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Electromagnetic Field Study

Electromagnetic field measurements: field sensor recommendations.

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Record of Revisions

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

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

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

2. INTRODUCTION

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

2.1 Purpose

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

2.2 Report Organization

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

3. METHODOLOGY

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

4. SENSORS

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

4.1 Electric Field Sensors

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

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

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

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

1. Frequency response: .01 Hz to 1 kHz
2. Dynamic range: $\geq$ 120 dB
3. Noise floor: $\leq$ 1 nV/m√Hz @ 1 Hz
4. Cost: as low as reasonably achievable

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

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

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

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

4.2 Magnetic Field Sensors

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

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

1. Frequency response: .01 Hz to 1 kHz
2. Dynamic range: $\geq$ 120 dB
3. Noise floor: $\leq$ 1 pT√Hz @ 1 Hz
4. Cost: as low as reasonably achievable

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

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

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

4.3 Data Acquisition Instrumentation

In both cases of electric and magnetic field sensors, a high resolution, multi-channel means of sampling and storing the acquired data is required. Commercial analog-to-digital converters (ADC) abound, with 16-bit converters commonplace, and 24-bit converter systems available. ADCs are advertised at a particular resolution, typically 16 bits or 24 bits, although in practice not all bits are effectively available; that is, a number of bits are essentially unusable for data due to noise limitations of the amplification and conversion process. A top-notch 24-bit ADC might offer 19 or 20 bits of dynamic range (<120 dB), which is marginal for EM measurement, unless amplifier gains can be adjusted to match the range to the widely dynamic environment—difficult at best for existing low-cost autonomously operated systems without incurring the expense of a customized electronics solution. Therefore, to ensure that the full dynamic range of the signal is captured, the basic ADC system should ideally be capable of provide a minimum of 22 bits of useable resolution (>130 dB dynamic range). Functional features required for EM field assessments therefore are comprised of the following minimum requirements:

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

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

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

5. AUXILIARY INSTRUMENATION

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

5.1 Orientation Sensor

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

5.2 Depth Sensor

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

[2] http://www.oceanserver-store.com/compass.html

[3] http://www.serialdatalogger.com/Products/Products.shtml

[4] http://www.meas-spec.com/

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

5.3 3-D Current Meter

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

5.4 Wave Buoy or Surface Radar

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

6. SUMMARY

This survey was commissioned to identify affordable EM sensor solutions that can provide repeatable and reliable EMF measurements in the marine environment at potential wave energy sites. The results stated herein were derived from a series of modeling reports, literature searches, and industry surveys to identify existing and predicted noise conditions, and requisite sensor and instrumentation sufficient to characterize EM conditions under various field conditions. Recommendations have been made for specific sensor solutions and design requirements for electric field, magnetic field, and auxiliary sensor configurations to achieve the stated measurement objectives for characterization of wave energy project sites. The results of this report will be used to develop a prototype EM measurement system to be used to acquire ambient EM signatures along Oregon's coast.

APPENDIX A – ACRONYMS

1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
ASW	anti-submarine warfare
B-field	magnetic field
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research Into The Environment
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
fT	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 – BIBLIOGRAPHY

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