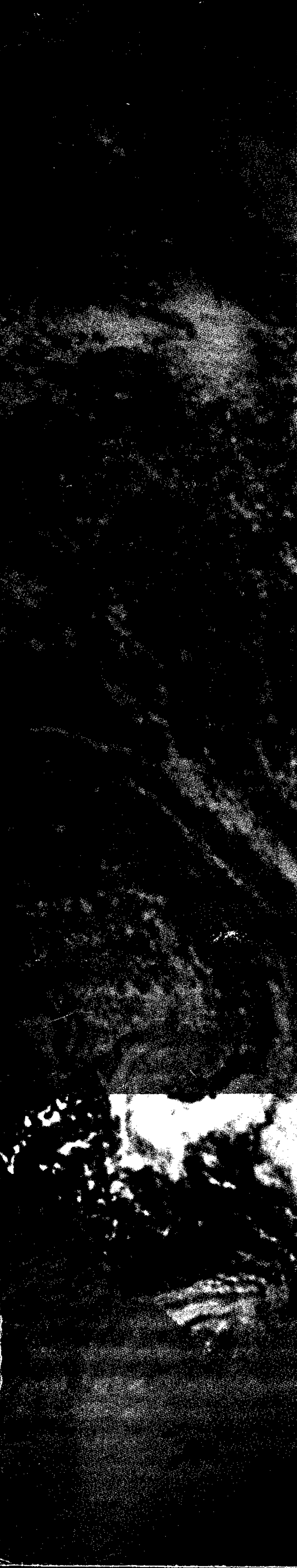

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# Enhancing Geophysical Data Acquisition, Quality Control, Processing, Analysis and Visualization for UXO Detection, Characterization and Discrimination

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## ABSTRACT

As earth scientists seek to address today's demands to detect, characterize and discriminate buried Unexploded Ordnance (UXO) for remediation and safe disposal, they are increasingly relying on high-resolution geophysical methods to provide accurate and efficient detection of land-based and offshore targets. In comparison with traditional sampling procedures, geophysical methods are especially well suited for this application because they minimize time, danger and cost factors -- yet maximize the amount of data, information and knowledge obtained.

Typical geophysical methods used in UXO detection include magnetic (vertical gradient and/ or total field) and electromagnetic (EM) surveys. Both methods offer convenience and the potential to locate and characterize UXO targets. The magnetic method is a technique with well-understood anomaly characteristics and their relationship to depth and location of ferrous sources. The EM method can determine locations of isolated metallic sources and is less sensitive to cultural noise.

To obtain meaningful geophysical information, UXO specialists must overcome a variety of challenges -- related to data acquisition, quality control, processing, analysis and visualization tasks. In this paper, we examine how UXO specialists can enhance results while performing each of these tasks -- emphasizing that reliable decisions depend ultimately on carefully controlling and monitoring each task.

This paper also introduces a model referred to as the Earth Science Information / Process (ESIP) model. This model is intended to provide a general framework for viewing the basic UXO problem-solving process and the relationship of data, information and knowledge throughout this process. In addition, the model provides a conceptual organizing structure for identifying the means in which data, information and knowledge can be enhanced for UXO characterization and discrimination.

Using data collected at a 'cluttered' test site (Fort A. P. Hill, Virginia), we review the requirements for acquiring sufficient and high-quality data. For data processing and analysis, we review the application of computer-based algorithms -- such as analytic signal, EM analysis and automated target selection -- to UXO analysis. We also examine how these procedures can speed the interpretation and improve the accuracy in identifying shallow ferrous and metallic targets.

Lastly, we look at how advanced visualization techniques can help address classical problems, such as delineating multiple, clustered bodies and jointly interpreting magnetic and EM61 data. This latter process can help in distinguishing UXO that have different physical property characteristics (i.e. magnetic signatures without accompanying EM61 signatures and vice-versa). This type of visual approach differs from traditional mathematical approaches (such as developing weighting coefficients based on several kinds of data) in that it outlines an interactive methodology for performing combined magnetic and EM interpretation.

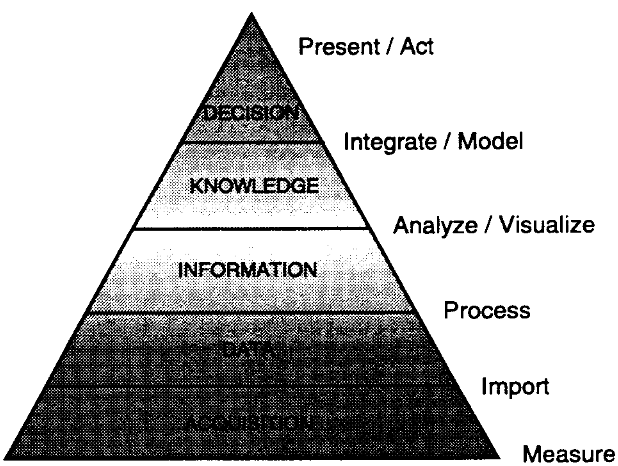



**Figure 1:** The Earth Science Information/Process Model (ESIP) is a representation that describes the life cycle of data as raw data is transformed into information and knowledge. When knowledge is realized, data completes its primary life cycle of usefulness – and a decision is made. This representation is not necessarily linear as tasks can be repeated as required.

## INTRODUCTION

The Earth Science Information / Process (ESIP) model is proposed as a starting point for understanding the general UXO process. Before proceeding further, we pause to define the ESIP model and illustrate the model's role in relating data, information and knowledge to the basic activities in the UXO specialist's decision-making process.

As shown in Figure 1, the ESIP model uses a pyramid to express the relationship between data, information and knowledge (defined as "primary components"), and the acquisition and decision components.

At the base of the pyramid is a measurement or sample. The acquisition component considers all relevant constituents related to data gathering, such as survey design, operator effectiveness, and physical or electronic collection of measurements or samples.

Data comprise the next level in the hierarchy. Stated most simply, data represent unprocessed observations. For instance, data could refer to single geophysical measurement made with a total field magnetometer or electromagnetic system.

The next level in the hierarchy is information. Information contrasts with data in that it represents an order or pattern recognized in the data. Essentially, raw data has been transformed through some process (human or computer-based). Examples in the UXO context include filtered, leveled or gridded geophysical data from total field magnetic or electromagnetic surveys.

The next level is knowledge. Knowledge represents organized information. Knowledge is the sum total of all experiences which combine the geoscientist's practical experiences, formal educational training, and the analysis and visualization of data or information.

At the top of the hierarchy lie decisions. The final outcome in any Earth Science investigation is to make a conclusion and act on this conclusion (or recommend an action). In Unexploded Ordnance (UXO) detection, the decision may be to remediate a subset of the detected targets to specific depth on a certain site.

## General Implications of the ESIP Model

As embodied in the ESIP model, we can further recognize certain characteristics that reflect both the pyramidal representation and the levels of organization within the model:

The data level is the most abundant component in the system followed by information and knowledge.

Data must progress through one or more transformations to become information.

Data transformations are focusing processes in which increase the scientific value of data through the manipulation of large volumes of data into information, knowledge and finally, decisions.

Decisions are ultimately based on data – when we break, forget or consciously choose to ignore this connection, we may be subject to a loss of "data context" and/or "data intimacy".

In the remainder of this paper, we look at the acquisition, quality control, processing, analysis and visualization components of the model as they apply to UXO characterization and discrimination -- focusing on how the UXO specialist can enhance results during each of these stages.

## Enhancing UXO Data Acquisition

As illustrated in the ESIP model, UXO results are entirely dependent on the initial acquisition process -- here defined as consisting of two parts (survey design and the actual survey process).

Survey design is critical -- both to obtain sufficient data at minimum cost and to avoid problems related to survey spacing (i.e. data sampling). Data sampling problems generally cannot be resolved during processing and therefore must be dealt with at the survey design stage. During the actual field survey, careful data acquisition can significantly streamline subsequent quality control tasks and help to minimize related processing costs.

Two types of standard surveys that are performed in UXO applications include magnetic (using total field and gradiometer instrument configurations) and electromagnetic surveys (this paper considers the EM61 instrument). Both are non-destructive, high-resolution techniques typically performed along parallel survey lines for speed and consistency.

The magnetic method is a passive geophysical technique (i.e. in which no external stimulus is required), and magnetic anomalies are produced by fundamental interactions between magnetic materials and ambient magnetic fields. The measured total field reflects the earth's magnetic field superimposed on the induced field and any existing remanent or permanent magnetization. Both types of field effects are observed in UXO surveys. Magnetic data can be used to locate ferrous objects (including) and to estimate specific characteristics, such as apparent depth and estimated weight.

The electromagnetic method is an active geophysical technique that uses an inducing primary electromagnetic field to generate secondary electromagnetic fields in the ground. In EM61 instrumentation, secondary field responses can be used to locate buried metallic objects (including UXO). In addition, mathematical relationships can be used to estimate specific characteristics, such as apparent depth.

## Optimizing Survey Design

Important survey design considerations for both magnetic and EM61 surveys include determina-

tion of station and line spacing (i.e. sampling density) so that UXO targets are sufficiently resolved that their location and depths (and other characteristics, such as weight) can be estimated reliably.
Since survey cost is directly related to sampling density, the focus at this stage is often to determine the optimal trade off between resolution and sampling density. However, prior to considering the economic aspects of a particular UXO survey, it is essential to objectively consider the physical size of the target and its potential for detection via certain survey methods (i.e. related ultimately to the instrumentation).
As a rule of thumb, for *very near surface sources*, the spatial extent of the magnetic or electromagnetic anomaly has the same order of magnitude dimension as its causative body. Generally four readings are required to accurately define an anomaly. Therefore, the size of the target (and not the acquisition cost) determines the sampling and line spacing distances. For deeper targets, the target depth plays a greater role than its physical size in determining anomaly spatial wavelength.
For UXO detection magnetic surveys commonly have a 1 or 0.5 m line spacing, with a station spacing of 10 to 20 centimetres. EM61 surveys are generally completed using 1 m line spacing with a 20 cm station spacing.
In practice, there are logical reasons for attempting to acquire as many samples as possible – particularly in magnetic surveys:
From a physical perspective, magnetic methods are potential field methods in which a wide variety of bodies can generate the same anomaly shape. As shown in Figure 2, additional sampling can assist significantly in improving the understanding of source. There are many sources that can produce the same solutions; therefore more definition can help in making interpretation less complex.
From a data processing perspective, adequately sampled data is a prerequisite because post-processing cannot resolve undersampling problems.
From an analysis perspective, many computer-based data analysis routines, such as the analytic signal and Euler deconvolution methods discussed later, provide better solutions if data is highly sampled. The location and depth calculations have the minimum sample size as their bounding limit.
Optimum line spacing in EM61 surveys is a function of the instrument's "effective search radius". Effective radius -- the radius in which meaningful information can be extracted -- for this instrument is determined by the coil size. Since the coil size is approximately 1 m, this limit should be used as the *upper* limit for station and line spacing. A 0.5 m transmitter coil, would nominally require a 0.5 m station and line spacing.

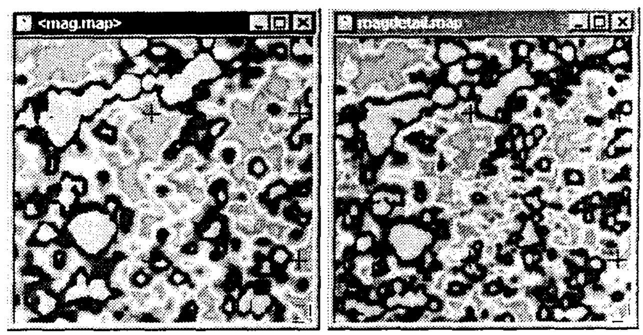



**Figure 2.** Magnetic data are typically acquired using very high sampling densities in UXO applications. Oversampling is effective for potential field data -- helping to resolve subtle target details as shown in these analytic signal data (coarse resolution on left and fine resolution on right).

Using a 0.5 m line spacing with a 1 m coil could be considered oversampling. It is worthwhile noting that while oversampling may increase field and data processing costs, there are valid reasons for acquiring more samples than nominally required. For example, it is valid to decrease *interline* spacing in EM61 surveys based on the premise that actual survey lines may not be absolutely straight. In the UXO case, where small targets can be easily missed, it is conceivable to use 0.5 m or 0.75 m line spacing. In addition, data redundancy can provide more flexibility for removing noise or cultural effects during data processing.

In summary, many UXO surveys aim to increase target resolution by acquiring as many samples along the line as possible. This approach is valid for magnetic surveys based on physical, data processing and analysis factors. For EM61 surveys, it must be recognized that station or line spacing more than 1 m are not usually appropriate -- based on the instrumentation configuration. Line spacing less than 1 m may be reasonable based the potential for missing smaller targets. These are key starting points in optimizing EM61 survey design.

**Optimizing Data Acquisition**

At survey time, there are a variety of factors affecting acquisition of high quality data for further processing and analysis. The most significant of these factors is survey positioning (i.e. controlling instrumentation positioning for accurate target location and anomaly resolution). Other factors that can affect data quality include instrumentation orientation.

One of the most commonly observed effects in towed array surveys or high-speed surveys is the appearance of "herringbone" patterns. Visible in gridded data, these patterns are indicative of distance (lag) and position (heading) related errors. Lag errors are related to an offset between the sensor location (measuring point) and the main instrumentation location (recording point). Heading errors are related to changes in direction, for instance, occurring when an EM61 survey is performed along a line in one direction and an adjacent line in the opposite direction. These effects can be controlled through careful data acquisition (carefully monitoring the measuring location during data recording); taking sufficient time in the field so that responses are not degraded due to high-speed acquisition; or post-survey processing utilizing a lag correction.

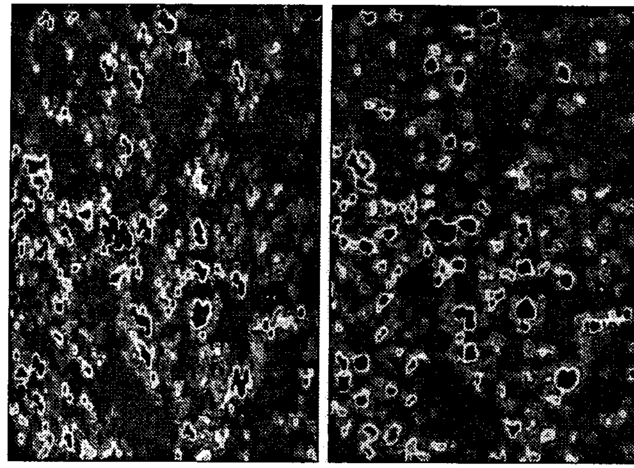


**Figure 3.** This figure shows EM61 data acquired at very high speed on left and lag-corrected data on right. Uncorrected data are characterized by elongated, drawn-out anomalies whereas corrected data show the expected focusing of anomalies over targets.

Another type of positioning error that can be controlled in the field is related to the EM61 system. With this instrument, losses in air pressure in the tires can reduce the circumference of the wheels on which the instrumentation is mounted. The effect is a mis-positioning of the measuring point. Standardized field practices can reduce this type of effect. The manufacturer (Geonics) now supplies the wheels with solid rubber tires to avoid this problem.

Instrumentation orientation can be an important consideration for gradiometer surveys. In the gradiometer instrument configuration, two sensors are arrayed vertically above one-another to measure the difference between magnetic field values over a known distance. This technique is commonly employed for near-surface surveys, of which, UXO surveys are a good example. Small deviations in vertical orientation can lead to significant deviations in gradiometer responses -- effectively, the instrumentation is sampling a different part of the potential field anomaly curve. Careful operator control is a prerequisite for managing these types of effects.

The effects of the diurnal variations in the Earth's magnetic field must be corrected for to ensure quality data. Spikes within the diurnal drift would appear as anomalies in the field data. Generally this correction is completed by the use of a base station magnetometer and is usually standard procedure for total field surveys. Vertical gradient surveys do not require this correction.

## Enhancing UXO Quality Control

Quality control procedures for UXO surveys include a variety of procedures for removing the positioning effects described previously, for compensating for instrumentation drift and for interactively editing data (where the UXO specialist has significant field and site experience to assess data validity). These procedures are typically computer-assisted and follow the importation of data into suitable quality control and processing environments.

As described previously, both magnetic and EM61 systems can be affected by positioning errors when operated in towed array configurations or when towed at high speed. In both cases, these effects can be controlled through simple computer-based procedures (lag and heading corrections) as shown in Figure 3.

Instrumentation drift primarily affects EM61 systems. Drift is related to temperature variations, operator error, instrumentation "glitches" and slowly varying diurnal magnetic fields.

Temperature drift is typically expressed as a baseline shift to below-zero values or an upward shift. These errors are small amplitude errors typically many orders of magnitude below the amplitude of UXO targets. Correcting this type of error is time-consuming since it requires hand leveling of data (i.e. specifying starting and end points, and then adding or subtracting a constant value to restore the data to background level).

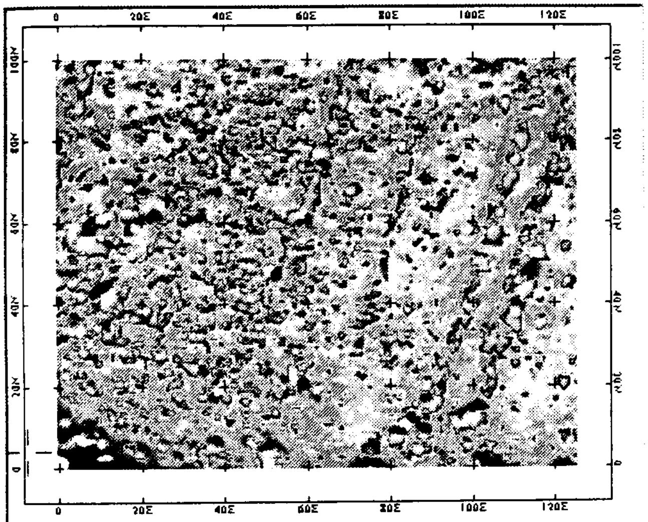
Slowly varying effects due to diurnal variations (long wavelength) create background mislevelling between lines surveyed at different times. These leveling variations are corrected using advanced leveling techniques or by high-pass filtering. One such approach is to use a time-referenced data value at points on each line throughout the survey to create a background level and then adjust all low amplitude values to this background. This is completed to bring all of the data to a common level and to minimize noise between lines. The result is the removal of diurnal long wavelength effects from the data.

Another type of quality control process that can be applied to both magnetic and EM61 data is manual data editing. Typically, the approach is to display data in profile format and to remove single "erroneous values" which are clearly single point errors. This type of quality control typically requires a field or data processing specialist familiar with geophysical data acquisition, instrumentation systems and site conditions.

## Enhancing UXO Processing

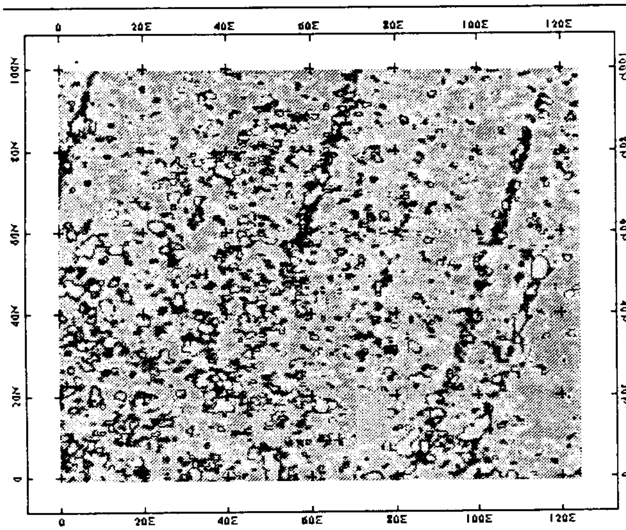
At the processing stage, the UXO specialist's objective is to convert raw line data into information, such as filtered and leveled data, or various types of grids and derivative product grids. In this section, we discuss enhancing UXO information through processing.

Gridding corrected data can be completed using various algorithms. The most commonly employed for line-based data are the bi-directional and minimum curvature methods. Bi-directional gridding products are shown in Figure 4.




Total Field Magnetics

**Figure 4.** This figure shows bi-directionally gridded total field magnetic data. Bi-directionally gridded EM61 data (bottom channel) is shown below. This method reinforces features perpendicular to the survey direction thereby helping to correlate linear UXO anomalies between lines.




EM 61 Bottom Coil

Either method can yield good results although the bi-directional method may stretch extreme values located on single lines perpendicular to the line direction. This results in a distorted anomaly shape. Alternately, the minimum curvature method is optimized for random data and does not honor line-to-line correlation particularly well.

As the geophysical data collected contains broadband information, data filtering may be used to enhance the data. As most of the targets of interest have short wavelengths, the removal of long wavelength regional trends often improves the visible detailed information. One application where filtering is useful is in the leveling of magnetic data which contains line-to-line base level differences.

## Magnetic Data Processing Procedures

Factors to consider when working with magnetic data include: shape, orientation from susceptibility, permanent magnetization, distance from and direction to the magnetic body. The permanent magnetization is a very significant factor as the production of man-made ferromagnetic objects generally produces a magnetization direction that differs from the induced field produced by the current Earth's magnetic field. Figure 5 shows the effect on the magnetic response for various permanent magnetization directions.

When dealing with magnetic field data, the goal is to simplify the complex information contained in the original data. One method that accomplishes this is the calculation of the 3D analytic signal from the total field data.

Typically, only a few of the survey area targets can be positively identified by the total field magnetic data. As shown in Figure 5, 3D analytic signal results show a positive peak over the center of each UXO, with the shape indicative of the type and orientation. The amplitude of the 3D analytic signal of the total magnetic field produces maxima over isolated magnetic sources regardless of the direction of the magnetization (MacLeod *et al.*, 1993).

The amplitude of the 3D analytic signal at any location can be derived from the three orthogonal gradients of the total magnetic field using the expression:

$$|A(x,y)| = \mathrm{sqrt}((dT/dx)^2 + (dT/dy)^2 + (dT/dz)^2)$$

where:

$|A(x,y)|$ is the amplitude of the analytic signal at (x,y).

T is the observed magnetic field at (x,y).

The 3D analytic signal is calculated from the gridded total field data utilizing a simple 3x3 convolution filter to find the (x,y) horizontal gradients and a Fast Fourier Transform (FFT) to find the (z) vertical magnetic gradient.

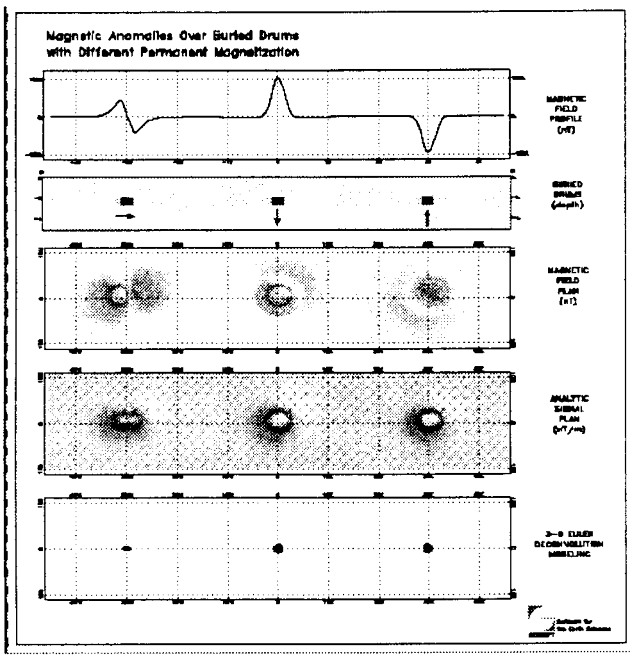



**Figure 5.** The top panel shows profile (1-D) representations of total field anomalies for various horizontal targets (barrels) with different remanent magnetization directions. The bottom two panels show the gridded (2-D) representations of total field and analytic signal anomalies. Analytic signal representations exhibit peaks over anomalies instead of the more complex dipolar signatures observed in total magnetic field representations.

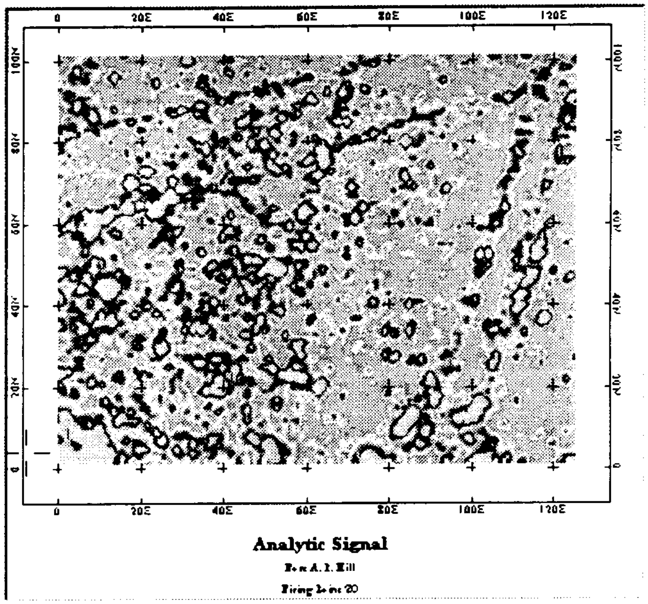



**Figure 6.** This figure shows analytic signal results for magnetic data shown in Figure 4 and a corresponding reduction in anomaly complexity. Also, note the strong definition of east-west linear anomalies in both original magnetic and analytic signal results. EM61 bottom and differential channel results in Figures 4 and 7 show only very weak trends in this direction -- possibly indicating a unique type of UXO source or depth-of-investigation relationships that require further quantification and analysis.

## EM61 Data Processing Procedures

The electromagnetic survey typically reveals high amplitude responses originating from the surface or from shallow buried metallic objects. The distribution of anomalous EM61 responses usually indicates buried metallic targets or other anomalous materials present at or near the surface.

Initial target picking and refinement of targets uses the bottom EM61 channel data since it is closer to the target and tends to have higher amplitude. Depth determination processing methods are described in the UXO analysis section. As shown in Figure 7, the difference channel (between top and bottom coils) often helps in target selection.

## Enhancing UXO Analysis

The objective of UXO analysis is to convert processed data into meaningful physical quantities -- specifically UXO location and target characteristics, including depth of burial and potentially, weight. In this section, we discuss how specific analysis techniques can help enhance the UXO specialist's existing knowledge.

## Applying Analytic Signal Analysis

After the analytic signal is calculated an automated peak selecting routine, such as the Blakely algorithm (Blakely and Simpson, 1986) can be used to automatically find peaks in the gridded analytic signal data. If the grid cell being examined has a higher value than those on all sides, it is selected as a target. (Note that the location can thus be determined only to the nearest grid cell location.) After the initial automatic selection, various methods can be used to reduce or increase the number of picked targets.

Once the target locations are known, the apparent depth to the magnetic source may be derived from Euler's homogeneity equation (Euler deconvolution). This process relates the magnetic field and its gradient components to the location of the source of an anomaly, with the degree of homogeneity expressed as a "structural index" (Yaghoobian *et al.*, 1992). The structural index (SI) is a measure of the fall-off rate of the field with distance from the source.

Euler's homogeneity relationship (Reid *et al.*, 1990) for magnetic data can be written in the form:

$$(x-xo)\delta T/\delta x + (y-yo)\delta T/\delta y + (z-zo)\delta T/\delta z = N(T-B)$$

where:

(xo, yo, zo) is the position of the magnetic source whose total field (T) is detected at (x,y,z,).

B is the regional magnetic field.

N is the measure of the fall-off rate of the magnetic field and may be interpreted as the structural index (SI).

The three gradients are calculated from the total magnetic field data as described earlier. The Euler deconvolution process can be applied at each target to determine the apparent depth results. The method involves setting an appropriate SI value and using least-squares inversion to solve the equation for an optimum xo, yo, zo and B.

The advantages of this technique over conventional depth interpretation methods (i.e., characteristic curves, inverse curve matching, etc.) are that the analytic signal method is based on two-dimensional data representations, the target analysis process is objective, the method is not affected by magnetic remanence, the process can be directly applied to large gridded data sets, and it does not assume a dipolar source.

Apparent weight calculations may be obtained from the magnetic data using a simple table lookup. Given the 3D analytic signal data, which is directly related to the magnetic moment and the calculated apparent depth of the magnetic source, the apparent weight can be found. The table of weight information included in the lookup table is based on theoretical and empirical evidence (moments were tabulated for various UXO targets by Pennella, 1982). The accuracy of the apparent weight calculation is very dependent on having an accurate depth determination. Coarsely sampled data will not yield accurate results.

## Applying EM61 Analysis

Due to its coil arrangements, the EM61 response curve for a discrete anomaly such as UXO is a single well-defined positive peak and the depth of the target can often be estimated from the width of the response or from the relative response from each of the two receiver coils.

Peaks may be picked using the same algorithm as that described above for the analytic signal data. Apparent depth estimation of buried targets is calculated by utilizing the ratio of the responses from the two EM61 receiver antennas (upper antenna placed 40 cm above the lower antenna).

The rigorous formula for calculating Apparent Depth is:

**$R(z)=k * f1(z)/f2(z)$**

where:

$k=2.8$

$z$=apparent depth in cm

$f1(z)=sqrt((h+z+l1)^2 + 2a1)^2 * (h+z+l1)^2 + a1^2)$

$f2(z)=sqrt((h+z+l2)^2 + 2a1)^2 * (h+z+l2)^2 + a1^2)$

where $h=42.2$, $l1=3.3$, $l2=43.3$, $a1=47.15$

## Enhancing UXO Visualization and Integration

The visualization and integration process is a key component of the UXO process-stream because decisions to remediate are based on the ability to visually communicate and justify results. From a knowledge perspective, the ability to extract information from visual representations of data and information provides a key opportunity for the UXO specialist to apply and enhance her/his own knowledge and experience. One of the areas in which visualization and integration techniques have the highest potential for enhancing the process of UXO location and characterization lies in the ability to visually query both magnetic and electromagnetic information.

A specific example of how this process works and where it may be effective is in the joint interpretation of magnetic and electromagnetic data. Since magnetic and electromagnetic instrumentation measure different physical properties of UXO (ferrous and conductive), it is logical to acquire both types of data in the field. However, once acquired, the practical question is how do we integrate different types of data for meaningful interpretation?

One approach is to calculate correlation coefficients or weighting factors based on both sets of data. This approach may be effective for high-volume datasets with well-behaved and distinct responses.

In cluttered sites or other sites with high magnetic backgrounds, however, where responses are not well behaved, the UXO specialists' eye remains a key interpretation tool -- enabling the

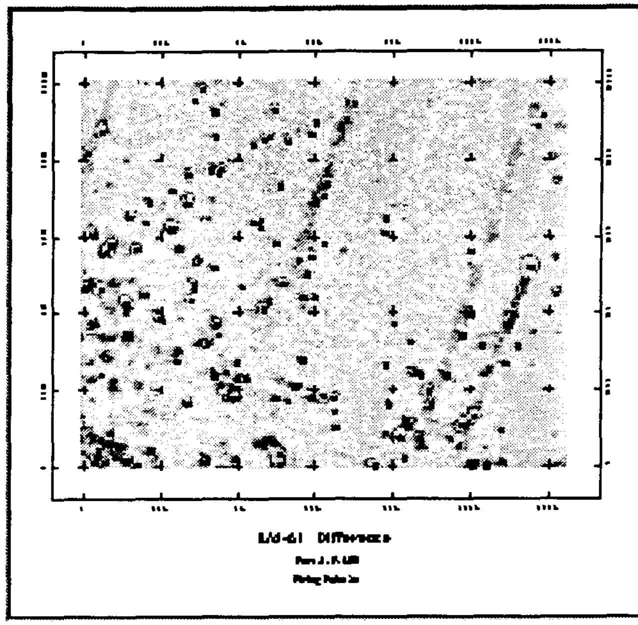


**Figure 7.** This figure shows EM61 difference grid with overlying UXO targets selected using semi-automated peak-picking algorithm.

specialist to interactively relate their experience and knowledge to the information at hand. In addition, there is always a project start-up phase during which the specialist must "tune" their knowledge to understand the physical characteristics of the UXO present at a new site. This "tuning" process is a prerequisite for any automated techniques that follow.

An evolving technique is the joint visualization of magnetic and EM61 data and information onscreen as shown in Figure 8. This technique enables the UXO specialist to compare magnetic and EM61 grids and original data interactively -- identifying objects which have ferrous signatures only, conductive signatures only or both ferrous and conductive signatures. Since the original data is also available for comparison, the specialist can interactively build a detailed catalogue of the different types of UXO expressions on a particular site.

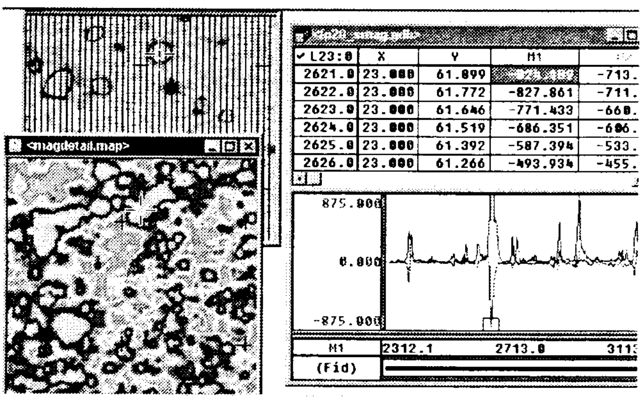



**Figure 8.** Evolving visualization techniques now enable UXO specialists to simultaneously interpret information and original data on a detailed basis. In this example, an EM61 difference grid (top left) is being evaluated in conjunction with an analytic signal grid (bottom left), original magnetic data (top right) and original magnetic data in profile form (bottom right). Interactive links enable the interpreter to visualize the same anomaly in map (2D), profile (1D) and data (0D) views. In addition to characterizing different types of signatures, this type of visualization can assist in resolving more complex UXO problems, such as delineating multiple, clustered bodies.

A related visualization technique takes advantage of colour merging capabilities. For example, the specialist can colour-code various types of behavior to visually discriminate different types of UXO expressions. A sample colour-coding scheme is yellow for magnetic only signatures, blue for EM61 only signatures, white for combined signatures and black for the absence of signatures (i.e. not detected or not present).

An important area of further research is to develop documented catalogues of signatures describing UXO, which have magnetic only, EM61 only or combined signatures. Currently, the UXO specialist must rely solely on their knowledge and experience -- additional UXO target information would be valuable in enhancing this knowledge.

## Conclusions

In summary, this paper has organized the key components of UXO problem solving into its data, information and knowledge components, and its individual processes based on a generic Earth Science Information / Process model. The objective is to provide a model for streamlining UXO decision-making and to identify opportunities to enhance the quality of results.

As indicated previously, there are numerous opportunities to enhance the results of any process, whether by tightly constraining the survey design or by applying specific analysis techniques or by implementing visualization techniques based on multiple types of data.

The success of UXO detection and characterization efforts depends on data quality and the ability to access and compare original data with processed results (information) at any stage of the process. UXO decisions (i.e. to remediate well-understood targets at specific depths) rely on the control that is maintained during each process step -- acquisition, quality control, processing, analysis and visualization.

Ultimate success, however, depends on the UXO specialists' ability in applying her/his knowledge and experience in the context of the high-quality data and information at hand.

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