The subject of this presentation is a process termed Geophysical System Verification (GSV). GSV is a process in which the resources traditionally devoted to a GPO are reallocated to support simplified, but more rigorous, verification that a geophysical system is operating properly, as well as ongoing monitoring of production work. Two main elements are considered in this presentation:

1. Instrument Verification Strip
2. Blind Seeding Program

Presentation Overview

- Introduction
- Concepts
- Science Behind Geophysical System Verification (GSV)
- Application to an Example Site
- Summary and Conclusions

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We'll start with an introduction to the munitions response process, outline some of the concepts that make up Geophysical System Verification, briefly discuss the science behind GSV and then walk through how GSV was applied at an example site.

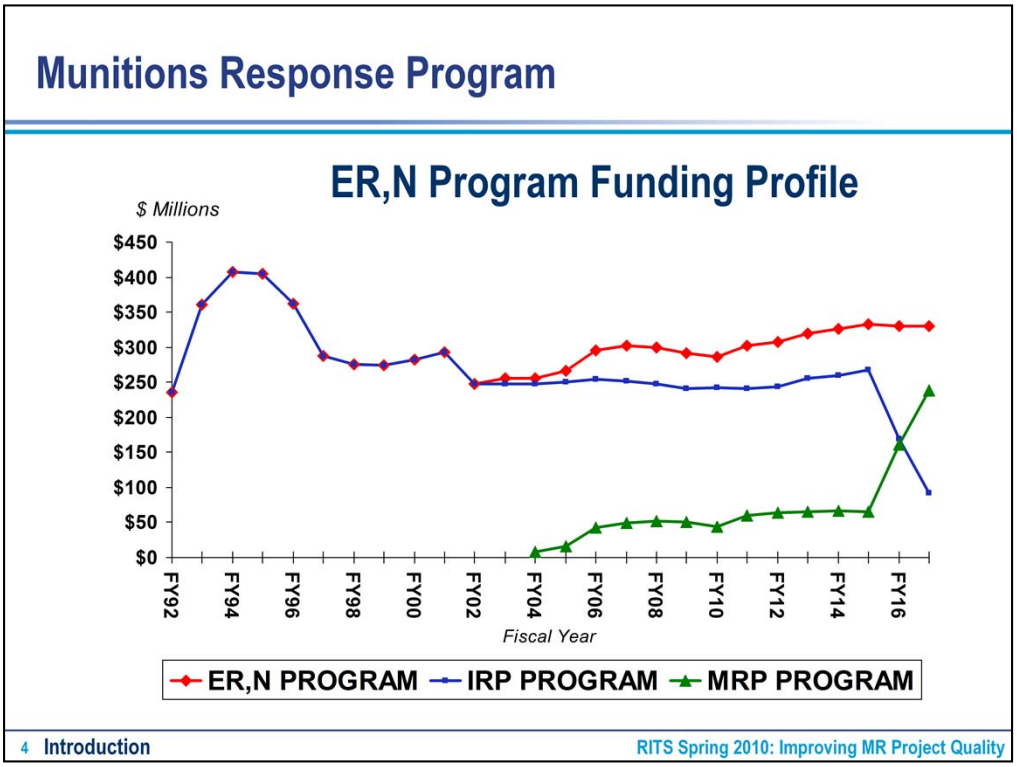
Munitions Response on Land and Underwater

UXO, DMM, and MPPEH removed from surface

All graphics are courtesy of U.S. Navy unless otherwise noted

3 Introduction RITS Spring 2010: Geophysical System Verification

The Navy, just like the other Services, is responsible for Munitions Response Sites (MRS) that are located on land and underwater. The photo on this slide shows some examples.



This chart shows the projections as of 2010 for the breakout of the Navy's component of the Defense Environmental Restoration Program (DERP). Since the inception of the program, most of the funding has gone to the Installation Restoration Program (IRP). Many of these IRP projects are achieving Remedy in Place (RIP) or Remedy Complete (RC), freeing up money for the Munitions Response component of DERP.

Munitions Response in CERCLA

- DoD authority derived from Defense Environmental Restoration Program
- DoD's Preferred Munitions Response Program (MRP) regulatory approach
- MRP differences
  - CERCLA phases slightly revised
  - Additional steps/organizations

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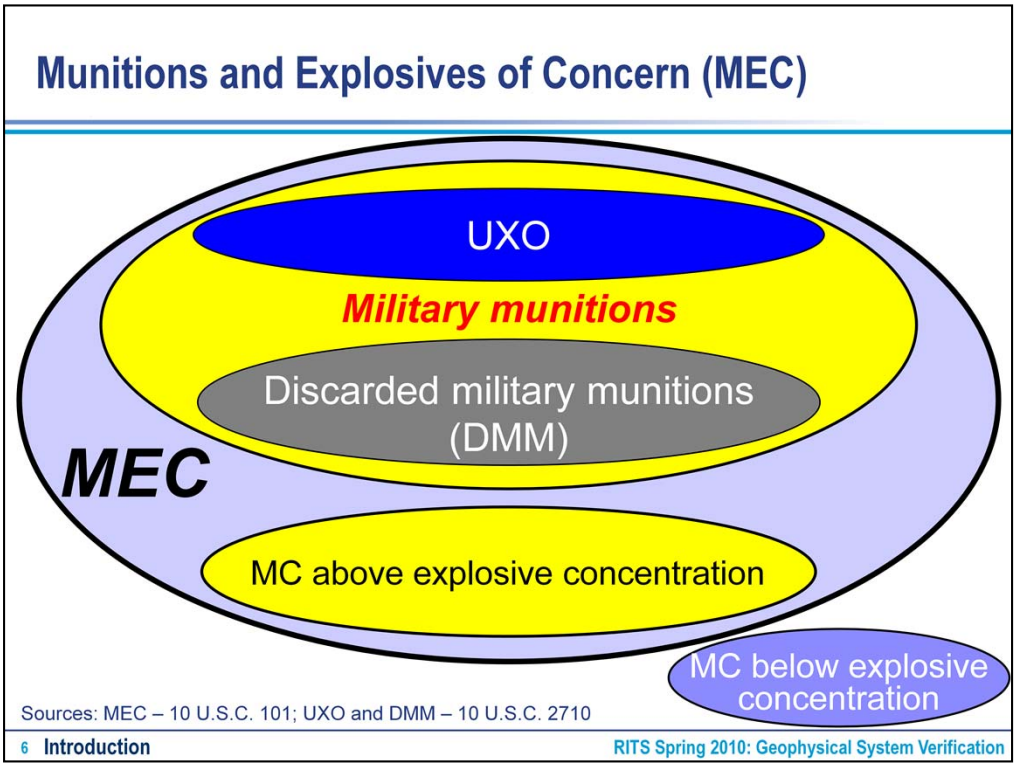
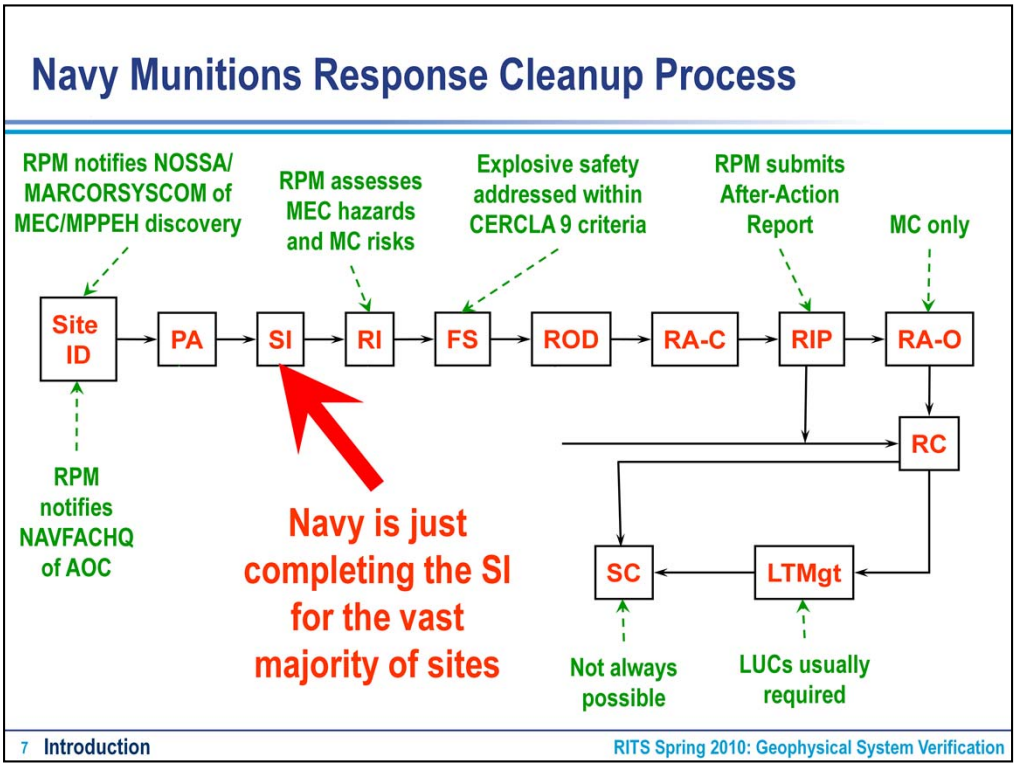
The Navy is cleaning up its munitions response sites using CERLA. EPA and DoD assert that when DoD addresses MEC/MC at other than operational ranges, a CERCLA release is triggered. EPA believes that ordnance and their constituents are really no different than any other hazardous substance. DoD agrees with the CERCLA approach for cleanup, DoD believes explosives safety considerations must be the exclusive purview of DoD

- ❑ DoD clearly prefers CERCLA where the Services can exercise their lead agent authority under CERCLA and DERP at active installations, BRAC properties, and under the FUDS program
- ❑ Federal Land Managers such as Interior and Agriculture also believe they have delegated lead agent authority for properties that they own such as park land that may have been leased to DoD for use as a range
- ❑ In some cases, other statutory authorities such as the RCRA, Clean Water Act, Clean Air Act, or Safe Drinking Water Act have been used to trigger cleanups.



Since we are going to discuss the use of metal detectors, the GSV is concerned with the subset of Munitions and Explosives of Concern (MEC) referred to as Military Munitions. These are either unexploded ordnance (UXO), that is munitions that were armed and delivered but failed to function, or munitions that were discarded before use (DMM). Munitions Constituents (MC) in high enough concentrations to present an explosive hazard are part of a munitions response but are not detected by the methods we are discussing here.

Small concentrations of the high explosive filler in the soil or water, while hazardous, are not addressed in a munitions response.



This is the familiar chart of the steps in the CERCLA process that has been shown in the previous presentation. It shows the responsibilities of the RPM for a munitions response at the various stages of the process. You should note that unlike most Installation Restoration sites, Munitions Response sites are at a very early stage of the CERCLA process; all SIs are required to be completed by the end of FY10.

Geophysical System Verification Supports the RI/FS and the Remedy

- The GSV supports the munitions response project quality assurance/quality control requirements
  - Verifies that the equipment is working properly during the remedial investigation and the remedy
  - Measures site noise from which the "dig list" is eventually developed
  - Production blind seeding provides ongoing monitoring of production geophysics
- GSV requirements need to be included in the RI Work Plan/QAPP and the plans for the remedial action

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The process outlined in this presentation is appropriately applied in all the following stages of the CERCLA process. During the RI/FS, GSV can ensure collection of high-quality data that give all stakeholders confidence in the results.

Geophysical System Verification Supports the RI/FS and the Remedy (cont.)

- The GSV helps evaluate potential remedies that permanently and significantly reduce the threat to public health, welfare, and the environment
- The GSV supports a cost-effective remedial action alternative that mitigates the threat
- The GSV helps achieve consensus among DON, EPA, state, and local authorities regarding the selected response action and provides evidence of its quality

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Similarly, during a remedial action the use of GSV ensures quality, believable data is collected.

The Munitions Response Problem

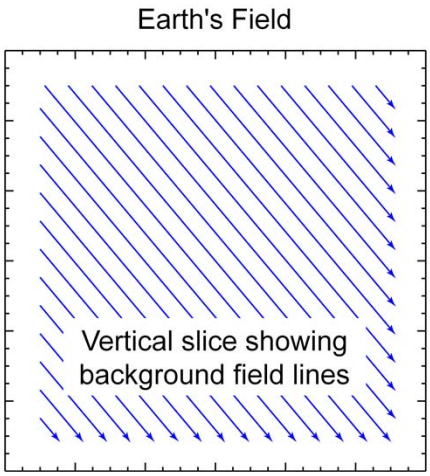
- Immediately after WWII, training was suspended at many ranges and entire installations were quickly converted back to civilian use
- Often, only a surface sweep was conducted leaving buried munitions in place
- Nationwide efforts began in the 80's
  - Two deaths at Tierrasanta, CA
  - National Defense Authorization Act (NDAA) of 2002 establishes Munitions Response Program as part of the Defense Environmental Restoration Program (DERP)
  - Improved geophysical sensors and inexpensive desktop computers

10 Introduction RITS Spring 2010: Geophysical System Verification

Many of the sites we are responsible for today date from WWI or WWII. At the end of those conflicts, training was stopped on many ranges and a number of installations were converted back to civilian use. The former are the responsibility of the Services' Environmental Restoration programs and the latter are part of the Formerly Used Defense Sites (FUDS) program. At the time of the closure of these sites, the technology did not exist to detect buried munitions so, in most cases, only a surface sweep was conducted. Beginning in the 1980's, attention started to be paid to these sites and a number of laws directed the DoD to start addressing them. About this same time, improved sensors and easy-to-use computers gave site managers the tools they needed to deal with these sites.

Magnetic Field Sensors

- **Magnetometers measure magnetic field strength**
  - **Background field is geomagnetic**

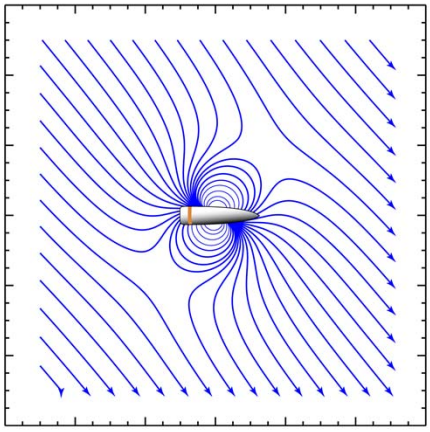


The picture on the left shows a man carrying a pair of Geometrics' G858 magnetometers. They can very accurately measure the strength of any magnetic fields that they are exposed to. The earth produces an ambient or background magnetic field, which is shown schematically in the diagram on the right. The bounding square represents a vertical slice of space with the horizontal axis pointing north and the vertical axis pointing up. The arrows pointing down to the right represent magnetic field lines showing the direction of the earth's magnetic field.

Magnetic Field Sensors (cont.)

- **Magnetometers measure magnetic field strength**
  - **Background field is geomagnetic**
  - **Magnetic (steel) objects distort the earth's field**

Earth's Field Disturbed



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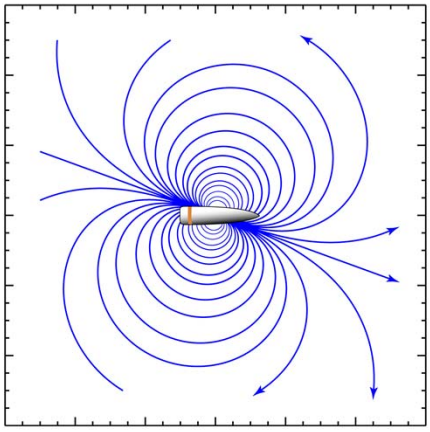
The diagram now shows the distortion of the magnetic field lines that might be produced by a munitions item. The steel strengthens the earth's field inside the object, creating new field lines which bend back around the object, like a magnet. A signal from a magnetometer passing over the object will vary in response to this magnetic field distortion.

Magnetic Field Sensors (cont.)

- **Magnetometers measure magnetic field strength**
  - **Background field is geomagnetic**
  - **Magnetic (steel) objects distort the earth's field**
  - **The distortion creates a "magnetic anomaly" in the background field**

Field Anomaly



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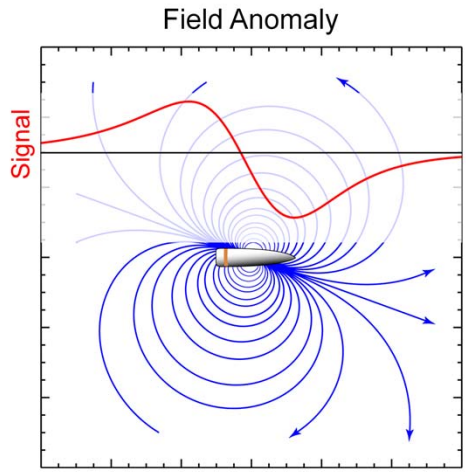
When we display magnetometer data, we subtract off the background geomagnetic or earth's magnetic field to emphasize field distortions or anomalies caused by munitions and other iron and steel objects. This picture shows the magnetic disturbance due to the munitions item with the earth's field subtracted off.

Magnetometer Signal

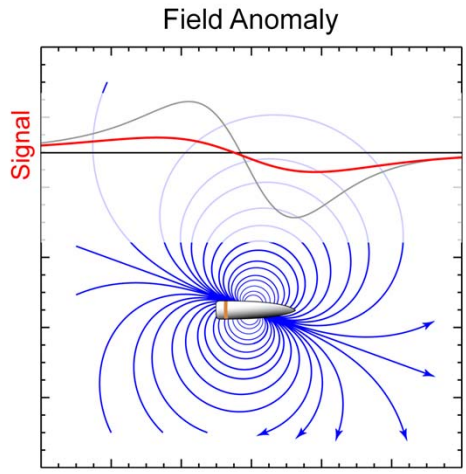
- **Magnetometers measure magnetic field strength**
  - **Proportional to density of field lines**



The magnetic field strength is proportional to the density of field lines - stronger when they are closer together, weaker when they are farther apart. The total magnetic field is weaker where the disturbance opposes the earth's field and spreads the field lines apart, and stronger where it reinforces the earth's field and draws the field lines together. When the earth's field is subtracted off, the signal is negative to the north of the object and positive to the south.

Magnetometer Signal (cont.)

- **Magnetometers measure magnetic field strength**
  - **Proportional to density of field lines**
  - **Decays as inverse cube of distance from target**



The strength of the magnetic signal falls off rapidly with increasing target depth. The magnetometer signal is inversely proportional to the third power of the distance between the object and the sensor.

Mapped Survey Data

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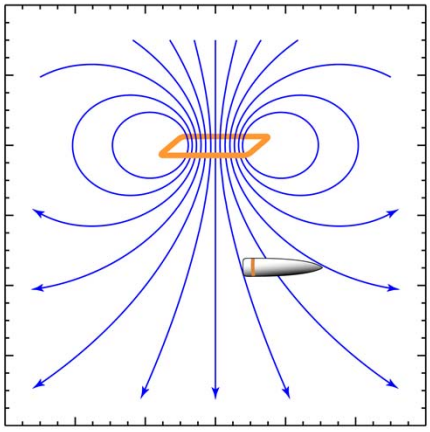
This video clip illustrates how magnetometer data is collected and displayed. The dotted lines show a perspective view of someone walking a magnetometer back and forth over a field, conducting a geophysical survey of the area. The red curves show the magnetic signal (background field subtracted) due to a munitions item in the ground. Note the positive and negative excursions to the south (near side) and the north (far side) of the object. Once the data have been collected, they are interpolated onto a regular grid of positions and mapped using a color scheme that highlights the size and shape of the magnetic anomaly.

Electromagnetic Induction

- **EMI sensors create their own field**

Primary Field



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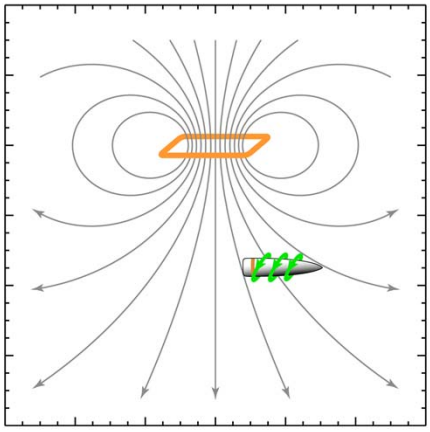
EMI sensors are sort of like magnetometers, but they create their own magnetic fields to excite targets in the ground rather than relying on the distortions of the earth's field. This is illustrated schematically by the diagram on the right. The orange rectangle represents the lower coil of the sensor. When a current is sent thru the coil, a magnetic field is set up. This is referred to as the primary field. The curved arrows show the primary field lines.

Electromagnetic Induction (cont.)

- **EMI sensors create their own field**
  - **Changes excite currents in the target**

Eddy Currents



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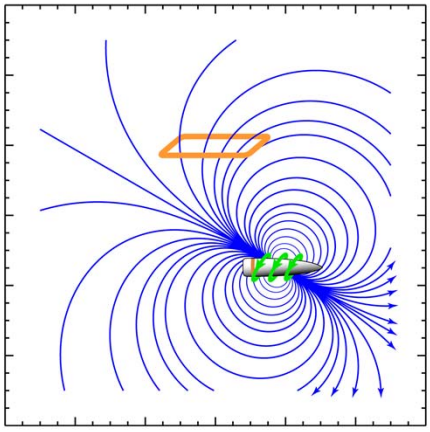
Current is supplied to the primary field coil as a series of pulses, and each primary field pulse produces electric currents in the target, represented by the green arrows encircling the UXO in the picture. These are called eddy currents. Because the earth's magnetic field is static, eddy currents are not involved in the magnetometer response.

Electromagnetic Induction (cont.)

- **EMI sensors create their own field**
  - Changes excite currents in the target
- **Sensor measures field induced by currents**
  - Less sensitive to magnetic soils
  - Also detects nonmagnetic metal objects (aluminum, etc.)

Induced Field



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The eddy currents induced in the target by changes in the primary field produce a secondary magnetic field which is measured by the sensor. The blue curved lines show the induced field. Note that the secondary field lines look similar to the field anomaly that was produced by the object in the earth's field. However, unlike the field distortion measured by magnetometers, an eddy current response occurs for all metal objects, including those made of non-magnetic metals like aluminum. The EMI sensor also tends to be less susceptible to effects associated with magnetic soils.

Evolution of the Geophysical Prove-Out (GPO)

- As these new detection technologies were introduced questions arose
  - What worked well in one place didn't always work at other sites
  - What worked for one team didn't always work for other teams
  - No comprehensive overview of what was being measured
- Site managers started to use GPOs
  - Select the sensor most appropriate for the site
  - Measure its performance under real world site conditions
    - Noise
    - Depth of detection
    - Fraction of emplaced items detected

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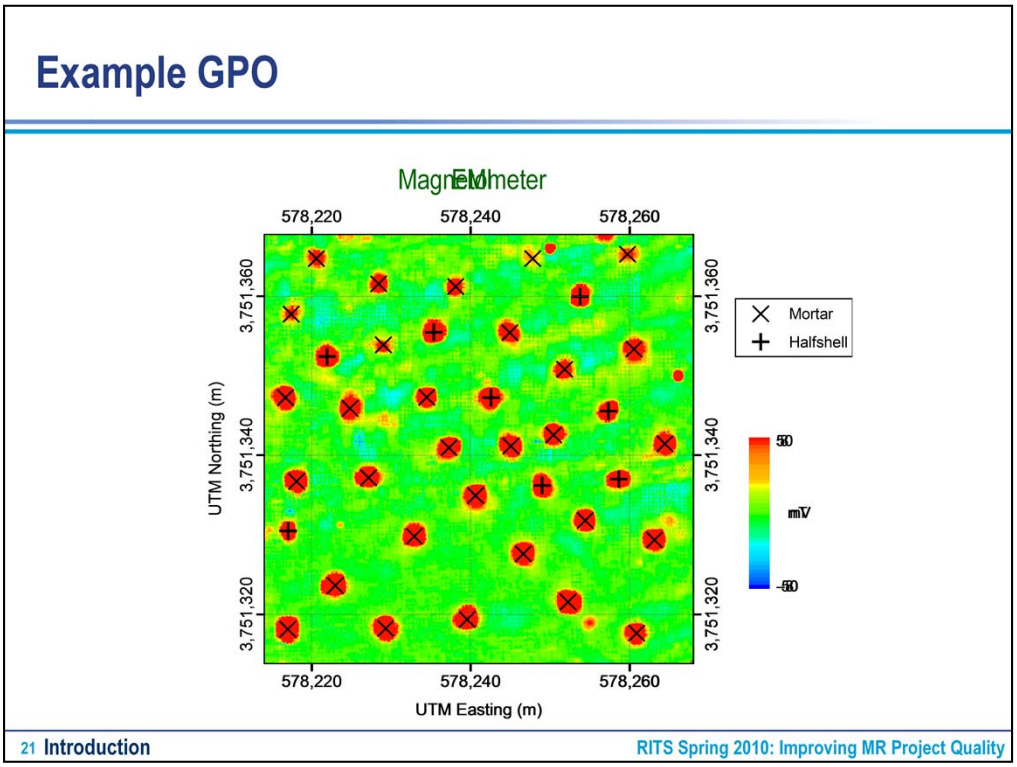
There were a number of problems at the early munitions sites. Sensors that worked at one site seemed to have problems at another. Different geophysical teams at the same site often got markedly different results with the same instruments. In response to this site managers started to use a Geophysical Prove-out, a small test plot that contained the items expected to be found on the site at the expected depths. This GPO was used to decide what geophysical instrument to use, measure detection performance, and qualify survey crews.



Munitions response projects began to use GPOs in an attempt to determine the capabilities and limitations of geophysical systems under controlled conditions near the work site. In a GPO, a known number of inert munitions, surrogates, and other objects are buried at precisely known locations and depths, and then the site is mapped with one or more geophysical instruments. The data are processed and targets selected based on some predetermined criteria, and the resulting geophysical map is used to display “anomalies” that represent potential munitions. Performance on the GPO is scored primarily based on the fraction of the emplaced targets that are associated with geophysical detections, often accompanied by many other secondary metrics. Over the years, the accumulation of empirical results from GPOs resulted in an understanding and documentation of sensor capabilities.

What Have We Learned in 15 Years?

- Experience base from scores of GPOs
  - Level of effectiveness of different geophysical sensors under differing site conditions
  - Optimum ways to employ these sensors
- Techniques have emerged from the research program to quantitatively predict the response of common sensors to targets of interest
  - Sensor response as a function of target depth and orientation is invariant
  - "Noise" level at the site determines detection ability

22 Introduction RITS Spring 2010: Improving MR Project Quality

The community has conducted scores of GPOs over the past fifteen years. This experience has taught site mangers and munitions contractors which sensors work best under different conditions and what survey methods work best. During this time the research community has made great strides in understanding the response of the commonly-used sensors and has developed tools to predict the response of these sensors to targets of interest. At this point, predicting the detection ability of a particular sensor only requires a measurement of the survey noise at a particular site.

Evolution of a New Approach

- 2007 UXO Forum paper by a number of authors questioning the continued value of GPOs
- LA District COE and CA DTSC discussed ways to use funding more efficiently – sought Industry input
- COE Huntsville begins to draft updated QC guidelines
- ESTCP convenes working group to formulate consensus approach

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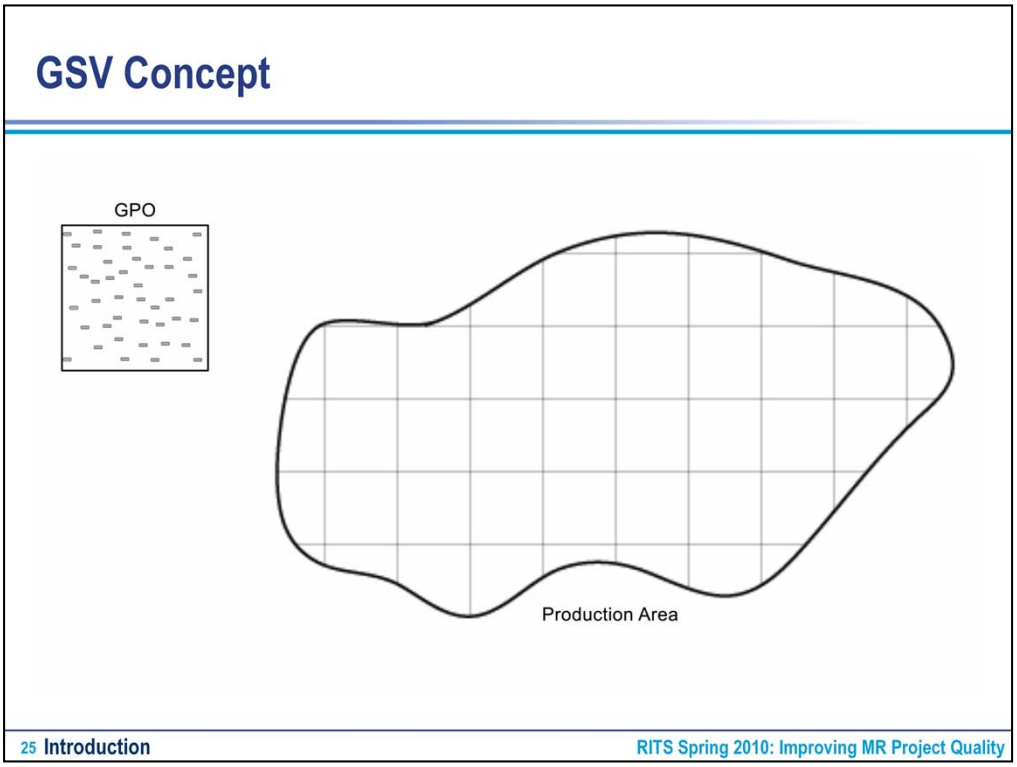
In the past three or four years a number of groups came to the realization that, although GPOs were a good idea originally, they have outlived their usefulness. Instead of devoting project resources to proving what we already know, it is a lot better to keep the minimum required functions of the GPO and move the rest of the resources to ongoing measurement of project quality. As this idea crystallized in the community, ESTCP convened a working group to develop a new approach.

Outcome of All This Activity

- We no longer need to perform a traditional GPO at every site
- But, we still need some of the functionality
  - Verify the sensor and team are functioning correctly
  - On-going monitoring of performance
- ***Bottom Line: Shift resources to better uses***
  - Less up-front confirmation of what we already know
  - More monitoring of production data quality

24 Introduction RITS Spring 2010: Improving MR Project Quality

This slide just summarizes what was discussed on the previous slide. We don't need to keep proving what we already know. It is far better to keep the essential parts of the GPO and shift the remaining resources to on-going monitoring of production data quality.



This slide shows a cartoon of the GSV concept. We move many of the items that were emplaced in a traditional GPO to the production site where they serve as on-going checks on the end-to-end process. We retain the few items necessary to check instrument function in a small area dubbed the Instrument Verification Strip.

Presentation Overview

- Introduction
- Concepts
  - Instrument Verification Strip
    - Verify that the Equipment is Working Properly
    - Measure Site Noise from which the Target Signal must be Extracted
  - Production Blind Seeding
    - Ongoing Monitoring of Production Geophysics
- Science Behind Geophysical System Verification (GSV)
- Application to an Example Site
- Summary and Conclusions

Similar to Chemical Sampling

- Develop an instrument calibration curve (or function)
  - Sensor Response Curve
- Method validation with a standard
  - Instrument Verification Strip (IVS)
- Periodic checks with a spiked sample
  - Production Blind Seeding

27 Concepts RITS Spring 2010: Improving MR Project Quality

In order to analyze for the presence of a particular contaminant, the analytical lab would undertake a number of steps. First, an instrument response function for the analyte of interest would be developed. Then, as the first samples came in, the lab would validate their methods suing a standard sample. Periodically during the course of the analysis, a spiked sample would be introduced as an additional check on the results. As you will see as we proceed, all of these actions have an analog in GSV.

The Instrument Verification Strip (IVS)

- Line of well-characterized targets and noise strip
  - Small and easy to construct
  - Convenient and representative location(s) on the site
  - Analogous to Standard Sample
- Data collection – as specified for production survey
  - Prior to production work
  - Twice daily
- IVS constructed, data collected and analyzed, and the results reviewed for consensus to proceed in a single day

28 Concepts RITS Spring 2010: Improving MR Project Quality

The IVS consists of a line of well characterized objects, preferably ISOs, buried in an area representative of the local site conditions. Data should be collected prior to beginning production work using the same protocols specified for the field data collection. The first day's IVS survey would verify that DQOs set prior to project initiation are met and that they are sufficient to meet project objectives.

Then, the IVS would be visited twice daily, at the start and finish of the field work, to verify proper sensor operation. Noise will be measured in a convenient adjacent area.

It should be possible to construct the IVS, collect and analyze the geophysical data, and review the results for consensus to proceed in a single day.

Production Blind Seeds

- One per day per crew
  - Cart ~ 1 per acre
  - Towed Array ~ 1 per 10 acres
- Sufficient frequency to be a useful QC tool
  - More in the grids to be done on the first couple days
- Recommend Industry Standard Objects (ISOs)
  - "Spiked samples"

29 Concepts RITS Spring 2010: Improving MR Project Quality

Blind seeds in the production area provide an on-going measure of process quality. On average, at least one seed should be encountered per day per crew. For a field crew using a cart-based EM-61, the daily production rate might be 1 acre. One seed per acre would be appropriate. For a towed array system, the production rate may be 5-10 acres per day. It may be advantageous to place a higher density of seeds in the lots to be surveyed in the first few days of production.

Presentation Overview

- Introduction
- Concepts
- Science Behind Geophysical System Verification (GSV)
  - Basis of GSV
  - Electromagnetic Sensors
    - Electromagnetic Induction (EMI) Fundamentals
    - Signal Response Curves
    - Industry Standard Objects
  - Summary
- Application to an Example Site
- Summary and Conclusions

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This module describes the science basis for Geophysical System Verification or GSV. The physics is important because it allows us to produce quantitative descriptions of how the sensors used in geophysical investigations will respond to targets of interest. That response does not vary from site to site or place to place within a site.

The module will focus on the EM61 but the whole GSV apparatus carries over directly to magnetic sensors.

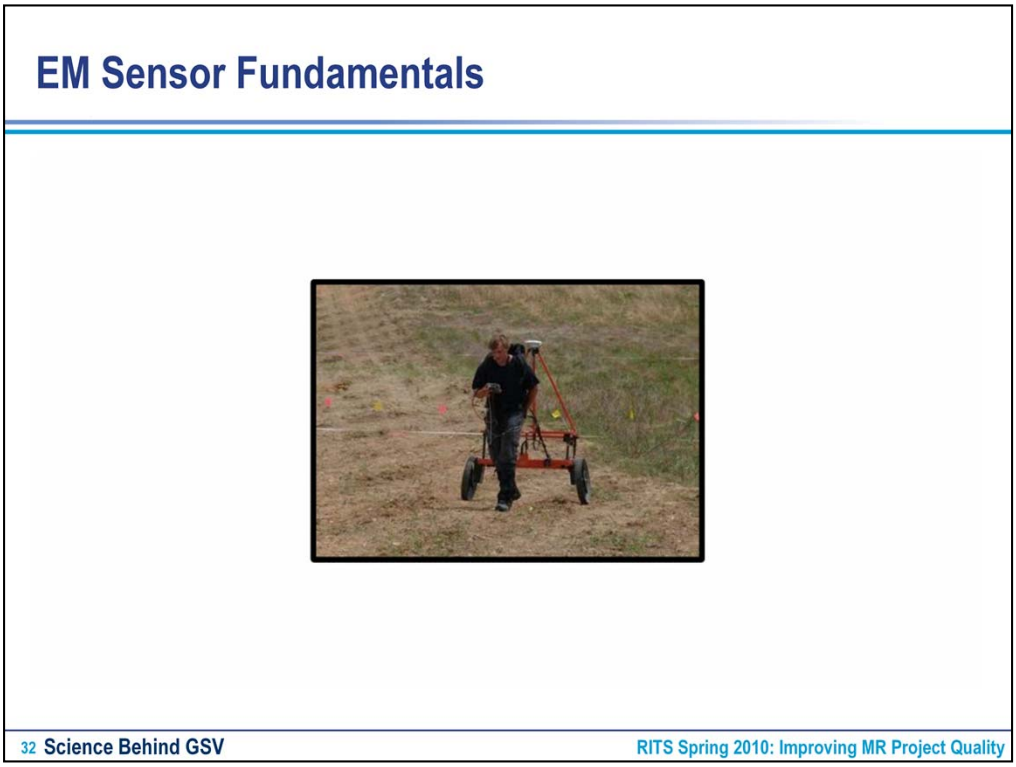
Requirements for Geophysical System Verification

- Well characterized sensor with predictable response
  - Standard total field magnetometer and EM61 metal detector
  - Emerging EM sensors to be documented
- Well characterized target
  - Common munitions
  - Standard munitions-like objects

31 Science Behind GSV RITS Spring 2010: Improving MR Project Quality

The underlying premise is that the basic physics of the sensor system is sufficiently well characterized and documented that we can calculate the expected response to munitions items and similar objects. This is the case for the commonly used total field magnetometers and EM61-MK2 sensors, and should also apply to new EMI sensor systems as long as their basic operating principles and parameters are transparent and well documented. Proprietary “black box” systems are not amenable to rigorous GSV procedures.

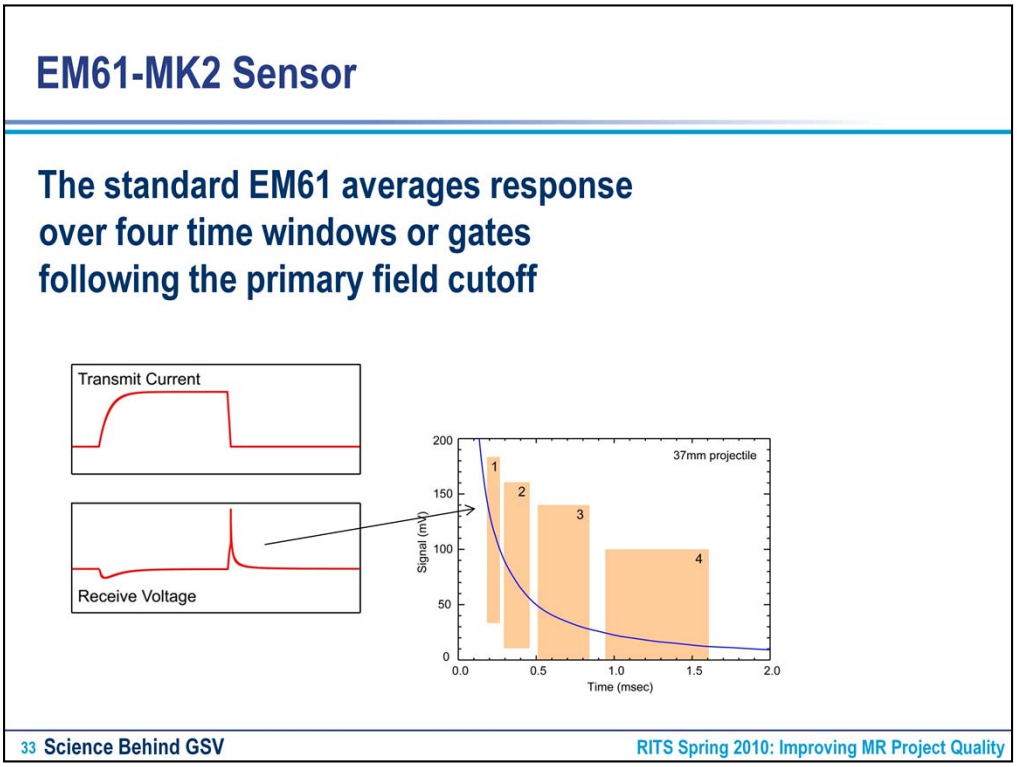
EM and magnetic signals are site invariant and any well characterized object may be used for GSV. Test objects may include the munitions of interest, but that’s not essential for confirming that the system is operating properly. We recommend using commonly available pipe sections, and propose a set of three different-sized stock items as Industry Standard Objects or ISOs. Together, the three sizes should meet the objectives of most munitions response projects in that the physics characteristics of one or more of the ISOs will be sufficiently similar to the targets of interest that they can be used to verify that the system is operating properly and can be expected to detect the targets of interest.



This video clip shows the fundamental concepts involved in EM measurements, starting with a picture of a typical EM sensor being pulled across a field.

The basic elements of an EM sensor are a transmit coil and a receive coil shown by the rectangular loops above the ground surface. A current pulse running through the transmit coil creates the primary EM field, illustrated by the arrows flowing along field lines shown in red. This pulse excites the munitions item under the sensor.

Changes in the primary field set up eddy currents in the object, shown schematically by the green arrows seeming to flow around the buried munitions item. - The eddy currents produce a secondary or induced EM field emanating from the object. This field can be represented by an induced dipole at the object's location. The strength and orientation of the dipole moment are determined by the primary field at the object and physical properties of the object such as its size and shape, as well as its orientation. - The induced field is measured by the receive coil, the output signal being proportional to the rate of change of the EM flux through the receive coil. - Using a sequence of current pulses to drive the primary field allows the eddy current response to be measured when the primary field is not around. Otherwise it would overwhelm the signal due to the induced field. The two plots show typical transmit and receive waveforms for a pulsed EM sensor and identify the three stages of the EM measurement process. (1) The object is magnetized only during the transmit pulse. (2) The eddy currents are excited in the target when the pulse abruptly ends. (3) The EM response is measured during the eddy current decay after the primary field pulse ends. This measured decay contains the information that is used to classify the target.



It is this last or eddy current decay stage which standard EMI sensors measure. The EM61-MK2, shown inset, samples the eddy current decay over four windows or time gates following the primary field cutoff. These time gates are shown by the shaded areas on the signal decay curve reproduced from the previous video clip. Measurements can be taken at a rate of 10 to 15 times per second, corresponding to a spacing along a survey line of about 10 cm at normal walking speeds.

EM Signal Calculations

- Dipole response model decomposes signal calculation into terms that depend only on
  - Sensor properties and sensor/target geometry
  - Target size, shape and composition

$$\underbrace{V(t)}_{\text{EM signal}} = \underbrace{\mu_0 n_R n_T I_0 \mathbf{C}_R \cdot \mathbf{C}_T}_{\text{Sensor/Geometry}} \underbrace{\mathbf{B}(t)}_{\text{Target}}$$

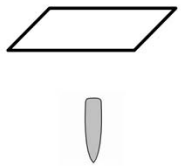
- Eigenvalues of target polarizability tensor B (response coefficients for three principal axes) are determined from controlled pit or test stand measurements

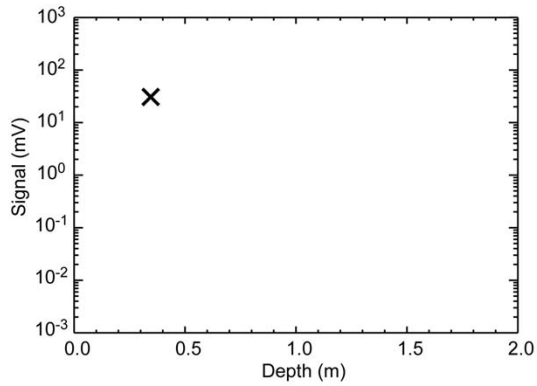
34 Science Behind GSV RITS Spring 2010: Improving MR Project Quality

We can use simple equations to represent the EMI response. When the distance between the sensor and the object is larger than the size of the object we use a far field dipole response model. This model splits the response into terms that depend on properties of the sensor and the sensor/target geometry and terms that depend on intrinsic properties of the target such as its size, shape and material composition. Mathematically, the effects of the intrinsic factors are represented by the eigenvalues of an electromagnetic polarizability matrix. These are called the object's response coefficients. The effect of the sensor and configuration dependent factors on the response is the same for all targets, while the contribution of the intrinsic factors depends only on what the target is, not where it is or how the sensor is being used. Once we have determined the response coefficients for an object (e.g. a 60mm mortar), we can easily calculate what the sensor response will be for any target depth, orientation, or location relative to a survey line.

Sensor Response Curves

- Target-specific signal vs. depth and orientation





- Measure response
- Strongest signal from vertical orientation

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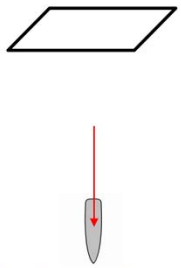
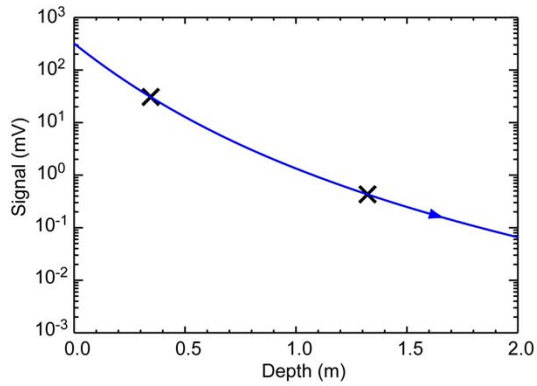
Sensor response curves show how the signal from some object varies with the depth and orientation of the object. This sequence shows how sensor response curves are created. We start out by measuring the target response at some depth and orientation. In this case, the target is oriented vertically, which creates the strongest signal and is most favorable for detection. The plot shows the measured signal at the corresponding depth. This measurement calibrates the equation for calculating how the response varies with target depth.

Sensor Response Curves (cont.)

- Target-specific signal vs. depth and orientation



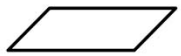
- Calculate signal vs. depth



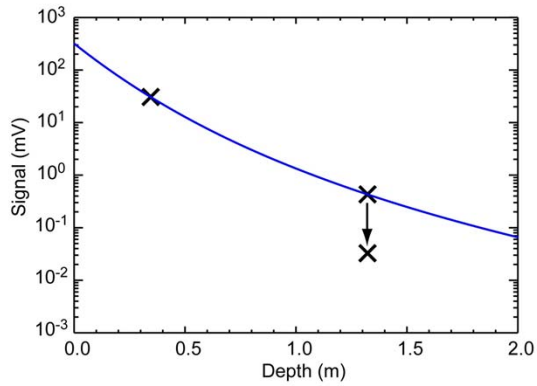
We then calculate how the response varies with depth using simple physics-based equation.

Sensor Response Curves (cont.)

- Target-specific signal vs. depth and orientation



- Weakest signal for horizontal orientation



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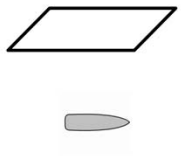
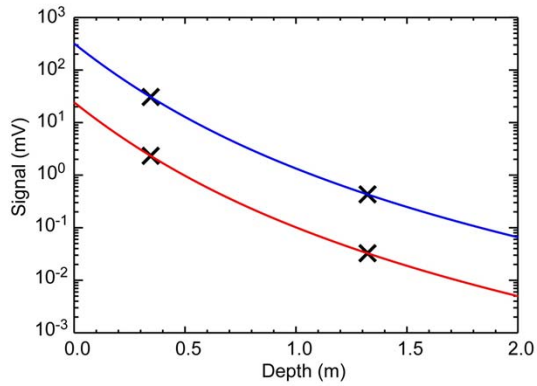
If the target is oriented horizontally, the signal is weaker. This is the least favorable orientation for detection. We measure this response to calibrate the equation for horizontal orientation.

Sensor Response Curves (cont.)

- Target-specific signal vs. depth and orientation



- Calculated signal vs. depth curve



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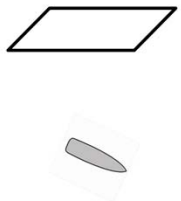
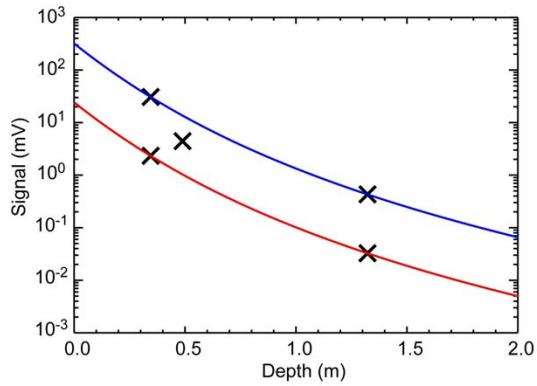
The variation of the minimum signal vs. depth is calculated using the same equations.

Sensor Response Curves (cont.)

- Target-specific signal vs. depth and orientation



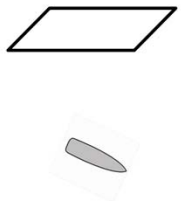


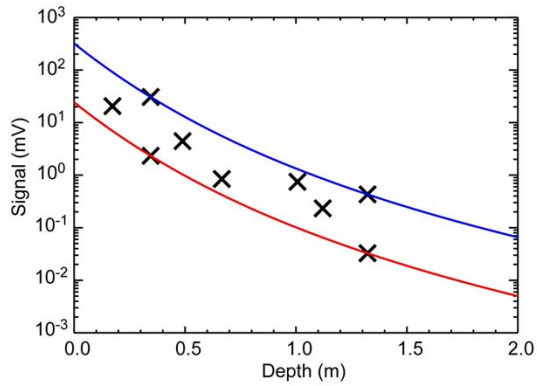
- Signals for targets at other orientation fall between curves

The response for some intermediate orientation will fall between the two curves.

Sensor Response Curves (cont.)

- Target-specific signal vs. depth and orientation

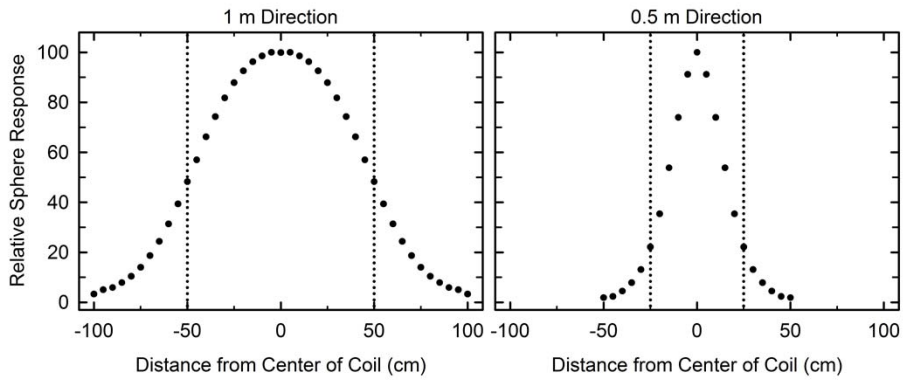




- Signals for targets at other orientation fall between curves

Signals for targets at any other combinations of depth and orientation will be bounded by the least favorable and most favorable response curves.

Variation of Response Across the Coil



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Response curves normally correspond to the case where the target is directly under the center of the sensor. The signal can vary quite a bit depending on exactly where the target is in relationship to the center of the coil.

Measured Response

- **Measured signal includes response to target plus noise**
  - **Limits detection performance**

$$\underbrace{S}_{\text{Measured Response}} = \underbrace{\mu_0 n_R n_T I_0 \mathbf{C}_R \cdot \mathbf{C}_T \mathbf{B}}_{\text{Signal from Target}} + \underbrace{N}_{\text{Noise}}$$

- **Noise levels can vary from place to place on the site due to variations in contributions from power lines, bouncing over uneven ground, geology, etc.**

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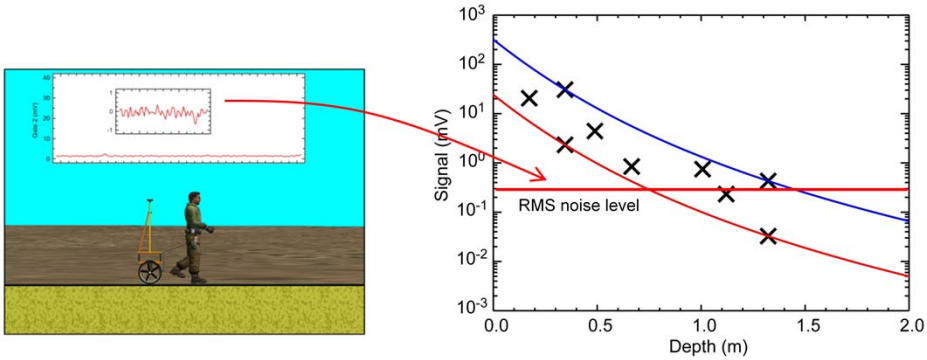
The response that is actually measured contains signal from the target plus noise. Any fluctuations in the sensor output that are not due to the target represent noise that ultimately limits the performance of the geophysical system. Noise arises from a variety of sources, including the sensor electronics, improper or careless operation of the sensor, bouncing and jolting over uneven ground, nearby power lines, geology, etc. Some of these factors can vary from place to place over the site and cause significant variations in the noise level.

Sensor Response Curve

- **Noise in sensor output limits detectability of deeper targets**



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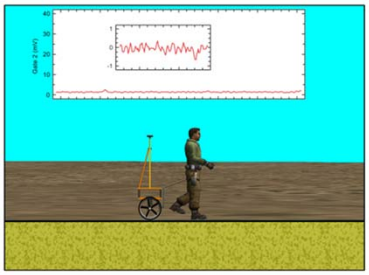
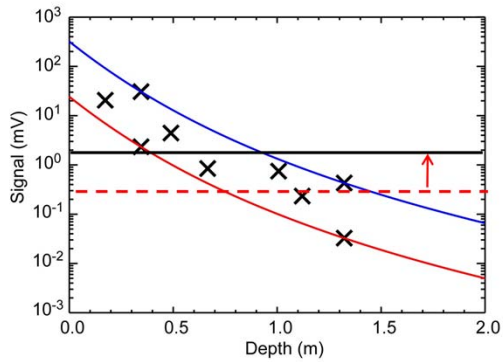
In this slide we add a line to the response curves showing the survey noise level. Whether or not a given object will be detected depends not only on how strong a signal it creates, but also on the level of noise in the measurements. Reliable detection requires a peak signal that is 5-6 times the RMS noise level. In this example, targets with signal levels that drop much below a millivolt will likely be obscured by the noise.

Sensor Response Curve (cont.)

- **Noise in sensor output limits detectability of deeper targets**
  - **Signal levels 5-6 times the RMS noise level are needed for reliable detection**





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Sensor Response Curve (cont.)

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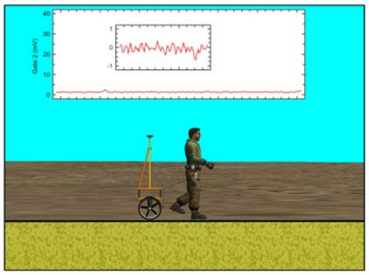

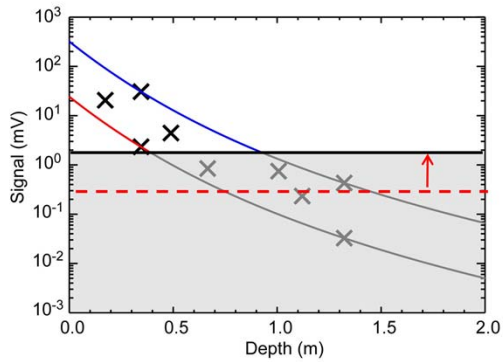

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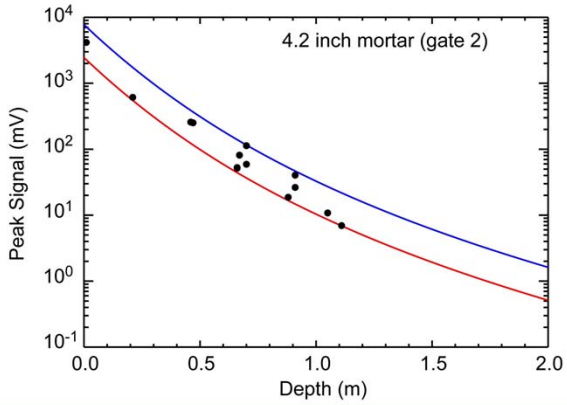
Response Curve Scaling

- **Response curves for different munitions items all have the same shape but are scaled by the specific item's response coefficients β_L and β_T**



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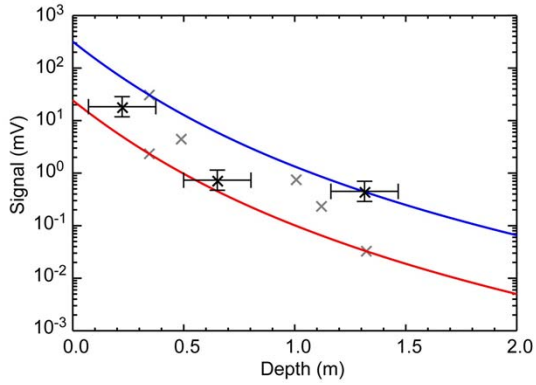
The response curves for different munitions items have the same shape but are scaled by the specific item's response coefficients. In this sequence, we start off with the response curves for a 60mm mortar. The dots show EM61 measurements at various depths and orientations. The lines show the response curves - red for the horizontal orientation (least favorable for detection) and blue for vertical (most favorable for detection). --click-- Next we include measured signals for a 4.2 inch mortar (the new set of dots) --click--click-- The curves simply shift up to match the new object's response.

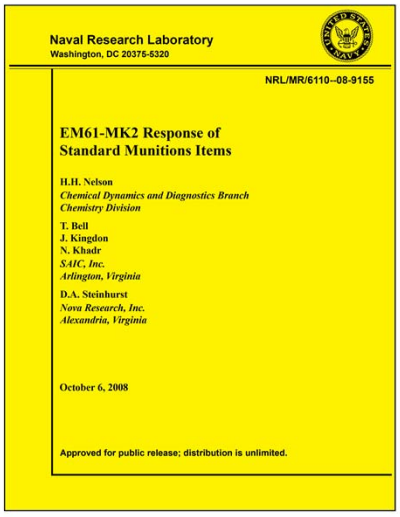
Response Curve Error Bars



- **Measurement uncertainty is captured by error bars on measured response values plotted on response curves**

When we compare field measurements with calculated response curves we have to take account of measurement uncertainty that can arise if the target is not directly under the sensor or is not at the nominally specified distance below the sensor or is not at quite the right orientation. This can be captured by including error bars on the measured response values.

Common Munitions Items



Naval Research Laboratory
Washington, DC 20375-5320

NRL/MR/6110--08-9155

EM61-MK2 Response of Standard Munitions Items

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Arlington, Virginia

D.A. Steinhurst
Nova Research, Inc.
Alexandria, Virginia

October 6, 2008

Approved for public release; distribution is unlimited.

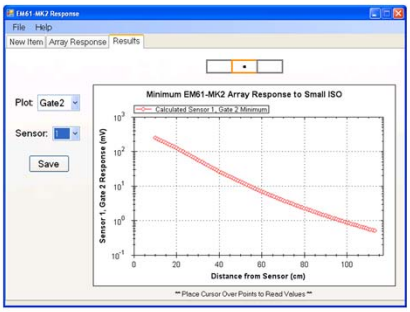
- Response curves for common munitions items published in NRL Report NRL/MR/6110-08-9155
  - 37mm projectile
  - 60mm mortar
  - 75mm projectile
  - 81mm mortar
  - 4.2" mortar
  - 105mm projectile
  - 105mm HEAT
  - 155mm projectile
  - 3" Stokes Mortar
  - 2.36" Rocket
  - 2.75" Rocket
  - MK2 Hand Grenade
  - M9 Rifle Grenade

Response curves for 13 common munitions items have been compiled by the Naval Research Laboratory and are available in a report which includes Excel spreadsheets for the curves in electronic form.

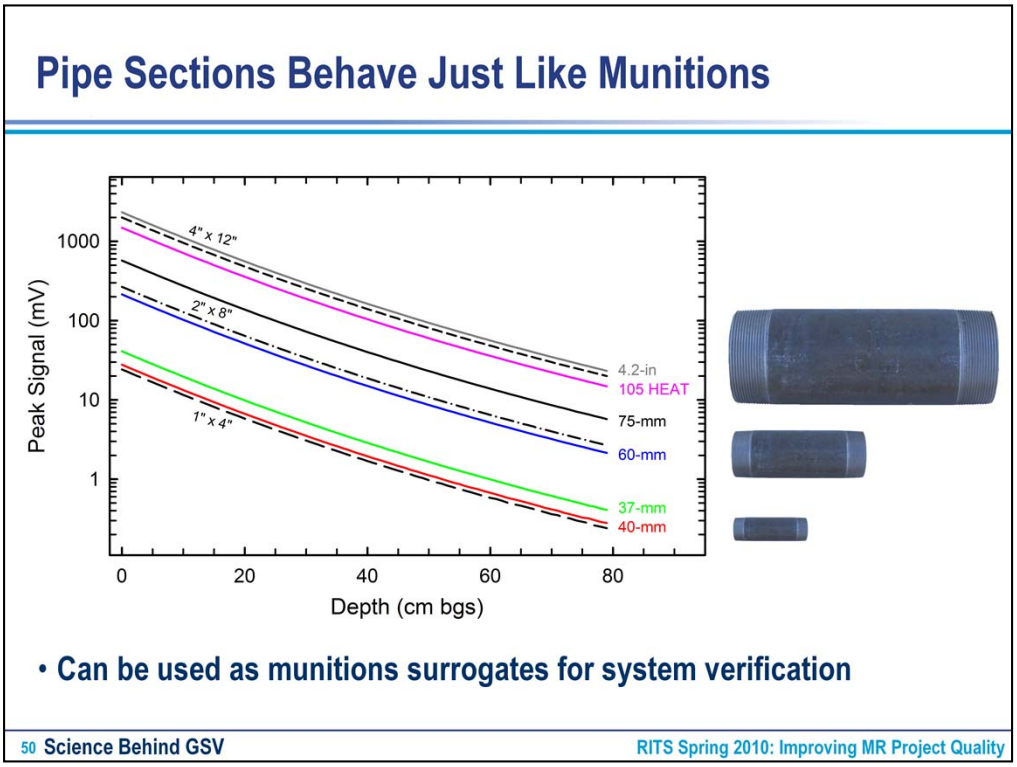
Response Curve Calculator

- EM61 array response curves for common munitions
- Single sensor response curves for new munitions items
  - Requires controlled measurements at several depths for scaling
- Distributed with GSV Report

Response Curve

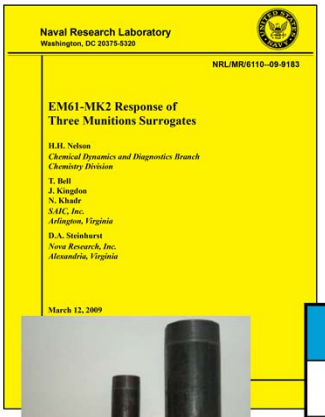


A simple stand-alone computer program for calculating response curves for arrays of EM61 sensors for those common munitions items is included with the Geophysical System Verification documentation. The tool can also be used to calculate single-sensor EM61 response curves for other munitions items. For new single-sensor response curves, the program needs to be supplied with controlled pit or test stand measurements of the response at several sensor-to-target ranges.



You don't need to measure the responses from munitions items to verify geophysical sensor performance. Using this physics-based approach, pretty much anything will do. The shape of the signal vs. depth response curve is the same for all objects. The signal level at any particular depth depends on the size, the shape, the composition (e.g. steel vs. aluminum) and the orientation of the object. Simple munitions-like objects (e.g. steel pipe sections) have response curves that are just like those of munitions items. They can be used instead of munitions items for purposes of geophysical system verification. The plot compares response curves (least favorable orientation) for various munitions items with the response curves for pipe sections for different sizes.

Pipe Sections as Munitions Surrogates


Naval Research Laboratory
Washington, DC 20375-5320

NRL/MR/6110--09-9183

EM61-MK2 Response of
Three Munitions Surrogates

H.H. Nelson
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Alexandria, Virginia

March 12, 2009

- **Readily available, similar in size and shape to common munitions items**
- **Documented response curves**
- **Repeatable, consistent EM signals for calibration and performance validation**

Item	Nominal Pipe Size	Outside Diameter	Length	Part Number[1]	ASTM Specification
Small ISO	1"	1.315" (33 mm)	4" (102 mm)	44615K466	A53/A773
Medium ISO	2"	2.375" (60 mm)	8" (204 mm)	44615K529	A53/A773
Large ISO	4"	4.500" (115 mm)	12" (306 mm)	44615K137	A53/A773

1. Part number from the McMaster-Carr catalog

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We recommend surrogate test items that are readily available, inexpensive, and similar in size and shape to common munitions items, and have identified a set of Industry Standard Objects (ISOs) with documented response curves which can be used to provide repeatable, consistent EM signals for sensor calibration and performance validation. The ISOs are shown in the inset picture. They are standard size sections of steel pipe as described in the table. The small ISO is roughly the size of a 37mm projectile, the medium sized one is comparable to a 60mm mortar, and the large ISO is comparable to a larger munitions item like a 105mm projectile or a 4.2 inch mortar. They will produce signals that are similar to those of the corresponding munitions items. The ISO response curves have been compiled in a report published by the Naval Research Laboratory.

Summary

- Modern geophysical sensors (mag and EM) produce repeatable, site invariant signals which can be accurately modeled using basic electromagnetic theory
- Signal strength vs. depth response curves can be constructed for any munitions item of interest
  - Combined with knowledge of on-site noise levels, response curves can be used to set anomaly selection criteria or evaluate expected performance
- Responses from simple industry standard objects (ISOs) can be used as surrogates for munitions items for instrument calibration and performance verification

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In summary, modern geophysical sensors (magnetometers and EMI sensors) produce repeatable, calibrated signals which can be accurately modeled using basic electromagnetic theory. Consequently, signal strength vs. depth response curves can be constructed for any munitions item of interest. Combined with measurements of the on-site noise levels, the response curves can be used to set anomaly selection criteria or evaluate expected performance. Because the responses of different targets scale in a well-defined, calculable way, the responses from simple standardized objects (ISOs) can be used as surrogates for munitions items for purposes of instrument calibration and performance verification.

Presentation Overview

- Introduction
- Concepts
- Science Behind Geophysical System Verification (GSV)
- Application to an Example Site
- Summary and Conclusions

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This section of the presentation will describe the application of the GSV process to an example site. The DQOs and procedures followed were agreed to by the project team. Some, or all, of them may not be appropriate for your site. If so, modify them to fit your needs.

Example Site

- 100-hectare (250-acre) site
  - Part of a former bombing and gunnery range
  - Slated for residential development
- A variety of munitions were used on the site
  - Primary concern is 37-mm projectiles
- EM61-MK2 chosen as the geophysical sensor
  - Targets of interest are relatively small
  - Not expected to be more than one foot deep
  - Survey lane spacing of 0.6 m
- Open field with good sky view throughout
  - GPS system is the choice for sensor location

54 Application to an Example Site RITS Spring 2010: Improving MR Project Quality

The example site to be considered is a 100-hectare (250-acre) site that is part of a former bombing and gunnery range. After remediation, the site is slated for residential development. The historical records indicate a variety of munitions were used on the site but the primary concern is 37-mm projectiles. Since the targets of interest are relatively small and are not expected to be more than one foot deep, the site team has chosen the EM61-MK2 as the geophysical survey instrument to be used at this site with a survey lane spacing of 0.6 m. The site is an open field with good sky view throughout so a GPS system is the choice for sensor location.

Quantitative Project Data Objectives

Parameter	Objective at this Site
Geophysical Instrument	EM61-MK2 on standard wheels
Geolocation System	RTK GPS (cm-level)
Survey Lane Spacing	60 cm
Gate for Primary Data Analysis	Gate 2
IVS Anomaly Amplitude Reproducibility	± 20%
IVS Item Position Reproducibility	± 25 cm
Location Accuracy of Seed Picks	± 50 cm

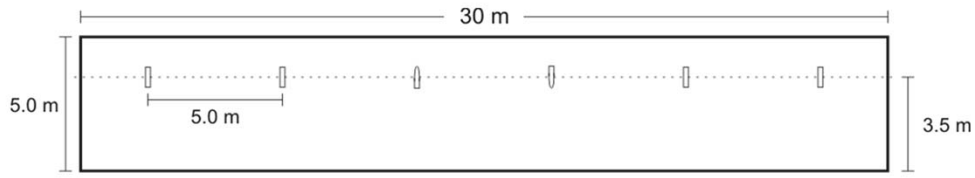
This table summarizes the decisions made by the site team. Notice that position reproducibility specification is tighter for the IVS items than for the seeds. The survey team should be able to center the sensor directly over the line of IVS items so the position reproducibility should be high.

Establishing the IVS

- Choose an area on the site that contains representative terrain, geology, and vegetation
- Make sure the area chosen is free of anomalies
- Bury the IVS items, recording the location and depth to a precision of ± 2cm

The expected time line for the first use of the strip involves the geophysical contractor arriving on the site the first day of operations, identifying a location for the test strip in conjunction with the program manager, conducting a background survey to identify a site suitable for a test strip, and emplacing the test items according to the specification in the previous slide. If the test strip location is not very cluttered, this may still leave time for an initial survey on the first day at the site; if not, the test strip can be surveyed at the beginning of the second day on site.

Instrument Verification Strip



Item	ID	Position (m)	Depth to Center	Predicted Response
1	Small ISO	2.5	11 cm (3X)	11.6 mV
2	Small ISO	7.5	26 cm (7X)	4.8 mV
3	37-mm Proj.	12.5	11 cm	18.3 mV
4	37-mm Proj.	17.5	26 cm	6.7 mV
5	Small ISO	22.5	11 cm	11.6 mV
6	Small ISO	27.5	26 cm	4.8 mV

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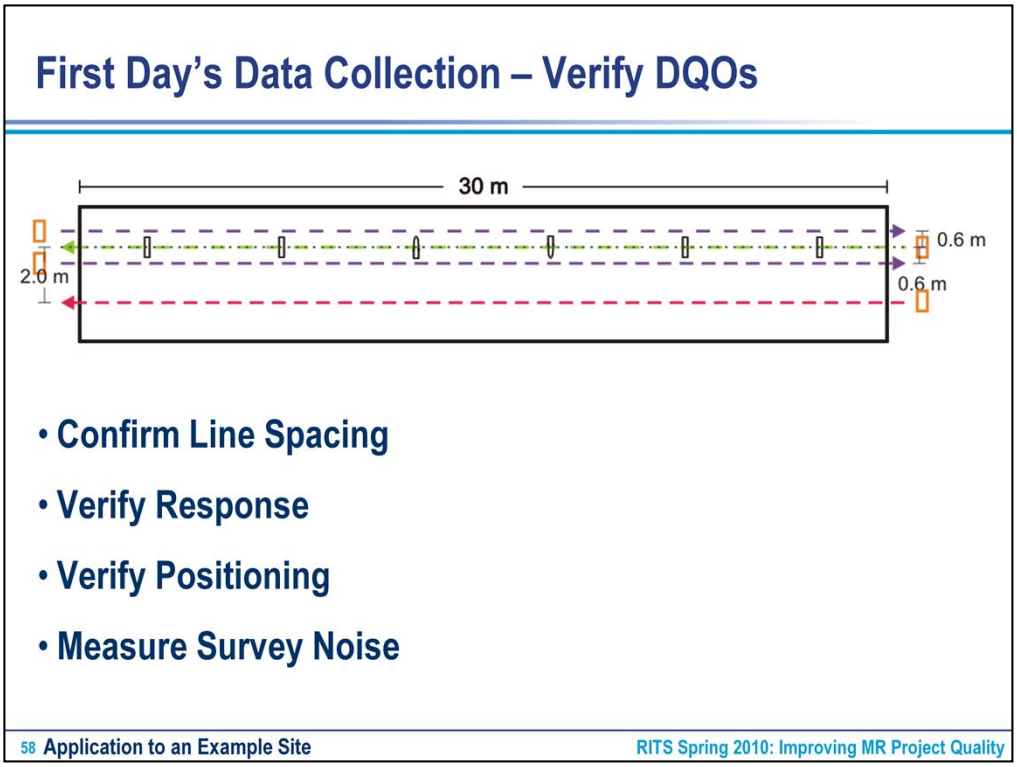
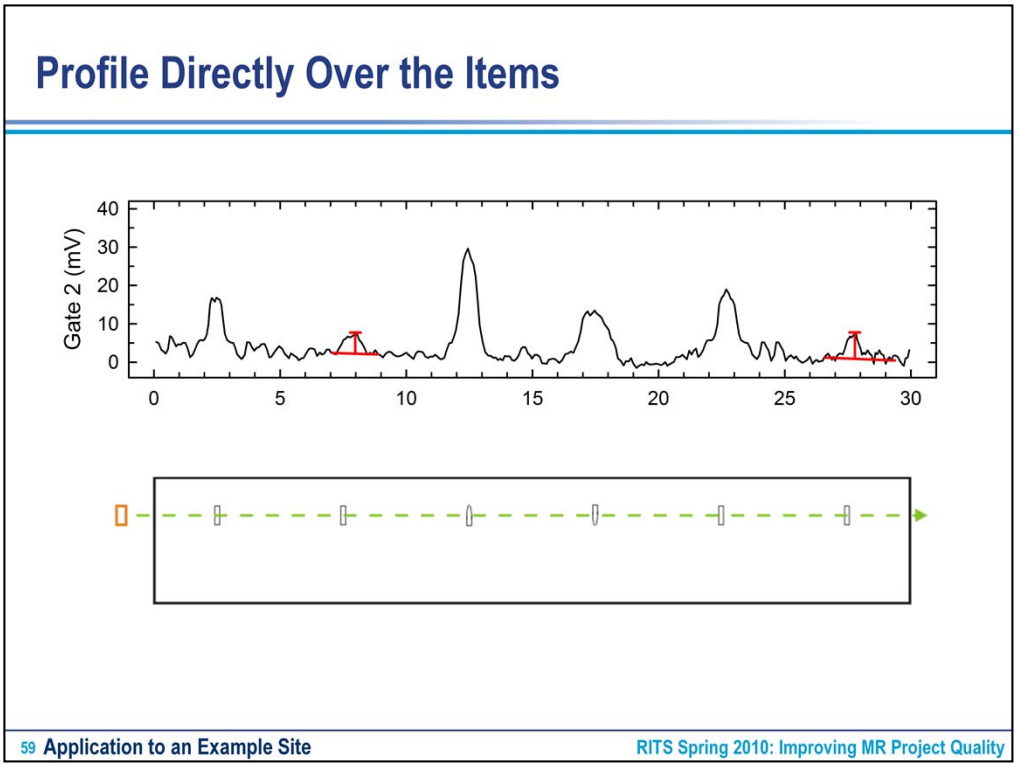
The first task in planning the instrument verification strip is to decide what items will be emplaced. The site team at this site decided that since the smallest, most difficult to detect, item of interest is a 37-mm projectile, the test strip would contain two inert 37-mm projectiles and four small Industry Standard Objects (ISOs) to serve as surrogates during the seed program. They will be placed in the IVS at two depths (3X and 7X their diameter) oriented across track for simplicity. Note that the deepest depth chosen is close to the maximum depth of interest at this site but that was not the reason for the choice. The goal of the IVS is to verify twice each day that the geophysical system is working correctly. To accomplish that with reasonable precision requires a high SNR on the sensor measurements. The two depths were chosen to ensure the required SNR is achieved.

The items to be emplaced are relatively small so the spatial extent of their signatures will not be large but an ancillary purpose of the test strip is to get a measure of site-specific survey noise. With this in mind, the site team decided to emplace the test strip items with spacing of 5 meters, leaving 2.5 meters clear on each end of the strip. This results in a test strip approximately 100 feet long.



The protocol for the first day's survey of the IVS. The first pass of the 1-m wide by ½ m EM61-MK2 is made with the sensor 0.6 m offset from the test item burial line. The site team has determined a line spacing of 0.6 m is appropriate to ensure detection of the 37-mm projectiles. The next pass is directly over the test items. This will allow the data analyst to determine the maximum signal expected from each item. The third pass is at an offset of 0.6 meter on the other side of the line of items. The final pass is two meters offset from the line of targets to make a measurement of survey noise at this location.

These four passes will allow us to verify the DQOs and ensure that our assumptions about detectabilty of the targets of interest were correct. We'll step through this on the following slides.



A trace of the measured data from the line directly over the targets. As in all cases in this example, these are actual field data measured over an IVS constructed as specified above.

Each of the items is detected with good SNR and the teams' choice of 5 m spacing between the items is confirmed; each anomaly returns to the baseline and there is a good section to measure noise between the anomalies. We can measure the anomaly amplitudes and compare them to our expectations. Targets 2 and 6 should have the same amplitude and we see here that they do.

May Consider Static Measurement for Absolute Response

- Simple wood jig on EM61 coil
  - Distance from coil is fixed
- First, measure sensor offset
- Then, measure item response

Some teams have had difficulty recovering the exact predicted anomaly amplitude from items in the IVS. This arises when the burial depth and angle weren't well controlled.

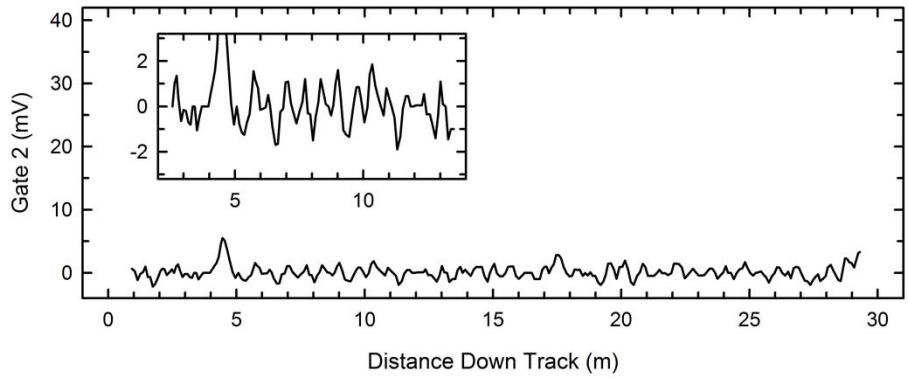
To guard against this, the site team at this site chose to perform a quick static test to confirm that the expected responses were obtained.

A simple wooden jig was fabricated to sit reproducibly on the EM61. A background is collected with no target and then a response with the target placed in a notch on the jig.

In this method, the distance of the target from the coil and the target orientation are precisely controlled and the predicted response should be obtained.

The IVS targets are still used to check reproducibility of response from day to day.

Profile From the Noise Measurement



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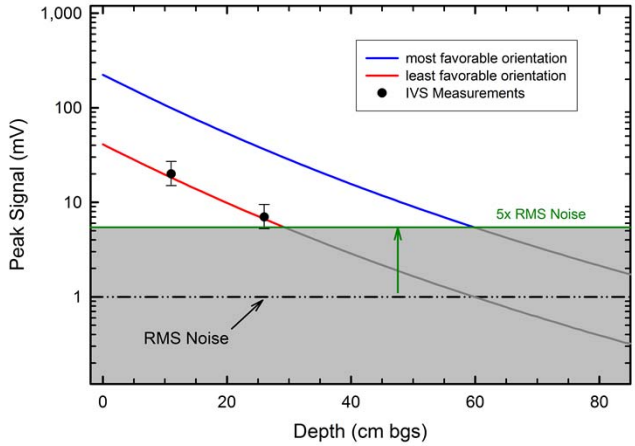
A trace of the measured data from the “noise” line plotted on the same scale as the signal trace with an inset at a higher magnification. There may be a small scrap item remaining about 4.5 m down the line but, otherwise, the contractor team has done a good job identifying a target-free area for the noise measurements. The RMS survey noise in this area 1.0 mV or about 5 mV peak-to-peak.

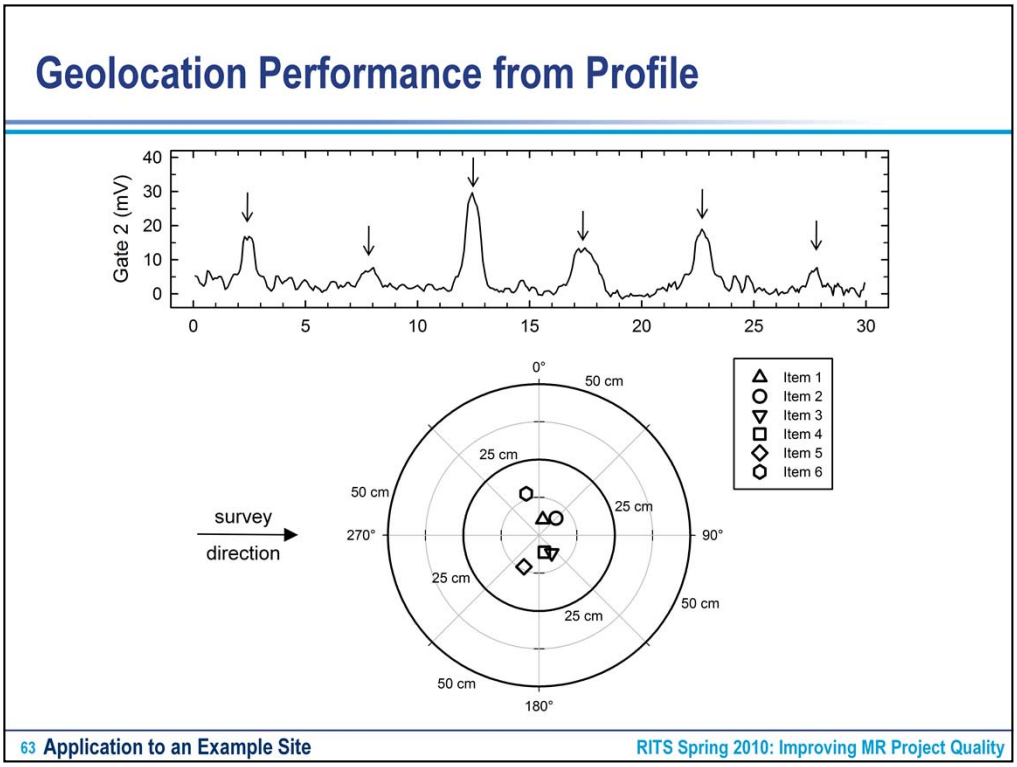
Can We Detect the Targets of Interest?



Detection at this site determined by site noise

The measured anomaly amplitude in Gate 2 for the two 37-mm projectiles and the RMS noise are compared to the predicted response. The blue curve corresponds to the signal expected when the item is in its most favorable (vertical) orientation and the red curve corresponds to expected signal when the item is in its least favorable (horizontal) orientation. The error bars on the measured points correspond to twice the RMS noise (vertical). Both of the 37-mm projectiles in the IVS are oriented horizontally so their signals should be close to the red curve if the sensor is operating normally, which it is in this case.

From the site noise data, the site team can confirm that the detection requirements for this item at this site can be met. The depth of interest for the 37-mm is 1 foot or ~30 cm. The minimum signal in gate 2 expected from a 37-mm projectile at this depth is a little over 5 mV. The measured survey noise in this gate at this site is 1.0 mV resulting in a minimum signal-to-noise ratio of almost 5 which is just above the requirements for reliable detection.



The second objective to be checked from the first day's data is the performance of the sensor geolocation system. One method to accomplish this is to find the position of the peak signal for each object and compare this to the known locations of the targets. Since the GPS system used at this site measures the position of the center of the EM61 coil, this cross-track location accuracy is limited by how carefully the senor operator positions the center of the coil directly over the line of items in the IVS. In this case the operator was very careful, resulting in the measured position deviations shown here in a polar plot. The IVS at this site is laid out E-W so, as expected, the greatest deviations are in the cross-track (N-S) direction. Had any of the deviations been larger than the objective of 25 cm, corrective action would have been required before consensus to proceed was achieved.

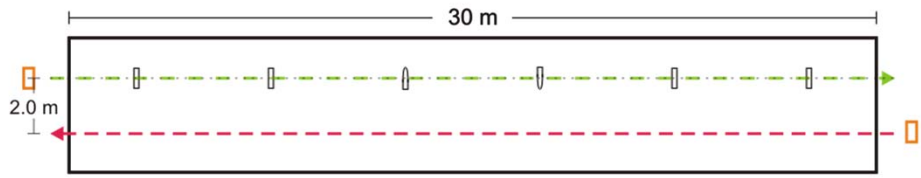
Results of First Day's IVS Survey

- Data collected on the IVS
  - Confirm sensor selection
  - Demonstrate the geophysical sensor and geolocation equipment are operating correctly
  - Establish detection ability at this site
- All site team members agree so *consensus is achieved* to proceed to production work

The IVS provides a simple, but rigorous, verification that the geophysical mapping system (sensor plus geolocation equipment) is operating properly. From the data collected on the first day, the site team is able to agree that the correct sensor has been chosen, that the targets of interest are detectable to the depth of interest in the presence of the measured survey noise, and that the data are being collected correctly.

Given these results, achieving consensus to proceed is straightforward.

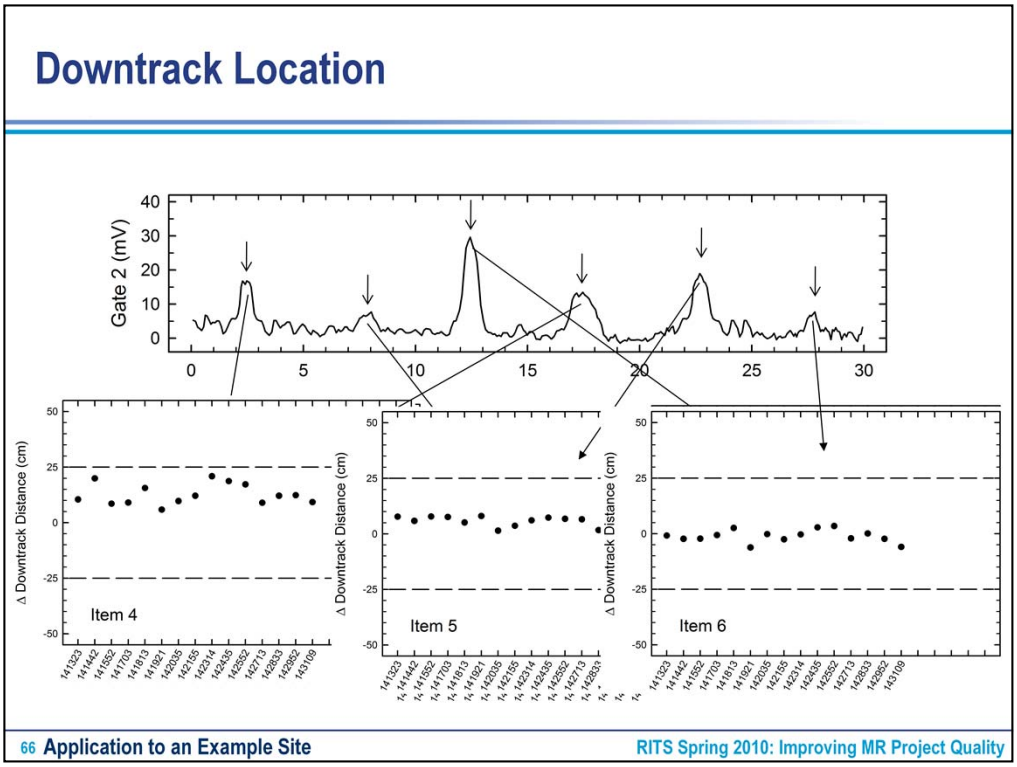
Twice Daily Data Collection



- Verify sensor response and geolocation performance
- Confirm survey noise

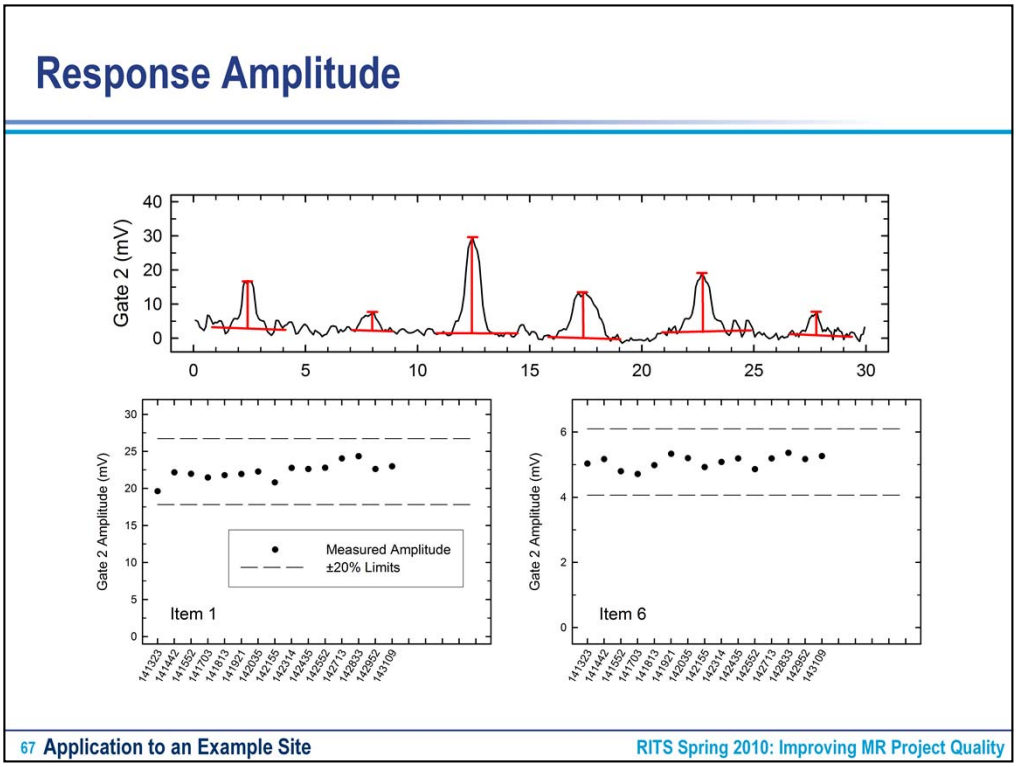
In addition to whatever function tests the contractor performs each day to ensure proper operation of their survey equipment, each survey crew will be required to survey the test strip at the beginning and end of each day. This will be a simplified survey as illustrated here, one pass over the line of emplaced targets to confirm sensor operation and one pass to confirm that the survey noise has not changed. If the sensor performance and system noise are within specifications before and after each day of surveying, it is reasonable to expect that the system was performing within acceptable bounds throughout the day. If the sensor performance is within performance criteria in the morning and not in the evening, the data must be examined to determine if any of it is usable.

The results of these twice-daily performance confirmation surveys will be reported in a continually-updated set of plots showing the down-track position error and amplitude variation for each target. As with the first day's measurements, any deviations outside of the data objectives will require a detailed failure analysis before survey operations can be resumed.



Plots of the down-track location of the measured anomalies corresponding to the IVS items. The points correspond to the locations determined each morning and evening and the dashed clines correspond to the ± 25 cm specification for this measurement.

Notice in that the measured down-track position of Item 4 appears to have an offset from the known value. This may well be the result of an emplacement error.



Twice daily variation in the measured anomaly amplitude for two of the IVS items. Similar plots corresponding to all six items are updated daily. The points correspond to the measured anomaly amplitudes and the dashed lines represent ± 20% of the mean for each item.

Production Blind Seeding

- The site team has hired a third party to design and implement a blind seed program in the production survey areas
- Only one component of QC plan for the site
  - Verifies geolocation, sensor performance, anomaly selection, and anomaly resolution on an on-going basis
- Based on the small ISO
  - Surrogate for 37-mm projectile

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The production blind seeds can be managed by the Government, the contractor's QC team or a third party. The only requirement is that they remain blind to the data collection and analysis crew and the UXO specialists that remove the items.

At this site, this is being handled by an independent third party.

All have agreed on the small ISO as the seed item.

Seed Plan

- Site has been divided into 50 m x 50 m grids
  - 400 grids
- Seeds will be emplaced in all the grids
  - ⅓ at 10 cm
  - ⅓ at 20 cm
  - ⅓ at 30 cm
  - Random orientations
- Three seeds in the first grid to be surveyed by each team

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The site has been divided into 50 m x 50 m grids. Under the conditions at this site, each survey team covers one grid per day. The site team has determined that to adequately measure the performance of each team, they will require a seed in each of the grids in addition to any seeding the contractor employs for their own quality program. This means ~400 seeds items will be required. One third of the seeds will be placed at 10 cm, one third at 20 cm, and one third at our depth of interest, 30 cm, in random orientations with all measurements corresponding to the center of the item. In addition to this, three seeds will be placed in the first grid surveyed by each of our three survey crews.

Evaluation of Performance

- Data from each grid and anomalies selected transmitted to consulting geophysicist
  - Were the seeds selected as a target?
  - Are the signal strengths and target locations within limits?
- If the seed is not on the target list
  - Why? – Instigate Root Cause Analysis
- After dig check
  - If the correct item is recovered

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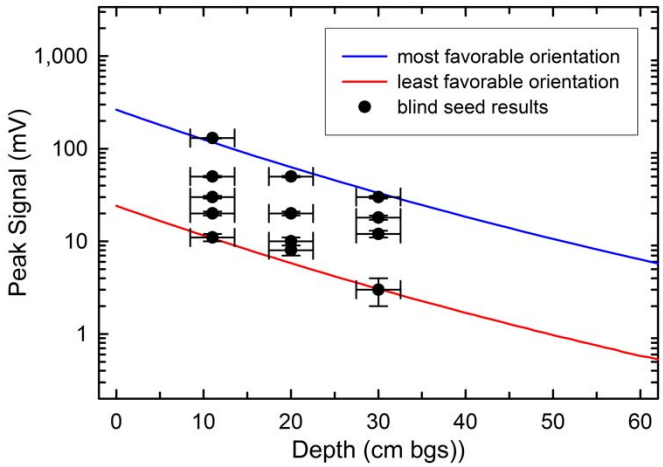
As the data from each grid are analyzed and targets selected, this information will be transmitted to the consulting geophysicist. For each grid that contains a seed, she will determine whether the seed(s) made it to the target list. If it did, she will ensure the signal strength and location accuracy are within contract specifications and, after the anomaly has been dug, make sure that the correct item is recovered. If the seed is not on the target list, she will begin a root cause analysis. Questions to be asked include: is there a geophysical signal at the seed location that should have been picked?; is there an anomaly but is it below the selection threshold?; is there an anomaly remaining that was below a more shallow anomaly?; and is there a sensor location issue?

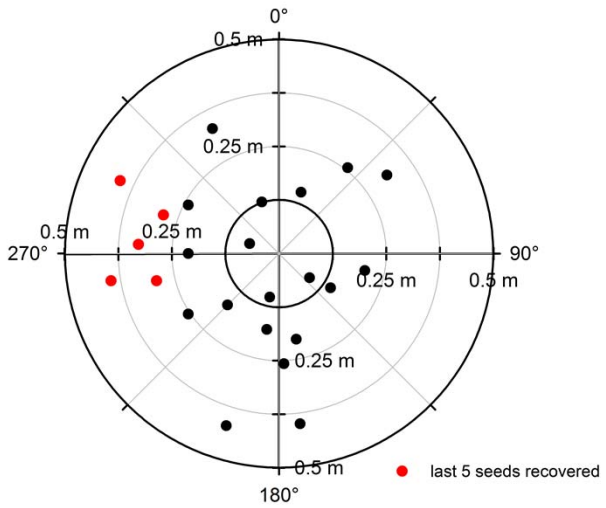
Evaluation of Performance – Anomaly Amplitude



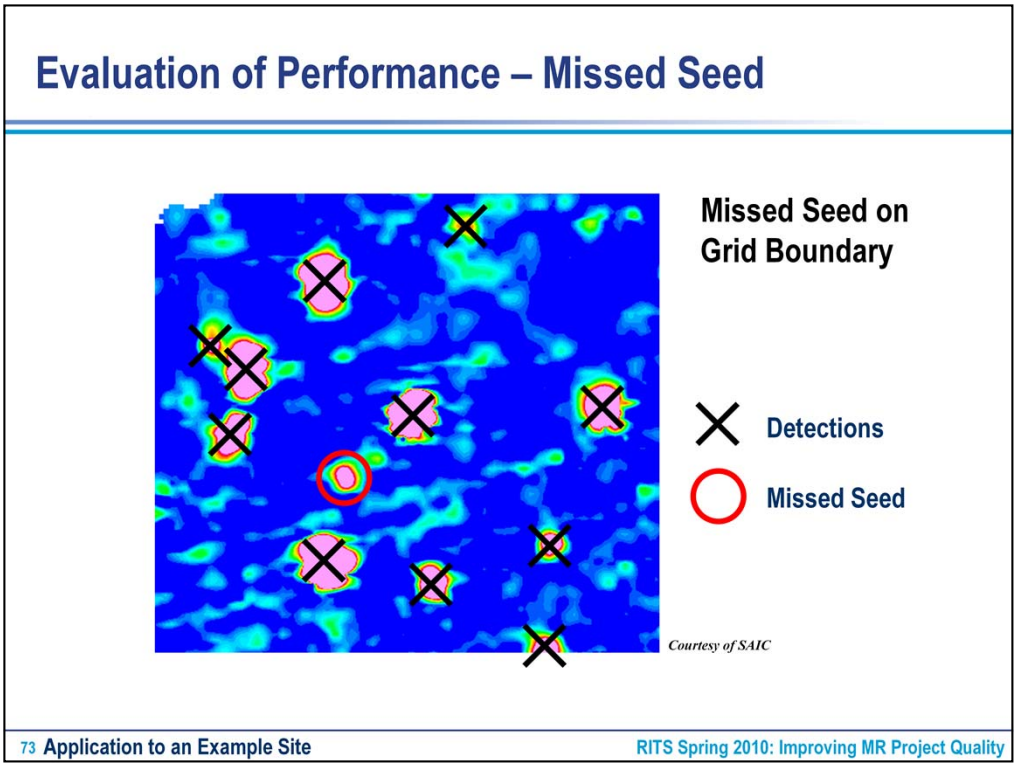
One of the products of the performance analysis is shown here. Just as for the IVS, the geophysicist checks to make sure the anomaly amplitude measured for each seed is within the expected bounds. Since the seeds were buried with random orientations, the measured amplitudes are expected to span the signal between the least- and most-favorable orientations.

The error bars on the measured amplitudes correspond to ± 2.5 cm in depth and twice the measured site noise.

Evaluation of Performance – Location Accuracy



Analysis of the seed location data shows that a bias to the west is beginning to be evident. Although the performance still meets the DQOs, it would be wise to begin to investigate the cause of this bias.



Geophysical data from an area of the site where a seed was missed. The X's represent targets that appear on the pick list, and the circle denotes the missed seed. In this case, a response is present at the location, but it was not picked in the analysis process. A root cause analysis would be initiated to identify the failure and, if necessary, prescribe a corrective action.

In this case, it was found that the missed seed was right on the boundary of the grids established by the contractor to facilitate their survey but was chosen in neither. A procedure was established to choose all anomalies on the boundary in both grids and then deal with the redundancy when the final list is compiled.

Project Summary

- IVS constructed and surveyed
  - Consensus to proceed on the same day
- Daily IVS verified continued system performance
- Production blind seeds
  - Detected a flaw in the data processing approach
  - Production results verified design criteria were met
- Coupled with other project QC built a strong and defensible case that if munitions were on our site and we went over them, they were detected and recovered

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Several important goals were accomplished by the use of the GSV process at this site.

The IVS was constructed and surveyed the first day on site and the analysis of the data allowed the team to reach consensus to proceed that evening. There was no need for the geophysical contractor to demobilize, write a lengthy report, and wait weeks for approval.

After production began, the IVS was surveyed each morning and evening by each geophysical crew on site. This gave all stakeholders confidence that the survey equipment was working to specification throughout the data collection.

A blind seed was missed in one area of the project. A root cause analysis was undertaken and a flaw in the target selection process identified. This was corrected promptly.

All of these measures, in conjunction with the normal QC procedures, built a strong and defensible case that the project objectives were achieved.

Presentation Overview

- Introduction
- Concepts
- Science Behind Geophysical System Verification (GSV)
- Application to an Example Site
- Summary and Conclusions

GSV Summary

- No longer need to conduct traditional GPO
  - 15 years' experience
  - Understanding of sensor physics
- Able to re-deploy resources from up-front evaluation to ongoing monitoring of performance
- Better idea that will lead to a better product
- One component of a quality project

76 Summary and Conclusions RITS Spring 2010: Improving MR Project Quality

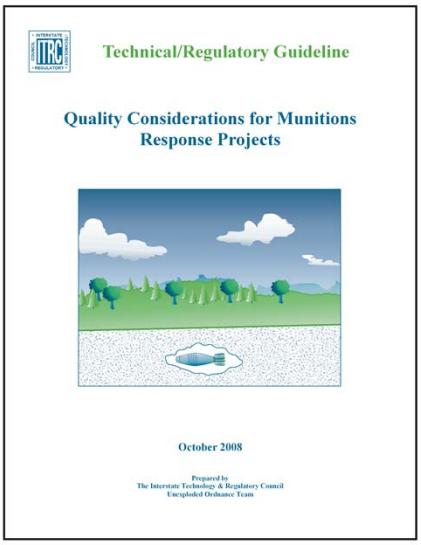
To summarize the presentation:

We have been employing GPOs at munitions response sites for 15 years. During that time, we have come to understand how each of the sensors used will respond at a particular site. In addition, an understanding of the sensor response has emerged from the research program that enables us to predict sensor response curves in advance.

This accumulated understanding allows us to move some of the resources formerly required for GPOs to on-going monitoring of project performance. This, along with quality control measures, will lead to a better project.

ITRC Tech/Reg Guideline

- See ITRC's Quality Considerations for Munitions Response Projects (UXO-5, October 2008)
- A guide to regulators on how to define quality, how to systematically plan for and achieve quality results, and how to apply these concepts to processes common to an MR project
- Download at ITRC's website under the guidance documents for UXO
- Archived training available at EPA's CLU-In website


Technical/Regulatory Guideline

Quality Considerations for Munitions Response Projects

October 2008

Prepared by
The Interstate Technology & Regulatory Council
Unexploded Ordnance Team

Here is another document that can help RPMs with quality. It was written for regulators but can be useful to RPMs as well

References

- "Survey of Munitions Response Technologies," ITRC
- ESTCP GSV Document, Web cast, and Animation