STANDARD 808-03

SIGNATURE MEASUREMENT STANDARDS GROUP

MAGNETIC SIGNATURE COLLECTION & METHODOLOGY STANDARD

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MAGNETIC SIGNATURE COLLECTION & METHODOLOGY STANDARD

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RANGE COMMANDERS COUNCIL

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PREFACE

The *Magnetic Signature and Methodology Standard* captures the corporate knowledge of personnel who have many years of magnetic sensor experience. These individuals are recognized and respected for their contributions to the discipline. Some 32 or more technical personnel contributed to making this document possible. This team effort involved multiple agencies from the government, military, universities and corporations. These organizations include, but are not limited to, the University of Texas; the National Ground Intelligence Center; Yuma Proving Ground; White Sands Missile Range; MITRE Corporation; Penn State University; the 46TW/TSR, Eglin AFB, FL; US Army Research Laboratory – Picatinny Arsenal; Sentech, Inc.; Arnold Engineering Development Center; US Army Waterways Experimental Station; Aberdeen Test Center; Bishop Multisensors Corporation; and BAE Systems.

Mr. John Sledge, Air Armament Center, the Chair of the Range Commanders Council (RCC), Signature Measurement Standards Group (SMSG), Seismic, Acoustic, and Magnetic (SAM) Committee, would like to give special recognition to several individuals for their tireless support of this effort: Dr. James Chambers from the University of Mississippi; Mr. Nino Srour, Dr. Alan Edelstein, and Mr. Jonathan Fine from the US Army Research Laboratory; Dr. Charles Burmaster from MITRE; Ms. De Loyd from the National Ground Intelligence Center; Mr. Alan Tinseth from Yuma Proving Ground; and Mr. Steve Reynolds from BAE Systems. Special recognition also goes to Mr. Frank Carlen from Aberdeen Test Center, the Signature Measurement Standards Group Chair, for making this collaboration possible.

The SMSG SAM Committee welcomes any comments, questions, corrections, and improvements to this document. All feedback should be addressed to:

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ACRONYMS AND INITIALISMS

ac	alternating current
A/D	analog to digital
AMR	anisotropic magneto resistive
AWG	American Wire Gauge
BNC	Bayonet, Neill-Concelman
C	Celsius
CD	compact disk
CPA	closest point of approach
cps	cycles per second
dB	decibel
dc	direct current
DoD	Department of Defense
G	gauss
GMR	giant magneto resistance magnetometer
GPS	Global Positioning System
H	henry
Hz	Hertz
ID	identification
IF	intermediate frequency
IM	intermodulation
IRIG	Interrange Instrumentation Group
ISO	International Standards Organization
kHz	kilohertz
ks	kiloseconds
log	logarithm
MET	meteorological
MHz	megahertz
MIL STD	military standard
N	Newton
nT	nanotesla
NCTR	non-cooperative target recognition
NIST	National Institute of Standards and Technology
NTIA	National Telecommunications and Information Administration
Oe	oersted
PVC	polyvinyl chloride
RCC	Range Commanders Council
RF	radio frequency
rms	root mean square
RPM	revolutions per minute
SAM	seismic, acoustic, and magnetic
SDT	spin dependent tunneling magnetometer
SQUID	super conducting quantum interference device
T	tesla
USD	United States Dollars
USGS	United States Geological Survey

SECTION 1

INTRODUCTION

1.1 General

Magnetic signature measurement standards are necessary within the Department of Defense (DoD) to control test procedures and site selection for magnetic testing. The results from different tests can then be compared and employed to establish a magnetic signature database. These standards are to be used to establish test compatibility between the sites at all DoD test centers. Therefore, this document is intended to ensure that, regardless of where a test is conducted, the same magnetic standards will be employed.

1.2 Purpose

The purpose of this document is to define a standard methodology for deploying magnetic sensors (commonly referred to herein as magnetometers) and a standard process for using the measurements from the sensors to develop target signatures. This methodology includes the definitions of sensor parameters, environmental data, instrumentation procedures, ground truth documentation, and calibration techniques needed for the collection of quality magnetic signatures. The standard is broad enough so that the magnetic signature data collected can be analyzed and processed in numerous ways. Application of this standard is intended for data collection from targets like wheeled vehicles, tracked vehicles, air-cushioned vehicles, inland watercraft, low flying aircraft, fixed power generation and distribution facilities, as well as electromagnetic impulses caused by explosives and explosive-type sources (artillery, general purpose bombs, mortars, etc.).

1.3 Background

Magnetometers are devices that measure changes in the magnetic field. Accordingly, they can be used to accurately determine the position of the sources responsible for these changes. Because the field strength of targets of interest typically decreases as $1/r^3$, the detection range for these low cost sensors is short - about 25 meters or less. Common applications for magnetometers include determining the approximate closest point of approach (CPA) and providing information for target classification. Although such sensors may be passive or active, this standard will only address the passive application.

There are different types of magnetometers. The most common types are total field magnetometers that measure the scalar magnitude of the magnetic field and vector field magnetometers that measure vector components of the magnetic field. These sensors can be used to provide the spatial or time rate of change of the magnetic field. Different types of sensors have varying frequency responses. More details on the various types of magnetometers and their usage can be found in Section 2.

Passive magnetometers have been used for military purposes since World War II when they were effective in mine detection. Such sensors are small, low-priced, and consume little power during operation. More recently, magnetometers have commonly been used along with other passive devices such as microphones and geophones because these three types of sensors complement each other very well. For example, magnetometers are insensitive to changes in weather, unlike acoustic sensors which are sensitive to weather induced variations. Passive magnetometers are frequently used for the detection, classification, and tracking of military vehicle systems.

Battlefield magnetometers have the potential for addressing several important military problems because of their passive nature and the ability of digital processing techniques to perform non-cooperative target recognition (NCTR) of a wide range of ground vehicles and low flying aircraft. Missions for these sensors include unattended perimeter surveillance and target detection, tracking, classification, localization, and possible identification for triggering smart weapons.

SECTION 2

MAGNETOMETERS

2.1 Types of Magnetometers

There are two basic types of magnetometers: vector magnetometers (see Table 2-1) and total field magnetometers (see Table 2-2). All magnetometers operate within a frequency range of a few millihertz to a few kilohertz. Magnetic anomalies indicative of slow moving targets like soldiers and ground vehicles occur in the lower portion of this frequency range. Rotating machinery and power line signatures typically occur in the higher portion of this frequency range. Filters are used in conjunction with these sensors to select the frequency range or frequency band of interest and to limit the influence of noise. As of 2003, the following types of magnetometers were in general use, although other types are under development.

TABLE 2-1. COMPARISON OF VECTOR MAGNETOMETERS

Type	**Nominal system Cost** ($ USD)	**Nominal sensitivity** (noise floor per root Hertz at 1 Hz (single vehicles as well as in moving convoys))	**Availability**
Hall Effect	100	1000 nT	Commercial
Anisotropic Magneto Resistive	100 - 500	1 - 7 nT	Commercial
Giant Magneto Resistance	100 - 500	10 nT	Commercial
Spin Dependent Tunneling	100 - 500	1 - 7 nT	Laboratory
Pick-up Coil	100 - 7000	20 ft at 60 Hz[1]	Commercial
Squid (super conducting quantum interference device)	10 000	10 ft (dc)	Commercial
Fluxgate	1000 - 9000	5 pT	Commercial
Kerr	100 -5000	20 pT	Laboratory

Note 1: This device measures the time rate of change of the magnetic field so the sensitivity is a function of frequency.

TABLE 2-2. COMPARISON OF TOTAL FIELD MAGNETOMETERS			
Type	**Nominal system Cost** ($ USD)	**Nominal sensitivity** (noise floor per root Hertz at 1 Hz)	**Availability**
Proton Procession	3000 - 5000	50 pT	Commercial
Optically Pumped	5000 – 10 000	1 - 5 pT	Commercial
Overhouser	5000 - 8000	10 pT	Commercial

For the purposes of this standard, the fluxgate magnetometer will be highlighted because of its sensitivity to background noise and because of its affordability. It should be noted that when applications call for mounting the magnetic sensor on a moving vehicle, total field magnetometers are preferred. Vector magnetometers, on the other hand, should be avoided in such applications because they suffer from spurious signals caused by platform rotational vibration in a strong ambient magnetic field like that of Earth. It should be further noted that it is difficult to align and calibrate the orthogonal components of a three-axis magnetometer to sufficient precision to accurately quantify the total field. Regardless of the type of magnetometer selected, each should be calibrated in accordance with good engineering practices as discussed in Section 3, paragraph 3.2.

2.1.1 Vector Magnetometer

The simplest form of vector magnetometer is the single axis magnetometer. This magnetic sensor detects one component of the magnetic field of a passing target. Any time single-axis magnetometers are deployed at least one 3-axis vector magnetometer will be part of each data collection effort to provide a baseline. At low frequencies, a single-axis fluxgate magnetometer can be used; however, for frequencies above a few Hertz, a coil system will typically have more sensitivity. The 3-axis vector magnetometer is composed of three orthogonal single axis sensors that measure the three components of the magnetic field and, thus, provide a complete set of magnetic signals at a given position. The magnetic sensor must be subjected to the same manufacturer calibration standards as those specified for single axis magnetic devices.

2.1.2 Total Field Magnetometer

The total field or scalar magnetometer measures the magnitude of the total magnetic field. Because the measurement of the total field is independent of sensor orientation, total field measurements are especially useful in tests where the magnetometer is on a moving platform such as a ground vehicle or aircraft. The three types of total field magnetometers listed in Table 2-2 make use of electron or nuclear transitions between appropriate quantum energy levels. The difference between these levels depends on the magnetic field. Because magnetic resonance techniques permit the precise determination of these differences by measuring absorption frequencies, these devices are very accurate. Furthermore, these devices are useful as total field magnetic measurement sensors since they utilize large numbers of molecules that have no preferred orientation. Total field magnetometers are fundamentally low frequency devices and are ideal for very sensitive magnetic anomaly measurements. Among total field magnetometers, there is a trade off between sensitivity, sampling interval, and cost. For a given magnetometer, a lower sampling interval (faster sampling) results in a loss of sensitivity.

2.2 Magnetometer Placement

2.2.1 Placement on Ground Surfaces. Magnetometers should be decoupled from ground or platform vibrations. Note that the mechanical transfer function for the magnetometer support structure can be designated to isolate a particular frequency band of interest. However, for magnetic anomaly detections, the following ad-hoc procedures have proven useful. The magnetometer should not be placed directly on the ground. Instead, segregate the sensor from the ground surface by means of a concrete pad. A 12x12x1-inch thick pad placed on top of a partially inflated inner tube is adequate for stabilizing the magnetometer. A slab of level granite and an inner tube will work even better. Not only will this combination decouple the sensor from the ground, it will prevent the introduction of seismic vibrations into the magnetic data. Also, a half-filled sandbag placed on the magnetometer probe will keep the sensor from moving (see Figure 2-1).

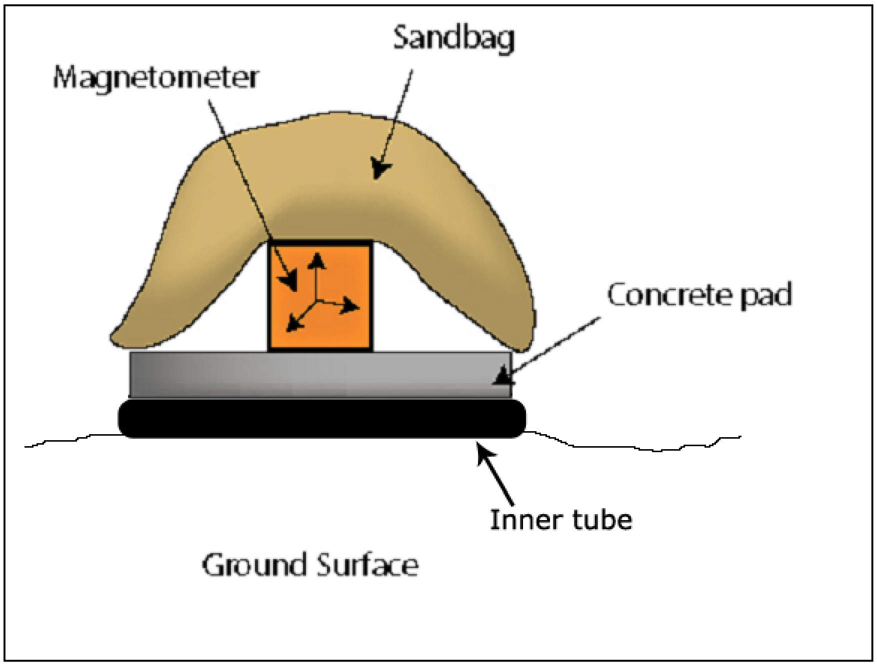

Figure 2-1. Magnetometer placement on the ground surface.

2.2.2 Typical Magnetometer Placement Along a Vehicular Test Track. A vehicular test track (typically 300 meters or more in length) is defined as a pathway for ground vehicle travel for the purpose of measurements. To enhance data collection, several magnetometers are normally placed along a test track at a distance of 25 meters or less from the centerline of the pathway at the midpoint of the track. This distance (25 meters or less) should provide a suitable signature. A magnetic probe is placed on the center of the pathway to acquire measurements of the vehicle's undercarriage.

2.2.3. Tower Configuration. If necessary, a suspended magnetometer probe can be deployed for overhead magnetic measurements. A tower made of non-magnetic materials is ideal for elevating the magnetic sensor. A geophone can be used to verify seismic de-coupling of the magnetometer. Magnetically shielded geophones (shielded with a highly permeable metal) should be used to preclude the magnetometer from acquiring signals generated in the geophone. Magnetometer placement scenarios for a vehicular test track are shown in Figure 2-2.

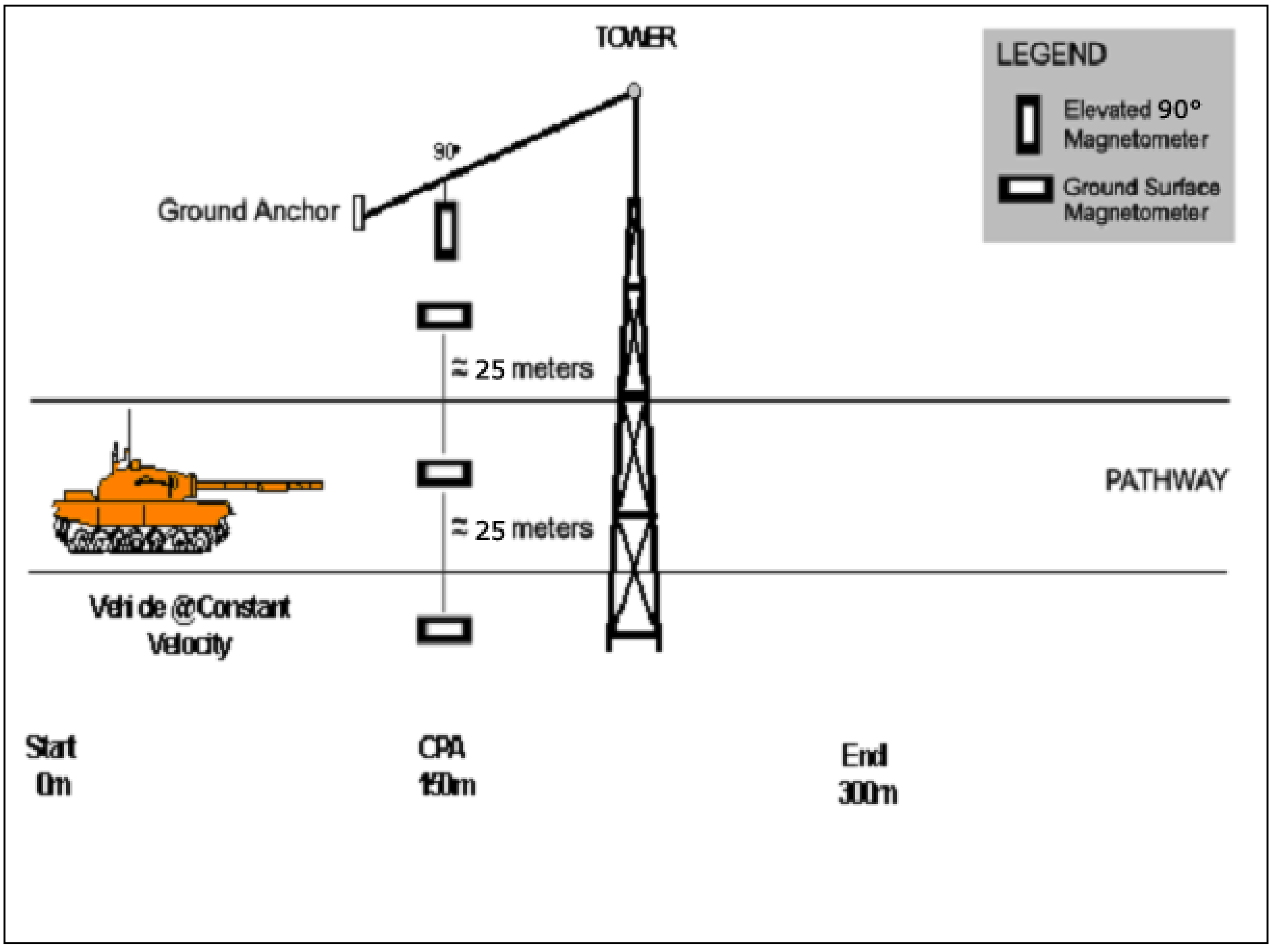

Figure 2-2. Magnetometer scenarios for a vehicular test track.

2.3 Signature Collection Methodology

2.3.1 Baseline Signature Standard. A calibrated 3-axis fluxgate vector magnetic sensor should be placed close to the target (near the CPA position for moving targets) during tests where magnetic signatures are measured. A collocated, calibrated, 3-axis magnetometer is required to provide the best reference signature (baseline) for the performance test of a pre-fielded magnetometer.

2.3.2 Collocating the Magnetometer with Seismic and Acoustic Sensors in the Field. Coupling of seismic and acoustic signals into the soil occurs during vehicle exploitation measurements. One seismic and acoustic sensor will suffice for the magnetometer array. These sensors are collocated to differentiate inputs from seismic and acoustic sources that could corrupt the magnetic data. A calibrated, magnetically shielded, geophone should be planted in the ground at a distance sufficient to avoid generating unwanted signals in the magnetometer. In a practical fashion, this range can be checked by exciting the geophone at increasing distances from the magnetometer until its signal is not detected. For a properly shielded geophone, this distance is approximately 1 meter. The seismic sensor should be planted in the ground in accordance with RCC Standard 805-01, *Seismic Signature and Methodology Standard*. Use the procedures in RCC Standard 806-03, *Acoustic Signature Collection Methodology Standard,* to deploy the acoustic sensor. Figure 2-3 shows the proper method to collocate the seismic, acoustic, and magnetic (SAM) sensors.

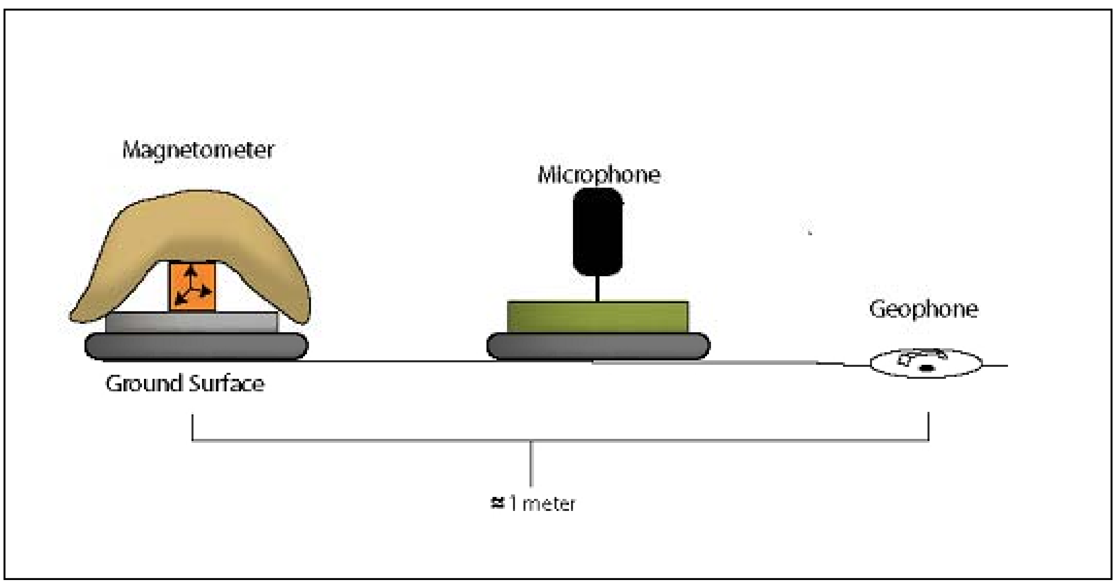

Figure 2-3. Collocation of SAM sensors in the field.

Frequency plots (spectrograms) of data collected from collocated SAM sensors can help identify signals that are magnetic in origin. If the magnetic spectrogram of one of the sensors is different from that of the other two, the signal is magnetic. On the other hand, if the magnetic spectrogram is the same as the seismic or acoustic spectrogram, further tests are required to determine if the signal is of magnetic origin. This technique is also commonly used to ascertain if acoustic and seismic noise are present in the magnetic spectra.

2.4 Operational Parameters of Magnetometers

2.4.1 Sensor Configurations. The 3-axis vector magnetometer consists of three magnetometers placed on an orthogonal mount. The typical orientation is for two of the sensing units to be placed horizontally and for the third sensor to be arranged vertically with the x-axis oriented to magnetic north, the y-axis oriented to magnetic west, and the z-axis oriented to the vertical. The relative speed of the source under study affects the selection of an optimum bandwidth. Operational parameters for most vehicles require a dynamic range of less than ± 100 μT. Noise should be less than or equal to 10 pT rms per Hz at 1Hz. It is recommended that a magnetometer with a transconduction sensitivity of 10 - 100 μV/nT be used to measure magnetic anomalies. Typical magnetic sensor parameters along with the recommended units and a conversion chart are provided in appendixes A and B, respectively.

2.4.2 Magnetometer Parameters

TABLE 2-3. FLUXGATE MAGNETOMETER

Parameter Name	Units
Frequency	Hz or cps
Magnetic drift (temperature or temporal)	nT/°C or nT/hour
Scale factor or transconduction sensitivity	μV/nT
Offset	± nT
Minimum magnetic field	nT
Maximum magnetic field	nT
Full-scale magnetic range	±nT

TABLE 2-4. ORTHOGONAL MAGNETIC PROBE	
Parameter Name	**Units**
Orthogonality between axes	± degree
Noise	nT peak-to-peak @ Hz
Accuracy	± percent @ ºC
Sensitivity (noise floor)	$nT/(Hz)^{1/2}$ @ 1 Hz

TABLE 2-5. MAGNETOMETER/MECHANICAL	
Parameter Name	**Units**
Probe dimensions	centimeters
Total weight	grams
Operating temperature range	degrees Celsius
Supply voltage	volts
Operating current	milliamps

2.4.3 Magnetometer Parameter Definitions

Accuracy: The capability of the magnetometer to follow a true value; the degree of freedom from error; expressed as plus-or-minus a percentage of full scale at a temperature measured in degrees Celsius.

Dynamic Range: The range of the magnetic field over which the magnetometer does not saturate.

Fluxgate Magnetometer: An instrument that detects magnetic fields. Three typical types include:

a. Fluxgate sensor: A magnetometer that uses a field coil to drive a soft magnetic material into saturation at angular ω and detects at 2ω. Fluxgate magnetometers are capable of detecting and measuring changes in a magnetic field that result from the passage of a vehicle on the order of 0.01 nT. Units of nano tesla (nT) are used in this standard.

b. Magneto resistive sensor: A magnetometer that changes resistance in the presence of a magnetic field.

c. Coil sensor: A magnetometer that provides a voltage proportional to the time rate of change of a magnetic flux passing through a coil.

Frequency Bandwidth: The frequency response of the magnetometer is its ability to respond with an approximately equal output to all constant amplitude signals within a specific frequency range; expressed in Hertz (Hz).

Hysteresis Errors: Changes in the scale factor or transconduction sensitivity as a function of the magnetic field history; expressed in percent error.

Input Power: The maximum and minimum input dc power at which the magnetometer will properly operate; expressed in Watts.

Linearity Errors: Deviations of the scale factor or transconduction sensitivity as a function of the magnetic field strength; expressed in percent error.

Magnetic Drift: A gradual and unintentional change in the magnetic output often resulting from changes in temperature or operation time. A magnetic drift caused by a shift in temperature; expressed nT per degrees Celsius per hour.

Magnetometer Response Time: The amount of time it takes the magnetometer to achieve 63% of its final value as a result of a sudden change in magnetic field intensity.

Maximum Magnetic Field: The largest magnetic field intensity value that the magnetometer is capable of measuring; expressed in nT.

Minimum Magnetic Field: The smallest magnetic field intensity value that the magnetometer is capable of measuring; expressed in nT.

Noise: Any unwanted magnetic signals or any disturbances caused by background and instrument effects; expressed as nT peak-to-peak within a frequency band.

Offset: The capability to remove the bias caused by steady fields in all axes with no degradation in the instrument drift or noise level; expressed in ± nT.

Operating Temperature: The minimum and maximum temperature limits at which the magnetometer can properly operate and remain stable; expressed in degrees Celsius.

Orthogonal Magnetic Probe: Generally a 3-axis magnetic sensing device that has its axes aligned at right angles to each other.

Probe Dimensions: The external height, length, and width dimensions of the magnetic probe; expressed in centimeters.

Resolution: The least change in magnetic field that the magnetic detector is able to perceive. This is equivalent to the noise floor integrated over the bandwidth of interest; expressed as nT.

Scale Factor or Transconduction Sensitivity: The ratio of the output voltage to the magnetic field input; expressed as microvolts per nT.

Sensitivity (Noise Floor): The RMS noise floor as a function of frequency; expressed as $nT/(Hz)^{1/2}$ @ 1 Hz.

Total Weight: The total weight of the magnetic probe; expressed in grams.

2.5 Magnetic Instrumentation

A typical magnetic circuit consists of a 3-axis (or single-axis) magnetometer, amplifiers for the sensor on each axis, connecting cables, a recording/playback system, and a dc power source. A discussion of these devices follows.

2.5.1 Amplifier. With a common magnetometer the amplifier is attached in the circuit as near to the sensor as possible. It is best if the amplifier and the magnetometer are a single unit. The input impedance of the amplifier and the magnetometer must match to maximize power transfers. A desirable low noise device amplifies signals in the magnetic region (0.01 to 1000 Hz). Such amplifiers generally have selectable fixed gains of 20 dB, 40 dB, and in some instances, 60 dB. The amplifier must have a relatively flat frequency response across the flat portion of the sensor bandwidth to allow the most accurate representation of the magnetic spectral signatures. The amplifier must also have a flat frequency response across the operating temperature range of the sensor.

2.5.2 Cables. Cables used in the magnetic data collection circuit must have low noise characteristics. The length of the cable can sometimes influence the quality of the analog data obtained from hardwired data-gathering systems. Therefore, cable lengths should be kept as short as possible, preferably less than 50 meters. Since the weather can vary from dry conditions to rain, individual shielded, twisted pair, 20 AWG, instrumentation cable with waterproof connectors should be employed.

2.5.3 Instrumentation Recorder/Playback System. This is a device used to capture and playback data that is sensed by the magnetometer. Such instruments must be of recognized scientific quality and able to undergo a calibration procedure traceable to the National Institute of Standards and Technology (NIST). The more bits or recording channels available, the greater the dynamic range that can be accommodated. A 24-bit resolution is desired for weak (<10nT) magnetic anomalies in a strong field, while 16-bits will suffice for the collection of larger magnetic signatures. Computers with A/D boards are commonly used for this purpose.

2.5.4 DC Power Source. Batteries are of paramount importance when collecting magnetic signatures because they eliminate the introduction of ac-power harmonics or other noise into the data stream. All instruments (equipment and sensors) discussed in this document are operated directly from battery sources.

Utility ac power, ac generators, and most commercial inverters have been found to generate unwanted magnetic noise. It is recommended that any devices that radiate spurious magnetic or electromagnetic noise be avoided and removed from the data collection apparatus. Changes in current draw from attendant electronic devices such as portable computers can also introduce anomalous magnetic fields even when using dc battery power.

Some devices draw a significant amount of current over a period of a few hours. In cases of this type, the battery voltage level must be automatically recorded to ensure that proper voltage levels are maintained. Voltage readings should be checked and recorded as part of the ground truth data product. Fortunately, some instrumentation devices have built-in alarms that warn of low-voltage readings.

2.5.5 Ancillary Instrumentation. The design of the magnetic data acquisition circuit must be kept simple. The addition of unnecessary equipment to the magnetic signature collection circuit generally increases complexity and introduces noise into the measurement. An example of a simple magnetic data collection circuit follows in Figure 2-4.

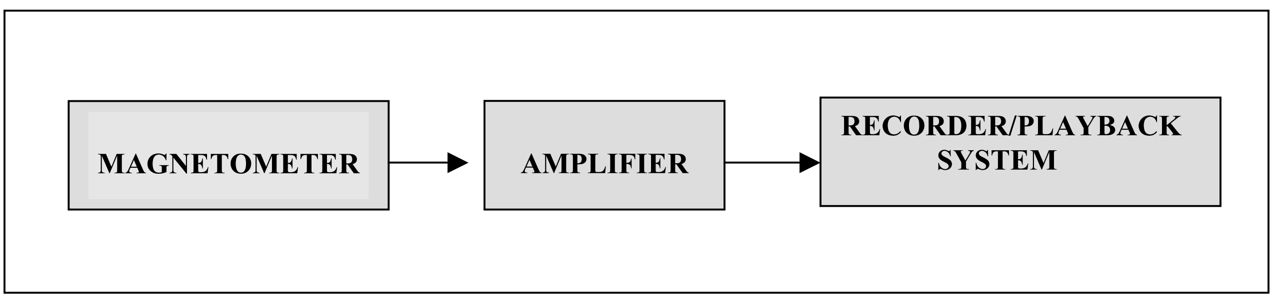

Figure 2-4. Magnetic data collection circuit diagram.

SECTION 3

CALIBRATION

3.1 Overview

Successful magnetic data collection requires proper calibration procedures. This section outlines the various calibration processes used during the collection of magnetic data and presents ways to insure that the magnetic data gathered in the field meets the highest standard of accuracy. It is important that high quality devices with fairly constant precision be used when making magnetic measurements. The following paragraph describes field calibration procedures and the equipment required.

Determine the location of magnetic north by using a 3-axis magnetometer. Make sure the magnetometer is pointed away from buildings, power lines, automobiles, and other sources of magnetic disturbances. Place the magnetometer on a flat and stable concrete pad that is accurately leveled. Feed the output of the magnetometer into the measuring instrument (if employing a multimeter, use the dc scale) and read the y-axis output. Rotate the magnetometer head in the horizontal plane until 'y' reads zero output. You are now aligned to magnetic north. Otherwise, use a good quality compass to locate magnetic north.

To orient the reader and facilitate the understanding of calibration techniques, one must understand the type of signature data to be collected (low or high frequency, type of source, etc.). Because the magnetic data product must always lend itself to various forms of analysis, proper calibration procedures must be followed during the data gathering cycle.

3.2 Calibration Techniques

The following techniques are discussed in order of increasing complexity.

3.2.1 Calibration Using Earth's Magnetic Field. It is possible to use Earth's known magnetic field at any location to calibrate a magnetometer. The sensor should be oriented as discussed above (x-axis north, y-axis west, z-axis up) and the measured values compared against tabulated values. This method is not applicable for an ac magnetometer such as a coil.

3.2.2 Calibration with a Known Magnetometer. It is possible to perform a comparative calibration by determining the output of an uncalibrated magnetometer and comparing it with the output of a calibrated magnetometer.

3.2.3 Calibration Using a Known Magnetic Field. A magnetic field generated by a calibrated source can be used to measure the response of the magnetometer in a given direction to a known or standard field in the same direction. For example, one could use the field in the center and along the axis of a Helmholtz coil system (Figure 3.1) for this purpose.

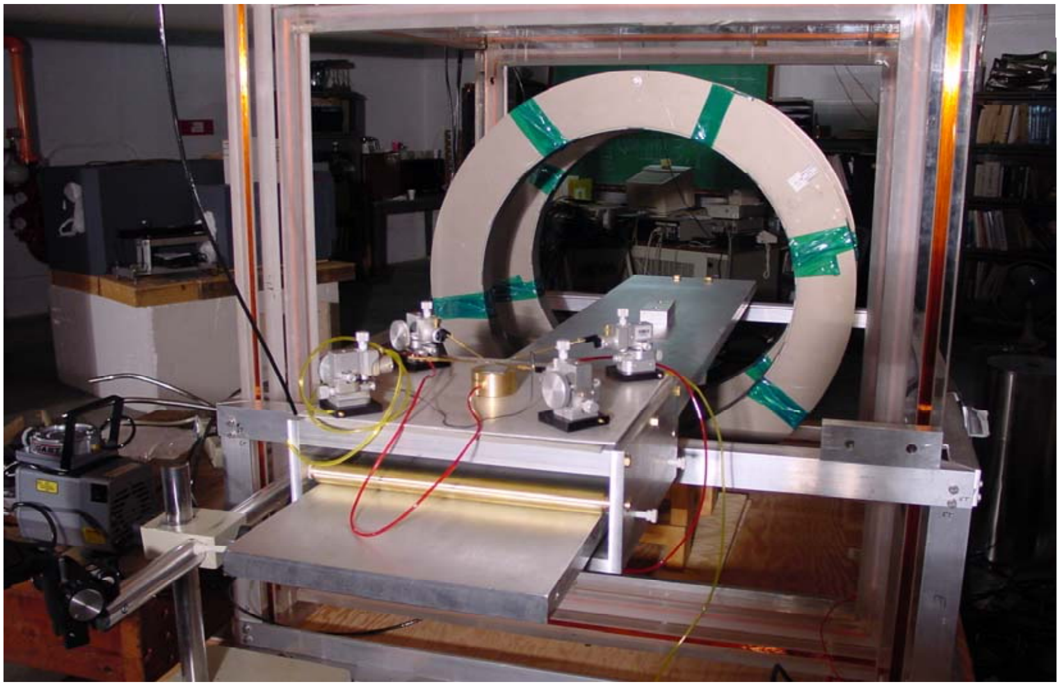

Figure 3-1. 3-axis Helmholtz coil system with a higher field single-axis Helmholtz coil system mounted inside.

Note that the Helmholtz coil system shown in Figure 3-1 consists of two short solenoid coils, each of radius a(m), N turns, and with the coils separated by a distance equal to the radius. The field along the axis in tesla is parallel to the axis and is given by the following equation:[1]

$$B_z = \frac{\mu_0 NI}{a} \bullet \frac{8}{5^{3/2}}, \tag{3-1}$$

where: I = the coil current in amperes

μ_0 = 12.57 • 10^{-7} henries/meter (= volt • sec/amp • meter)

N = number of turns

a = radius of solenoid coils

Alternatively, one can place the magnetometer inside a long solenoid. In this case the field in tesla (=10^9 nT) is given by the equation:[2]

$$B_z = \frac{\mu_0 NI}{L} \tag{3-2}$$

[1] John Reitz, Frederick Milford, and Robert Christy. Foundations of Electromagnetic Theory, Ed III. Reading, MA, Addison-Wesley Publishing Company, 1979, P. 170.-

[2] Reitz et al, Ibid., p. 172.

where L is the length of the coil, and the other symbols are as defined above.

This process is repeated for the other two axes and is applicable for both ac and dc calibration. It should be noted that for ac calibration it is necessary to actually measure the current as opposed to inferring it from voltage drops across the coils and resistance values of the coil typical of dc measurements. Insert a resistor with a previously known value in series with the coil. To measure the current, use a high impedance voltmeter and determine the voltage drop across the known resistance. To avoid incorporating unnecessary errors, do not rely solely on the value listed in the manufacturer's specification. Always measure the actual resistance.

3.3 Field Calibration

3.3.1 Calibration Using Earth's Magnetic Field. This calibration technique uses the Earth's known magnetic field at any location to calibrate a magnetic sensor. The sensor should be oriented as discussed above (x-axis north, y-axis west, z-axis up) and the measured values compared against tabulated values. This method is not applicable for an ac magnetometer such as a coil.

3.3.2 Calibration with Known Magnetometer. This calibration technique involves comparing the output of an unknown magnetometer with the output of a known, calibrated, magnetometer.

3.3.3 Calibration Using a Known Magnetic Field Generated by a Calibrated Source. It is possible to calibrate a magnetometer using a calibrated source in a manner similar to that described in paragraph 3.2.3. Unfortunately, the devices employed are typically too bulky to be practical for field operations.

3.3.4 Field System Operational Checkout. The entire measurement system including magnetometer, amplifiers, cable harness, and the data collection system must be calibrated by the use of a standard that generates a repetitive magnetic field. One method for achieving the basic relative calibration of a magnetic sensor in the field consists of employing a 24-inch aluminum rail inclined at a 30-degree angle. At the top of the rail a steel ball is released at a point 2/3 of the way along the rail so the steel ball passes in front of the magnetic sensor. Data is recorded at the beginning of the signature data collection cycle and at the end. The relative field magnetic data will then be collected in all four cardinal directions based on magnetic north. A minimum of three rolls of the steel ball is necessary. This procedure will also be done at the beginning and end of the data collection cycle. Avoid magnetizing the steel ball. In the event that the steel ball is magnetized, a modulation will show prominently in the calibration data. Figure 3-2 shows the relative field data operational checkout device decoupled from the ground surface.

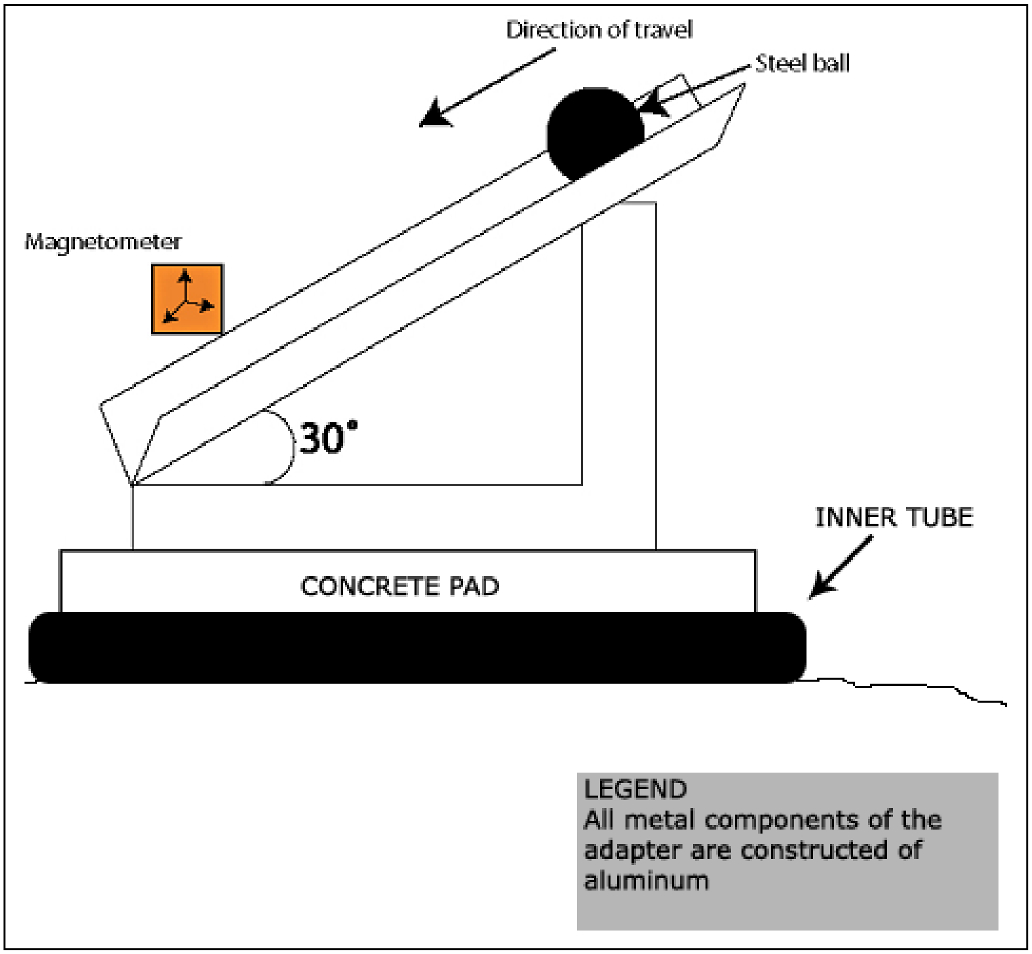

Figure 3-2. Field relative data operational checkout device.

An alternate approach for diagnosing signal flow and highlighting problems like faulty cabling is to use a portable coil and signal generator to introduce a repeatable signal into the measurement system. If this technique is performed in a repeatable, systematic manner, it can provide information on the repeatability and stability of the measurements.

3.4 Absolute Magnetic Field Calibration of Magnetometers

Vector field magnetometers measure each component of the magnetic field. Fluxgate magnetometers and magneto resistance magnetometers are types of vector field magnetometers. There are at present three types of magneto resistance magnetometers: anisotropic magneto resistance magnetometers (AMRs), giant magneto resistance magnetometers (GMRs), and spin dependent tunneling magnetometers (SDTs). Magneto resistance magnetometers are lower cost and less sensitive than the total field magnetometers described above. When a vector or three-axis magnetometer is set in the absolute field mode, each axis of the magnetometer measures the corresponding ambient or Earth's magnetic field component plus the anomaly field produced when a target passes by. Since the target field usually is several orders of magnitude less than the ambient field, the resolution of the useful signal is reduced. To obtain the full dynamic range for the smaller field, subtract the quiescent ambient field value from the absolute field reading before passing the difference signal to the A/D converter. This differential is the relative field measurement. Sometimes the vector field magnetometer is used in the absolute field mode. For example, the absolute field mode should be used when employing the magnetometer as a compass to determine magnetic north at a test site.

For a vector field magnetometer, align each axis calibrated only in the direction of the field used in the calibration. This technique will determine if the readings of the magnetometer agree approximately with the known value of Earth's magnetic field at the given latitude and longitude in this direction.

3.5 Absolute and Relative Measurements with Total Field Magnetometers

In calibrating a total field (or scalar) magnetometer, it is best to align any applied field along Earth's magnetic field or null out Earth's magnetic field. Calibration of the magnetometer in the field can be performed in one of the following ways.

Calibrate the magnetometer by comparing the reading of the total magnetometer to the readings of a total magnetometer that is known to be correct. As an additional check, see if the readings agree approximately with the known value of Earth's magnetic field at the given latitude and longitude.

Another way to calibrate the magnetometer is by measuring the response of the total magnetometer to a known or standard field like that along the axis of a Helmholtz coil system or a long solenoid. This approach can be used to measure the change in the total field magnetometer readings caused by a known change in the total magnetic field produced by either of these devices. To calibrate the absolute reading of the magnetometer, use the Helmholtz coil system or some other means to null out the ambient field before applying a known field. Measure the response to determine if the readings of the magnetometer agree with the known value of Earth's magnetic field at a given latitude and longitude.

3.6 Scientific Grade Magnetometers

The magnetometers used must be of scientific quality and have an annual calibration traceable to NIST. Although the manufacturers calibrate single-axis and 3-axis magnetometers, such calibrations are only valid for a finite period of time. Annual calibration of the magnetometer is mandatory by the manufacturer or by other means.

3.7 Magnetic Ambient Noise from the Signature Collecting Sensor

Periodic variations in the ambient magnetic field resulting from solar flare activity and the Earth's rotation require frequent samples of background ambient noise to be collected when acquiring absolute magnetic data and when detecting weak magnetic signals. Such variations are dictated by the repetition of solar flare activity (K-index). The ambient samples should not be less than a minute in duration and can be as long as five minutes. Magnetic background noise samples are generally found to have a large range of values that depend on solar flux. Figure 3-3 shows typical magnetic ambient noise. Ambient noise can vary from site to site. This sample of ambient noise does not include Earth's magnetic field. It consists of instrument noise and local sources such as lightning, radar energy, utility power, and other similar sources. For example, the magnetic field of Earth is typically between 50 to 60 µT for the Florida Panhandle.

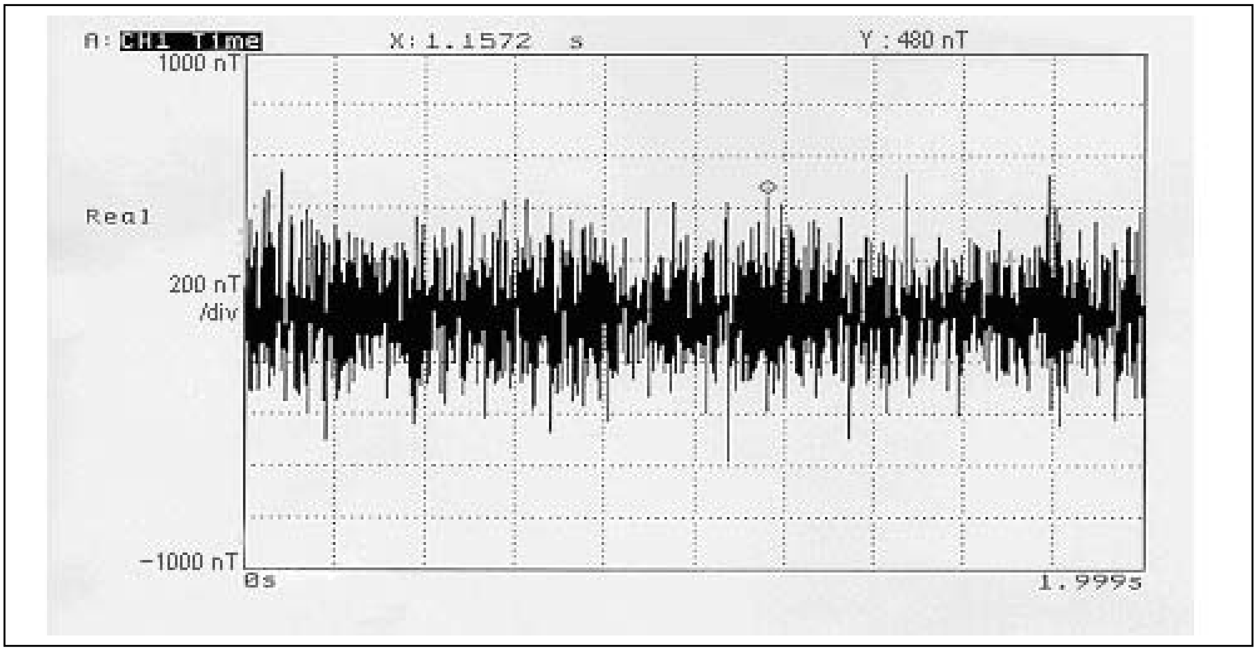

Figure 3-3. Typical magnetic instrument and site ambient noise with the bias nulled out.

3.8 White Noise Injection

A calibrated white noise source is used to inject a signal into the electronic magnetic array. This source is applied prior to the amplifier (see Figure 3-4). It travels the length of the cable and into the recording system. The spectral bandwidth of the white noise should extend beyond the entire range of the system. This method will identify any inherent filter characteristics in the system that may cause degraded measurements. The white noise source should have an annual calibration certification traceable to NIST. See Figure 3-4.

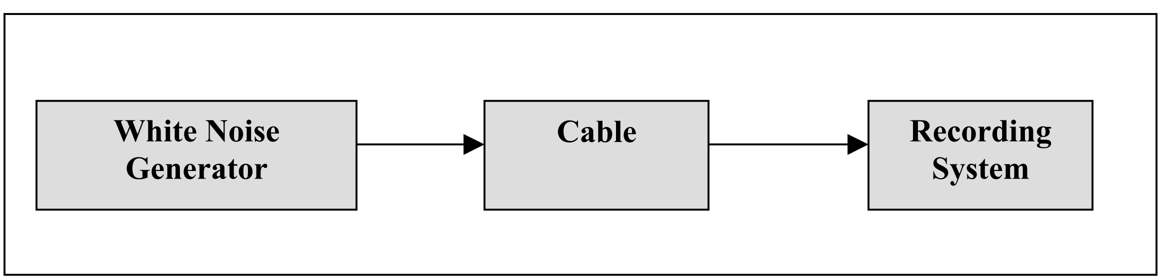

Figure 3-4. White noise injection into the magnetic recording circuit.

3.9 Differential Magnetics

Two calibrated fluxgate magnetometers are used to collect coherently subtracted differential magnetic data. One magnetometer collects signatures from the item or source undergoing measurements. The other unit is placed 75 meters or more from the source under study so it will not be influenced by any magnetic moment from the source. It is then used to collect continuous and time synchronous data with the target collection background or ambient magnetic noise. Under no circumstances should the second magnetometer be allowed to sample the source. Later, both sets of magnetic measurements can be compared for further study. Geomagnetic noise that is correlated over relatively large distances can be negated by calculating the difference between the signals measured by these spatially separated magnetometers.

SECTION 4

GROUND TRUTH

4.1 Definition

Ground truth is ancillary technical information that adds substance to the interpretation of magnetic data. Documentation of ground truth in data logs is critical in this process. Examples of data log information (ground truth) follow.

4.2 Data Logs

A data log is a time-referenced document that includes source information that may or may not change with time during the test. Source information may be continuous, impulsive, or constant in nature during a particular test. For vehicular, watercraft and/or aircraft measurements, the information in Table 4-1 should be recorded.

TABLE 4-1. VEHICLE DATA LOG INFORMATION

Vehicle Data Log Parameter	Descriptive Remarks	Type of Vehicle
Type	Model, series	All
Speed	km/hr	Ground & Watercraft
RPM as a function of time	Type of tachometer	Ground & Watercraft
Transmission gear	First, second, etc.	Ground & Watercraft
Direction of travel	Coordinate direction	All
Transmission low range	If used during tests	Ground
Countermeasures	Nets, foliage, mud, color, etc.	All
Configuration	Missile empty/full, combat loaded, hatches open/close	All
Air speed	Knots	Aircraft
Engine	Design, internal combustion, jet, other	All
Auxiliary Power Unit	Design, internal combustion, jet, other	All

4.3 Ancillary Information

Such information includes changes of amplification and anti-aliasing filter bandwidth range, sensor replacements, data channel assignments, identification of other noise sources, and other unusual events that take place during the test. All information of this nature should be written in the log or placed on a recorder voice channel. Similar data for other test targets should also be noted.

4.3.1 Data Contamination. To prevent data contamination, all non-essential personnel will leave the test area when the data collection process begins. Remaining personnel will maintain a distance of at least 25 meters from the magnetic sensing area.

4.3.2 Voice Channel. Voice, which is used to provide the real time narration of all events taking place at the site during the test, is critical for later interpretation of the data. A channel on the data recorder can be used to transfer the narration to another appropriate medium such as a compact disk (CD).

4.3.3 Instrumentation Description. Specifications for all instrumentation should be annotated in the log. When the manual for an individual piece of equipment is quite long, include a copy of the specifications, the model type, and a description of the location of the manual in the log. The log should also reference calibration certificates and sensitivities where appropriate. Always monitor the health of the equipment, especially power sources. (Refer to Sections 2 and 3 for additional instrumentation specifications.)

4.3.4 Sensor Orientation and Placement. Document the placement and location of sensors (x, y, and z), the number of sensors used, and other characteristics like sensor gains, pattern, range to target, differential applications, etc. (Refer to Section 2 for more sensor orientation and placement criteria.)

4.3.5 Site Description. A description of the test site should include the length and width of the test track, the position of test track markers, the composition of the track, the size and type of nearby vegetation or ground cover, the type of soil in the area, and the type of snow if present. Also document the position of sensors in relation to the test track and any metal objects, power lines, power transformers, discarded military vehicles, or natural barriers with geological features that may be present. A map or diagram of the site with the proper United States Geological Survey (USGS) topographic references should be appended to the log.

4.3.6 Vehicle Tests. Inputs for the data log include but are not limited to vehicular runs, type of vehicle, Interrange Instrumentation Group (IRIG) time, vehicle speed and rpm, transmission gear, transmission range, direction of travel, changes in instrumentation amplification, sensor placement, sensor gains, data channel assignments, differential Global Positioning System (GPS) data, other noise sources, observable environmental changes, and any unusual events that take place during the test.

4.3.7 Aircraft Tests. Inputs include but are not limited to the vehicular run, flight profile, type of aircraft, IRIG time, changes in instrumentation amplification, sensor placement, sensor gains, data channel assignments, noise sources, differential GPS data, and any unusual events that take place during the test.

4.3.8 Photos and Drawings. These materials are used in technical reports and for reconstruction of the experimental layout. If practical, all photos and drawings should be provided in electronic format.

4.3.9 Operator Interviews. Contacts with the vehicle operator/aircraft pilot may reveal additional details about the operation of the vehicle. In the case of the vehicle operator, for example, information on gear changes (in what gear activities started and finished) might be useful.

4.3.10 Identification of Test Team. A listing of the test team participants should be included in each log so that information can be exchanged more readily at a later date.

4.3.11 Differential Global Positioning System (GPS) Configurations. Documentation of GPS configurations is needed for archiving magnetic data. The reference point and accuracy of the location should be included.

4.3.12 Vehicle Position Information. Vehicle position is determined by using differential GPS techniques. It is necessary to use differential GPS for the archiving of data. Depict the type of format used in the data collection process.

4.3.13 Test Track Markers. These are upright position markers that are placed along one side of the test track, usually numbered consecutively, and spaced at 50-meter intervals (minimum). The marker positions are reference points that should be included in the overall site survey. Such markers can also be used when GPS tracking is not available.

4.3.14 Vehicle Specifications. The more information that is known about a vehicle, the better the signature interpretation will be. Vehicle specifications should include a description of the engine, the type of fuel used, a description of the propeller (number of rotor blades), the odometer reading, the type of exhaust system, the number of exhaust outlets, the number of wheels and their sizes, the number of points in the star-chain drive sprocket, the distance between the track pins, mechanical drawings, the number of forward and reverse gears, the number of engines, the manufacturer's engine specifications (whether 4-cycle or 2-cycle), and associated gear ratios. Additionally, the tail and bumper numbers of the vehicle should be documented. Maintenance records will generally show any modifications made to the vehicle, and these modifications should also be noted in the log.

4.3.15 Survey and Positioning. All ground-placement positions of magnetometers should be precisely surveyed so that their locations can be referenced to GPS data from both stationary and moving vehicles. To determine their location, a GPS time-space position information (TSPI) system should be installed in all ground vehicles undergoing study or exploitation (single vehicles as well as moving convoys) regardless of travel scenario. The location of the GPS antenna on the test vehicles should be noted. In cases where data collection systems are geographically separated, IRIG satellite clocks are used to ensure that all data is properly synchronized.

4.3.16 Magnetic Anomalous Conditions. Such conditions occur when the source under study exhibits unusual magnetic readings. An accumulation of foreign ferrous objects like barbwire, iron-contaminated soil in the form of mud, welded fixtures on the source, etc., can cause anomalous readings. Measurements may also be affected by degaussing processes. Military ground vehicles undergoing measurements can be affected by other natural and man-made magnetic sources as well. Table 4-2 lists some of the sources and agents that can influence magnetic measurements.

TABLE 4-2. MAGNETIC ANOMALOUS SOURCES AND AGENTS

Anomalous Source/Agent	Cause of Change in Magnetic Field
Fence wire	Gets tangled in vehicle road wheels or tires
Fence wire	Dragged by moving vehicle
Soil with high iron content	Attached as mud to moving vehicle, tank tracks, or tires
Snow and ice with high iron content	Attaches to moving vehicle, tank tracks, or tires
Direction of travel east/west	Vehicles exhibit different magnetic values
Welding	Magnetizing effect
Battle damage	Design modification
Battlefield supplies	Additional fuel drums, ammunition, etc.
Armed troops	Troops riding on vehicles

4.3.17 Meteorological (MET) Data. The climatic environment also has an impact on the magnetic field. MET instruments should be in the immediate vicinity of the test site and MET data sample averages should be determined at intervals not to exceed every 10 minutes. Typical MET and environmental data are shown in Table 4-3.

TABLE 4-3. MAGNETIC METEOROLOGICAL AND ENVIRONMENTAL DATA	
MET Parameter	**Units**
Meteorological station date and time	days, months, years, hours, minutes
Wind speed	meters/second
Wind direction	degrees
Surface temperature	Celsius
Dew point	Celsius
Barometric pressure	millibars
Soil moisture content	percent
Solar wind	K-index
Soil sample metal analysis	percent

4.3.18 Magnetic Meteorological and Environmental Parameter Definitions:

Barometric Pressure: The actual pressure of the air in the vicinity of the magnetic site; expressed in millibars.

Dew Point: The temperature at which the air reaches a relative humidity of 100% (beginning with the volume of air initially at a particular temperature, barometric pressure, and relative humidity as the temperature of the air is reduced); expressed in degrees Celsius.

Meteorological Station Date & Time: The date and time that the magnetic data was collected. The standard Zulu format (dd mon yyyy & HH:MM) applies. The use of *seconds* is optional.

Surface Air Temperature: The temperature of the air measured at 30 centimeters above the ground surface as read on a calibrated thermometer when the sensing element is dry; expressed in degrees Celsius.

Soil Moisture Content: The relative portion of the weight of a sample of soil that is composed of moisture; expressed as a percent.

Soil Sample Metal Analysis: Identification of ferromagnetic material found in soil at the site is obtained by sampling three locations along the test track. A soil sample should be collected at the CPA and at each end of the pathway. Be sure that each soil sample is stored in a separate container. A laboratory can analyze the soil samples for iron content; expressed as a percent.

Solar Wind: Ionized particles flowing radially outward from the sun creating magnetic disturbances; expressed as the K-index. Information on the K-index and other associated space weather phenomena is available at the following government web site: http://dx.qsl.net/propagation/propagation.html.

Wind Direction: The direction from which the wind is blowing at the test site; measured clockwise from true north; expressed as degrees.

Wind Speed: The average wind speed measured at the test site; expressed as meters/second.

SECTION 5

MAGNETIC SURVEY AND MAPPING OF A MILITARY GROUND VEHICLE

5.1 Example of a Typical Military Vehicle

A military vehicle is typically a ferromagnetic mass capable of disrupting Earth's geomagnetic field that can be detected by a magnetometer. If the opportunity presents itself, it is advisable to conduct a near field magnetic survey of the item under study. All findings should be documented in the ground truth log (see Section 4.0).

5.2 Vehicle Survey Using a Magnet

The T-72 tank shown in Figure 5-1 is a good example of a military magnetic source. Using a hand held magnet, and with the engine turned off, touch the various exterior areas of the tank to determine which metals attract the magnet. Document these findings.

5.3 Vehicle Survey Using a 3-Axis Magnetometer

While the engine is running at idle, use a 3-axis magnetometer to survey the electromagnetic fields generated by the vehicle's various electric motors. Repeat the process with the main engine (diesel or gasoline) running at fast idle. Determine which electric motors are running and document this information. To best identify electromagnetic sources, a process of elimination is recommended. Thus, initialize the individual electric motors one at a time.

The best survey method to follow is to open the engine compartment area and use a magnetometer to sample the various magnetic fields present. The safest way to do this is while the engine is operating at idle. Keep track of the engine revolutions per second (rpm). Attach the magnetometer probe to a wooden stick and probe the various areas for electromagnetic signals. It is not unusual to find that even automotive components like centrifugal oil filters radiate strong electromagnetic signals. Once the mapping of the various electromagnetic signals is accomplished, move away from the sources and use the magnetometer probe to sample how far the sources radiate. Document the findings in the ground truth log (see Section 4.0).

Table 5-1 shows the areas of magnetic interest from the T-72 tank shown in Figure 5-1. These sources are classified into three categories: the induced moment, the permanent moment, and the onboard moment. The induced moment source is induced by magnetic fields, most commonly Earth's magnetic field. The permanent moment exists in the absence of an applied field. The onboard moment sources are produced by all the other electrical systems that are part of the vehicle including its electric motors, centrifugal oil filters, radar emissions, tachometer motors, radios, etc. An example of a magnetic signature that shows all three moments is depicted in Figure 5-2.

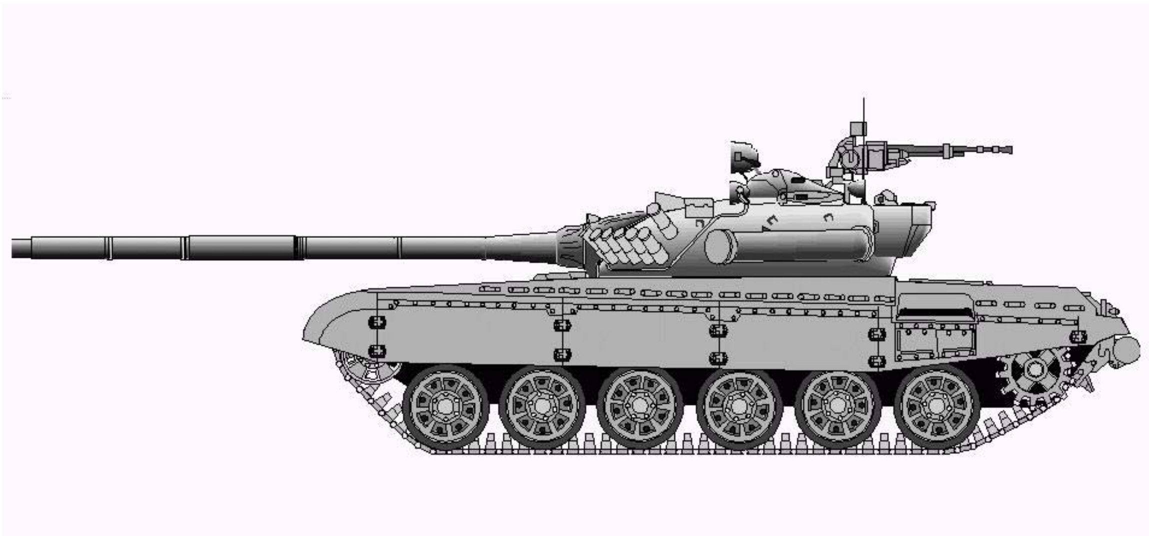

Figure 5-1. T-72 military vehicle: a magnetic source.

TABLE 5-1. TYPICAL MAGNETIC SOURCES FROM A DIESEL ENGINE MILITARY VEHICLE	
Magnetic Source	**Induced, Permanent, Onboard Moment**
Road Wheels	Induced
Track Pins	Induced
Gun Barrel	Induced, permanent
Glacis	Induced
Undercarriage	Induced
Overhead Area	Induced
Vehicle in Motion	Induced
Exhaust Plume	Onboard
Centrifugal Oil Filter	Onboard
Electric Motors	Onboard
Turret Motor	Onboard
Communications	Onboard
Gun Barrel Firing	Onboard

In Figure 5-2, the induced and permanent moments are depicted by the temperature at which the air reaches a relative humidity of 100% and by the sine wave-like signal. The onboard moment is the modulation or signal. Further study of the onboard moment indicates that it can be detected prior to sensing the induced moment.

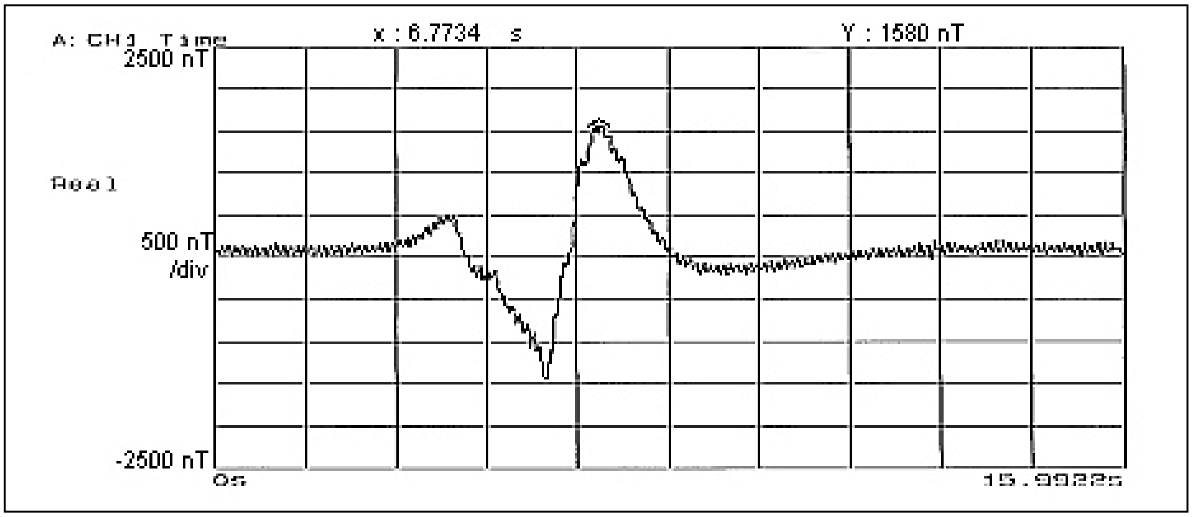

Figure 5-2. Magnetic signature shows the induced and onboard moments.

APPENDIX A

STANDARD 3-AXIS FLUXGATE MAGNETOMETER SPECIFICATIONS FOR A COLLECTION OF FIELD MAGNETIC SIGNATURES

TABLE A-1. MAGNETOMETER SPECIFICATIONS FOR COLLECTION OF FIELD SIGNATURES

Parameter	Units
Axial alignment	Orthogonality better than ± 1degree
Input voltage	+ 12 Vdc
Field measurement range	100 μT
Accuracy	±0.75% of full value (0.5% typical)
Linearity	+0.007% of full scale
Sensitivity	100 μV/nT
Scale factor temperature shift	0.007% full scale/ degree Celsius
Noise (typical)	≤10 pT/√Hz @ 1Hz
Output ripple	3 millivolts peak to peak @ 2nd harmonic
Analog output @ zero field	±0.025 volt
Zero shift with temperature	±0.6 nT/degree Celsius
Susceptibility to perming	± 8 nT shift with ± 500 μT applied
Output impedance	332 Ω ± 5%
Frequency response	3 dB @ >500 Hz (to > 4 kHz wideband)
Overload recovery	± 500 μT slew < 2 milliseconds
Random vibration	> 20 G rms 20 Hz to 2 kHz
Temperature range (operating)	−55° to +85° Celsius
Acceleration	>60G
Enclosure	PVC underwater
Size	Not to exceed 11" by 3.5" diameter ± 1" OD
Connector	BNC (X, Y, Z), (Power ground (banana connectors) not water tight

APPENDIX B

CONVERSION AND UNITS TABLES

TABLE B-1. CONVERSION TABLE

Tesla	Gauss	Oersted
1 T	10,000 G	10,000 Oe
100 mT	1,000 G	1,000 Oe
10 mT	100 G	100 Oe
1 mT	10 G	10 Oe
100 µT	1 G	1 Oe
10 µT	100 mG	100 mOe
1 µT	10 mG	10 mOe
100 nT	1 mG	1 mOe
10 nT	100 µG	100 µOe
1 nT	10 µG	10 µOe

TABLE B-2. BASIC UNITS TABLE

Quantity	Name	Symbol
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z