FINAL REPORT

Simultaneous Magnetometer and EM61 MK2 Vehicle-Towed Array for Wide Area Assessment

ESTCP Project MM-0531

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SAIC, Inc.

Environmental Security Technology Certification Program

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14. ABSTRACT

The Vehicular Simultaneous EMI and Magnetometer System (VSEMS) was deployed at the former Kirtland Bombing and Gunnery Range during the fall of 2006 as part of the ESTCP Wide Area Assessment Pilot Program. Magnetometer and EM61 Mk2 data were concurrently acquired on pre-planned transects (generated by Visual Sampling Plan on the basis of existing data from a Conceptual Site Model) to bound the extent of known bombing targets and assist in discovery of new ones. Data were analyzed overnight to provide inversion results (location and depth estimates) for objects of interest in the data. These data were used by another contractor, and by the ESTCP program office, to refine the CSM and to specify new transects. High-resolution 100% geophysical survey data were also acquired in areas located radially outward from bombing targets to determine anomaly fall-off, and in areas that were flagged as being of interest after interrogation of data from the airborne sensing layers. 193 acres of transects and 159 acres of 100% geophysical survey areas were acquired, for a total of 352 acres. 9969 anomalies were extracted from the 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 Sciences Board
EM:	Electromagnetic
EMI:	Electromagnetic Induction
EQT:	US Army Environmental Quality Technology Program
FUDS:	Formerly Used Defense Sites
GPS:	Global Positioning System
JPG:	Jefferson Proving Grounds, Indiana
MPC:	Magnetometer Period Counter
MTADS:	Multi-sensor Towed Array Detection System
NAVEODTECHCEN:	Naval Explosive Ordnance Technology Center
NRL:	Naval Research Lab
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

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Abstract

The Vehicular Simultaneous EMI and Magnetometer System (VSEMS), developed under ESTCP project MM-0208, was deployed at the former Kirtland Bombing and Gunnery Range during the fall of 2006 as part of the ESTCP Wide Area Assessment Pilot Program. Magnetometer and EM61 Mk2 data were concurrently acquired on pre-planned transects (specified by another contractor running Visual Sampling Plan on the basis of existing data from a Conceptual Site Model) to bound the extent of known bombing targets and assist in discovery of new ones. Both magnetometer data and EM61 data were examined overnight to extract visually-derived information on whether the transects appeared to run over a bombing target. Magnetometer data were analyzed overnight to provide inversion results (location and depth estimates) for objects of interest in the data. These data were used by another contractor, and by the ESTCP program office, to refine the CSM and to specify new transects. In addition to transects, high-resolution 100% geophysical survey data were also acquired in areas located radially outward from bombing targets to determine anomaly fall-off, and in areas that were flagged as being of interest after interrogation of data from the airborne sensing layers. 193 acres of transects and 159 acres of 100% geophysical survey areas were acquired, for a total of 352 acres. A total of 9969 anomalies were extracted from the data.

1 Introduction

1.1 Background

One of the recommendations of the 2003 Defense Sciences Board (DSB) Report on Unexploded Ordnance was to immediately assess the scope of ordnance contamination of roughly ten million acres of land on FUD and BRAC sites and rapidly ascertain what percentage of this acreage actually contains UXO. Airborne technologies are well-suited for acquiring data over sites comprising thousands of acres and assessing the degree of UXO contamination. High-altitude fixed-wing airborne visual and LIDAR technologies have been shown to be effective in detecting ordnance-related features, and helicopter-based magnetometry has been shown to be effective in detection of individual UXO objects of a range of sizes. However, because magnetic field strength falls off as one over the cube of the distance ($1/R^3$), the increased sensor height of helicopter-based sensors makes detection of objects smaller than 60mm very difficult. Pulsed induction sensors such as the Geonics EM61, frequently the sensor of choice for ground-based UXO detection, have an even steeper ($1/R^6$) falloff. Further, there are limits to the safe terrain-following of helicopter-based systems. For these reasons, ground-based DGM systems have a role to play in wide area assessment, both for close-in detection of object boundaries, as well as in validation and verification of the results from airborne surveys. The technology used for this project – the Vehicular Simultaneous EMI and Magnetometer System (VSEMS – formerly known as the Simultaneous Multisensor STOLS) has the added benefit of collecting total field magnetometer and EM61 data *simultaneously* in a single survey pass, thereby acquiring data

from the two sensors most widely used for UXO detection and most widely accepted by regulators. For Wide Area Assessment, the two sensors can be useful in a) detecting different objects, b) providing redundant data in the event of unanticipated noise or clutter situations, and c) helping to screen out geology.

1.2 Objectives of the Demonstration

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

- To use VSEMS to collect magnetometer and EM61 DGM data on pre-planned transects (generated by another contractor running Visual Sample Plan (VSP) transect-planning software) so that the WAA project as a whole could use these data to refine bombing target locations, extents, and edges that were already approximately known from conceptual site models.
- To visually inspect and interpret the transect-based data for the presence of bombing target edges or extent, or evidence of other subsurface entities such as trenches and pits, that might be of interest in a WAA context.
- To extract anomaly locations and size estimates from the transect data and generate anomaly lists which, in turn, were fed to VSP to design further sets of transects.
- To use VSEMS to collect and analyze full-coverage data over selected areas for validation purposes, extracting anomaly locations and depth and size estimates from the surveyed areas.
- To visually inspect and interpret the full-coverage data for the presence of bombing target edges or extent, or evidence of other subsurface entities such as trenches and pits, that might be of interest in a WAA context.
- To demonstrate and validate the use of VSEMS, which had been further improved over prior fieldings with the installation of a new EM61 Mk2 array, as a viable survey-ready DGM tool that consistently and reliably generates very high-quality concurrent EM61 and magnetometer data.

All of the above objectives were met. The system collected over 350 acres of concurrent magnetometer and EM61 Mk2 data at the Former Kirtland Bombing and Gunnery range, and these data were an asset to the Wide Area Assessment Pilot Program.

1.3 Regulatory Drivers

The Wide Area Assessment Pilot Program itself was driven by congressionally-mandated desire to shrink the footprint of potentially UXO-contaminated land as per the DSB report. 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.

1.4 Stakeholder / End-User 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 end-user issues above those that apply to all DGM data.

2 Technology Description

2.1 Technology Description and Application

Overview

The VSEMS used on this project was originally developed by SAIC with support from ESTCP under project MM-0208, implemented through a CRADA between SAIC and the US Army Corps of Engineers Huntsville Center (CEHNC). VSEMS is the only system in the world that simultaneously collects high-quality data from COTS total field magnetometers and COTS EM61 Mk2 pulsed induction sensors on a single towed platform. It substantially leveraged GEO-CENTERS' (now SAIC) existing "STOLS" GPS-integrated towed magnetometer array as a development platform, and augmented it with newly designed interleaving hardware, a new proof-of-concept non-metallic towed platform, and existing EM61 electronics and coils. Further development which integrated modern Geonics EM61 Mk2 hardware was funded by the US Army EQT program and by ATC. Because portions of the system are 13 years old whereas other portions were only designed to survive a single 2002 APG fielding, the system is best operated by its inventors. Through continuous incremental improvement and careful operation, the system has proven itself capable of reliably prosecuting large geophysical surveys.

Theory of Operation

Historically, simultaneous deployment of magnetometers and pulsed EM such as the Geonics 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 nT, rendering concurrently-collected magnetometer data useless.

Under ESTCP Project MM-0208, SAIC developed hardware that monitors the pulse from the EM61, 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 newly-developed 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 EM61 transmission pulse. The system timing then uses a programmable waiting period and a sampling period. The 75 Hz EM61 transmission pulse 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 figure 1. Note that in this new design, acquisition of magnetometer data is triggered by the receipt of a 75 Hz strobe from the EM61 electronics after the GPS' 1 PPS.

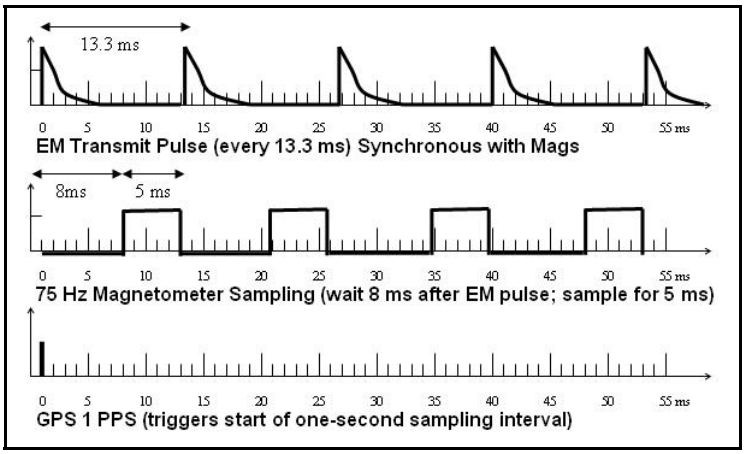

Figure 1: Conceptual Timing Diagram of Synchronous EM61 and Magnetometer Data Acquisition. Note that magnetometer sampling only occurs when EM61 transmission pulse has died down.

Key Design Criteria

In addition to the interleaving electronics and software that sample the magnetometers after the secondary field induced by the EM61 pulse has rung down, the total system design that hosts both the magnetometers and the EM61s in a low-noise environment, utilizing a low-ferrous vehicle and a non-metallic towed platform, is a key design factor.

Schematics, Figures, and Layout

The timing diagram for synchronous data acquisition is shown in the figure above. The system, showing the major components (low-ferrous vehicle, non-metallic platform, GPS, magnetometer array, and EM61 array), is shown below in figure 2.

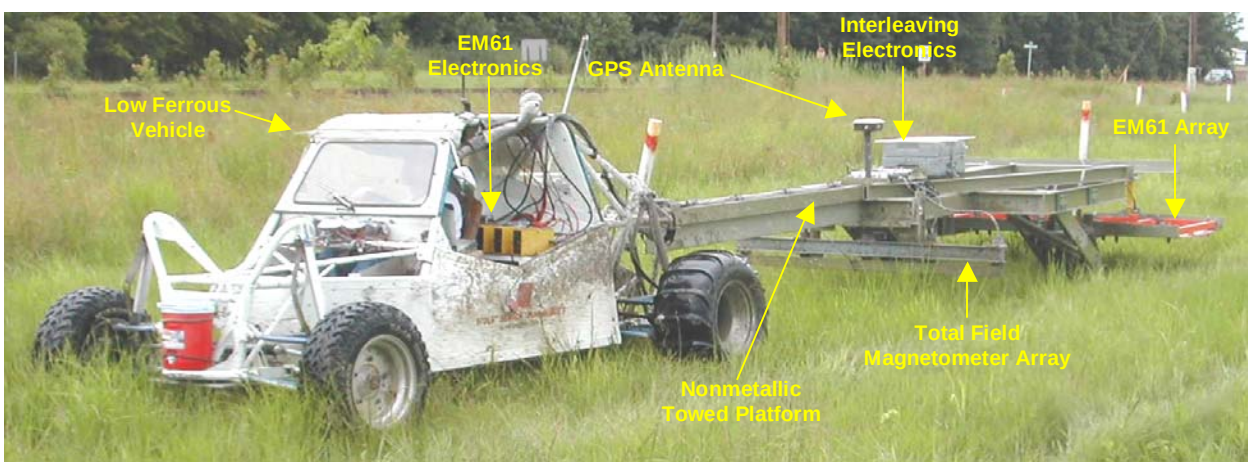

Figure 2: Layout of Major VSEMS Components

2.2 Previous Testing of the Technology

The VSEMS technology is well-tested as described in the final reports for project MM-0208. Additional improvements and deployments of the technology include:

- 2003. Incremental improvements funded by CEHNC (platform reinforcement).

- 2003. VSEMS surveys 100 acres at the Former Lowry Bombing and Gunnery Range in Aurora, CO.
- 2003. Incremental improvements funded by CEHNC (additional EM61 channels, larger EM61 coils, rugged computer, and additional platform reinforcement).
- 2003. VSEMS surveys 100 acres at Portland International Airport.
- 2004. VSEMS surveys 100 acres at a mid-Atlantic housing site.
- 2004. Incremental improvements funded by EQT (new EM61 Mk2 array).
- 2005. VSEMS surveys APG and YPG Standardized UXO Test Sites.

2.3 Factors Affecting Cost and Performance

The economics of surveys bid at a fixed acreage rate per day depend on the coverage rate. Smooth, grassy areas that have already been run over by heavy equipment are far more vehicularly navigable than rocky or stumpy areas, and resulting lower coverage rates engender higher survey cost. This is particularly true due to the proof-of-concept nature of the fiberglass towed platform, which has exceed all expectations but still must be treated gently.

Any activity that lessens the percentage of the survey day actually spent collecting data dramatically cuts into survey efficiency. These include: daily drive to the survey site; mandated breaks for UXO techs; mandated daily QC procedures; time spent locating site boundaries, grid squares, and transect endpoints; and downtime due to equipment malfunction and troubleshooting. These things are not unique to VSEMS but should not be overlooked.

Because VSEMS is a vehicular-towed array, it requires a tractor / trailer to transport it, which is more costly than using a man-portable system that can be cheaply shipped. As such, driving services must be contracted.

At the Kirtland site, the following factors, in approximate decreasing order of priority, affected productivity:

- GPS issues stemming from the size of the site (the distance between GPS base and rover), and interference in the radio link between base and rover stemming from the high amount of construction activity in Albuquerque using GPS
- Learning curve in first inputting, then following, pre-planned transects
- Switching between transect surveys and 100% geophysical surveys (driving to, then locating, the corners of the 100% geophysical survey areas)
- Downtime due to mechanical and electrical issues
- Limitation of forward rate of advance due to roughness of terrain and fragility of prototype fiberglass towed platform
- Slow forward rate of advance needed to maintain planned down-track EM61 data spacing, particularly in 100% geophysical survey areas
- Fences interfering with planned transect lines
- Weather
- Geometry of 100% geophysical survey areas (short lines requiring many turn-arounds)

Individually, the COTS total field magnetometers and EM61 Mk2 sensors used by VSEMS have well-documented performance envelopes that are not altered by their presence in VSEMS. As

such, the system's performance has the sensors' fundamental limitations of sensitivity; the magnetometer signal falls off as $1/R^3$; the EM61's as $1/R^6$. Magnetometers are sensitive to the presence of both ferrous cultural objects as well as iron-bearing soils, and thus their usefulness is limited on sites with dense building configurations or complex geologies. EM61s are more immune to these things, but this is partially due to their inherent decreased sensitivity, and as such they will not detect deep UXO objects as well as magnetometers.

2.4 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 VSEMS. 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. MTADS, in both its NRL and Blackhawk-fielded configurations, has a separate towed magnetometer and towed EM61 platform, and thus requires two separate surveys to acquire both mag and EM data sets. Further, since VSEMS' sensors are mounted on a common rigid sensor platform, this all but ensures that the two sensors will run over the same ground locations, and thus essentially eliminates another problem of performing two separate surveys – that the data acquired in separate survey passes may not traverse the same objects in the same way, if at all, which may limit the efficacy of the data for discrimination algorithms. Note that, in descriptions of data processing below, when we refer to the data being processed on a 10 cm grid, this refers to the use of in-house software to visualize the magnetometer and EM61 data and to invert the magnetometer data. However, when the magnetometer and EM61 data sets are each geolocated and processed and written out in an ASCII format for importation into Geosoft Oasis Montaj™, there is no 10 cm quantization of the geolocation data.

The main limitations of the technology as compared to MTADS are that the cross-track magnetometer spacing in MTADS is tighter than VSEMS (1/4 meter versus ½ meter). The MTADS sensor platforms are instrumented to measure pitch and roll, and their data processing software uses these data to more accurately position sensor updates. However, note that these are limitations on the specific *implementation* of the technology as manifested in the current VSEMS. The core technology – interleaving acquisition of magnetometer data between EM61 pulses – does not have these limitations. The main limitation of the core interleaving technology is that it applies only to pulsed induction EM systems, and is not applicable to frequency-domain EM systems. There are other competing technologies for concurrent magnetometry and EM (G-Tech, AETC), but as of this date, none of them use a commercial-off-the-shelf industry-standard EM61, and none of them are conducting real-world 350-acre surveys.

There is an argument that the forward rate of advance of VSEMS is limited by the EM61's slower update rate (10 Hz as compared to 75 Hz for the magnetometer update rate), and thus that the concurrent use of mags and EM61s is inherently less productive than magnetometers alone. We feel that, if all factors were equal, this would be true, but that all factors are almost never equal. For example, at the Kirtland survey, we could not have driven much faster than we already did while towing our prototype fiberglass platform. On extremely hospitable (e.g., soccer field) topography, the concurrent use of EM61s *will* limit speed, but this should be taken in the context of the list of other factors above.

3 Demonstration Design

3.1 Performance Objectives

The following were the primary performance objectives from the demonstration test plan. These were provided by the ESTCP Program Office for both of the ground-based systems on the Wide Area Assessment Pilot Program (e.g., MTADS and VSEMS).

Table 1: Primary Transect Performance Objectives/Metrics and Confirmation Methods Relating to Detection of Target Areas and Target-Free Areas

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Objective Met?
Qualitative	*Reliability and Robustness*	*General Observations*	*Operator feedback and recording of system downtime (length and cause)*	*System was Reliable* *Yes*
	Terrain / Vegetation Restrictions	*General Observations*	*Correlation of areas not surveyed to available data (topographical maps, etc.)*	*System surveyed vehicularly navigable areas* *Yes*
Quantitative	*Survey Rate*	*12.5 acres / day*	*Calculated from survey results*	*9.5 acres/day* *No*
	Data throughput	*All data from day x processed for anomalies and submitted by end of day x+1*	*Analysis of records kept / log files generated while in the field*	*Analyzed Anomalies Submitted by Next Day* *Yes*
	Percentage of Assigned Coverage Completed	*>95% as allowed by topography*	*Calculated from survey results*	*All Transects Completed* *Yes* *75% of 100% geophysical survey Areas Completed* *No*
	Transect Location	*95% within 2 meters of requested transects*	*Calculated from survey results*	*Most Transects Aligned* *Yes*

These are discussed fully in section 4 below.

The following were the secondary performance objectives from the demonstration test plan, again, as provided by the ESTCP Program Office.

Table 2: Secondary Transect Performance Objectives/Metrics and Confirmation Methods Relating to Characterization of Target Areas

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Objective Met?
Qualitative	*Ability of Analyst to Visualize Targets from Survey Data*	*All targets in survey area identified*	*Data Analyst feedback and comparison to 100 geophysical survey data / other demonstrators results*	*Targets Readily Visualizeable Yes*
Quantitative	*Location of Inverted Anomalies*	*< 0.15 m horizontal < 30% vertical*	*Comparison to Test Strip Ground Truth*	*0.13 m horizontal 0.20 m vertical Yes*
	Probability of False Alarm	*<5% of identified anomalies correspond to no ferrous metal source*	*Validation Sampling (100% survey) and/or Remediation Sampling (digging)*	*13.5% correspond to apparent geology No*
	Signal to Noise Ratio (SNR) for Calibration Objects	*+/- 10% of expected from Standardized UXO Technology Demonstration Site Performance*	*Comparison of Calibration Objects results to documented Standardized UXO Technology Demonstration Site performance*	*Inconsistent No*
	Data Density	*> 15 pts / m^2*	*Calculated from survey results*	*Average 22 pts / m^2 yes*

These are discussed fully in section 4 below.

3.2 Selecting Test Site

The Former Kirtland Precision Bombing Range (PBR) was selected by the ESTCP Program Office due to a combination of size, topography, and development pressure. It was a nearly ideal site for use of a ground-based system on a Wide Area Assessment Pilot Program, as the topography was extremely hospitable to ground-based vehicular technology.

3.3 Test Site History / Characteristics

The former Kirtland PBR consists of a total of ~38,000 acres, encompassing multiple target areas. It is located west of Albuquerque, NM, and served as a training area for Kirtland Air Force Base during WWII. The WAA Pilot Program was conducted on two parcels totaling 5000 acres on either side of Double Eagle Airport. The study area is known to contain three precision bombing ranges and an additional simulated oil refinery target. Munitions known or suspected to have been used on the site include 100-lb practice bombs and 250-lb high explosive bombs. A certificate of clearance was issued for one portion of the site, Target N3. It is reported that 17,000 lbs of scrap were stored in this area.

3.4 Present Operations

Currently the WAA study area is undeveloped. Portions are planned for commercial or industrial development within the next decade, and airport expansion into these lands is possible.

3.5 Pre-Demonstration Testing and Analysis

VSEMS was successfully demonstrated at the Standardized UXO Demonstration Test Site at Aberdeen Proving Grounds (APG) in 2002 as part of ESTCP project MM-0208. In 2003, VSEMS was successfully employed to survey 100 acres surrounding the Jeep Demo Range at the Former Lowry Bombing and Gunnery Range in Aurora CO. The original EM configuration of three ½ x ½ meter coils was replaced with five 1 x ½ meter coils, and in 2004 the system was used to characterize a 100 acre site suspected of containing a munitions-filled trench at a site near Portland International Airport, OR. The original single time gate EM61 electronics were replaced with modern EM61 Mk2 electronics, and the system was used for five separate commercial UXO surveys at formerly used defense sites at Myrtle Beach, SC.

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start-Up

The equipment was mobilized via tractor trailer from Newton, MA to Albuquerque, NM. Upon arriving at the site, a lockable CONEX box was procured, large enough to allow VSEMS to be driven inside without disassembling the system. Pre-arranged office space at the Double Eagle Airport was inhabited. GPS base station monuments were located, as was the test strip that had been emplaced by the ESTCP Program Office and representatives from CEHNC. By the end of the first day, all equipment had been set up and checked out, and the calibration strip had been surveyed. The daily maintenance schedule included vehicle oil check, cleaning air filters, and greasing the axles of the tow platform. Major unforeseen problems included persistent jamming of our GPS base-to-radio link equipment by other GPS equipment used by the myriad of construction teams in the booming valley below; the high-mesa survey location exacerbated this problem by almost ensuring that any other competing signal on the same channel would propagate up the valley to our location. This problem was ameliorated by setting up the GPS in the northwest corner of the site (the highest available), using a 30’ high mast for the radio antenna, and programming our rover to listen only to the channel our base was broadcasting on, but others were frequently broadcasting on this channel as well. At times, the channel needed to be changed several times a day. Other unforeseen problems including a faulty battery charger boiling the lead/acid vehicle batteries, causing them to leak acid and out-gas hydrogen sulfide (necessitating immediate replacement), and failure of tow platform glue and rivet joints on the original proof-of-concept platform, necessitating daily checks and replacement of broken rivets with brass bolts.

3.6.2 Period of Operation

Survey Begin	21-Sep
Survey Break	20-Oct
Survey Return	7-Nov
Survey End	19-Nov

3.6.3 Area Characterized

The survey area at the Kirtland PBR had a northern and a southern section. Transects were designed to cover the suspected N2, N3, New Demolition, and Simulated Oil Refinery Target (SORT) bombing targets in the northern section. Additional transects were designed to cover the southern section where there was no suspected bombing target. A total of 192 acres of transects were acquired. These transects are shown in the figure below.

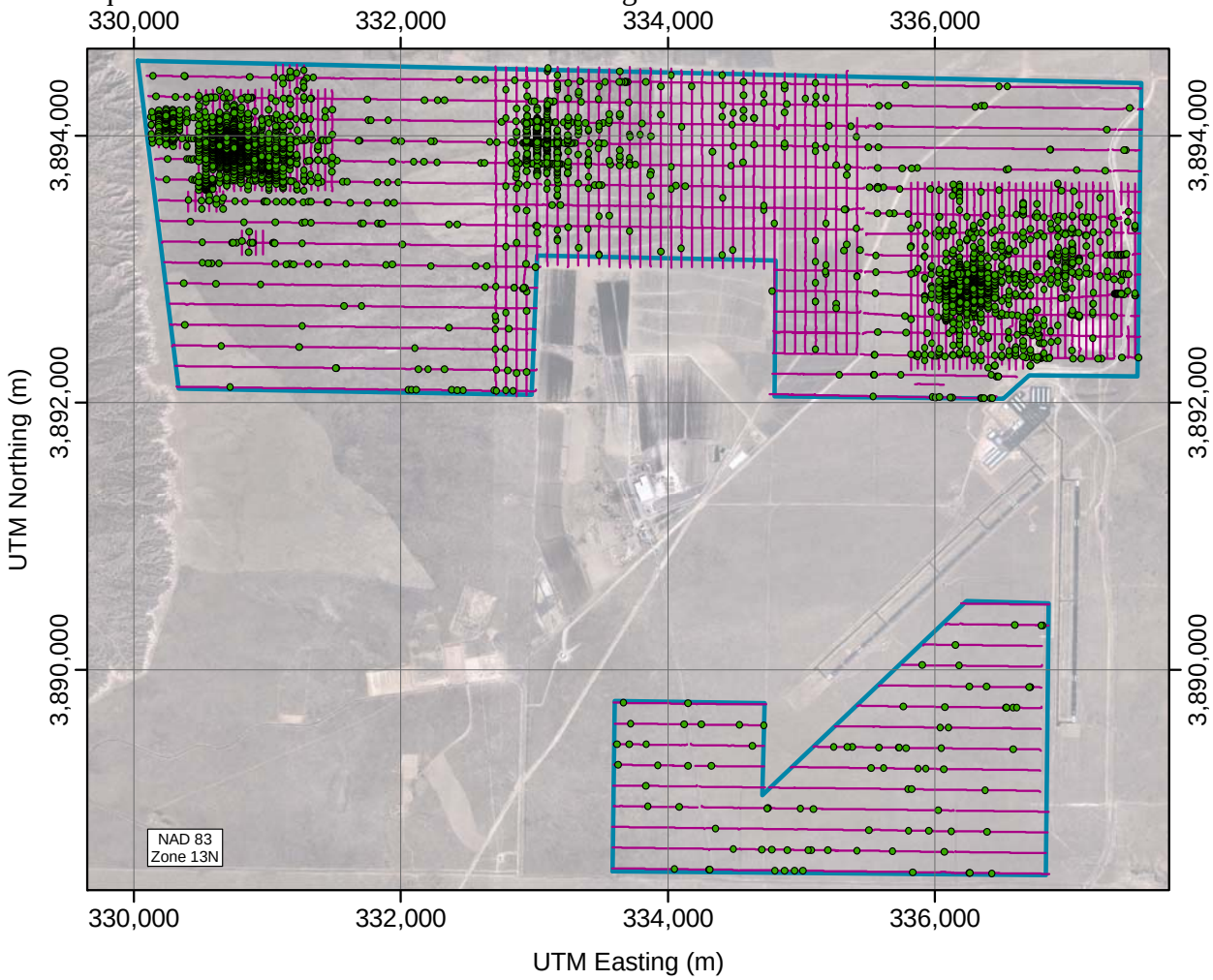

Figure 3: Transect coverage of the Kirtland PBR

The 100% geophysical survey areas were selected to be near suspected bombing targets as these data became known from other WAA layers. The relationship of these areas to the suspected bombing targets can be seen from the table below. These areas are overlaid on the Kirtland PBR site map in the figure below. In total, 158 acres of 100% geophysical survey areas were surveyed, broken down by area in the table below.

Table 3: Breakdown of acreage by 100% geophysical survey area

area	near	acres surveyed
Area1a	N2	7.2
Area1b	N2	15.1
Area1c	N2	7.2
Area2a	Oil Refinery Target	13.4
Area2b	Oil Refinery Target	13.2
Area2c	Oil Refinery Target	13.4
Area3a	Oil Refinery Target	15.8
Area3b	New Demolition	6.2
Area4a	N3	5.5
Area4b	N3	8
Area4c	Oil Refinery Target	14
Area4d	New Demolition	3
Area4e	South Site	20.3
Area4f	South Site	15.7

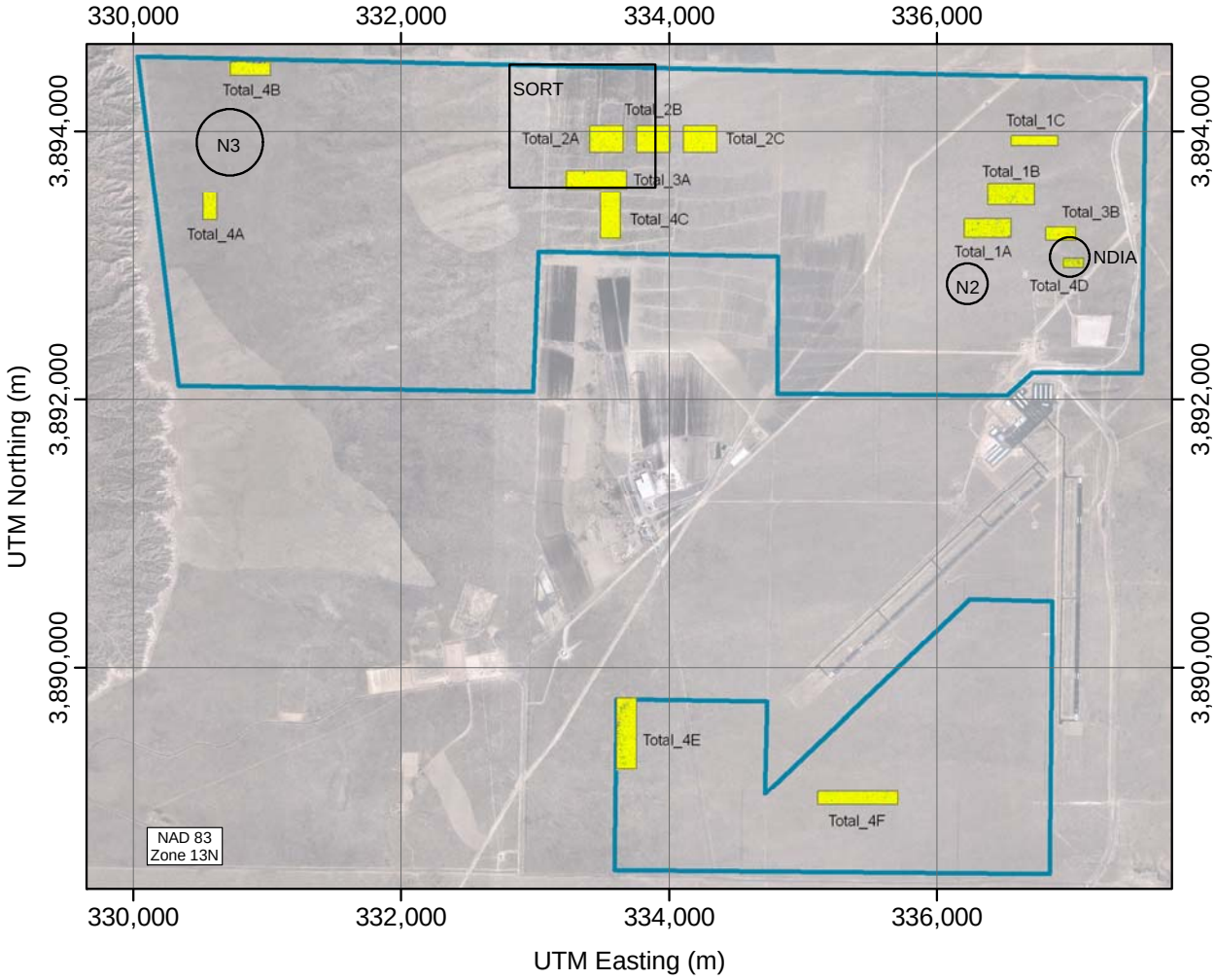

Figure 4: 100% geophysical surveys at the Kirtland PBR

3.6.4 Residuals Handling

Not applicable.

3.6.5 Operating Parameters for the Technology

3.6.5.1 Magnetometers

VSEMS collects five channels of total field magnetometer data, triggered primarily by the 1 PPS signal from the GPS, and secondarily by the PSYNC signal of the EM61 Mk2, for a short 5 ms window after the secondary field has rung down and before the next PSYNC pulse. For an unmodified EM61, PSYNC is a 75 Hz signal, hence the 5 ms window for sampling the magnetometer data is repeated at 75 Hz. The five magnetometers are spaced 0.5 meters apart on the sensor boom resulting in a physical magnetometer sensor swath width of 2.0 meters. Sensor standoff is 30.5 cm. Because of the primary 1 PPS triggering, magnetometer data is always correctly triggered by the GPS, and no GPS-to-magnetometer latency correction is required.

3.6.5.2 EM61

VSEMS collects five channels of EM61 Mk2 data, triggered by a 10 Hz triggering signal that is generated by using the 1 PPS from the GPS and dividing it. Five EM61 Mk2 electronics boxes are configured in a master/slave configuration. Five 1 x ½ meter EM61 coils are employed, spaced 55 cm apart, approximately in line with the five magnetometers (the ½ meter EM61 coil width is measured from the center of the 2.5 cm-wide coil; thus the edge-to-edge size is actually 55 cm). The edge-to-edge EM61 physical sensor swath width is 2.75 meters, but since the data are considered to be in the center of the coil, the "electronic" sensor swath width is 2.20 meters – just slightly wider than the magnetometer swath width. Sensor standoff is 38.1 cm (the same as when the EM61 lower coils are deployed on their native wheels). Although the system is capable of using EM61 upper coils and employing the "D" setting on the electronics, we typically do not deploy the upper coils and instead deploy only the lower coils and employ the "4" setting on the electronics box. This uses time-gates sampled at 256, 406, 706, and 1306 μsec, respectively.

3.6.5.3 RTK GPS

The VSEMS GPS equipment incorporates a Trimble 5700 base station, and three Trimble MS750 rovers and antennas, used in a differential RTK configuration. One GPS antenna is located over the center magnetometer. The other two are located over the two outer EM61 coils. The GGK output string is used to capture time, position, and fix quality at a 10 Hz update rate.

3.6.5.4 Number and Orientation of Passes

For the transect surveys, we collected data along whatever transects we were directed to by the ESTCP program office. For the 100%-coverage surveys, we collected data in the areas we were directed to by the ESTCP program office, using passes with a desired ½ meter overlap (2 meter line spacing) along whatever axis was longest to maximize survey efficiency.

3.6.5.5 Data Density

As stated above, the cross-track data spacing is 0.5 meters for the magnetometer data, and 0.55 meters for the EM61 data. The down-track spacing is a function of sampling rate and speed. The EM61 outputs at 10 Hz, which is slow compared to the magnetometers' 75 Hz output rate. 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 approximately 2 mph. Because this was not a detection and remediation survey, we felt that a lower bound on the down-track data density of

one EM61 update per 20 cm was more appropriate, yielding a forward rate of advance of between 4 and 5 mph. Note that, with a 0.5 meter magnetometer spacing, down-track spacing of 20 cm translates into a density of 15 data points per square meter, which is the number used in table 1. Since the magnetometers were updating at 75 Hz, they easily satisfied the 20 cm spacing metric; the down-track magnetometer data spacing at this rate was one update every 2.6 cm. As per discussions with the Program Office, we drove the transects at less than 4 or 5 mph to achieve a 20 cm down-track EM61 data spacing, but on the 100%-coverage surveys, we slowed down and drove approximately 2 mph to achieve a 10 cm down-track EM61 data spacing. The actual metric listed in the table is not a down-track value, however, but an area density of >15 points per square meter. The measured EM61 area density for the 14 100% geophysical survey areas was over 22 points per square meter.

3.6.5.6 Labor

For safety reasons, there is a de-facto requirement that the survey vehicle be in sight of a field person at all times. Therefore, on a large survey site such as the Kirtland PBR, the VSEMS crew nominally includes a driver and two flaggers, one at the end of each survey line. Because of the next-day data analysis turnaround requirement, a data analyst was in the field, analyzing the previous day's data (normally the analyst would be one of the flaggers). This resulted in a total crew size of four.

Site maps of transect data and 100% geophysical survey data are shown in section 4 below.

3.6.5.7 Data Processing Steps

For the transect surveys, all data processing and analysis occurred in our own software. For the 100% geophysical survey surveys, additional processing occurred in Geosoft Oasis Montaj™.

Positioning: GPS data are viewed and corrected as necessary to fix jumps that come from non-RTK solutions. At the Kirtland PBR site, there were many sources of radio frequency (RF) interference almost certainly due to surveying and construction crews using similar GPS equipment. As such, many data sets required manual correction of non-RTK solutions. These corrections take the form of "connecting the dots" between valid RTK solutions. Because the vehicle was slow-moving and the transects were extremely regular, it is not felt that correction of these outages compromised the data.

Before this survey, VSEMS had a single GPS with its antenna over the center magnetometer. In support of an EQT-funded project, the system is being improved to increase the accuracy of the positioning of the EM61 coils. Shortly before the Kirtland deployment, VSEMS was modified to include two additional GPS antennas over the outboard two EM61 coils and two additional Trimble GPS RTK receivers. The 10 Hz data stream from all three antennas were recorded on all transect and 100% geophysical surveys. While in the field, software was written to view and position-correct the three streams of position data.

The addition of the two GPS antennas and receivers had the unintended benefit of supplying redundant equipment. There were times when GPS1, the one over the center magnetometer and the one used by default, received non-RTK data over an entire line or transect, making that data unusable for analysis. However, these positions could be recovered because, at these times, GPS2 and GPS3 were outputting valid data, and their locations could be used to reconstruct the

location of GPS1. Without these redundant units, more lines would have needed to be resurveyed.

Magnetometer Data: The magnetometer data are positioned using the GPS. They are then lightly median-filtered to remove spikes, notch-filtered to remove the 15 Hz sine wave that comes from the 60 Hz ambient electrical hum from the power grid that, due to the system's 75 Hz sampling, aliases at 15 Hz. The data are then passed to a dynamic background filter that determines the median of a six-second window, then subtracts that median value from the data. This effectively removes large-scale geology, the remnant signature of the vehicle, and diurnal drift from the data. The data are then gridded on a 10 cm grid and visualized.

EM61 Data: The EM61 data, as described above, are positioned using the GPS over the center magnetometer. Successive GPS updates are smoothed and used to determine heading. The heading, platform geometry, and GPS position are used to determine the positions of the centers of all five EM61 1x1/2 meter coils. The EM61s are powered by two large car batteries, and are zeroed in the field in the morning and after lunch. This combination results in data with a minimum of drift, and as such, gross background leveling of the EM61 data was not necessary for visual anomaly detection on the transect surveys. Like the magnetometer data, the EM61 data are gridded on a 10 cm grid and visualized. For 100% geophysical surveys, the EM61 data was background-leveled in Geosoft Montaj™ using a nonlinear filter.

The gridded magnetometer and EM61 data were then viewed together in our own software for anomaly picking (described below).

In addition to processing in our own software. Magnetometer and EM61 data sets were brought into Geosoft Montaj™. Project files, database files, grid files, map files, and geotiff files were created and delivered to the Program Office.

3.6.6 Demobilization

The GPS base station and its 30' radio mast were taken down. The tractor/trailer was packed and driven off site. The company from whom the CONEX box was rented was contacted for its removal.

3.7 Selection of Analytical/Testing Methods

Not applicable.

3.8 Selection of Analytical/Testing Laboratory

Not applicable.

4 Performance Assessment

4.1 Performance Criteria

The following were the primary performance objectives from the demonstration test plan. (these were also listed in section 3.1):

Table 4: Primary Transect Performance Objectives/Metrics and Confirmation Methods Relating to Detection of Target Areas and Target-Free Areas

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Objective Met?
Qualitative	*Reliability and Robustness*	*General Observations*	*Operator feedback and recording of system downtime (length and cause)*	*System was Reliable* *Yes*
	Terrain / Vegetation Restrictions	*General Observations*	*Correlation of areas not surveyed to available data (topographical maps, etc.)*	*System surveyed vehicularly navigable areas* *Yes*
Quantitative	*Survey Rate*	*12.5 acres / day*	*Calculated from survey results*	*9.5 acres/day* *No*
	Data throughput	*All data from day x processed for anomalies and submitted by end of day x+1*	*Analysis of records kept / log files generated while in the field*	*Analyzed Anomalies Submitted by Next Day* *Yes*
	Percentage of Assigned Coverage Completed	*>95% as allowed by topography*	*Calculated from survey results*	*All Transects Completed* *Yes* *75% of 100% geophysical survey Areas Completed* *No*
	Transect Location	*95% within 2 meters of requested transects*	*Calculated from survey results*	*93% of Transects Aligned(after learning curve)* *Yes*

The following were the secondary performance objectives from the demonstration test plan (these were also listed in section 3.1):

Table 5: Secondary Transect Performance Objectives/Metrics and Confirmation Methods Relating to Characterization of Target Areas

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Objective Met?
Qualitative	*Ability of Analyst to Visualize Targets from Survey Data*	*All targets in survey area identified*	*Data Analyst feedback and comparison to 100% geophysical survey data / other demonstrators results*	*Targets Readily Visualizeable* *Yes*
Quantitative	*Location of Inverted Anomalies*	*< 0.15 m horizontal* *< 30% vertical*	*Comparison to Test Strip Ground Truth*	*.13 m horizontal* *.20 m vertical* *Yes*
	Probability of False Alarm	*<5% of identified anomalies correspond to no ferrous metal source*	*Validation Sampling (100% survey) and/or Remediation Sampling (digging)*	*13.5% correspond to apparent geology* *No*
	Signal to Noise Ratio (SNR) for Calibration Objects	*+/- 10% of expected from Standardized UXO Technology Demonstration Site Performance*	*Comparison of Calibration Target results to documented Standardized UXO Technology Demonstration Site performance*	*Inconsistent* *No*
	Data Density	*> 15 pts / m^2*	*Calculated from survey results*	*> 22 pts / m^2* *Yes*

4.2 Performance Confirmation Methods

The above two tables are discussed below.

4.2.1 Primary Metrics

Reliability and Robustness: The system's reliability and robustness were generally good for a prototype system. During the eight-week survey, two full days were lost to downtime. One was due to the battery charger malfunctioning and boiling the acid in the vehicle batteries, and necessitating their immediate replacement. The other was due to chasing down and solving a noise problem on the magnetometers due to a current ground loop. The proof-of-concept fiberglass towed platform degraded during the survey, as its glued-and-riveted joints began to fail. Near the end of one survey day, one assembly holding the EM61 array failed completely. It was repaired that evening with brass bolts. On all subsequent days, we inspected the platform every morning and replaced any missing rivets with brass bolts, with no further downtime due to platform malfunction.

Terrain/Vegetation Restrictions: There were very few terrain or vegetation restrictions; the former Kirtland PBR was generally a flat, open area with low, scrubby vegetation. The main restrictions came from several fence lines cutting across the site, preventing some of the transects from being followed exactly as planned.

Survey Rate: The average survey rate was 9.5 acres, averaged over all survey days, including days when GPS interference severely hobbled productivity, down days, and days when we switched from transects to 100% geophysical surveys. As stated above, the persistent jamming of the GPS base-to-rover radio link was the single largest factor affecting productivity. Despite locating the GPS base station in the northwest corner of the site (the highest point), using a scanner to find an open channel, and putting the base station radio antenna on a 30' high mast, on most days the base/rover link would be severed when another differential GPS system in the valley was switched on; we could hear the interference on the previously unused channel on our scanner. We would then have to locate a new clear channel with the scanner, drive up to the base station in the corner of the site and change the channel, and do the same in the rover. On some days this procedure needed to be repeated two or three times. On the days when there was no such interference, the system and personnel were certainly capable of high productivity; nine days were over 12.5 acres per day, six were over 15, and one was over 20.

Data Throughput: Data was analyzed and anomaly lists were supplied to the ESTCP Program Office by the end of the next day.

Percentage of Assigned Completed Coverage: All of the planned transects were covered (with the exception of N/S transects though the northwestern corner of the site that were deleted in concurrence with the program office because the target they were designed to find had been found). All of the 100% geophysical survey areas were surveyed, but in acreage, 75% of the assigned total coverage was accomplished. This is because the first three assigned 100% geophysical survey areas were 30 acres each, and we were initially instructed to survey as much of each one as could be completed in a day. All subsequent 100% geophysical survey areas were 100% surveyed.

Transect Location: Transect locations from the first two days were off by as much as tens of meters due to learning curve issues in programming and following the track guidance equipment in the vehicle, but subsequently, the geodetically-located sensor swath locations overlaid the planned transects in nearly all data sets. A numerical off-track metric was obtained by calculating, for every transect, the average orthogonal distance from the nearest planned transect. These results are shown in the figure below. The degree to which track following improved enormously after the second day is clear. The magenta line represents the 2-meter metric. When including the poor results from the first two days, the percentage of tracks within 2 meters of the planned tracks is 93%, just missing the 95% metric, but if these learning-curve days are excluded from the calculation, 98% of the tracks are within the metric. 81% of the tracks were within 1 meter of the planned transects, and 53% were with ½ meter.

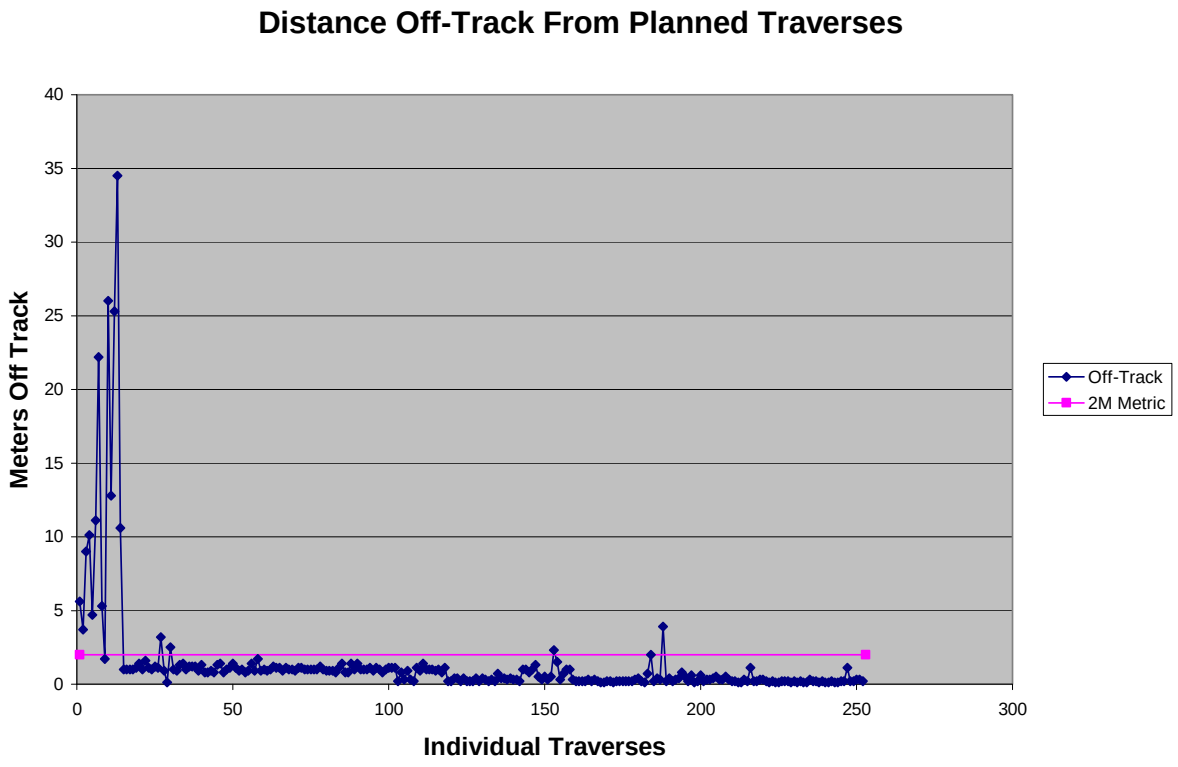

Figure 5: Distance Off-Track from Planned Traverses. The 2-meter metric is represented by the magenta line.

4.2.2 Secondary Metrics

Ability to Visualize Targets: Targets (both individual anomalies and entire bombing targets) were readily visualizable in VSEMS survey data.

Location of Inverted Anomalies: Unfortunately, no independent measurement was made of the actual location of the ground truth items that were dug. In the absence of this information, we analyzed the location accuracy of the test strip items, and found average accuracies of 13 cm horizontally with a standard deviation of 5.2 cm, and 20 cm vertically with a standard deviation of 7.7 cm.

Probability of False Alarm: We will address the false alarm issue in detail, in section 4 below, as it goes to the heart of the utility of a concurrent multisensor system. A summary of the probability of false alarm is below.

Table 6: Reduction in False Alarms with Reanalysis of Data

Probability of false alarm (no-finds → probable geology) from original Program Office Dig Sheet (includes anomalies from VSEMS ground-based data plus other data)	18%
Probability of false alarm using anomalies only from VSEMS ground-based data on the 14 100% geophysical survey areas for which there's ground truth on the Program Office Dig Sheet	13.5%
Probability of false alarm removing objects whose mag signatures are clearly non-dipolar (the best the analyst could do with mag-only data)	8%
Probability of false alarm requiring a confirming signature in the EM61 data	1%

Signal to Noise for Calibration Objects: The signal from calibration objects was not sufficiently consistent to meet the desired metric, but this is more a reflection of platform motion than it is a symptom of anything wrong; this is discussed in detail in section 4 below.

Data Density: The data density in the 100% geophysical survey areas, from the magnetometers was, on average, 165 points per square meter. The data density from the EM61s was, on average, 22 points per square meter.

4.3 Data Analysis, Interpretation and Evaluation

4.3.1 Test Strip Data

The test strip was emplaced by Program Office representatives and contained the 15 items listed in the table below.

Table 7: Test strip items

ID	Item	Easting (m)	Northing (m)	Elevation	Description	comment	civil survey depth (cm)	measured depth (cm)
100	7	335959.849	3892136.536	1773.654	#4 RBR - 100m	rebar		
200	15	336059.693	3892134.106	1773.108	#4 RBR - 200m	rebar		
1000	1	335859.939	3892139.374	1774.14	#4 RBR - 0m 10	rebar		
10_R	3	335870.63	3892139.87	1773.86	10 ROUND	shotput - 16 lb.	21.3	25.40
107_M	8	335967.129	3892136.729	1773.184	107 MIDDLE	81 mm mortar	36.1	40.64
113_M	9	335972.98	3892136.491	1773.468	113 MIDDLE	60 mm mortar	6.7	10.16
128_M	10	335987.547	3892136.206	1772.867	128 MIDDLE	105 mm Proj.	59.6	60.96
144_R	11	336003.792	3892135.719	1773.365	144 ROUND	shotput - 16 lb.	7.2	10.16
165_M	12	336024.826	3892135.665	1772.915	165 MIDDLE	155 mm Proj.	4.7	48.26
180_M	13	336039.83	3892134.869	1772.443	180 MIDDLE 180	155 mm Proj.	79.9	91.44
195_M	14	336054.724	3892134.429	1772.877	195 MIDDLE	60 mm mortar	22.5	25.40
23_M	4	335883.353	3892139.827	1774.069	23 MIDDLE	37 mm Proj. simulant	-0.5	5.08
39_M	5	335899.42	3892139.428	1773.627	39 MIDDLE	105 mm Proj.	37.4	40.64
4_M	2	335864.045	3892139.522	1774.072	4 MIDDLE	37 mm Proj. simulant	9.1	25.40
66_M	6	335926.44	3892138.068	1773.529	66 MIDDLE	81 mm mortar	26.9	26.67

The yellow highlighting comes directly from the file "WAA_kirtland_cal_strip_v1.xls" distributed by the Program Office. A comment embedded in that file states that the highlighting "means that the civil measurements don't agree well with the in-field measurements."

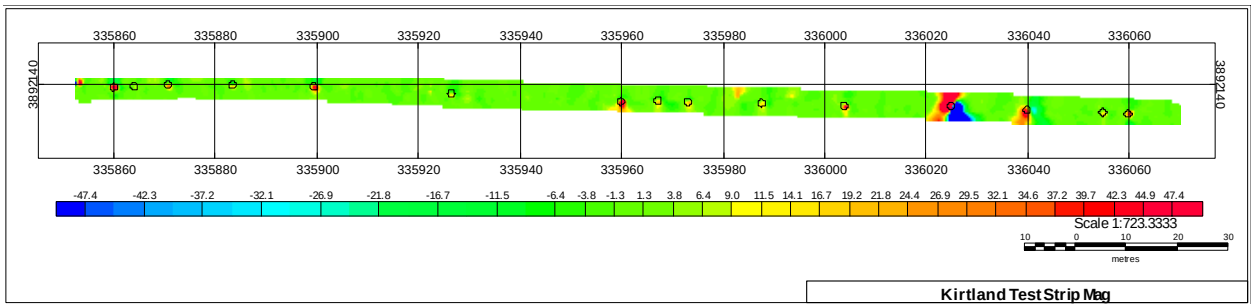

Figure 6: Sample Test Strip Data with Ground Truth Overlaid, Mag

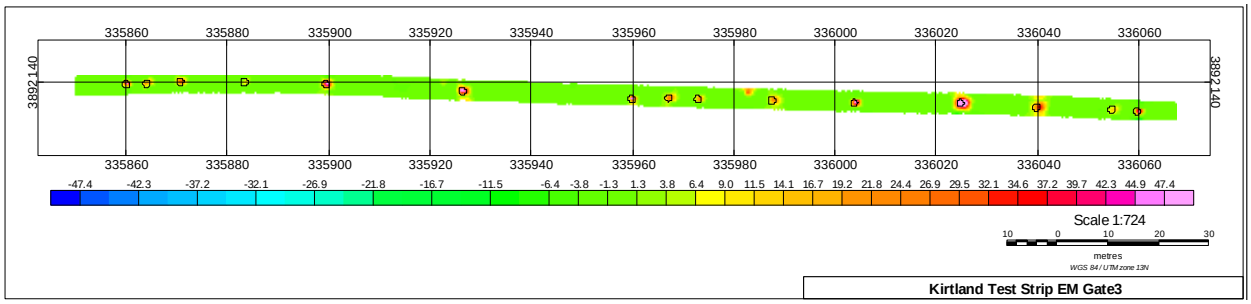

Figure 7: Sample Test Strip Data with Ground Truth Overlaid, EM61 Gate3

The test strip was used to determine detection thresholds to employ on the site. In the figure below, magnetometer data from the test strip are shown and color highlighting above a given threshold is employed. We do this in our own software as the color thresholding in Oasis is a bit cumbersome. The top panel shows magnetometer data displayed at +/-50nT in grayscale with no color highlighting. The 37mm stimulant has virtually no signature, but all other objects do. The middle panel shows the data highlighted, with everything over 10nT colored in red. The 10nT threshold detects all items except the 37mm stimulant, with one false alarm, probably due to geology. In the third panel, the threshold is dropped to 5nT, which produces ten false alarms, probably due to geology. This supported the use of a 10nT magnetometer detection threshold. (A 10nT detection threshold is also three times a nominal system noise floor of 3nT.)

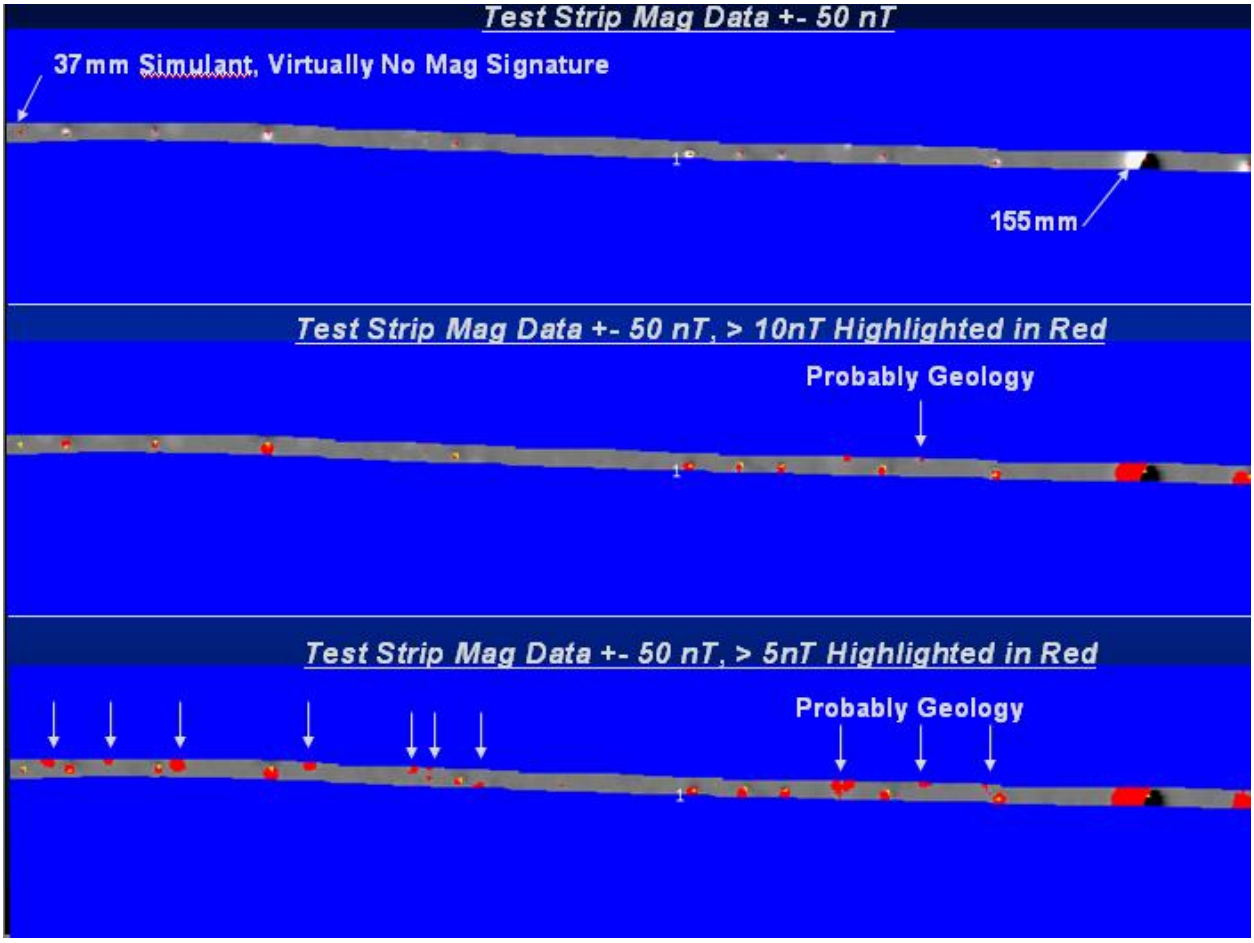

Figure 8: Magnetometer test strip data (200 meters) showing that lowering detection threshold brings in likely geology

For EM61 data analysis, gate3 was used, as it frequently is for production geophysical surveys of bombing ranges suspected of containing medium to large objects. The figure below shows EM61 gate3 data over the test strip. The top panel is un-highlighted; the bottom panel is highlighted with all data >3 mV colorized in red. All objects test strip objects were detected in the EM61 data at this threshold. However, the maximum depth of objects in the test strip was < 1 meter, so there was the possibility that the magnetometers would still be needed to detect objects at greater depths that the EM61 could not detect. In retrospect, the 3mV EM detection threshold proved to be a bit low, resulting in a large number of probable clutter picks that the operator assigned as low-likelihood anomalies.

Figure 9: EM61 gate3 test strip data (200 meters) with anomalies >3 mV highlighted in red

The test strip was run over in the morning and again at the end of the day to verify correct sensor operation. Test strip data was analyzed by extracting and plotting the peak sensor value, as well as the peak fit magnetometer value over each item. The fit data was employed in the hope that they would be more consistent than the raw data. These data were plotted and presented to ESTCP at the Wide Area Assessment Data Exchange Meeting in November 2005. The data were summarized in the WAA Pilot Program Data Report for UX-0531 submitted to ESTCP on 12/29/2005. We will display three of the plots here.

The strongest item in the plot was item 12, the 155mm shell at 90cm depth. The run-to-run plots are displayed in the figure below. The blue plot is raw peak magnetometer data in a pre-set area of interest over the object, the magenta plot is the peak value of the inverse-modeled (fit) data over the object, and the yellow plot is the raw peak EM61 gate3 value. On this plot, the raw magnetometer data range from 449 to 557 nT, which is close to being consistent to within +/- 10%. However, the plots for other weaker objects show data that are less consistent.

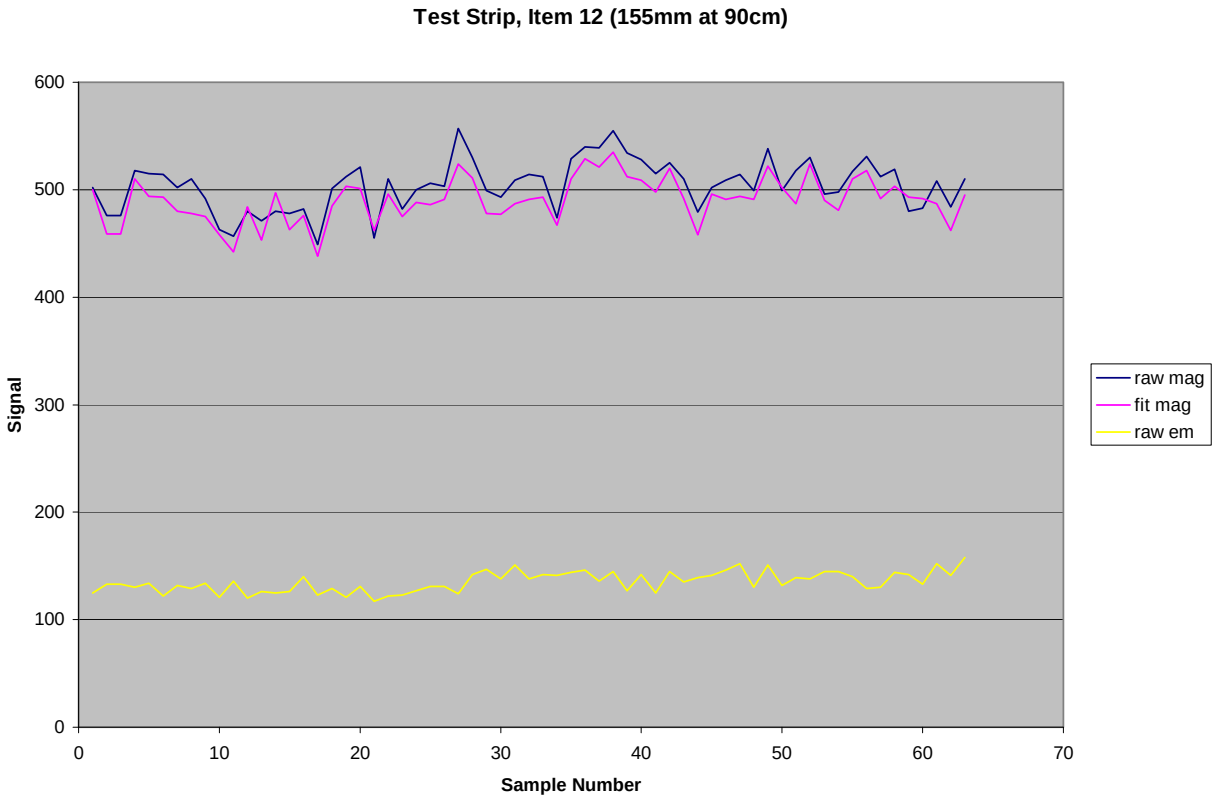

Figure 10: Test strip data, raw EM value (yellow) and raw and fitted mag values (blue and magenta) for 155mm projectile at 90cm depth

Item 5, which was the 105mm projectile at 40cm, is shown below. The EM61 gate3 data vary from 41 to 64mV; the magnetometer data vary from 60 to 85nT. We feel that the lack of consistency was largely due to slight differences in towed platform position on the test strip, and to platform motion as it went down the test strip. It is noted that there is a slight upward drift in these data. It is possible that this is due to both the rutting of the test track with increasing use, and to a slight sagging of the towed platform that was observed over the duration of the eight-week survey. The presence of some visual correlation between the dips in the EM61 and magnetometer plots lend credence to the suggestion that the lack of run-to-run consistency is due to platform motion. The peak values of the fit magnetometer data show the same lack of consistency, indicating that the raw peak values are not simply spuriously high readings – the region of data in the area immediately surrounding the object is biased up or down. This is why, even after fitting with a point dipole, the peak value of the fit data is largely tracking the real data. Note that the median filter that is employed to remove long-wavelength effects such as broad scale geology does not compensate for this because, by design, the median filter operates with a window sufficiently long (six seconds) that it has little effect on spatial wavelengths the size of an MEC object.

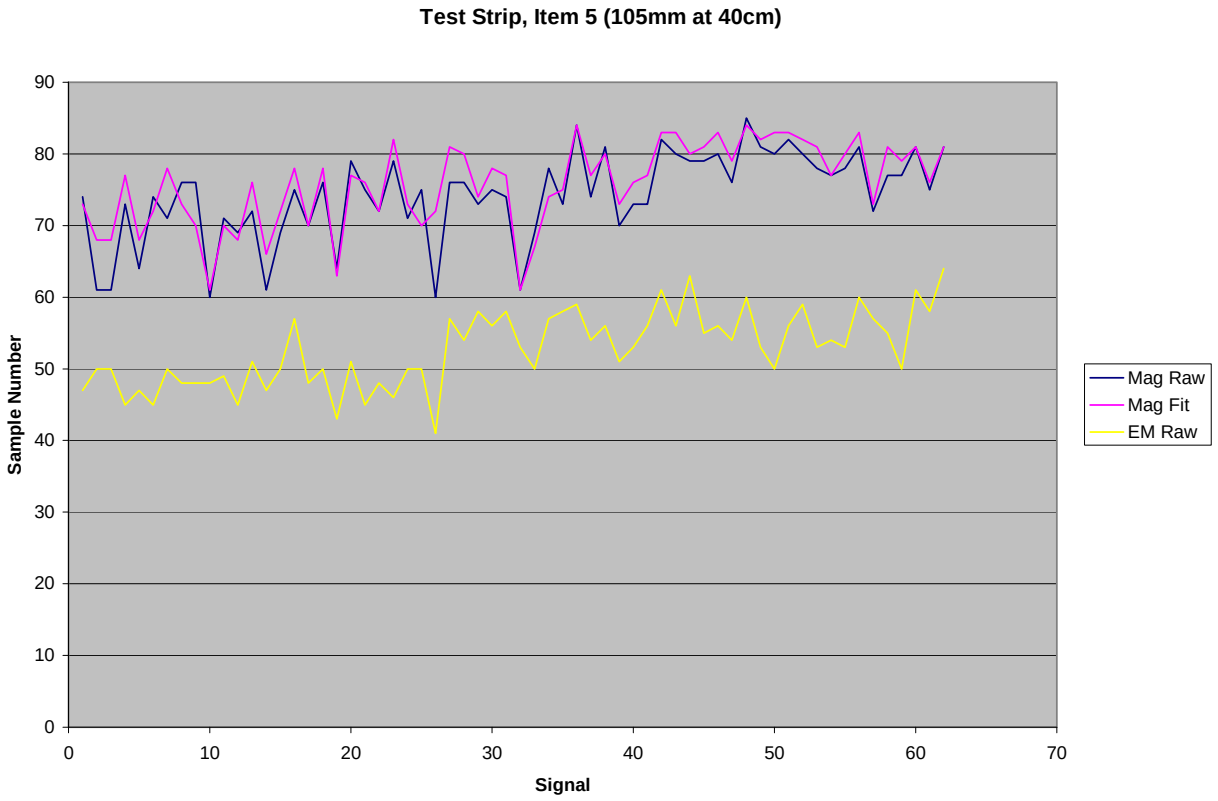

Figure 11: Test strip data, raw EM value (yellow) and raw and fitted mag values (blue and magenta) for 105mm projectile at 40cm depth

For comparison, data from one of the weakest items is plotted below – the 37mm stimulant at 25cm depth. This object was barely visible to the magnetometers at all, but had a clear signature to the EM61. The magnetometer data range from 7 to 27 nT; the EM61 gate3 data from 11 to 23mV. This numbers clearly are not within the desired +/-10% of accepted readings from the Standardized UXO Demonstration Test Sites. The likely cause is a combination of the towed fiberglass platform used for the Kirtland PBR survey, the motion engendered in the platform by uneven terrain, and variation in vehicle path. This platform was originally developed under ESTCP project MM-0208 to host three ½ x ½ meter coils and was only designed to survive a single APG deployment. Prior to the Kirtland PBR survey, the platform was modified and reinforced to host five 1 x ½ meter coils – nearly four times the weight of the original coils. To maximize the survivability of the platform, it employed a "porch swing" design that allowed the coils to swing back upon encountering a low obstacle such as a tree trunk. This degree of freedom allowed the EM coils to sway slightly even without encountering obstacles, and added to the uncertainty of the position of the coils relative to the platform. The fiberglass platform has since been replaced with a carbon fiber platform built with the specific design goal of having as little unregistered motion of the EM61 coils as possible; rigidly-mounted EM61 coils are now employed. The magnetometers on the fiberglass platform show similar variations in signal. Our experience is that it doesn't take much terrain-induced variation for the 1/R3 (mag) or 1/R6 (EM) signal dependency to produce the variations seen on the test strip.

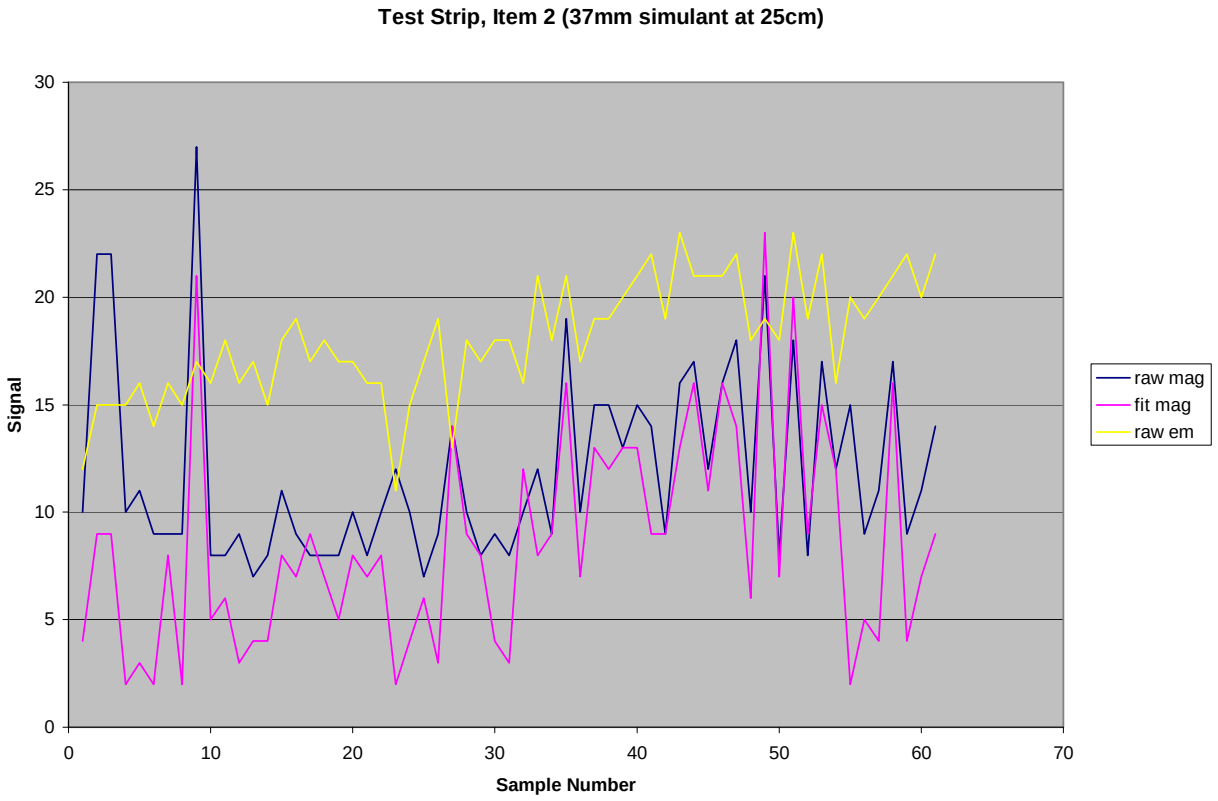

Figure 12: Test strip data, raw EM value (yellow) and raw and fitted mag values (blue and magenta) for 37mm simulant at 25cm depth

We have generated these plots for all 15 test strip items and have included them in an appendix.

4.3.2 Transect Data

Because of the large amount of transect data, only a subset will be shown. For most areas, we were given "sparse" transects spaced 150 meters apart and "dense" transects spaced 75 meters apart to run, typically in orthogonal directions. With these transects, the VSEMS ground-based data easily located the known targets N2 and N3, and helped to locate the Simulated Oil Refinery Target (SORT). The figure below shows the site with the suspected target areas and subsequently derived areas of interest overlaid, with a red circle shown over the N2 and New Demolitions targets. The following two figures below show EM61 data from the sparse WE transects and the dense NS transects over this area, and magnetometer data from the same area.

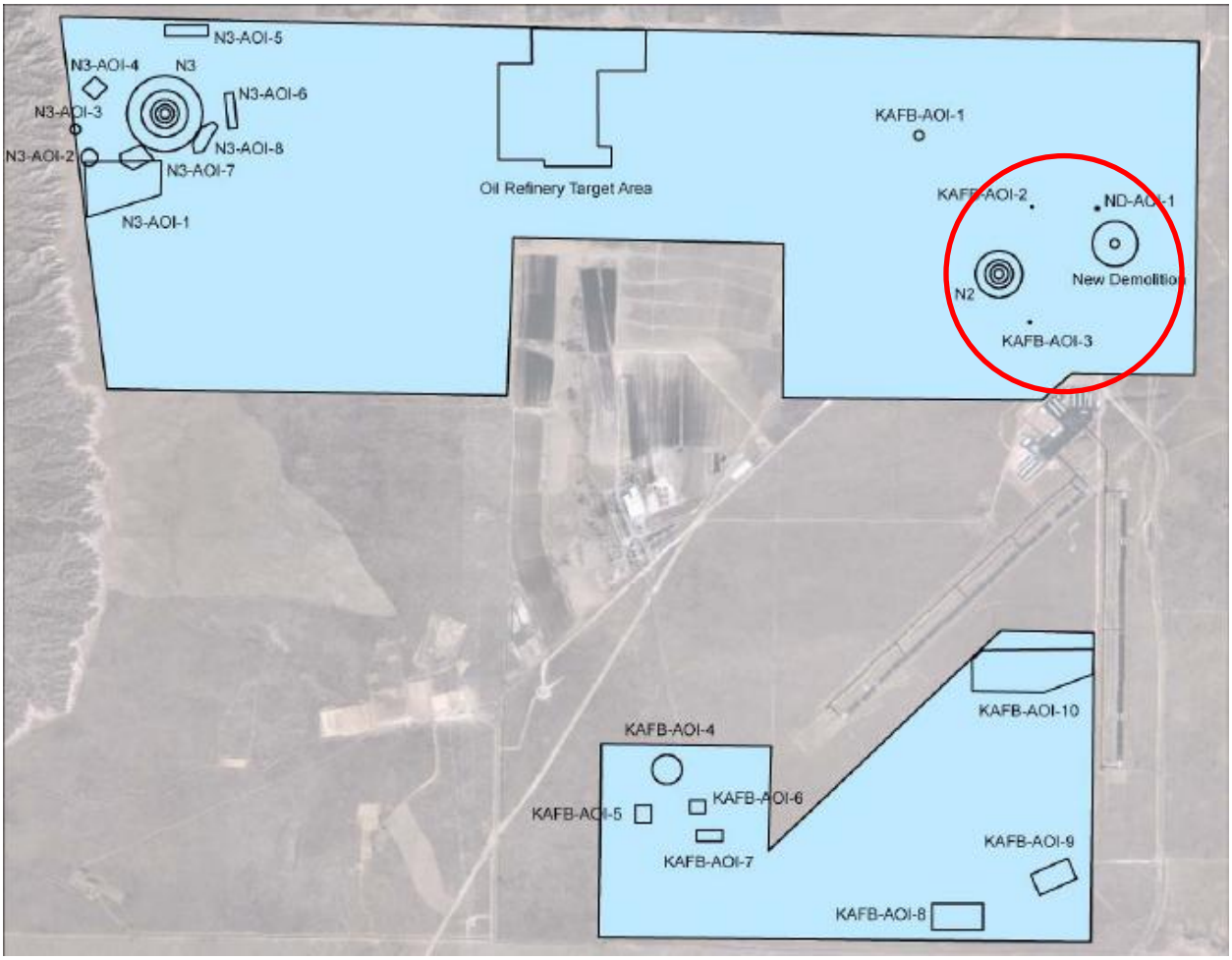

Figure 13: N2 and New Demolitions Target

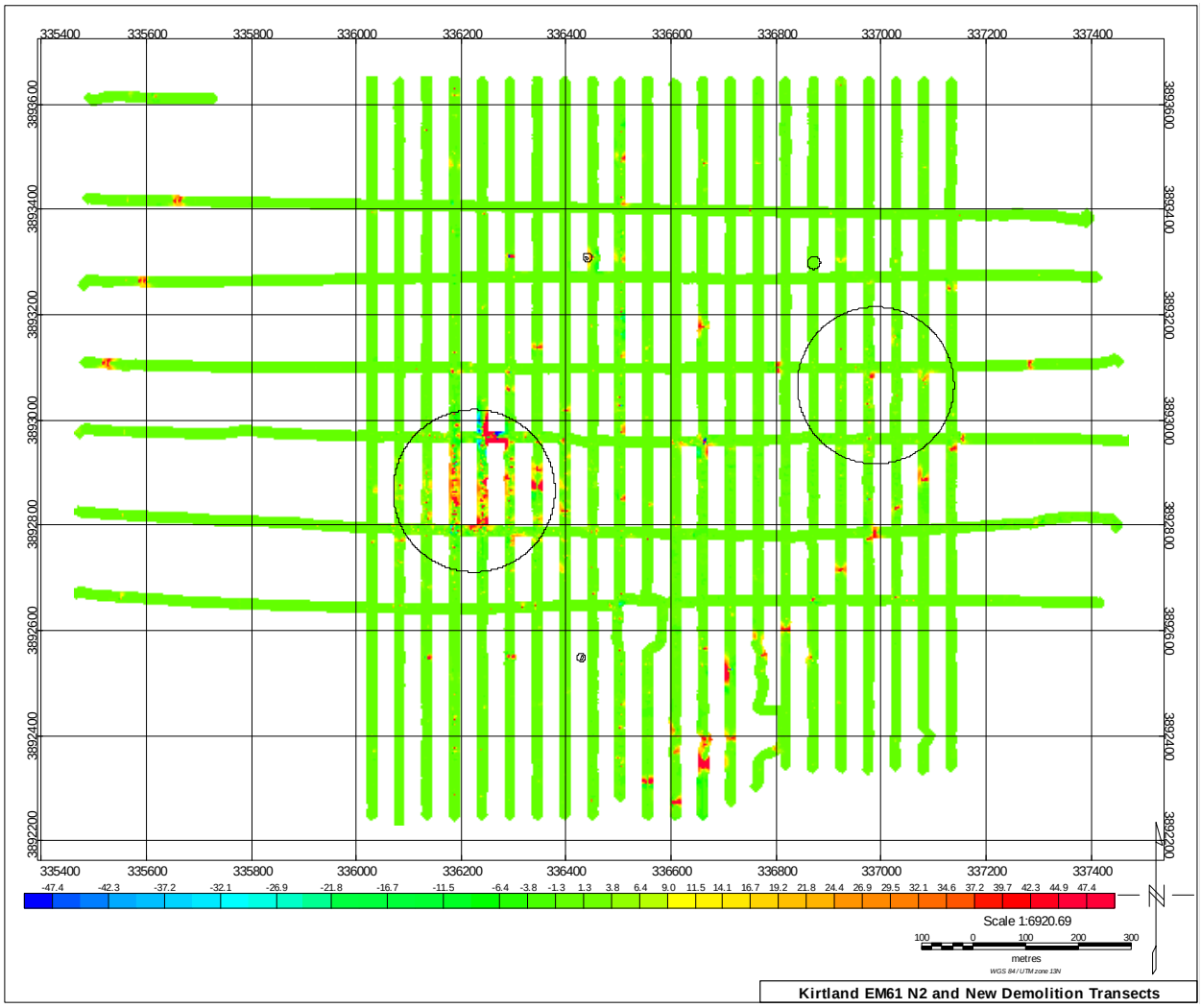

Figure 14: Sparse WE transects (150m spacing) and dense NS transects (75m spacing) over N2 (circle, left) and new demolition (circle, right) targets, EM61 gate3 data (+/- 50 mV)

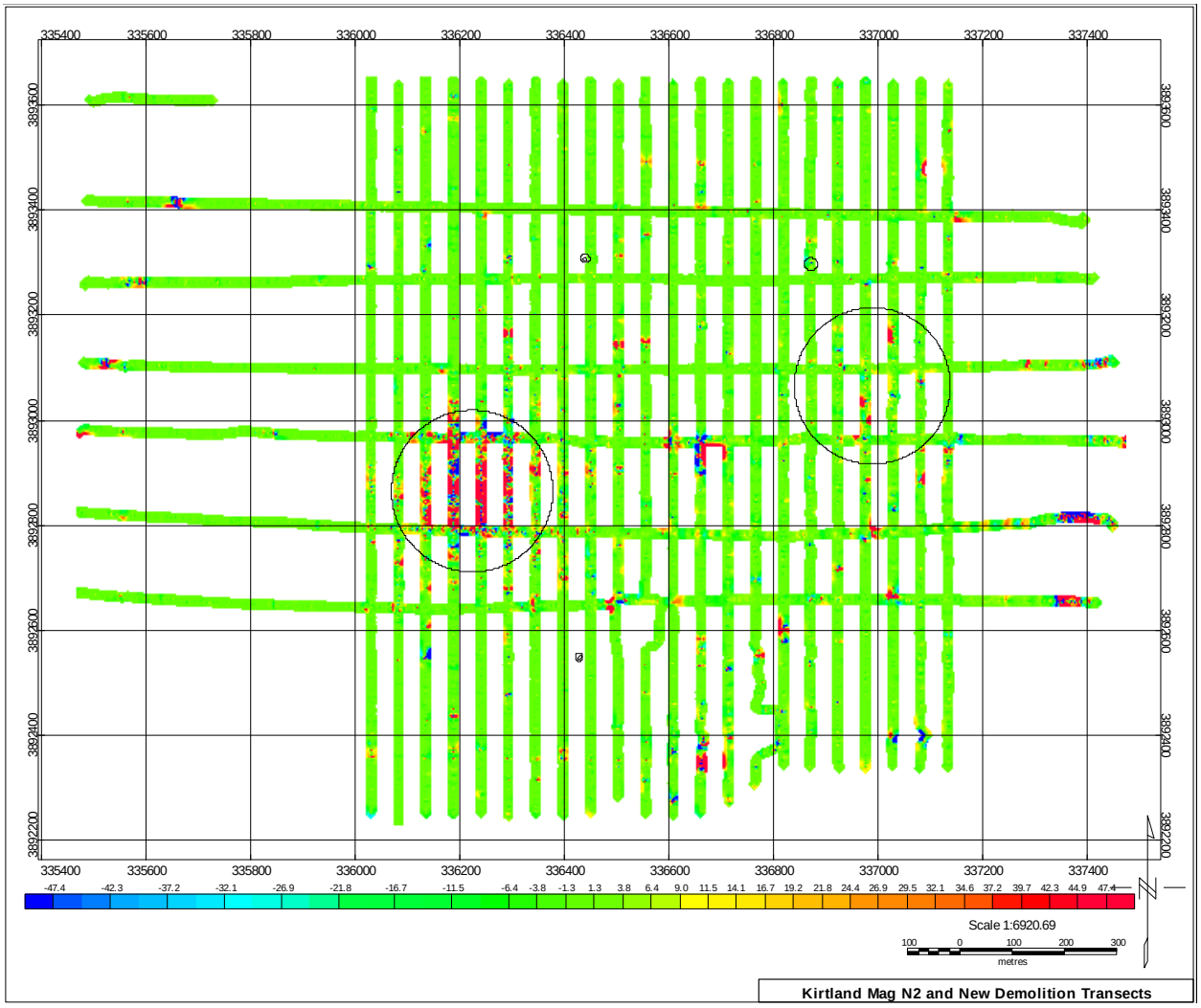

Figure 15: Sparse WE transects (150m spacing) and dense NS transects (75m spacing) over N2 (circle, left) and new demolition (circle, right) targets, mag data (+/- 50 nT)

Below, representative magnetometer and EM61 data are shown from the SORT target. The sparse and dense mag and EM61 data over this target are shown in the next figures.

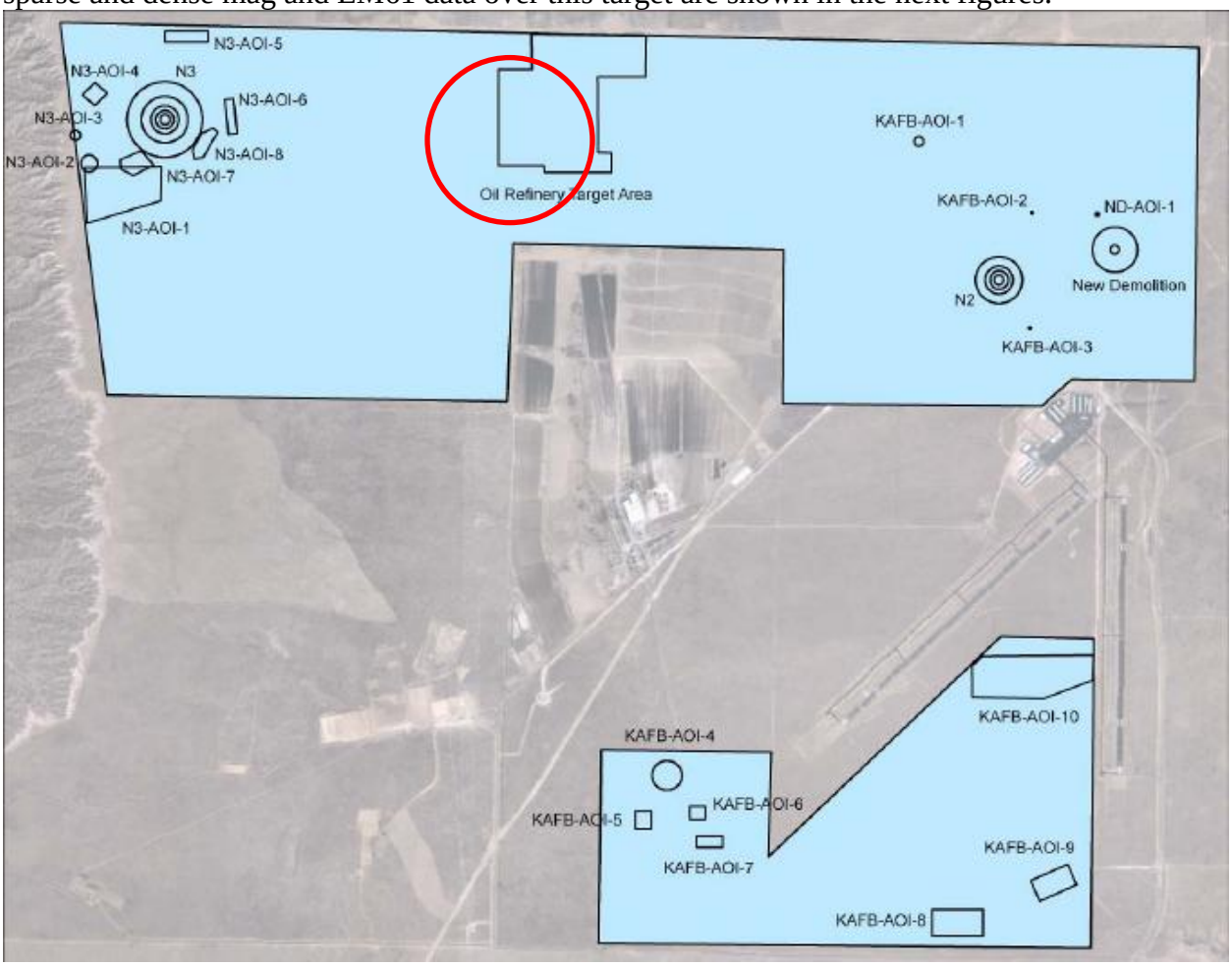

Figure 16: Red circle denotes location of Simulated Oil Refinery Target (SORT)

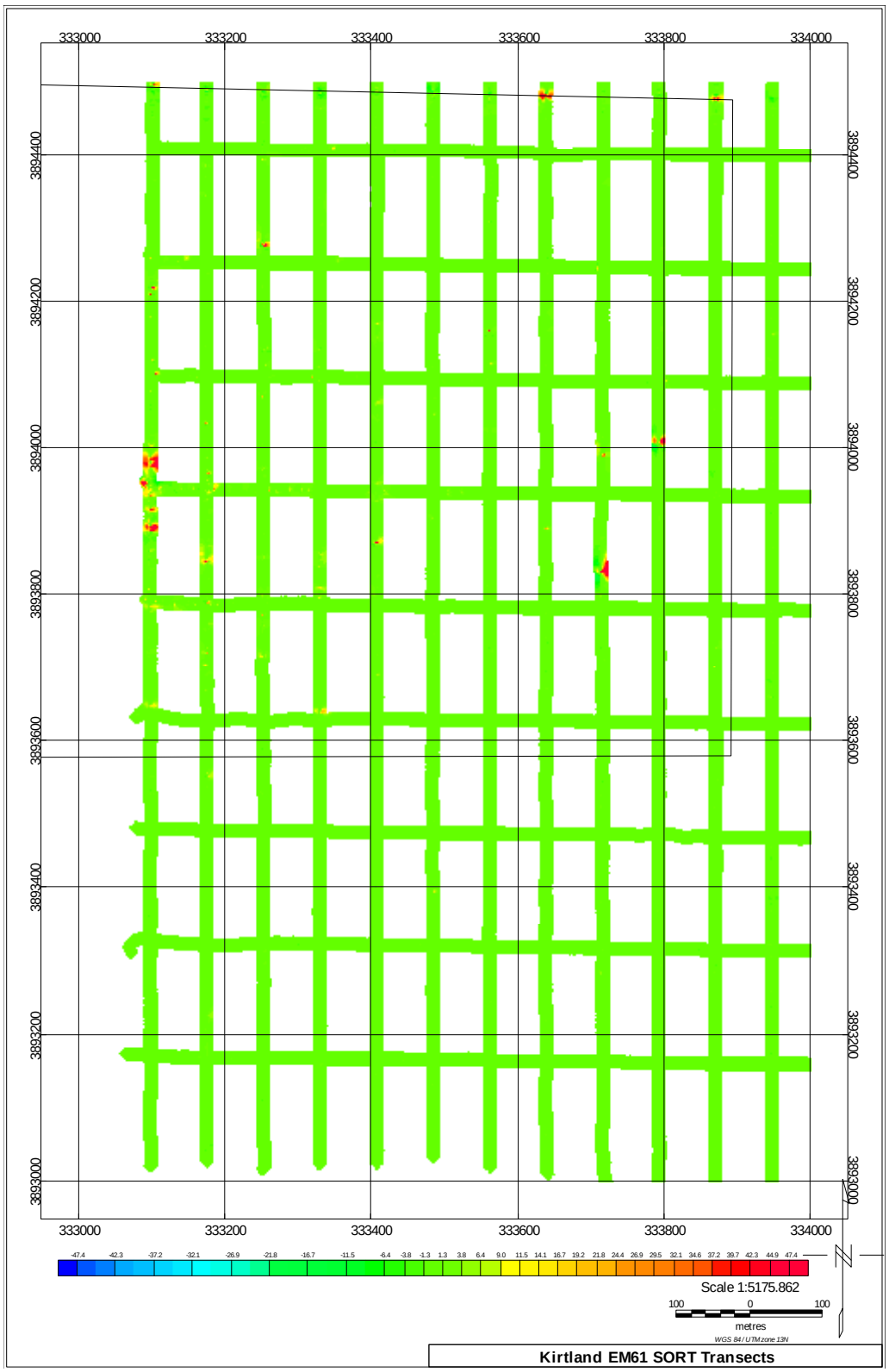

Figure 17: Sparse WE transects (150m spacing) and dense NS transects (75m spacing) over SORT, EM61 gate3 data (+/- 50 mV)

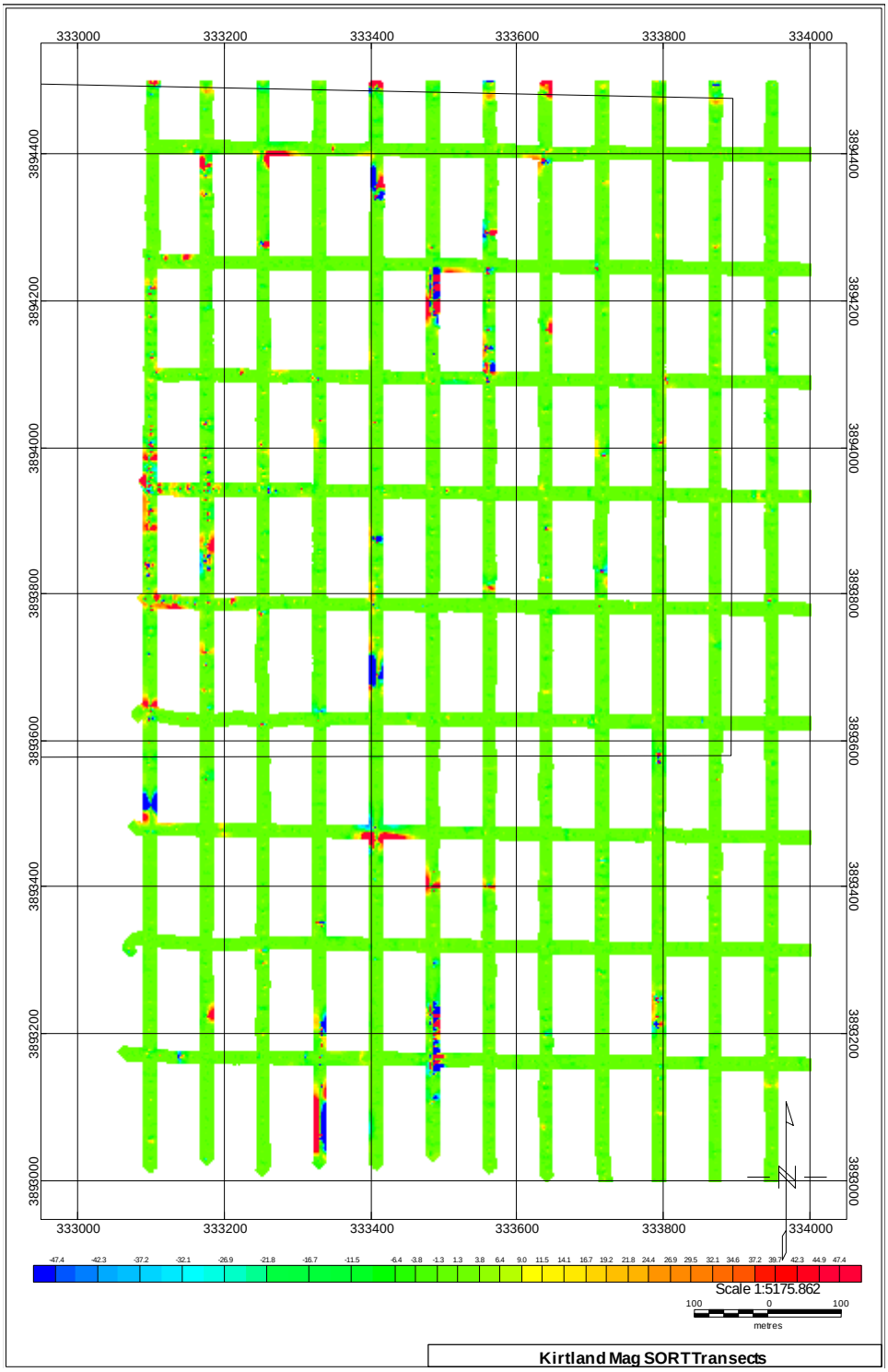

Figure 18: Sparse WE transects (150m spacing) and dense NS transects (75m spacing) over SORT, mag data (+/- 50 nT)

The red circle in the figure below shows the location of the N3 target. The next two images show the sparse and dense traverses over that target.

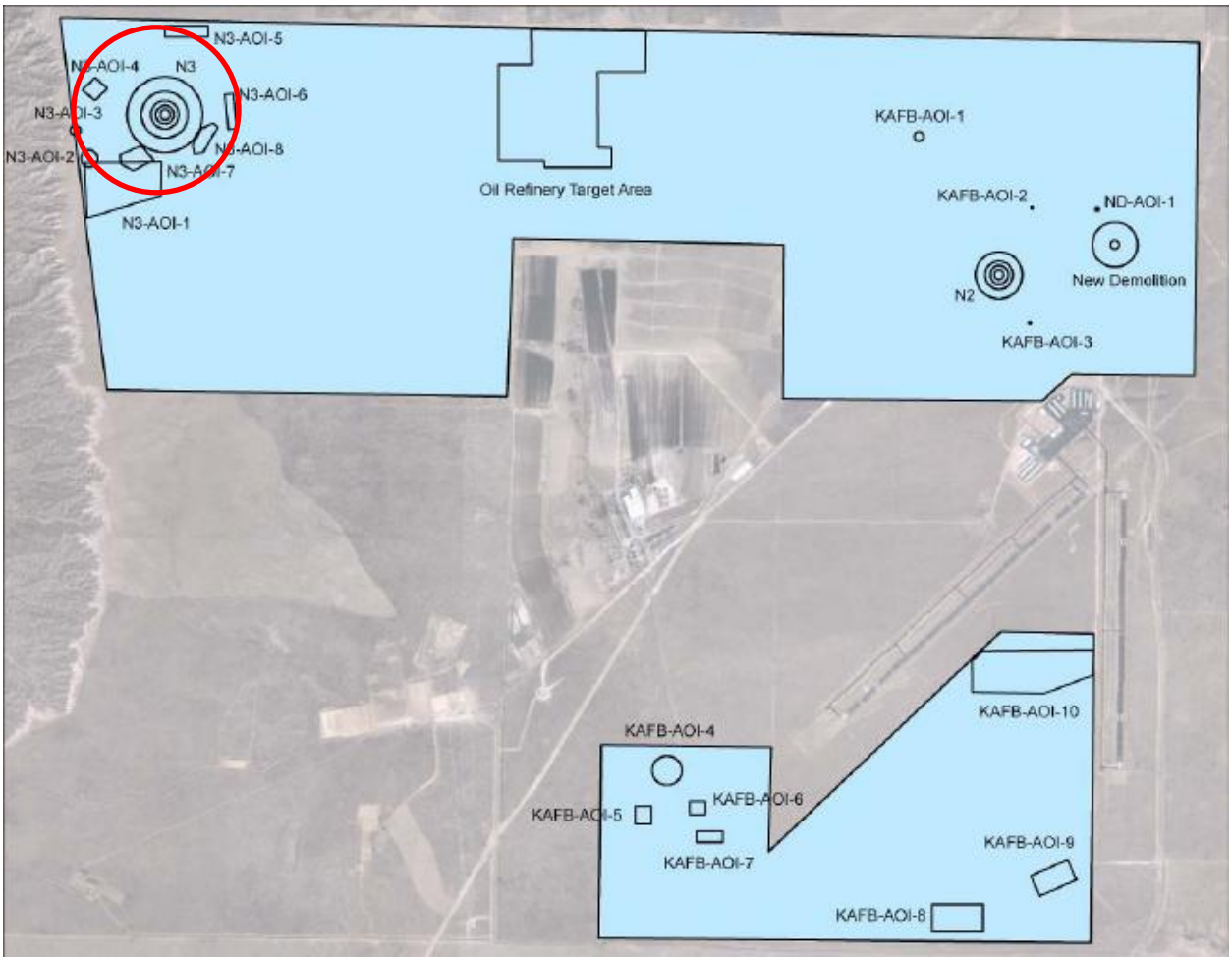

Figure 19: N3 target

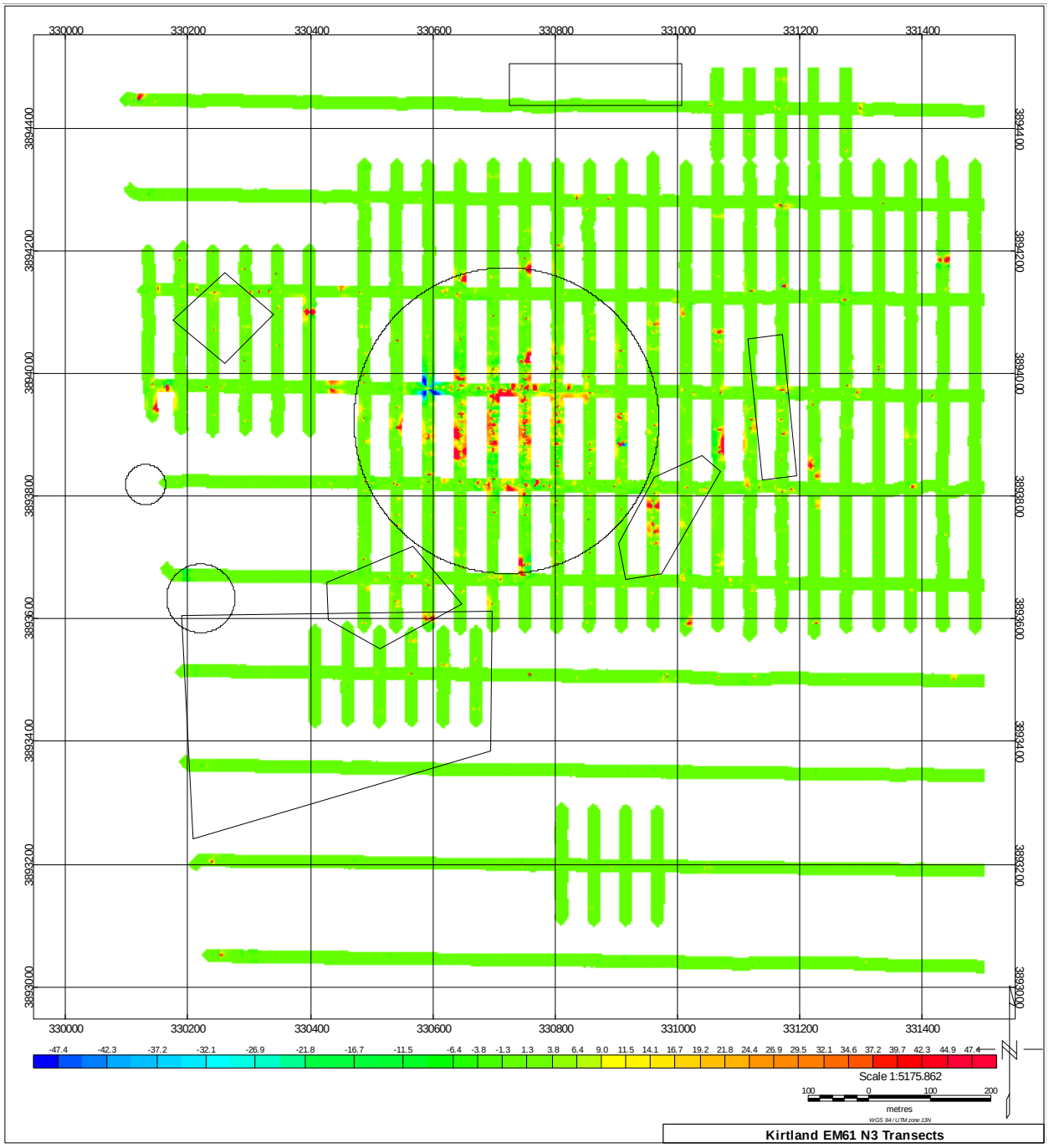

Figure 20: Sparse WE transects (150m spacing) and dense NS (50m spacing) over target N3 (red circle), EM61 gate3 data (+/- 50 mV)

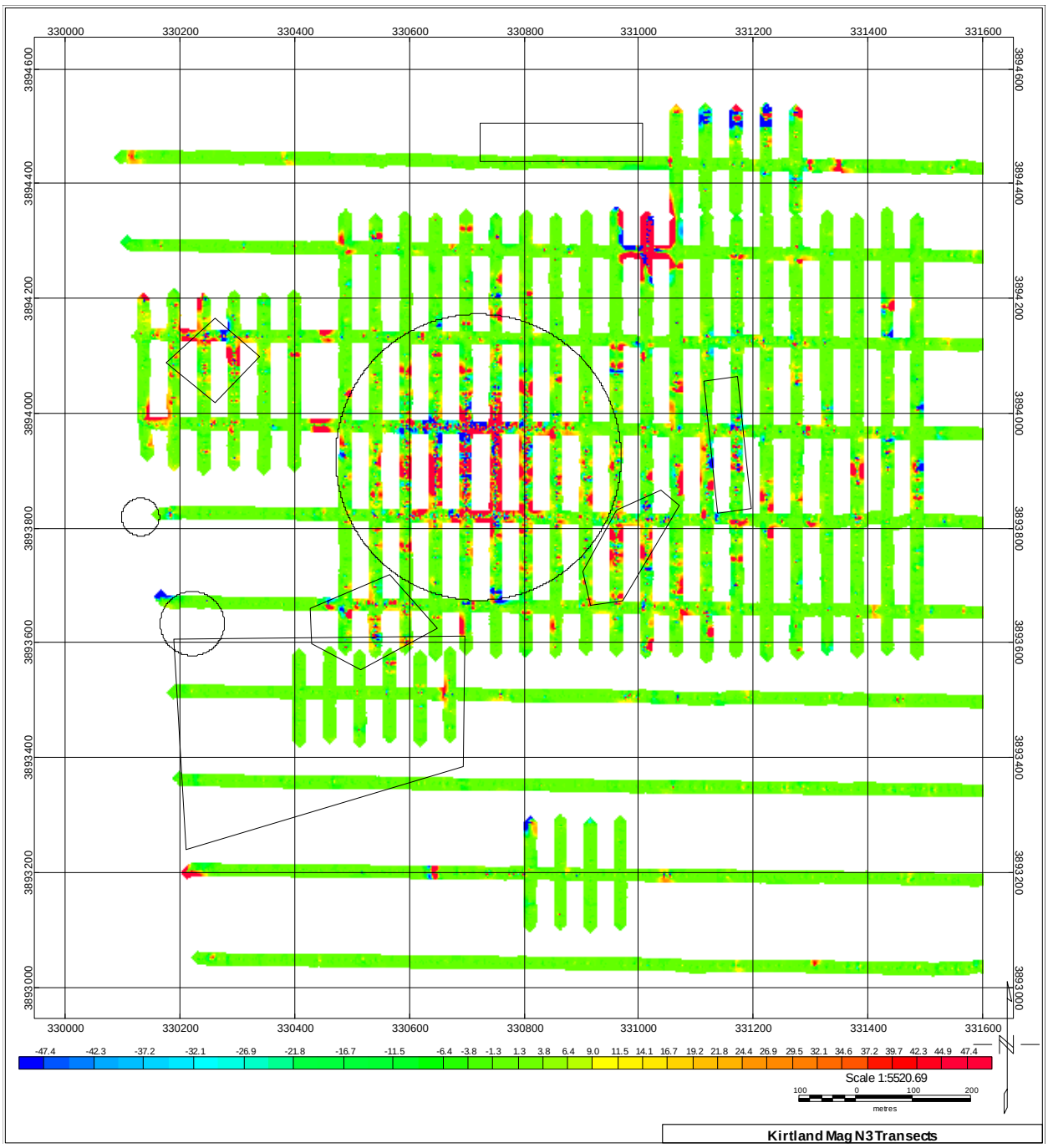

Figure 21: Sparse WE transects (150m spacing) and dense NS (50m spacing) over target N3 (red circle), mag data (+/- 50 nT)

The images below show transect data acquired in the southern part of the site.

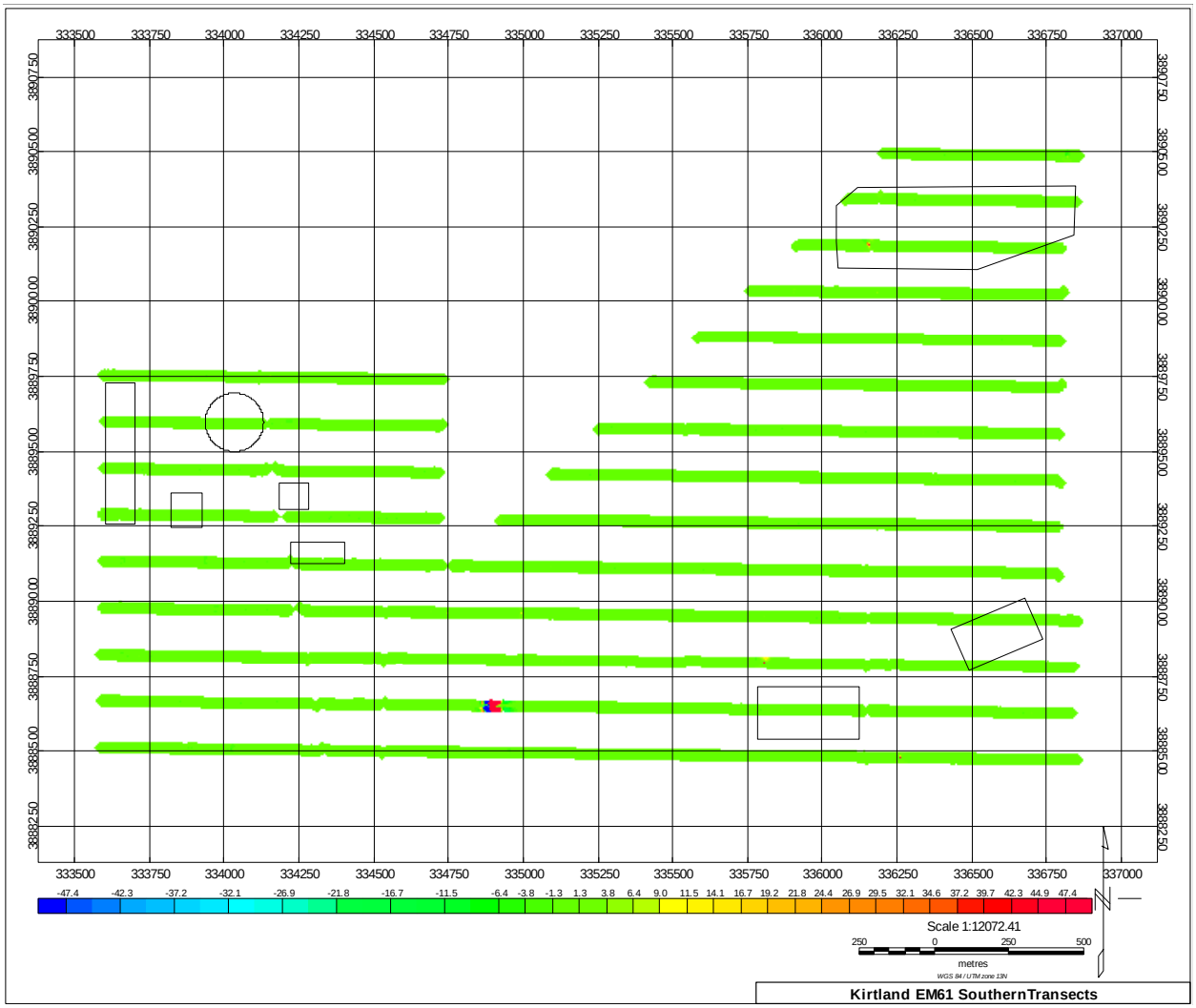

Figure 22: Sparse WE transects (150m spacing) over southern section, EM61 gate3 data (+/- 50 mV)

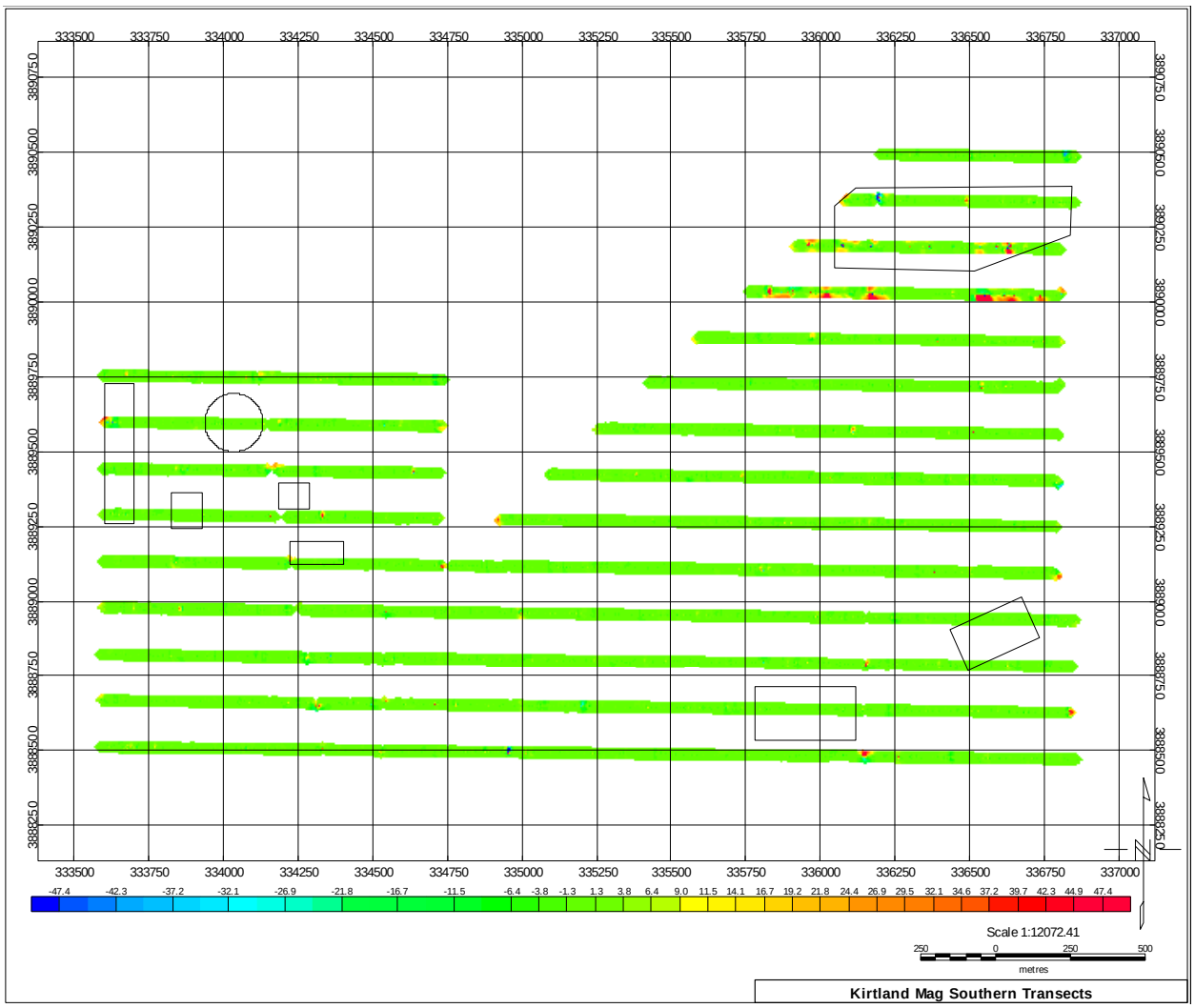

Figure 23: Sparse WE transects (150m spacing) over southern section, mag data (+/- 50 nT)

For transect data, all analysis was performed using our own data analysis software. All target picking was performed manually. Magnetometer data and EM61 data were simultaneously displayed on the screen using linked copies of our software. Panning, zooming, and scrolling in one set of data (e.g., magnetometer data) results in the same action in the other set (e.g., EM61 gate3 data). Typically, because the magnetometer data contains a superset of anomalies due to the more sensitive $1/R^3$ response, magnetometer data is viewed as the "primary" sensor, and areas of interest are drawn around anomalies in the magnetometer data. This automatically results in the same area being drawn around the corresponding location in the EM61 gate3 data. The detection thresholds determined from the test strip (10 nT for magnetometer data, 3 mV for EM61 gate3 data) are used as a visualization aid, with any data above the specified threshold colorized in red. This colorization is typically flipped on and off by the operator so he can see can see variations in what would otherwise be solid blotches of color.

The software then inverts the magnetometer data inside the specified area of interest using a model of a point dipole. Parameters from the inversion include location, depth, size, moment, and goodness of fit estimates; these are recorded in a file, as is an optional operator-entered

comment field. The peak sensor value and peak fit value are also recorded. Our software has no EM inversion capability, but the peak EM sensor value is recorded in the file.

As discussed at length above, the operator then enters a “likelihood” value intended to broadly triage candidate anomalies into three different classes. Likelihood 2 anomalies are those that the operator feels are of a size and shape consistent with whole a compact ferrous object. These typically have magnetic signatures that are classic dipoles, with a clear, round, strong, well-defined positive lobe, and a clear, mushroom cap-shaped, strong, well-defined negative lobe. The operator looks at both magnetometer and EM61 data and uses his judgment when making the likelihood determination. The anomaly may have a weak or no magnetic signature, but may still be flagged as Likelihood 2 if the EM61 signal is broad and strong enough. Likelihood 0 anomalies are those that the operator feels are due to noise or geology in either the magnetometer or EM61 data. Likelihood 1 anomalies are those that are neither Likelihood 2 or likelihood 0. These are generally anomalies that have a discernible signature in the magnetometer and/or EM61 data, but are not the largest strongest anomalies in the data set, and are smaller and/or weaker than the candidate anomalies in the test strip. Anomalies with a spatial extent consistent with frag were classified as Likelihood 1.

After the operator has viewed all of the magnetometer data, the data sets are “flipped,” and the EM61 data is viewed as the primary sensor. With all of the anomalies selected thus far overlaid on the EM61 data, the operator then carefully combs the data and selects any anomalies above the EM threshold that were not selected from the magnetometer data because they had no signature or too weak a signature. These are then added to the data set.

The following table summarizes the number of anomalies from each submitted set of transect data, and the breakdown of anomalies by likelihood.

Table 8: Breakdown of anomalies by day and likelihood

date	number of anomalies
21-Sep	144
22-Sep	569
23-Sep	180
24-Sep	185
26-Sep	99
27-Sep	483
28-Sep	13
30-Sep	161
1-Oct	218
4-Oct	655
5-Oct	261
6-Oct	279
10-Oct	302
14-Oct	231
15-Oct	36
18-Oct	78
19-Oct	1680
20-Oct	210
12-Nov	1458
14-Nov	225
total	7467
# of L 2	3597
# of L 1	2457
# of L 0	1413
	7467
mag primary	5875
EM primary	1592

It should be understood that, because anomalies are extracted from the mag and EM61 data simultaneously, it is misleading to talk about “mag anomalies” and “EM anomalies.” There are not separate lists; there is a single list containing all selected anomalies, and entries in the list include the peak mag and EM signals in the selected area, as well as which sensor was viewed as the primary sensor during analysis. If it is important to answer the question “did this sensor see object X,” one could look at which sensor was the primary sensor, and combine that with the peak sensor reading, or re-examine the original data.

4.3.3 100% Geophysical Survey Area Data

Fourteen 100% geophysical survey areas were specified by the ESTCP Program Office and surveyed with VSEMS. The locations of these areas relative to the Kirtland PBR site are depicted in figure 4 above. The 28 individual site images (14 sites, mag and EM61) are below, with brief comments. A more complete discussion of the data and results follows the images.

Area1a, area1b, and area1c were located near target N2, situated radially outward from the target to collect data from which anomaly falloff and background information could be ascertained. After several weeks of performing widely-spaced transect surveys, area1a was the first 100% geophysical survey area we attempted. Due to operator error, the line spacing (set by visually positioning the vehicle's tire tracks) was close enough that only minor missed area appears in the EM61 data. However, more noticeable missed area appears in the magnetometer data. This apparent discrepancy is due to the fact that the five magnetometers are on 50cm centers yielding a 2 meter swath, whereas the EM61s due to the physical coil width are on 55cm centers, yielding a 2.2 meter swath width. After this data set was viewed, we carefully calculated the spacing of tire tracks needed on adjacent survey lines to overlap the outboard magnetometer on line N with the inboard magnetometer on traverse N+1, and verified that the lines were being driven in this manner. Area1a contained 347 anomalies, of which 127 were flagged by the analyst as Likelihood 2 anomalies. Area1b contained 209 anomalies, of which 49 were flagged by the analyst as Likelihood 2 anomalies. Area1c contained 48 anomalies, of which 11 were flagged by the analyst as Likelihood 2 anomalies. Particularly in the magnetometer data of area1a, many of the Likelihood 2 anomalies are of a very consistent size and shape. Digging verified that the majority of these were parts from M38 bombs. The falloff in number of likelihood 2 anomalies per acre is depicted in the able below.

Table 9: Falloff in Anomaly Density Near Target N2

	number of likelihood 2 anomalies	near target	acreage	anomaly density (number per acre)
Area1a	127	N2	7.2	17.6
Area1b	149	N2	15.1	9.9
Area1c	11	N2	7.2	1.5

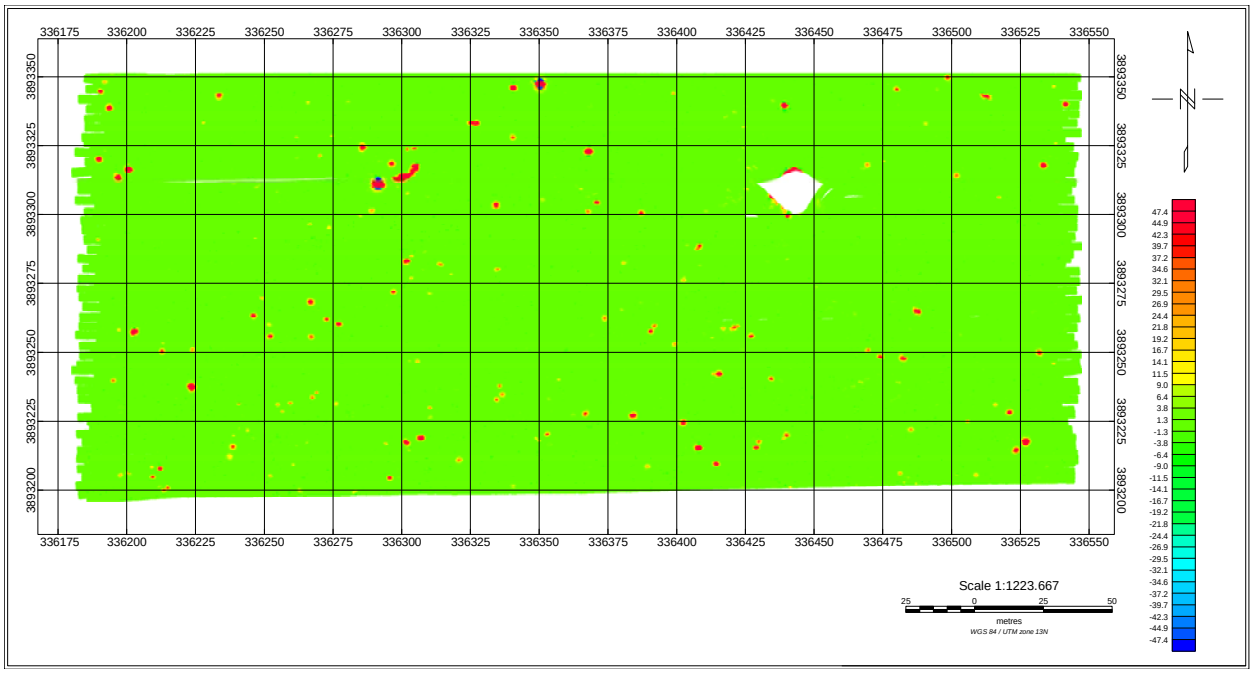

Figure 24: area1a near target N2, 7.2 acres, EM61 gate 3, +/- 50 mV

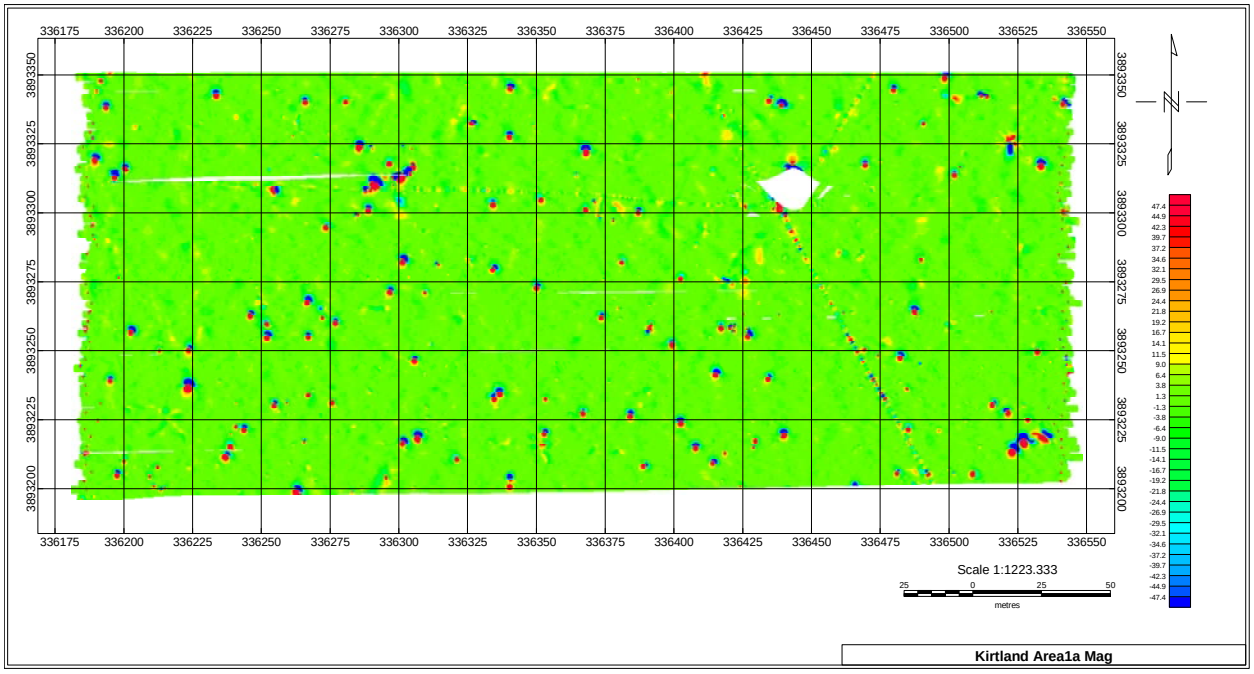

Figure 25: area1a near target N2, 7.2 acres, mag, +/- 50 nT

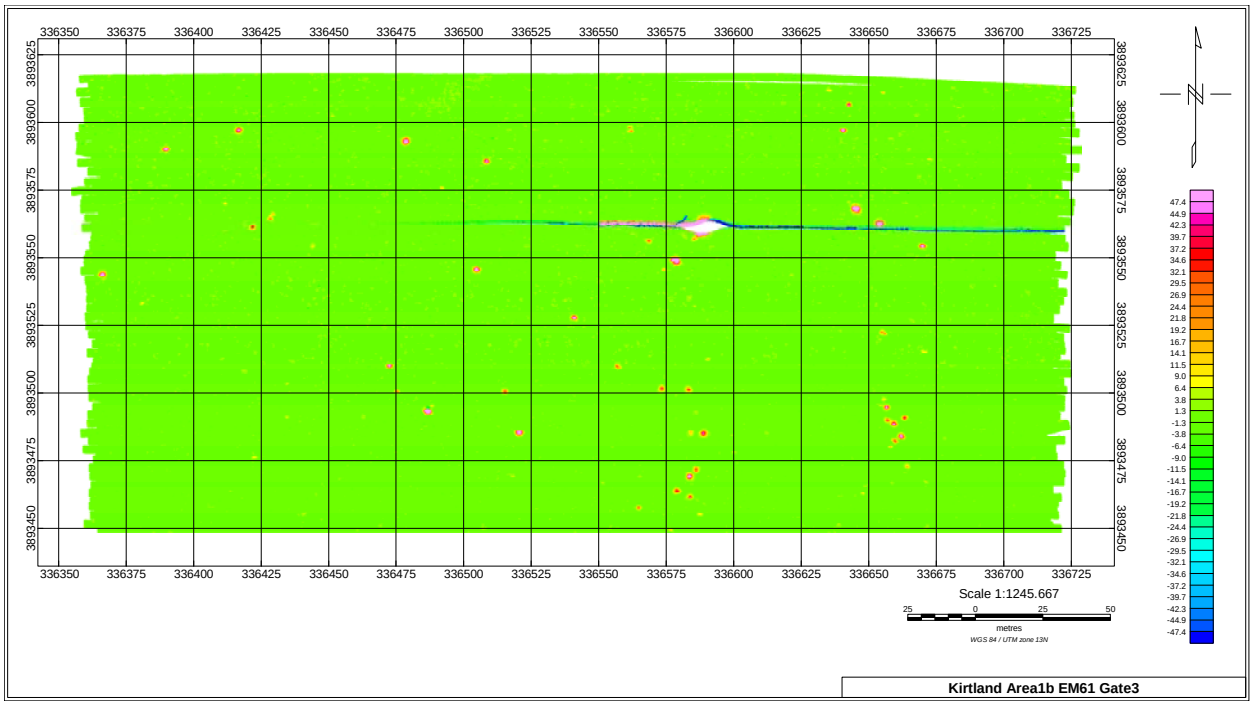

Figure 26: area1b near target N2, 15.1 acres, EM, gate3, +/- 50mV

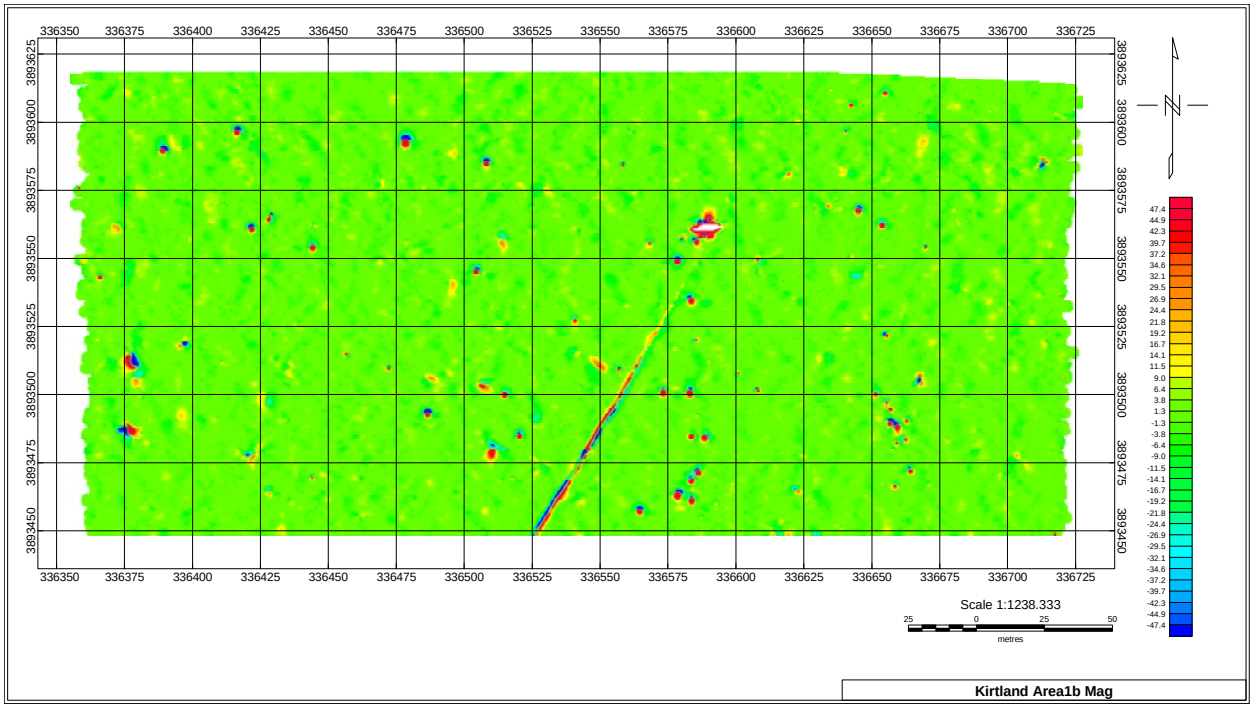

Figure 27: area1b near target N2, 15.1 acres, mag, +/- 50nT

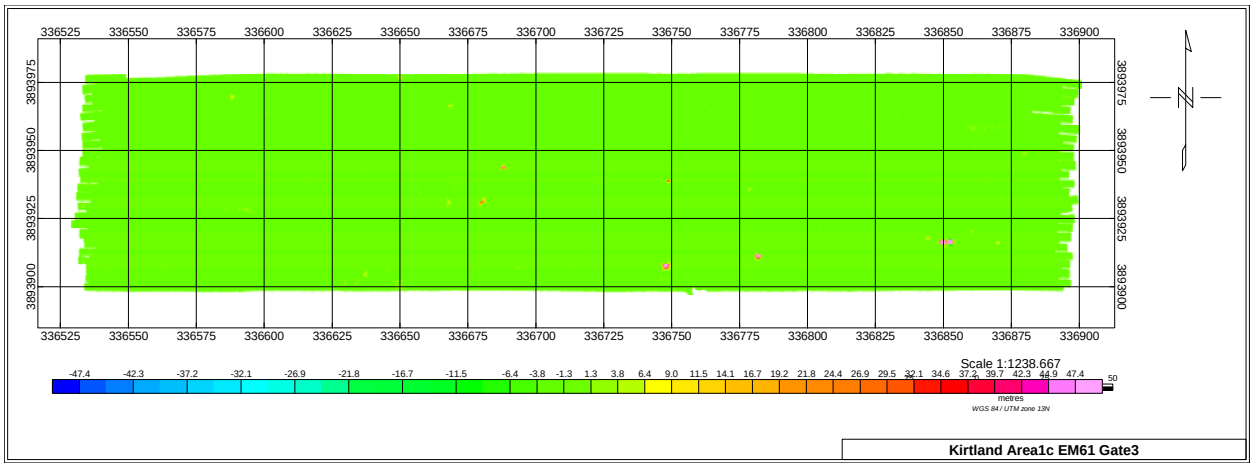

Figure 28: area1c near target N2, 7.2 acres, EM, gate3, +/- 50mV

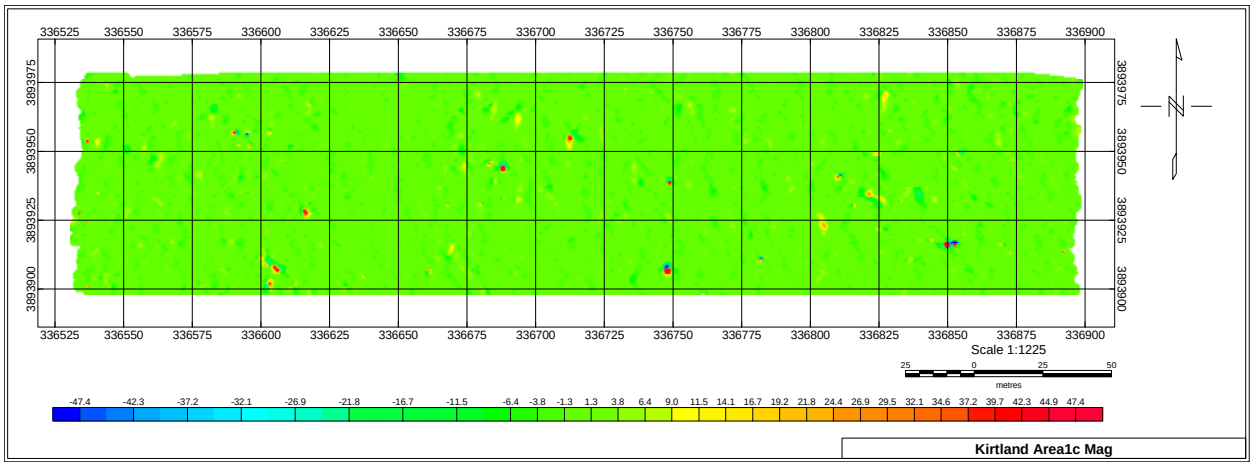

Figure 29: area1c near target N2, 7.2 acres, mag, +/- 50nT

Area2a, area2b, and area2c were situated radially outward from the previously unknown target in the area of the Simulated Oil Refinery Target (SORT). Area2a in the figures below show four large, round features the analyst affectionately deemed "crop circles." These features are large (23 meters in diameter), and lie on the corners of a 108 meter square. Most interesting, they ring out quite clearly in the EM61 data, but are very difficult to see in the magnetometer data. A total of 160 anomalies were analyzed in area2a, 81 of which were flagged as Likelihood 2. A total of 111 anomalies were analyzed in area2b, 38 of which were flagged as Likelihood 2. A total of 80 anomalies were flagged in area2c, 15 of which were flagged as Likelihood 2. As was the case with area1a, area2a contains many anomalies, particularly in the magnetometer data, of a very consistent size and shape, and digging also revealed that most of these were parts of M38 bombs. The falloff in the number of Likelihood 2 anomalies per acre is depicted in the table below.

Table 10: Falloff in Anomaly Density Near SORT

	number of likelihood 2 anomalies	near target	acreage	anomaly density (number per acre)
Area2a	81	SORT	13.4	6.0
Area2b	38	SORT	13.2	2.9
Area2c	15	SORT	13.4	1.1

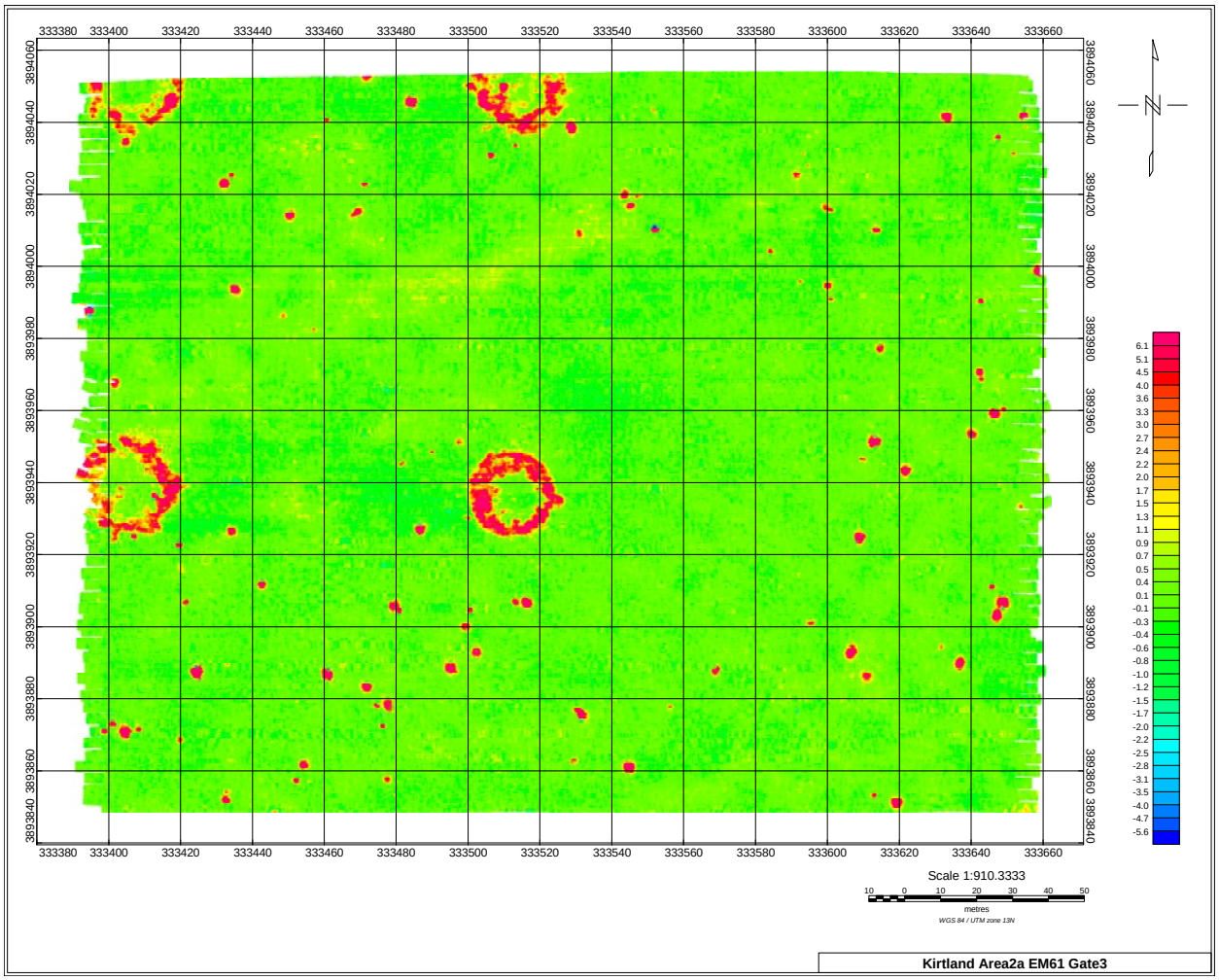

Figure 30: area2a near SORT, 13.4 acres, EM, gate3, +/- 50mV

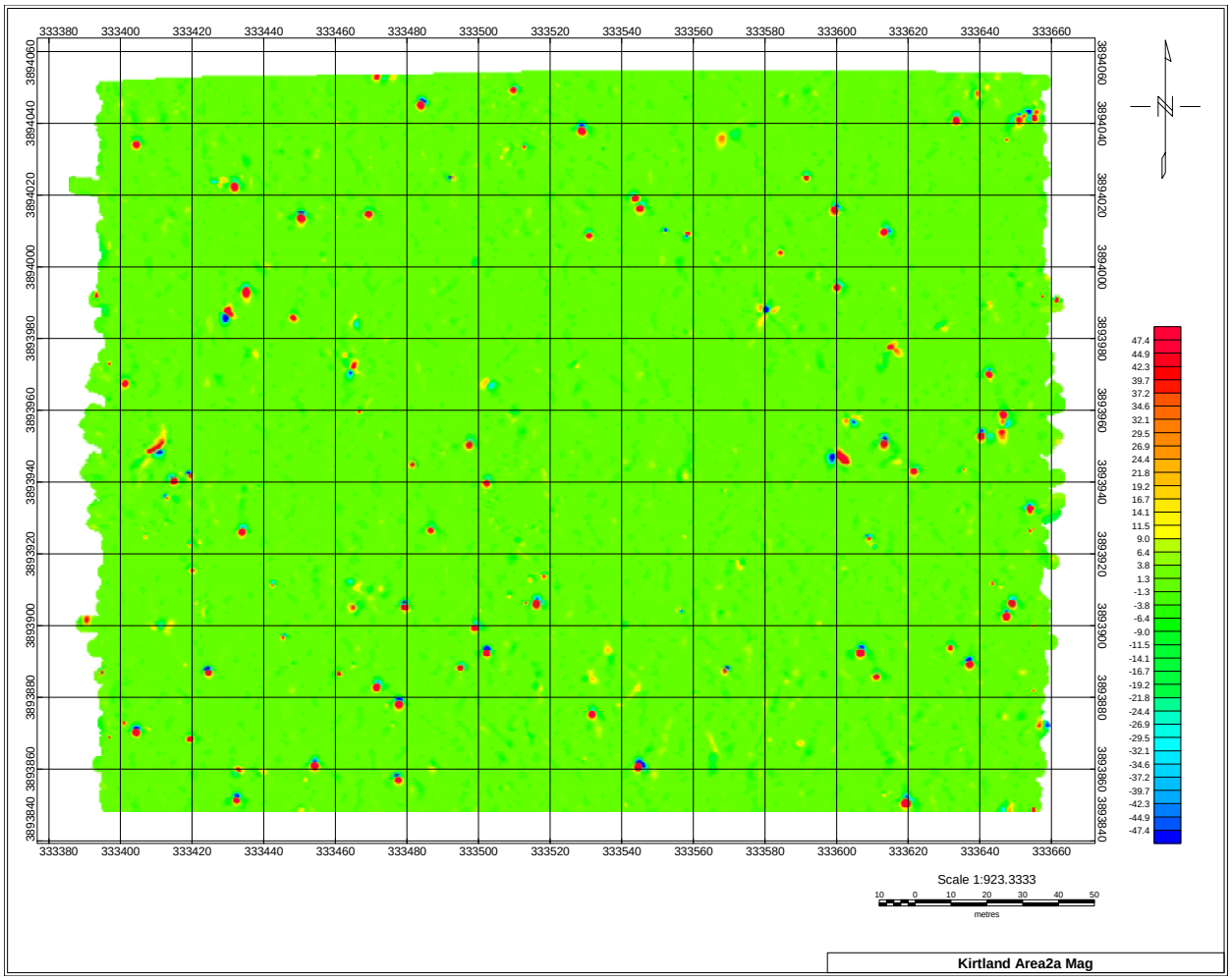

Figure 31: area2a near SORT, 13.4 acres, mag, +/- 50nt

Below are blowups of one of these circular anomalies. In the first set of images, EM61 gate3 data are shown at two different display scales. In the second set, magnetometer data are shown at two different display scales. The anomalies are faintly visible in the magnetometer data, but were not apparent to the analyst until he saw them in the EM61 data. It is unlikely that they would have been seen had a magnetometer-only survey been performed. The origin of these anomalies, and the physical material creating them, is unknown; since it is in the area associated with the SORT, our conjecture is that these are remnants of large metal-skinned structures such as tanks. The centers of two of these circular anomalies were flagged as Likelihood 2 targets, with a comment in the target file indicating their diameter, but they both were reported on the dig sheet as no-finds. It is unknown if the reconnaissance included examination of the ground not only at the center, but at the radius we were reporting. The clear magnetic dipole circled in red in the magnetometer image below is object k-611, which is listed in the dig sheet as “M38 bomb parts.” Since the location of this object is right on the circumference of one of the circles, and since no 23-meter aluminum cistern was reported when it was dug, it is possible that the circular anomalies are due to flaked-off or rusted remnants structures that have long since been removed.

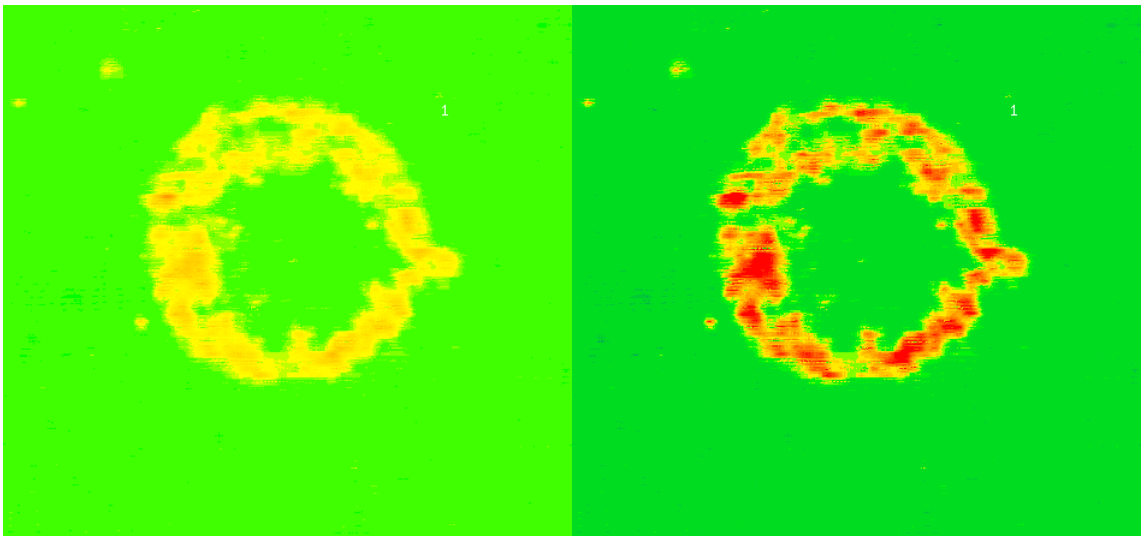

Figure 32: EM61 gate3 data at +/- 50mV (left) and +/-10mV (right) of the lower right "crop circle." Circle is 23 meters in diameter.

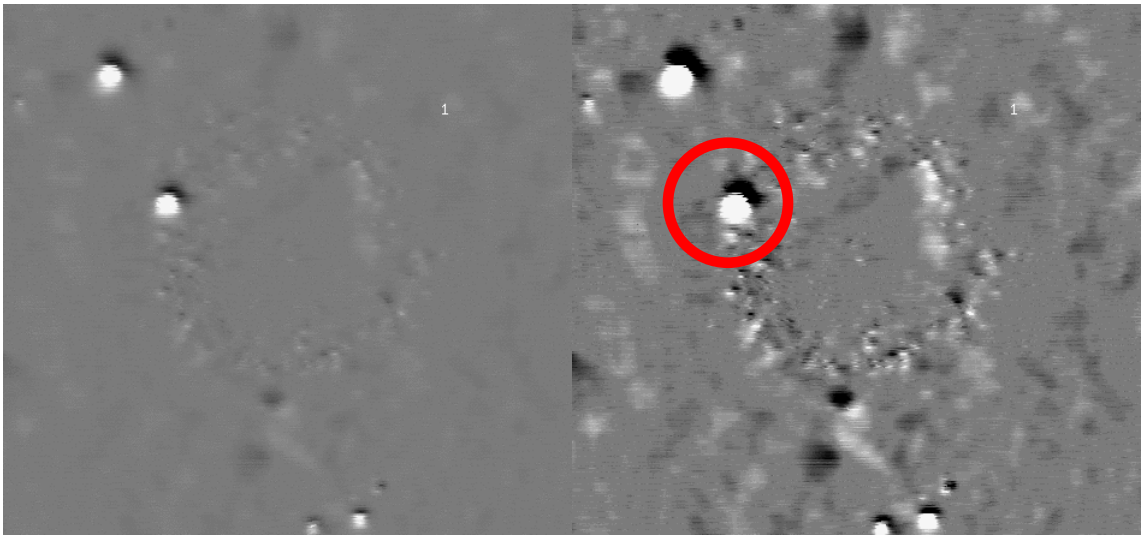

Figure 33: Magnetometer data at +/- 50nT (left) and +/-10nT (right) of the lower right "crop circle." Magnetic dipole circled in red is object k-611. Only M38 bomb parts were discovered when this location was dug, making it unlikely that whatever is causing these circles are actually large metallic structures still inset into the ground.

In the image below, LIDAR data from URS Corporation is displayed with VSEMS EM61 gate3 data overlaid. From here, it is seen that the centers of the "crop circles" overlay exactly on the centers of the grid squares that the LIDAR detected. This reinforces the conjecture that there were structures of some sort in the middle of these grid squares.

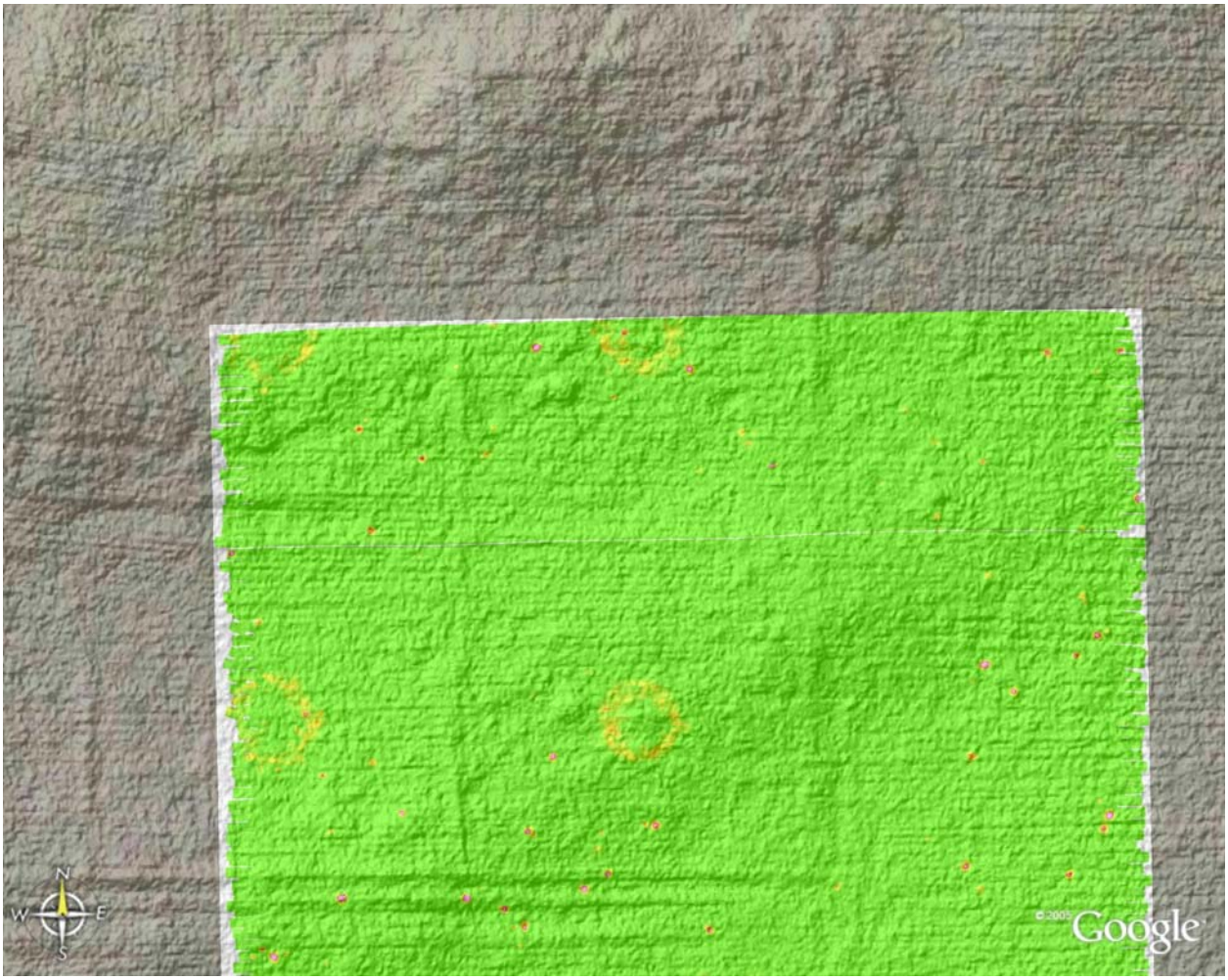

Figure 34: EM61 Mk2 gate3 data from area2a near the suspected SORT target, overlaid on LIDAR data. The "crop circles" are exactly correlated with the centers of the grid-like features uncovered by the LIDAR.

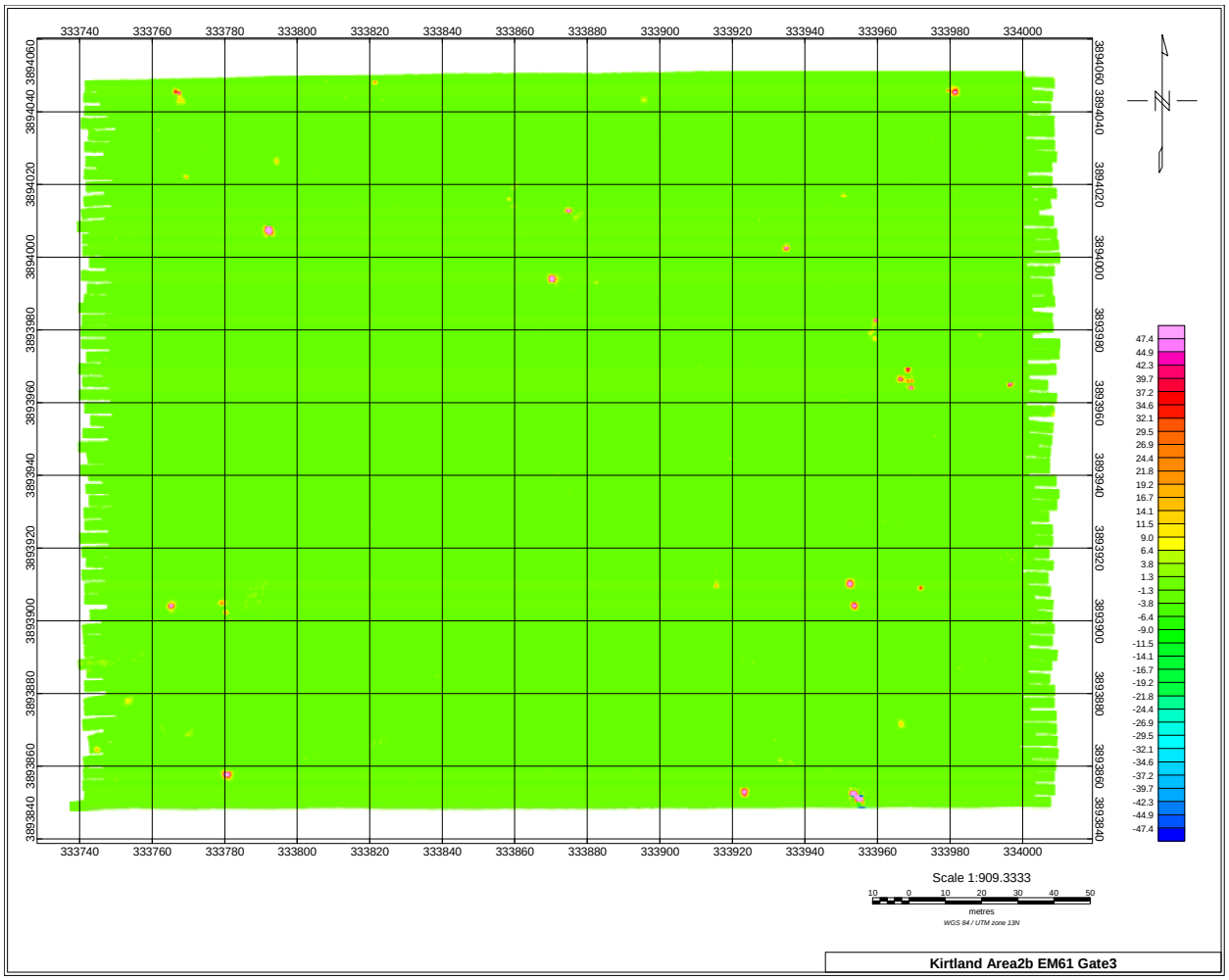

Figure 35: area2b near SORT, 13.4 acres, EM, gate3, +/- 50mV

In the magnetometer data from area2b below, the density of anomalies typical of compact ferrous objects is relatively low, which allows the eyeball to be drawn to the irregular non-dipolar features of the anomalies that are likely geology. Even at this coarse distance scale showing the entire 13.4 acres, it is clear that these anomalies show up in the magnetometer data but not the EM61 Mk2 data; this is discussed in detail in section 4. The same is true for area2c below, where the density of anomalies typical of compact ferrous objects is even less.

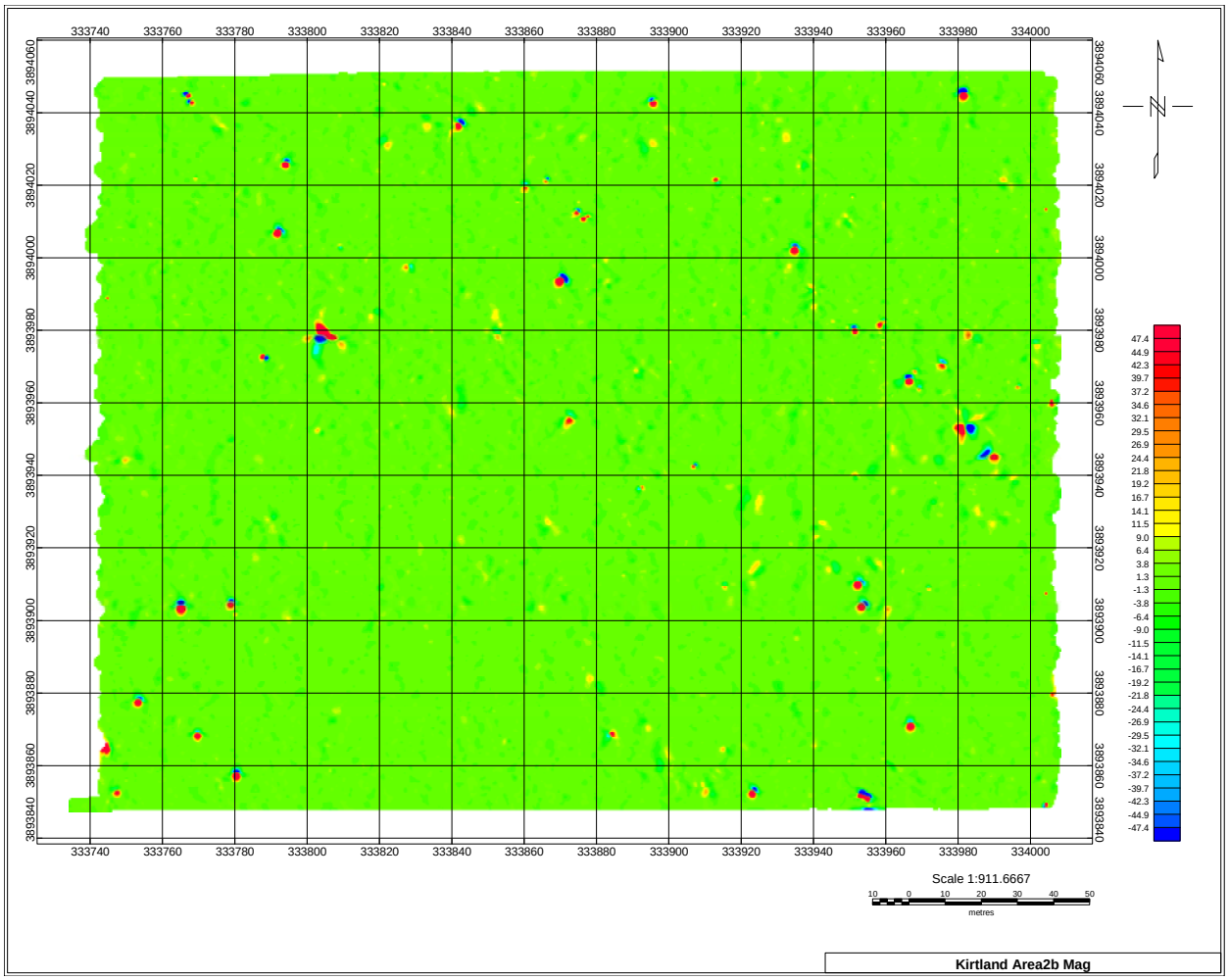

Figure 36: area2b near SORT, 13.2 acres, mag, +/- 50nT

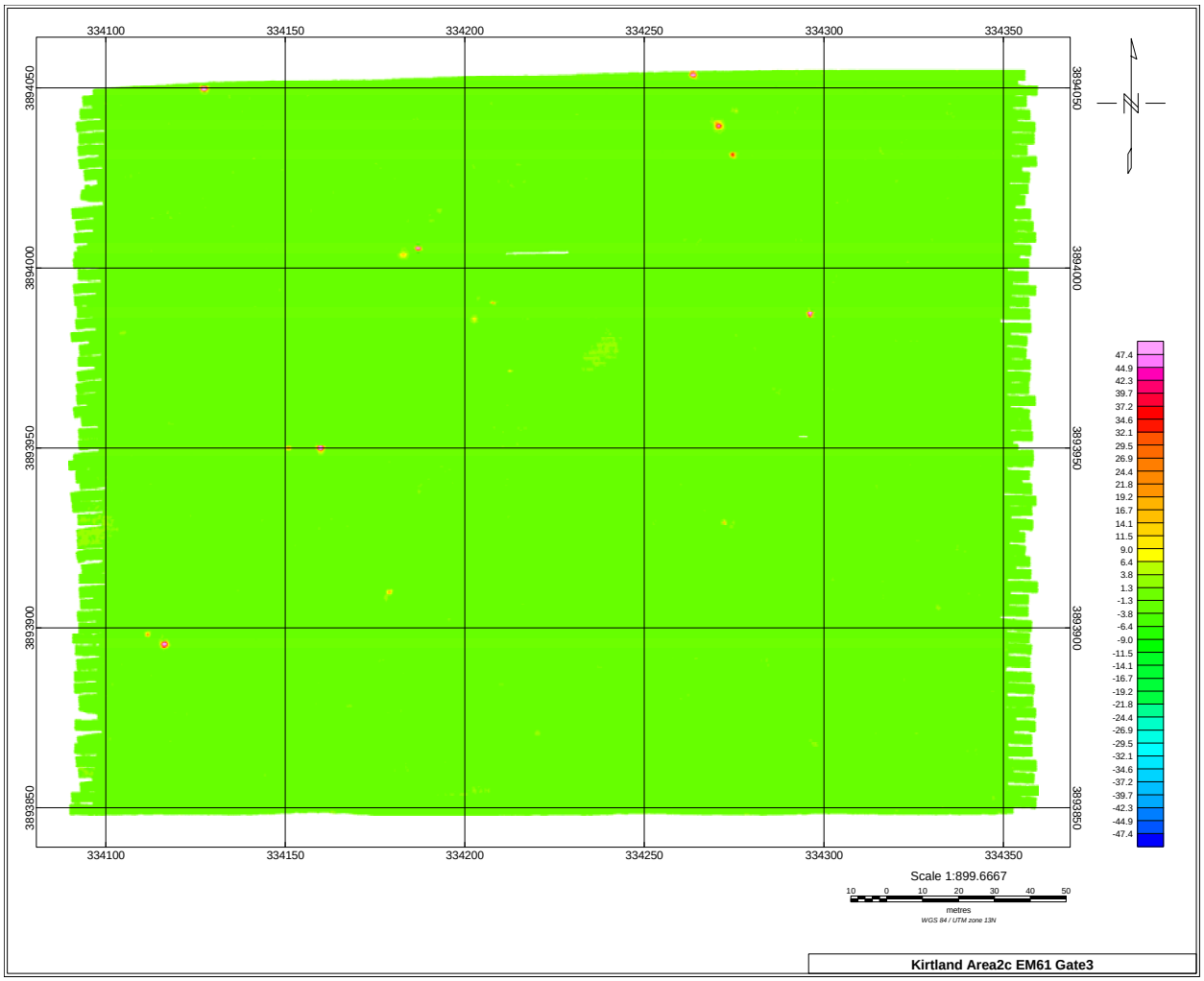

Figure 37: area2c near SORT, 15.8 acres, EM, gate3, +/- 50mV

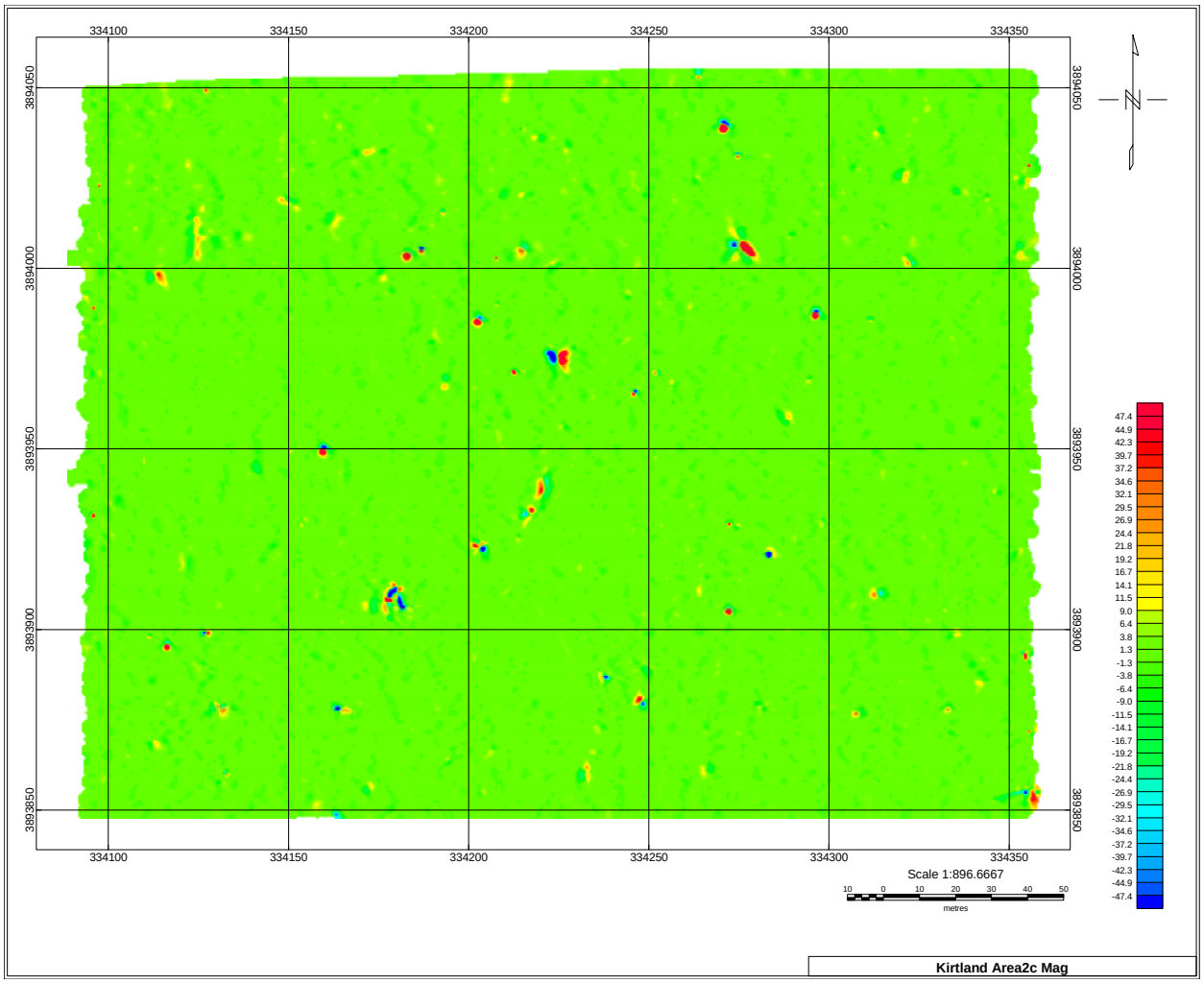

Figure 38: area2c near SORT, 13.2 acres, mag +/- 50nt

Area3a was located south of the SORT. 185 anomalies were analyzed, 85 of which were flagged as Likelihood 2.

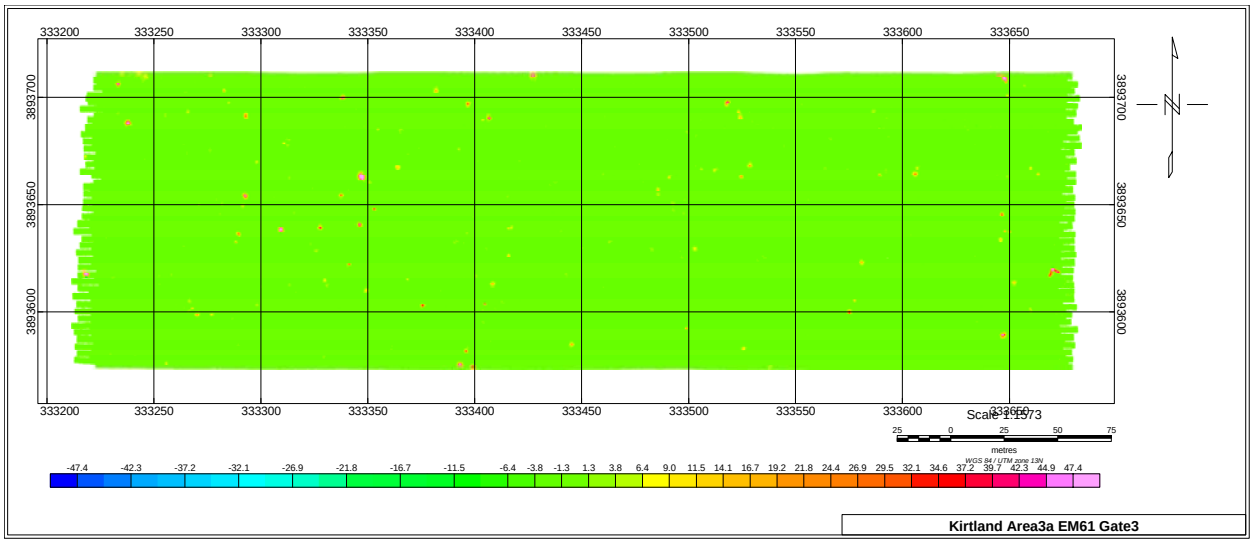

Figure 39: area3a SORT, 15.8 acres, EM, gate3, +/- 50mV

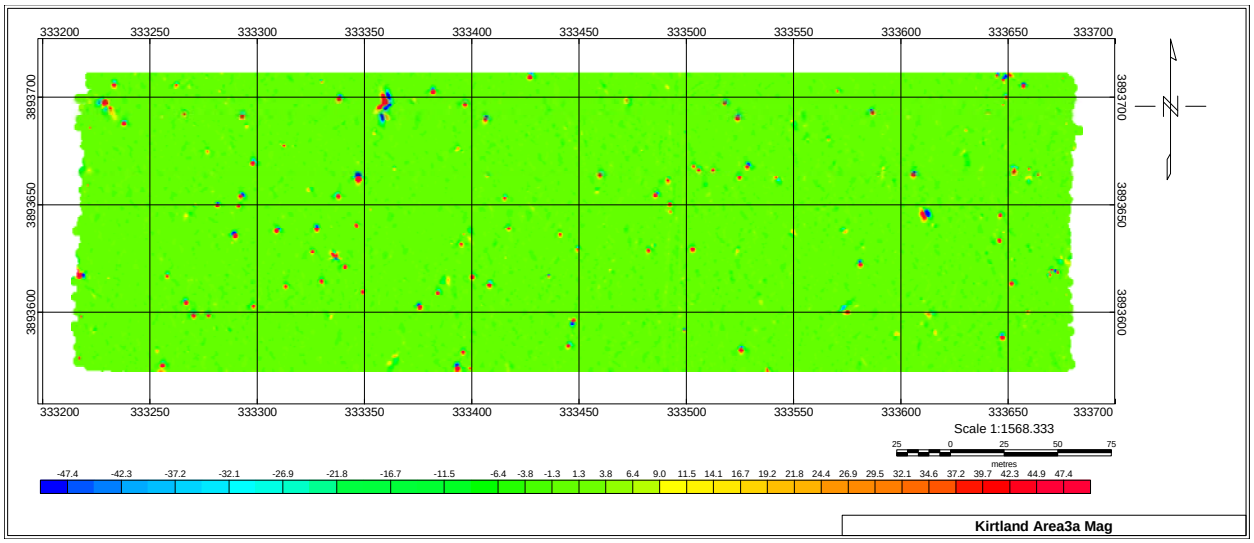

Figure 40: area3a near oil refinery target, 15.8 acres, mag, +/- 50nt

Area3b was located near the New Demolition target. This was a more cluttered area than had been seen before, with a large number of anomalies in both the magnetometer and the EM61 data. A pipeline is clearly visible in the magnetometer data, but does not show up in the EM61 data. A total of 243 anomalies were analyzed in area3b, 68 of which were flagged as Likelihood 2.

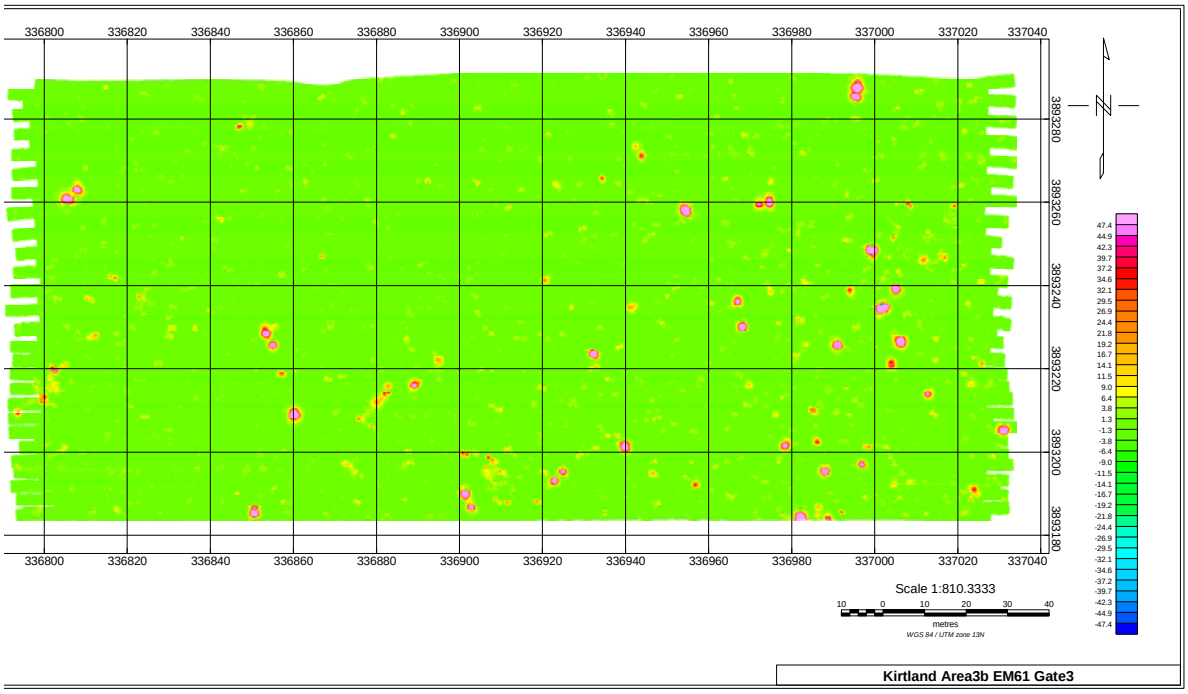

Figure 41: area3b near new demolition target, 6.2 acres, EM, gate3, +/- 50mV

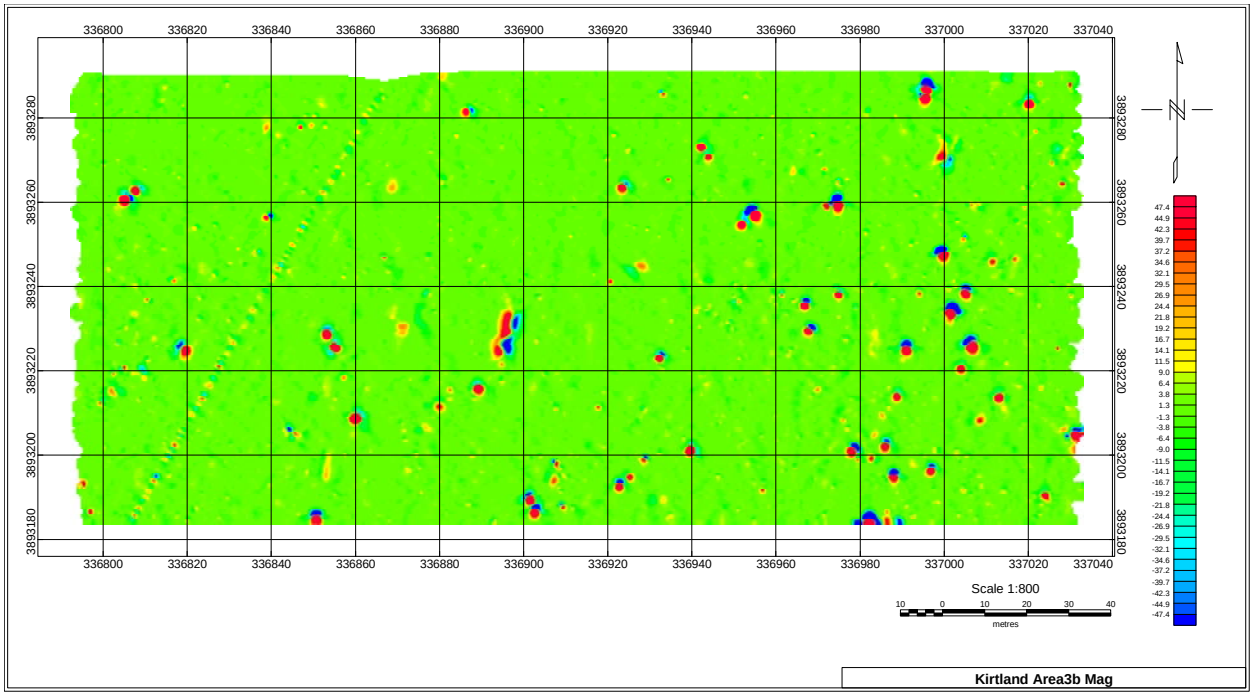

Figure 42: area3b near new demolition target, 6.2 acres, mag, +/- 50nT

Area4a was located in the northwest corner of the site, south of target N3. The consistency of the size of the anomalies, particularly in the magnetometer data, is striking. The majority of these were parts of 100 lb practice bombs. 78 anomalies were analyzed of which 39 were Likelihood 2.

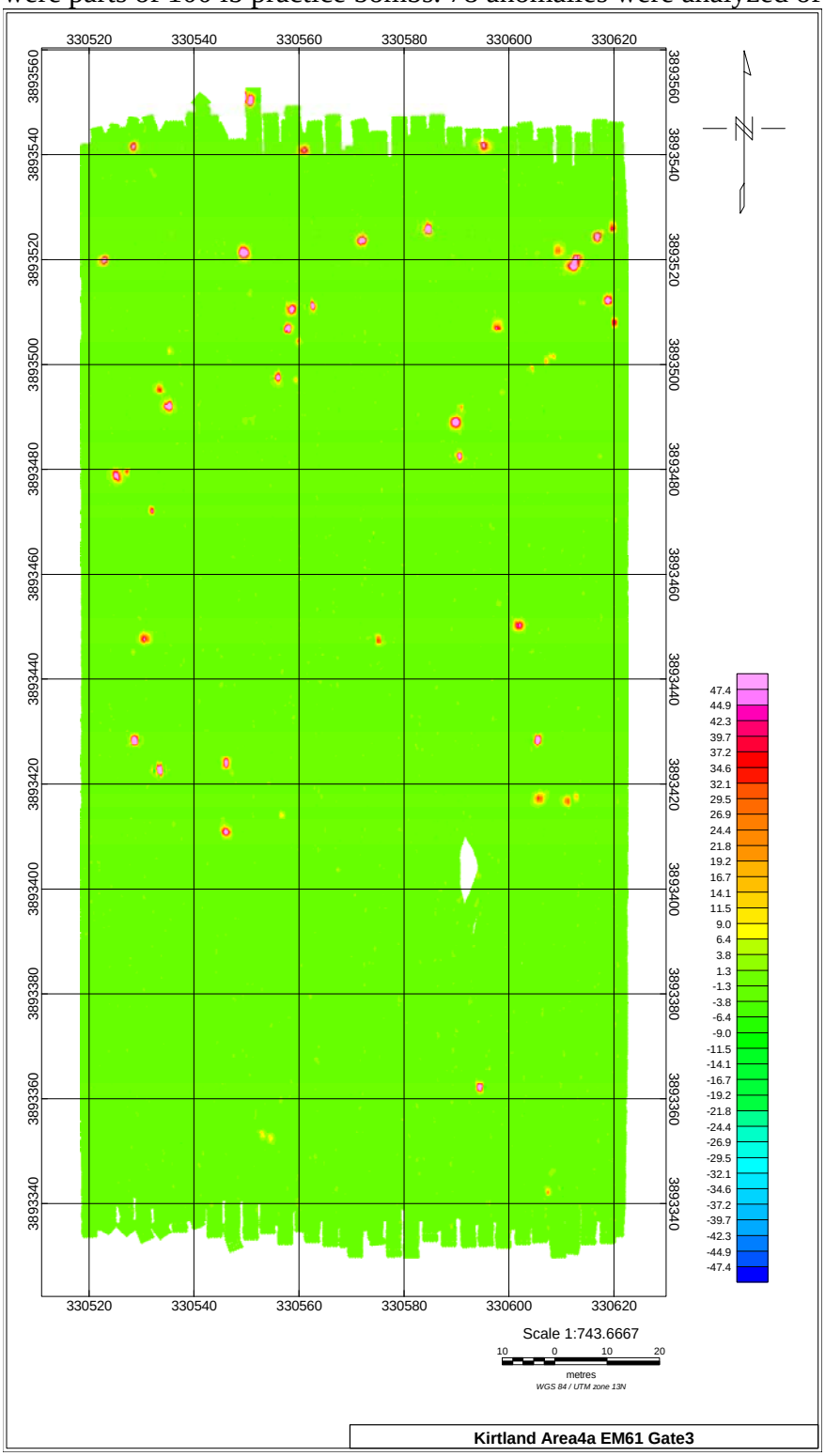

Figure 43: area4a near target, N3, 5.5 acres, EM, gate3, +/- 50mV

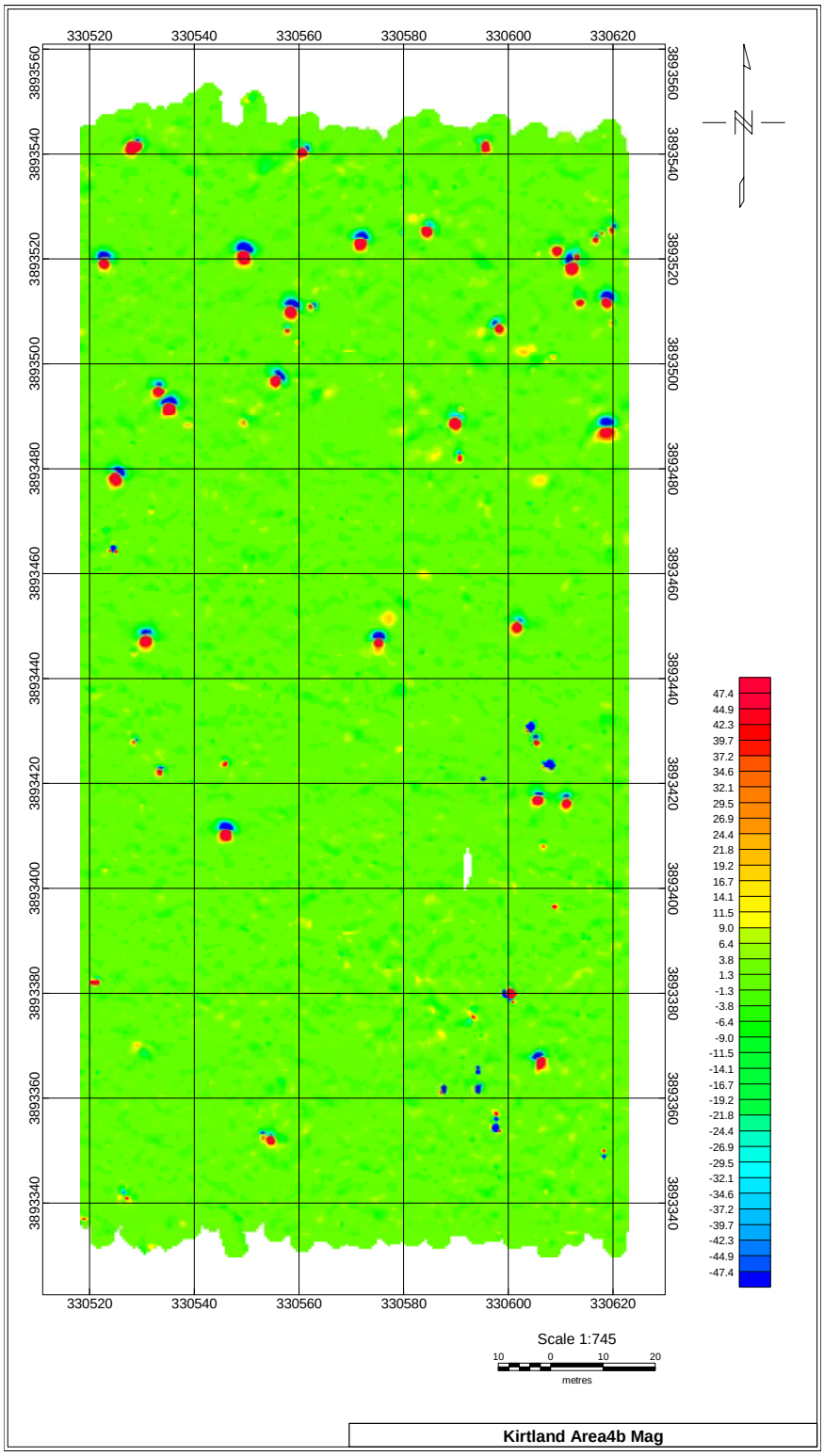

Figure 44: area4a near target, N3, 5.5 acres, mag, +/- 50nT

Area4b was located just north of target N3, in the extreme northern corner of the site. The rippling visible in both the magnetometer and EM data images is due to the proximity of the area to the power line that runs along the northern edge of the site. The magnetometer data become

unusable right near the power line. The EM61 data, however, while noisy, are still quite usable. This is an example of the inherent advantage of a concurrent multisensor system. 102 anomalies were analyzed, of which 38 were declared as Likelihod 2.

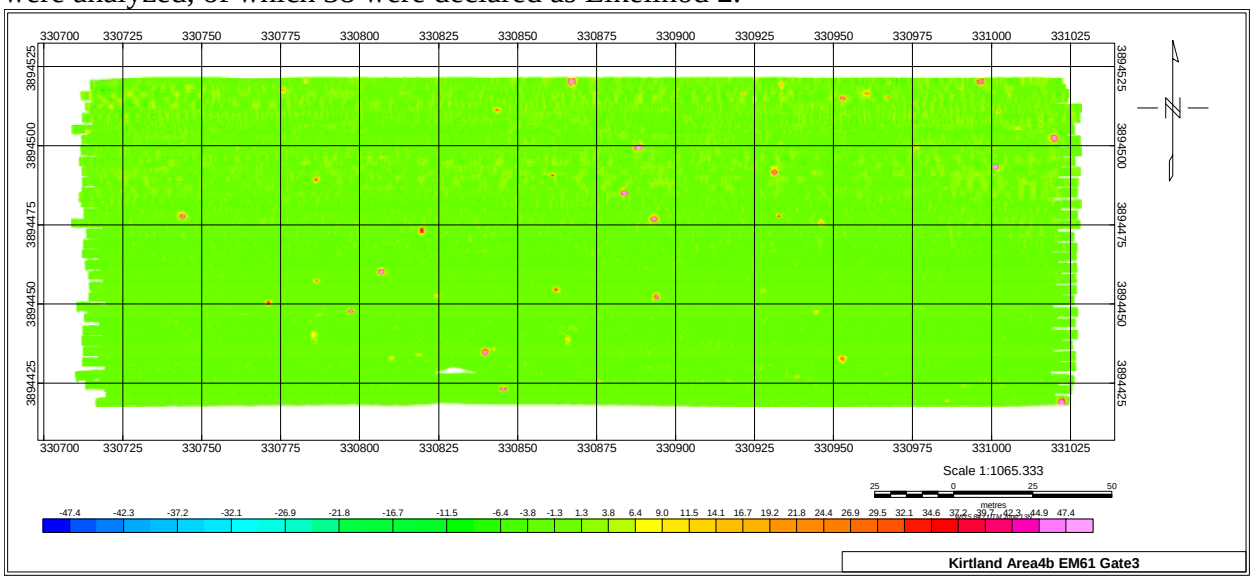

Figure 45: area4b near target, N3, 8 acres, EM, gate3, +/- 50mV

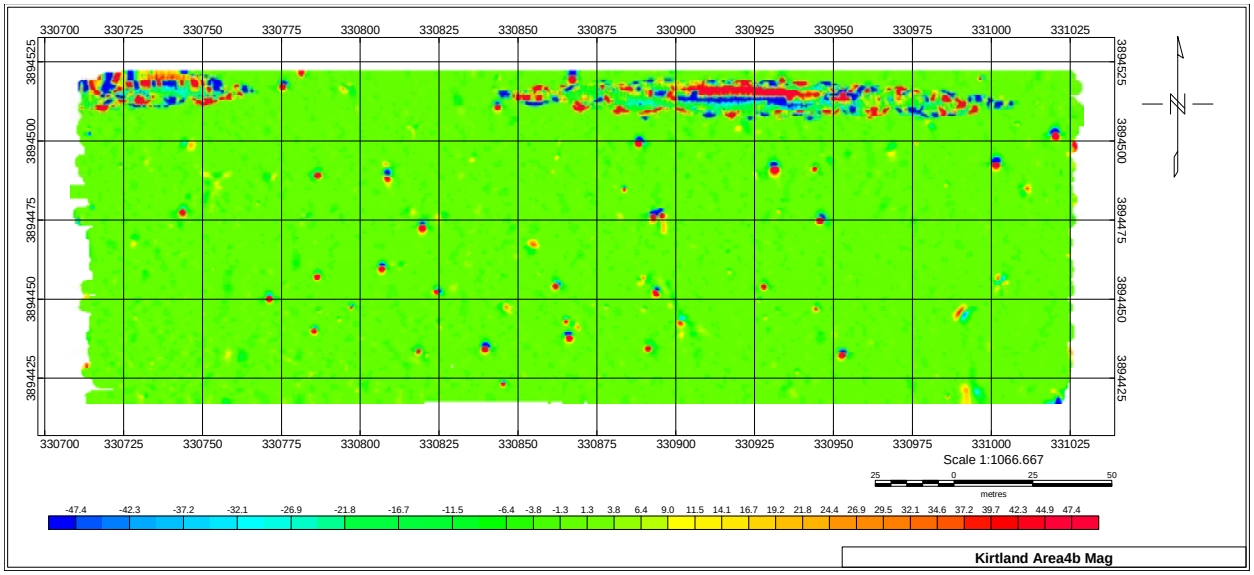

Figure 46: area4b near target, N3, 5.5 acres, mag, +/- 50nT

Area4c was located near the SORT target. 66 anomalies were analyzed, 19 of which were declared as Likelihood 2.

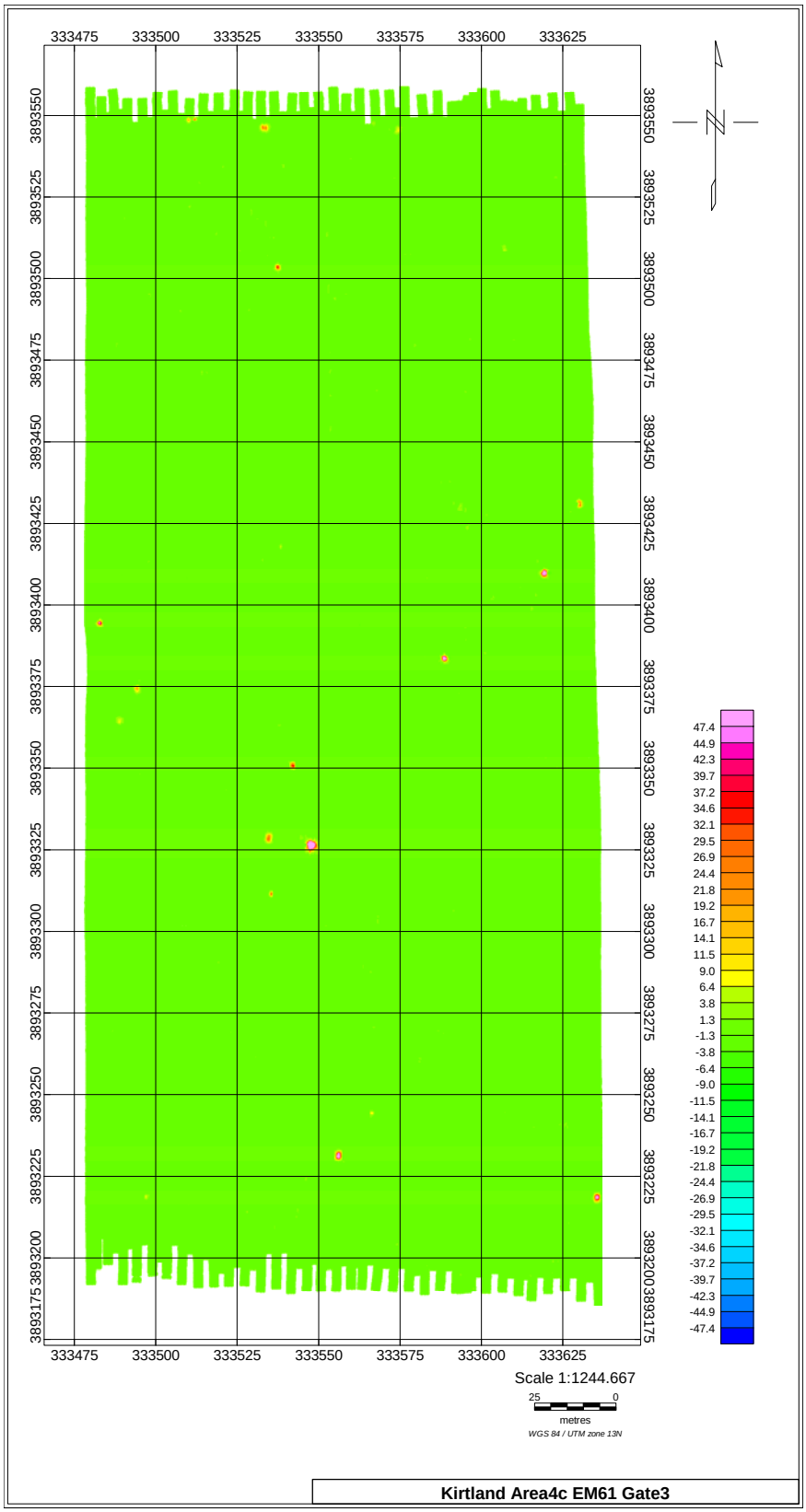

Figure 47: area4c near oil refinery target, 14 acres, EM, gate3, +/- 50mV

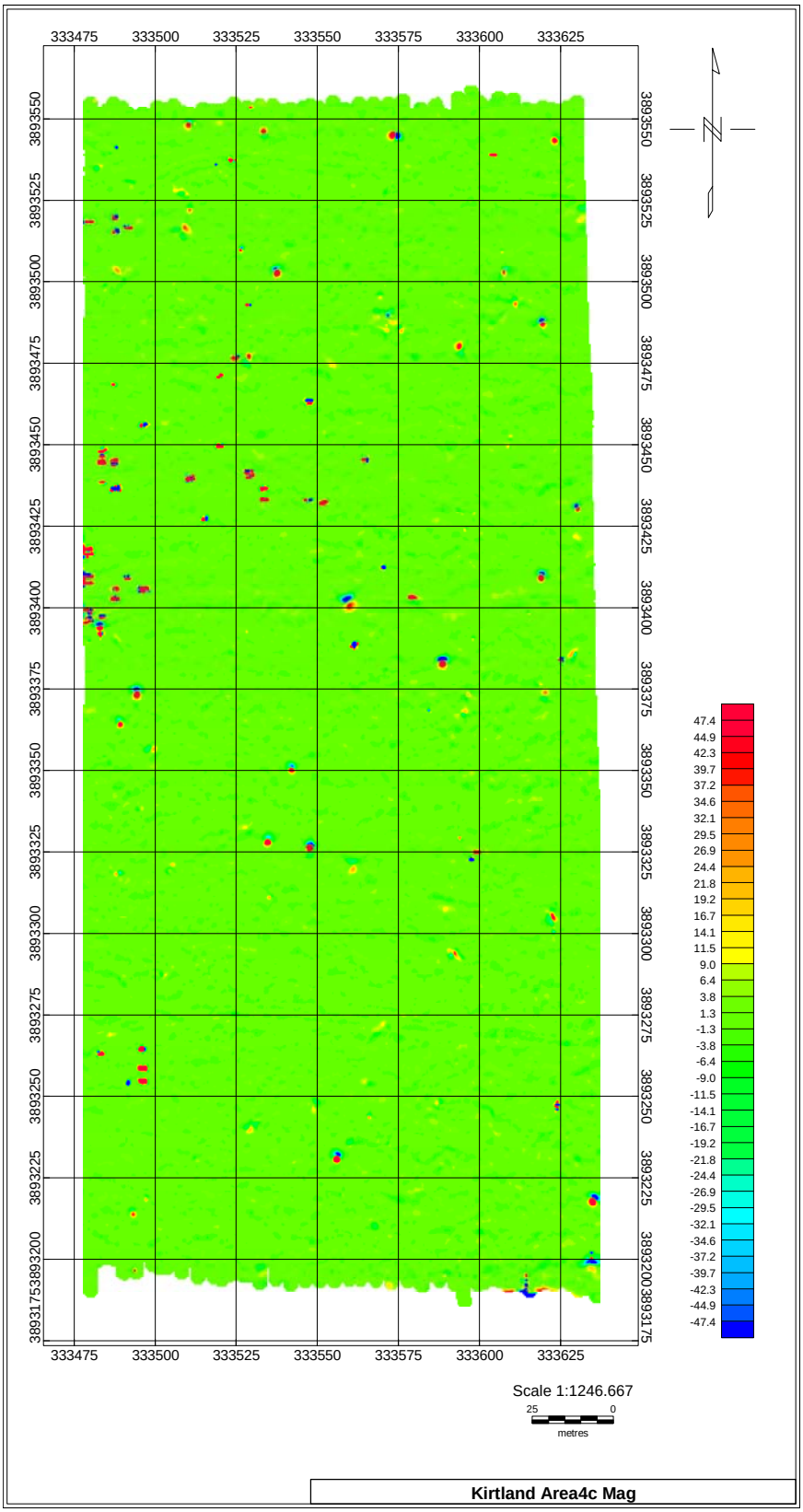

Figure 48: area4c near oil refinery target, 14 acres, mag, +/- 50nT

Area4d was located near the New Demolitions target. This was the most active of all the 100% geophysical survey areas, with a very high anomaly density in both the magnetometer and the EM61 data, indicating that most of the signals were most likely not geology but metallic in origin. 382 anomalies were analyzed, of which 87 were declared as Likelihood 2.

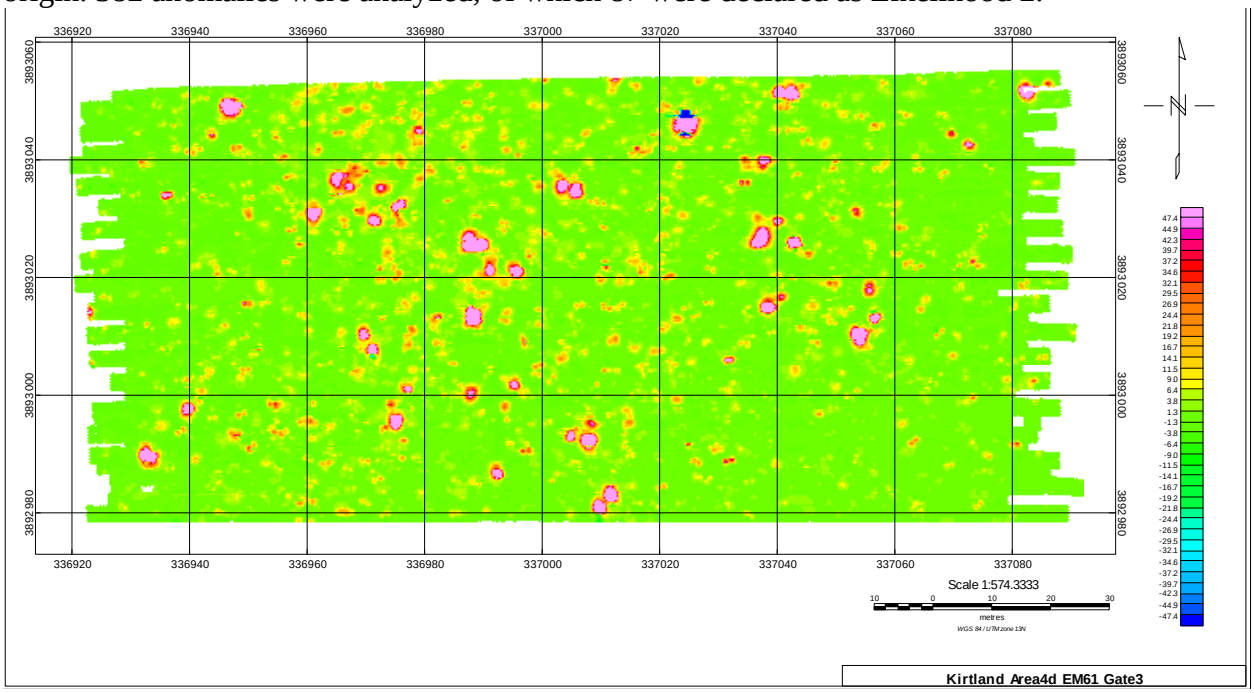

Figure 49: area4d near new demolition target, 3 acres, EM, gate3, +/- 50mV

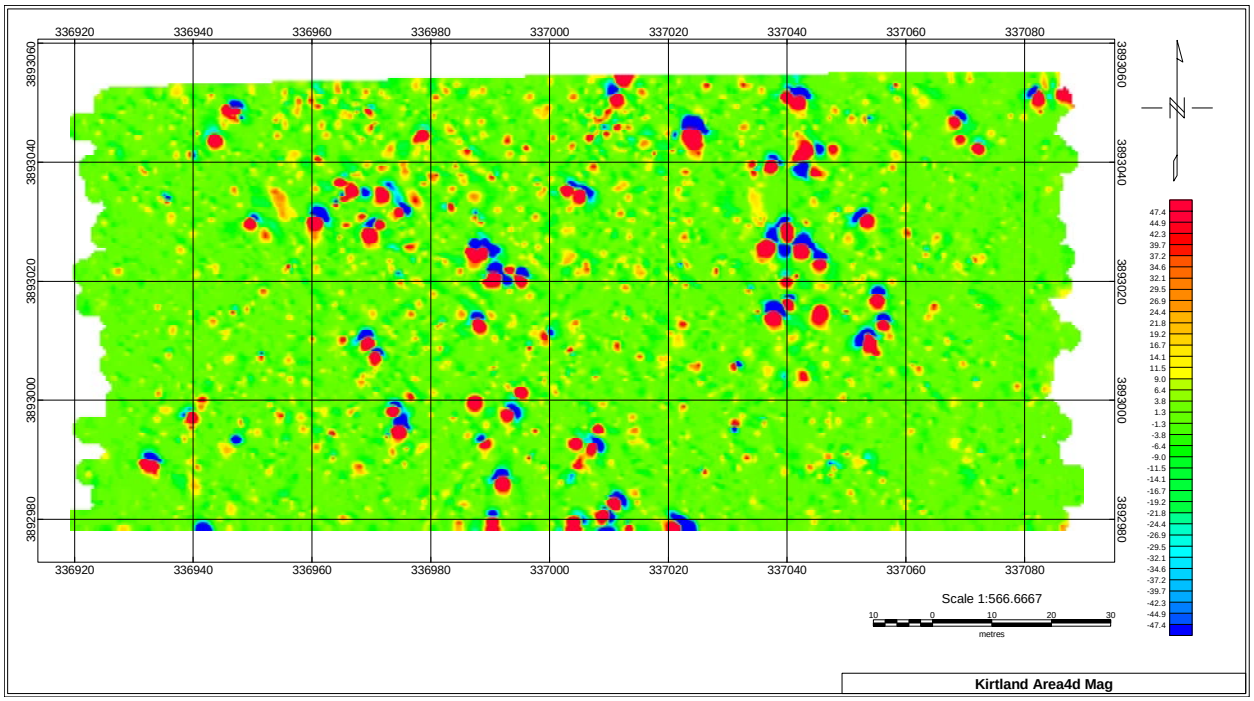

Figure 50: area4d near new demolition target, 3 acres, mag, +/- 50nT

Area4e was located in the southern part of the site. Of all of the 100% geophysical survey areas, area4e was the most geologically cluttered. This geological activity is evident from the number of misshapen dipoles in the magnetometer data that have no corresponding anomaly in the EM61 data. A total of 363 anomalies were analyzed, of which 41 were declared as Likelihood 2.

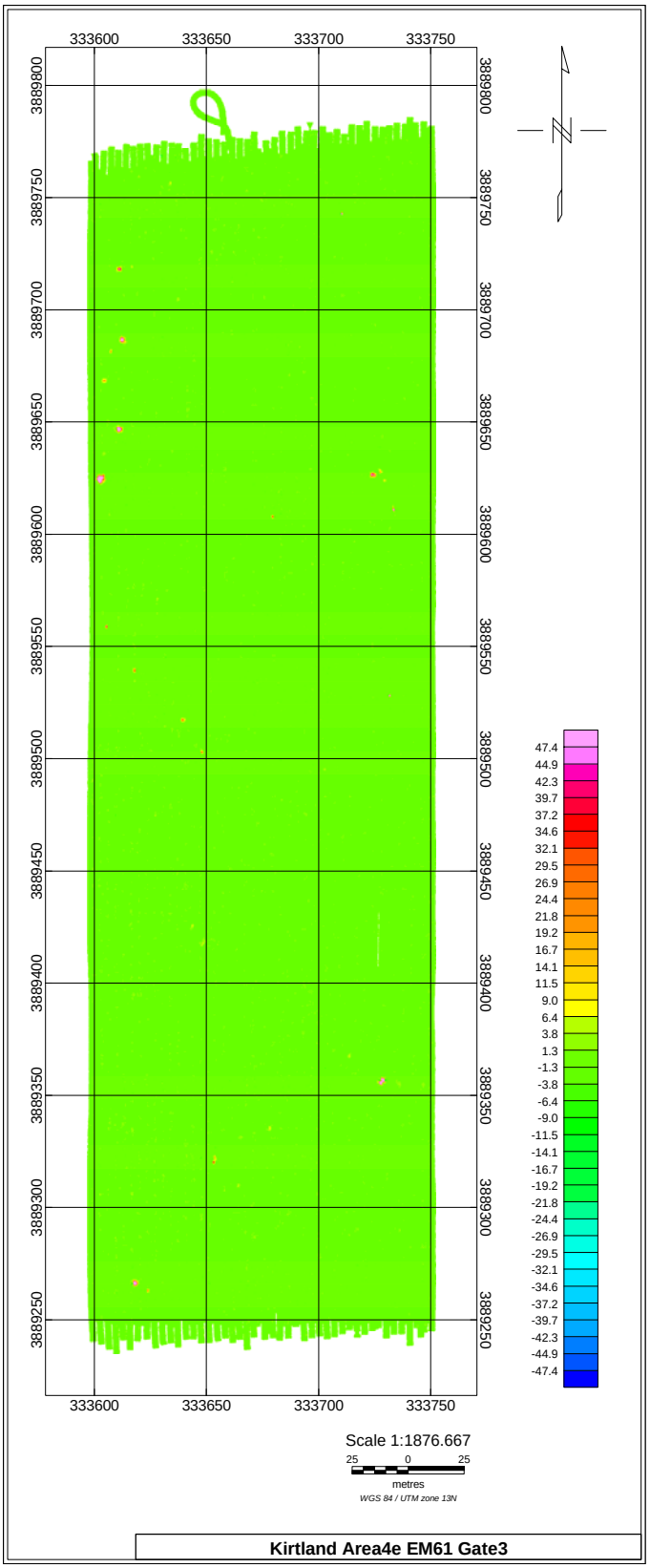

Figure 51: area4e on south site, 20.3 acres, EM, gate3, +/- 50mV

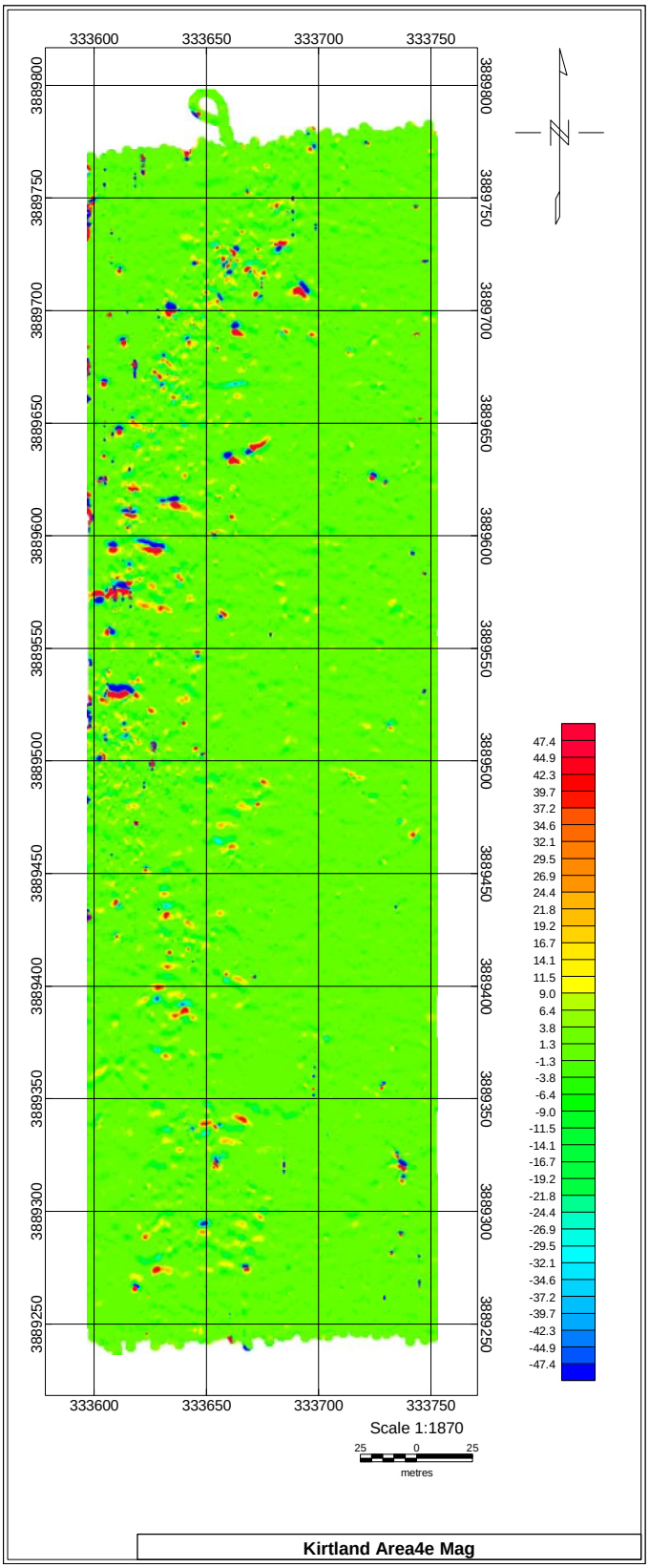

Figure 52: area4e on south site, 20.3 acres, mag, +/- 50nT

Area4f was also on the southern part of the site. 141 anomalies were analyzed, of which 7 were declared as Likelihood 2.

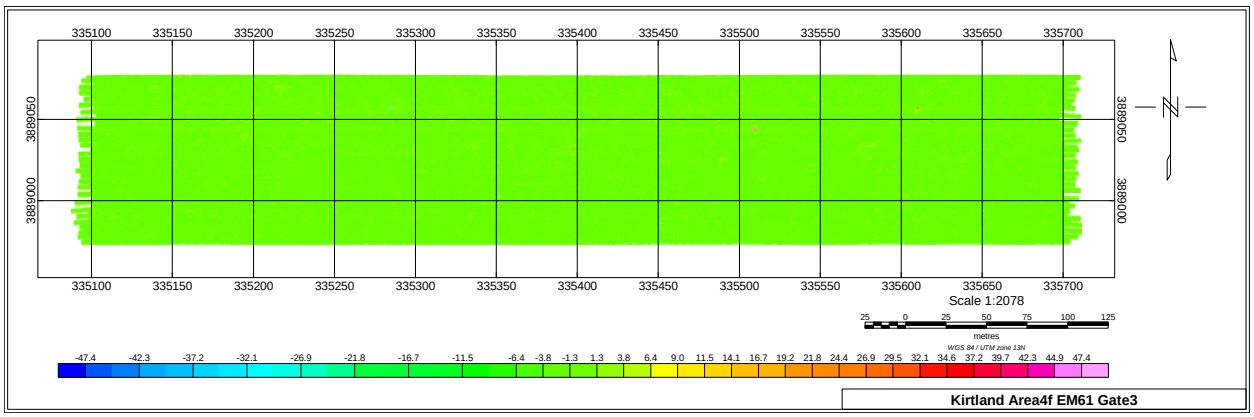

Figure 53: area4f on south site, 15.7 acres, EM, gate3, +/- 50mV

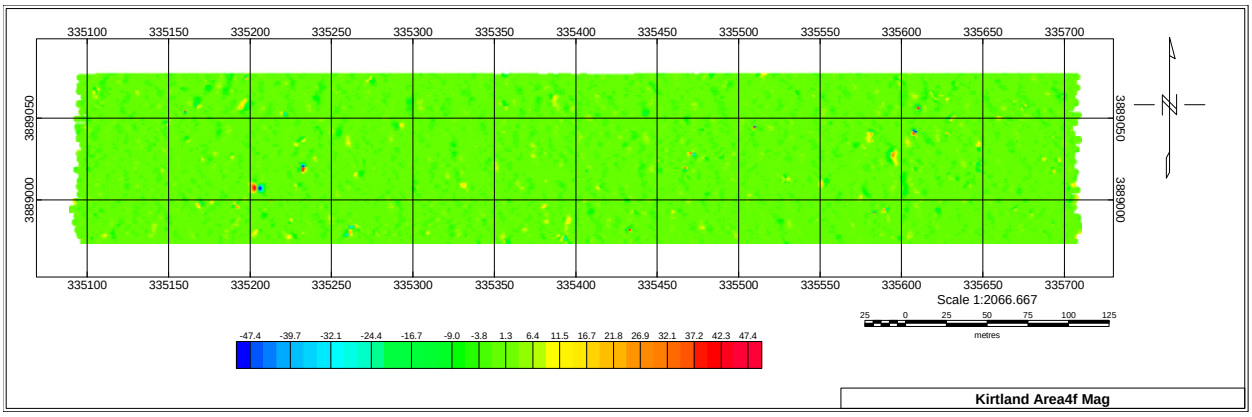

Figure 54: area4f on south site, 15.7 acres, mag, +/- 50nT

The anomaly densities for areas 3a and 3b and 4a through 4f do not reveal a specific trend in the way that those of areas 1a, 1b, and 1c, and 2a, 2b and 2c did, since only these later areas were designed to directly measure the falloff of target density. We include the anomaly densities of the other areas here for completeness.

Table 11: Anomaly Density of Non-Radially Situated Areas

	number of likelihood 2 anomalies	near target	acreage	anomaly density (number per acre)
Area3a	85	SORT	15.8	5.4
Area3b	68	New Demolition	6.2	11.0
Area4a	39	N3	5.5	7.1
Area4b	38	N3	8	4.8
Area4c	19	SORT	14	1.4
Area4d	87	New Demolition	3	29.0
Area4e	41	South Site	20.3	2.0
Area4f	7	South Site	15.7	0.4

4.3.4 Analysis of 100% Geophysical Survey Data

The ground truth file ("kirtland all areas 9-22-06.xls") distributed by the ESTCP Program Office contains an analysis of the percentage of the 778 dug anomalies at the Kirtland PBR that were assigned to each class. The breakdown is intact ordnance (1%), ordnance-related scrap (73%), non-ordnance-related scrap (8%), and no-find (geo) (18%). The 18% no-find rate is higher than we expected, so the geophysical data underlying these no-find locations were examined closely. All the sample images below are from area4e, as this was the most geologically active of the 14 100% geophysical survey areas and had the highest number of no-finds. However, the analysis was performed not just in area4e but in all 14 areas.

As part of the Kirtland survey in autumn of 2005, the ground-based data from all 14 of the 100% geophysical survey areas were examined. A total of 2502 anomalies were analyzed in these areas, of which a total of 705 were declared as Likelihood 2. Anomaly lists containing these anomalies were submitted to the Program Office. The Final Kirtland Validation Plan distributed by the Program Office makes distinctions on an area-by-area basis as to which geophysical data sets (helicopter, ground-based, or both) were used to determine which anomalies to dig in which area. However, for the sake of this false alarm analysis, we regard these equally. That is, any dug anomaly whose ground truth was located in one of the 14 100% geophysical survey areas covered with VSEMS was included in this analysis. There were 289 such anomalies. Of these, 251 were metallic objects of some sort, and 39 are listed in the dig sheet as "geology (no-find)." By this calculation, the probability of false alarm for digging and not finding metal is 13.5%.

It should be noted that although the dig sheet does include digger's comments that attempt to distinguish between the distinct categories of "hot rock," "geo layer," and "no contact," all three of these are encapsulated by the dig sheet in the single category "geology (no-find)," and the dig usage is inconsistent, sometimes using several of the terms for one item. For this reason, we did not attempt to split out, for example, hot rocks from no contacts, and instead regarded all "geology (no-find)" objects equally. The sole exceptions are the two truly explainable no-finds caused by the analyst's flagging the centers of two of the "crop circles" as Likelihood 2 targets; these have already been excluded from the list of 39.

We wished to see how we performed in our original heuristic classification of anomalies as likely geology. Further, we were interested in what the probability of false alarm would fall, to with the application of two post-survey geologic screening strategies.

Because VSEMS concurrently collects both magnetometer and EM61 data, it provides the potential for an experienced operator to exclude many, if not most, geologic anomalies. However, note that there is, at present, no objective, algorithmic, turn-key mechanism to analyze both sensor streams and determine if the anomaly of interest is likely geology or MEC. At present, this operation is performed heuristically by the analyst. At the beginning of the Kirtland survey, we felt that a anomaly with strong, clear, round dipolar lobes in the magnetometer data, a good fit to a point dipole, but no discernable EM61 signature was most likely an MEC object that had penetrated too deep for detection by the EM61 (the Kirtland PBR was, after all, a bombing range). ***After examining the Kirtland ground truth, however, the evidence is compelling that, at this site, the "good mag signature / no EM61 signature" combination strongly connotes not a***

deep MEC item, but instead a geologic false positive. That is, the weird, irregular-looking anomalies turned out (no surprise) to be geology, but so did many of the regular-looking dipoles (surprise) that lacked a confirmatory EM signature. Thus, one strategy is to look at the false alarm reduction gained by requiring a confirming EM61 signature. The other is to simply reexamine the magnetometer signatures to see if the analyst could have done a better job screening out mag signatures indicative of geology.

The false alarm analysis began with locating the analyzed target that correlated with the dug no-find location (the original numbering scheme was different). When the anomaly was originally analyzed, the operator assigned it a heuristic classification of 2 if he thought it was ordnance-like, 0 if he thought it was geology, noise, or clutter-like, and 1 for everything between. Our understanding is that only our Likelihood 2 anomalies were considered for digging. *Thus, the likelihood 0 anomalies (anomalies we felt were likely geology or noise) were already screened out*. For example, the figure below shows two anomalies in the magnetometer data. The left anomaly, anomaly k-864 (VSEMS anomaly 74) was selected by the analyst as Likelihood 2 because it was dipolar (though imperfect) and thus it was dug. When dug, it was a no-find. The anomaly to its right was selected by the operator as Likelihood 0 because of its non-compact geometry, and thus was never dug.

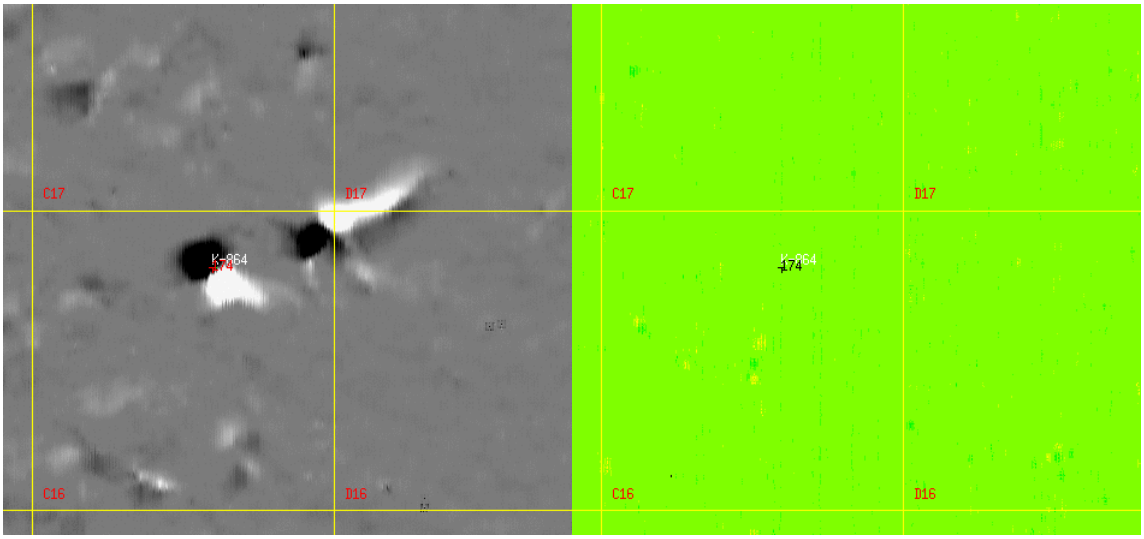

Figure 55: Magnetometer data (left, +/- 50nT) and EM61 gate3 data (right, +/- 50mV) from area4e. Yellow grid squares are 50 meters on edge. Anomaly k-864 (VSEMS anomaly 74) was selected (and was a no-find), but the anomaly to the right was flagged as likelihood 0 due to its clearly non-dipolar shape.

It should be understood that the incorporation of some anomalies that were likely geology into the anomaly list was intentional. In the Data Report for this project, submitted to the Program Office on December 29th 2006 (immediately after analysis of the 100% geophysical survey areas), the PI, Rob Siegel, reported:

> "Note that, for these total coverage areas, the definition of "Likelihood 2" has been stretched somewhat to include large targets that could conceivably be geology. That is, in the transect data analysis, Likelihood 2 was reserved for targets

> that the operator was convinced were subsurface metal of a size and shape consistent with MEC, and large strong anomalies the operator thought were geology were listed as likelihood 0. For these [total coverage] areas, the operator, in essence, is willing to entertain the possibility… that he is incorrect, and large, strong, magnetic anomalies that are dipolar but not classically dipolar (do not have a round positive and a mushroom-cap-shaped negative) are listed as Likelihood 2, but with a comment indicating that they are probably geology. It will be instructive to see what these turn out to be after validation."

Note that all of these intentionally-included questionable anomalies turned out to be geology (6 of the 20 no-finds in area4e were, in fact, commented by the analyst as "big but probably geology"), but that having been said, other anomalies that turned out to be geology were thought to be representative of compact ferrous objects by the analyst. In other words, a more liberal classification of magnetic anomalies as geology-like would exclude more false alarms, but that would not be sufficient; it still result in digging up quite a bit of geology. This is quantified below.

To attempt to quantify the number of false alarms, we sorted the official dig sheet by ground truth category, and examined the mag and EM61 data over the dug anomalies in the 14 100% geophysical survey areas that were listed as no-find / geologic in nature. The dig sheet contains a total of 39 such anomalies. The breakdown is as follows:

Table 12: Breakdown of dig sheet results within 14 100% geophysical survey areas by category

Category	Number	Explanation
A	1	Analyst said it was geology, and it was
B	15	Mag dipole is geology-like, but analyst was overly conservative
C	13	With the benefit of hindsight, the mag dipole isn't classically typical of a compact ferrous object, but isn't clearly geology either
D	7	mag dipole resembles a compact ferrous objects; no clear way to tell it's geology other than the lack of a confirming EM61 signature
E	3	Dig results said no-find, but there's a confirming EM61 signature so the analyst is concerned that the real object may have been missed

It may seem surprising that there is only one entry in category A ("analyst said it was geology, and it was"), but this is because anomalies that the analyst felt were geology were flagged as Likelihood 0, and we were told that only our Likelihood 2 anomalies were used as part of the multilayer analysis. Thus the surprise is not that there weren't more of these, but how this one crept in. It is likely that the helicopter mag system flagged this as an anomaly of interest.

In category B, as per the above comment from the Data Report, there were some anomalies that the analyst thought were likely to be geology, but were intentionally flagged as Likelihood 2 both to be conservative as well as to get verification via intrusive sampling. Examples are shown in the figure below. Anomalies k-876 and k-877 (VSEMS anomalies 251 and 252) are distorted dipoles in the mag data, with no confirming EM signature, but the operator felt that it was

possible (though unlikely) that they were actual objects embedded in active geology, and thus flagged them as Likelihood 2. 15 of the 39 no-finds in the 100% geophysical survey areas fell into this category, where if the analyst was simply more conservative, they would be excluded.

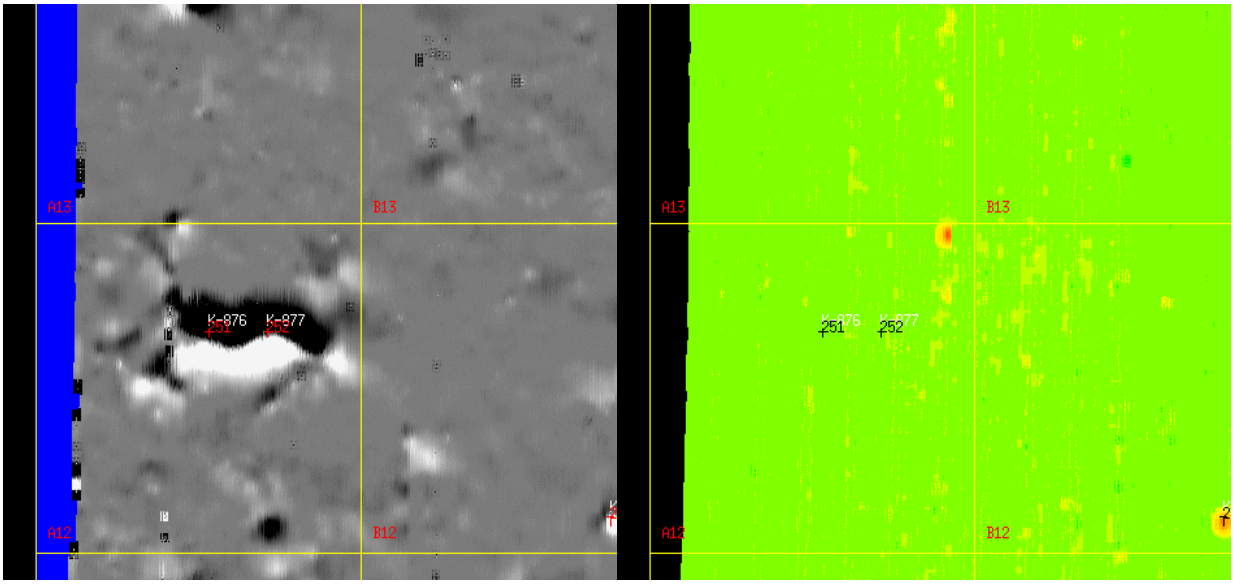

Figure 56: Magnetometer data (left, +/- 50nT) and EM61 gate3 data (right, +/- 50mV) from area4e. Yellow grid squares are 50 meters on edge. Operator selected anomalies k-876 and k-877 (VSEMS anomalies 251 and 252) because of the possibility that MEC was embedded in geology. During remediation, both were listed as no-find (geology). These could be excluded simply by the analyst being more conservative.

Skipping down to category D, 7 of the 39 dug no-finds had mag dipole signatures that were typical of compact ferrous objects; even with hindsight, the analyst cannot say that, given mag data only, he would not have selected them as potential MEC. A sample is shown in the figure below.

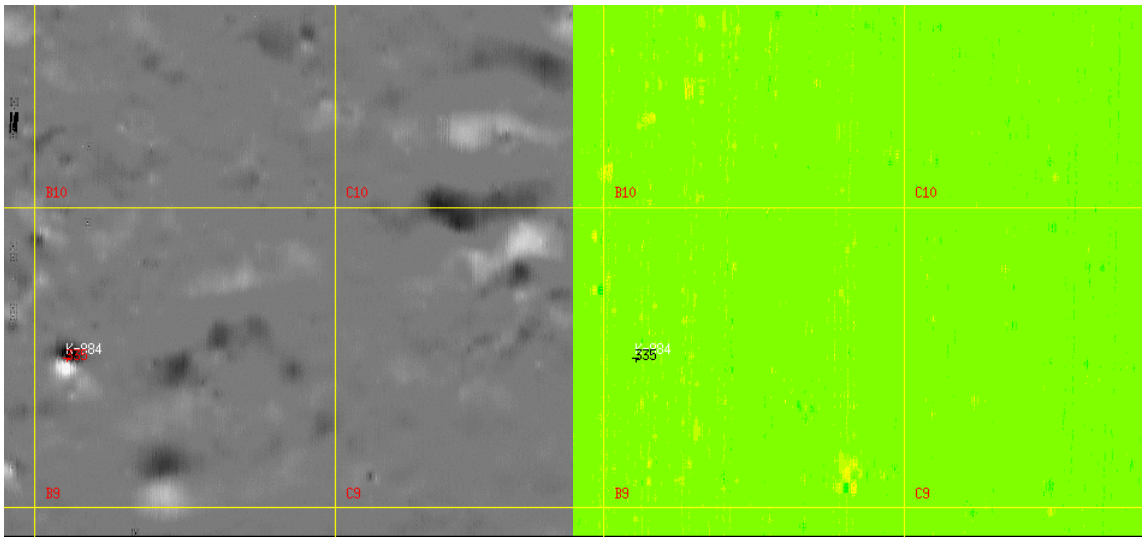

Figure 57: Magnetometer data (left, +/- 50nT) and EM61 gate3 data (right, +/- 50mV) from area4e. Yellow grid squares are 50 meters on edge. Anomaly k-884 (VSEMS anomaly 335) presents a compact dipolar signature with tight round north-facing lobes. Even with hindsight, the operator can't say that it is anything other than typical of a compact ferrous object. Only the lack of a confirming EM signature suggests that it is geology, which apparently it is.

Anomalies in category C, representing 13 of the 39 anomalies, fell somewhere between the two – that is, anomalies in this category did not have perfectly-formed mag dipoles, but neither were the shapes so irregular that were clearly geologic in origin. Examples of this are shown in the figure below with anomaly 856, which is dipolar but non-ideal. It is not north-aligned, its lobes are somewhat diffuse, the negative lobe does not wrap around the positive lobe with the classic mushroom-capped shape.

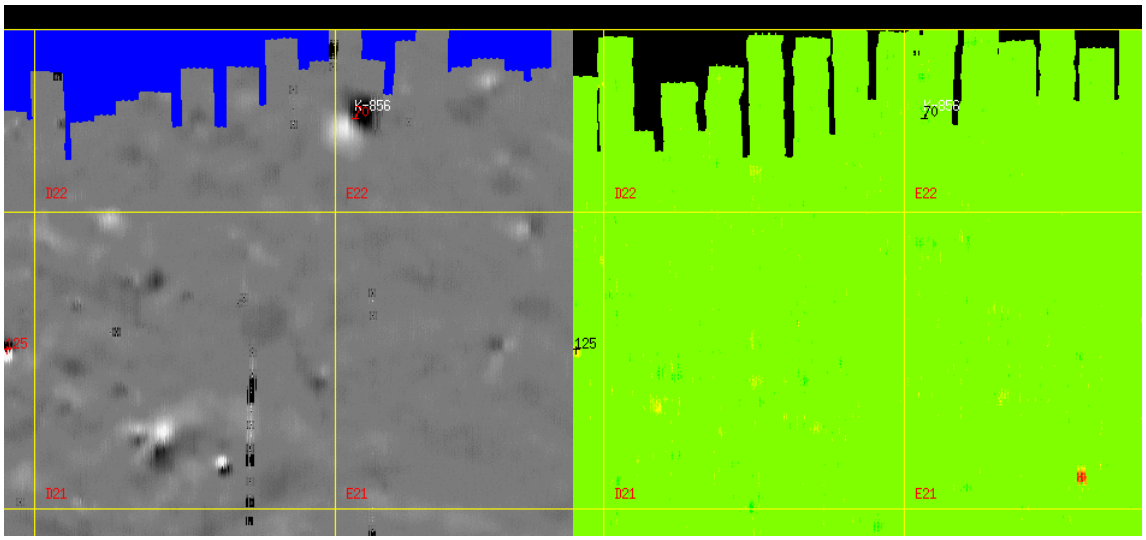

Figure 58: Magnetometer data (left, +/- 50nT) and EM61 gate3 data (right, +/- 50mV) from area4e. Yellow grid squares are 50 meters on edge. Anomaly k-856 (VSEMS anomaly 70) presents itself in the magnetometer data (left) as a weak dipole with somewhat diffuse, non-north-aligned lobes and no EM61 signature.

The significant thing is that, ***for cases A through D, comprising 36 of the 39 no-finds in the 100% geophysical survey areas, none of the mag dipoles had a confirming EM61 signature. That is, these 36 apparent geologic false alarms could have been screened out by simply requiring the EM61 to present a confirming signature.***

In category E, the remaining three no-finds *did* have a confirming EM61 signature. An example of this is shown in the figure below. Anomaly k-844 presents itself in the magnetometer data (left) as a strong dipole with well-shaped, north-aligned lobes. The EM61 gate3 data (right) shows a strong, well-formed, largely round confirming signature. The digger's comment says "hot rock 4' under stake." There are several possible reasons for this apparently anomalous behavior. One is that the "hot rock" was indeed hot to the EM61 as well as the mag (e.g., that some, but not most, of the volcanic geology on the Kirtland site does indeed present itself to the EM61). The other is that the object actually producing the signal was not found by the digger. But it is important to note that these three cases correspond to false positives. That is, they would still be dug; MEC would not be left in the ground.

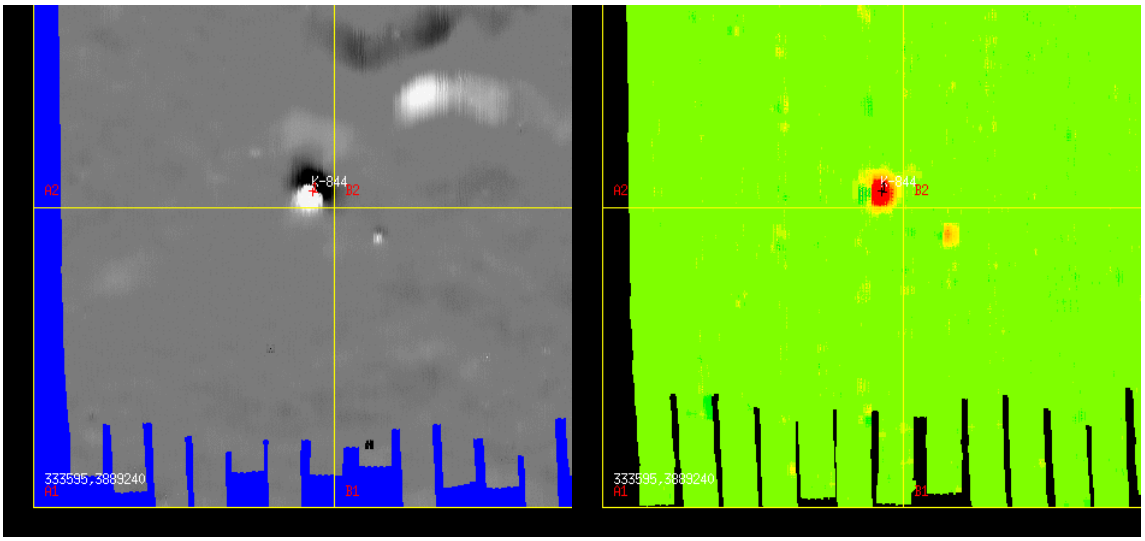

Figure 59: Magnetometer data (left, +/- 50nT) and EM61 gate3 data (right, +/- 50mV) from area4e. Yellow grid squares are 50 meters on edge. Anomaly k-844, listed by the dig team as no-find (geology), has a strong magnetic dipole (left) with round, north-aligned lobes and a very strong confirming EM61 signature (right), making us wonder if the dig team successfully relocated and dug the object producing the signal, or if the EM61 signal actually is geologic in nature.

The probability of false alarm can be recalculated two ways. First, if we re-examine the geophysical data and screen out the anomalies whose mag signature is clearly geology-like (anomalies that the analyst only included because he was being overly conservative and wanted to, in fact, generate digs for some anomalies that were likely geology), the probability of false alarm is not 39/289 but 23/289, or about 8%. This represents the best that the analyst could've done without taking advantage of the EM61 data.

However, if we take advantage of the position that a confirming EM61 signature is required to rule out geology, then the probability of false alarm falls to 3/289, or about 1%.

The four false alarm numbers are encapsulated in the table below.

Table 13: Probability of false alarms before and after data reexamination

Probability of false alarm (no-finds → probable geology) from original Program Office Dig Sheet (includes anomalies from VSEMS ground-based data plus other data)	18%
Probability of false alarm using anomalies only from VSEMS ground-based data on the 14 100% geophysical survey areas for which there's ground truth on the Program Office Dig Sheet	13.5%
Probability of false alarm removing objects whose mag signatures are clearly non-dipolar (the best the analyst could do with mag-only data)	8%
Probability of false alarm requiring a confirming signature in the EM61 data	1%

We believe this to be a highly significant result that helps to justify the use of concurrent multisensor technology. The Kirtland PBR was a bombing range where air-dropped ordnance potentially was used, including potentially 250 lb bombs, making it the kind of site where, if you had to choose one sensor (magnetometers or EM61s), you would likely choose magnetometers (as were chosen for all of the other WAA sites). Simply by co-deploying EM61s and requiring a confirmatory signature, the probability of false alarm could be cut from 13.5% to 1%. We note that this would need to be combined with, at minimum, a depth determination so that you wouldn't exclude the very objects – the deep UXO – that the magnetometers can detect but the EM61s cannot. There is insufficient data to attempt a depth-based cutoff analysis with results from the Kirtland PBR, as there were no 250 lb bombs found, there were only five 100 lb practice bombs found, and the deepest was at 3.1 feet. Note that, had 250 lb bombs been found at the Kirtland site, exclusion-zone requirements would have precluded digging.

4.3.5 Survey Speed, EM61 Data Quality, and Productivity

The magnetometer's custom sampling electronics outputs data at 75 Hz, resulting in very dense down-track mag data spacing, but the output rate of the COTS EM61 Mk2 is a comparatively slow 10 Hz, resulting in much sparser down-track data spacing. For transect surveys, we endeavored to keep speed below 2 meters per second in order to generate EM61 data at least every 20 cm, but for the 100% geophysical survey areas, we generally capped speed at a lower rate of one meter per second to generate EM61 updates at 10 cm down-track intervals. Both of these speeds may strike some as slow in comparison to survey speeds with magnetometer-only systems. This fuels the perception that, when deploying VSEMS, a productivity hit is taken in order to collect the EM61 data – that you could drive faster, and thus be more productive, if you collect magnetometer-only data.

Our position is that productivity – acres per day – is a function of many factors. At the Kirtland PBR, as we described above, the major productivity factor was GPS jamming. We feel that, in theory, all things being equal, the slower EM sampling rate *does* affect productivity, but in practice, all things are rarely equal, and that other factors frequently dominate this one.

That having been said, because we in fact collected data over the 100% geophysical survey areas not only at the "slow" speed but at the "fast speed" (twice by accident and once by design), we can see if the higher speed creates an effect that we can see in our EM61 data.

The table below shows the data density for the fourteen 100% geophysical survey areas. Due to a miscommunication with the driver, the first two areas surveyed (1a and 1b) utilized the higher 2 m/s survey speed. The last area surveyed (4f) was intentionally traversed at higher speed due to our trying to complete the survey before an engine oil leak felled the survey vehicle. The other surveys were conducted at speeds near 1 m/s.

Table 14: Data density for the fourteen 100% geophysical survey areas

	Data Density (points / m2)	
	mag	em
area1a	95	15
area1b	108	14
area1c	195	26
area2a	241	32
area2b	195	26
area2c	192	25
area3a	192	25
area3b	163	22
area4a	179	24
area4b	172	23
area4c	147	19
area4d	151	20
area4e	179	24
area4f	107	14

Area2a is representative of slow speed data, and area1b is representative of high speed data. In the image below, a section of EM61 gate3 data from area2a, acquired at a slow 1 meter per second, is shown. The section is intentionally chosen to be relatively free from obvious anomalies due to subsurface objects. The background appears as a clear, solid green color.

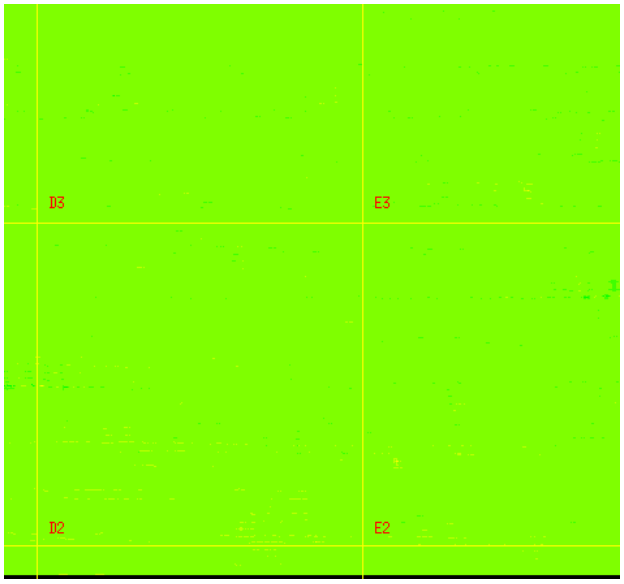

Figure 60: EM61 gate3 data, +/- 50 mV. Yellow grid squares are 50 meters on edge. Background EM61 gate3 data from area1c acquired at 1 m/s appears clean

Below we show some representative time-series data from EM61 gate3 in area1c. Statistical analysis of a larger representative section shows the RMS variation to be .29 mV.

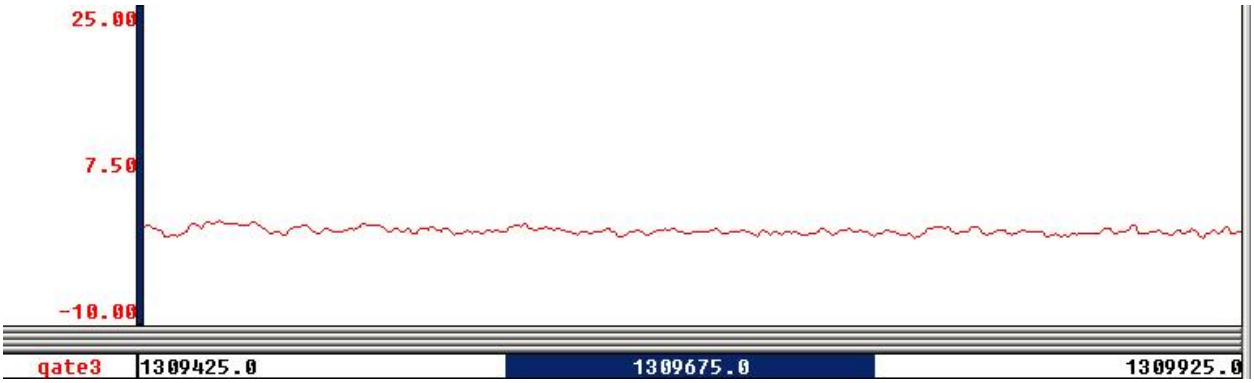

Figure 61: Oasis time-series plot of 30 seconds of EM61 gate3 background data from area2a. Like the above image, data are relatively clean.

In the next image, background EM61 gate3 data from area1b acquired at a fast 2 meters per second, is shown. The image shows an obvious stippling of the background that is not present in the slower survey shown above.

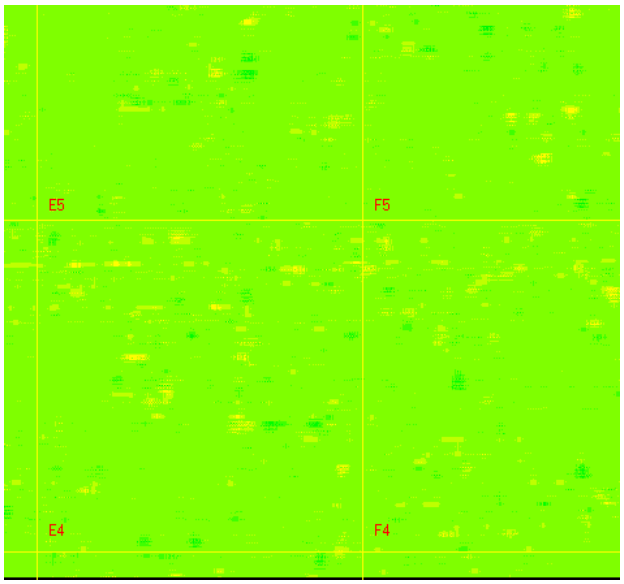

Figure 62: EM61 gate3 data, +/- 50 mV. Yellow grid squares are 50 meters on edge. Background EM61 data from area1b acquired at 1 m/s appears slightly noisy

The time-series data from EM61 gate3, below, confirms the stippling in the image data. Statistical analysis of a larger representative section shows the RMS variation to be .52 mV.

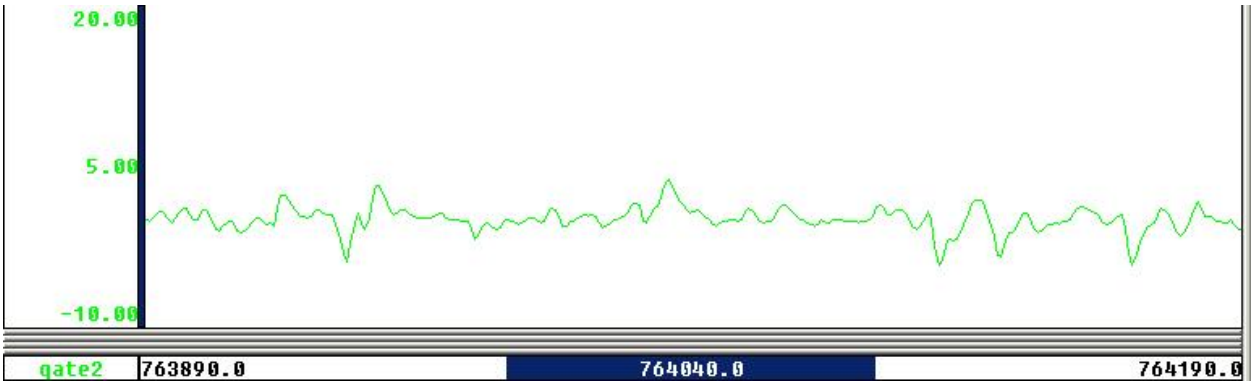

Figure 63: Oasis time-series plot of 30 seconds of EM61 gate3 background data from area1b. Like the above image, data are slightly noisy.

We believe that what we are seeing here has nothing to do with data density, but is the effects of EM61 array motion caused by platform motion. Although the slower survey speed was intended to create higher down-track data density, it had an additional positive effect of reducing EM61 sensor motion. As we've said above, the prototype fiberglass towed platform used on VSEMS was only intended to survive a single fielding at APG in 2002. In order to survive subsequent real-world surveys at Lowry, Kirtland, and other sites, survivability modifications were made. These included mounting the EM61 lower coils in a porch-swing configuration that allowed them to swing back (rather than breaking off) if they encountered an obstacle, and the incorporation of titanium snowmobile springs to provide a simple suspension. These certainly improved the platform's longevity by giving ground-induced shock somewhere to go, but probably increased EM61 sensor motion. This fiberglass platform has since been retired and has been replaced with a new carbon-fiber platform with a wider track, a tuned suspension, and no "porch swing" for the EM61s.

From the above data, it appears that the platform configuration used to host the EM61s at Kirtland is not one that would be optimal for assessing the degree of site contamination with small objects with weak signals, such as 20mm projectiles, at high speed (though it may be fine at low speeds). It may be difficult if not impossible to separate the original question (what is the effect of speed and the resulting down-track data density on EM61 data quality) from what we have found (that speed appears to engender platform motion, which has a negative effect on EM61 data quality). However, note that this noise does not prevent strong signals from ringing out very clearly in the EM61 data, as shown in the plot below. The anomaly in the cross-hairs corresponds to target k-536, which was M38 bomb scrap. The anomaly produced by gate 3 has a width above background of approximately 3.5 meters, and has a full width at half max of approximately 1.5 meters. Even at the higher 2 m/s survey speed, this anomaly contains 14 data points above background, indicating that, for objects of this size, higher survey speeds can create data with sufficient density to allow object detection.

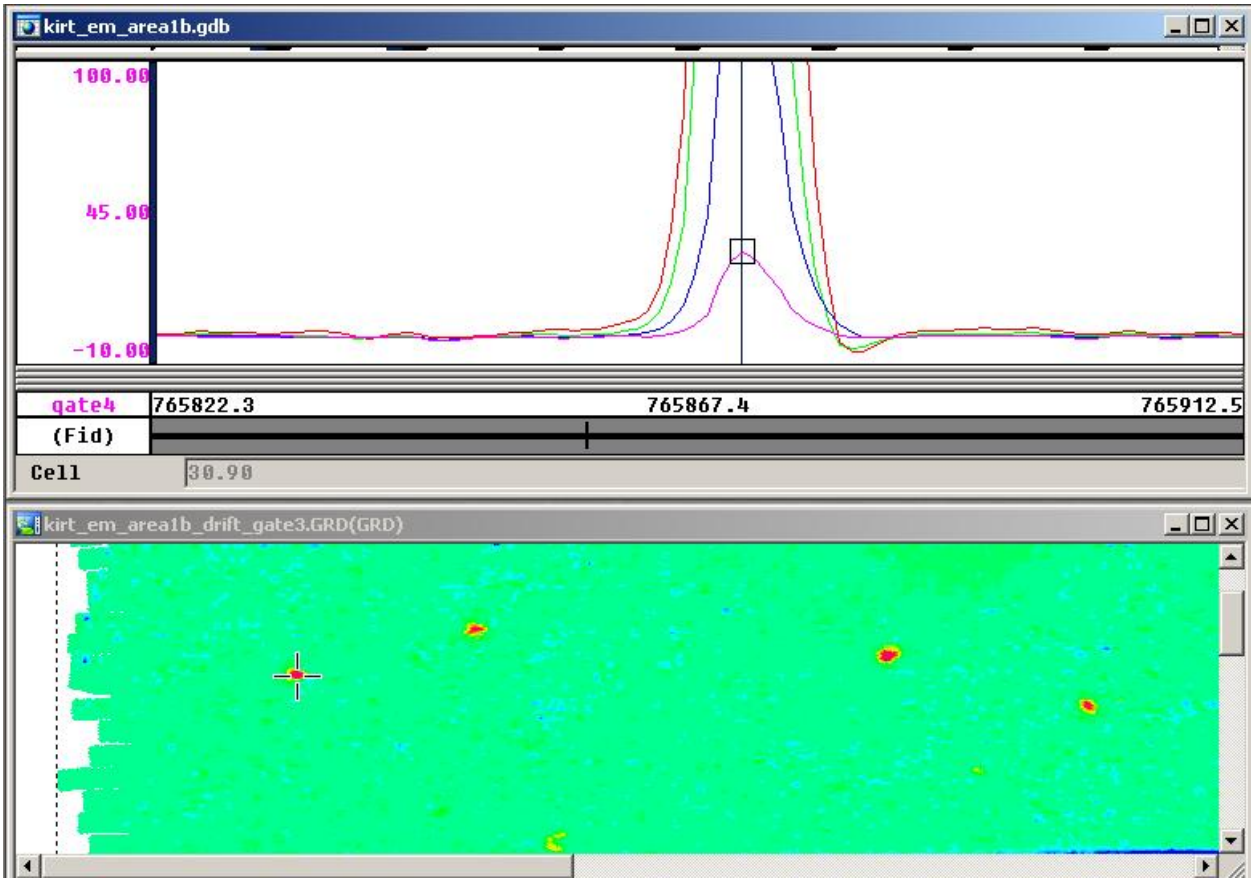

Figure 64: EM61 data over M38 bomb scrap in area1b clearly shows a good, sharp target response even with increased background noise due to elevated survey speed

The speed at which the survey is conducted should be a function of several things. Higher speed may increase productivity, but it beats up survey equipment. How the speed affects EM61 data quality certainly should be considered, but rather than merely specify a maximum speed in order to meet a minimum EM61 data density metric, the way in which the EM61 data are to be used should be considered. If the goal of using the EM61 is not to detect small objects with weak signatures, but instead to screen against geologically-induced false alarms, then higher speed (and with it, lower data densities, likely higher noise, and likely increased need for platform maintenance) can probably be tolerated.

4.3.6 Inversion of EM61 Data in 100% Geophysical Survey Areas

In analyzing the transect data for next-day turnaround, SAIC's existing mag dipole inversion was used, as its speed and ease of use enabled next-day turnaround of results. The EM61 data was always collected, processed, and displayed (the analyst always views both data sets during analysis, as the presence or absence of correlating anomalies in both data sets is important information), but the EM61 data was not inverted as part of the transect analysis, as both the VSEMS data analysis software and Geosoft Montaj™ lack EM inversion code. As we focused on the analysis of the 100% geophysical survey areas, however, the Program Office requested that we propose a method for inverting not only the magnetometer data, but the EM61 data as well. We supplied the Program Office with several options for this, and the one selected was to use the UxAnalyze module for Oasis being developed by AETC and Geosoft with funding from

ESTCP. To accomplish this, we received training in Oasis while in Albuquerque, and traveled to AETC for training on UxAnalyze.

After the data acquisition was complete, we began using Montaj™ to analyze the 100% geophysical survey area data. It was our assumption that we would adopt the approach used by many UXO geophysicists and use the automatic anomaly picking feature in Montaj's UxDetect module to pick anomalies similar to those picked manually from the transect data. Then we assumed we would feed this anomaly list to UxAnalyze. However, a number of things made this problematic.

Firstly, in order to perform automatic anomaly selection on magnetometer data, one first must create analytic signal (essentially the two-dimensional spatial derivative) to convert the positive-negative dipolar anomalies into unipolar anomalies. However, since analytic signal has a spatial component, there is no direct correspondence between the threshold-based manual picking employed on the transect data (everything over 10 nT and over a certain spatial size) and the values picked in the analytic signal data. Thus it was difficult using this technique to pick anomalies in a method that is consistent with what was already done with the transect data.

Second, when using UxDetect to automatically pick anomalies, these anomalies must be vetted by a trained operator. Inappropriate picks must be deleted, additional picks must be added, and clusters of picks that represent the same object must be merged. There are utilities to perform these steps in Oasis, but they are time-consuming enough that we decided to stick with hand-picking anomalies in our own software.

Third, the familiarity we have with our own data and how it is processed, gridded, and viewed in our own software, is valuable in the overall context of expert analysis. One example of this involves spurious data. After processing and viewing the VSEMS magnetometer data from one of the 100% geophysical survey areas in our own software, we brought it into Montaj™, created analytic signal, and used UxDetect to automatically select anomalies. When sanity-checking the results, numerous picks had been automatically selected that overlaid strong, sharp anomalies that we did not remember seeing in the data. We viewed the data in our own software to see what these signals were, and they were coming from spurious readings on the order of 50 nT that had squeaked through our median filter, which normally rejects spikes over 100 nT. In our own software, when gridded, these spurious readings created small square interpolation artifacts that are ignored by expert eyeballs, but in Oasis they were iteratively gridded until they created spectacularly strong anomalies.

For all of the above reasons, we decided to hand-pick anomalies from the 100% geophysical survey areas using our own software in a method as close as possible to that which was used in the transect data, and to then pass these locations to the EM inversion routines in UxAnalyze. Note that, for these 100% geophysical survey areas, the definition of "Likelihood 2" was stretched somewhat to include large anomalies that could conceivably be geology, as described above.

In consultation with Dr. Dean Keiswetter at AETC and the ESTCP Program Office, it was decided that the "Likelihood 2" anomalies presented a good candidate set for UxAnalyze due to their generally strong signatures. This corroborates our experience, as during our foray into UxAnalyze, we discovered that many anomalies with visible anomalies above threshold failed to converge because the signal was too weak or because they did not contain enough data to generate high-quality results.

Because of delays in obtaining a qualified, tested copy of UxAnalyze that correctly models our EM61 data as an array with one large transmitter and five individual receivers, Dr. Keiswetter performed the analysis himself. He took our Likelihood 2 anomaly picks, chose polygons that wholly surround the objects, and ran the EM inversion. We used his results to perform a visual correlation of the depth estimates from mag and EM inversion. Three examples are shown.

The figure below shows the depth estimates for the Likelihood 2 anomaly picks in area4a. Correlation of depth results from the two sensors is generally good, with the exception of the outlier caused by the EM-generated depth from point 32. This was item k-187, which according to the dig sheet, was a no-find. Including this outlier, the r-squared correlation (RSQ, or the proportion of the variance in the second array attributable to the variance in the first array) between the mag and EM depths is 0.28 and the covariance is 0.53. Excluding this outlier changes the results only slightly; the RSQ increases to 0.30 and the covariance increases to 0.54. The mag and EM-derived depths, plotted both against item number as well as against each other, are shown in the next two figures, and the anomaly data for item k-187 is shown in the third figure.

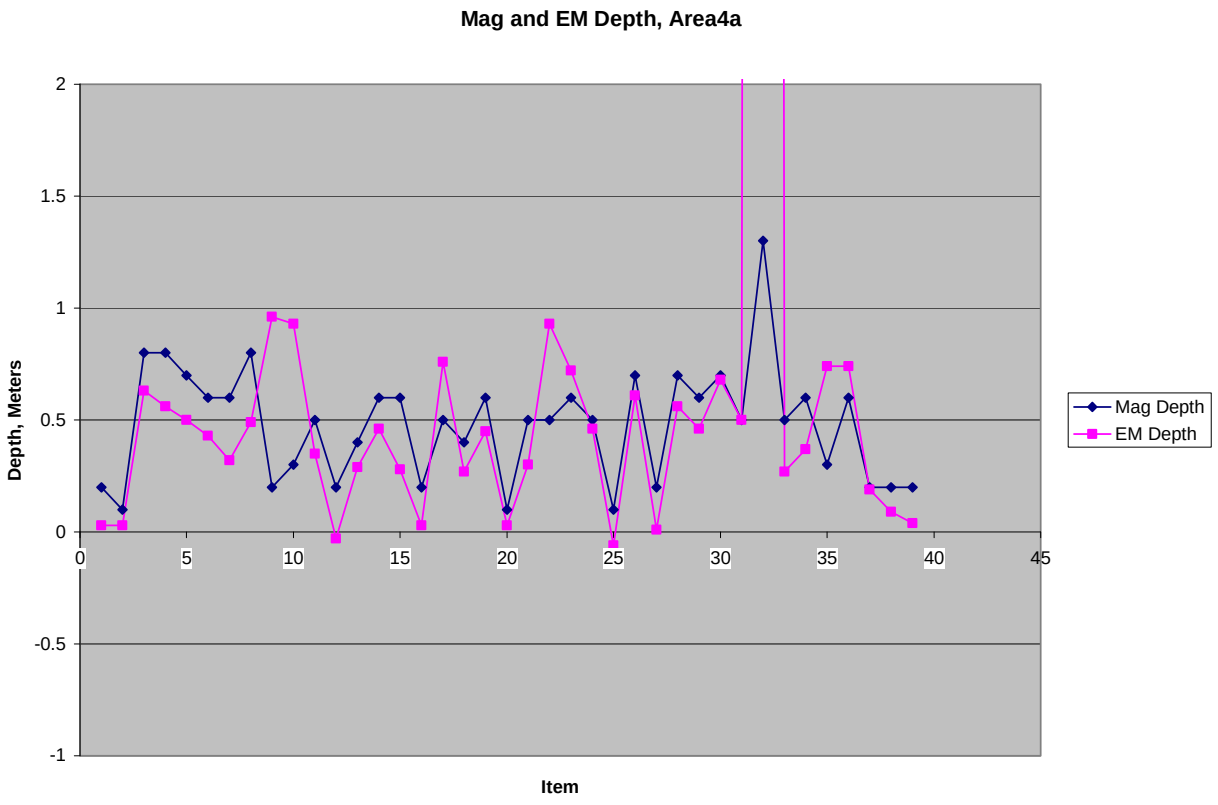

Figure 65: Depths derived for Likelihood 2 anomalies from mag (blue) and EM (magenta) inversion in area4a

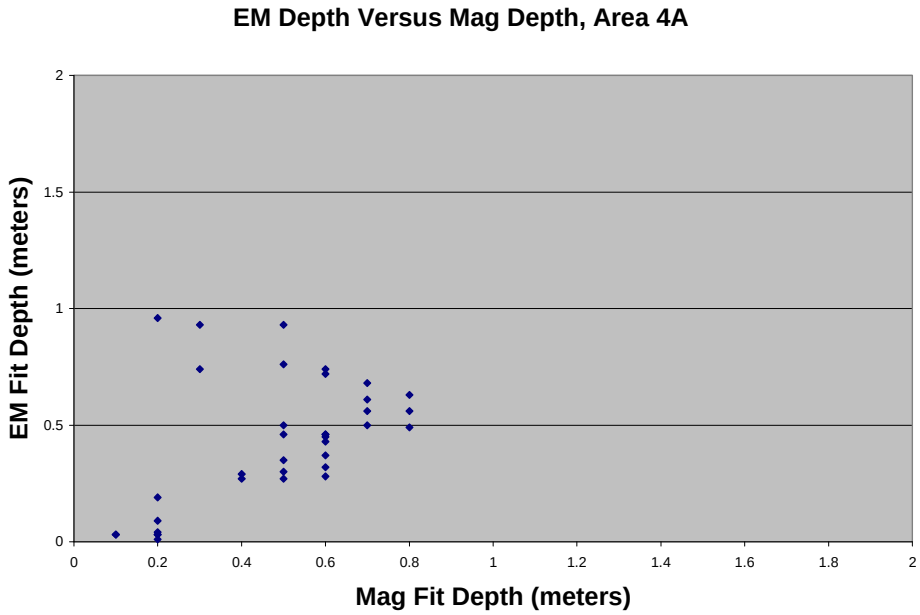

Figure 66: EM-derived and mag-derived depths plotted against each other for Area4a

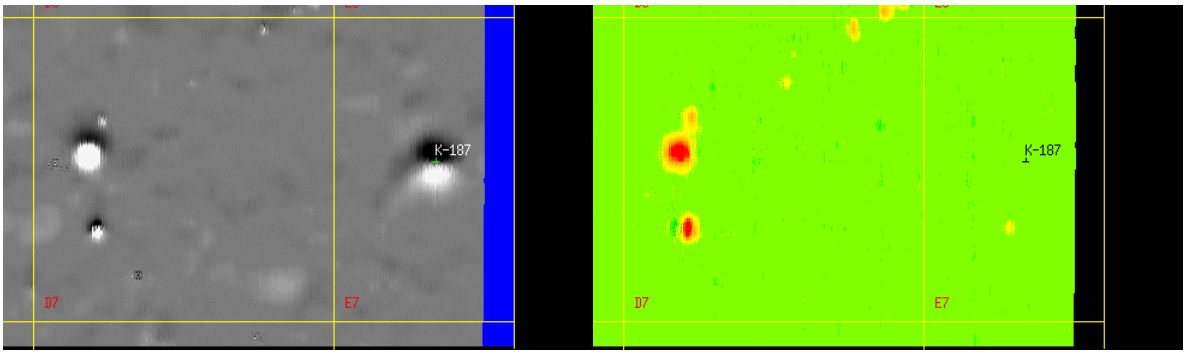

Figure 67: Magnetometer data (left, +/- 50nT) and EM61 gate3 data (right, +/- 50mV) from area4a. Yellow grid squares are 50 meters on edge. Item k-187 on the right side of each image, a no-find, caused the outlier in the depth comparison chart above.

In the figure below, the mag-derived and EM-derived depths for area4e, a very geologically-active area, are shown. The EM depth fails to converge on six occasions, correlating (like the example above) with no-find results in the dig sheet, and anomalies that exist only in the magnetometer data. Not surprisingly, the EM fit coherence is poor for these six outliers (0.16, 0.001, 0.0, 0.003, 0.201, and 0.018). The magnetometer depth fails to converge on the third point (where the EM also fails to converge). This is target k-846, shown in the two images below. Due to the outliers, the results are not well-correlated; the RSQ correlation between the mag and EM-derived depth estimates is 0.0007 and the covariance is 0.028. With the outliers removed, the RSQ increases substantially to 0.12 and the covariance to 0.35. The mag and EM-derived depths, plotted both against item number as well as against each other, are shown in the next two figures, and anomaly data showing item k-846 is shown in the third figure.

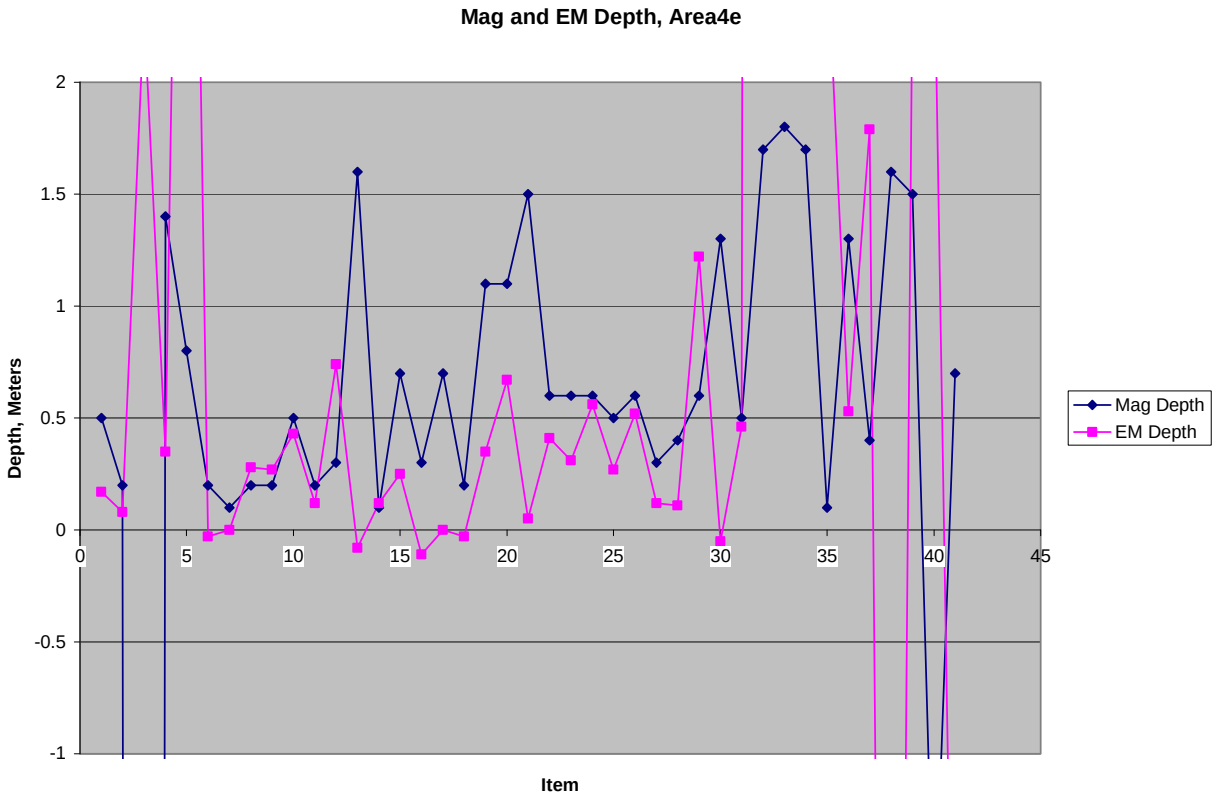

Figure 68: Depths derived for Likelihood 2 anomalies from mag (blue) and EM (magenta) inversion in Area4e

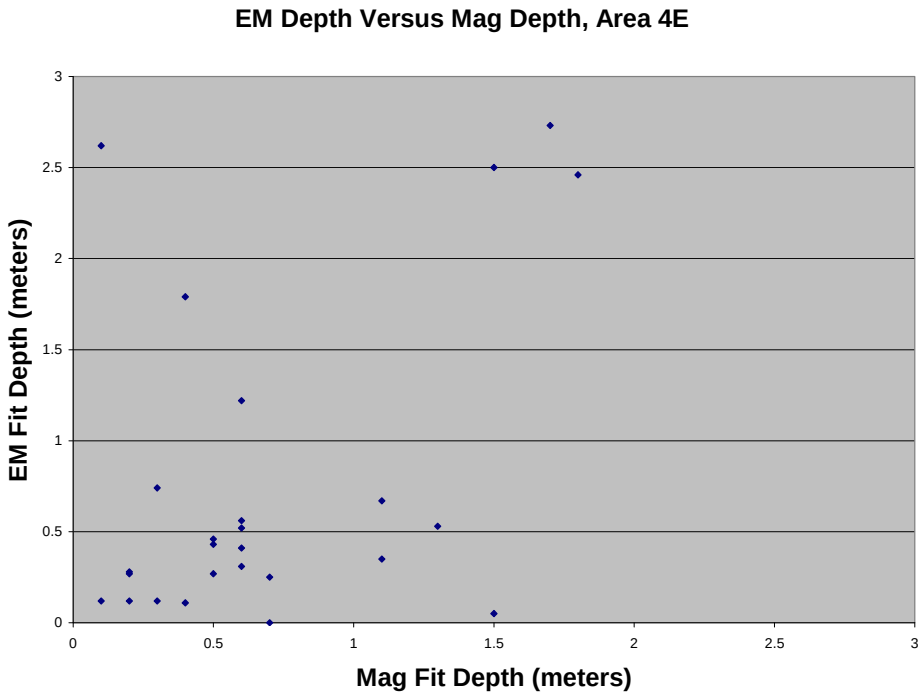

Figure 69: EM-derived and mag-derived depths plotted against each other for Area4e

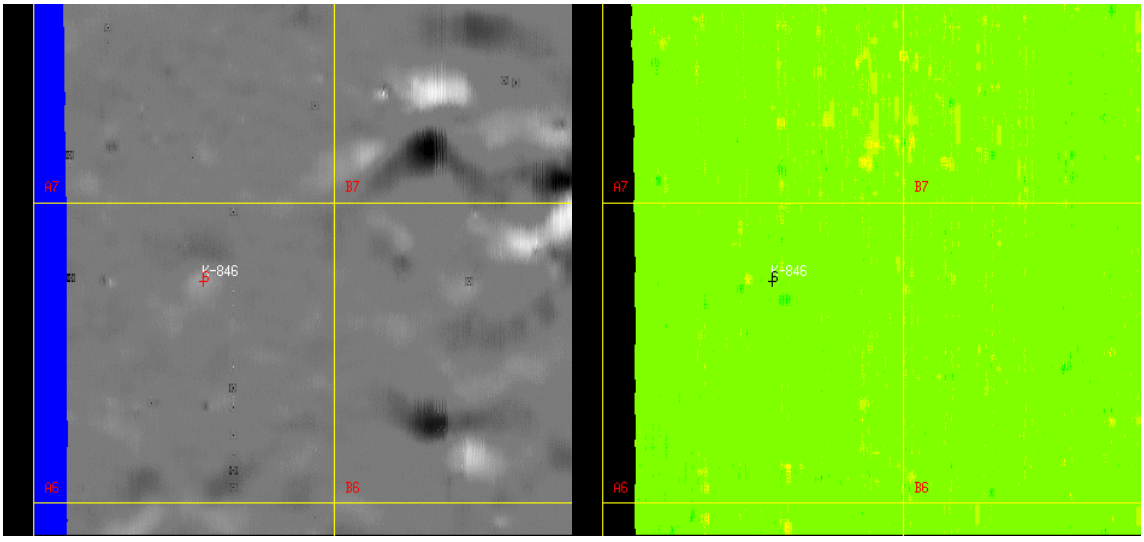

Figure 70: Magnetometer data (left, +/- 50nT) and EM61 gate3 data (right, +/- 50mV) from area4e. Yellow grid squares are 50 meters on edge. Item k-846, a very faint positive swell in the magnetometer data and nothing in the EM61 data, was a no-find, and caused the first outlier in the depth comparison chart above.

The other outlier in the mag data was caused by item k-883, a geologic no-find. This pick was caused by an anomaly in the magnetometer data that was highly geology-like but looked like it was possible (though unlikely) that there was an object embedded in the geology as well. Both the mag and EM inversions failed to converge – the mag because the signature did not well-resemble and dipole, and the EM because there was essentially no signal there (see the figures below).

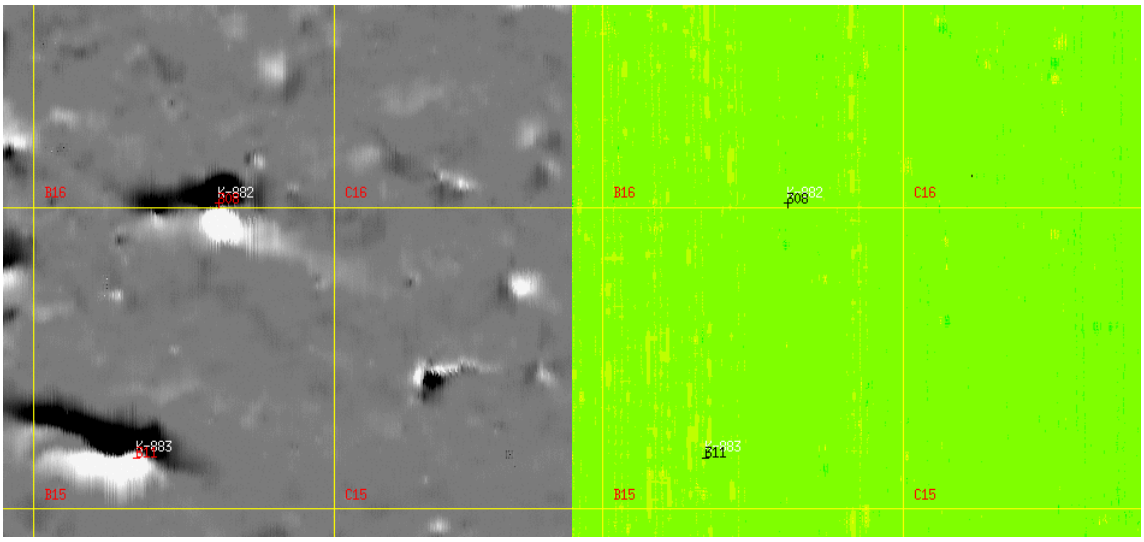

Figure 71: Magnetometer data (left, +/- 50nT) and EM61 gate3 data (right, +/- 50mV) from area4d. Yellow grid squares are 50 meters on edge. Item k-883 (lower left), a no-find in the lower left of each image, caused the outlier in the depth comparison chart above. The magnetometer data is non-dipolar; there is virtually no signal in the EM data.

Other EM-derived depths from analyses that failed to converge in Area4e correlate to no-find targets where there was little or no EM signal.

5 Cost Assessment

5.1 Cost Reporting

A by-task cost of performing the demonstration of VSEMS at the Kirtland PBR consists of the following:

- The cost of reinforcing the proof-of-concept fiberglass platform to help it survive the survey
- The cost of mobilization/demobilization (driving the tractor/trailer to and from Albuquerque)
- The cost of a five-week and a three-week survey stint in Albuquerque
- The cost of analyzing the data back at SAIC
- The cost of project management and report writing

The actual breakdown by task is below. Mob/demob includes driving the tractor/trailer from Newton MA to Albuquerque NM and back, plus travel for the crew for the two separate mobs. The Survey task includes the four-man crew onsite for 40 days, plus all related survey ODCs. The Analysis task includes the time spent analyzing the 100% geophysical survey data after the actual on-site survey. It also includes the costs of training in Geosoft Montaj™ and AETC's UxAnalyze plug-in, and the time spent analyzing EM61 data. The Project Management task includes the site visit, all meetings and presentations, classical project management, and reporting. SAIC's VSEMS already includes the tow vehicle, towed platform, magnetometers, EM61s, GPS, and computers. As such, none of these items needed to be purchased for this project. An UXO tech escort from EOTI was provided by the ESTCP program Office and acted

as the fourth member of the field crew; a cost estimate for his presence is included in the costing below.

Table 15: Breakdown of Actual Survey Costs

Reinforce Platform	$ 11,458.06
Mob/Demob	$ 27,507.75
Survey	$ 226,366.58
Analysis	$ 34,436.61
Project Management	$ 66,063.95
Total	$ 365,832.95
Number of Acres	5000
Cost Per Acre	$72

5.2 Cost Analysis

5.2.1 Cost Comparison

There are no other concurrent mag/EM61 vehicular systems. The other vehicle-towed arrays which have non-simultaneously-deployed EM61 and magnetometer platforms are 1) the original NRL-fielded MTADS, and 2) the Blackhawk (now Zapata)-fielded MTADS. The NRL MTADS technically is not a commercially available system but a system for scientific study, and is usually fielded by a large crew of scientists and engineers on jobs intended to showcase the system's ability to collect discrimination-quality data. The Blackhawk (Zapata)-fielded MTADS was intended to be the commercially-available version of the NRL-developed MTADS; it is uncertain if it is still in use. Members of the National Association of Ordnance Contractors (NAOC) with vehicle-towed EM61-only arrays include Parsons, Sky Research, USA Environmental, Weston Geophysics, Naeva, ARM, Shaw, Tetra Tech, SAIC (a different division than the one fielding VSEMS), and UXB. We are not familiar with every one of these systems, but we know how difficult it is to correctly deal with the system timing issues necessary to collect correctly geo-located data. In order to account for the latency of EM61 data (the fact that it is "old" when it comes out of the box) and correctly synchronize it with geolocation data, it is necessary to time-stamp the data as it arrives at the computer, and then to perform a latency correction by time-shifting the data. To do this, the timestamps must be accurate. Some contractors merely set the PC clock to the Universal Time Coordinate (UTC) time derived from the GPS. However, the drift of the PC clock, combined with the coarse 66ms precision of reading this clock under Microsoft Windows, make this a fundamentally inaccurate way to collect EM61 data. Data sets acquired by this method often have anomalies with "chevron" artifacts because the anomalies are shifted in the direction of travel due to these timing issues. Some contractors use the commercial data acquisition software MagLog, but that does not solve this timing problem, although MagLog combined with a commercial GPS timing card does.

The only NAOC members with vehicle-towed magnetometer-only arrays are Sky Research and ARM Group. The smaller number of towed magnetometer systems is due to several factors, including the preponderance of statements of work from the US Army Corps of Engineers that mandate use of an EM61, the historical reliance of towed magnetometer arrays on expensive

custom vehicles with low magnetic signatures (this has been evaluated in ESTCP project MM-0605, which has concluded that there are commercial-off-the-shelf vehicles that work nearly as well for towed array magnetometry as the custom vehicles), and the necessity of a well-engineered system due to the sensitivity of magnetometers to any nearby ferrous metal, including the beads in the tires on the platform. Our understanding is that both the Sky and the ARM system are well-engineered systems that pay appropriate attention to timing and signature issues and generate high-quality data.

Since VSEMS uses COTS EM61s and total field magnetometers, there is little about VSEMS' data streams that individually distinguish them from mag or EM61 data from properly-synchronized data acquired by the above contractors. Although these sensors have a broadly overlapping detection envelope, the nod generally goes to EM61s for sites where the objects of interest are small (20mm and 40mm), even though the EM61's 10 Hz output rate limits the survey speed. Conversely, for the WAA objectives of detecting extent of bombing targets contaminated with air-dropped munitions, magnetometers were the sensor of choice, even though the magnetometer's response to geology can limit the interpretability of the data. Geology was not expected to be a problem at the Kirtland PBR, but it was. The analysis in section 4.3.4 shows that the EM61 was unaffected by this geology, and since VSEMS was driven slowly in order to collect high-quality EM61 data anyway, and since there were no deep mag-only objects recovered at Kirtland, one could argue that an EM61-only survey by a commercial contractor with a well-synchronized array would be sufficient. However, the absence of deep mag-only objects is likely a function of the lack of digging of the target centers themselves. Indeed, finding a live 250 lb bomb would've proven problematic at Kirtland, as such a discovery probably would've necessitated closure of the Double Eagle airport.

Similarly, note that the vehicular surveys at the other Wide Area Assessment sites were all performed by the MTADS magnetometer platform. At the Victorville PBR Y site, the system encountered unexpected magnetic geology, requiring additional surveying with man-portable EM61 equipment. Use of simultaneous mag/EM at this site would have concurrently acquired this EM61 data and obviated the need for a separate EM61 survey.

5.2.2 Cost Basis

The cost basis included a crew of four.

5.2.3 Cost Drivers

The largest cost driver is the time spent actually collecting survey data. This is affected by many things, including downtime, site access, site geometry, and weather. A secondary cost driver is the vehicular hospitability of the survey site and the resulting forward rate of advance. A list of factors affecting cost and performance were included in section 2.3 of this report.

5.2.4 Life Cycle Costs

Historically, deployment of the VSEMS commercial UXO survey work has included a $1950/day rental charge. This charge was originally used to amortize the internal development of the original GEO-CENTERS "STOLS" system that VSEMS grew out of, and thus represented the life cycle cost. Presently, the daily rental charge is typically used to maintain the system and repair broken sensors (the total field magnetometers are now 15 years old and sometimes die at the rate of one per week, necessitating a $5000 repair). The daily rental charge is typically waved

for a project that is contracted through the Cooperative Research and Development Agreement (CRADA) that SAIC has with CEHNC (that is, waiving the rental charge is SAIC's contribution to the CRADA). However, the Wide Area Assessment project was not contracted through the CRADA, and thus the proposal included the daily rental charge.

6 Implementation Issues

6.1 Environmental Checklist

Other than the emissions created by the tow vehicle's gasoline-powered internal combustion engine, no residuals or pollutants are produced by the system.

6.2 Other 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.

6.3 End-User Issues

The envisioned end-user is the Army Corps of Engineers Huntsville (CEHNC) and the contractors that they employ for UXO site assessment and cleanup. The applicability of the technology is largely a function of the vehicular navigability and GPS coverage on a particular site; these are factors that apply to any towed vehicular sensor array, not just VSEMS.

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 end-user issues above those that apply to all DGM data. The interleaving concurrent multisensor hardware used in this project was developed under ESTCP Project MM-0208, and completed dem-val under that project. Since then, the VSEMS system was successfully used to survey nearly 500 acres of commercial and government MEC, OE and HTRW sites before being deployed to the Kirtland PBR. There appear to be no end-user issues stemming from the interleaving technology.

7 References

Siegel, Robert. 2002. *Work Plan for Test, Evaluation, and Demonstration of the Combined Electromagnetic and Magnetometer Data Acquisition and Processing System*, GEO-CENTERS, July 2002

2004. *Proceedings of the 2004 UXO Countermine Forum*, March 2004.

Siegel, Robert. 2004. *Combined Electromagnetic and Magnetometer Data Acquisition and Processing, Project MM-0208, Final Report*. Submitted to ESTCP Program Office 10/27/2004.

Siegel, Robert. 2005. *WAA Pilot Program Data Report for Project UX-0531: Simultaneous Magnetometer and EM61 Mk2 Vehicle-Towed Array for Wide Area Assessment.* Submitted to ESTCP Program Office December 29th, 2005.

ESTCP Program Office, *Validation Plan, Wide Area Assessment Pilot Program Demonstration at the Former Kirtland Precision Bombing Range, NM, Draft January 2007.*

8 Points of Contact

POINT OF CONTACT Name	Organization Name Address	Phone/Fax/email	Role in Project
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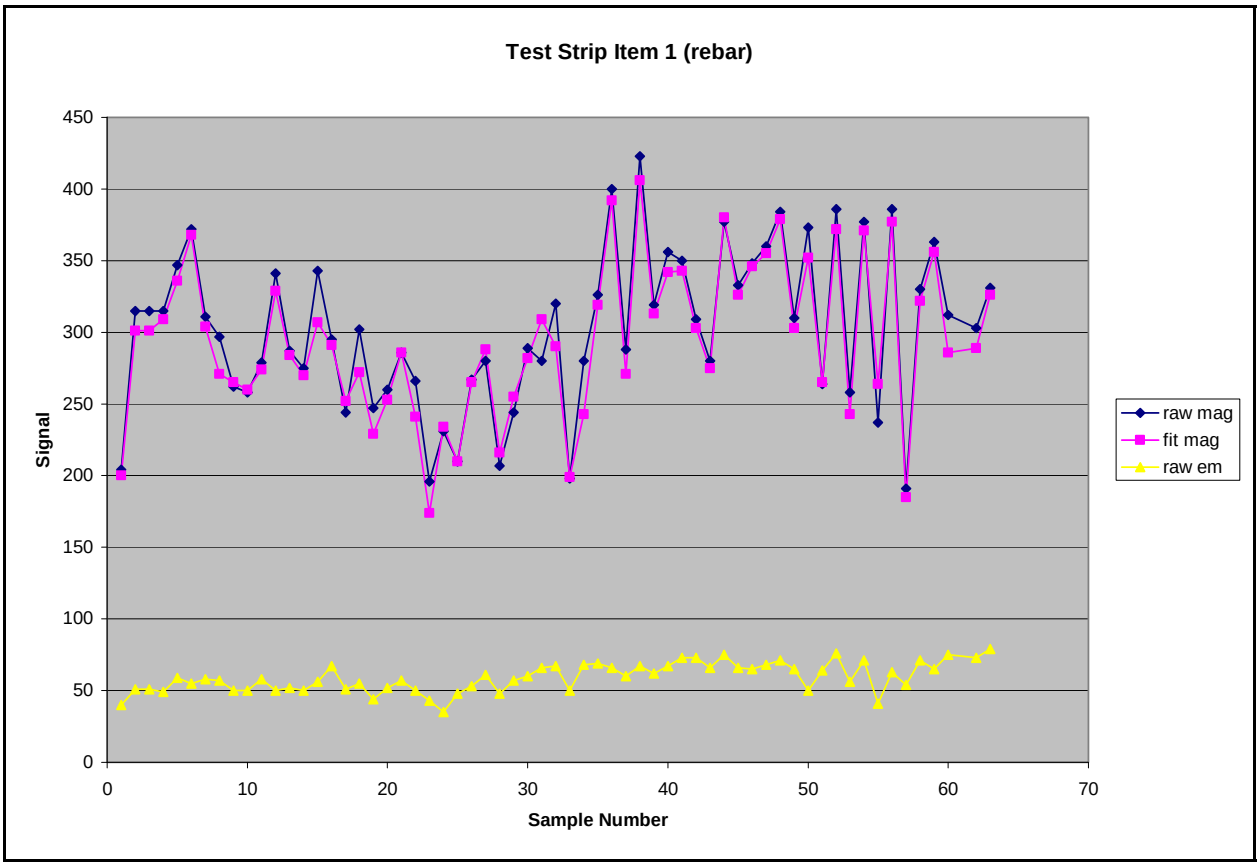
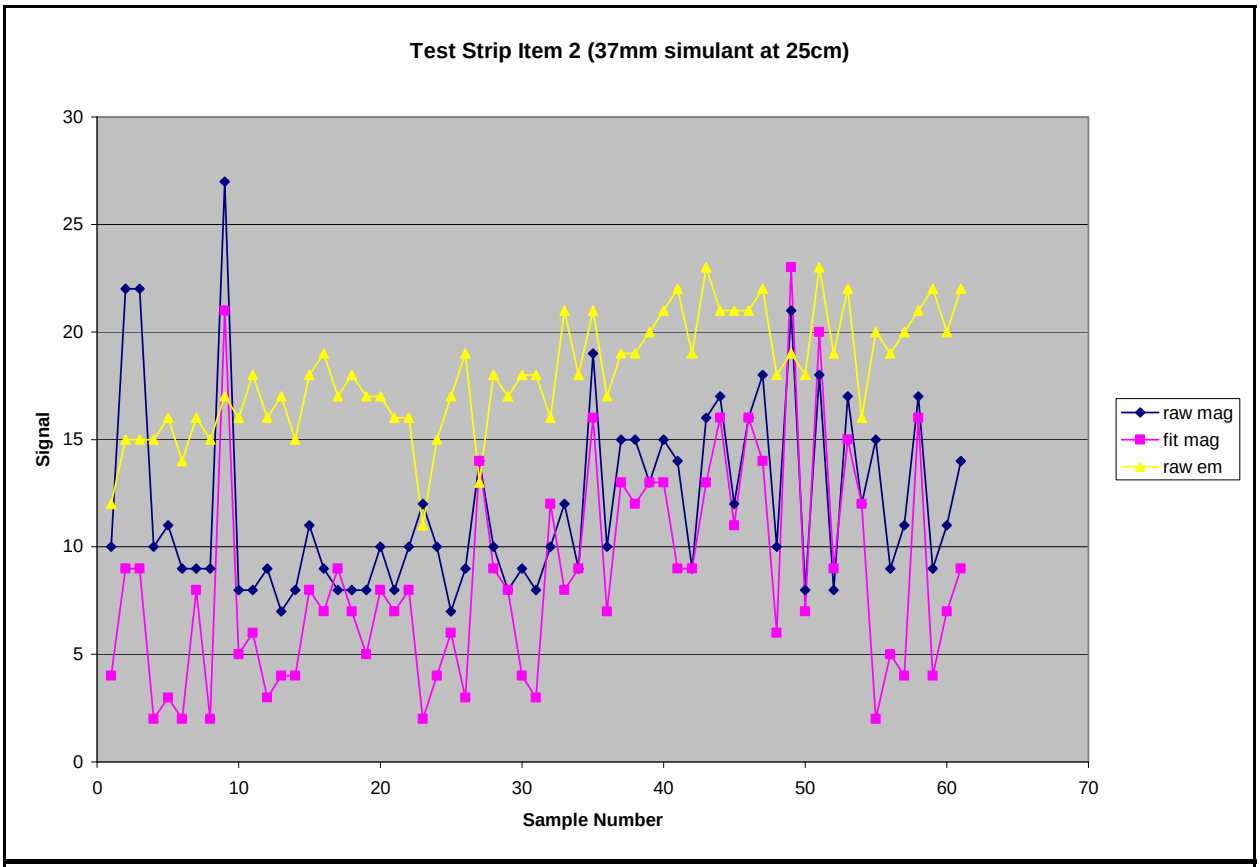
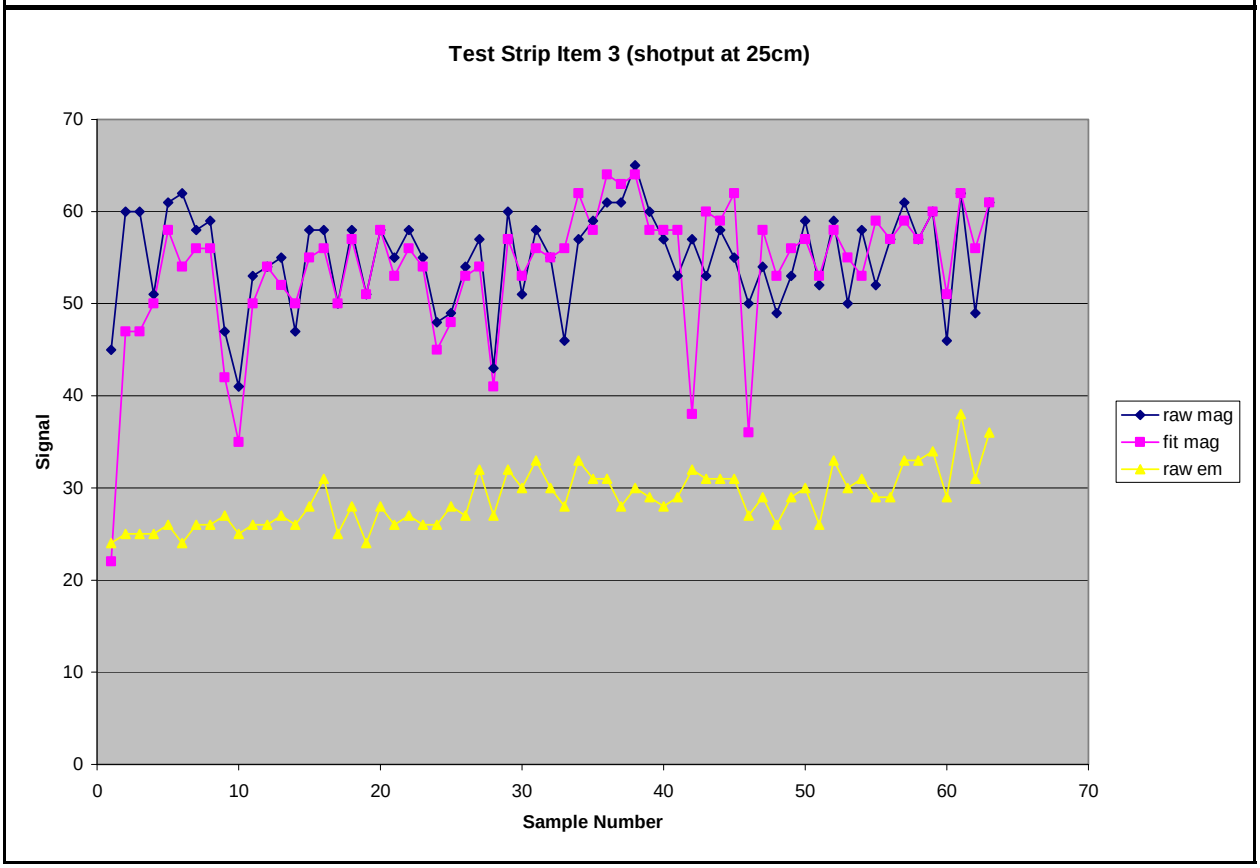
Dr. Herb Nelson	Naval Research Laboratory, Code 6110 4555 Overlook Avenue, SW Washington, DC 20375-5342	(202) 767-3686 Fax: (202) 404-8119 herb.nelson@nrl.navy.mil	ESTCP Program Office's Technical Representative
Bob Selfridge	US Army Corps of Engineers, Huntsville 4820 University Square Huntsville, AL 35816-1822	256-895-1629 256-895-1737 bob.j.selfridge@hnd01.usace.army.mil	COR, UX-0531

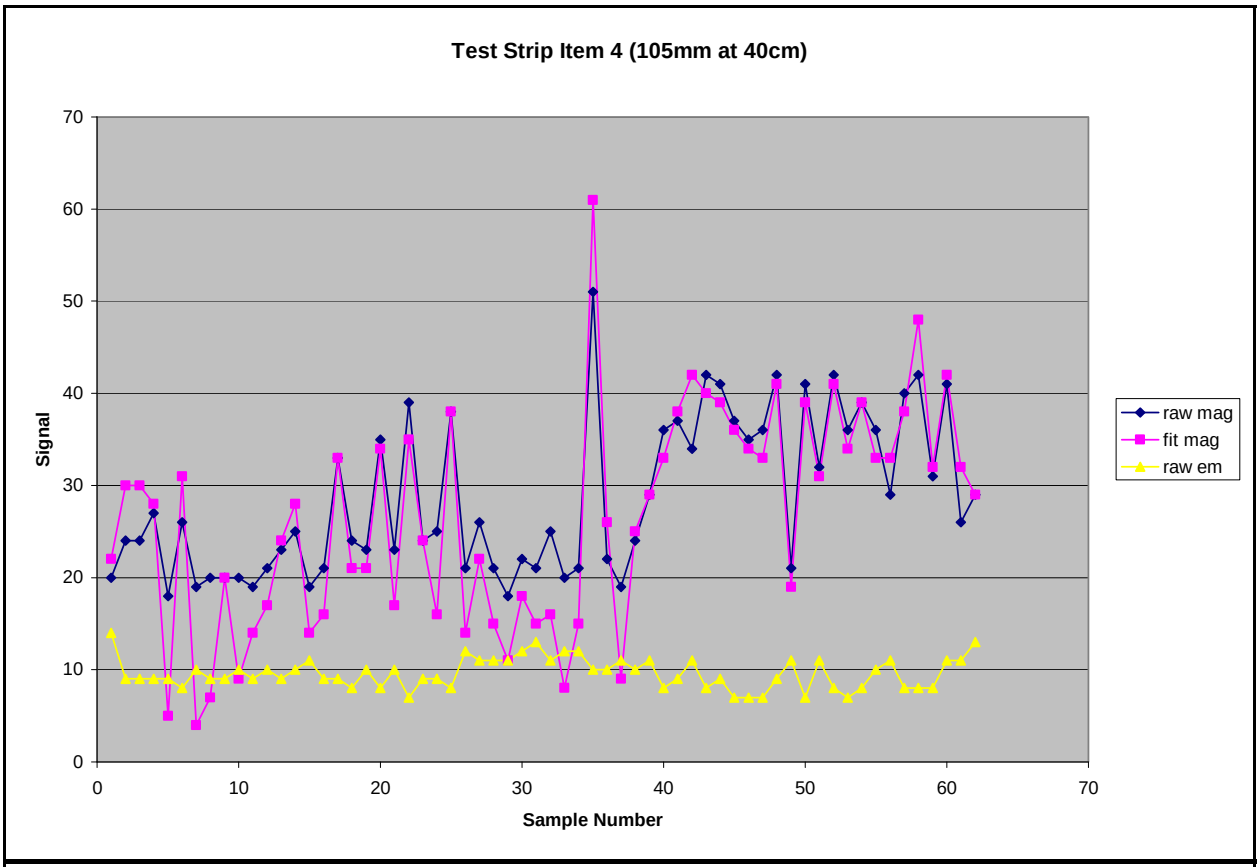
Appendix: Test Strip Results

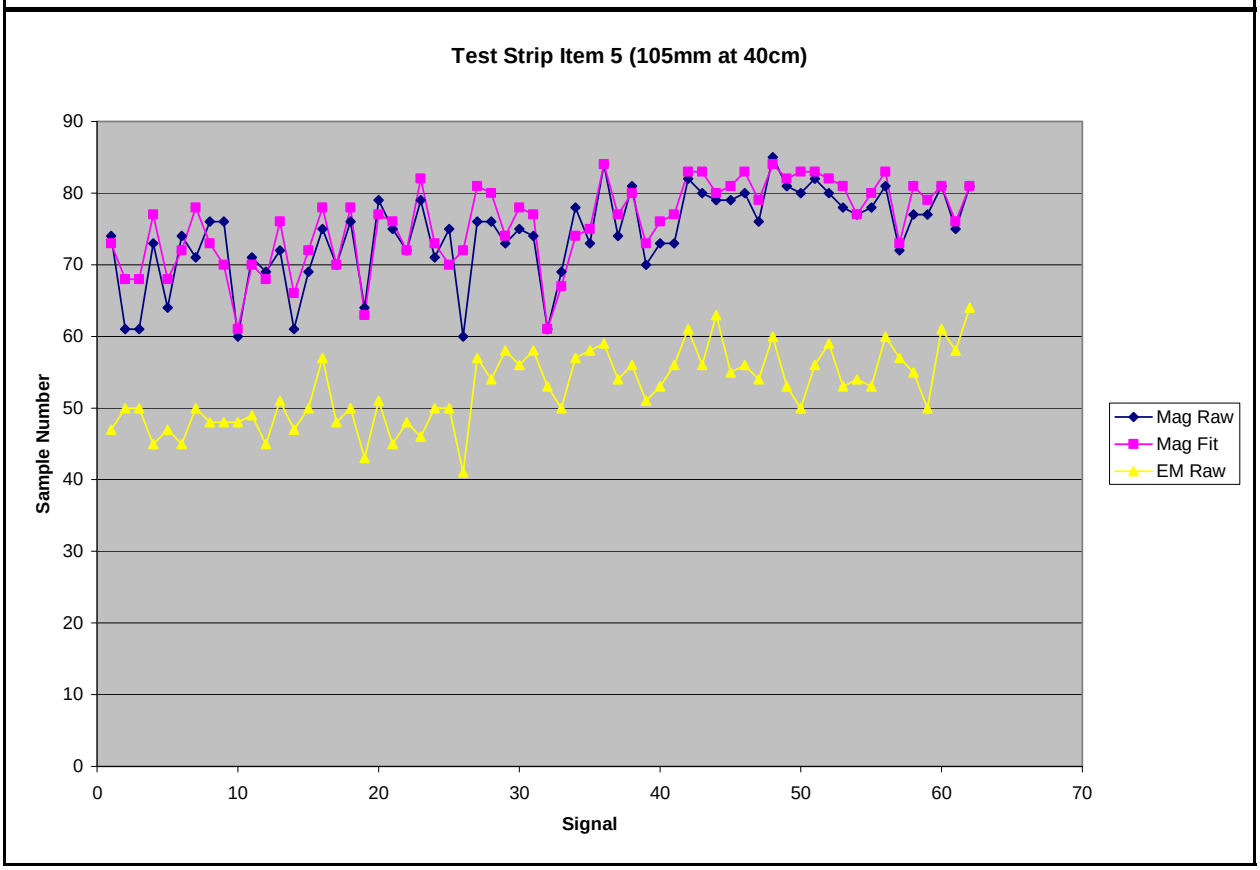
The figures below plot the response for the 15 items in the test strip. For all 15 figures, the horizontal axis represents the individual strip tests taken morning and afternoon during the eight-week survey. The magnetometer data (blue) in nT, the fit results to magnetometer data (magenta) in nT, and EM61 gate 3 (yellow) in mV are plotted on the same chart. Obvious outliers have been removed. As said in the body of the document, we attribute the variation to the motion of the sensors on the towed platform.

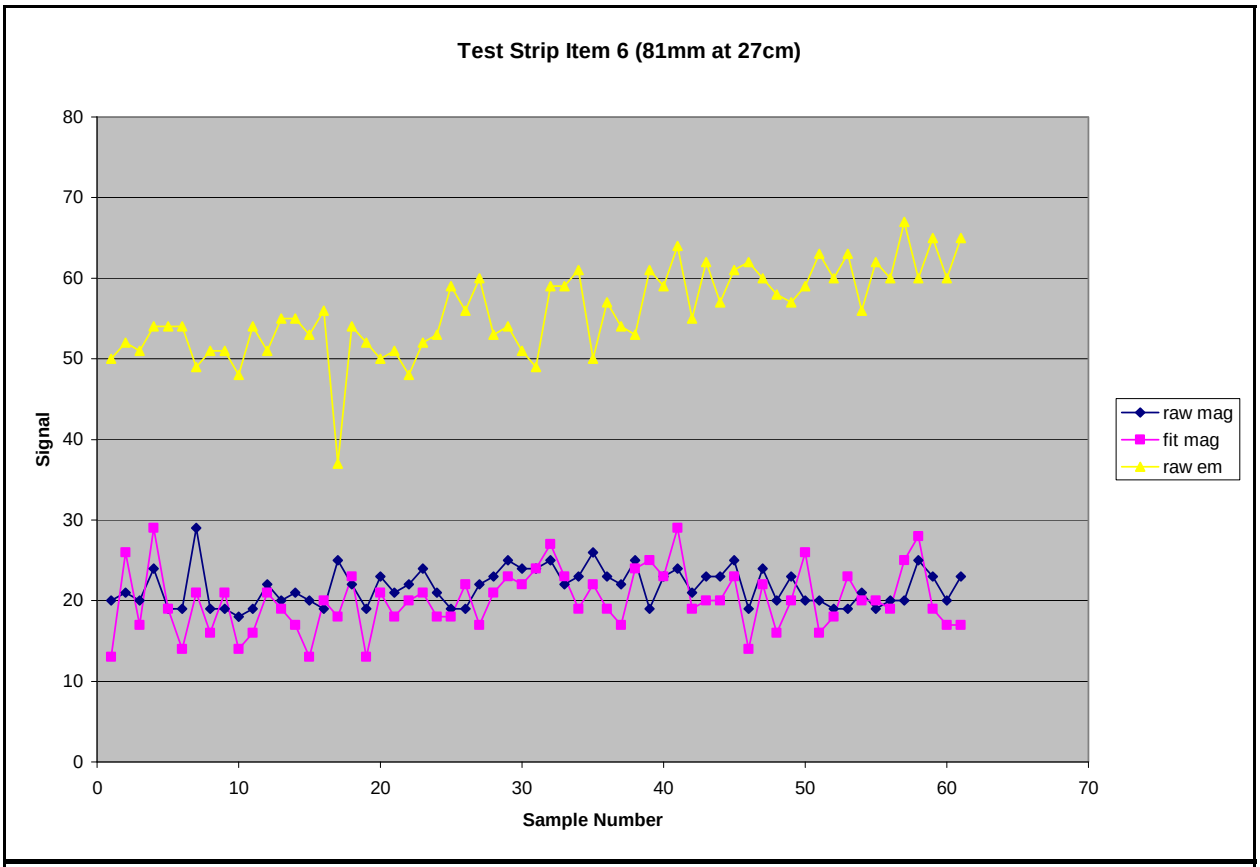


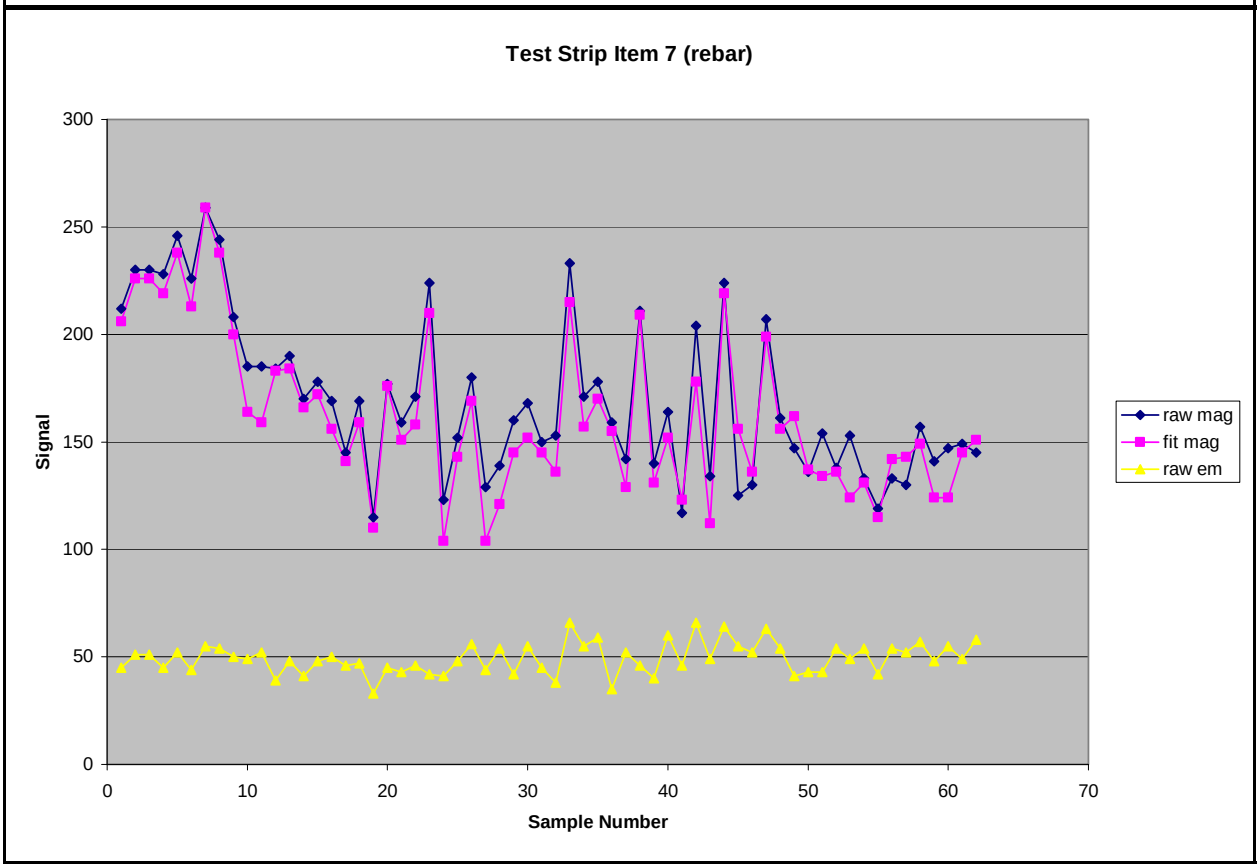

Test Strip Item 2 (37mm simulant at 25cm)
Signal
Sample Number
raw mag
fit mag
raw em
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70

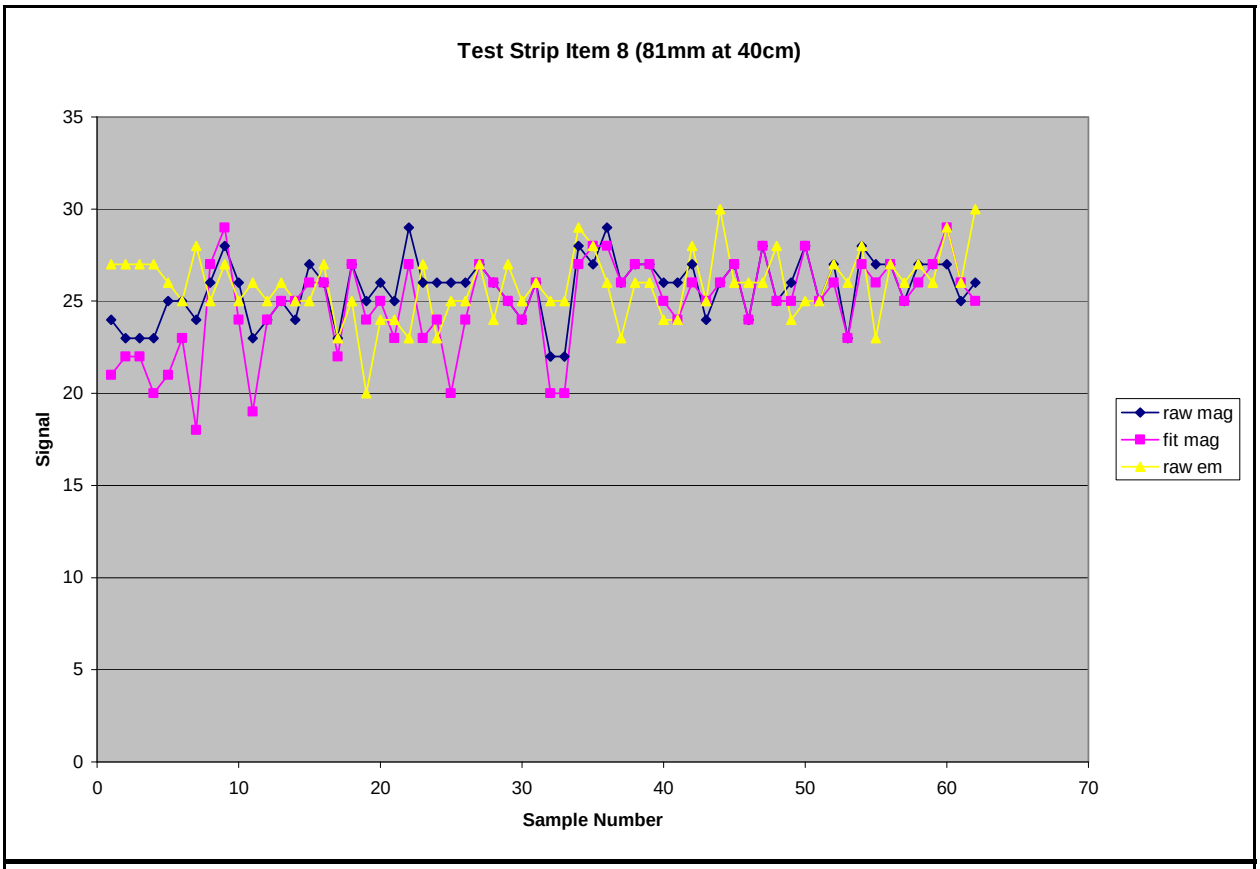

Test Strip Item 3 (shotput at 25cm)
Signal
Sample Number
raw mag
fit mag
raw em
0
10
20
30
40
50
60
70
0
10
20
30
40
50
60
70

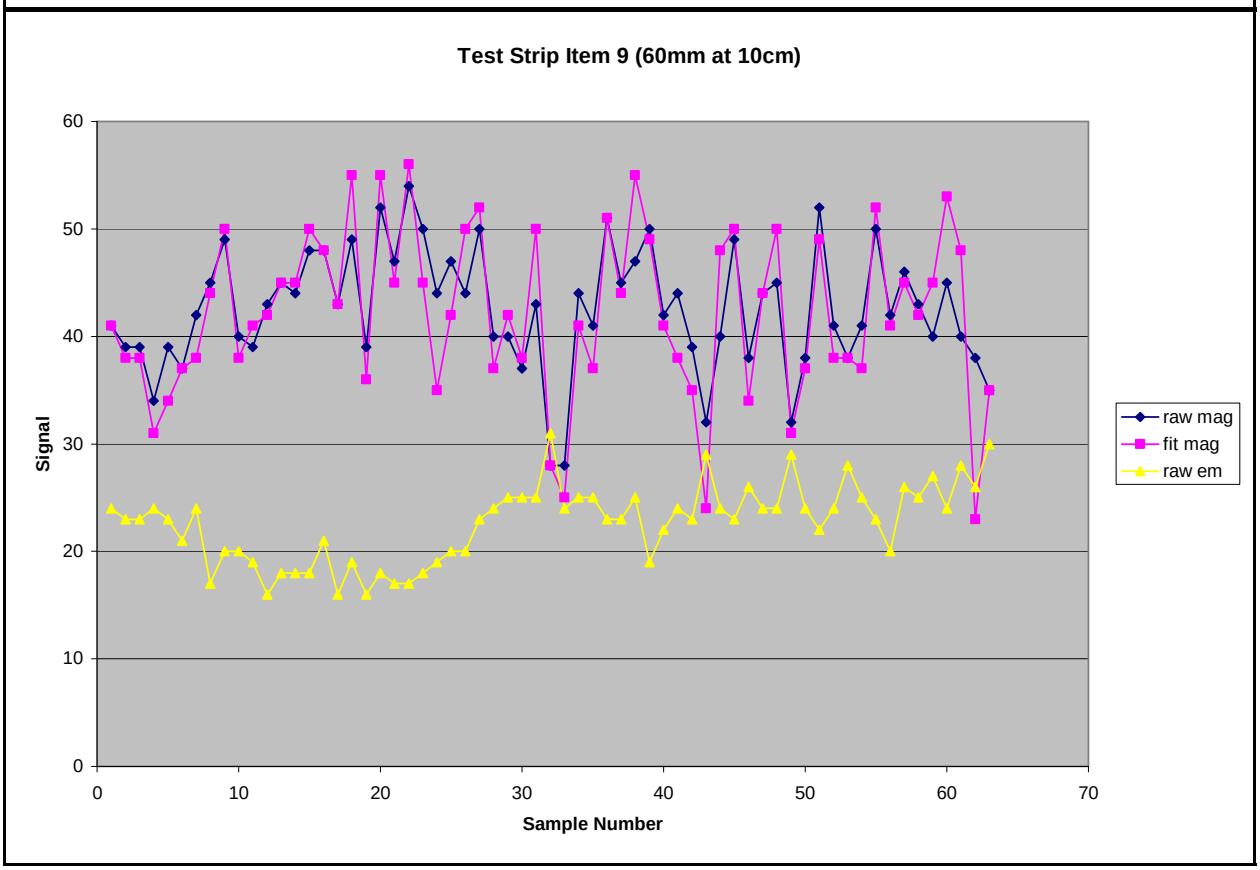

Test Strip Item 4 (105mm at 40cm)
Signal
Sample Number
raw mag
fit mag
raw em

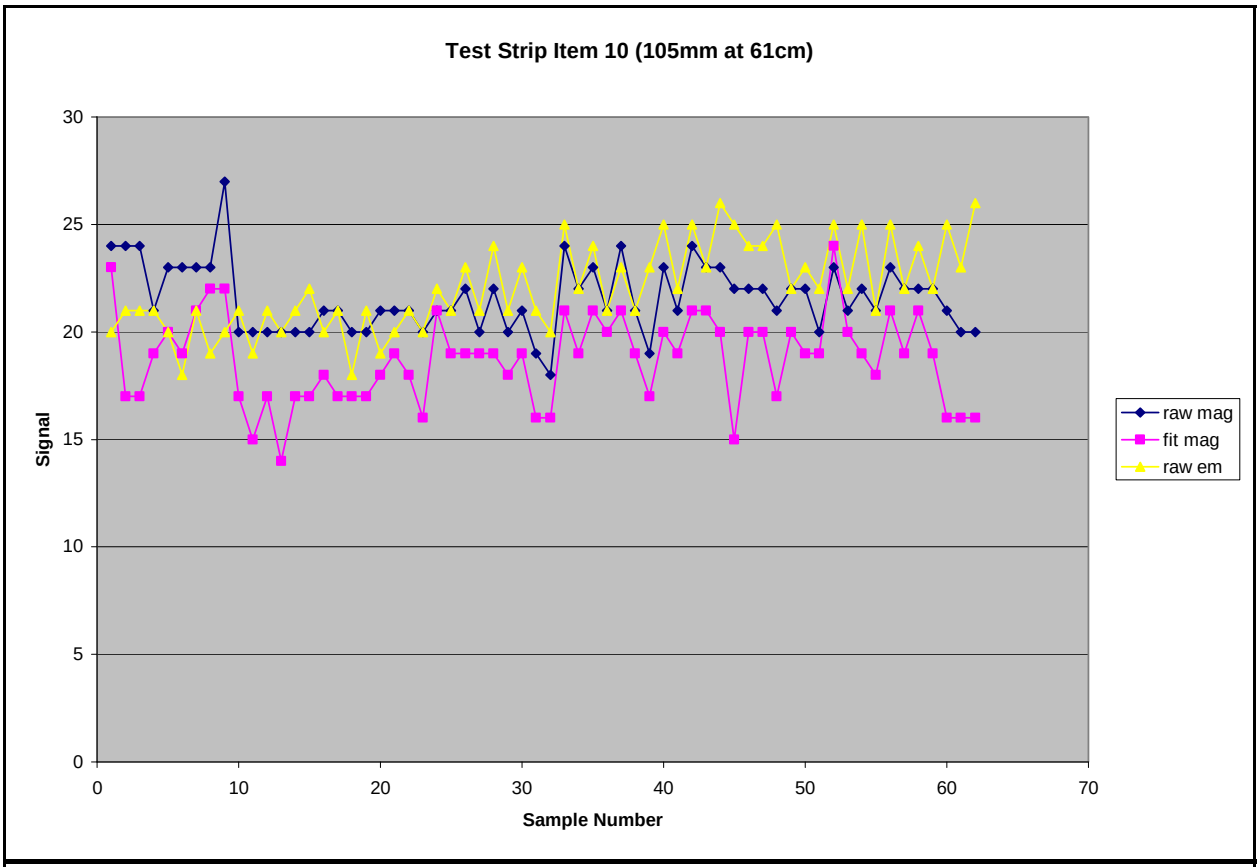

Test Strip Item 5 (105mm at 40cm)
Sample Number
Signal
Mag Raw
Mag Fit
EM Raw

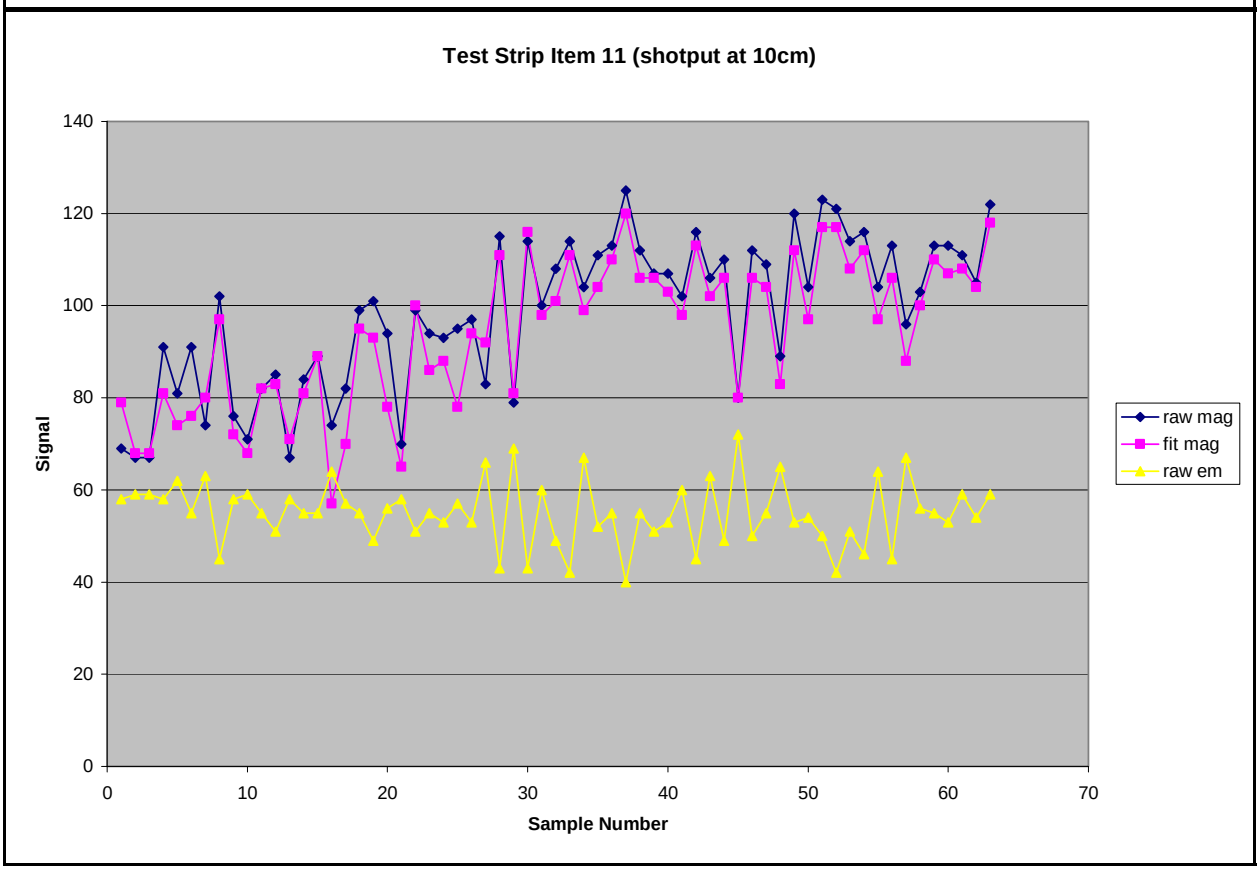

Test Strip Item 6 (81mm at 27cm)
Signal
Sample Number
raw mag
fit mag
raw em
0
10
20
30
40
50
60
70
80

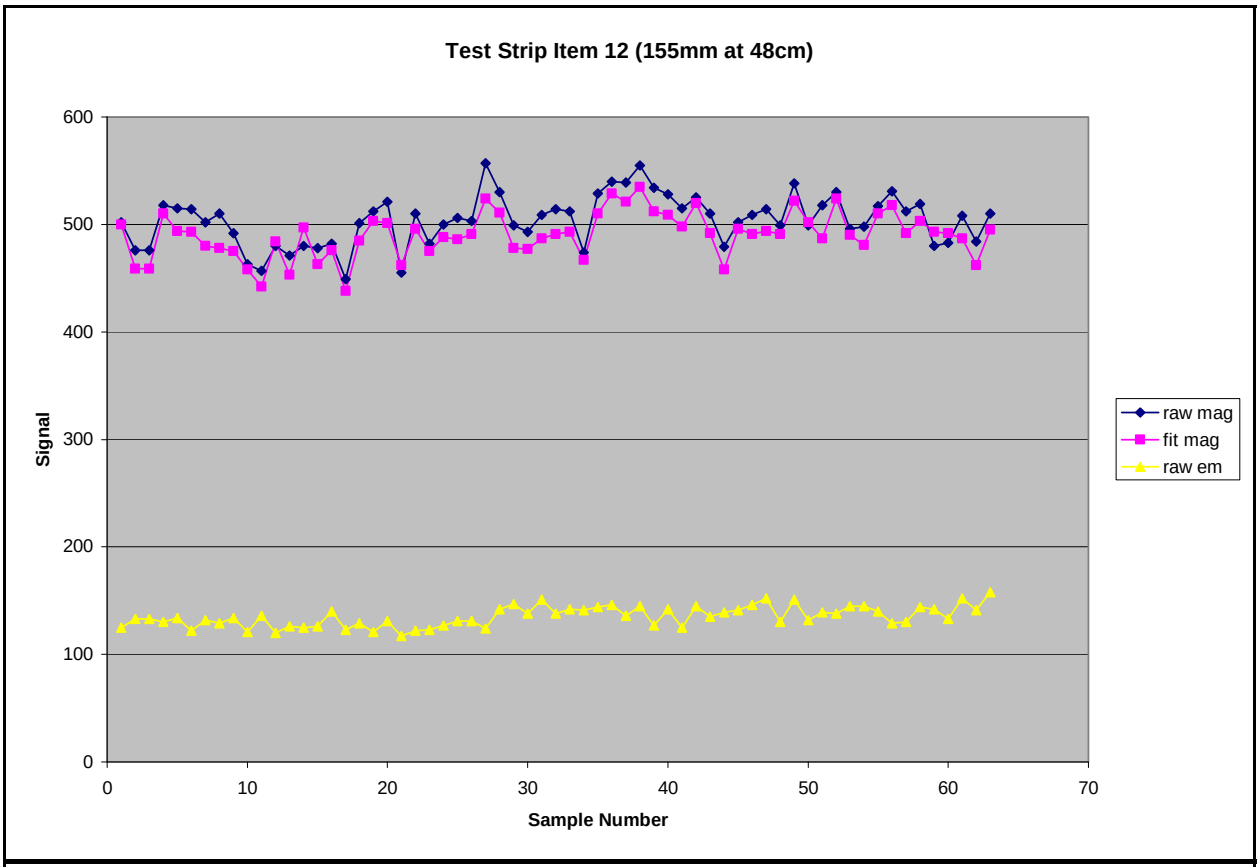

Test Strip Item 7 (rebar)
Signal
Sample Number
raw mag
fit mag
raw em
0
50
100
150
200
250
300

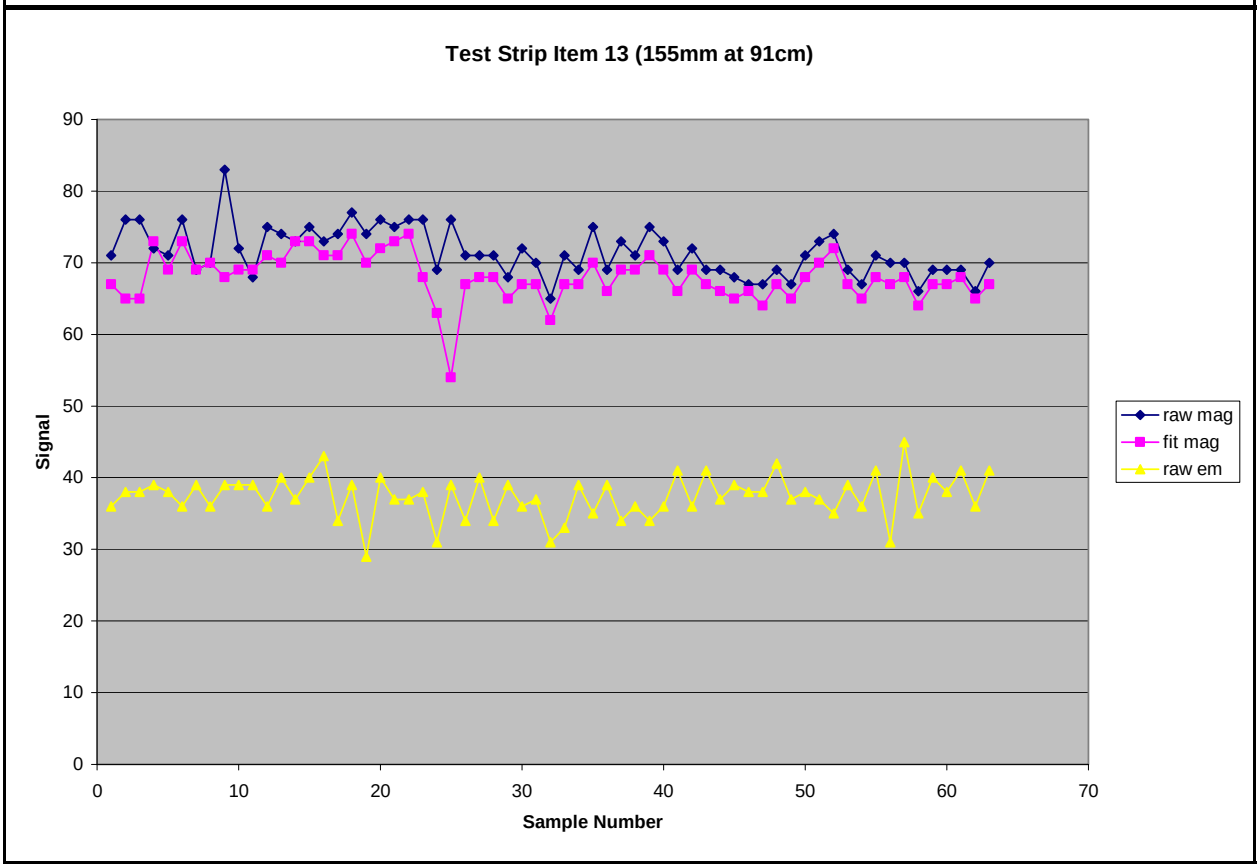

Test Strip Item 8 (81mm at 40cm)
Signal
Sample Number
raw mag
fit mag
raw em

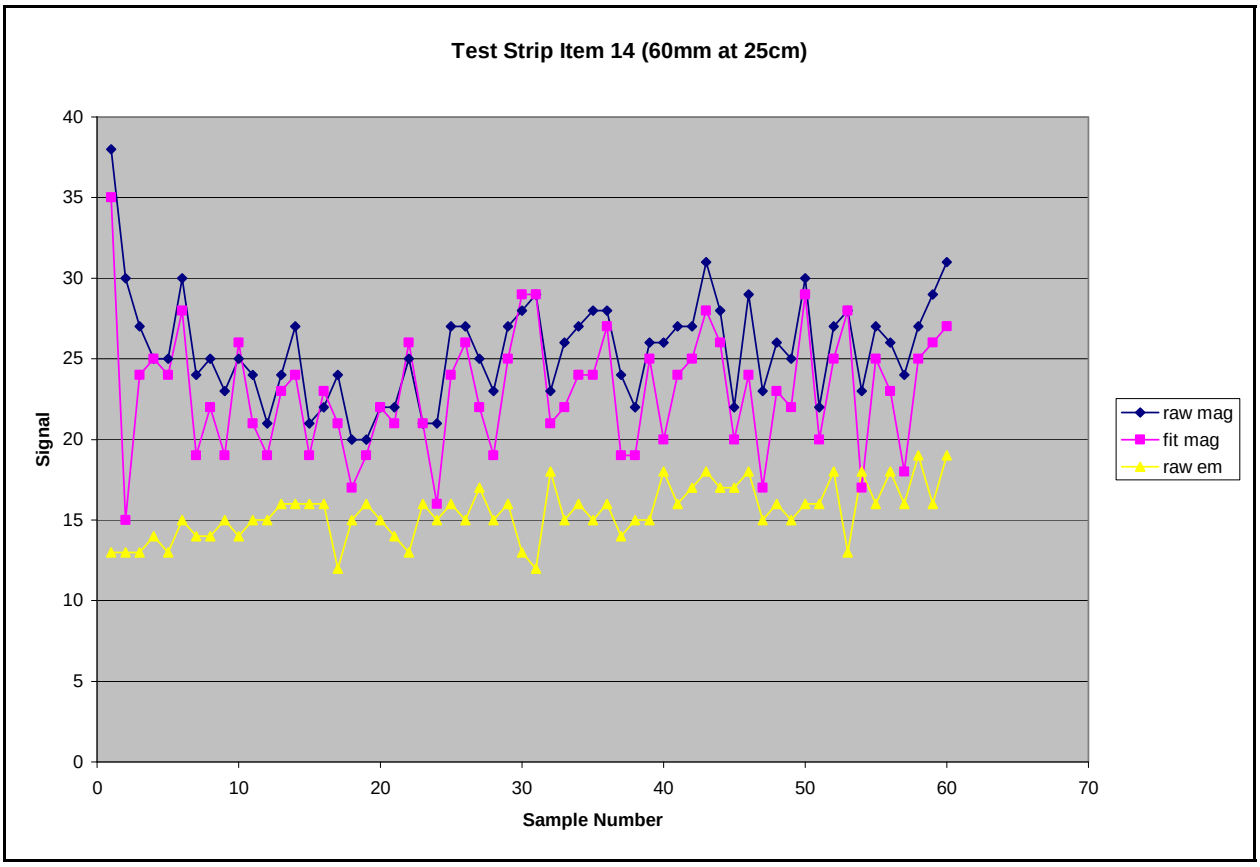

Test Strip Item 9 (60mm at 10cm)
Signal
Sample Number
raw mag
fit mag
raw em

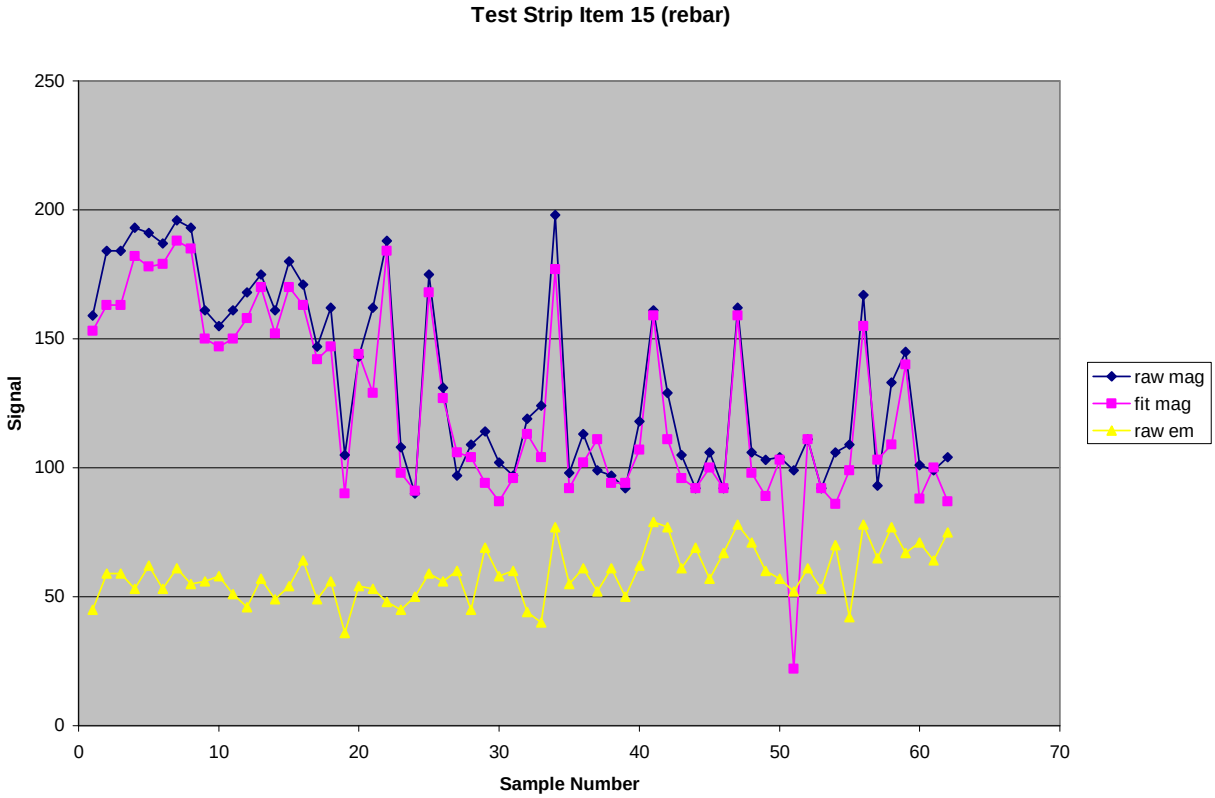

Test Strip Item 10 (105mm at 61cm)
Signal
Sample Number
raw mag
fit mag
raw em


Test Strip Item 11 (shotput at 10cm)
Signal
Sample Number
raw mag
fit mag
raw em


Test Strip Item 12 (155mm at 48cm)
Signal
Sample Number
raw mag
fit mag
raw em
0
100
200
300
400
500
600
0
10
20
30
40
50
60
70


Test Strip Item 13 (155mm at 91cm)
Signal
Sample Number
raw mag
fit mag
raw em
0
10
20
30
40
50
60
70
80
90
0
10
20
30
40
50
60
70


Test Strip Item 14 (60mm at 25cm)
Signal
Sample Number
raw mag
fit mag
raw em


Test Strip Item 15 (rebar)
Signal
Sample Number
raw mag
fit mag
raw em