Sep 10

Electromagnetic Field Study

Trade study: commercial electromagnetic field measurement tools.

Prepared by
Michael Slater, Science Applications International Corp.
Dr. Adam Schultz, consultant
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

TABLE OF CONTENTS

1. EXECUTIVE SUMMARY 1

2. INTRODUCTION........ 1

2.1 PURPOSE 1
2.2 BACKGROUND........ 2
2.3 REPORT ORGANIZATION 2

3. APPROACH........ 2

4. ELECTROMAGNETIC TOOLS: PHYSICS-BASED INSTRUMENTS 3

4.1 EARLY DISCOVERIES 3

5. COMMERCIAL EM METHODS........ 9

5.1 MOTIVATION FOR OCEANIC EM INSTRUMENTATION 9
5.2 MAGNETOTELLURIC METHODS........ 10
5.3 AUDIO-MAGNETOTELLURIC........ 11
5.4 CONTROLLED SOURCE METHODS 11
5.4.1 Controlled Source Magnetotellurics........ 11
5.4.2 Controlled Source Audio-Magnetotellurics........ 12
5.4.3 Controlled Source Electromagnetics 12
5.5 DIRECT CURRENT RESISTIVITY 13
5.6 MAGNETOMETRIC RESITIVITY 13
5.7 VELOCITY MEASUREMENT METHODS USING ELECTRIC POTENTIAL 13
5.8 OTHER MARINE EM METHODS........ 14
5.9 MARINE SURVEYS........ 14
5.9.1 Magnetic Field Object Location 15
5.9.2 Electric Potential Corrosion Assessment........ 16
5.10 SHIP SIGNATURE MEASUREMENT 16

6. CONCLUSION 17

APPENDIX A – GLOSSARY OF TERMS 19

APPENDIX B – ACRONYMS........ 20

APPENDIX C – BIBLIOGRAPHY 21

TABLE OF TABLES

TABLE 1 – TYPES OF MAGNETOMETERS........ 5

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 pV/√Hz and 1nV/√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 nV/√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 Resitivity

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 (4pT/√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

[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 seafloor[22].

[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

Chave, A.D., S.C. Constable, R.N. Edwards. (1991). "Electrical Exploration Methods for the Seafloor." In M.N. Nabighian (Ed.), Electromagnetic Methods in Applied Geophysics (Vol 2, pp. 931-966), Society of Exploration Geophysicists, pp. 931-966.

Crona, Lennart, A. Brage. (1997). "Carbon Fibre Electrodes and their Qualities in Salt Water." Proceedings from MARELEC 97, International Conference on Marine Electromagnetics, London, United Kingdom, Contribution 11.3.

Dalberg, E. (2001). *A Measurement of the Underwater Electric Field off the West Coast of Sweden* (Technical Report FOI-R--0146--SE). Stockholm, Sweden: FOI – Swedish Defence Research Agency, downloaded from http://www2.foi.se/rapp/foir0146.pdf

IEEE Std 644-1994-R2008. (1995). *IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields From AC Power Lines* The Institute of Electrical and Electronics Engineers, Inc., New York, NY. Originally published 1995, reaffirmed 2008.

Sanford, T. B., R. G. Drever, J. H. Dunlap. (1978). "A velocity profiler based on the principles of geomagnetic induction." Deep-Sea Research (Vol 25). Pergamon Press. pp. 183 to 210.

von Arx, William A. (1950). "An Electromagnetic Method for Measuring the Velocities of Ocean Currents from A Ship Under Way." Papers in Physical Oceanography and Meterology (Vol XI, No 3), Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, March 1950.

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.