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Electromagnetic Field Study

Electromagnetic field measurements: instrumentation configuration.

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Oregon Wave Energy Trust (OWET) is a nonprofit public-private partnership funded by the Oregon Innovation Council. Its mission is to support the responsible development of wave energy in Oregon. OWET emphasizes an inclusive, collaborative model to ensure that Oregon maintains its competitive advantage and maximizes the economic development and environmental potential of this emerging industry. Our work includes stakeholder outreach and education, policy development, environmental assessment, applied research and market development.

Record of Revisions

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

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

2. INTRODUCTION

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

2.1 Purpose

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

2.2 Report Organization

This report contains six primary sections, and includes supporting appendices. The first sections contain the executive summary and introduction, and provide the project background. The methodology for how the results were prepared is presented in Section 3. Section 4 briefly discusses calibration theory, while Section 5 provides top-level sensor calibration factors, and identifies the general methods and technical issues associated with obtaining valid calibrations and resulting measurements. A brief summary is made in Section 6. Appendix A contains an acronym list, and Appendix B contains detailed test procedures and data log forms to be used for the calibration and characterization of sensor instrumentation. A bibliography of sources is provided in Appendix C.

3. METHODOLOGY

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

4. THEORY OF CALIBRATION

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

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

The general approach to instrument calibration is based on comparison of a measured value against a known value. Using a known signal level as an input factor to a device under test, the output is measured, accounting for signal losses or gains along the way, and compared to the input signal. Once calibration factors have been determined, they are applied to the raw output signal to ensure that results have been corrected to the degree of precision possible with the calibration test setup.

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

5. CALIBRATION SETUP

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

5.1 Electric Field Instrumentation Calibration

A number of critical technical evaluation factors are required during the electric field instrumentation calibration procedure. These factors apply regardless of instrumentation selected. Thorough characterization of the instrument performance only need be conducted once, until a change is made to the configuration, such as replacement of a component or sensor. Once the characterization has been done, a routine verification of sensor transfer function and basic functionality should be ideally performed and documented prior to each deployment of the instrument to ensure the best possible integrity in the measured results.

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

1. Frequency response: .01 Hz to 1 kHz
2. Dynamic range: ≥ 120 dB
3. Noise floor: ≤ 1 nV/m√Hz @ 1 Hz

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

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

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

5.1.1 Test Set-up

This specific procedure has been prepared to calibrate the specific instrumentation recommended, but the procedures and data forms could be modified to suit equivalent instrumentation following the same protocol. The basic philosophy to calibration is to introduce a signal into the front end of the equipment, measure the signal with a calibrated meter, and compare the results with the instrument output. This process is conducted over the desired frequency range of interest of the sensor to determine the calibration factor (transfer function) from sensor input voltage to digital output. In general, the transfer function will be a frequency dependent "curve", and may depend on system gain or other configuration changes. Using this same basic test setup, a series of tests are required to characterize and calibrate the system. Appendix B contains the full calibration test procedure.

5.1.2 In-Situ Observation

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

5.1.3 In-Situ Source Verification

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

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

[1] http://www.subspection.com/downloads/sensor-electricfield.pdf

5.2 Magnetic Field Sensor Calibration

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

1. Frequency response: .01 Hz to 1 kHz
2. Dynamic range: ≥ 120 dB
3. Noise floor: ≤ 1 pT√Hz @ 1 Hz

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

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

5.2.1 Test Set-up

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

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

$$B = \mu_0 n I$$

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

n = number of turns per unit length of coil in units of meters^{-1}

I = electrical current in coil, in amperes

Alternatively,

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

where N = number of turns in coil

L = length of coil in meters

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

Thus, calibration of magnetic field sensors will require construction of a suitable coil, the dimensions of which will depend on the basic instrument sensitivity and the physical size of the sensor. For the recommended Zonge Engineering ANT-5 product, the instrument has a basic sensitivity of 100mV/nT in the passband. The number of turns for a suitable calibration coil will depend on the maximum field the sensor can sense without overloading the input, the amount of current required in the coil to create that level, and furthermore, the availability of the test equipment to measure the calibration current to the resolution required. A second factor involves the physical length of the sensors. Since solenoid coils are known to have non-linear effects near the ends of the coil, it is important to ensure that the coil is many times longer than the sensor. The Zonge ANT-5 magnetic sensor is approximately 18 inches in length, thus a coil length of 12 feet is recommended (8x sensor length). Based on the availability of a 6.5 digit calibrated voltmeter and the basic instrument sensitivity, between 100 and 300 coils are estimated to provide a reasonable range of values over the frequency range of interest. For purposes of calibration of the prototype instrument a 12 foot coil (12" diameter) was constructed of 144 wraps, or 1" per wrap. Use of precisions resistors and voltage divider circuitry may be required to match the dynamic range of a given instrument.

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

5.2.2 In-Situ Observation

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

5.2.3 In-Situ Source Verification

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

As with the electric field source verification tests, cable simulation tests are not a precise calibration method. Therefore, care should be taken to use cable simulation tests as a means for equipment verification, and not as a substitute for the coil calibration procedure provided in the appendix.

5.3 Data Acquisition Instrumentation

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

5.4 Calibration of Auxiliary Sensors

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

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

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

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

6. CALIBRATION SUMMARY

This report describes the essential elements of EM sensor calibration and in-situ observation to ensure proper operation of the recommended instruments, and verification of the accuracy of the sensor output. Specific recommended procedures are contained with this report to characterize specific EM instruments, and with sufficient explanations provided to extend these results to EM site assessments using equivalent EM sensors.

APPENDIX A – ACRONYMS

1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
ASW	anti-submarine warfare
B-field	magnetic field
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research Into The Environment
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
fT	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
NIST	National Institute of Standards and Technology
nT	nano Tesla
nV	nano volts
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
pT	pico Tesla
SEMC	Seafloor Electromagnetic Methods Consortium
SI	International System of Units
SIO	Scripps Institute of Oceanography
UK	United Kingdom
US	United States
WA	Washington
WEC	Wave Energy Converter

APPENDIX B – TEST PROCEDURES

Electric Field Sensor Electronics Calibration Procedure

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

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

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

TEST PROCEDURE:

1. Set up the test equipment as shown in Figure 1.

2. Connect a programmable AC/DC source and precision voltmeter to the instrument as shown.

3. Replace the probes in the circuit by substitution of the probes with a precision termination resistor of the equivalent value as the probes. If possible measure probe resistance in seawater solution at spacing of 1 meter. Expected value is between 2 and 10 ohms. Record equivalent resistance value: __________ ohms

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

4. Configure the electronics board to acquire signal data at 0 dB gain, 1 kHz sampling rate.

5. Energize the source with a sine wave at 100 Hz, output voltage of 1 Vrms. Adjust source output to achieve 1 Vrms across termination resistor as measured by the precision voltmeter.

6. Record data for 10 seconds.

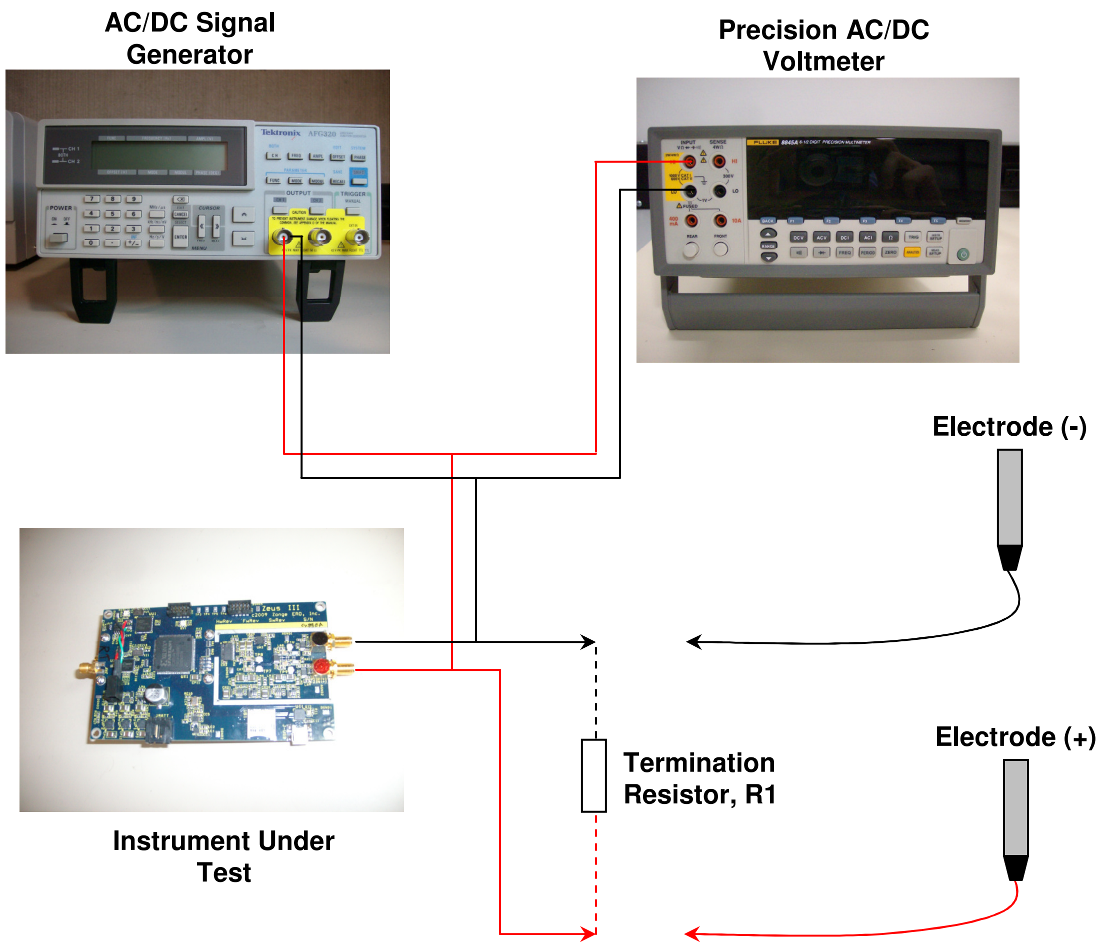

Figure 1 – Test Setup Schematic For Instrument Calibration

7. Stop recording, retrieve data file and compare recorded results to precision voltmeter. Ensure proper operation of recording system and storage of acquired data.

8. Complete Data Form for all values.

Table 1 – Instrument Calibration Data Log

Unit Serial Number: ____________ Date: _____________

Termination Resistance (ohms): _________ Calibrated by: ________________
Input Gain (dB): ________________
Sampling Rate (Hz): ________________
Nominal Source Output (Vrms): _____________

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

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

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

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

9. Compute transfer function at each frequency.

10. Repeat step 8 for all gain values. Reduce source level at each gain stage to obtain nominal 1 Vrms recorded output. Log results in data forms.

11. Subtract gain from transfer function, and chart all transfer function curves.

12. Compare error and identify anomalies in linearity.

13. At gain of 0 dB gain setting, and 100 Hz source frequency, adjust source input level in steps of 0.1 Vrms. Record data for 10 seconds. Increase source level until manufacturer specification for maximum input level is exceeded. Fill in table. Stop procedure when clipping is noted in recorded data, or when output is no longer linear. This is the maximum operating input level.

Table 2 – Linearity Data Log

Frequency[Note1, 2] (Hz)	Source Output Level (volts)	Measured Output (counts)	Measured Output (volts)	Linear? (Y/N)
100	1			
100	1.1			
100	1.2			
100	1.3			
100	1.4			
100	1.5			
100	1.6			
100	1.7			
100	1.8			
100	1.9			
100	2.0			
100	2.1			
100	2.2			

14. Remove board from test set up. Short electrode (+) and electrode (-) leads together. Configure board for 1 kHz sampling rate, and 0 dB gain. Record data for 5 minutes.

15. Compute FFT of resulting spectrum into 1 Hz bandwidth using uniform (boxcar) windowing. Compute RMS average spectra. Chart results. This result is noise floor in per root Hz bandwidth at 0 dB gain setting.

16. Repeat step 14 and using mid-gain and maximum gain settings. Record gain. Chart results.

    a. Mid – gain setting (dB): ____________

    b. Maximum gain setting (dB): ___________

17. Turn power off to board. Reconnect to Figure 1 test setup. Repeat steps 1 through 8. Overlay results to determine repeatability of transfer function. Identify errors in excess of .25 dB.

18. Provide photographs, sketches, of test setup and test environment.

19. Log unusual results or explanations to deviations to the test procedure.

20. End of procedure.

Magnetometer Calibration Procedure

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

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

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

TEST PROCEDURE:

1. Set up the test equipment as shown in Figure 2.

2. Connect a programmable AC/DC source and precision voltmeter to the calibration coil as shown.

3. Place a precision resistor in series with the coil. Select the value of the resistor to reflect the desired strength of the magnetic field to be created. Record calibration resistor value: __________ ohms

4. Voltage output may be measured using the precision voltmeter, or by use of a calibrated data acquisition board. If the data acquisition board is used, configure the electronics board to acquire signal data at 0 dB gain, 1 kHz sampling rate.

5. Energize the coil to create a field of approximately 10 nT using a sine wave at 100 Hz. This should produce a nominal output of the ANT-5 sensor of 1 Vrms. Adjust source output to achieve the proper current in the coil to achieve the required field strength.

6. Using data acquisition board configured for 0 dB gain, 1 kHz sampling rate, record data for 10 seconds. Stop recording, retrieve data file and compare recorded results to precision voltmeter. Ensure proper operation of recording system and storage of acquired data.

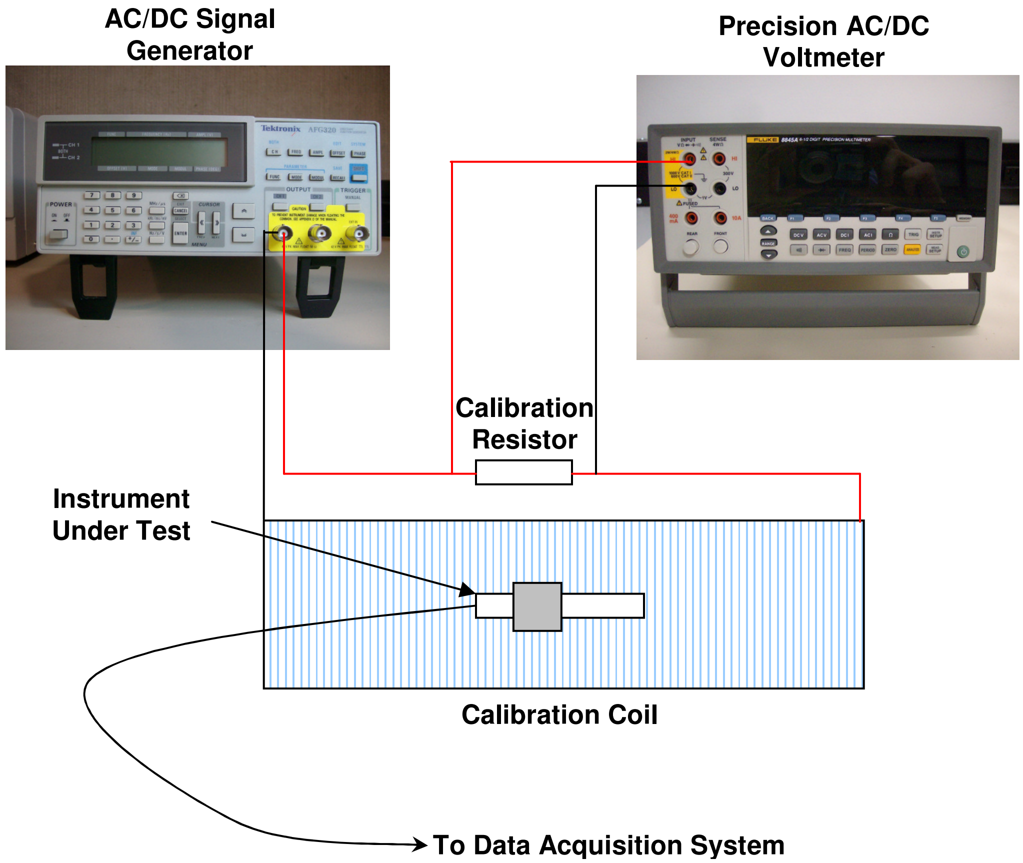

Figure 2 – Test Setup Schematic For Instrument Calibration

7. Complete Data Form for all values.

Table 3 – Magnetometer Calibration Data Log

Unit Serial Number: ____________ Date: _____________

Termination Resistance (ohms): _________ Calibrated by: ________________

Input Gain (dB): ________________

Sampling Rate (Hz): ________________

Nominal Source Output (Vrms): _____________

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

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

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

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

8. Compute transfer function at each frequency.

9. Repeat step 8 for all gain values. Reduce source level at each gain stage to obtain nominal 1 Vrms recorded output. Log results in data forms.

10. Subtract gain from transfer function, and chart all transfer function curves.

11. Compare error and identify anomalies in linearity.

12. At gain of 0 dB gain setting, and 100 Hz source frequency, adjust coil output in steps of 1 nT. Record data for 10 seconds. Increase source level until manufacturer specification for maximum input level is exceeded. Fill in table. Stop procedure when clipping is noted in recorded data, or when output is no longer linear. This is the maximum operating input level.

Table 4 – Magnetometer Linearity Data Log

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

13. Move electrode and data acquisition board to electrically quiet location to minimize effect of low-frequency magnetic fields. Outdoors away from buildings, power lines, and other influences as much as possible. Record data for 5 minutes.

14. Compute FFT of resulting spectrum into 1 Hz bandwidth using uniform (boxcar) windowing. Compute RMS average spectra. Chart results. This result is noise floor in per root Hz bandwidth at 0 dB gain setting.

15. Repeat step 14 and using mid-gain and maximum gain settings. Record gain. Chart results.

a. Mid – gain setting (dB): ____________ Ensure that data is not clipped, e.g. < 2 volt output.

b. Maximum gain setting (dB): ___________ Ensure that data is not clipped, e.g. < 2 volt output.

16. Turn power off to board. Reconnect to Figure 1 test setup. Repeat steps 1 through 8. Overlay results to determine repeatability of transfer function. Identify errors in excess of .25 dB.

17. Provide photographs, sketches, of test setup and test environment.

18. Log unusual results or explanations to deviations to the test procedure.

19. End of procedure.

APPENDIX C – BIBLIOGRAPHY

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