Experiences with unexploded ordnance discrimination at a live-site in Montana

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Unexploded ordnance, discrimination, magnetics, total-quality management

Abstract

A 200 acre magnetic survey was collected and processed under production survey conditions over a site in Montana contaminated with unexploded ordnance (UXO). All anomalies with fitted moments above 0.05 Am² were excavated. During the survey the magnetic remanence metric was predicted but not used to guide the discrimination. The retrospective analysis presented here reveals that discrimination using remanence would have significantly reduced the total number of anomalies (with good dipolar fits) that needed to be excavated, from 524 to 290 while still recovering all 69 UXO. The false alarm rate (FAR) was reduced from 6.3 to 2.9 non-UXOs excavated per UXO found. At a cut-off of 75% remanence, 77% of anomalies due to shrapnel and metallic debris and 64% of geological anomalies were rejected.

Magnetic geology in the area introduced a significant human-element into the interpretation process. Three different interpreters added a total of 305 additional anomalies that were not fit with a dipole model and which were later found to be non-UXO. Between 40-50% of anomalies picked by the two relatively inexperienced interpreters who analyzed the data turned out to be geology, as compared to 14% for an experienced interpreter. Critical analysis of results, operator training and feedback from the UXO-technicians validating the anomaly are essential components towards improving the quality and consistency of the anomaly interpretations. This is consistent with the tenants of Total Quality Management (TQM). We compare the actual FAR that resulted during the survey when there was little feedback between UXO technician validation results, to a hypothetical result that could have been achieved had there been a constant feedback system in place at the onset of operations. Feedback would have significantly reduced the number of geological anomalies and decreased the FAR from 10.7 to 4.0.

The hypothetical results presented here demonstrate the value of using TQM principals to guide the UXO remediation process. They further show that improvements in the efficiency and costs of UXO remediation require both technological advances and operational optimization of the technology when implemented in a production setting. Furthermore, by treating geophysical modeling and UXO validation as separate entities, both with respect to contracting and operational reporting, there is little incentive for the geophysicist to leave an anomaly off the dig-sheet. Only potential negative consequences will result if that anomaly is later found to be a UXO. An incentive based mechanism that rewards the geophysicist for reductions in follow-on

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costs would have a strong potential to reduce the number of unnecessary excavations, and hence reduce the total cost of the UXO remediation effort.

1 Introduction

In the field of UXO detection and discrimination, the R&D effort has largely focused on technological solutions rather than application or “optimization” of existing technologies such as training and team structure. In our experience, there is often a considerable disparity between results under highly controlled research conditions and those obtained in actual production geophysics. In this paper we will show that some of the disparity in results is due to the way in which the technology is applied and in the training and experience of the teams in the field.

In production geophysics, the use of electromagnetics has become more or less an industry standard (Bell et al., 2001; Collins et al., 2001, Pasion and Oldenburg, 2001). In part, the dominance of this technology may be due to the inherent ambiguity in magnetic modeling and the influence of the training and experience of the geophysical team involved in the subjective interpretation of magnetic data. We found that: (1) impressive results can be obtained using total field magnetics when remanent magnetism (Billings, 2004) is incorporated in the discrimination model alone and (2) the overall performance of this modeling technology is greatly improved when relatively modest training and feedback is incorporated into its application. We suggest that this is consistent with Deming’s Total Quality Management (TQM) principles (Deming, 1986).

TQM was originally developed within a manufacturing context and provides a generic framework for continuous improvements of procedures in order to optimize productivity and quality. Within UXO remediation we seek to find all UXO (our quality objective) while minimizing the time and costs of geophysical survey and anomaly excavation (our productivity objective). Deming developed a fourteen point plan for continuous improvement and for UXO remediation his points 5, 6 and 9 are particularly relevant:

(5): Find the problems; constantly improve the system of production and service: The problem in UXO remediation is inefficiency in that many non-UXO are excavated for each UXO found. To improve performance requires both technological advance and advances in the application of that technology in a production setting. For magnetic discrimination we use remanence as our technological advance and indeed can improve performance. However, there is a significant human factor that the technology does not address. In particular, this human factor is most important for anomalies that lie in the overlap region between the two end member classes. These end members comprise the well defined class of anomalies that must definitely appear on the dig-sheet (data quality good, model displays the character of a UXO) and the class of anomalies that do not need to appear on the dig-sheet (data quality good, model displays large remanence and/or moment is too small). For these end member classes, different interpreters applying both manual and automatic discrimination routines will inevitably come up with the same answers. It’s the anomalies that don’t clearly lie in either class that are of most concern. Such anomalies may have poor data fits due to data quality or coverage issues, overlapping signatures with adjacent anomalies, interference with magnetic geology, or may simply be due to geology itself. Dealing with these anomalies in a consistent and sensible manner requires training and experience and this brings us to Deming’s point 6.

(6): Institute modern methods of training and education for all. Use statistical methods to discover when training is complete: If the interpreter is too conservative, many more anomalies
than necessary appear on the primary dig-sheet (false-positive) and the remediation costs rise (and indeed that was our experience at Chevallier). On the other hand, if the interpreter is too aggressive, then there is a strong potential that UXO will be left off the dig-sheet (false-negative). Only through monitoring interpreter performance can specific problems with interpretation be identified and corrective action taken. This brings us to Deming’s point 9.

(9): Break down barriers between departments and staff areas. Barriers result in sub-optimization as each area tries to do what is best for itself rather than co-operating in order to achieve what is good for the organization as a whole: Constant feedback from the dig-teams is a critical element in monitoring and improving interpreter experience. The discrimination process cannot end at the point the geophysicist hands the dig-sheet over to the Unexploded Ordnance technician. The UXO-tech is a critical and integral part of the process and is in an excellent position to provide feedback to the geophysical interpreter (and vice-versa). The notion of “feedback” between the UXO technicians “validating” the anomalies and the UXO geophysical team “picking” the anomalies for validation is intuitive and conceptually “easy.” However, within the UXO clearance industry, timely feedback has proven to be operationally difficult and rare. In part, this is because each of these two functions – geophysical modeling and UXO validation - require highly specialized skills that are disparate in both culture and training. Historically, each respective area of UXO clearance has been treated as a separate entity, both with respect to contracting and operational reporting.

In this paper, we compare and contrast the FAR that resulted during a 200 acre magnetic survey at Chevallier Ranch, Montana, from little feedback between UXO technician validation results to a hypothetical result that could have been achieved had there been a constant feedback system in place at the onset of operations. We conclude that UXO anomaly picking and validation are simply opposite sides of the same coin and that the current institutional and cultural barriers to integration and feedback result in sub-optimal results that are at variance with Deming’s model on TQM.

2 Description of the production survey

Chevallier Ranch is located in the northwest extent of the Helena Valley, approximately 10 miles north-northwest of the City of Helena. The site was used for artillery and tank training by the Montana Army National Guard (MTARNG) in the 1940’s and 50’s. The main ordnance types present are 76 mm anti-tank and high explosive (HE) projectiles, 105-mm HE, Illumination and White phosphorous (WP) projectiles anti-tank rounds and 155 mm HE, WP and illumination projectiles. The majority of the site is located on a gentle sloping hillside, containing sage brush, shallow draws and sporadic pine trees (Figure 1). While the site is relatively open, the height of the sage-brush often exceeds 0.5 meters which has prevented the use of cart-based systems in the area (as the MTARNG wants to avoid the expense and visual effects of vegetation clearance). This was a contributing reason to the decision by the MTARNG to use man-portable magnetometers for digital geophysical surveying (Figure 1 a). Magnetic survey data were collected by Sky Research on approximately 200 acres at Chevallier Ranch between October and November 2004.

A central requirement for reliable application of discrimination is the ability to test performance on an on-going basis throughout the survey. The usual practice for UXO remediation projects is to conduct a geophysical prove out (GPO) to test, evaluate and demonstrate geophysical systems before the start of a survey and conducted again during a survey if any substantial changes are
made to either equipment or personnel (ITRC, 2004). However, the GPO does not test the discrimination performance under the varying conditions experienced at a site, the potentially variable quality of the sensor and positional data or the potentially variable quality of the data interpretation. To test discrimination performance, the MTARNG emplace inert rounds at random locations throughout the survey area and only disclose those locations to the geophysicist after the data for that area have been interpreted.

### 2.1 Data collection

The total field magnetic survey conducted at Chevallier Ranch utilized a man portable magnetometer array consisting of four Geometrics G-823 optically pumped cesium vapor magnetometers for survey data acquisition, and a G-856AX1 proton precession magnetometer for base station measurements. The G-823 measures the intensity of the Earth's magnetic field in nanoTeslas (nT). At Chevallier Ranch, the magnetic intensity is approximately 55,700 nT, the inclination 71° and the declination 15.1°. The G-823 sensor separation was 0.5 m covering a 2.0 m data swath. The G-823 system was configured to stream data at ten samples per channel per second (10 Hz). At a nominal traverse rate of 0.76 m per second, this equates to approximately one sample per 0.07 - 0.1 m of forward advance.

For sensor positioning, Sky Research deployed the Leica TPS1200 robotic laser tracking system. The backbone of the TPS1200 is a motorized robotic total station that uses automatic target recognition to track the location of the prism and has a highly accurate distance/azimuth measurement system to produce +/-5 mm +2 ppm accuracy. This technology is ideally suited for UXO geophysical surveys, producing positional data with 3D accuracy of approximately 1 cm at a 7 Hz rate.

Each day, the following calibration and standardization tests were conducted: warm-up, time calibration and heading correction tests. The magnetic sensors were allowed to warm up to a point where there was <3 nT variation in the sensor readings before data collection could begin. Time calibrations were performed several times during the day along a North trending line approximately 6 m in length. A board with a thin steel wire was placed at the mid-point of the segment and the magnetometer array was walked forward and then backward along the 6 m line. The time calibration test is used to calculate the time slew value to precisely merge the magnetometer sensor data with the positional information from the RTS. The heading correction tests involved traversing over a common point in 8 cardinal directions (N to S, S to N, E to W, W to E, NE to SW, SW to NE, NW to SE, SE to NW). The intersections of each sensor at each direction are found and the field values compared. Any difference in field value of more than 5 nT indicates a problem with the data collection system (e.g. operator carrying ferrous metal) that needs to be remedied before the survey can proceed.

### 2.2 Data processing

At the end of each day, the magnetic data were processed in the following way:

1. The raw sensor, position and magnetic base-station data were merged using a common time-reference.
2. The magnetic data were corrected for diurnal variations and heading error.
3. The magnetic data were filtered using a moving median filter to estimate the long-wavelength components of the magnetic field signal.

4. The data were interpolated onto a 0.125 meter grid,

In Figure 2, we show an image of the median filtered magnetic data over the entire Chevallier Ranch site. UXO and other metallic debris manifest themselves as small dipolar anomalies distributed throughout the image. Prevalent in the area are linear, roughly East-West trending features that are related to dikes that radiate from a volcanic plug several hundred meters west of the area shown. There are also weaker NW to SE trending features which are predominately associated with the North-South drainage pattern in the area. These geological features are one of the reasons why the human element plays such a significant role in magnetic data interpretation.

2.3 Data interpretation

For each 100 m by 100 m tile, the following processing sequence was followed

1. The Automated Wavelet Detection (AWD) Algorithm (Billings and Herrmann, 2003) was used to detect all anomalies of amplitude 10 nT or greater.

2. The automated anomalies picks were augmented by inspecting the sensor data and adding manual picks as required.

3. Using an estimate of the anomaly size returned by the AWD algorithm, segments of data about each anomaly were extracted for additional analysis.

4. A magnetic dipole model was fit to each anomaly.

5. The magnetic dipole fit was used to estimate the magnetic remanence (Billings, 2004) of each anomaly assuming there were 76, 90, 105 and 155 mm caliber munitions on the site. An important point is that the magnetic remanence discriminator was not used to make discrimination decisions and was calculated prior to the geophysicist having access to ground-truth. This allows us to conduct an unbiased test of the discrimination performance later in the paper.

6. Each anomaly was classified as either Primary, Secondary or Geology as follows:

*Primary anomalies:* All anomalies with moments greater than 0.05 Am² were placed on the primary dig-list (Figure 3a). Where data quality precluded accurate recovery of the dipole moment the interpreter used their own judgment to decide whether to include it on the primary dig-list.

*Secondary anomalies:* All anomalies with moments less-than 0.05 Am² (Figure 3b), and any anomalies with poor dipole fits that were judged to be too small to be a UXO. These anomalies are all placed on a secondary dig-sheet that is used to provide a record that the anomaly in question was modeled by the interpreter and deemed to be unlikely to be due to UXO.

*Geology anomalies:* Anomalies that appear to have the characteristics of a geological anomaly but where the interpreter judged there was a potential that the source was a UXO or other piece of metal. Figure 3c illustrates an example, where the anomaly shape is non-dipolar and extends over several meters. The main concern with this item is that the negative trench lies to the North of the positive peak which could be indicative of a UXO.
Over the duration of the survey, there were three different interpreters used. One was highly experienced and had worked with data from sites in Montana in the past. The other two were geophysicists with little previous experience with magnetic data that were trained during the course of the survey. Every interpretation was checked by the same quality control (QC) geophysicist who would ascertain whether any anomalies were left off the primary dig-sheet or missed entirely. They would only add anomalies and would never remove an anomaly that had already been picked (unless it was a duplication).

3 Results

The MTARNG excavated 100% of the primary picks and geology, and approximately 15% of the secondary picks as part of a quality assurance (QA) measure. This 15% comprised a certain number of the top-ranked secondary picks for each tile (typically around 5-10), along with 100% excavation of certain tiles. In total, there were 1127 anomalies for which ground-truth was obtained. These anomalies represent 524 primary picks, 298 secondary picks and 305 geology picks (Table 1).

Sixty-nine UXO were recovered along with twenty-three emplaced items. All 69 of the UXO were primary picks, while 22 of the emplaced items were on the primary list and 1 on the secondary. There were a total of 395 anomalies for which nothing was found or for which the response was found to come from the geology. The false-alarm rate (FAR), which we define as the number of non-UXO divided by the number of UXO, is a good measure of the efficiency of the UXO remediation procedure. Including emplaced items as UXO, the FAR = 11.4, while excluding them we find a FAR = 15.0. These numbers are close to the FAR goals set by the recent Defense Science Advisory Board report (Delaney and Etter 2003), but could be improved further as we now seek to demonstrate.

Dissecting the above results we identify three key quality and productivity issues:

Issue 1: Discrimination algorithm has a high FAR: All UXO should appear in the primary dig-list with a minimal number of scrap metal and geological anomalies included. From Table 1, we see that 130 of the primary anomalies were from geology, 168 from shrapnel and 135 from junk metal, giving a FAR of 6.3 (or including the emplaced items the FAR = 4.8). The discrimination algorithm is reliable (as all UXO and all but one emplaced item were correctly classified), but is not very efficient. This inefficiency of the algorithm increases the total costs of the remediation efforts as more anomalies than necessary have to be excavated. In the next section, we replace the simple discrimination algorithm based on the size of the moment, with a more sophisticated and effective algorithm based on magnetic remanence.

Issue 2: One emplaced round appeared in the secondary dig-list: This would particularly be of concern if the misclassification was a problem with the technology itself rather than the application of the technology (e.g. true moment was less than 0.05 Am²). It turns out that this round was emplaced for an on-the-fly geophysical prove-out conducted on the very first day of the survey. The round lay in a shallow gully, in an area where a shrub prevented line-of-site between the prism and the total station, so that the data coverage was variable. The fitted moment was 0.041 Am², and the interpreter failed the fit and put the anomaly in the secondary dig-list. This anomaly is an example of one that sits within the overlap between those anomalies that must be excavated and those that can safely be left in the ground. Its moment places it in the class that can be left in the ground, but the data-fit is very poor and the moment fit cannot be trusted. As a
consequence of this missed round, a procedural change was made whereby all anomalies with poor fits and a predicted moment greater than 0.03 Am$^2$ were included in the primary dig-list.

**Issue 3:** Large number of geological anomalies: There were 305 anomalies classified as potential geology that were recommended for excavation. Of these, 65 were associated with metallic items (shrapnel or junk metal) and the rest were of geological origin. None of the items were a UXO or emplaced item. UXO technicians tend to have analog equipment with lower detection capability and sophistication than that used for anomaly excavation. Any item that has a geological source is particularly problematic as it tends to increase the time-on-target (TOT) required to validate the anomaly during excavation (Youmans et al., 2005). When an anomaly has a metallic source, the validation has an unambiguous end-point, corresponding to the identification and removal of the item. A geological anomaly, on the other hand, typically has no obvious identifiable source and the UXO-technician must decide if ambiguity remains as to the source of the original anomaly listed on the dig sheet. This decision is almost entirely experience based and we have found that there is considerable opportunity for error without highly experienced UXO technicians following a very systematic protocol. This experience and protocol developed only after the UXO technicians partnered with the geophysical teams and shared information and knowledge. This information exchange occurred “in-the-field” which we believe was essential. The geophysicist was able to explain the reason’s for their decision by reference to a contour map of the magnetic field. The UXO-technicians were able to demonstrate the use of their analog equipment and between the two teams a sensible protocol for resolution of geological anomalies was developed.

Decreasing the UXO technician’s TOT is only one aspect of addressing the issue of geological anomalies. The other is how those anomalies ended up on the dig-sheet and whether their inclusion was warranted. The number and character of the geological anomalies added to the dig-sheet depend strongly on the level of interpreter training and experience (Table 2). Only 7% of the anomalies picked by the experienced interpreter (who had spent time in the field with the UXO-tech’s) were listed as geology. In contrast, 17 and 30% of the two inexperienced interpreter’s anomalies were interpreted as geology. In addition, the inexperienced interpreters added more anomalies to the primary dig-list that ended up having a geological source (25 and 39 % compared to 10 % for the experienced interpreter). We define efficiency as 100 minus the percentage of anomalies with a geological source. The experienced interpreter’s efficiency is 86% compared to 50 and 57% for the two inexperienced interpreters. This is a very significant difference and emphasizes the value of experience in the subjective process of dealing with anomalies with a geological source. Only by appropriate training and feedback from the UXO technicians can the number of geological anomalies added to the dig-sheet be minimized, without significantly increasing the risk of false-negatives.

Note that there was a considerable difference in the number of anomalies picked by each interpreter (Table 2) and that one interpreter picked only 52 anomalies. The differences in picks are significant at the 95% confidence limit but could conceivably be due to structural differences in the areas interpreted. Manual inspection of the different areas does not reveal any significant differences in the geological characteristics, data quality or number of anomalies. We therefore believe that the differences evident in Table 2 are a result of the different levels of experience and training of the interpreters.
4 Hypothetical performance using remanence and TQM

We now access the discrimination performance in a hypothetical setting where we used magnetic remanence as the technology and incorporated constant performance monitoring and feedback into the process.

4.1 Improving the technology

The magnetic remanence method was developed by Billings (2004) and consists of defining a library of items expected to occur in the area. The shape, size and magnetic properties of each item can then be used to define a dipole feasibility curve that comprises all possible dipole moments that ordnance could produce, in the absence of remanent magnetization. The magnetic data from each anomaly are inverted to produce a dipole model. The recovered dipole moment from the inversion generally does not lie on one of the feasibility curves. This may be due to variability in the material properties and shape (deformation) of individual UXOs, remanent magnetization effects, positional errors in the data, or higher modes not captured in the dipole model. For each item, \( i \), in the library, the orientation is calculated that causes the minimum difference, \( \Delta m_i \), between the moment of the ordnance and the moment determined through the inversion, \( m \). For each item in the library we then estimate the ***minimum percentage of remanent magnetization*** required to best match the observed dipole,

\[
\text{rem}_i = 100 \frac{\| \Delta m_i \|}{\| m \|}.
\]  

We then rank items according to their remanent magnetization. Items with low remanent magnetization are more likely to be UXO and are excavated first. Items with high remanent magnetization are assumed to be highly unlikely to be UXO and can be left in the ground. The success of the procedure depends on

1) shock demagnetization on ordnance impact erasing the majority of the remanent magnetization of the UXO;

2) accurate recovery of the dipole moment of the anomaly; and

3) an accurate model of the dipole feasibility curve for each UXO expected to occur in the area.

As mentioned earlier, we are in a position to conduct an unbiased test of discrimination performance as the remanence was calculated during the production survey prior to ground-truth being available. In Figure 4, we show the recovered dipole moments of anomalies in the UXO, emplaced and other classes. Also shown are the dipole feasibility curves for the 4 ordnance items expected in the area (these were obtained by modeling the ordnance response as a spheroid with a similar aspect ratio). Most of the anomalies cluster around the feasibility curve for the 76 mm. This is due to all but three of the anomalies being 76 mm rounds, with one each of the other 3 types of ordnance. Curiously, the 105 and 155 mm anomalies have moments that lie almost directly on their respective feasibility curves and were classified correctly. The 90 mm projectile (which was emplaced) was closer to the 105 mm feasibility curve and classified as such. Eighty-one of the eighty-nine 76 mm projectiles were correctly classified, while one was not classified
at all (data quality unreliable). The ability (or inability) of the magnetic method is not of any real
significance in and of itself, it simply shows that moments tend to cluster around their respective
dipole-feasibility curves.

We turn now to the distributions of the remanence of the different classes (Figure 5a). From the
figure, 80% of UXO and emplaced items have remanence less than 35% compared to only 11%
and 15% of scrap and geology. All but one UXO have remanence less than 75% compared to
only 23 and 36% of scrap and geology. For the remanence there is one outlier with a remanence
of 105.6%.

If we prioritize our excavations as a function of remanence (Figure 5b) we would need to dig 388
items to recover all UXO and emplaced items (including the outlier), which is still less than the
524 primary picks required by the original method. The second to last UXO was recovered in
hole 281 which is 107 holes before the final item. Thus, finding the last UXO requires an
increase in almost 40% of the number of holes to dig. To determine whether the outlier
represents a limitation of the technology (e.g. item not shock demagnetized), or an issue with
methodology and quality control, we plot the measured magnetic field over the item (Figure 6).
We also show the locations of the sensor readings. Immediately, one can see that this anomaly
has not been properly sampled and that its dipole fit should not be accepted. In fact, in the
original interpretation the interpreter was obviously concerned about the fit quality and placed
the item on the primary dig-sheet, even though its recovered remanence of 0.039 Am$^2$, lay below
the cut-off value of 0.05 Am$^2$. Thus, with a reasonable degree of confidence, we can conclude
that even in a remanence based discrimination mode, an interpreter would have placed the item
on the dig-list.

In Billings’ (2004) original paper on magnetic remanence, the emplaced items were found to
have a significantly different distribution of remanence than the undisturbed UXO items. The
emplaced items, on average, had a higher remanence. The results here do not display a
significant difference in the distributions of remanence. If anything, the emplaced items have a
tendency to have a lower remanence, but this could be due to a sample bias (as there were only
22 emplaced items).

4.2 Constant performance monitoring and feedback

Magnetic remanence can reduce the FAR by providing more effective separation of the UXO and
shrapnel/scrap metal classes (77% of shrapnel/scrap metal rejected at a magnetic remanence of
75%). It is also effective at defeating geological anomalies for which dipole models were
predicted (64% of geology rejected at 75% remanence). Magnetic remanence has little impact
on those geological anomalies included on the dig-sheet, and for which no moment was
predicted. These anomalies are added at the discretion of the interpreter if they feel the anomaly
could potentially be due to a UXO. As we saw in the results section, experience and constant
feedback from the UXO-technician are required to defeat these types of anomalies.

On the assumption that feedback is rapid and effective, we estimate that the number of geological
picks at Chevallier would have been reduced by a factor of four (one could make the argument
that they could have been eliminated completely as none of them turned out to be UXO). Thus, in
place of 305 geology picks there would have been closer to 76. Now, combined with a
remanence criterion of 75% there would have been 290 primary picks, for a total of 366 items on
the dig-sheet. Excluding the emplaced rounds this would result in a FAR = 4.0, while including
the emplaced rounds produces a FAR = 3.0. Now such a dig-procedure would have been
augmented by a certain number of excavations of the items on the secondary dig-sheet. We
assume that the same number of excavations would have been undertaken which would have added 298 digs. Thus in total, we predict that had we used magnetic remanence and rapid and constant feedback that a total of 664 excavations could have been made in place of the actual 1127. This would have resulted in a reduction of the total FAR from 15.0 to 8.3 (or including emplaced rounds from 11.3 to 6.2).

5 Discussion

The industry trend in recent years has focused on the use of electromagnetics for the detection and discrimination of UXO. This method has been shown in numerous controlled tests to have the greatest potential for reliable discrimination with low FARs (e.g. Collins et al., 2001). This study shows that under the right set of site specific conditions (favorable geology, munitions of 60 mm caliber or greater), magnetics is a viable alternative technology. This is particularly the case in rugged, vegetated terrain where man-portable arrays of magnetometers can be deployed and used to reliably and rapidly map large areas.

The key to providing effective solutions to the UXO remediation problem lies both in developing new technologies and in effective integration and implementation of those technologies into a production setting. For example, the results in this paper demonstrate that there is a significant human element to the use of magnetics that must be understood and addressed before the method can fulfill its full potential. This human factor is partly due to the presence of geological anomalies that can obscure or be mistaken for metallic items, and partly due to the dipolar nature of magnetic anomalies. The signature of a dipole is a less intuitive concept that the typical positive peak exhibited in an electromagnetic survey. Therefore, we anticipate that the human-factor will play less of a role in electromagnetics. However, there will still be cases where anomalies are in the region of overlap between potential UXO and items that can be safely left in the ground. In these situations, training and experience will be required to make consistent, reliable decisions. The most effective way to obtain that experience will be through constant feedback from the UXO technicians conducting the anomaly validations.

Deming’s Total Quality Management is a framework that can be used to optimize productivity and quality. Its important tenants are a commitment to continual improvement through critical analysis of all aspects of the problem and effective teamwork and communication between different stakeholders. The hypothetical results presented here demonstrate the value of using these principals to guide the UXO remediation process.

Viewing the UXO clearance problem in its entirety, the results here can be extended one layer down to include the government or industry group sponsoring the clearance. Historically, geophysical modeling and UXO validation have been treated as separate entities, both with respect to contracting and operational reporting. In this environment, there is little incentive for the geophysicist to leave an anomaly off the dig-sheet. They are not paying for the clearance and therefore have no immediate financial gain from that decision; instead, they face only potential negative consequences if the anomaly is later found to be a UXO. An incentive based mechanism that rewards the geophysicist for reductions in follow-on costs would have a strong potential to reduce the number of unnecessary excavations, and hence reduce the total cost of the UXO remediation effort. We conclude by emphasizing that only by considering the total-system can one aim to achieve total quality in all aspects of that system.
6 Acknowledgment

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7 References


### Tables

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>UXO</th>
<th>Emplaced</th>
<th>Geology or Nothing</th>
<th>Shrapnel</th>
<th>Junk</th>
<th>Total</th>
<th>FAR</th>
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**Table 1:** Number of anomalies for which ground-truth is available, broken out according to interpretation class (primary, secondary and geology) and the identity of the item.

<table>
<thead>
<tr>
<th>Level</th>
<th>Total picks</th>
<th>Primary picks</th>
<th>Secondary picks</th>
<th>Geology picks</th>
<th>Primary pick nothing found</th>
<th>Secondary pick nothing found</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry level 1</td>
<td>975</td>
<td>48%</td>
<td>22%</td>
<td>30%</td>
<td>25%</td>
<td>7%</td>
<td>57%</td>
</tr>
<tr>
<td>Entry level 2</td>
<td>52</td>
<td>60%</td>
<td>23%</td>
<td>17%</td>
<td>39%</td>
<td>42%</td>
<td>50%</td>
</tr>
<tr>
<td>Experienced</td>
<td>100</td>
<td>30%</td>
<td>64%</td>
<td>7%</td>
<td>10%</td>
<td>6%</td>
<td>86%</td>
</tr>
</tbody>
</table>

**Table 2:** Performance of different interpreters at Chevallier Ranch, showing the percentage of primary, secondary and geology picks, along with the failure rate of the primary and secondary picks. Also shown is the “efficiency” which is defined in the text.
**Figures**

**Figure 1:** (a) Quad-sensor magnetometer array with Leica RTS in action at Chevallier Ranch. (b) EOD-tech relocating an anomaly with a Ferrex gradiometer prior to excavation. Sage-brush at heights exceeding 0.5 meters are present in both photos.

**Figure 2:** Demedian filtered magnetic field data over the entire 280 area of Chevallier Ranch (including 80 acres in the North-South gully collected with GPS that have not yet been validated). The data are shown with a linear color-stretch of -5 to 15 nT.

**Figure 3:** Example signatures of three different anomalies: (a): Anomaly on the primary dig-sheet with moment 0.15 Am$^2$ and magnetic remanence of 1.3%. The anomaly was validated as a 76 mm APC M62; (b) Anomaly on the secondary digsheet with a moment of 0.03 Am$^2$ and a magnetic remanence of 193%. The item was validated as a piece of shrapnel; (c) Anomaly on the geological pick list which was subsequently found to be geological.

**Figure 4:** Recovered dipole moments of UXO, emplaced and other items overlain with the dipole feasibility curves for the 4 ordnance items expected in the area. The moments are split into components parallel and perpendicular to the Earth’s field.

**Figure 5:** (a) Cumulative distributions of remanence for UXO, emplaced items, shrapnel/scrap metal and geology; (b) Percentage of UXO and emplaced items recovered as a function of excavation order when items are ranked according to remanence.

**Figure 6:** Image of the UXO with the largest remanence of 105.6% showing an obvious data coverage issue that would most likely have been picked up by the interpreter or during QC.
Figure 1:
Figure 2: Gully with data collected by GPS
Figure 4
Figure 5(a)

Figure 5(b)
Figure 6