OregonWaveEnergy TRUST

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Electromagnetic Field Study

Summary of commercial electromagnetic field sensors for the 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

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

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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 report[1] 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 Subspection Ltd., www.subspection.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), Subspection (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, Subspection 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 nV/√Hz. By way of example, Fempto[3] 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/√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 4pT/√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 Ltd[7] and Teledyne TSS Ltd[8] 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_specsheet.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	fempto Tesla
Hz	Hertz, cycles per second
kHz	kilo Hertz
µT	micro Tesla
µV	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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