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Electromagnetic Field Study

Ambient electromagnetic fields in the nearshore marine environment.

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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.

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 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 elasmobranches (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 field[1].

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 Tesla[3] (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 1/60th 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 Union[4], 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.

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[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/√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√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√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 be 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 field[6]. 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.

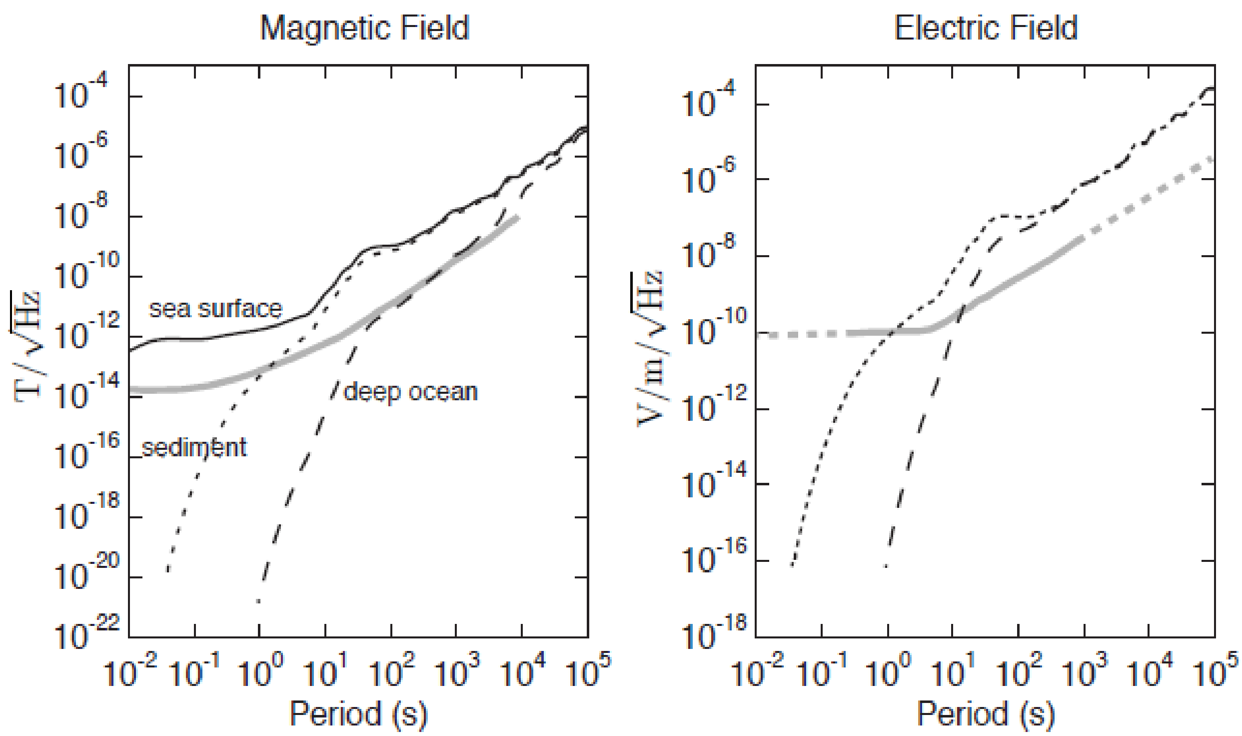

Figure 1 – Represenative Modeled Magnetic and Electric Field Spectra in Ocean Environment, from Key (2003).

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)

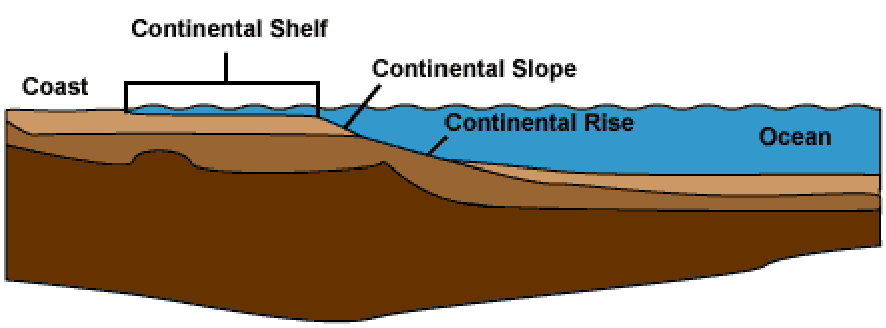

Figure A1 – Ocean Regions

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

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