Abstract

Magnetic soils are a major source of false positives when searching for landmines or unexploded ordnance (UXO) with electromagnetic induction sensors. In regions with high concentrations of viscous remnant magnetic (VRM) soils, the large background signal can produce electromagnetic anomalies of the same spatial wavelength and magnitude as buried metallic targets. In adverse areas up to 30% of identified electromagnetic (EM) anomalies are attributed to geology (Cargile et al., 2004).

Several techniques have been developed to distinguish between anomalies originating from UXO and geology. These techniques generally include a combination of (1) spatial filtering of data and (2) comparing the EM response of the data to a soil model. Spatial filtering is based on the assumption that the spatial wavelength of anomalies from magnetic geology are larger than the anomalies of metal targets. This process is only partially effective in areas of highly magnetic soil since variations in sensor height and orientation, as well as small variations in the surface topography can produce anomalies similar to those from UXO (Walker et al., 2005).

Due to the difficulties in spatially distinguishing between soil and metal anomalies, it is important to compare the TEM decay, or equivalently the frequency response, to the soil response. Viscous remnant magnetic soils produce a well known $1/t$ step-off time domain electromagnetic voltage response. Clearly, there is a danger of misclassification when the response of the soil closely matches the response of a target. Ware (2003), in addition to spatial filtering, compared how soundings measured on Kaho‘olawe by the Geonics EM63 deviated from a magnetic soil model. A direct comparison is feasible with the Geonics EM63 due to the number of time gates (26) and the range of times at which the EM63 records the decay (gates centered from 180 microseconds to 25 milliseconds). Bosnar (2001) compared the expected soil model using 4 time channel Geonics EM61-MK2 TEM data. Candy (1996) suggested a technique which compares the measured response to a soil model when the transmitter illuminates the ground with pulses of different lengths. The success of Candy’s procedure relies on relative differences between excitations from short and long pulse lengths for metal and VRM soils. This technique has been implemented in the Minelabs F1A4 sensor.

Introduction

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In this paper, we study the effectiveness of varying the transmitter waveform characteristics applied to an EM61-MK2 sensor. This study is motivated by several practical and theoretical reasons. Although the Minelabs F1A4 sensor is effective in detecting small targets in a VRM soil setting, it has difficulties with the larger deep targets. In addition, it is difficult to perform advanced processing, in particular inversion, on Minelabs F1A4 data due to proprietary on-board data processing. Decay curve comparisons using a Geonics EM63 sensor may be possible in principle, but is difficult to use in many realistic field settings due to its large weight on a wheeled cart platform. The EM61-MK2 is the most common EM tool used in UXO remediation. It has a greater depth of investigation than the Minelabs F1A4, and is a much lighter, field ready alternative to the EM63. Although the EM61-MK2 only has four channels, the addition of multiple pulse widths provides additional data that will enhance the differences between a metal target decay to a soil decay. In this paper we study soil and metal TEM responses and show how these responses differ as a function of the transmitter waveform. We investigate how size variations in the buried metal targets affect the effectiveness of the differential illumination EM technique.

The TEM Response of VRM Soils and Metallic Objects

The TEM method of detection consists of an EM sensor illuminating the subsurface by time varying magnetic field. A secondary field is produced by decaying eddy currents induced in conductive bodies, or by magnetic domains rotating to align themselves with the primary field. This secondary field is then sensed by the receiver. The background geologic response measured by EM sensors in highly magnetic regions is primarily due to viscous remnant magnetization, or magnetic after-effect, that is characteristic of ferri-magnetic minerals such as magnetite and maghaemite. Viscous remnant magnetization refers to the finite time required for the magnetic grain’s magnetization vector to rotate from its minimum energy orientation prior to the application of field, to its new orientation. Neel (1949) developed the theory for non-interacting single domain grains. The time for a rotation of the magnetization vector is characterized by the Néel relaxation time $\tau$. Let us consider a primary field $H_P$ that illuminates the soil, then is turned off at $t = 0$. The magnetization of a collection of grains with time constants distributed log-uniformly between $\tau_1$ and $\tau_2$ is

$$M(t) \approx \frac{H_P \chi_o}{\log(\tau_2/\tau_1)} (-\gamma - \log t - \log \tau_2)$$

(1)

where $\chi_o$ is the dc susceptibility, $H_P$ is the magnitude of the primary field before step-off, and $\gamma \approx 0.577$ is the Euler constant. In the derivation of (1) it is assumed $\tau_1 \ll \tau_2$ and the time of interest $t$ lies within the range $1/\tau_2 \ll t \ll 1/\tau_1$. Most TEM sensors measure the time derivative of the secondary field, and are therefore sensitive to the time derivative of the magnetization

$$\frac{\partial M}{\partial t} \propto -\frac{H \chi_o}{\log(\tau_2/\tau_1)} \frac{1}{t}$$

(2)

For the derivation of equations (1) and (2) we direct the reader to Billings et al. (2003). The step-off $1/t$ response predicted by equation 2 has been observed in mineral exploration (Buselli, 1982), archaeological prospecting (Colani and Aitken, 1966), and UXO detection (Ware, 2003). To model a spatial distribution of VRM material, a complex, frequency dependent susceptibility based on the assumption of a log-uniform distribution of time constants is used (Pasion et al., 2002a).

The theory of the TEM response of metal targets is well understood. Similar to the response of VRM soils, the response of a compact metal target can be expressed as a function of time constants. Kaufman (1994) derived a general form for the field caused by currents induced in a confined conductor. By assuming quasi-static fields, the secondary field produced by currents in a confined conductor can be written as

$$H_i(t, p) = \left( H_P \cdot \hat{\mathbf{l}} \right) \sum_{n=1}^{\infty} d_{ni} (p) \exp \left( \frac{-t}{\tau_n} \right)$$

(3)
where $H_{\hat{l}}(t, p)$ is the secondary field in the $\hat{l}$ direction, observed at a point $p$, and at a time $t$ following the termination of the primary field. The coefficients $d_{n\hat{l}}(p)$ depend on the target location, size and shape, and upon the geometry of the primary field. The time constants $\tau_n$ are also dependent on the permeability, size and shape of the target, but not the target location and geometry of the primary field. The largest time constant, $\tau_1$, determines the onset of the late time, exponential stage of the decay and is referred to as the diffusion time constant of the conductor. The form of the time constant is $\tau_1 = L^2 \mu \sigma / \pi^2$ where $L$ is a target diameter, $\mu$ is the target’s magnetic permeability, and $\sigma$ is the target conductivity. Prior to the late time stage, the cumulative effect of the summed exponentials produces a power law decay. The power law behavior has been verified experimentally and theoretically. Measurements have shown that a combination of a power law and exponential, $V(t) = kt^{\beta} \exp(-t/\tau)$, can be used to model the decay observed within the time range of the Geonics EM63 sensor (Pasion and Oldenburg, 2001). The power law exponent $\beta$ is a function of the shape of the target, and we have observed $\beta$ values ranging from $1/2$ to $3/2$ fit metallic targets.

To this point we have only been considering the response due to step off transmitter field. For an arbitrary waveform $g(t)$ that turns off at time $t = 0$, the measured response is obtained by convolution of the waveform with the impulse response

$$\frac{\partial H(t)}{\partial t} = \int_{-\infty}^{0} g(t') \frac{\partial H^I(t-t')}{\partial t} dt'$$

where $\frac{\partial H^I(t)}{\partial t}$ is the time derivative of the impulse response. For this presentation, we will consider four different transmitter waveforms. Each waveform consists of an exponential turn-on, followed by a linear ramp turnoff (Figure 1). The turn-on for each of the waveforms has the same exponential time constant of 3.46 ms and approximately the same linear ramp slope. Figure 2 illustrates how the transmitter waveforms described in Figure 1 alter the $V(t) = 1/t$ step-off soil response and the $V(t) = kt^{-\beta} \exp(-t/\tau)$ step-off metallic target response. For this example, the metallic response is calculated using time constants of $\tau = 0.1, 1, \text{ and } 10 \text{ ms, and a power law with } \beta = 1/2$. In evaluating (4) we differentiate $V(t)$ to get the impulse response. In order to compare the changing decay characteristics due to the different waveforms, the metal and soil responses are normalized to unity at 1 ms.

Figure 2 indicates that a target’s time constant size, relative to the transmitter on-time, controls how the target decay varies with the length of transmitter on-times. Targets with small time constants are less sensitive to changes in transmitter on-time. The target with $\tau = 0.1 \text{ ms has the same decay for each waveform since the transmitter on-times for each waveform is greater than } 0.1 \text{ ms. Targets with larger time constants demonstrate increased sensitivity to the changes in on time. The response of VRM soil response is also sensitive to the changes in transmitter on-time since the VRM soil response is due to a collection of magnetic grains with a log-uniform distribution of time constants.}

The smaller change of the TEM response for short time constant targets illuminated by different on-times compared to the larger changes in the soil response, suggests that variable waveform instrument responses could be effective for detecting small targets in a magnetic soil background. However, time constants for steel targets are large.
relative to the transmitter on-times that we are considering. For example, due to the large magnetic permeability of steel (> $200\mu_0$), a steel sphere with a diameter of 5 cm has a time constant of 40 ms.

**Acquiring Multi-Waveform TEM Data**

In September 2004, we acquired TEM data on the island of Kaho’olawe, Hawaii. Kaho’olawe was ideal for this study due to its well documented problems of UXO detection as a result of viscous remnant magnetic soils (Cargile et al., 2004). The TEM data were collected using a modified Geonics EM61-MK2 sensor. A single electronics chip in the EM61-MK2 controls the transmitter waveform characteristics and the receiver times. Since it was not possible to transmit different charge-up times using a single chip, Geonics produced four chips, each with a different transmitter waveform and receiving times (Figure 1). The 1 ms chip was not used in this study due to its inability to produce a stable signal.

Positioning of the EM61-MK2 was recorded using a Leica Robotic Total Station. Before and after each series of measurements, a lag test was performed to monitor timing errors between the sensor and the positioning system. A zero background reading of the instrument was established by placing the EM61-MK2 cart on a pair of plastic saw horses. The instrument drift was also accounted for by remeasuring the background at the end of the survey. We subtracted an instrument drift that was assumed to be linear.

Due to the highly magnetic background environments small sensor movements produced large changes in the measured voltage (Walker et al., 2005). In order to compare relative differences in signal due to transmitter waveform changes, we needed to minimize changes in sensor location and orientation when repeating measurements with different chips. For single soundings, marks were painted on the ground for accurate placement of the sensor.
To replicate a multiple line grid survey, we placed wooden planks on the ground to provide an easily repeatable wheel path for the EM61-MK2 cart (Figure 3(a)). The planks also minimized sensor orientation changes due to topographic variations. Differences in line paths over successive surveys were within a few centimeters. The data from the different chips surveys were linearly interpolated to the same station locations.

Two sets of data were acquired at the Navy QA grid on Kaho‘olawe. The first set was collected along the planks with each of the 10, 4, and 2 ms chips (Figures 4(a)-(c)). These background measurements show the large background signal due to the soil and the large variations in signal simply due to the topography within the survey area. The surveys were then repeated with a small nut (Figure 3(a)) placed on the surface at \((X, Y) = (0.56, 2.32)\text{ m}\) and a 90 mm projectile (Figure 3(b)) placed on the surface at \((X, Y) = (2.92, 1.81)\text{ m}\) (Figures 4(d)-(f)). Since the 90 mm target was placed on the surface, its anomaly dominates the gridded data.

**Soil Model Fitting Applied to Variable Transmitter Waveform TEM Data**

Fitting measured data to a soil model is a simple way of determining which soundings are background responses and which soundings have a contribution from the presence of a metal body. If the observed sounding can be well fit with the response of the soil, then the measured response is likely from the background soil only. If we assume that the magnitude of the soil and metal target responses are independent, we can write the measured sounding from a particular chip as \(V(t) = \alpha S(t) + T(t)\), where \(V(t)\) is the observed decay, \(S(t)\) is the characteristic soil response, and \(T(t)\) is the response due to a metal target. The coefficient \(\alpha\) is included because any observed soil response will be a multiplicative factor of \(S(t)\). Since the coefficient \(\alpha\) is a function of the soil characteristics, it is independent of the sensor characteristics (i.e. it will be the same for all chips).

There are two potential problems in fitting a soil model and analyzing a data misfit. Firstly, if the background soil response \(\alpha S(t)\) is large relative to the target response, then there is a potential of obtaining a good fit to the data. In order to avoid this problem, an estimated soil response is subtracted from the data prior to fitting. A second potential problem would be if the decay of \(T(t)\) is similar to the soil decay. We noted earlier that the variable waveform has the potential to alleviate this problem, but this would not be possible here due to the transmitter waveforms used in this study and the size of targets that can be detected by our sensor. However, the hope is that sampling 4 points of the decay curve will be sufficient in observing differences in soil and metal decays.

The fitting of the soil model represents the simplest of inverse problems: determine a single parameter by fitting multiple data. We define data vector where the TEM decays are normalized by the first time channel:

\[
d = \left[ \tilde{V}^i(t_j) \right],
\]
Figure 4: The first channel of TEM data (in mV) interpolated to common locations. The steel nut and 90 mm projectile locations are indicated by the ‘□’ and ‘△’ symbols, respectively.

where \( \tilde{V}^i(t_j) = V^i(t_j)/V^i(t_1) \) for time channels \( j = 1..4 \), and \( i = 1, 2, 3 \) representing data from the 2, 4, and 10 ms waveforms. We fit the data vector with a normalized soil model, with elements \( \tilde{S}^i(t_j) \), multiplied by a parameter \( \beta \). The soil model was determined by measuring the soil response at a number of locations on the Navy QA grid. A coefficient \( \beta \) is determined by dividing the data vector by the soil model element by element, and then taking the median of the quotients. To quantify the fit we use a least squares measure of the misfit

\[
\text{misfit} = \frac{1}{4N} \sum_{i=1}^{N} \sum_{j=1}^{4} \left[ \tilde{V}^i(t_j) - \beta \tilde{S}^i(t_j) \right]^2
\]

Figure 6 compares the characteristic soil model with soundings recorded with and without a metal target present, at the location of the bolt and the location of the 90 mm target. The observed soundings of the background soil (Figure 6(a) and (b)) fit the 10 ms and 4 ms data quite well, but the noise level of the 2 ms data makes it difficult to fit. The inability to fit the observed decay with a soil model is clear when a metal target is present.
An indication of potential advantages of using soil model fitting rather than raw data for detection can be obtained by looking at line profiles. Figure 7 compares the misfit calculated along the second line of data \((X \approx 0.5)\). The red lines indicate data with the nut present and the blue lines are fit without the nut. Panel (a) contains the raw data. The large jump in amplitude at the beginning and end of each line is due to the EM61-MK2 cart rolling onto and off of the planks. The dip in amplitude at approximately \(Y = 3\) m is due to a small rivulet. Panels (b) to (d) plot the misfit along the line. The steel nut appears clearly, even when including the noisy 2ms data in the fitting procedure. The misfit plots are insensitive to the changes in the raw data due to topography. Figure 8 plots the data from the 4 ms chip and the misfit using the 10 ms and 4 ms data. The misfit is plot on a scale similar to Figure 7. The large variation due to topography is not reflected in the misfit plot. This emphasizes the utility of the misfit as a means of reducing the amount of geologic anomalies chosen as potential targets.

The example presented here suggests that detection of metal objects can be achieved by determining the range of misfit values expected for magnetic soil in the survey area, then selecting anomalies outside this range as potential targets and candidates for advanced analysis. In addition, the information from analyzing the misfit can be used to determine which data are likely from soil only. These data can then be interpolated over the survey area to establish the soil model. Pasion et al. (2002b) used a similar approach, incorporating horizontal component data for target picking, to construct a soil model. The soil model was subsequently subtracted from the data, and the residual anomalies were inverted for physical parameters of the metal target.

**Conclusion**

In this paper we modelled, collected and analysed multi-waveform data for a modified Geonics EM61-MK2
sensor. Modelling was used to determine how a measured decay curve is altered by changing the length of transmitter on-time. As expected, we saw that the response of targets with time constants less than transmitter on-times are less sensitive to the length of the on-time than targets with larger time constants. Soil model fitting was applied to data collected on Kaho‘olawe, Hawaii. The inability for the soil model to fit the observed data proved to be a good indicator of the presence of metal.

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References


Figure 7: Line 2 misfit comparison. The peak in the misfit aligns itself with the location of the bolt, whereas the raw data peak does not.


Figure 8: Line 5 signal/misfit comparison.

