FINAL REPORT

Man-Portable Simultaneous Magnetometer and EM System (MSEMS)

ESTCP Project MM-0414

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14. ABSTRACT

EM61 pulsed induction sensors and total field magnetometers are the two primary sensors employed for MEC detection on formerly used military properties. While these two sensors have a broadly overlapping performance envelope, each sensor has unique strengths. Unfortunately, co-deployment of the two sensors is normally impossible due to the active nature of pulsed EM which creates noise on any nearby magnetometer. A prior ESTCP project developed the technology needed to co-deploy these two sensors through the process of interleaving (sampling the magnetometer between the EM61's pulses when the EM61 is quiet), and deployed that technology on a vehicular platform. Under this project, a Man-Portable Simultaneous EMI and Magnetometer System (MSEMS) was developed. The interleaving hardware was made smaller and lighter to enable man-portable deployment. A box with standard interfaces was developed that allows any geophysical contractor with EM61s, total field magnetometers, and GPS equipment in inventory to connect them to the interleaving hardware and concurrently collect magnetometer and EM61 data.

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List of Acronyms

APG:	Aberdeen Proving Grounds, Maryland
BRAC:	Base Realignment and Closure
CEHNC:	US Army Corps of Engineers Engineering and Support Center, Huntsville
COTS:	Commercial Off The Shelf
CRADA:	Cooperative Research and Development Agreement
CSM:	Conceptual Site Model
DGM:	Digital Geophysical Mapping
DSB:	Defense Science Board
EM:	Electromagnetic
EMI:	Electromagnetic Induction
EQT:	US Army Environmental Quality Technology Program
FUDS:	Formerly Used Defense Sites
GPS:	Global Positioning System
HTRW:	Hazardous Toxic Radiological Waste
JPG:	Jefferson Proving Grounds, Indiana
MEC:	Munitions and Explosives of Concern
MPC:	Magnetometer Period Counter
MTADS:	Multi-sensor Towed Array Detection System
mV:	Millivolts
NAVEODTECHCEN:	Naval Explosive Ordnance Technology Center
NRL:	Naval Research Lab
nT:	Nanotesla
SNR:	Signal-to-Noise Ratio
STOLS:	Surface Towed Ordnance Location System
UTC:	Universal Time Coordinate
UXO:	Unexploded Ordnance
VSEMS:	Vehicular Simultaneous EMI and Magnetometer System
VSP:	Visual Sample Plan
YPG:	Yuma Proving Grounds, Arizona

Acknowledgements

The authors wish to acknowledge the ESTCP Program Office for funding this project, and Jeffrey Warren from SAIC and Rick MacNeil from USA Environmental for fielding the equipment.

Executive Summary

Pulsed induction sensors (particularly the Geonics EM61 Mk2) and total field magnetometers are the two primary sensors employed for detection of munitions and explosives of concern (MEC) on formerly used military properties. While these two sensors have a broadly overlapping performance envelope, each sensor has unique strengths. The EM61 is the better sensor for detection of small and/or non-ferrous projectiles, while the magnetometer excels at detection of large deep objects. Unfortunately, co-deployment of the two sensors is normally impossible due to the active nature of pulsed EM which creates noise on any nearby magnetometer. A prior ESTCP project (MM-0208) developed the technology needed to co-deploy these two sensors through the process of interleaving (sampling the magnetometer only between the EM61's pulses when the EM61 is quiet), and deployed that technology on a vehicular platform. Under this project, a Man-Portable Simultaneous EMI and Magnetometer System (MSEMS) was developed. The interleaving hardware was made smaller and lighter to enable man-portable deployment. A box with standard interfaces was developed that allows any geophysical contractor with EM61s, total field magnetometers, and GPS equipment in inventory to connect them to our interleaving hardware and collect high-quality concurrent mag/EM61 data. Two physical configurations were developed using this hardware: a configuration with an unmodified EM61 and the magnetometer four feet in front of the EM61 coil; and a configuration using an EM61 whose pulse repetition rate was slowed to allow the magnetometer to acquire interleaved data when placed in the middle of the EM61 coil. Both were evaluated in a demonstration at Yuma Proving Grounds (YPG). The "mag-in-the-middle" configuration proved to have unacceptably low signal to noise, but the version using the unmodified EM61 concurrently collected high-quality EM61 and magnetometer data. This configuration has since been used on several government and commercial MEC and HTRW surveys. A patent has been granted for the method and apparatus of interleaving magnetometer data between EM61 pulses. The box containing the interleaving hardware is the basis for the mag/EM data acquisition hardware in another ESTCP project. There is serious commercial interest from three firms in purchasing an interleaving box.

1 Introduction

Under this project, hardware was developed that allows total field magnetometers and Geonics EM61 sensors – the two sensors most frequently deployed against MEC and accepted by regulators for cleanup of formerly used defense sites in this country – to be deployed together on a man-portable platform.

1.1 Background

The technology demonstration exercises at Jefferson Proving Ground in the mid-1990s yielded the broad conclusion that metal detectors – specifically, total field magnetometers and pulsed induction sensors – were the most effective sensors against a range of MEC. The recent ITRC

Report[1] reiterated that conclusion, calling out the Geonics EM61 Mk2 pulsed induction sensor and the total field magnetometer (manufactured by Geometrics and other companies) as being the two most-deployed and most-effective sensors. Each of these sensors has its own strengths and weaknesses. Total field magnetometers, due to their $1/R^3$ response (where R is the distance between the source and the sensor) and their exquisite sensitivity, are the sensors of choice for detection of deep major caliber air-dropped munitions such as 250 lb bombs, provided that the site geology does not contain iron-bearing soils. However, the responsiveness that allows magnetometers to detect object to great depths also makes them susceptible to fields from cultural objects such as buildings and cars. Pulsed induction sensors are less responsive as a function of depth than magnetometers (the $1/R^3$ response comes into play for the outgoing pulse as well as the detected field, resulting in a depth response of $1/R^6$), but because they detect all metals, they outperform magnetometers for the detection of small objects such as 20 and 40mm projectiles that have little or no ferrous content. In addition, because the field generated by a transmit coil is greatest directly beneath the coil, a pulsed induction sensor is less sensitive to anthropogenic clutter such as buildings and cars than a magnetometer. Ideally the two sensors should be deployed together, but the pulsed induction sensor is an active sensor whose electronics ramp up a current and then abruptly switches it off to generate the transmit pulse. This is a textbook example of a rapidly-changing electric field that, according to Maxwell's equations, generates a magnetic field. For this reason, EM61s can not be deployed within approximately 30 feet of a nearby magnetometer. Attempting to co-deploy them on a common platform results in ruinous levels of noise in the magnetometer data. Thus, use of both sensors at a site necessitates two separate surveys, with its consequent cost.

Under a prior project (MM-0208), ESTCP funded CEHNC and GEO-CENTERS (now SAIC) to develop electronics to concurrently acquire EM61 and total field magnetometer data through the technical approach of interleaving – monitoring the EM61's synchronization signal and only sampling the magnetometers during the short interval when the EM61 and all the secondary fields it generates are quiet. Project MM-0208 was successful, and resulted in the Vehicular Simultaneous EMI and Magnetometer System (VSEMS) – the world's only concurrent mag/EM61 vehicle towed array.

The goal of this project was to take the basic interleaving technology designed and demonstrated under MM-0208 and redesign it to enable man-portable application. This involved:

- Conducting a tradeoff study to determine the closest distance a total field magnetometer can be reliably operated near an unmodified EM61
- Altering the timing parameters of the EM61 to ascertain if a magnetometer can be placed in the middle of the EM61 coil and still collect high-quality data
- Redesigning the boards in the interleaving hardware to make them smaller and lighter
- Building a Man-Portable Interleaving (MPI) box with standard interfaces that allowed use of existing sensors and cables already in inventory, and of a form factor that allowed easy mounting with the other COTS EM61 equipment
- Constructing a system of our own, built around the MPI box, to enable us to demonstrate the new hardware

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[1] SERDP ESTCP ITRC Survey of Munitions Response Technologies, June 2006

1.2 Objectives of the Demonstration

The stated objectives of the demonstration as listed in the YPG Demonstration Plan were:

- To test the new prototype MSEMS hardware, software, and platform in a controlled environment, and demonstrate that the MSEMS can withstand the rigors of real deployment
- To acquire magnetometer-only survey data as a baseline to compare with the concurrent EM and magnetometer survey data
- To acquire EM-only survey data as a baseline to compare with the concurrent EM and magnetometer survey data
- To acquire concurrent magnetometer and EM survey data, from each of two configurations, in order to be able to judge the quality of the data and the efficacy of the system design. The two configurations are:
    - Sensors physically separated by roughly four feet using an unmodified EM61 operating at 75 Hz
    - Sensors spatially co-located with the magnetometer in the middle of the EM61 coil, and the EM61 slowed down to 15 Hz

The system was demonstrated at YPG the week of 6/12/2006. All of the above objectives were met. The results of the demonstration were:

- The system functioned well, with only minor cabling and software glitches to be expected of prototype hardware deployment.
- The 75 Hz mag-in-front configuration collected high-quality concurrent magnetometer and EM61 data, with no discernible difference between single-sensor data and concurrently acquired data.
- The 75 Hz mag-in-front configuration, with its “cart” design and 3rd wheel, proved to be quite usable (the deployment produced a list of desired incremental improvements, all of which have since been made).
- The magnetometer can be left vertical when using the 75 Hz mag-in-front configuration, simplifying deployment logistics.
- The 15 Hz mag-in-the-middle configuration functioned as designed, collecting high-quality magnetometer data when the magnetometer was properly oriented for each survey line.
- There was no discernible difference between single-sensor magnetometer data and concurrently acquired magnetometer data.
- However, the factor-of-five loss in EM61 signal when operating at 15 Hz as compared to 75 Hz is very real, particularly over small weak objects, making the “mag-in-the-middle” configuration of questionable use for real-world DGM over anything except very strong objects.

Since the YPG demonstration, we have ceased work on the mag-in-the-middle configuration. The system with the magnetometer in its front-mounted configuration has undergone substantial incremental improvements, has been deployed on several government and commercial surveys, and is the basis for a new Simplified Combined EMI and Magnetometer Prototype (SCEMP) being funded by the US Army Laboratory at Fort Belvoir MD for out-of-country (southeast Asia)

MEC detection. As of this writing, we have several companies interested in purchasing the MPI box.

1.3 Regulatory Drivers

The primary driver is the continued need to develop tools to detect MEC. MSEMS will extend the benefits of VSEMS to sites that are not vehicularly navigable, and small sites that do not warrant the high deployment costs of a towed array.

2 Technology

2.1 Technology Description

2.1.1 Overview

MSEMS is a man-portable evolution of the interleaving electronics in VSEMS, which was a concurrent mag/EM61 system funded under ESTCP Project MM-0208. VSEMS' interleaving electronics were too big, bulky, and power-hungry for a man-portable application, and had interface requirements that were specific to the vehicular configuration. These electronics were redesigned for MSEMS. The primary goals for the MSEMS project were:

- To design and build hardware that would enable the use of a COTS Geonics EM61 Mk2 and a COTS Geometrics total field magnetometer for concurrent operation in a man-portable configuration
- To build a Man-Portable Interleaving (MPI) box with standard interfaces that allows use of existing sensors and cables already in inventory, and of a form factor that allows easy integration with the other COTS EM61 equipment
- To build a system using this new hardware in order to perform the required ESTCP demonstrations

The resulting system mounts on a COTS EM61 system with its native backpack, coil, and wheels, concurrently collects magnetometer and EM61 data, and is operable by a single person.

2.1.2 Theory of Operation

Historically, simultaneous deployment of magnetometers and the EM61 on a common platform has not been possible due to the fact that the EM transmission pulse is asynchronous with the magnetometer sampling, and thus is picked up by the magnetometers as noise. Even at 10 feet – a practical separation distance for sensor co-location on a common towed platform – EM61-induced noise is over 100 nanotesla, rendering concurrently-collected magnetometer data useless.

Under project MM-0208, GEO-CENTERS (now part of SAIC) developed interleaving hardware that monitors the so-called PSYNC signal on the EM61's sync connector. The PSYNC signal is a square wave that Geonics presents on pin 5 of their sync connector to allow EM61 units to be configured in an array using a master/slave configuration. The interleaving hardware uses the PSYNC signal to time the interleaving of magnetometer data between EM61 pulses. It waits a preset amount of time for the pulse and the secondary fields generated by the pulse to ring down, then samples the magnetometer for a short window. The Magnetometer Period Counter (MPC) board is designed to interleave the magnetometer and EM61 data acquisition cycles as follows. The MPC circuitry looks for the 1 Pulse Per Second (PPS) from the GPS, then looks for the rising edge of the next PSYNC signal indicating pulse output. The system timing then uses a programmable waiting period and a sampling period. The 75 Hz PSYNC signal comes in every 13.3 ms. The board waits 8 ms, at which point the EM61 transmission pulse has died off (this has been verified by direct measurement). The MPC board then samples the magnetometers for 5 ms, during the period in which the EM61s are not transmitting. In this way, the magnetometers are only sampled when the EM61s are quiet. The timing diagram for this interleaved synchronous data acquisition is shown in the figure 1 below. The red square wave is the EM61's 75 Hz

PSYNC signal on pin 5 of the sync connector. The rising edge of PSYNC is coincident with the EM61's transmitter current being shut off, which initiates the transmit pulse. The green plot is the Larmor from the magnetometer. In the figure, we see that the shut-off of the transmitter adversely affects the Larmor signal. The 8 ms waiting period and 5 ms sampling period are labeled in blue on the figure.

However, on VSEMS, the magnetometers are 8.5 feet from the EM61 array. This is too far for effective configuration on a man-portable platform. In developing a man-portable version of the interleaving technology for this project (MM-0414), a trade-off study was first conducted to determine how close the magnetometer could be placed with respect to the EM61 coil and still collect high-quality data. The goal was to put the magnetometer as close as possible to the EM61 coil to maximize the benefits of sensor co-location and minimize the complications in positioning that may result from having sensors cantilevered out in front of the GPS antenna. It was determined that, using an unmodified EM61 pulsing at 75 Hz with a 25% duty cycle (manifested in a 3.3 ms wide PSYNC signal), the magnetometer could be placed somewhere in the 3 to 4 foot range from the edge of the EM61 coil and still collect viable data. In order to put the "mag in the middle," it was determined in the tradeoff study that the EM61 needed to be slowed from a 75 Hz pulse rate to a 15 Hz pulse rate while maintaining a 3.3 ms PSYNC width (in other words, with the duty cycle reduced from 25% to 5%). This is accomplished using an EPROM chip supplied by Geonics. Changing the chip is a simple five-minute operation that requires opening the EM61 box.

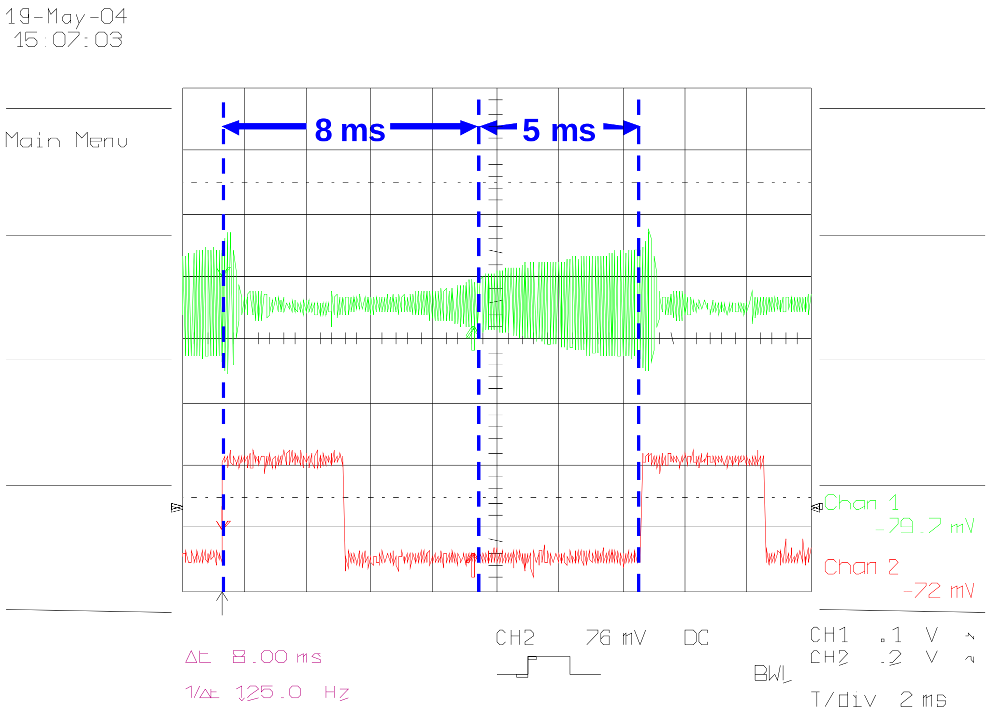

Figure 1: Timing Diagram of Synchronous EM61 and Magnetometer Data Acquisition for the 75 Hz mag-in-front configuration. Red square wave is EM61 PSYNC. Green waveform is magnetometer Larmor signal.

2.1.3 Key Design Criteria

The key design criteria are the timing considerations manifested in the interleaving electronics (and related software) that sample the magnetometers after the secondary field induced by the EM61 pulse has rung down. We have applied for and received a patent for this. The total system design that hosts both the magnetometer and the EM61 in a low-noise environment is another key design factor. For mag-in-the-middle operation, slowing the EM61 down from 75 Hz to 15 Hz while maintaining a 3.3 ms PSYNC width (changing the duty cycle from 25% to 5%) is a key design factor. We designed the physical components of MSEMS to allow both of these configurations – a more conservative configuration with the magnetometer 4’ in front of the EM61 coil, and a more aggressive configuration with the magnetometer in the middle of the EM61 coil. The design of the MPI box to easily mount on the COTS EM61 equipment and to employ standard interfaces is a key design factor as far as real-world usability and eventual operator acceptance.

2.1.4 Schematics, Figures, and Layout

As deployed at YPG, the MSEMS system consists of six basic subsystems:

- **A COTS Geonics EM61 Mk2 backpack system** with EM61 Mk2 electronics box, backpack, battery, cables, coil, wheels, handle, and Allegro hardened PDA and its mount
- **A COTS Geometrics 822A** cesium vapor total field magnetometer with sensor bottle, sensor head, cable, and battery pack
- **A COTS GPS** (on loan from SAIC – not strictly part of the project)
- **The Man-Portable Interface (MPI) box** and related cabling
- **The magnetometer mount** (mag-in-the-middle and mag-in-front versions)
- **The custom MSEMS data acquisition software** that runs on the Allegro

The timing diagram for synchronous data acquisition is shown above. The layout, showing the major subsystems, is shown in the following figures. The same basic interleaving design was employed as was used for VSEMS in project MM-0208, but the interleaving electronics and the related data acquisition system were all redesigned and made smaller, lighter, and less power hungry. The resulting Man-Portable Interface (MPI) utilizes the same enclosure Geonics uses for their EM61 electronics. This design allows the MPI box to mount on the backpack, on top of the EM61 box, using the same set of through holes. The MPI box can accept up to two magnetometers and up to two EM61s, but it is configured for use in MSEMS with a single magnetometer and a single EM61. The MPI box weighs about 2 lbs.

Figure 2 below shows the backpack fully populated with EM61 battery, the GPS, and all related cabling. The GPS shown is not technically part of MSEMS – it is a GPS of opportunity, SAIC’s Trimble 5700 with integral batteries and radio, supplied to the project at no cost under the CRADA SAIC has with CEHNC. It is mounted to the backpack, on top of the EM61 battery, by a Velcro strap, and using a right-angle bracket so it doesn’t slide off the battery. This allows the GPS to be quickly removed so the EM61 battery can be changed. Ideally, an all-in-one GPS receiver such as the Trimble 5800 where the antenna, receiver, and radio are all part of a single unit would be used. Note that subsequent incremental improvements to MSEMS include the use of a Geonics EM61 Mk2A, where the backpack is completely eliminated and both the Geonics electronics and the MPI box are mounted on the handle. We will discuss this configuration –

which was not directly funded by this project – near the end of this report. But the fact that the MPI box can be used in either a Mk2 (backpack) or Mk2A (no backpack) configuration, as well as in vehicular and marine applications, attests to the flexibility of the design.

Figure 2: COTS EM61 backpack with standard COTS EM61 electronics (left), and with additional MPI box mounted on top of EM61 box using through-holes (right)

Figure 3: Close-ups of EM61 backpack with EM61 electronics box, EM61 battery, MPI box, and GPS. The GPS is strapped to the backpack with a velcro strap, and has a right-angle bracket so it won't slide off the battery.

A COTS Geometrics battery belt pack powered the magnetometer and the MPI box. The battery belt pack was worn around the waist. Field testing revealed this to be a lot of weight on the operator, and uncomfortable due to close proximity to the EM61 backpack's waist strap, so in later deployments a small Pelican road case was procured to hold the magnetometer batteries and was mounted on the boom. This had the additional benefit of providing a better distribution of weight (indeed, in the photo at YPG below, the gray bulge behind the magnetometer is a gallon jug of water used as ballast). The EM61 battery on the backpack powers its native EM61 hardware. The GPS is powered by its own internal batteries.

The figure below shows MSEMS at YPG, with the operator wearing the backpack and magnetometer battery belt pack, and pushing the EM61 platform with the magnetometer mounted on a boom 4' in front of the EM61 coil, and hosted at a constant height above ground by a 3rd EM61 wheel.

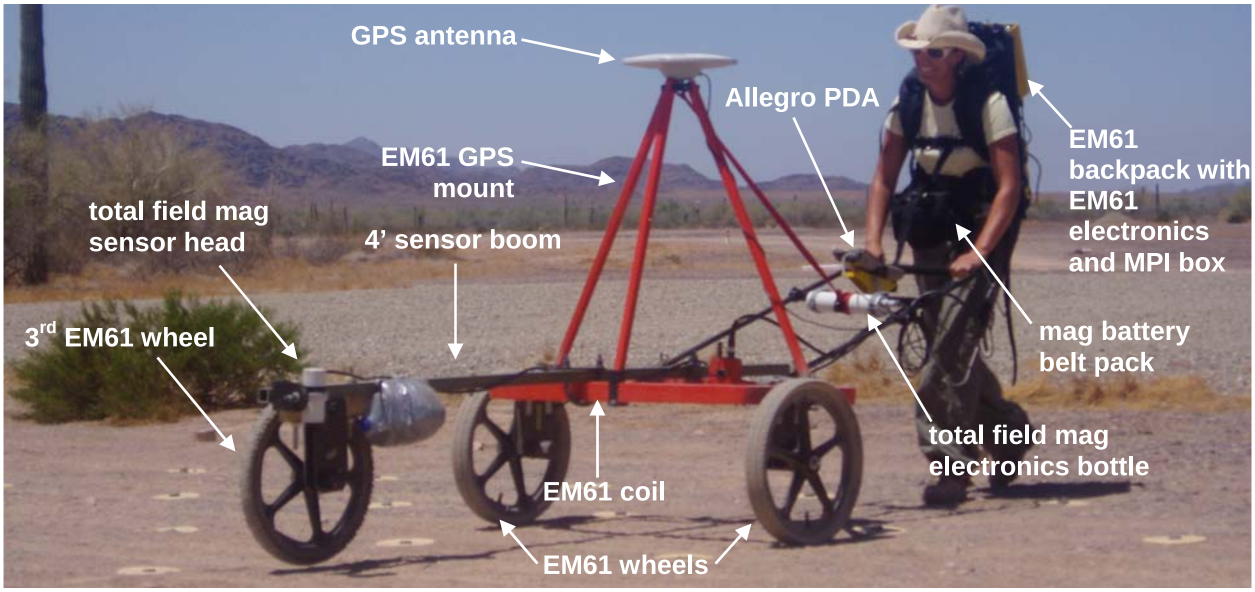

Figure 4: MSEMS at YPG configured with the magnetometer 4' in front of the EM61 coil.

The figure below shows the system in its more aggressive mag-in-the-middle configuration.

Figure 5: MSEMS at YPG configured in mag-in-the-middle configuration

The Allegro is an environmentally hardened PDA that comes as part of the full-up EM61 Mk2 system. We are using it to host our custom data acquisition software. Rather than having the EM61 connected to the Allegro, however, the EM61, magnetometer, and GPS are all connected to our MPI box, and the MPI box is connected to the Allegro. This allows the Allegro, running our own custom software, to collect all geophysical data.

The magnetometer is held in a custom pivoting mount. This mount enables the magnetometer to be optimally oriented with respect to the Earth's magnetic field, then easily swung around to face the other way at the start of the next survey line (in practice, this has not been necessary). The mount is hosted by the EM61 coil and wheels, mounted either in the middle of the coil or four feet in front of the coil. A close-up of the magnetometer in its pivoting mount is shown in the figure below.

Figure 6: Magnetometer in its pivoting mount.

2.2 Technology Development

The interleaving technology itself, as present in VSEMS, has been tested in over a thousand acres of government and commercial MEC and HTRW survey activity since 2002. MSEMS employs the same technology, only in a smaller package, and with a single EM61 and magnetometer.

Data from a tethered mockup constructed for the tradeoff study showed that the magnetometer could be operated three to four feet in front of the coil, or in the middle of the coil if the EM61 were slowed down from 75 Hz to 15 Hz. These data were presented in detail to ESTCP at the 10/6/2004 IPR. Data acquired with an un-tethered mockup over a 25-foot plot were presented at the 5/4/2005 IPR. On the basis of these data, the basic design for MSEMS, and for the MPI box, was codified. The MPI box was built, tested and debugged. Although the design of the basic interleaving circuitry from the VSEMS electronics was heavily leveraged, MSEMS' testing and integration took longer than anticipated due to changes necessary to support new software tools needed to program the Field Programmable Gate Array (FPGA) chip used to control the timing.

Prior to mobilizing to YPG, the MPI box for MSEMS had been fully operational for several weeks. During that time, we collected data in the parking lot at SAIC that verified the gross functionality of the system. This is a very high-noise environment, and experience has shown that it is sufficient to verify gross functionally but not fine gradations of performance. We acquired two short passes of MSEMS over a surface-emplaced inert 60mm object. We did this for both the 75 Hz "mag in front" configuration and the 15 Hz "mag-in-the-middle" configuration. These data are presented below.

Figure 7 below shows 75 Hz EM61 Mk2 data. The peak response values from the four time gates are plainly visible, showing that the EM61 was functioning nominally.

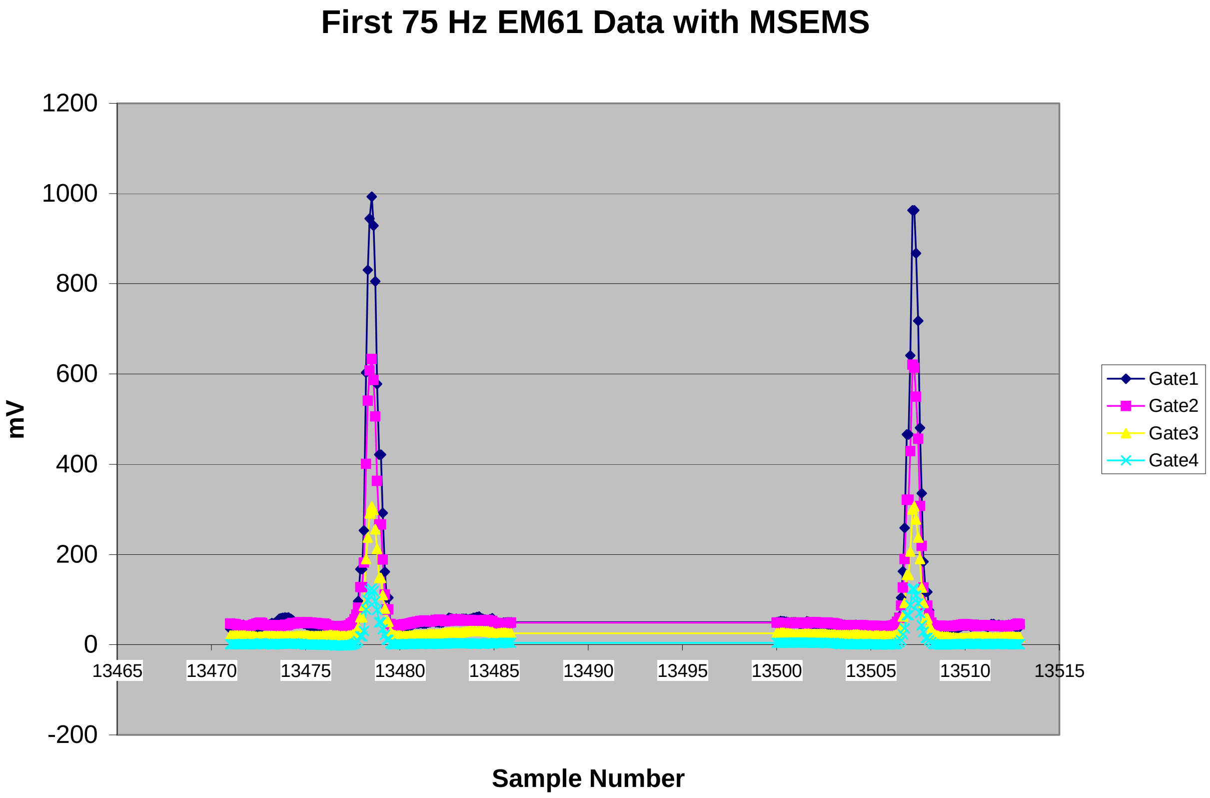

Figure 7: MSEMS EM61 Mk2 data acquired at 75 Hz with the magnetometer 4' in front, showing two passes over a 60mm shell in the parking lot. The peak responses from the four time-gates are plainly visible.

Figure 8 below shows the concurrently-collected magnetometer data. The peak responses over the object are visible, though obscured by some other gross subsurface feature in the parking lot, possibly a water main. Figure 9 shows a blowup of the peak. High-frequency ringing is clearly visible in the data. This is completely expected. Our magnetometer period counter, when driven at 75 Hz, aliases the ambient electrical hum (and there is a lot of hum in the parking lot) flawlessly at 15 Hz, which is what is seen in the figure. We see this in VSEMS data, and we chop it out with a notch filter. These figures show that MSEMS' interleaving magnetometer period counter was functioning as expected.

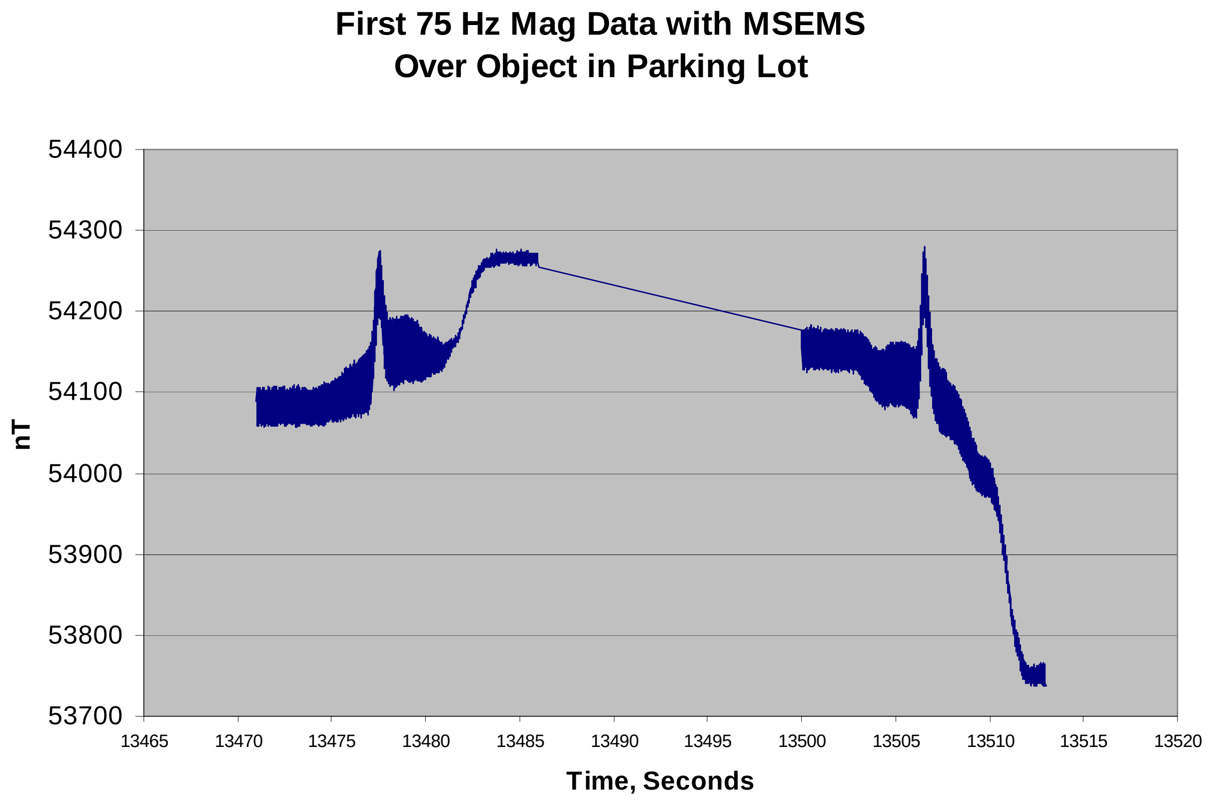

Figure 8: MSEMS magnetometer data showing two passes over a 60mm shell in the parking lot. The peak response over the object is visible though somewhat obscured by a large background signal.

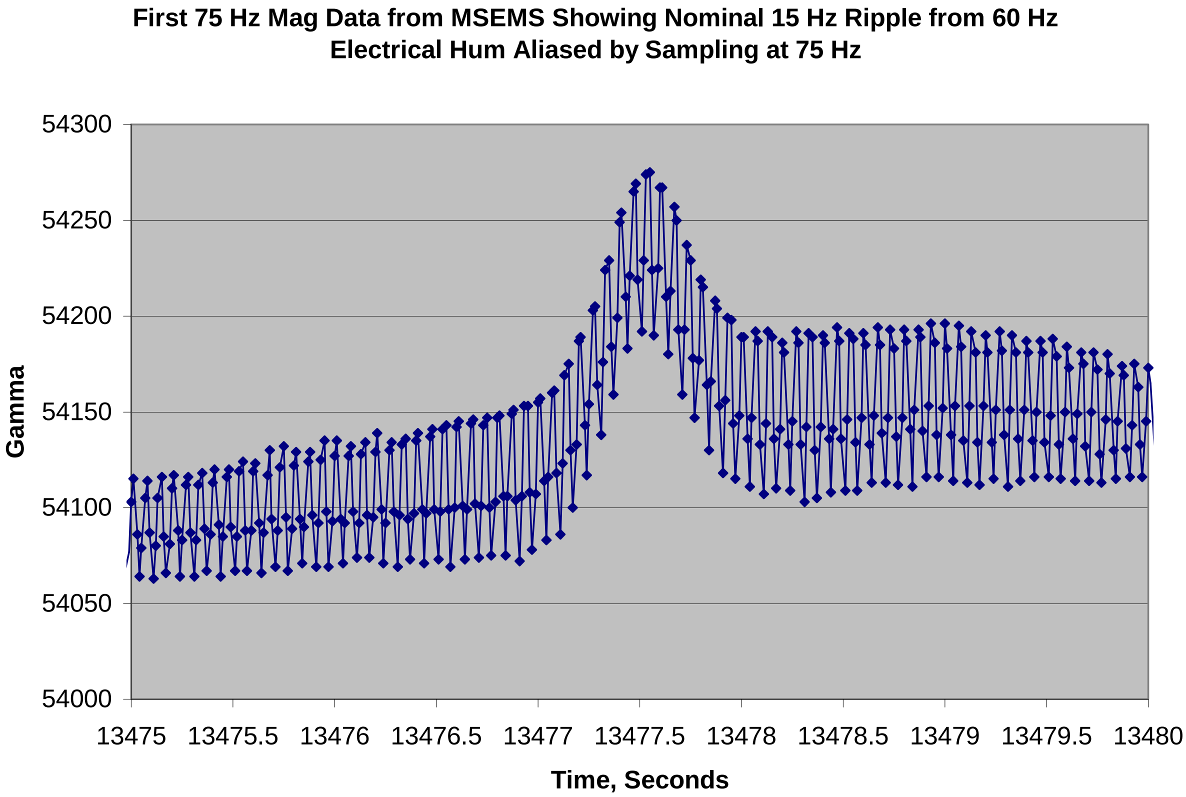

Figure 9: Blowup of first peak of magnetometer data. The high frequency ringing is 60 Hz electrical hum subsampled at 75 Hz and aliasing at 15 Hz. This is expected, and is removed with a notch filter.

The magnetometer mount was then changed to deploy the magnetometer in the middle of the EM61 coil, and the EPROM in the EM61 was changed to trigger the unit at 15 Hz instead of 75 Hz. Two passes were taken over the same 60mm object (which was moved, so the background is not the same). The data in figure 10 below show the clearly identifiable peak responses from the four time gates over the object, indicating that when pulsing at 15 Hz, the EM61 is functioning nominally. Note also that the peak signal in the 15 Hz EM61 data is approximately 1/5 what the peak signal is in the 75 Hz EM61 data. For this surface-emplaced object, there is still plenty of signal. However, the loss of signal over weaker objects turns out to be crucially important, as we shall see below when we interpret the YPG data.

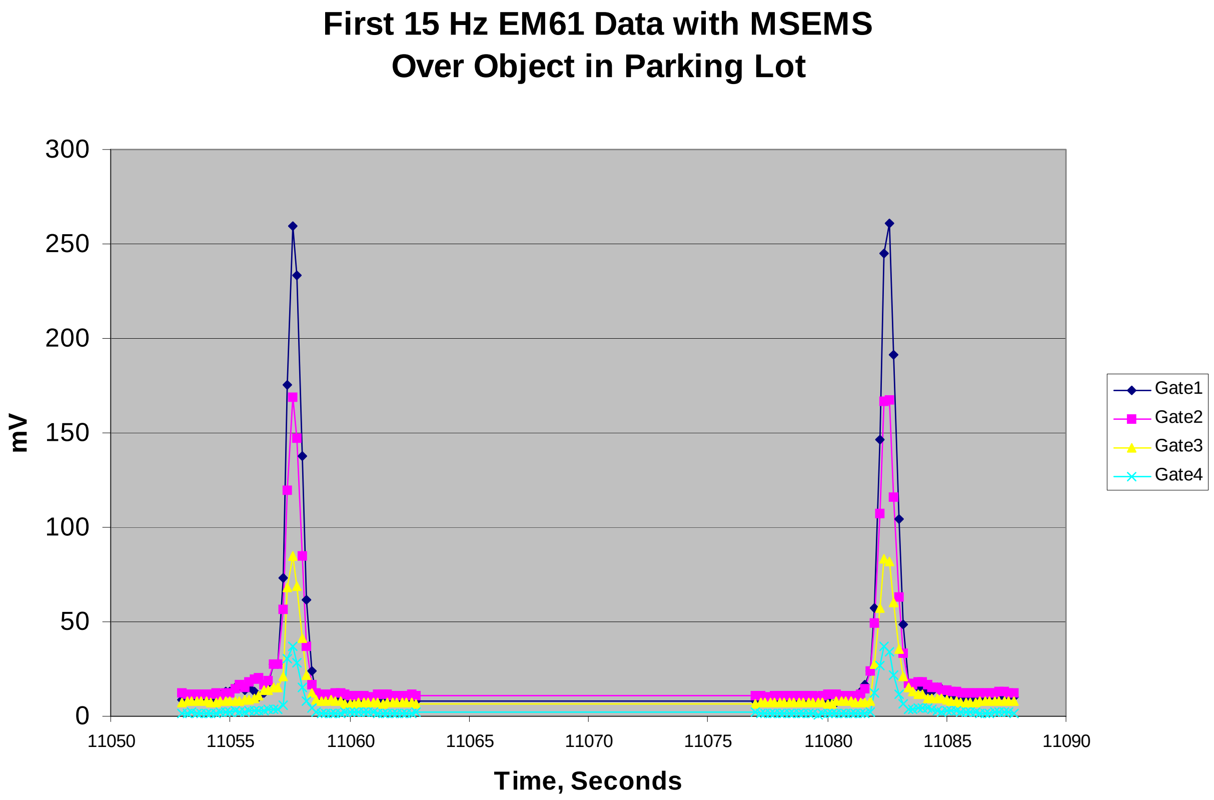

Figure 10: MSEMS EM61 Mk2 data acquired at 15 Hz with the magnetometer in the middle of the coil, showing two passes over a 60mm shell in the parking lot. The peak responses from the four time-gates are plainly visible.

Figure 11 below shows magnetometer data acquired in the mag-in-the-middle configuration. Note that, because it is triggered by the EM61, when the EM61 is pulsing at 15 Hz (not 75 Hz), the magnetometer is sampling at 15 Hz (not 75 Hz), and thus there are fewer points on the profile as compared to the data acquired at 75 Hz. The peak responses in each pass over the 60mm object are plainly visible. This verified the gross functionality of the system when the magnetometer was in the middle and the EM61 is pulsing at 15 Hz.

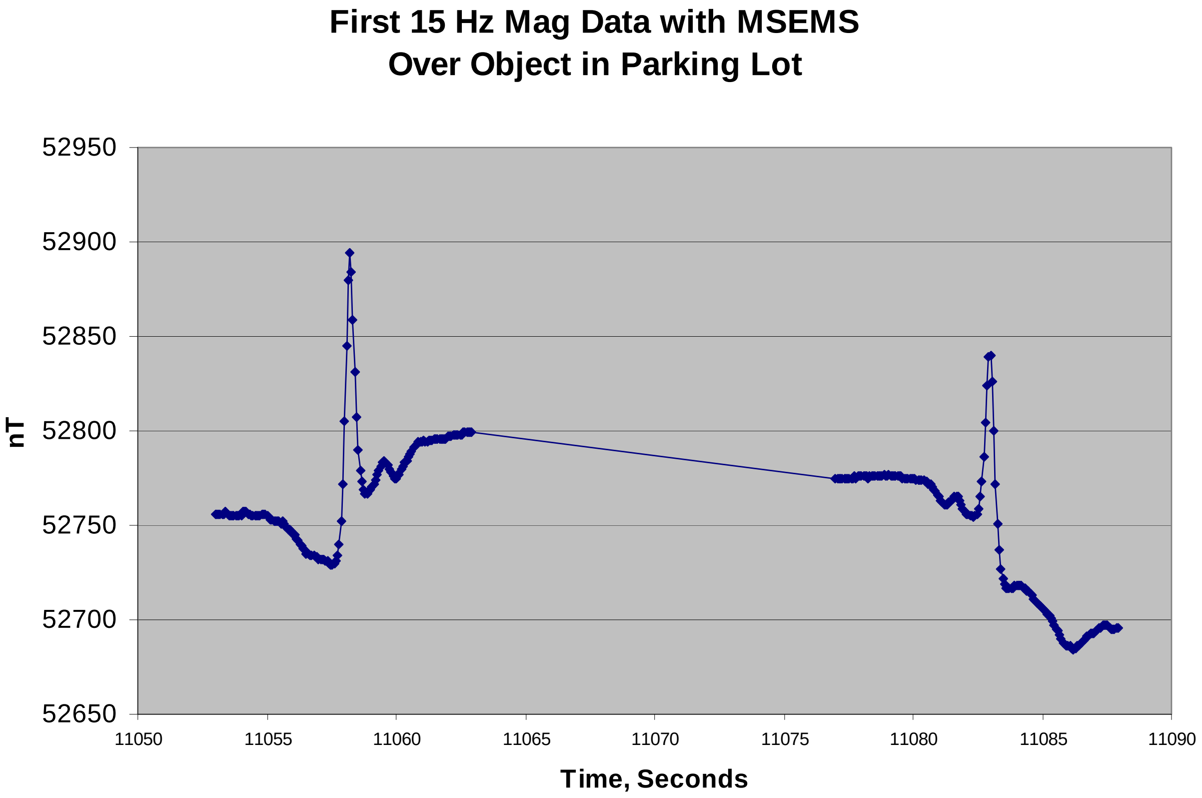

Figure 11: MSEMS magnetometer data acquired at 15 Hz with the magnetometer in the middle of the coil, showing two passes over a 60mm shell in the parking lot. The peaks are plainly visible.

2.3 Advantages and Limitations of the Technology

The complimentary nature of the weaknesses of the sensors described above is one of the very things driving their concurrent use in MSEMS. The overriding advantage of the technology is the ability to *concurrently* collect both magnetometer and EM61 data in a single survey pass and thus compensate for each other's shortcomings. Separate man-portable magnetometer and EM61 surveys can be contracted through many geophysical houses, but MSEMS is unique in its ability to concurrently collect data from these two industry-standard sensors in a man-portable configuration. Our experience with VSEMS has been that, on site after site, project managers are surprised by the MEC population and geology, and the use of both sensors puts them in the best position to deal with the unexpected. Further, the data from MSEMS, because they are acquired on a common rigid sensor platform, are spatially co-registered, whereas data acquired in separate survey passes may not traverse the same objects in the same way, which may limit the efficacy of the data for discrimination algorithms.

There are several other competing technologies for concurrent magnetometry and EM, but as of this date, none of them use a commercial-off-the-shelf industry-standard EM61.

The main limitation of the core interleaving technology is that it applies only to pulsed induction EM systems; it is not applicable to frequency-domain EM systems. For the magnetometer, the technology is currently limited to cesium vapor magnetometers outputting a Larmor signal. It cannot, as presently configured, be used with less expensive fluxgate magnetometers. This is because the interleaving hardware is expecting a Larmor signal as input; it performs period counting of the Larmor signal between EM61 pulses to convert the frequency-based Larmor signal into nanotesla. A fluxgate magnetometer does not employ the resonance mechanism of an alkali vapor magnetometer and as such does not output a frequency-based Larmor signal.

A minor limitation is the way that heading is currently handled. On a COTS EM61, the GPS antenna is configured on a tripod directly over the sensor. Thus, an EM61 can be turned around quickly at the end of a survey line and positioned for the next line without engendering any heading error because there is no moment arm in the geodetic calculation separating the sensor from the GPS antenna. Because MSEMS utilizes two sensors, however, the GPS antenna can't be over both sensors. If the GPS antenna is configured over the EM61 coil (as it was at YPG), then it is over four feet from the magnetometer sensor head. Heading is calculated in post-processing by using adjacent GPS updates and by making assumptions about smooth motion (requiring that the sensor head align itself along the GPS track). This works fine except when the handle is pushed down, the front wheel is lifted up, and the system is swung around quickly on the back wheels. As such, on survey grids, the system is best operated by pausing data acquisition at the end of each line, and carefully positioning it at the beginning of the next line before restarting data acquisition. This takes less than ten seconds for a trained operator to do, and does not represent a major limitation. In eventual releases of the system we may consider the addition of a compass to directly measure fast-changing heading instead of inferring it from GPS location and smooth operation.

3 Performance Objectives

The stated objectives of the demonstration as listed in the YPG Demonstration Plan were:

- To test the new prototype MSEMS hardware, software, and platform in a controlled environment, and demonstrate that the MSEMS can withstand the rigors of real deployment
- To acquire magnetometer-only survey data as a baseline to compare with the concurrent EM and magnetometer survey data
- To acquire EM-only survey data as a baseline to compare with the concurrent EM and magnetometer survey data
- To acquire concurrent magnetometer and EM survey data, from each of two configurations, in order to be able to judge the quality of the data and the efficacy of the system design. The two configurations are:
  - Sensors physically separated by roughly four feet using an unmodified EM61 operating at 75 Hz
  - Sensors spatially co-located with the magnetometer in the middle of the EM61 coil, and the EM61 slowed down to 15 Hz

These result in the performance objectives in the table below.

Table 1: Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Qualitative	*Reliability and Robustness*	*General Observations*	*Yes*
	System Usability	*General Observations*	*Yes*
Quantitative	*Concurrent Magnetometer Data Quality*	*Signal and Noise Similar to Magnetometer-Only Data*	*Yes*
	Concurrent EM61 Data Quality	*Signal and Noise Similar to EM61-Only Data*	*Yes*
	15 Hz Mag in the Middle Magnetometer Data Quality	*Signal and Noise Similar to 75 Hz Data*	*Yes*
	15 Hz Mag in the Middle EM61 Data Quality	*Signal and Noise Similar to 75 Hz Data*	*No*

The metrics for judging similarity of signal and noise of concurrently-collected data to single-sensor data are a visual comparison of image and waveform data over background and over targets, and measured values for signal and noise, again, over background and over targets.

All of the above objectives were met. The results of the demonstration were:

- The system functioned well, with only minor cabling and software glitches to be expected of prototype hardware deployment.
- The 75 Hz mag-in-front configuration collected high-quality concurrent magnetometer and EM61 data, with no discernible difference between singularly acquired data and concurrently acquired data.
- The 75 Hz mag-in-front configuration, with its “cart” design and 3rd wheel, proved to be quite usable (the deployment produced a list of desired incremental improvements, all of which have since been made).
- The magnetometer can be left vertical when using the 75 Hz mag-in-front configuration, simplifying deployment logistics.
- The 15 Hz mag-in-the-middle configuration functioned as designed, collecting high-quality magnetometer data when the magnetometer was properly oriented for each survey line.
- There was no discernible difference between single-sensor magnetometer data and concurrently acquired magnetometer data.
- However, the factor-of-five loss in EM61 signal when operating at 15 Hz as compared to 75 Hz that was first seen in the parking lot test is very real, making the “mag-in-the-middle” configuration of questionable use for real-world DGM.

4 Site Description

4.1 Site Selection

The demonstration was conducted at the Standardized UXO Demonstration Test Site in Yuma, AZ. This site was selected as the initial test site because of a planned deployment of the vehicular VSEMS to YPG, and the opportunity for MSEMS to be demonstrated at the same time by personnel already on the site.

4.2 Site History

The APG and YPG sites were established in 1999 to provide a standard demonstration area for emerging MEC detection-related technologies. YPG is located adjacent to the Colorado River in the Sonoran Desert. The UXO Standardized Test Site is located south of Pole Line Road and east of the Countermine Testing and Training Range. The open field range, calibration grid, blind test grid, mogul area, and desert extreme area comprise the 350 m by 500 m general test site area. The open field site is the largest of the test sites and measures approximately 200 m by 350 m. To the east of the open field range are the calibration and blind test grids that measure 30 m by 40 m and 40 m by 40 m, respectively. South of the open field is the 135 m by 80 m mogul area consisting of a sequence of man-made depressions. The desert extreme area is located south east of the open field site and has dimensions of 50 m by 100 m.

4.3 Site Geology

Through prior fieldings at YPG, we know that the soil and rocks are somewhat ferrous, causing relatively minor noise on the magnetometers. The geology has been comparatively inert to the EM61s.

4.4 Munitions Contamination

We surveyed the calibration grid and the blind test grid. The calibration test grid contains clutter items, steel spheres, loops of wire, and 20mm, 40mm, M42, BLU-26, BDU-28, 57mm M86, MK 118, 60mm, 81mm, 2.75”, 105mm, and 155mm ordnance items. The blind grid contains the same mix of items. A map of the YPG site is shown in the below.

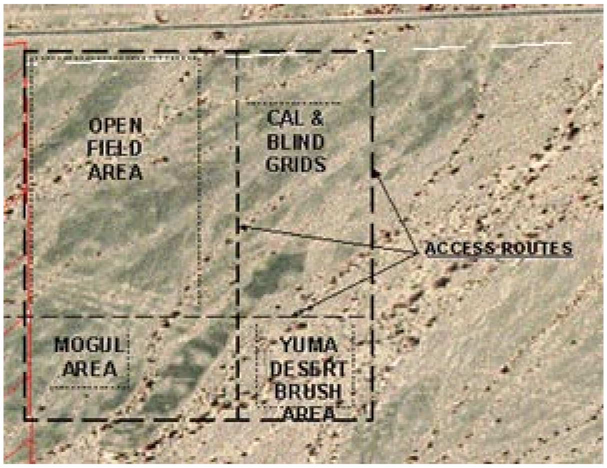

Figure 12: Standardized UXO Demonstration Test Site at Yuma, AZ

5 Test Design

5.1 Conceptual Experimental Design

MSEMS was deployed and tested at YPG to provide general equipment shakedown, to verify that the new version of concurrent mag/EM hardware (previously validated under MM-0208) worked as designed, and to evaluate the performance and deployment tradeoffs of the two physical configurations (75 Hz mag-in-front and 15 Hz mag-in-the-middle).

5.2 Site Preparation

Not applicable.

5.3 System Specification

5.3.1 Operating Parameters for the Technology

As said above, the tradeoff study conducted at the beginning of the project showed that the magnetometer can acquire high-quality interleaved data when it is three to four feet from an EM61 coil running at 75 Hz, and also showed the promise of successfully acquiring interleaved data with the magnetometer in the middle of the EM61 coil if the EM61 pulse repetition rate is slowed down from 75 Hz to 15 Hz. These two configurations are summarized in the table below. It should be remembered that, throughout this document, when we say “75 Hz data,” the magnetometer is always four feet in front of the EM61 coil, and when we say “15 Hz data,” the magnetometer is always in the middle of the EM61 coil.

Table 2: Magnetometer Sampling Parameters for the Two Coil-To-Magnetometer Sensor Spacings

Magnetometer Location	**EM61 Pulse Rate**	**Wait**	**Sample**
4’ outside EM61 coil	75 Hz (unmodified)	8 ms	5 ms
In the middle of EM61 coil	15 Hz (modified with EPROM)	60 ms	5 ms

There is an additional parameter that was varied – whether the magnetometer was optimally oriented with respect to the Earth’s magnetic field or was left vertical. On MTADS and VSEMS, the magnetometers are left vertical, but testing in the Tradeoff Study showed that, due to the strong fields generated in close proximity to the EM61, unless the magnetometer was optimally tilted with respect to the Earth’s magnetic field (as is recommended by the manufacturer), the signal from the magnetometer was not stable, and small variations in angle due to rough terrain could result in out-of-range magnetometer readings. However, this initial result may have been due to our use of an older magnetometer; subsequent testing with the new Geometrics 822A magnetometer purchased for the project showed the readings to be more stable with respect to small changes in magnetometer angle over uneven terrain. Since optimally orienting the magnetometer requires tilting it in different directions at the start of survey lines facing different ways, not having to tilt it would simplify field logistics. As such, the test matrix included acquiring concurrent mag/EM61 data with the magnetometer left vertical, and acquiring concurrent mag/EM61 data with the magnetometer optimally tilted.

5.3.1.1 Magnetometer

MSEMS collects total field magnetometer data, triggered primarily by the 1PPS signal from the GPS, and secondarily by the PSYNC signal from the EM61 Mk2, for a short window after the secondary field has rung down and before the next PSYNC signal indicating the start of a new EM pulse. For an unmodified EM61, PSYNC is a 75 Hz signal, creating a 13.3 ms cycle. We wait for 8 ms and then sample for 5 ms. This sampling window is repeated at 75 Hz. During the Tradeoff Study we varied the waiting time and the sampling time, and found this to be the best trade-off. For mag-in-the-middle operation, the EM61 is run at 15 Hz, creating a 66.6 ms cycle. Here, we wait for 60 ms and then sample for 5 ms. Triggering the magnetometer period counter with the GPS' 1PPS creates magnetometer data that is always correctly synchronized with the GPS data and requires no latency correction. Magnetometer height is 30.4 cm (12") – slightly below the height of the EM61.

5.3.1.2 EM61

MSEMS collects EM61 Mk2 data, clocked by the EM61's internal PSYNC square wave. An unmodified EM61 internally pulses at 75 Hz. We employ this configuration when the magnetometer is 1.22 meters (four feet) in front of the EM61 coil. For mag-in-the-middle operation, the EM61's EPROM was replaced with one from Geonics that runs the system at 15 Hz rather than 75 Hz. Like the 75 Hz EPROM, the 15 Hz EPROM holds the PSYNC square wave high for 3.3 ms.

Note that with the EM61, there is a distinction between the internal pulse repetition rate and the rate at which it spits out the serial data updates. The EM61 will spit out an output to the recording computer when it is sent a triggering byte that is generated by the data acquisition software. We nominally send this triggering byte at 10 Hz. We always believed that the EM61 "stacks" (averages) data between triggers, so at its 75 Hz internal pulse repetition rate, we expected the EM61 to be averaging five times more readings when it generates an output than it is at 15 Hz. We expected to see some effect of the inverse root N dependency when we compared EM61 data taken at the 15 Hz pulse repetition rate to data taken at 75 Hz. However, after the YPG deployment, upon speaking with Geonics, we learned that the "stacking" belief turned out to be fallacious; see the data interpretation section below.

EM61 sensor standoff is unchanged from the COTS configuration of 42 cm. Although the system is capable of using an EM61 upper coil and employing the "D" setting on the electronics, we typically do not deploy the upper coil and instead deploy only the lower coil and employ the "4" setting on the electronics box. This uses time-gates sampled at 256, 406, 706, and 1306 usec, respectively. The EM61 batteries are expected to last 3-4 hours, and thus are expected to be changed once or twice daily.

5.3.1.3 RTK GPS

Purchase of positioning equipment was not part of the MSEMS project; MSEMS was demonstrated at YPG using differential GPS RTK equipment on loan from SAIC under a CRADA with CEHNC. This equipment consists of a Trimble MS750 base station, Trimble TrimMark III base radio, and a Trimble 5700 rover receiver with integral radio and batteries. We recorded GPS data at 1 Hz. Note that while MSEMS will function with any GPS offering a 1PPS output and a standard ASCII position string output, the selection and placement of any GPS equipment must be accompanied by noise and signature testing to see what static, directional, and time-varying effects the equipment has on both the magnetometer and the EM61 data. Trade-offs typically need to be made between placing the antenna near the sensor (which increases both positional accuracy and signature) and high (which decreases both positional accuracy and signature). In keeping with the design philosophy of allowing contractors to use equipment already in inventory, an integrated all-in-one receiver such as the Trimble 5800 would be used instead of a separate receiver/antenna configuration, as this receiver has the electronics, batteries, and antenna all housed in a single unit that can be mounted on the tripod, keeping additional electronics, cabling and weight off the backpack. Commercial contractors frequently deploy these integrated units via a tripod supplied directly by Geonics that holds the unit one meter above the coil. Whether this is a low-noise configuration would need to be verified by direct signature and noise evaluation.

5.4 Calibration Activities

No calibration activities were performed on these COTS sensors.

5.5 Data Collection

5.5.1 Scale

The scale of the test was relatively small, utilizing the 40m x 30m calibration grid and the 40m x 40m blind grid.

5.5.2 Sample Density

The 1 x ½ meter EM61 coil is located with the 1-meter axis cross-track. We ran the traverses down the center of the lanes in the calibration and blind grids, with extra traverses on the lane markers themselves, yielding an 0.5 meter lane spacing. Traverses were run North-South.

The down-track spacing is a function of sampling rate and speed, and is effectively a function of the EM61's output rate, since it is much slower than the magnetometer's output rate. The EM61 outputs at 10 Hz. In order to achieve a nominal down-track data spacing of one EM61 update per 10 cm, the speed needs to be no greater than 1 meter/second, or 2.23 mph. This was the planned speed for the YPG surveys. As we will describe below, we also surveyed at an exaggerated slow speed of approximately 0.3 meters/second, which yields a down-track data spacing of 3 centimeters.

5.5.3 Quality Checks

Data quality checks included a five-minute warm-up period, a transient object response test (placing and then removing a metallic object), and in-field processing by the PI.

5.5.4 Data Summary

For the calibration grid, we acquired concurrent mag/EM data at 75 Hz with the mag remaining vertical, concurrent mag/EM data at 75 Hz optimally tilting the mag at the start of each survey line, and single sensor mag and EM data at 75 Hz. We acquired similar data at 15 Hz, except that the tilt/no-tilt test was not performed because it was already known that, with the magnetometer in the middle of the EM61 coil, it had to be optimally tilted. An extra set of slow-walked data, both mag-alone and concurrent mag/EM, was acquired at 15 Hz. This yielded the following set of data files for the calibration grid:

- 75 Hz mag-in-front, EM only
- 75 Hz mag-in-front, mag only
- 75 Hz mag-in-front, concurrent mag/EM, magnetometer vertical
- 75 Hz mag-in-front, concurrent mag/EM, magnetometer tilted

- 15 Hz mag-in-the-middle, EM only
- 15 Hz mag-in-the-middle, mag only
- 15 Hz mag-in-the-middle, concurrent mag/EM, magnetometer tilted
- 15 Hz mag-in-the-middle, EM only, slow-walked
- 15 Hz mag-in-the-middle, concurrent mag/EM, magnetometer tilted, slow-walked

The blind grid matrix was similar to the calibration grid matrix, except that, on the basis of the calibration grid data, we left the mag vertical for the 75 Hz test. This resulted in the following set of files for the blind grid:

- 75 Hz mag-in-front, EM only
- 75 Hz mag-in-front, mag only
- 75 Hz mag-in-front, concurrent mag/EM, magnetometer vertical

- 15 Hz mag-in-the-middle, EM only
- 15 Hz mag-in-the-middle, mag only
- 15 Hz mag-in-the-middle, concurrent mag/EM, magnetometer tilted
- 15 Hz mag-in-the-middle, EM only, slow-walked
- 15 Hz mag-in-the-middle, concurrent mag/EM, magnetometer tilted, slow-walked

These data reside at SAIC in Newton, MA, on the server, in an ASCII comma-delimited format (easting, northing, sensor_number, line_number, time, value (value2, value3, value4)) format. Magnetometer data has a single value in nanotesla. EM61 data has the four time-gate values in mV.

5.6 Validation

No digging was performed on this project.

6 Data Analysis and Products

Data processing was geared toward producing geodetically-registered data files that could be read into Geosoft Oasis Montaj and gridded.

6.1 Preprocessing

The data were:

- Navigation-corrected using our own Linux-based software to remove spurious jumps that occur when the GPS fix quality does not have a value of 3 (which indicates a cm-level RTK fix). The heading of the cart is calculated at the same time.
- Geolocated using the time of each sensor's update, the time of the closest pair of GPS updates, the heading of the cart, and the GPS antenna-to-sensor offset.

Magnetometer data were:

- Median-filtered (de-spiked) to remove spurious values
- Notch-filtered to remove 60 Hz-induced noise subsampled with the 75 Hz sampling rate
- Reference-corrected to remove diurnal drift

And EM61 data were:

- Lag-corrected using an empirically-determined time shift to align parts of anomalies acquired in separate directions
- Background-leveled using a median filter to dynamically determine background before subtracting it off

6.2 Target Selection for Detection

Target selection for detection was not performed. As per previously submitted YPG Report, analysis centered on signal and noise comparisons between concurrent-operating and separately-operating configurations, and between 75 Hz and 15 Hz configurations.

6.3 Parameter Estimates

Not applicable.

6.4 Classifier and Training

Not applicable.

6.5 Data Products

ASCII comma-delimited files as described in section 5.5.4 were produced. These files were imported into Geosoft Oasis Montaj, and gridded data and maps were produced.

7 Performance Assessment

7.1 Performance Criteria

Performance criteria are listed the table below.

Table 3: Performance Criteria

Performance Criteria	Description	Primary or Secondary
Concurrent Magnetometer Data Quality (75 Hz)	Signal and noise in magnetometer data compared to standalone mag data	Primary
Concurrent EM61 Data Quality (75 Hz)	Signal and noise in EM61 data compared to standalone EM61 data	Primary
15 Hz Mag-in-the-Middle Magnetometer Data Quality	Signal and noise similar to 75 Hz mag data	Primary
15 Hz Mag-in-the-Middle EM61 Data Quality	Signal and noise similar to 75 Hz mag data	Primary
Reliability and Robustness	Downtime due to system problems	Secondary
System Usability	General ease of use of MSEMS including custom hardware and data acquisition software	Secondary

7.2 Performance Confirmation Methods

Concurrent mag/EM61 data were acquired at the nominal 75 Hz rate (that is, with the EM61 internal pulse repetition rate unchanged from its COTS 75 Hz setting and the magnetometer four feet in front of the EM61 coil). These data were examined in Geosoft Oasis Montaj to determine signal and noise levels. This examination occurred both heuristically (visually examining the image and waveform data) as well as analytically (building tables of noise and signal over background and targets). These noise and signal levels were compared to those with MSEMS data acquired with the sensors operating individually (that is, data that has no possibility of noise from sensor interference). On the calibration grid, noise levels were benchmarked using a static section of data at the start of the first line. Several representative objects were selected to compare signals. The EM61's EPROM was then replaced with an EPROM that allowed the system to run at 15 Hz instead of at 75 Hz, the magnetometer was moved to the center of the EM61 coil, and additional EM61 and magnetometer data were acquired. These data were compared to the 75 Hz data in a similar way, except that the noise confirmation method had to be changed from a static measurement to a dynamic measurement over areas in the grid where there were no emplaced objects.

The conclusions, summarized in the table below, are that:

- With the magnetometer four feet in front of the EM coil, concurrent magnetometer / EM data were very similar to the single-sensor magnetometer and EM data for that configuration, validating (as was validated with VSEMS) that there is no apparent loss in magnetometer or EM61 data quality from concurrent sensor operation.

- However, when changing to the mag-in-the-middle configuration and reducing the EM's pulse repetition rate from 75 Hz to 15 Hz, the EM61 data suffers a substantial decrease in signal as well as a substantial increase in noise that effectively rules this configuration out for production geophysics.

Note that the "signal within 15%" metric has nothing to do with concurrent mag/EM and is simply a reasonable expectation of repeatability.

Table 4: Detailed Performance Criteria

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Method	Actual (post demo)
PRIMARY CRITERIA (Performance Objectives)			
Concurrent Magnetometer Data Quality (75 Hz)	Noise within 1 nT of standalone mag data Signal within 15%	Compare idle noise at the start of survey line in concurrent magnetometer data to that in standalone mag data. Compare signal over selected objects.	Noise difference very small (within 0.2 nT) Signal difference < 11%
Concurrent EM61 Data Quality (75 Hz)	Noise within 1 mV of standalone EM61 data Signal within 15%	Same as above	Noise difference very small (within 0.1 mV) Signal difference < 11%
15 Hz Mag-in-the-Middle Magnetometer Data Quality	Noise within 1 nT of 75 Hz mag data Signal within 15%	Compare noise and signal in 75 Hz mag data to 15 Hz mag data	Noise difference very small (within 0.2 nT) Signal difference < 11%
15 Hz Mag-in-the Middle EM61 Data Quality	Noise within 1 mV of 75 Hz EM61 data Signal within 15%	Compare noise and signal in 75 Hz EM61 data to 15 Hz EM61 data	Normalized noise at 15 Hz is almost 9 mV more than noise at 75 Hz Normalized signal at 15 Hz is within about 18% of signal at 75Hz
SECONDARY CRITERIA (Performance Objectives)			
Reliability	< 20% downtime	Measure downtime during surveys	< 20% downtime (one afternoon out of three days)
Ease of use	System is sufficiently usable to complete data acquisition	Discuss with operator after demonstrations	System was usable; completed data acquisition; improvements made post-survey

7.3 Data Analysis, Interpretation and Evaluation

7.3.1 Calibration Grid 75 Hz Magnetometer and EM61 Data – Heuristic Analysis

Figures 13 and 14 below show concurrent magnetometer and EM61 data, respectively, taken over the calibration grid. When visually examined, these confirm, as expected, that MSEMS functions correctly, and simultaneously acquires nominal quality magnetometer and EM61 Mk2 data.

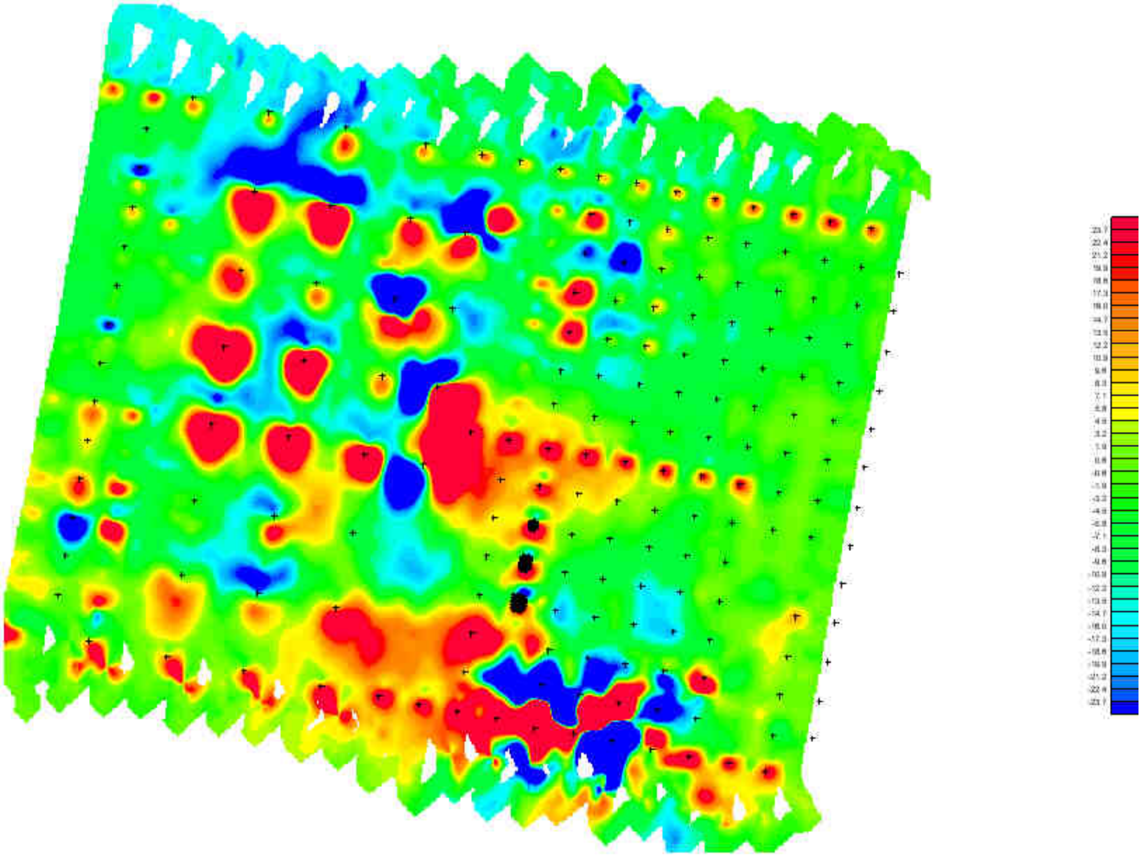

Figure 13: 30m x 40m YPG calibration plot, 75 Hz mag-in-front concurrent magnetometer data, magnetometer vertical, +- 25nT

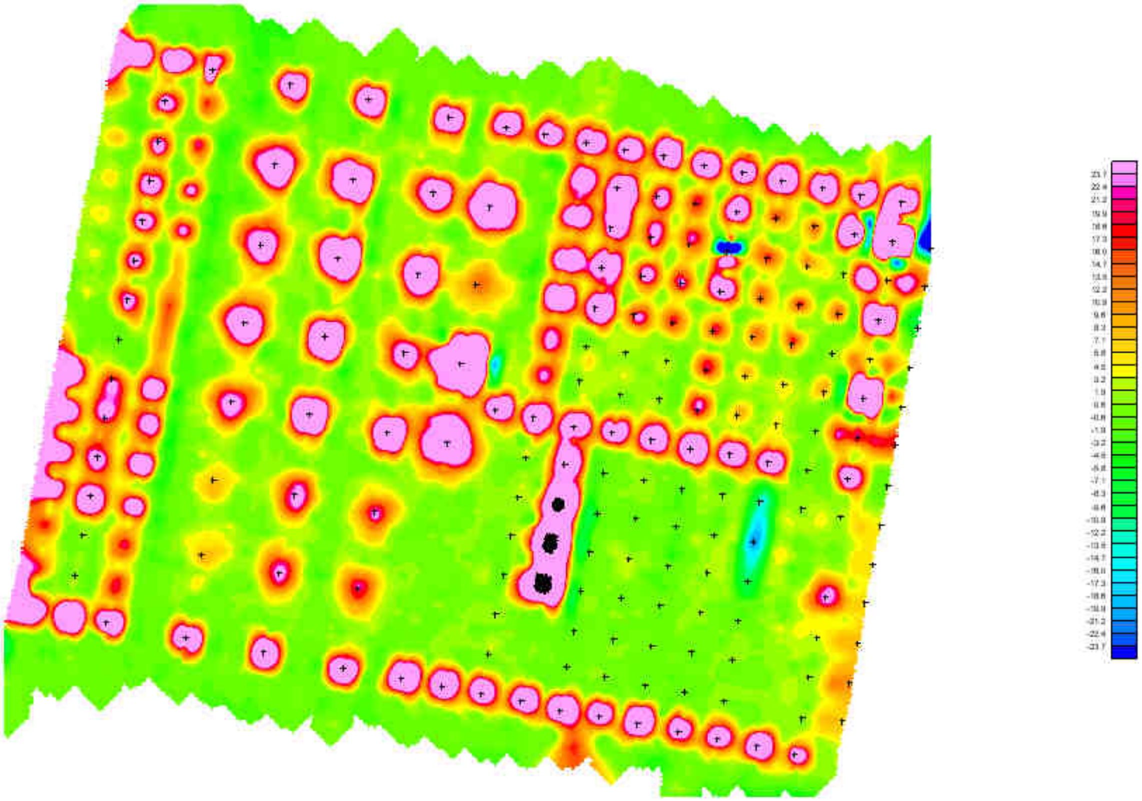

Figure 14: 30m x 40m YPG calibration plot, 75 Hz mag-in-front concurrent EM61 gate1 data, +- 25mV

7.3.2 Calibration Grid 75 Hz Magnetometer Data – Heuristic Analysis

Figure 15 below shows MSEMS magnetometer data acquired with the EM61 switched completely off. The very high degree of visual similarity between figure 13 (interleaved magnetometer and figure 15 (magnetometer alone) indicates, heuristically, that there is not a loss of magnetometer data quality when performing interleaved acquisition. Again, this is not surprising, as this was verified with the vehicular VSEMS system in 2002 in project MM-0208. This indicates that in developing the new smaller interleaving electronics for MSEMS, we did not fundamentally alter anything that was functioning in VSEMS. Items B13 and D13 are marked with black areas of interest; they are referred to in the signal-to-noise analysis below.

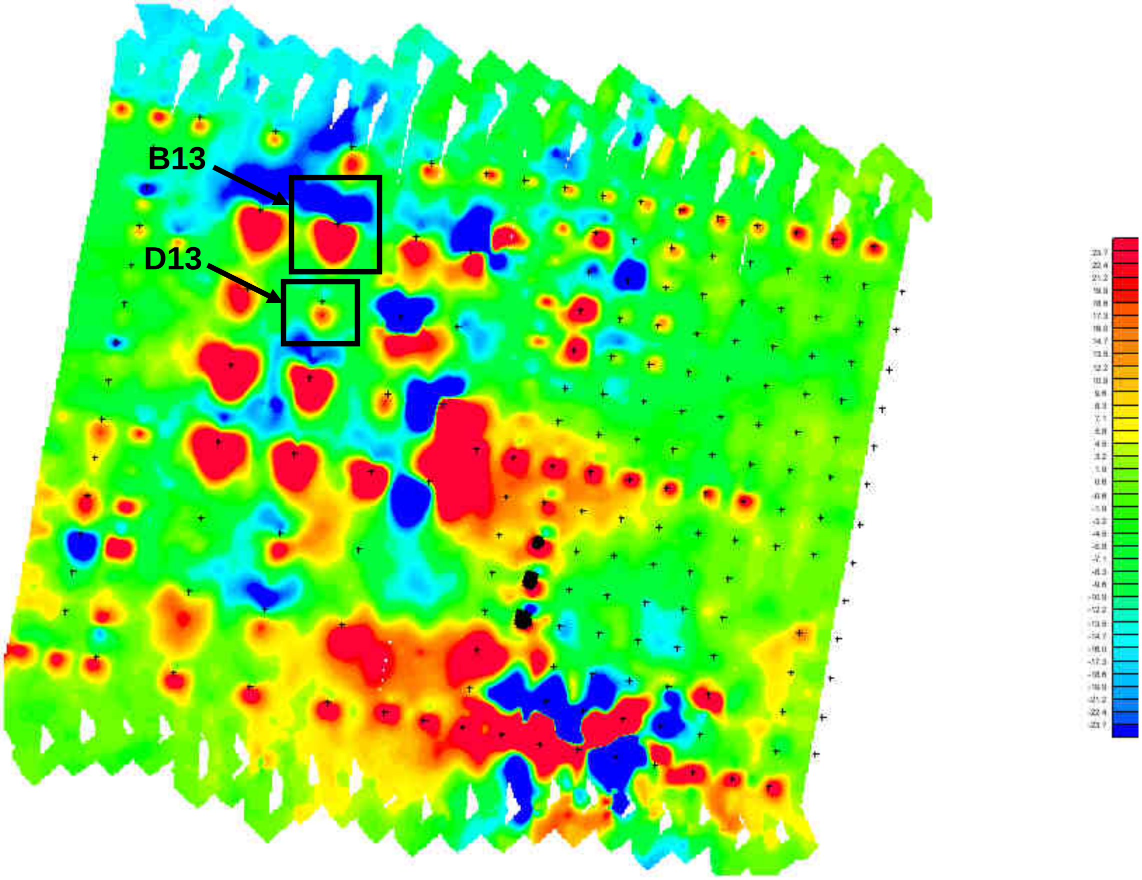

Figure 15: 30m x 40m YPG calibration plot, 75 Hz mag-in-front single-sensor magnetometer data, magnetometer vertical, +- 25nT, showing items B13 and D13

7.3.3 Calibration Grid 75 Hz Magnetometer Data – SNR Analysis

Because the image comparisons above are heuristic, below we perform an analysis on raw magnetometer waveforms and compare signal and noise for two representative objects in the magnetometer-only data set and in the interleaved data set. Item B13 is a 105mm M60 at a depth of 40cm and an inclination of 45 degrees (nearly aligned with the Earth's field) that generates a very strong signal. Item D13 is the same 105mm item at the same depth, but with an angle of inclination of -45 degrees (nearly anti-aligned with the Earth's field) that generates a much weaker signal. For reference, these two items are marked with black areas of interest in figure 15 above.

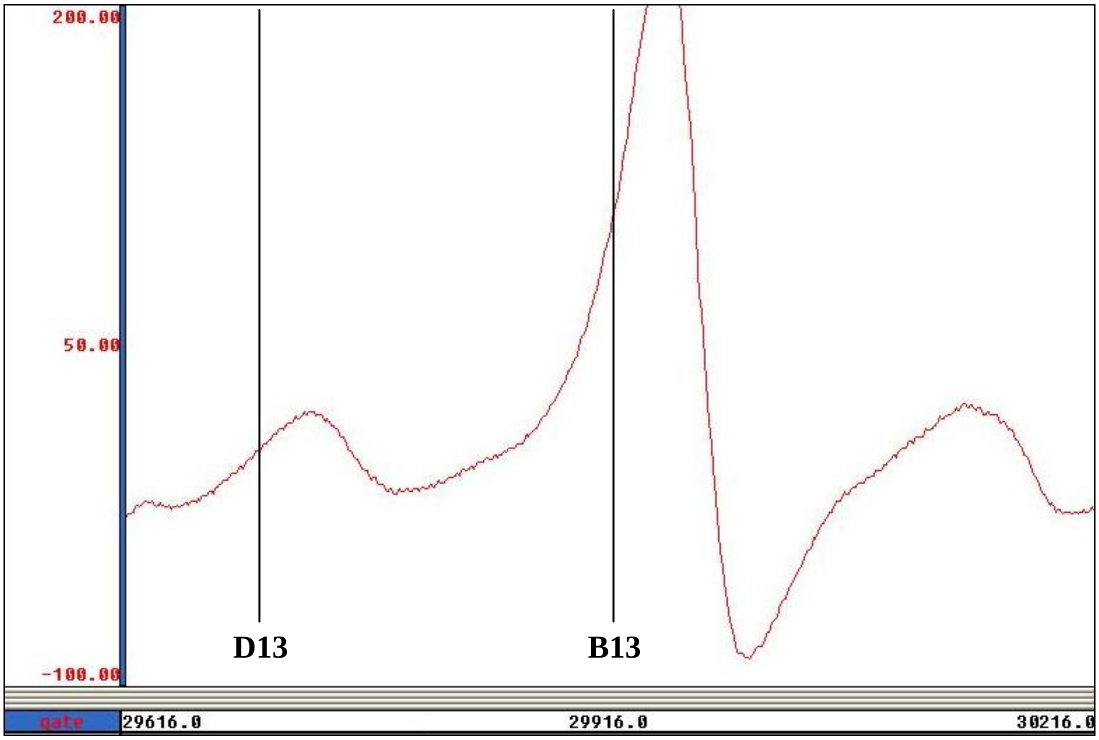

Figure 16: Eight seconds of standalone magnetometer data over calibration grid items B13 and D13 (nT versus point number of 75 Hz updates)

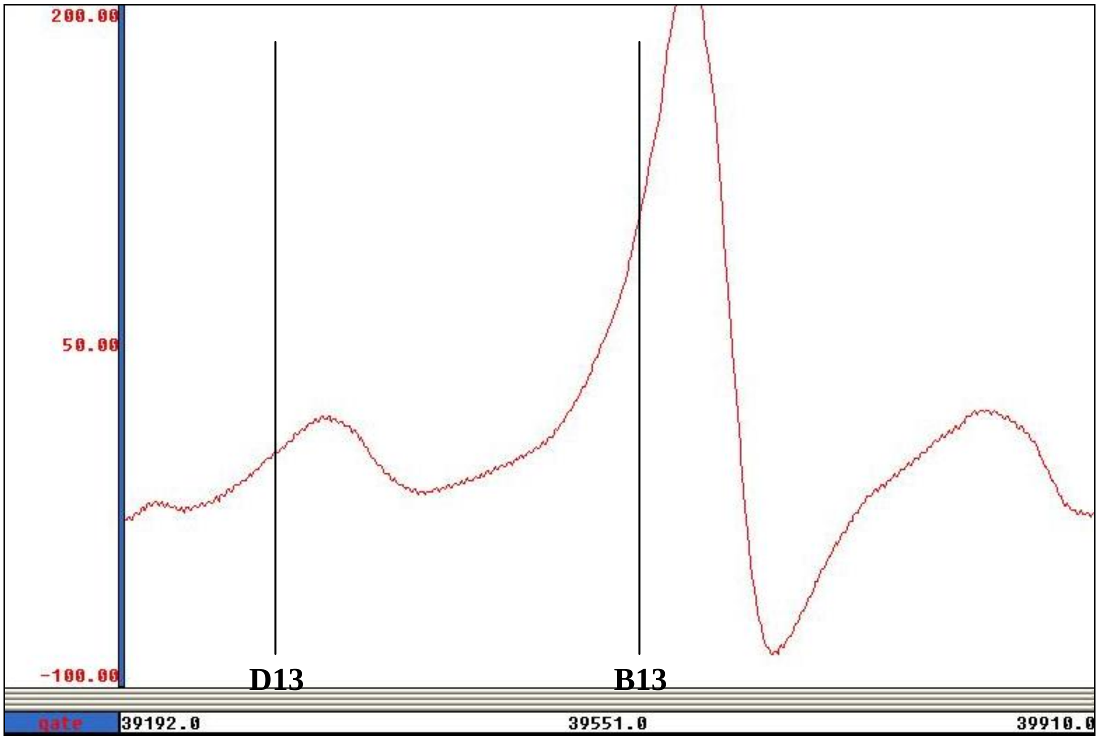

Figure 17: : Eight seconds of concurrently collected magnetometer data over calibration grid items B13 and D13 (nT versus point number of 75 Hz updates)

Figure 16 (magnetometer only) and figure 17 (concurrent mag/EM61) show similar signal and noise characteristics. The noise – the lightly visible ripple on top of the signal – is due to three sources. Firstly, the combination of sampling rate, clock speed, and dynamic range used in the design of our interleaving period counter results in a reading that is accurate to between .5 nT and 1 nT. Second, because of the just-under-1nT accuracy, for data storage reasons, all magnetometer data is truncated to 1 nT and stored as integers (we are modifying the system to change this anachronistic behavior). Third and most significant, the power lines near the YPG site generate 60 Hz hum that get coupled into the system and, given the 75 Hz sample rate, aliases as a 15 Hz sine wave. In normal processing, we use a notch filter to remove the hum, then we lightly smooth the result. For this analysis, to be as transparent as possible, we are not applying the notch filter or smoothing, and instead are using raw data. In the table below, we show the noise, the strong signal from item B13, the weak signal from item D13, and the resulting signal to noise, for both the magnetometer-only data and the concurrent mag/EM data. The results in signal are very similar; any discrepancies in signal can probably be traced to slightly different sensor paths over the object. The noise results (standard deviations from a statistical analysis performed in Oasis using the beginning of the first line, before the system moved) do show a minor (.14 nT) increase in noise in the concurrent mag/EM mode, but we feel this is not significant, as both results are below the 1 nT accuracy of the period counter and resolution of the stored data.

Table 5: Comparison of Magnetometer Signal to Noise for Mag-Only and Concurrent Mag/EM61 Data

	noise (nT)	b13 signal (nT)	b13 s/n	d13 signal (nT)	d13 s/n
concurrent mag/EM	0.68	236	347.1	33	48.5
mag only	0.54	218	403.7	36	66.7

7.3.4 Calibration Grid 75 Hz Magnetometer Data – Answering the Tilt Question

Next we examine the issue of whether the magnetometer needs to be optimally oriented with respect to the Earth's field or can be left vertical. Figure 18 below shows magnetometer data acquired with the sensor tilted. As described above, the reason that the test matrix included acquisition of magnetometer data with the sensor vertical versus tilted is that magnetometers have a zone of acceptance (they should be operated tilted away from the direction of the Earth's magnetic field). On both VSEMS and MTADS, the magnetometers are left vertical, allowing surveying in any direction. But with MSEMS, during the tradeoff study, we found that the closer the magnetometer was placed to the EM61 coil, the more likely it was to collect invalid data if it was tilted the wrong way, even slightly, when going over rough terrain. We were unsure whether we could reliably collect mag-in-front data if the magnetometer were left vertical (note that, for mag-in-the-middle operation, the sensor *must* be oriented correctly for each survey line). We since discovered that the fragility during the trade-off study with respect to vertical orientation for the mag-in-front operation was largely due to the use of a 15 year old magnetometer; when the MSEMS project purchased a new magnetometer, the issue of tilt for mag-in-front operation went away. The data in figure 18 have major problems, with lines of missing and nonsensical data. It turned out that the equipment operator was confused about which way to tilt the sensor (the PI felt that "*tilt the mag away from the Earth's field*" was sufficiently clear instruction). The experiment proved something unintended – that there is risk in reorienting the sensor during the survey if you are not exactly sure which way North is and which way you are supposed to tilt it.

Because the vertical data are fine, the experiment showed that the magnetometer can be and should be left vertical for mag-in-front operation.

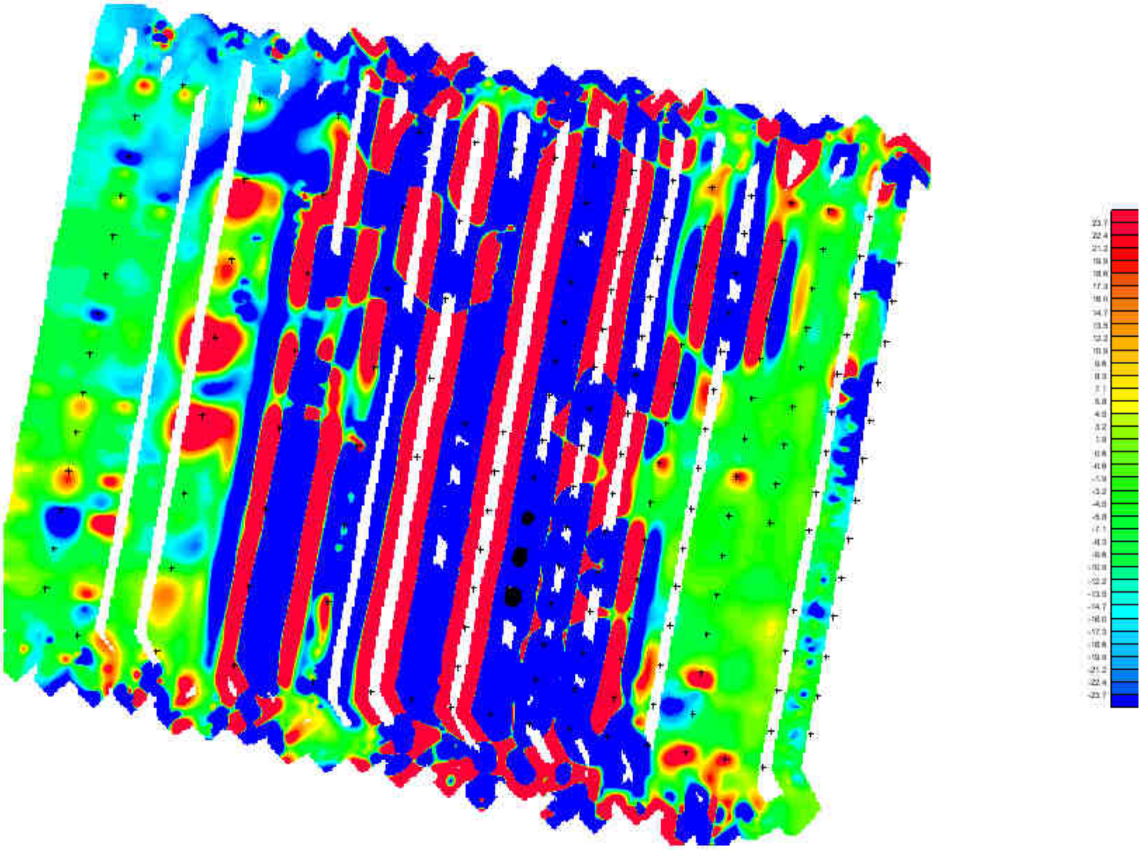

Figure 18: 30m x 40m YPG calibration plot, 75 Hz mag-in-front concurrent magnetometer data, mag less-than-optimally oriented, +- 25nT, clearly showing problematic data because the magnetometer was tilted the wrong way.

7.3.5 Calibration Grid 75 Hz EM61 Data – Heuristic Analysis

In figure 19 below, the EM61 is operated alone, with the magnetometer completely removed from the MSEMS platform. The high degree of visual similarity between this image (EM alone) and figure 14 above (EM61 data concurrently collected with magnetometer data) indicates, at least heuristically, that the presence of the magnetometer is not adversely affecting the EM61.

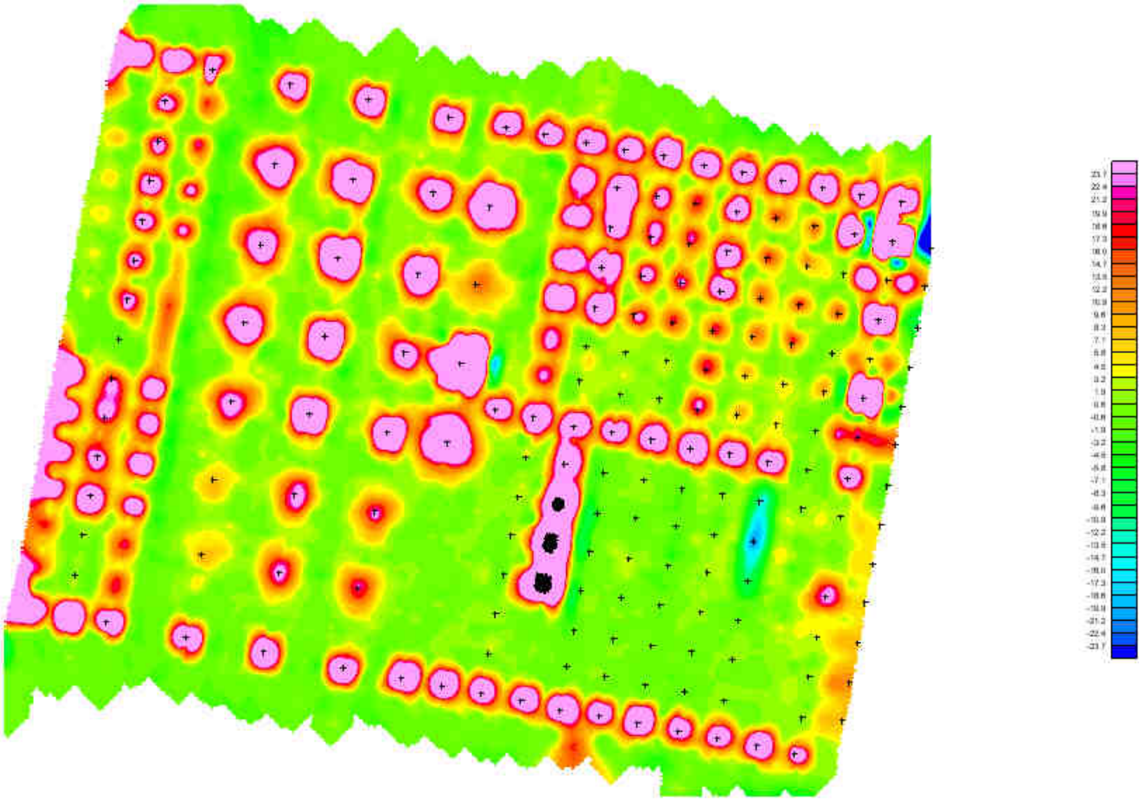

Figure 19: 30m x 40m YPG calibration plot, 75 Hz single sensor EM61 gate1 data, +- 25mV

7.3.6 Calibration Grid 75 Hz EM61 Data – SNR Analysis

Performing the same noise analysis as was done with the magnetometer data, and calculating the noise as the standard deviation of gate1 at the start of the first line before the system is moving, produces the following table. The noise levels in EM/mag and EM-only configurations were virtually identical. The signals are very similar; as with the magnetometer data, these discrepancies in signal can probably be traced to slightly different sensor paths over the object.

Table 6: Comparison of EM61 Signal to Noise for Mag-Only and Concurrent Mag/EM61 Data

	noise (mV)	b13 signal (mV)	b13 s/n	d13 signal (mV)	d13 s/n
concurrent mag/EM	0.4	145.7	364.2	136.8	342.0
EM only	0.4	153.5	383.7	151.9	379.7

7.3.7 Calibration Grid 15 Hz Magnetometer Data – Heuristic Analysis

The next set of images were acquired with the magnetometer in the middle of the EM61 coil, and the coil pulsing at 15 Hz. The magnetometer was always optimally oriented with respect to the Earth’s field, re-oriented at the beginning of each survey line. In figure 20 below, streaks along the direction of travel are a directional offset between North-going and South-going passes. This can be background-leveled out, but we have left it in because it is instructive to see this effect of the proximity of the magnetometer to the EM61 coil, handle, and backpack. This directional effect is present not only in the concurrent mag/EM data below, but also in the mag-only data in figure 21, further reinforcing that the effect is due to the physical structure and not to the EM actually pulsing.

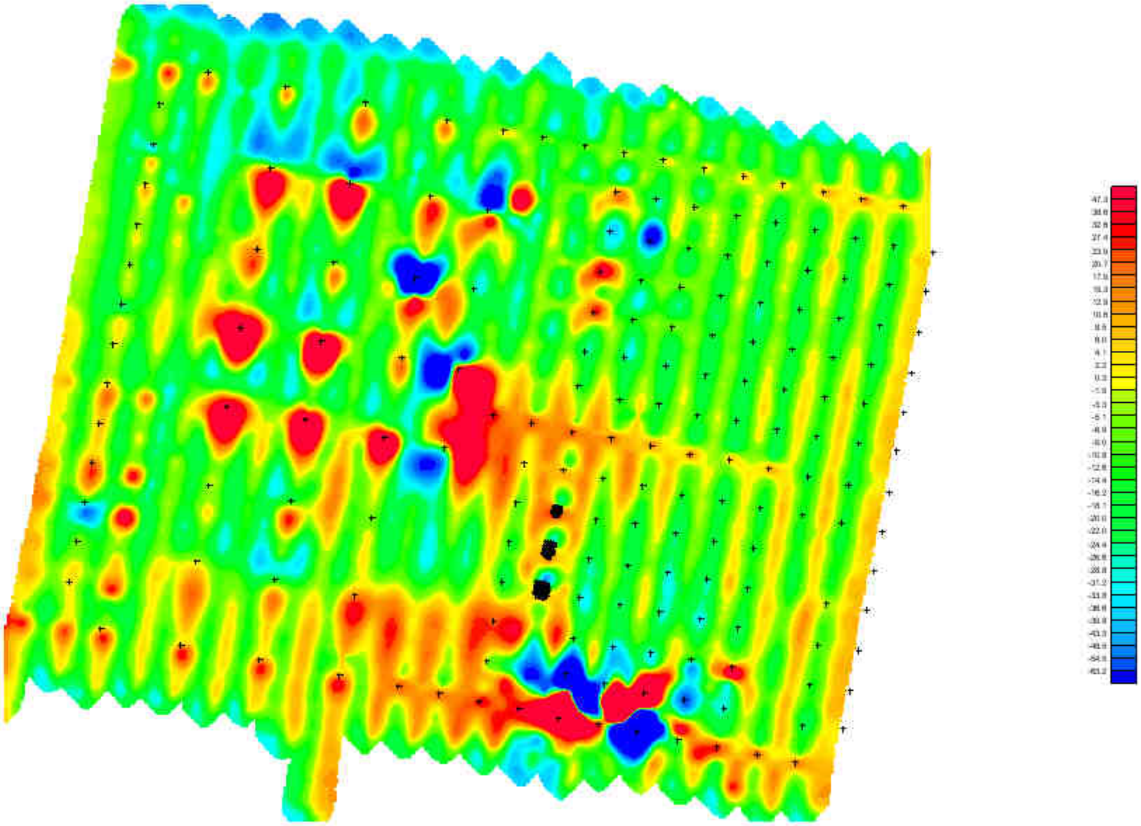

Figure 20: 30m x 40m YPG calibration plot, 15 Hz mag-in-the-middle concurrent magnetometer data, +-25nT

Figure 21 below shows mag-only data acquired with the magnetometer in the middle of the EM61 coil but with the coil disconnected. The eastern side of the data set is truncated due to a cable malfunction. These data show the same directional streaking as the concurrent data, verifying that the effect is not due to proximity to the *pulsing* EM61 coil, but proximity to the structure itself, which includes the GPS antenna, coil, handle, wheels, backpack, GPS, etc.

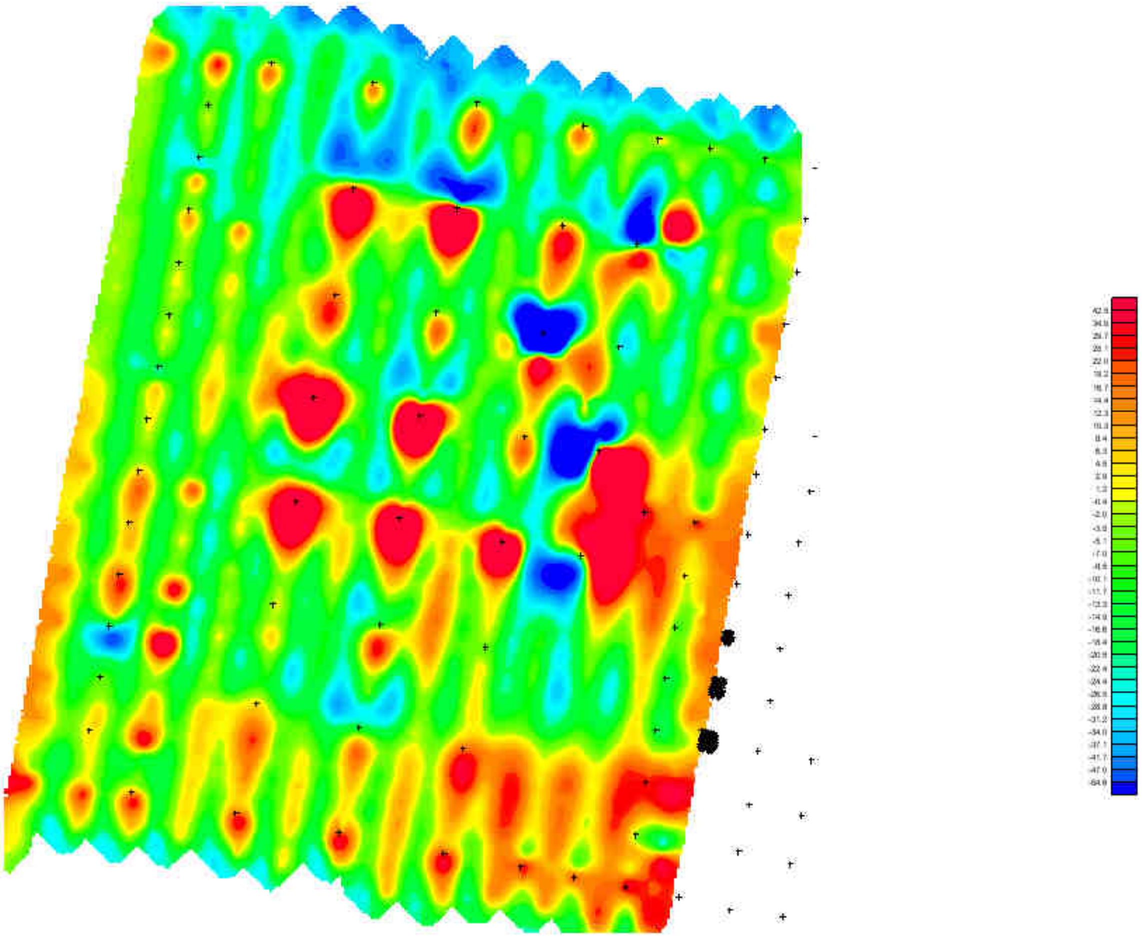

Figure 21: 30m x 40m YPG calibration plot, 15 Hz mag-in-the-middle single sensor magnetometer data, +-25nT

7.3.8 Calibration Grid 15 Hz EM61 Data – Heuristic Analysis

Figure 22 below shows concurrently collected EM61 gate1 data corresponding to the above magnetometer image. The image is displayed to the same +- 25mV scale as all other EM61 images. It is immediately obvious that this is poorer quality data than the 75 Hz EM61 data, with weaker, less-well-defined anomalies and lower signal. We will discuss this further below.

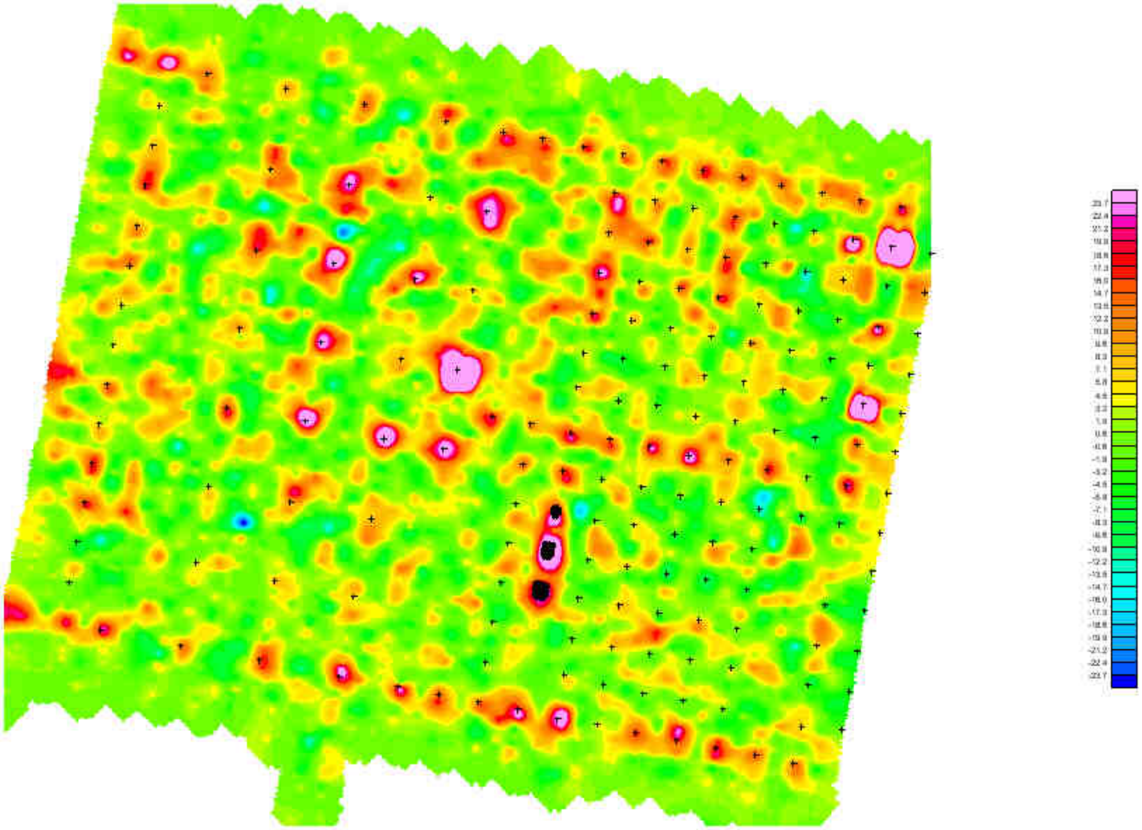

Figure 22: 30m x 40m YPG calibration plot, 15 Hz mag-in-the-middle concurrent EM61 gate1 data, +- 25mV

Figure 23 below shows 15 Hz EM61-only data (gate1) without the magnetometer present on the platform – essentially operating the EM61 without the rest of MSEMS, but at a 15 Hz rate. Note that this image is similar to the concurrently-collected image in figure 21 above – that is, the poor signal to noise is evident without the magnetometer present, indicating that that issue is specific to the EM61 running at 15 Hz rather than 75 Hz and has nothing specifically to do with MSEMS, interleaving, or the physical presence of the magnetometer.

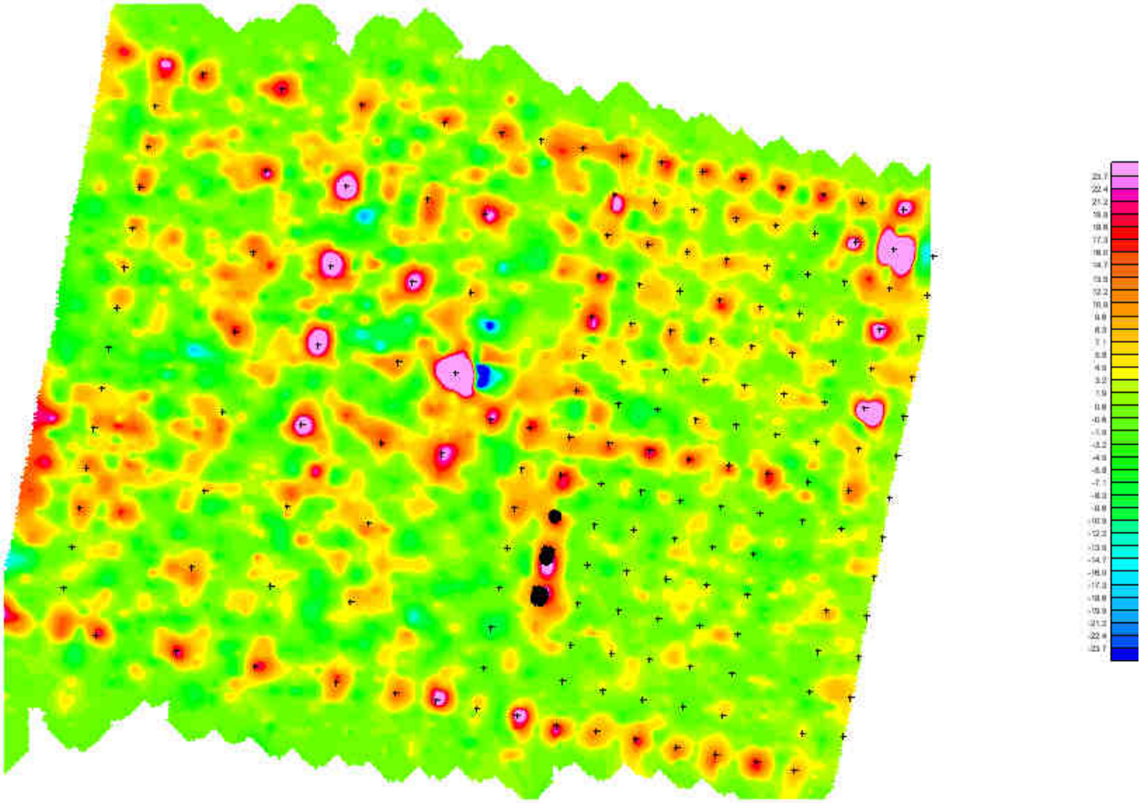

Figure 23: 30m x 40m YPG calibration plot, 15 Hz mag-in-the-middle single sensor EM61 gate1 data, +-25mV

It should be noted that these data were processed and viewed in the field at YPG. When it became apparent that the 15 Hz mode had EM signal and noise issues, we acquired additional data, slowing the EM61 data output rate, and slowing the pace of walking to accommodate the slower output rate. Figure 24 below shows EM61 data acquired while the EM61, pulsing internally at 15 Hz, was outputting at a 2 Hz rate (instead of the nominal 10 Hz output rate), and while the operator was walking extremely slowly (about 0.3 meters/sec). Visually, these data appear to be of somewhat better data quality than the 15 Hz EM61 data in figure 23 with a nominal 10 Hz output rate and a normal walking speed, but are still clearly inferior to the standard 75 Hz data set in figures 14 and 19.

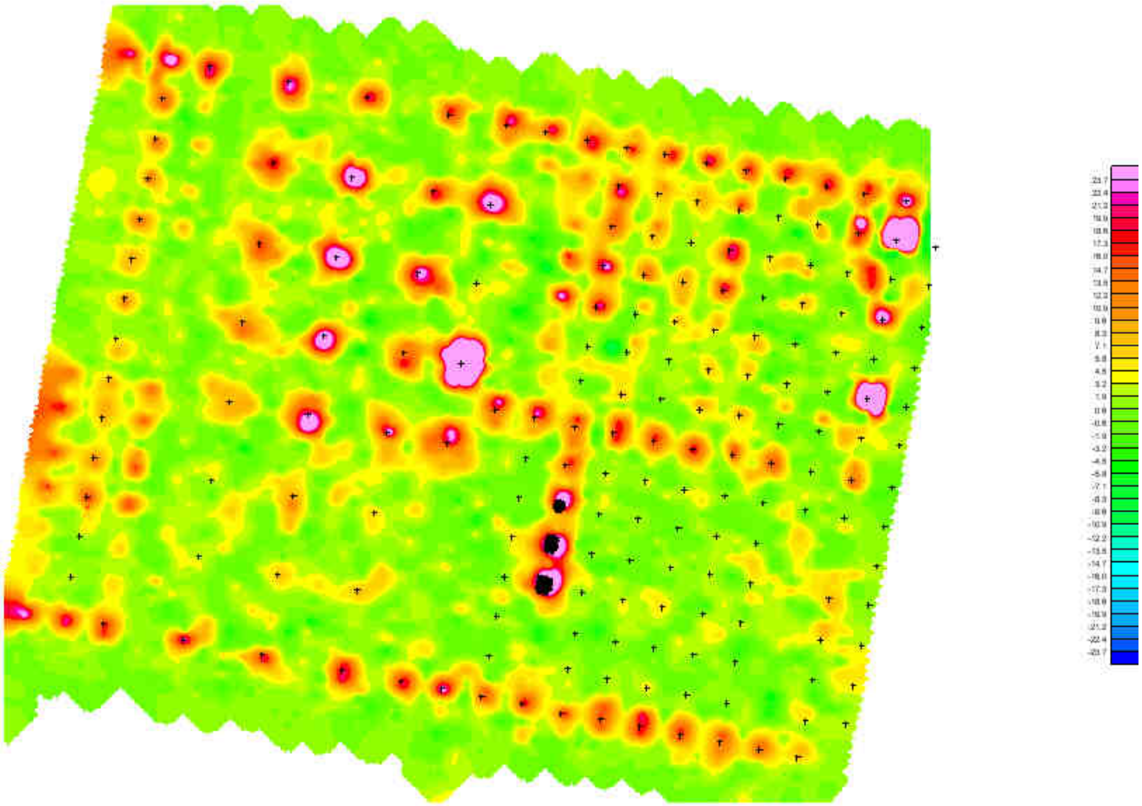

Figure 24: 30m x 40m YPG calibration plot, 15 Hz mag-in-the-middle single sensor EM61 gate1 data triggered at 2 Hz and walked very slowly, +- 25mV

To summarize the heuristic analysis above: The magnetometer data obtained in the mag-in-the-middle configuration look promising, other than some directionally-dependent offsets from the MSEMS electromechanical structure. However, there are substantial noise and signal issues with the EM61 data obtained in the mag-in-the-middle configuration at the 15 Hz rate. We examine this in more detail below.

7.3.9 Calibration Grid EM61 Data – SNR Analysis

In the magnetometer noise analysis section above, we represented the noise as the standard deviation of the magnetometer signal extracted from the short idle period at the start of the first line of data, before the system was in motion. This definition was meaningful because any noise observed in the magnetometer data appeared to be independent of whether or not the system was moving; there did not appear to be additional systemic noise in the magnetometer data once the survey was underway. However, this definition is *not* useful for the 15 Hz EM61 data. Viewing the EM61 time-series data (below) shows that, once the system is in motion, there is a substantial degradation in the quality of the data acquired in the different 15 Hz modes as compared to the nominal 75 Hz data, presenting noise that is over and above the standard spectral noise one could expect simply from the decreased pulse repetition rate.

Figures 25 through 27 below show the four time gates of EM61 data, all acquired on the bottom coil, from the first survey line in the calibration grid. Gate1 is red, gate2 is green, gate3 is blue, and gate4 is magenta. In the top figure (25), acquired with the EM61 pulsing at its nominal 75 Hz rate and outputting at 10 Hz (and the magnetometer 4' in front supported by the 3rd wheel) we see what looks like high-quality EM61 data, with mostly smoothly varying peaks over objects, and quiet where there are no objects. In the second figure (26), the EM61 is pulsing at 15 Hz and outputting at 10 Hz. This data set not only has about ¼ of the signal of the 75 Hz data, but it also simply looks poor, with noise, apparently coherent across the four time gates, completely obscuring the weaker set of objects that are plainly visible in the 75 Hz data. The last figure (27), with the EM61 pulsing at 15 Hz but the output rate slowed down to 2 Hz and the sensor walked extremely slowly, still has only about ¼ the signal of the top set, but has gained back some of the data fidelity (we quantify this further below).

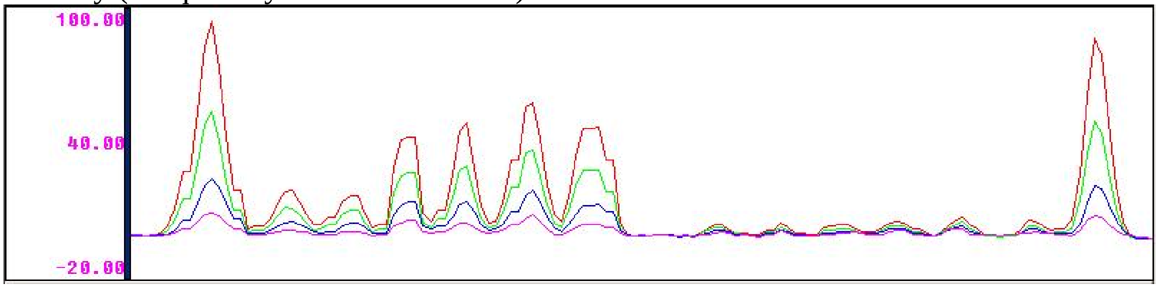

Figure 25: COTS EM61 pulsing at 75 Hz, outputting at 10 Hz, nominal walking pace

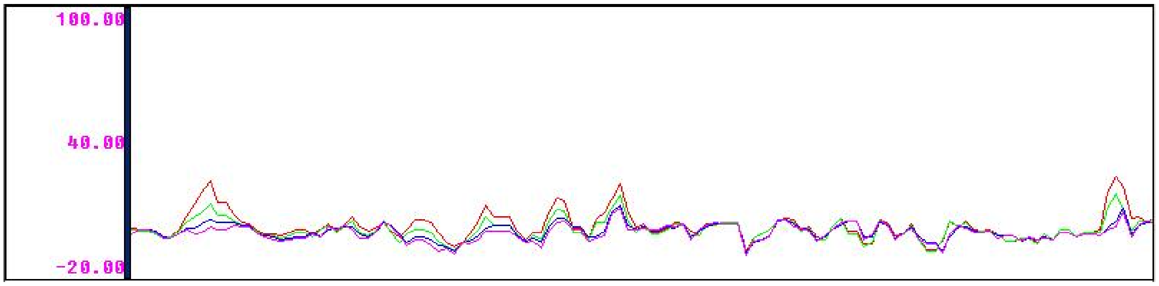

Figure 26: EM61 pulsing at 15 Hz, outputting at 10 Hz, nominal walking pace

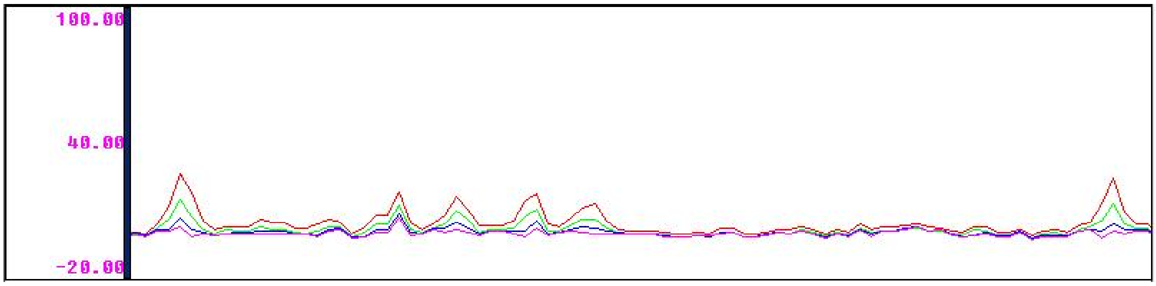

Figure 27: EM61 pulsing at 15 Hz, outputting at 2 Hz, very slow walking pace

The conclusion from viewing these figures is that the EM61 data are substantially compromised when running in the 15 Hz mode – more so than we expected. At the outset of the mag-in-the-middle tradeoff study, we spoke with Miro Bosnar at Geonics about the effect of decreasing the EM61 pulse rate by a factor of 5 (from 75 Hz to 15 Hz) in order to allow the magnetometer time to recover from the rapidly changing EM fields, and he said that, for spectrally flat noise, one would expect the noise to vary with the square root of the pulse repetition rate. When we did our pre-YPG tests – at an area that literally was a soccer field, with surface-emplaced objects that generated strong signals – what jumped out at us was not an increase in noise, but a decrease in signal as compared to standard 75 Hz data (these pre-YPG results were presented in the spring 2006 IPR). Mr. Bosnar's response about both noise and signal were:

`“The number of pulses that the EM61 instrument integrates (measures) is proportional to the repetition rate. For example: if the instrument transmits 15 pulses per second (15 Hz repetition rate) receiver will receive 15 decays per second, versus 75 if repetition rate is 75 Hz. As a result the output (signal) will be 5 times smaller. In the same time noise adds as a square root of ratio of the repetition rate - assuming spectrally flat noise. So as a result signal-to-noise ratio falls as square root of repetition rate ratio.”`

(In later conversations with Mr. Bosnar, he said that, if desired, Geonics could configure our custom 15 Hz EPROM to preserve the same signal level as the standard 75 Hz configuration (albeit with higher noise). He explained that Geonics' choice to have the signal level output tied to the pulse rate stemmed from complaints from customers who had purchased early versions of the EM61-HP with the high power option (which operates at 150 Hz) and did not see an increase in the output signal.)

From these comments, when we went to YPG, we expected that the 15 Hz mode would bring both an increase in system noise and a decrease in signal. The question was how significant either of these would turn out to be – as Dr. Hunter Ware has pointed out, the dominant issue with the use of EM61s on sites has been the geological noise, not the system noise. But in addition to the decrease in signal amplitude, we did not expect the signal itself to be so obviously degraded as a result of the 15 Hz modification.

After analyzing the Yuma data, we discussed the results with Mr. Bosnar. His response was:

`“Regarding the loss of amplitude in the EM61 response, as we discussed earlier, this is one of the penalties for reducing transmitter repetition rate.  Due to the lower number of transmitted pulses and consequently signal decays that are averaged per unit time, output signal is reduced.`

`The reduction of signal will depend on the response characteristics of target: if signal decays fast, to near zero inside 3.3 ms (transmitter pulse width) signal reduction will be proportional to the ratio of frequencies; five in your case. If the signal decays to zero over time larger than Tx pulse width, reduction in signal amplitude will be smaller than the frequency ratio, depending on the "slowness" of` decay. The effect is knows as a run-on effect. It is due to the negative response from leading edge of transmitter pulse that subtract signal form signal generated by trailing edge of transmitter pulse.

On the other hand, effect of change (reduction) of repetition rate on the noise will depend on spectral characteristics of noise. If external noise is uniform with frequency (white noise) the output noise will be reduced. Unfortunately noise is not spectrally flat, especially in rough terrain where coils are moving randomly in earth's magnetic field at frequency in range of or near operating frequency, so that output noise could even increase."

This addressed the observation that the decrease in amplitude is not exactly a factor of five. In later conversations with Mr. Bosnar, he reiterated that, in his opinion, the components of the motion of the coil near the 15 Hz operating frequency was probably responsible for the basic loss of data quality ("the noise's spectral distribution may not be uniform at the lower (15 Hz) frequency; an additional noise spectral component will be detected inside the noise bandwidth with 15 Hz repetition rate").

To estimate signal to noise, in the calibration lane, for the 75 Hz and 15 Hz cases, in the table below, we look at the gate1 signal and noise (standard deviation of the gate1 signal before the cart starts moving) for objects B13 and D13 (105mm item at 40 cm depth, roughly aligned and anti-aligned with the Earth's field, respectively).

Table 7: Signal and static noise in 75 Hz and 15 Hz EM61 data over objects B13 and D13

	static noise (mV)	b13 signal (mV)	b13 SNR	d13 signal (mV)	d13 SNR
75 Hz Pulse Rate, 10 Hz Output	0.21	60.40	287.62	65.04	309.71
15 Hz Pulse Rate, 10 Hz Output	0.004	18.20	4550.00	19.36	4840.00
15 Hz Pulse Rate, 2 Hz Output (slow walk)	0.24	16.93	70.54	17.99	74.96
Average of the Two 15 Hz Signals		17.56		18.67	
Ratio of 75 Hz Signal to 15 Hz signal		3.44		3.48	

From this table, we do not see a clear root(5) relationship in noise between the 75 Hz data and the several variants of 15 Hz data. In fact, according to these data, the faster we requested an update from the EM61, the lower the noise seemed to be. We doubt that these SNRs have real meaning, because the dominant noise appears not to be the RMS noise measured while the system is still, but the noise while the system is moving. For this reason, we redid the analysis using dynamically-measured noise. We *do* see the signal over objects in the 15 Hz data decrease by approximately a factor of four as compared to the 75 Hz data.

Before we redo the analysis, it is important to understand that there is a distinction in the EM61 between the *pulse repetition rate* (the rate at which the transmitter is pulsed) and the *sample output rate* (the rate at which the electronics spit out a serial update). For years, our understanding had been that the EM61 collects data at the pulse repetition rate, and then averages that data together when it is sent a trigger. For a COTS EM61, that trigger is supplied by an encoder on the tickwheel, but for GPS-integrated EM61s, including MSEMS, the trigger is typically supplied in software at a rate between 2 and 10 Hz. MSEMS nominally triggers the EM61 to generate output at a 10 Hz rate. While at YPG, upon viewing these preliminary results, we made an attempt to increase signal to noise at the 15 Hz pulse rate. We decreased the EM61 soft triggering from 10 Hz to 2 Hz in order to increase the number of raw readings averaged between triggers. Then we collected another calibration data set, walking extremely slowly (about 0.3 meters/sec) to compensate for the slow output rate.

Subsequent conversations with Miro Bosnar have revealed that our understanding of the way that triggering and averaging work – that the system averages raw data between triggers (which is, in fact, a common understanding in the industry) – is not, in fact, correct. According to Mr. Bosnar, the averaging time constant is set in hardware in the EM61 box, and is unaffected by the rate at which the unit is triggered in software to output data. Slower walking speed certainly may have a positive effect on data quality regardless of the issue of triggering by reducing vibration-induced noise.. Mr. Bosnar felt that the coil motion's interaction with the 15 Hz rate was likely the source of low data quality, and that this motion was likely lessened as we walked slower, but also suggested that it is possible that something was still not right in the 15 Hz EPROM he generated for us (it was a one-off chip).

As we said, because the RMS noise during the static period is not a good metric to use, we switched to a dynamic noise metric, extracting the RMS noise in the empty area south of object H11 and north of the line that denotes the edge of the grid. When we recalculate the table using this noise metric, it clearly shows the degradation in signal to noise at all of the 15 Hz pulse rate data sets, and properly shows the slight increase gained back in the slowly-walked 15 Hz data set with the 2 Hz output. We include a row with both the signal and noise of the slow-walked 15 Hz results multiplied by the expected factor of 5 to allow for a direct comparison of signal and noise levels with the 75 Hz data, as per table 4.

Table 8: Signal and dynamic noise in 75 Hz and 15 Hz EM61 data over objects B13 and D13

	dynamic noise (mV)	b13 signal (mV)	b13 SNR	d13 signal (mV)	d13 SNR
75 Hz Pulse Rate, 10 Hz Output	1.06	60.40	56.98	65.04	61.36
15 Hz Pulse Rate, 10 Hz Output	4.48	18.20	4.06	19.36	4.32
15 Hz Pulse Rate, 2 Hz Output (slow walk)	1.96	16.93	8.64	17.99	9.18
15 Hz Pulse Rate, 2 Hz Output (slow walk, multiplied by factor of 5)	9.75	84.65	(same)	89.95	(same)

Comparing the noise in the first and last row, the normalized noise in even the best 15 Hz data (the slow-walked data) is almost 9mV higher than in the 75 Hz data. Examining the signals from B13 and D13 for both cases, we see that the signal levels are within about 18% of each other. Some of this difference is likely due to simple issues of repeatability (e.g., walking the line the same way) whereas some portion may be due to the explanations offered by Mr. Bosnar.

The more appropriate comparison is to examine the ratios of the 75 Hz and 15 Hz SNR numbers. These are shown in the table below.

Table 9: Ratio of Signal to Noise for 75 Hz and 15 Hz Data for Items B13 and D13

Ratio (75 Hz SNR / 15 Hz SNR)	Item B13	Item D13
Normal-Walked	14.03	14.20
Slow-Walked	6.59	6.68

Thus, at a standard walking pace, the signal to noise for the 15 Hz configuration is worse than the COTS 75 Hz configuration by a factor of approximately 14, and even when walking extremely slowly, it is still worse by a factor of approximately 6.

Several conclusions can be drawn. Firstly, the expectation that signal would remain the same and noise would increase by root(5) does not take into account the EM61's operating details (including the averaging that is performed by the EM61 in hardware and the fact that the averaged signal is not normalized to the pulse repetition rate), nor the apparently non-uniform spectral distribution of the noise. Second, and far more important, the use of such a statically-derived RMS figure as a noise metric (as we did with the magnetometer data) is not applicable when the dominant noise source is not merely spectral noise from system electronics but instead appears magnified when the sensor is in motion. Third, in addition to the 3rd wheel helping the magnetometer maintain constant height above ground in the mag-in-front mode, it has the added benefit of providing stability to the EM61 platform. That is, when the EM61 is only supported on its two native wheels, it can rock and tilt, whereas with the 3rd wheel in place, it cannot. It is possible that some of the difference in figures 25, 26, and 27 is due to the stability induced by the

3rd wheel in generating the data. Fourth, and most important, although the coherent noise while the platform was in motion appeared to be reduced by a factor of 2 or 3 when triggering at 2 Hz and walking very slowly (as compared to triggering faster and walking faster), this is not practical; no one could afford to walk that slowly in a production geophysical context. Plus, as shown by figure 27, the loss in signal to noise is still substantial. It is difficult to imagine a situation where mag-in-the-middle would be of net benefit when the loss of signal is so steep and the survey time is so slow. We will return to this in the conclusions section.

7.3.10 Blind Grid Data – Heuristic Analysis

The blind test grid at YPG is a 40 meter by 40 meter grid seeded with the same items as are present in the calibration grid. The test plan called for us to acquire data on the blind grid in whatever magnetometer orientation (vertical or tilted) was borne out by the calibration grid data, and to survey the blind grid in both 75 Hz mag-in-front mode and 15 Hz mag-in-the-middle mode. After surveying and analyzing the calibration grid, there were no surprises in the blind grid data, but we present them here for completeness.

The image below shows magnetometer data from the blind grid, acquired in the 75 Hz mag-in-front mode. Unlike the calibration data magnetometer images which were shown at +- 25nT, because of the high density of strong objects in the grid, these are shown at +- 50 nT.

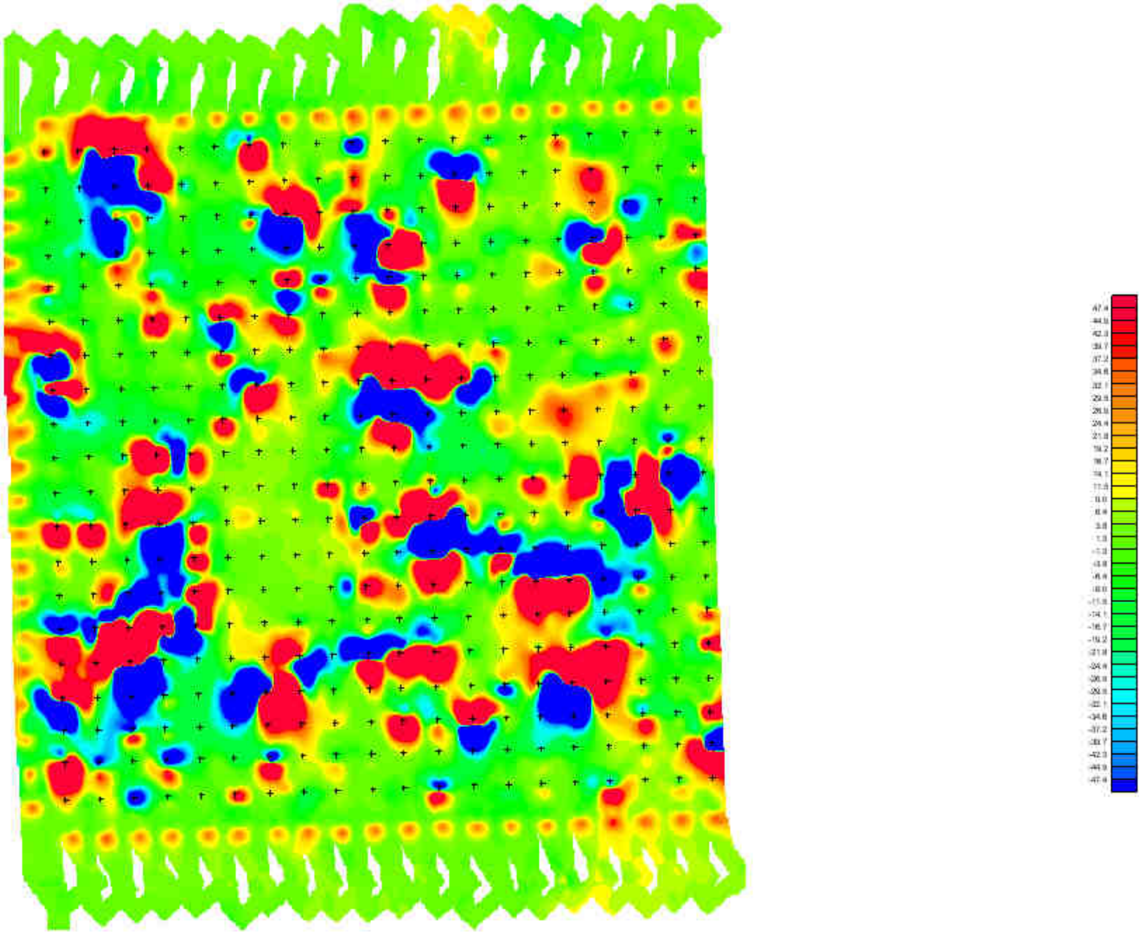

Figure 28: 40m x 40m YPG blind grid, 75 Hz mag-in-front concurrent magnetometer data, +- 50nT

The image below shows EM61 gate1 data from the blind grid, acquired in the 75 Hz mag-in-front mode.

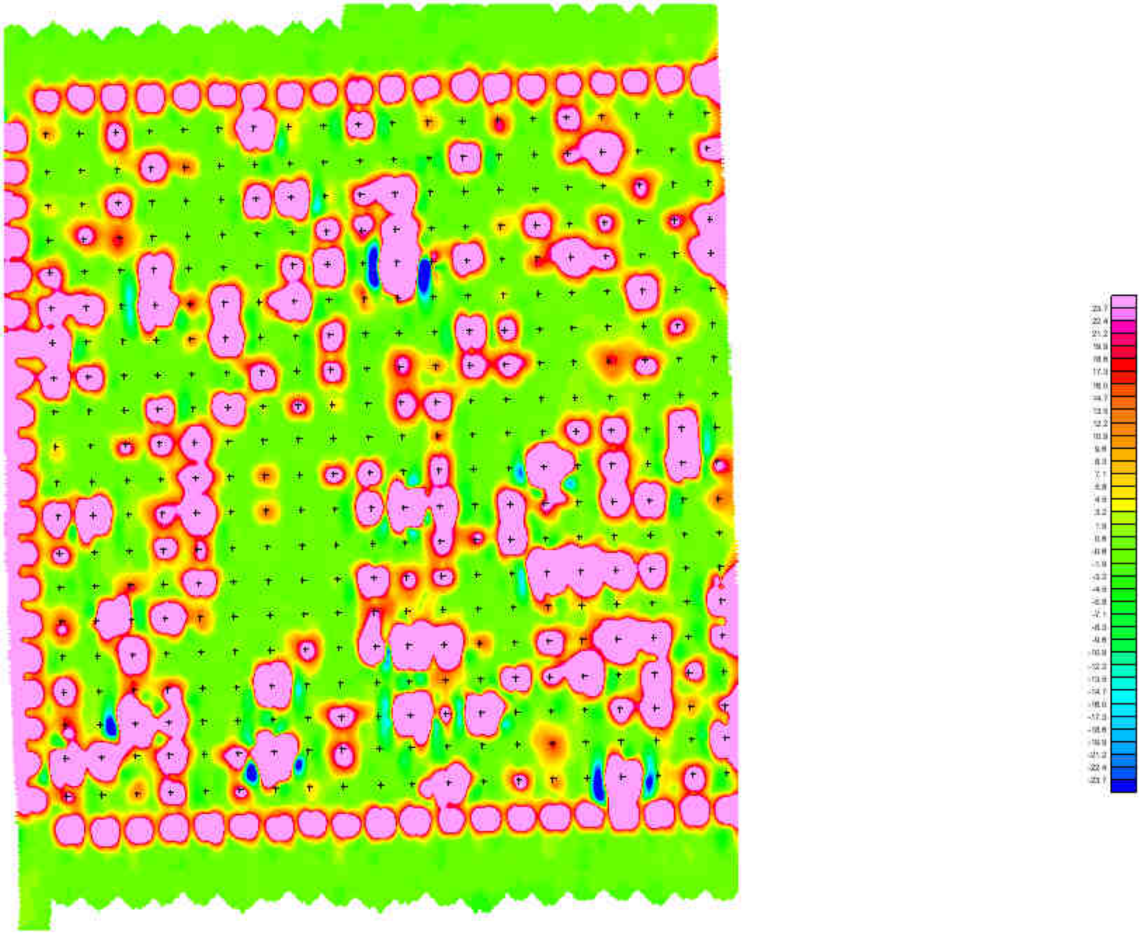

Figure 29: 40m x 40m YPG blind grid, 75 Hz mag-in-front concurrent EM61 gate1 data, +- 25mV

The image below shows magnetometer data from the blind grid, acquired in the 15 Hz mag-in-the-middle mode, at +- 50nT. The same light directional offset seen in the cal grid 15 Hz mag data is also present in these data.

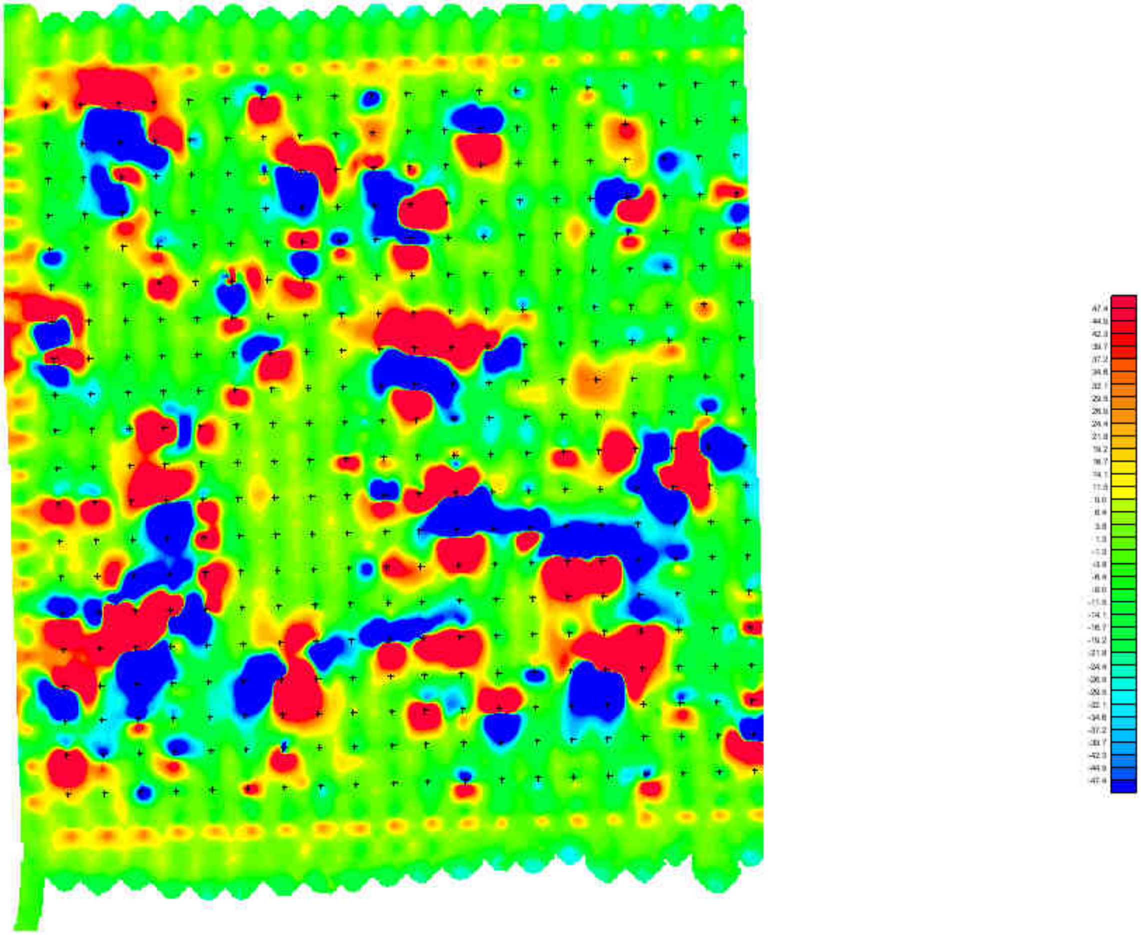

Figure 30: 40m x 40m YPG blind grid, 15 Hz mag-in-the middle concurrent magnetometer data, +- 50nT

The image below shows EM61 gate1 data from the blind grid, acquired in the 15 Hz mag-in-the mode, triggering at 2 Hz, and walking very slowly (about 0.3 meters/sec). At first glance, this looks like fairly high-quality EM61 data, but visually comparing the image data to the 75 Hz data in figure 29 above, the 75 Hz data has six times more signal, and a close examination shows that there are objects that are apparent in the 75 Hz data that fade into the background in the 15 Hz data due to the lower signal to noise. This analysis is performed more rigorously in the following section.

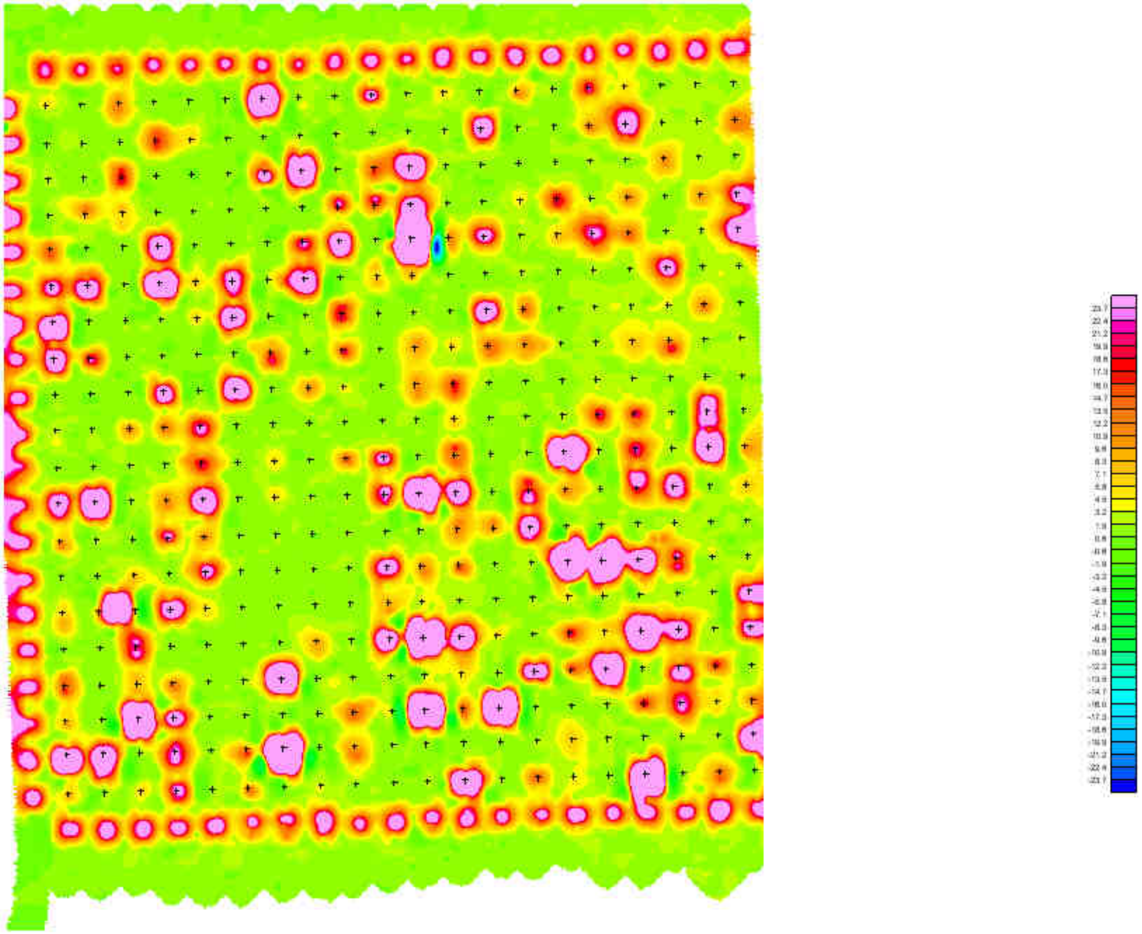

Figure 31: 40m x 40m YPG blind grid, 15 Hz mag-in-the middle concurrent EM61 gate1 data, +- 25mV

7.3.11 Blind Grid Data – SNR Analysis

As with the heuristic analysis, there are no surprises in the signal-to-noise analysis of the blind grid data, but, as originally requested by the Program Office, a signal to noise analysis of a line of data in the blind grid is included for completeness. The second line of data in the blind grid appears to run over objects of varying size, so we selected this line for scrutiny. It is instructive to look at these anomalies in time-series form. The top set of profiles was acquired at normal walking speed at 75 Hz with the magnetometer in front. The middle set of profiles was acquired at a painfully slow walking pace (approximately 0.3 meters/sec) at 15 Hz with the magnetometer in the middle. The bottom set is the data from the middle set multiplied by a factor of 5, bringing the signal to the same level as the 75 Hz data so the differences in noise can be evaluated. Even though, to the eye, the 15 Hz profiles have the appearance of good data (smooth peaks with quiet valleys), when bringing up the signal and noise by a factor of 5 and comparing apples-to-apples to the 75 Hz data, the increased noise can clearly be seen. This is especially significant when one considers that the data in figure 34 took three times as long to acquire than the data in figure 32, due to the reduced walking pace.

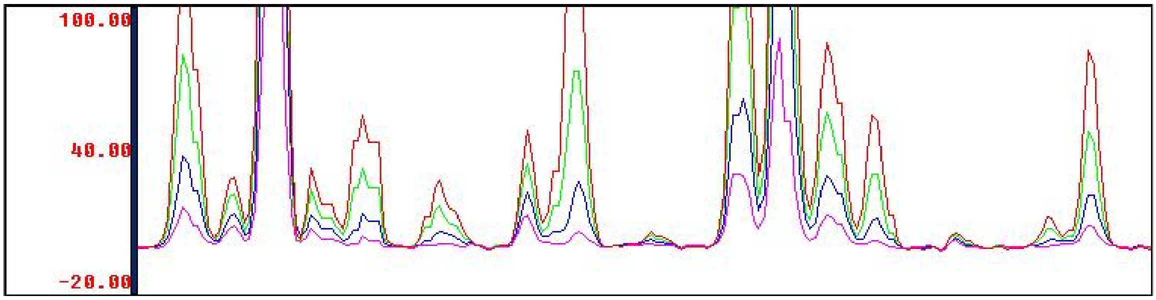

Figure 32: YPG blind grid, 75 Hz mag-in-the middle concurrent EM61 data, line 2

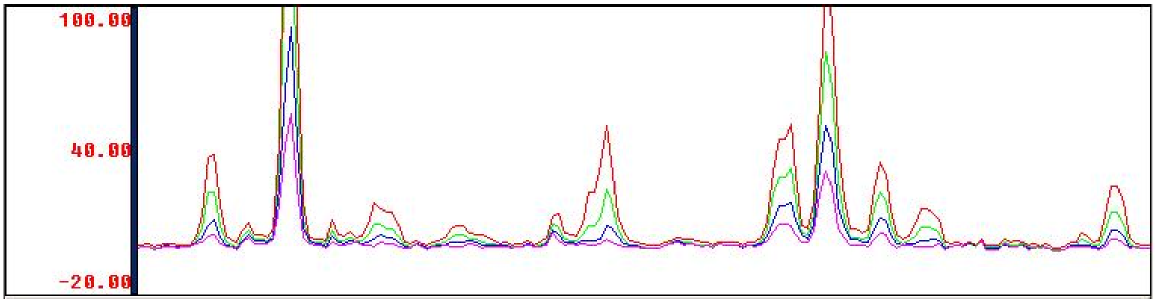

Figure 33: YPG blind grid, 15 Hz mag-in-the middle concurrent EM61 data, line 2, slow walk

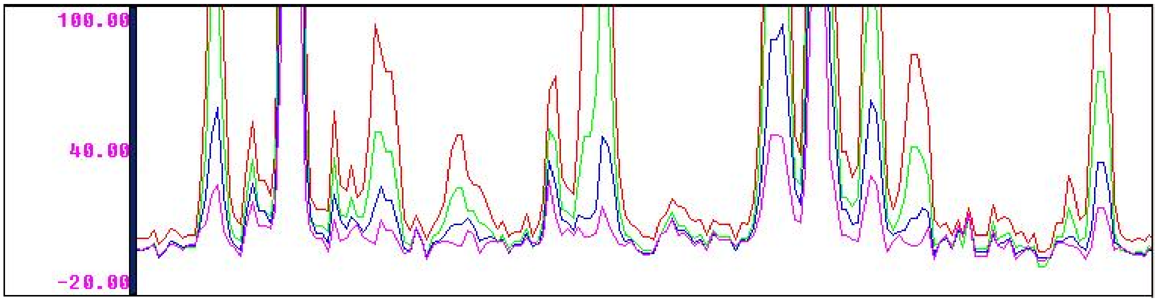

Figure 34: YPG blind grid, 15 Hz mag-in-the middle concurrent EM61 data, line 2, slow walk, multiplied by a factor of five

A signal to noise analysis has been performed on the second line of targets. The table below shows data from gate1. Instead of measuring noise statically at the start of the survey, noise was measured dynamically using data in an area stretching from grid cell F8 to grid cell K8 where there do not appear to be any emplaced targets. Signal-to-noise values are given for each grid cell in line 2 that clearly contains an object. The last column in the table is the ratio of the signal-to-noise from the 75 Hz data to that extracted from the 15 Hz data. From here, it is clear that there is a loss of approximately a factor of 6 to 8 in signal to noise when running the EM61 using the 15 Hz pulse repetition rate, even when trying to mitigate the loss in data quality by walking approximately one third the speed at which the 75 Hz data were collected and decreasing the output rate to 2 Hz. This is consistent with the results from the calibration grid.

Table 10: Signal and Noise Analysis of Line 2 in YPG Blind Test Grid

noise	0.29 mV		0.61 mV		
	75 Hz Signal (mV)	75 Hz SNR	15 Hz Signal (mV)	15 Hz SNR	Ratio
b2	70.79	244.10	21.02	34.46	7.08
f2	12.79	44.10	3.62	5.93	7.43
i2	58.71	202.45	19.09	31.30	6.47
m2	20.81	71.76	7.30	11.97	6.00
o2	77.56	267.45	24.70	40.49	6.60
q2	16.56	57.10	5.94	9.74	5.86

7.3.12 Reliability and Usability

The system proved very reliable at YPG, suffering a broken cable and running the internal GPS battery down once. Total downtime amounted to approximately one afternoon out of a three-day deployment.

The system operators found the user interface presented by our custom Allegro software to be quite usable (it has a look and feel similar to Geonics' software). Operators liked the 3rd wheel because it enabled them to let go of the handle without having the system fall over (as it does in a COTS two-wheeled EM61). The main operator complaint was that having the EM61 backpack *and* the magnetometer battery belt pack on the operator was too much. The magnetometer batteries were subsequently relocated onto the boom and packaged in a hardened case.

7.3.13 Conclusions

At the start of this project, when planning what was necessary to operate a magnetometer in the middle of the EM61 coil, we were primarily concerned about the effect on the magnetometer data quality. We did not expect that the primary degradation in data quality would be not to the magnetometer but to the EM61. When research showed that, by slowing the EM61 down from 75 Hz to 15 Hz, we apparently *could* operate the magnetometer in the center of the coil, we were certainly aware that the EM61 noise would vary as one over the square root of the pulse repetition rate, but we did not know whether this would be a significant source of noise to the system as a whole, much less the most significant source. The YPG deployment showed that the degradation in signal to noise when operating in this mode is crippling to the EM61 data quality. It is possible that further work with Geonics could solve some of the unknowns of our particular one-off 15 Hz EPROM. However, the 75 Hz mag-in-front configuration with the 3rd wheel is a mechanically stable platform that generates high quality EM61 and magnetometer data. For this reason, after the YPG deployment, we have not further pursued the mag-in-the-middle configuration. Further, from a purely practical standpoint, we have begun using Geonics' COTS EM61 Mk2A as the basis for a newer version of MSEMS (see below). The Mk2A has the battery relocated from the backpack to the center of the EM61 coil. It would be difficult to co-locate the magnetometer there as well.

Lastly, at conferences and symposia, several researchers have suggested that we may still be able to run with the magnetometer in the middle while operating the EM61 at 75 Hz by building a bucking coil and nulling out the EM61's field at the magnetometer. That may be true, but the goal of this project was to be able to use a COTS or near-COTS EM61 and magnetometer, build a box into which you could plug sensors and a GPS already in inventory, and design and build a man-portable system around those sensors and that box. The bucking coil design would violate the spirit of the design philosophy and add weight and complexity to the system.

The YPG deployment was a crucial shakedown test for MSEMS. It validated the system's ability to collect high-quality concurrent magnetometer and EM61 data at 75 Hz with the magnetometer four feet in front of the EM61 coil and supported by a 3rd wheel, and raised sufficient questions about signal-to-noise the 15 Hz mag-in-the-middle mode that we elected not to pursue it further at this time. Important bugs were unearthed and fixed, and feedback from experienced operators was obtained. Post-YPG, these issues were addressed, resulting in a string of successful fieldings at a variety of government and commercial MEC and HTRW sites.

8 Cost Assessment

8.1 Cost Model

The cost model is presented in the table below.

Table 11: Cost Model

Cost Element	Data Tracked During Demonstration	Estimated Costs
Instrument cost	Component costs and integration costs • Engineering estimates based on current development • Lifetime estimate Track consumables and repairs	• $25,000
Mobilization and demobilization	Cost to mobilize to site Derived from demonstration costs	• $10,800
Site preparation	No unique requirements encountered	
Instrument setup costs	Unit: $ cost to set up and calibrate Data Requirements: • Hours required • Personnel required • Frequency required	• $275 • 1 hour • 2 people • One-time setup
Survey costs	Unit: $ cost per hectare Data requirements: • Hours per hectare • Personnel required	• $2826/hectare • 8.3 hours/hectare • 2 people
Detection data processing costs	Unit: $ cost per hectare as function of anomaly density Data requirements: • Time required • Personnel required	No detection performed
Discrimination data processing	Unit: $ per anomaly • Time required • Personnel required	No discrimination performed

Instrument Cost: We estimate the instrument cost of MSEMS as follows. The Geonics EM61, the RTK GPS, and the Geometrics total field magnetometer, are COTS equipment used on many DGM surveys that are either purchased and amortized or rented by DGM contractors. This is precisely why the design philosophy of MSEMS was to allow the use of these existing sensors if a contractor already had them in inventory. Approximate costs of these sensors are listed in the table below. The MSEMS-specific pieces consist of the MPI box and its associated cabling, ancillary EM61 cables and the 3rd EM61 wheel, and the custom magnetometer boom and battery box. We have recently duplicated the MPI box and are attempting to accurately segregate non-recurring engineering (NRE) costs from production costs; the $20k number to build an MPI box represents an estimate, not an actual production cost.

Table 12: Estimated Equipment Cost for MSEMS Hardware

COTS Equipment	
Geonics EM61 Mk2A	$35,000
RTK GPS	$40,000
Geometrics 822A Magnetometer	$25,000
MSEMS-Specific Equipment	
Ancillary EM61 (3rd wheel, sync cable)	$2,000
Custom MPI Box and Cabling	$20,000
Custom Boom and Battery Box	$3,000
Total	$125,000

From this estimate, the cost of the MSEMS-specific pieces is $25k, or about 20% of the total cost. Note that, under this project, the EM61 and magnetometer were purchased but the RTK GPS was loaned by SAIC.

Mob/Demob: Because MSEMS is man-portable, deployment costs are low; it can be crated and shipped and does not require tractor-trailer transport like a vehicular system. The main components pack into the standard Geonics EM61 silver road cases. A hard ski case has been procured to protect the magnetometer boom. The mob/demob for the two-man crew, including appropriate preparation and packing, is approximately $10.8k, which includes $1000 for shipping.

Site Preparation: No site preparation above that which is necessary for a COTS EM61 is required.

Instrument Setup Costs: The instrument setup is similar to a COTS EM61, with a few extra boxes and cables. The two-man crew has routinely set the system up and began collecting data within an hour of arriving at a site. Thus we estimate the cost as an hour of two people.

Survey Costs: The survey costs are similar to those of a COTS EM61, and these of course depend on many factors, including site topography, hours of access to the site, weather, GPS problems, etc. EM61 work is often quoted using a one to two acre per day coverage rate, depending on the line spacing. Slightly more care must be taken with MSEMS to pause the system at the end of a line, and turn it around and orient it properly before beginning to collect additional data. It has been estimated that this takes no more than ten seconds per line. To calculate an actual per hectare cost based on the YPG demonstration, we multiply the 18 data sets and the size of the blind grid to get a total of 28,800 square meters, or 2.88 hectares (7.1 acres). The length of the survey was three days, yielding .96 hectares per day, or about 8.3 hours per hectare using a two-man crew. The daily rate for the PI and an equipment operator in the field was $2713/day, yielding $2826/hectare.

Detection Data Processing Costs: Processing of MSEMS' EM61 data is no different than processing data from a COTS EM61; the data must be de-spiked, lag-corrected, and background-leveled. These steps are performed in Geosoft Oasis Montaj. MSEMS' magnetometer data requires the additional step of notch-filtering out the instrument-specific 15 Hz hum (created by the 60 Hz ambient electrical hum aliasing at 15 Hz because it is sampled at 75 Hz). We usually perform this step in our own software, but Oasis is capable of notch-filtering the data as well. Because our magnetometer data is 1PPS-triggered, it never requires latency correction. The magnetometer and EM61 data can independently be read into Oasis and independently thresholded to generate a mag dig sheet and an EM61 dig sheet. *At present, however, there is not a turnkey method of combining these dig sheets.* Different survey jobs have had different requirements. Production surveys have tended to utilize EM61-derived target picks, with any additional unique magnetometer target picks added in by hand. We have recently developed spatial correlation software to read in Oasis-generated mag and EM target databases and output a single database with a column indicating whether each target was detected by the EM61, by the magnetometer, or by both.

Discrimination Data Processing Costs: The scope of this project, to date, has not included discrimination processing.

8.2 Cost Drivers

In analyzing cost, it cannot be stressed enough that each survey has different requirements, and that these differ from ESTCP's dem/val requirements. Additional work such as GIS, advanced discrimination processing, target relocation, digging, and remediation are not included.

In early surveys using new technology, a primary cost driver is the presence of the senior inventor/engineers on the site. With the vehicular system VSEMS, the inventor's presence is necessary because of the degree of complexity of the equipment. It is expected that, because MSEMS is a simpler system, hosted on an EM61 man-portable platform, this will not be as crucial an issue. Because MSEMS is man-portable and uses COTS sensors, and because the magnetometer is hosted on the EM61 coil, there is no tow vehicle or towed platform; thus the components can be crated and shipped. We also employ fewer personnel on-site than some production geophysical houses. SAIC generally performs surveys using a crew of two expert operators. This is sufficient except when survey traverses are difficult to see due to site size or terrain; in this case, "flaggers" are employed, usually as local temporary labor, to hold flags to help the vehicle driver to see his previous traverse. For surveys on active MEC ranges contracted through the Army Corps of Engineers, a higher level of on-site EOD support is mandated, whereas on these demonstration surveys, no EOD support is required.

8.3 Cost Benefit

The technology unique to project MM-0414 and the prior project MM-0208 – interleaving magnetometer data between EM61 pulses which allows total field magnetometer and EM61 data to be acquired simultaneously – should result in a nearly 50% cost reduction in geophysical data collection efforts as compared to use of magnetometers and EM61s sequentially instead of simultaneously. The question then becomes: When is the use of both sensors strictly necessary, and what is the cost benefit in surveying with both sensors? The Program Office's view has been that a benefit *may* come from the added discrimination information to be gained from the increased data quality derived from having both sensors co-located on a common platform. Validating this is not part of this or the previous program, and as such the assertion has never been proven either way (though we should find out by deploying MSEMS in the upcoming San Luis Obispo Classification Study). In contrast, the PI's view is that discrimination is not required in order for concurrent mag/EM to be useful. Both VSEMS and MSEMS have been deployed on real sites, and unique detections – anomalies of a size and shape consistent with MEC – have been pulled out of both sensor data sets. Due to a lack of ground truth, we do not have the validation data to prove that these unique detections were in fact MEC.

Viewed narrowly, sites that may require surveys with multiple sensors include sites where the MEC population and/or disposal history is not well known, sites with complex or unexpected geology, or sites where the detection and discrimination requirements are very stringent, such as Camp Sibert or the Former Lowry Bombing and Gunnery Range, where the presence of chemical munitions made the economics of simply digging every item above threshold impossible. Our experience, however, has shown us that nearly *every site* has an MEC population and/or disposal history that is not well known.

9 Implementation Issues

9.1 Environmental and Regulatory Issues

Because the technology involves combining the two sensors most validated against UXO for digital geophysical mapping – total field magnetometers and EM61 pulsed induction coils – there are no specific regulatory issues above those that apply to all DGM data. Any applicable regulatory issues involve detection and discrimination systems of all kinds (i.e., how clean is clean, etc) and are not specific to this project or technology.

9.2 End-User Issues

Because the sensors are not only COTS but the very sensors already well-used for MEC DGM, there should not be serious impediments to use. The design philosophy of MSEMS was to build a box that let us and/or other DGM contractors plug a COTS EM61 and magnetometer and GPS into it, and we have hewn close to that philosophy. We have the added benefit of using the EM61 Mk2 which is a fairly ergonomically well-thought-out system. The fact that MSEMS is hosted on an EM61 makes it look familiar to the user community and should help acceptance. We have tried to disturb it as little as possible, even using the Allegro hardened PDA as the data acquisition computer (running our software instead of Geonics').

9.2.1 Post-YPG System Improvements

Since the YPG demonstration, many incremental improvements have been made to the system.

Elimination of Doubly-Recorded Data Values: A bug in the software was causing EM61 data values to occasionally be doubly recorded. This manifests itself as steps on the steep parts of the anomaly curves in the plots shown above, which make the peaks look unnaturally jagged. This bug was corrected immediately after the YPG deployment.

Magnetometer Battery and Balance of the Cart: Three pieces of operator feedback at YPG were that 1) the COTS Geometrics waist-worn magnetometer battery belt pack interfered with the COTS Geonics backpack; 2) collectively the backpack and magnetometer battery placed a lot of weight on the operator, and 3) in the mag-in-front configuration, the front end of the MSEMS cart was light and tended to lift too easily. We addressed the later in the field by strapping a gallon jug of water to the boom, but it occurred to us that all of these problems could be solved by relocating the magnetometer battery off the operator and mounting it on the magnetometer boom to act as ballast. The new battery box is shown in the figure below.

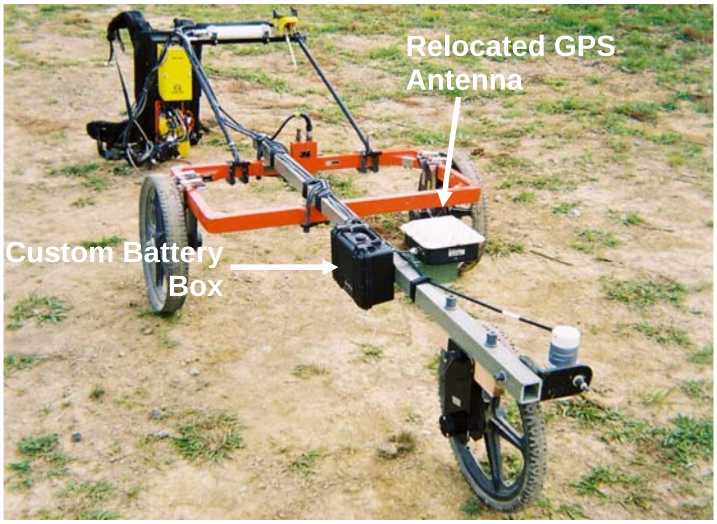

Figure 35: MSEMS post-YPG with custom battery box relocated to boom

Being Able to Pull as Well as Push: Another important piece of feedback from YPG was that pushing the cart was only possible because the calibration and blind grids were extremely smooth. In real-world DGM, rough terrain often makes it necessary to pull the EM61 behind you, and our use of a 3rd wheel amplifies that necessity. Pulling rather than pushing is mostly an issue of knowing where the GPS antenna is relative to both sensors, and being able to correctly interpret "sensor in front of the GPS" versus "sensor behind the GPS." We relocated the GPS antenna down onto the boom, halfway between the sensors (figure 37 above), effectively splitting any positional error between the sensors and used a different GPS antenna with a lower signature to both sensors. The resulting system, with the battery box and GPS antenna relocated, and capable of being pulled as well as pushed (figure 39 below), was demonstrated at Camp Sibert, AL.

Figure 36: MSEMS cart, with relocated battery and GPS, pulled over rough terrain at Camp Sibert Site 8

Improved Error Reporting: The MPI box not only houses the interleaving hardware; it also acquires all magnetometer, EM61, and GPS data. It sends these data every second to the Allegro PDA running custom software that acts as the operator interface. If any data stream (magnetometer, EM61 or GPS) ceases arriving at the MPI box, it has to figure out what’s wrong and send a message to the Allegro so that the operator can see “EM Battery Low,” “GPS Data Stopped,” “no magnetometer data,” or other messages. These messages were not all working at YPG. Subsequent to YPG, much software development time was put into error reporting between the MPI box and the Allegro. This has been highly successful, as battery and cable failures are the bane of DGM, and quick troubleshooting of these common failures greatly reduces downtime.

Incorporation of EM61 Mk2A with No Backpack: Under contract W909MY-08-C-0011, SAIC is developing a Simplified Combined EMI and Magnetometer System (SCEMP) for the Humanitarian Demining division of the Night Vision and Electronics Sensors Directorate at Fort Belvoir VA. The goal is to simplify the concurrent mag/EM technology much as possible for use by a lightly-trained deminer for MEC detection in Southeast Asia. The new configuration will include no backpack, unified packaging of electronics boxes, reduced cabling, and a simplified GUI. Pursuant to those goals, an EM61 Mk2A system was purchased from Geonics. The Mk2A has no backpack; instead, the EM61 electronics box is mounted on the handle, and the EM61 battery is mounted in the center of the coil. As part of early testing of SCEMP, we have combined MSEMS pieces with the EM61 Mk2A. The resulting system (figure 37) is more comfortable for the operator, and has fewer cables.

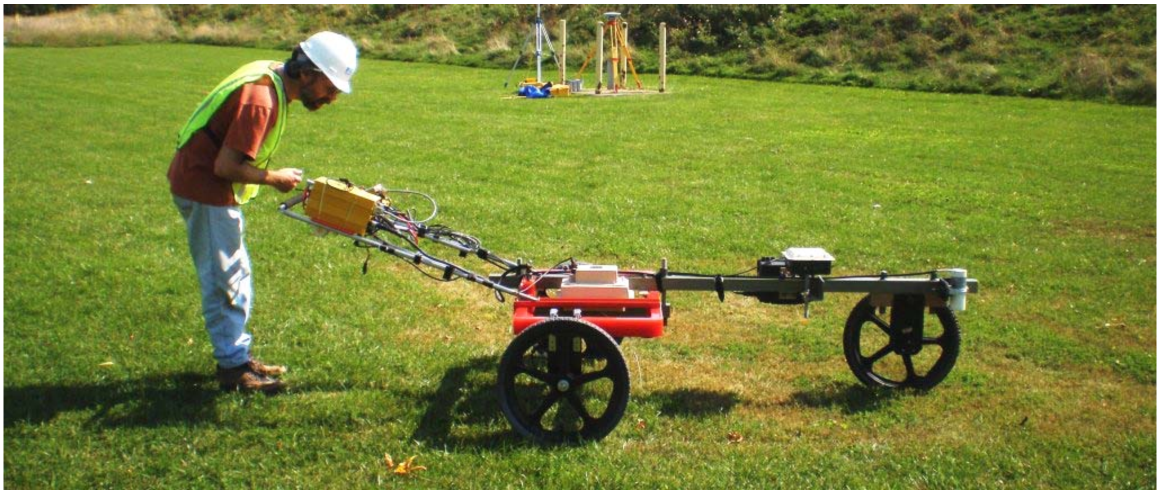

Figure 37: MSEMS utilizing an EM61 Mk2A with no backpack as part of testing of a Simplified Combined EMI and Magnetometer Prototype (SCEMP) for NVESD HD division

Use of GPS without 1PPS Output: Like the previous interleaving hardware developed under MM-0208 (VSEMS), MSEMS’ interleaving hardware uses the 1PPS output from a GPS to trigger the magnetometer data acquisition in one-second data blocks (the interleaving between EM pulses is conducted within each data block). This method acquires magnetometer data that is always correctly synchronized to GPS and thus requires no latency correction. However, the compact integrated all-in-one GPS units such as the Trimble 5800 favored by geophysical contractors do not have a 1PPS output. Unlike the VSEMS hardware, the newer MSEMS hardware was designed with the capability to function without an external 1PPS and to generate its own internal timing if 1PPS is not available. In order to maximize the ability to allow geophysical contractors to combine an MPI box with equipment they already have in inventory and support these compact integrated GPS devices, we have modified the firmware in the MPI box to make use of the designed-in capability to function without a 1PPS input. Note that, when used in this mode, the benefit of driving the magnetometer data acquisition with 1PPS is lost, resulting in magnetometer data that, like other geophysical data acquired by many COTS systems, may require latency correction.

9.2.2 Subsequent Use of the Technology

Camp Sibert Survey: In May 2007, CEHNC deployed MSEMS to Camp Sibert AL for further shakedown and testing under the CRADA. MSEMS surveyed the Pineview Circle geophysical proveout plot, then completed two acres of data acquisition in Site 8. This was a substantially more rugged area than YPG, and was treed. The site is shown in figure 36 above. Magnetometer and EM61 data are shown in the figures below.

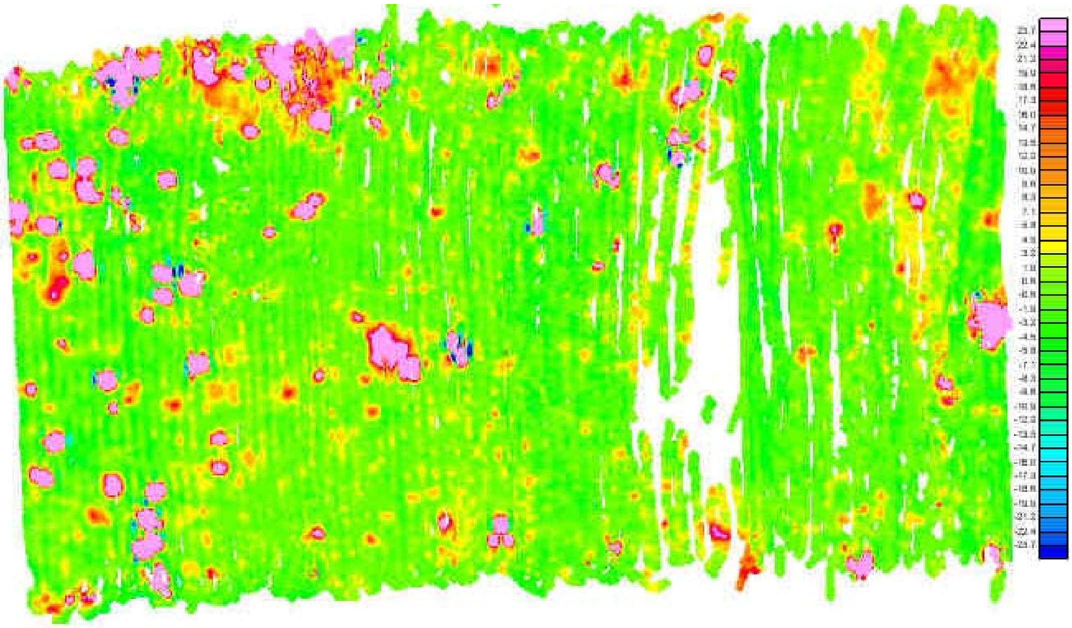

Figure 38: 2 acres of EM61 data (gate1) acquired with MSEMS at Camp Sibert Site 8 (+- 25 mV)

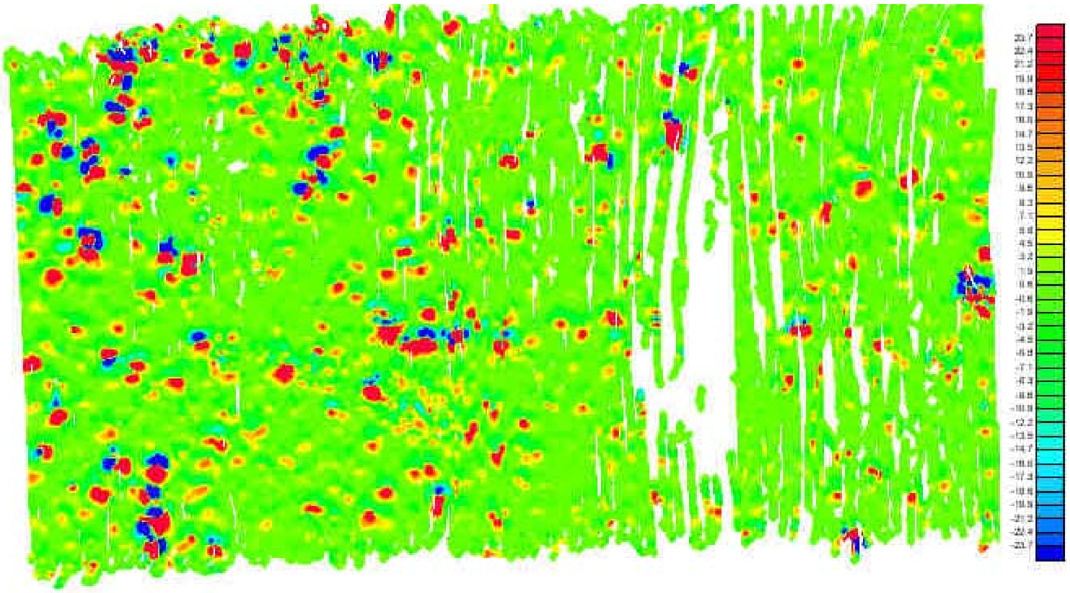

Figure 39: 2 acres of magnetometer data acquired with MSEMS at Camp Sibert Site 8 (+- 25 nT)

Camp Howze Survey: In July 2007, CEHNC deployed both MSEMS to Camp Howze TX to survey a set of discrimination grids on a live 60mm site. A GPO plot and eight 100x100 foot grids were surveyed.

Use of the MPI Box to Evaluate Vehicle Magnetic Signatures: During 2006 and 2007, the MPI box was used extensively in support of ESTCP project MM-0605 (Use of COTS Vehicles for Towed Array Magnetometry). Although MSEMS employs a single magnetometer and EM61, the MPI is capable of hosting two of each sensor. The small form factor of the box enabled us to design an easily transportable electronics package and a small towed platform with two magnetometers and two EM61s, and move the platform and all related electronics quickly and easily between different vehicles used for small area surveys to measure vehicle magnetic signature. The resulting “TSEMS” system may be used for areas too large for MSEMS but too small to justify the deployment costs of the full-sized VSEMS.

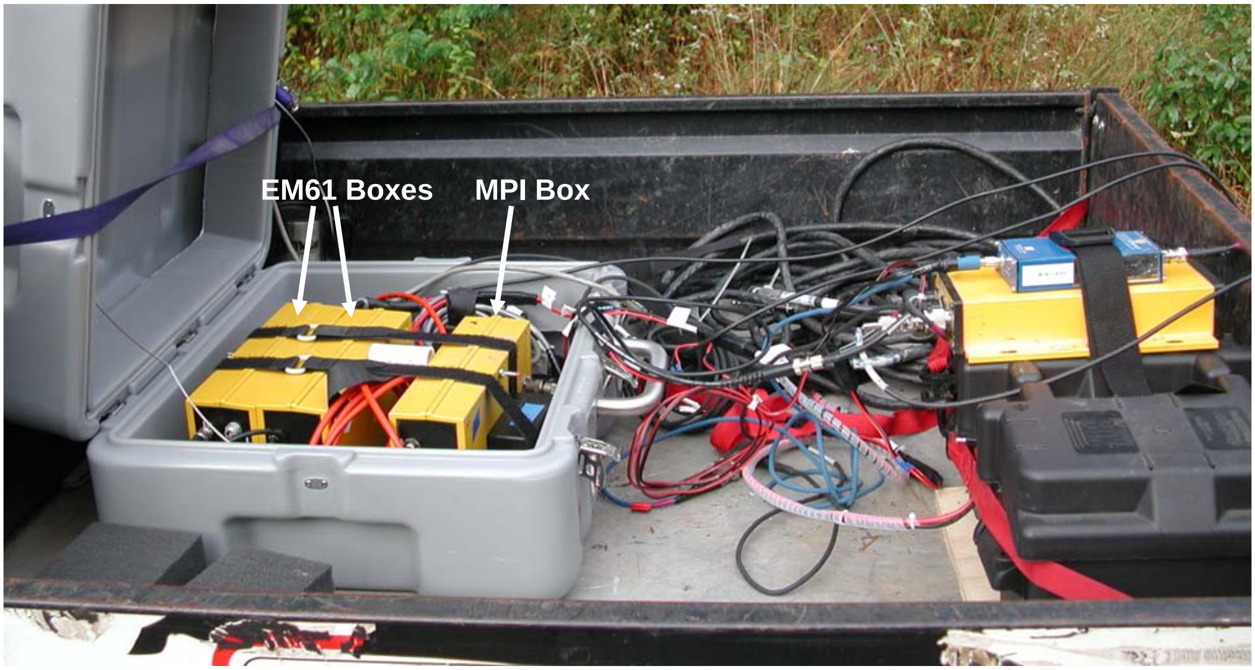

Figure 40: MPI box used in support of vehicle magnetic signature measurement

Figure 41: "TSEMS" using MPI box, two magnetometers and two EM61s, towed by an ATV

Chappaquiddick MEC Survey: In July 2008, MSEMS was employed by CEHNC to survey several miles of beach along Chappaquiddick island, off Martha's Vineyard MA, where several MEC items had been found by bathers. In one survey pass, CEHNC was able to collect both magnetometer and EM61 data to be used to evaluate which sensing technology should be called for in an eventual RFP.

Underground Storage Tank Survey: In September 2008, MSEMS was deployed in a commercial survey to detect underground storage tanks at an HTRW site. The site was extremely cluttered, with above-ground storage tanks fed by overhead plumbing. Contrary to the assumption that the EM61 would outperform the magnetometer in such a cluttered environment, several potential tank targets became apparent once the magnetometer data were reduced to analytic signal in Oasis.

NAOC Tech Transfer Workshop: The system generated much interest when it was demonstrated at the 2008 NAOC Tech Transfer workshop. Comments were publically made in the Q&A session at the end of the workshop that, of all the technologies demonstrated, MSEMS was the only one that was field-ready.

Development of Additional MPI Boxes: We have made minor changes in connector placement on the initial MPI box, and have updated all documentation to allow the production of additional boxes. The first of these was produced and tested in August 2008. Naeva Geophysics, Parsons, and Weston Geophysics have all expressed serious interest in demonstrating and / or purchasing an MPI box.

Planned Use of an MPI Box in MM-0733: ESTCP project MM-0733 (Underwater Simultaneous EMI and Magnetometer System, or USEMS) is planning on using an MPI box in a COTS fashion to simultaneously acquire magnetometer and EM61 data from a towfish rigidly attached to the back of a boat. Initial USEMS testing is expected in early 2009.

9.3 Relevant Procurement Issues

The EM61, GPS, and magnetometer are COTS, but the MPI box is custom. We have updated the drawing package and are attempting to segregate NRE costs from manufacturing costs in order to develop an accurate cost model for small-scale production.

9.4 Availability of the Technology

As above, we are on the verge of building more boxes. We plan to put together a “kit” consisting of the MPI box that performs the interleaving, the custom cabling, and a magnetometer mount, and supply this to CEHNC. If CEHNC regards the kit as viable, we will try and market it to other DGM contractors. As said above, we already have serious interest from three DGM contractors.

9.5 Specialized Skills and Training

Because the sensors are not only COTS but the very sensors already well-used for MEC DGM, training is minimal. MSEMS has already been operated by field technicians accustomed to operating an EM61 with a few hours of training.

10 References

Siegel, Robert. 2004. *Combined Electromagnetic and Magnetometer Data Acquisition and Processing, Project MM-0208, Final Report*.

Siegel, Robert. 2006. *MM-0414 MSEMS Demonstration Plan for YPG Survey*, submitted to ESTCP Program Office 6/8/2006.

Siegel, Robert. 2007. *MM-0414 MSEMS YPG Report*, submitted to ESTCP Program Office 12/21/2007

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