250 feet. Electric field sensors were fabricated in a laboratory environment with commonly available materials, again, following the basic technical approach used in the terrestrial geophysical exploration industry. A market survey for integrated wideband marine EM measurement equipment revealed that some components were available for EMF measurement, but the cost for an off-the-shelf integrated measurement solution was cost prohibitive, with vendors generally focusing on petroleum exploration and military markets. Hardware costs to replicate the prototype probe were found to be less than one-third the cost of commercial integrated systems, demonstrating that excellent progress was made to achieve the measurement affordability objective. The prototype probe was shipped via common carrier motor freight and pickup trucks, staged within a few hours, and deployed and retrieved using modest vessels, including local fishing vessels or working craft.

8.3 Measurement Repeatability

Calibration methodologies for EM measurements were developed and demonstrated using the prototype probe to obtain accurate signature measurement at different times and locations. In general, the calibration processes developed use commonly available bench top electrical equipment to verify sensor and recording integrity with traceability to NIST standards, and thus provides the basis for measurement repeatability from location-to-location, and at the same location over a long time horizon. Rigorous calibration methodologies are essential for comparison of data from different measurement sites, or by using different measurement equipment. Measurements and calibrations made with the prototype probe were shown to follow robust sensor and recording system calibration protocols. Our use of standard FFT processing techniques, including the application of standardized spectral processing bandwidth (e.g. spectrum level reporting of measured levels) encourage the adoption of de-facto standards to directly compare results at multiple sites or measurements made at different locations and periods of time using a common frame of reference.

In summary, three objectives of the study were achieved and demonstrated by use of the prototype EM probe system. Modeling, calibration, measurement, and processing protocols and techniques identified within this study serve to advance the science of marine EM measurements in coastal waters, and promote a standardized methodology that is reliable and repeatable.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary Observations

At the most basic level, electric and magnetic fields are part of our everyday lives, and emanate from both natural (solar, planetary, geological, and oceanic processes) and man-made (electrical generation and transmission equipment, appliances, machinery) sources. EM theory predicts that such fields are expected to exist in air, underwater, and within the earth and seabed, with extremely low electric field levels in the ocean due to the electrical conductivity of the water which serves to substantially attenuate any E-field values compared to in-air conditions. Magnetic conditions are significantly affected by the varying seawater and geologic conditions

along the coast. In particular, B-field propagation is directly impacted by the water column, as well as by the air/sea interface and the sub-seafloor electrical resistivity structure. This study demonstrated that such fields do indeed exist in the near-shore marine environment, and can be accurately quantified with a reasonable investment of care and ingenuity in instrumentation and understanding of the physical characteristics of the measurement problem. Naturally occurring background measurements can be made in the marine environment, and furthermore, reasonably precise assessments can be made of submerged AC power cables.

9.2 Application of the Technology

This study laid the groundwork for what is both known and unknown in the science of reliable, affordable, and repeatable marine EM measurements. Although few measurements exist in real-world shallow water environments, available theories and supporting literature provide ample evidence of EM field generation and propagation behavior in this context. Use of the prototype probe and the measurement approach in general can provide site assessment capabilities and meet EMF quantification requirements. As required, application of this equipment and generalized measurement approach can also be used to provide the physical baseline for on-going monitoring of potential wave energy sites. In addition, this equipment and related calibration and measurement techniques can support mesocosm or other behavioral and habitat experiments with marine species to best inform and correlate with potential or observable impacts of introducing power generating or transmission sources into the marine ecosystem. EMF propagation is strongly related to local physical conditions, and in-situ observations would provide realistic interpretations to biological responses.

9.3 Additional Technical Recommendations

As a result of a literature review, it became clear that specific published effects to marine species with respect to power frequencies from submarine cables were lacking. A fair bit of research has been published on effects to elasmobranchs (sharks and rays), and to a lesser degree information was available on turtles, but very little information was found on marine mammals, other fish species (including sturgeon and salmonids) or benthic organisms. Application of equipment and techniques documented within this study could easily be adapted to provide

repeatable, quantifiable EM field data to ensure that observable conclusions are based on valid data sets.

Recommendation: Conduct additional biological study to better understand and quantify observed effects to biota from man-made EMF. Apply equipment and techniques developed in this study in support this of biological research.

Due to the limited scope of the study, the long-term temporal variability of naturally occurring EM fields was not quantified in terms of range or extent. In terms of daily, monthly, or even seasonal variations, no conclusions were drawn as to how much environmental factors could change in a given location. Because man-made sources such as energized power cables are well known and quantified, however, it is reasonable to assert that emanations from operational cables can be estimated and monitored in real-time. Such parameters are a function of cable physical design factors, installation geometry, local geology or physical conditions (weather, salinity), and operational characteristics (e.g. applied voltage, applied current, and relative phase in the case of multi-phase cables). Longer term monitoring or periodic sampling would provide better insight into the naturally occurring environment.

Recommendation: Conduct long-term monitoring with energized cables. As part of monitoring, collect electrical and physical data to correlate measured levels to physical phenomena.

Modeling and predictions of E- and B-field strengths used in this study relied on homogenous, simplified approaches, and did not involve the use of specific, localized geology to predict unique EM propagation behaviors at specific locations. Two methods are available to perform this activity:

1. preparation of a three-dimensional model of the local geology and postulated wave energy site layout to predict the EM fields generated; and
2. acquisition of in-situ measurements of the environment before, during, and after such an installation.

From a cost and predictive standpoint, the modeling approach coupled with in-situ measurements to “spot check” results would provide useful results during the planning stages of site evaluation,

and would not require extensive field work to fully map EM fields in the local environment. Literature results highlighted in this study revealed that the strength and orientation of electromagnetic fields depends strongly on the water depth and conductivity, the geometry, and electric current density of the electric power generation and transmission lines, and on the geometry and electrical resistivity structure of the seabed and sub-seabed geologic formations. The presence of electrically resistive formations in the shallow sub-seabed can act as a waveguide that can channel EMFs to greater distances from their point of generation than would be indicated by simpler conceptual models. The air-sea interface also affects the long distance propagation of EMFs, a consideration that is not factored in the basic propagation models. Development of a detailed modeling protocol was beyond the scope of this study, but this capability currently exists at Oregon State University's Geoelectromagnetic Laboratory, the home of the National Geoelectromagnetic Facility (NGF).² NGF has developed a high performance computing capability necessary to calculate realistic EMF propagation in complex three dimensional submarine settings, for near-shore and deeper water environments, including calculations that can extend EMF propagation on land as well as at sea. Advancement of this technology to generate predictions of EMFs would serve to reduce the amount of effort and expense to conduct field measurements, and hence, encourage development of marine energy power sources.

Recommendation: Evaluate and improve existing modeling capabilities with measured data at wave energy sites. Consider performing this activity while concurrently monitoring energized cables along Oregon's coast.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the Oregon Wave Energy Trust, the OWET Board of Directors, and in particular, the Mr. Jason Busch, OWET Executive Director, for enabling this research as an important piece of marine renewable energy technology.

² ngf.coas.oregonstate.edu

APPENDIX A – ACRONYMS

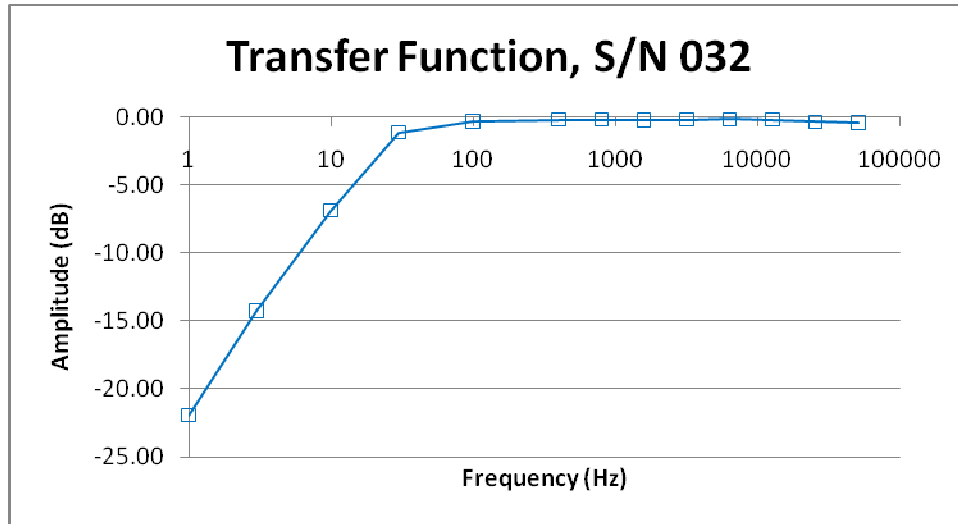
1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
ASW	anti-submarine warfare
B-field	magnetic field
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research into the Environment
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
fT	femto Tesla
Hz	Hertz, cycles per second
kHz	kilo Hertz
μ T	micro Tesla
μ V	micro volts
mHz	milli Hertz
mT	milli Tesla
mV	milli volts
MKS	meter-kilogram-second
MMS	Minerals Management Service
NIST	National Institute of Standards and Technology
nT	nano Tesla
nV	nano volts
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
pT	pico Tesla
SEMC	Seafloor Electromagnetic Methods Consortium
SI	International System of Units
SIO	Scripps Institute of Oceanography
UK	United Kingdom
US	United States
WA	Washington
WEC	Wave Energy Converter

APPENDIX B – PROBE CALIBRATION LOGS

Magnetometer Calibration Data Log

Unit Serial Number: 032 Date: 9/8/2010
 Calibration Resistor: 988 ohms Calibrated by: M. Slater
 Sensitivity 0.1 V/1nT

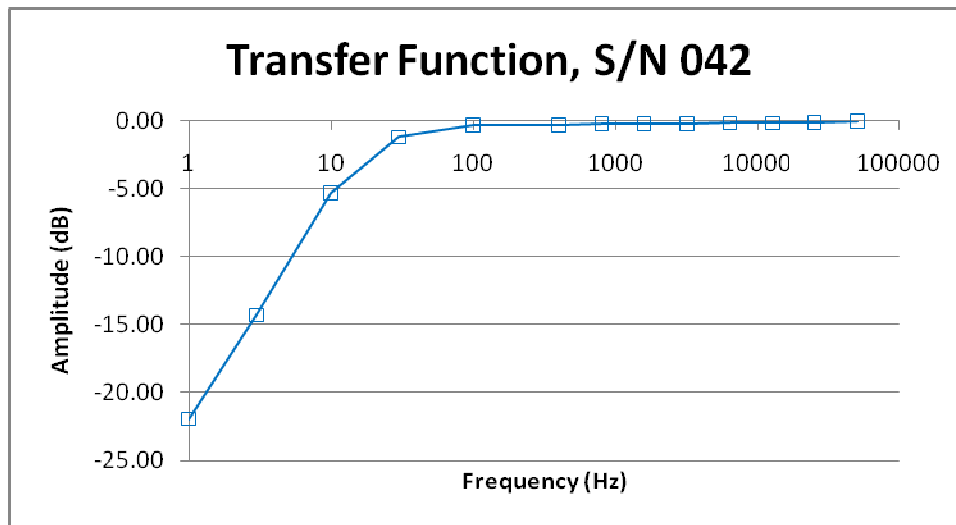
Input Frequency (Hz)	Coil Current (μ Arms)	Coil Field Strength (nT)	Calculated Output (dBVrms)	Measured Output (dBVrms)	Transfer Function (dB)
1	168	8.31	-1.606	-23.56	-21.95
3	200	9.89	-0.092	-14.36	-14.27
10	200	9.89	-0.092	-6.97	-6.88
30	201	9.94	-0.049	-1.18	-1.13
100	201	9.94	-0.049	-0.390	-0.34
400	201	9.94	-0.049	-0.24	-0.19
800	201	9.94	-0.049	-0.24	-0.19
1600	201	9.94	-0.049	-0.29	-0.24
3200	201	9.94	-0.049	-0.24	-0.19
6400	200	9.89	-0.092	-0.25	-0.16
12800	200	9.89	-0.092	-0.29	-0.20
25600	202	9.99	-0.005	-0.36	-0.35
51200	203	10.04	0.037	-0.37	-0.41



Magnetometer Calibration Data Log

Unit Serial Number: 042 Date: 9/8/2010
 Calibration Resistor: 988 ohms Calibrated by: M. Slater
 Sensitivity 0.1 V/1nT

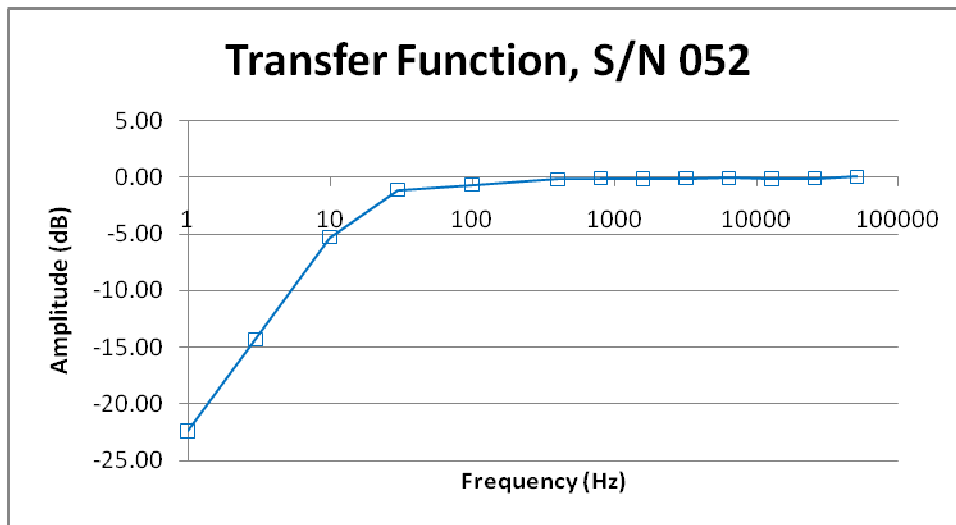
Input Frequency (Hz)	Coil Current (μ Arms)	Coil Field Strength (nT)	Calculated Output (dBVrms)	Measured Output (dBVrms)	Transfer Function (dB)
1	201	9.94	-0.049	-21.99	-21.94
3	201	9.94	-0.049	-14.35	-14.30
10	201	9.94	-0.049	-5.36	-5.31
30	201	9.94	-0.049	-1.25	-1.20
100	201	9.94	-0.049	-0.380	-0.33
400	201	9.94	-0.049	-0.36	-0.31
800	201	9.94	-0.049	-0.29	-0.24
1600	201	9.94	-0.049	-0.29	-0.24
3200	201	9.94	-0.049	-0.29	-0.24
6400	200	9.89	-0.092	-0.27	-0.18
12800	200	9.89	-0.092	-0.26	-0.17
25600	200	9.89	-0.092	-0.24	-0.15
51200	203	10.04	0.037	0.01	-0.03



Magnetometer Calibration Data Log

Unit Serial Number: 052 Date: 9/8/2010
 Calibration Resistor: 988 Ohms Calibrated by: M. Slater
 Sensitivity 0.1 V/1nT

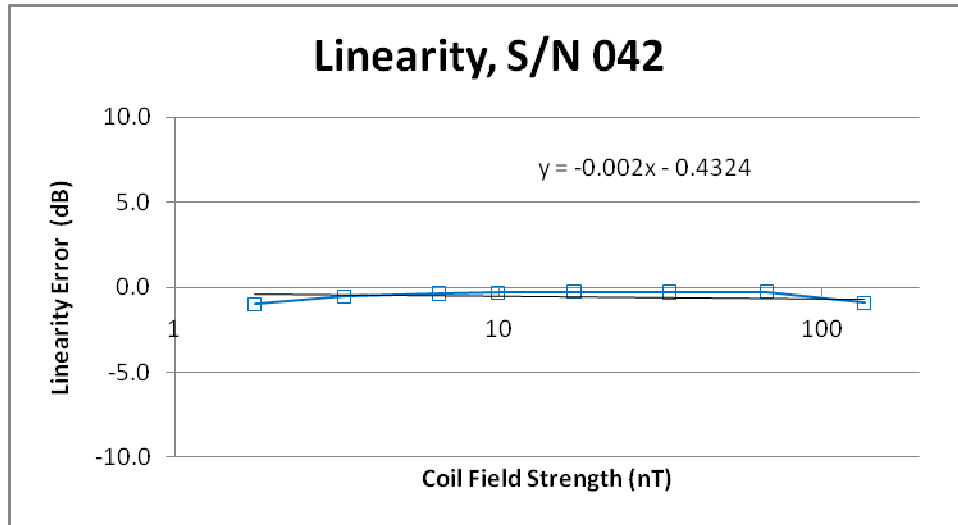
Input Frequency (Hz)	Coil Current (μ Arms)	Coil Field Strength (nT)	Calculated Output (dBVrms)	Measured Output (dBVrms)	Transfer Function (dB)
1	167	8.26	-1.658	-24.06	-22.40
3	201	9.94	-0.049	-14.36	-14.31
10	201	9.94	-0.049	-5.33	-5.28
30	201	9.94	-0.049	-1.15	-1.10
100	201	9.94	-0.049	-0.700	-0.65
400	201	9.94	-0.049	-0.23	-0.18
800	201	9.94	-0.049	-0.16	-0.11
1600	201	9.94	-0.049	-0.17	-0.12
3200	201	9.94	-0.049	-0.16	-0.11
6400	200	9.89	-0.092	-0.14	-0.05
12800	200	9.89	-0.092	-0.24	-0.15
25600	202	9.99	-0.005	-0.09	-0.08
51200	202	9.99	-0.005	0.04	0.05



Linearity Data Log

Unit Serial Number: 042 Date: 9/8/2010
 Calibration Resistor: 988 ohms Calibrated by: M. Slater
 Sensitivity 0.1 V/1nT

Input Frequency (Hz)	Coil Current (μArms)	Coil Field Strength (nT)	Calculated Output (dBVrms)	Measured Output (dBVrms)	Linearity Error (dB)
100	36	1.76	-15.083	-16.09	-1.01
100	67	3.33	-9.539	-10.08	-0.54
100	132	6.53	-3.701	-4.08	-0.38
100	201	9.94	-0.049	-0.38	-0.33
100	345	17.07	4.644	4.380	-0.26
100	682	33.74	10.563	10.28	-0.28
100	1363	67.43	16.577	16.3	-0.28
100	2725	134.82	22.595	21.66	-0.93



Noise floor of calibration environment: -75dBV/vHz, at 100 Hz, equivalent to 1.78 pT/vHz, or $\sim 10^{-12}$ T

APPENDIX C – REFERENCE DOCUMENTS

- (a) Slater, M.A., Schultz, A. (2009). “Electromagnetic field measurements: field sensor recommendations.” Oregon Wave Energy Trust, www.oregonwave.org
- (b) Webb, S. C., S. C. Constable, C. S. Cox, T. K. Deaton. (1985). “A Seafloor Electric Field Instrument.” Journal of Geomagnetic and Geoelectric Studies (Vol 37), pp. 1115-1129.
- (c) Petiau, Gilbert. (2000). “Second generation of Lead-Lead Chloride electrodes for geophysical applications.” Pure and Applied Geophysics (Vol. 157). pp. 357-382.
- (d) Slater, M.A. (2009). “Electromagnetic field measurements: instrumentation configuration.” Oregon Wave Energy Trust, www.oregonwave.org