Abstract

An em 37-47 profile over a known target at one to three m depth is described here. The response of the highly conductive target is easily separated from the background response of the moderately conductive till and is traced from the earliest gate of the em-47 ultrahigh range (7μs after turn off), to the latest gates of the em-37 medium range (28ms after turn off). Three separate responses are identified on the basis of their decay characteristics and spatial variation. They are interpreted to be: a galvanic response, a vortex response, and a viscous magnetic remanence (VRM) response. In time and frequency domain electromagnetics the vortex response is often expected to be the dominant response, indeed, the galvanic response has only recently been added to many modeling packages. In this environment - a very good conductor, with high permeability, at shallow depth in a moderately conducting host, the galvanic response is the largest, followed by the viscous magnetic remanence. The vortex, or inductive, response is only briefly above the noise level.

Many other em surveys have been performed over this target, including VLF, em-31 and maxmin. These show either no response, or a response that is barely above the noise level. The frequencies used in these techniques (less than 56 kHz) are probably too low to strongly excite the galvanic or VRM modes, and it is possible that they are only exciting the relatively weak vortex mode. Thus, time domain em is not only effective in this environment, it is the only one of the common em techniques that is effective.

Introduction

The target is constructed from three separate 24 gage galvanized steel sheets pop-riveted together to form an electrically continuous target nine m long by one and a half m wide. The target is oriented almost EW, with a small plunge of about ten degree to the west, and no dip. At the up-plunge end (104W and 89E in survey coordinates) the top of the target is about half a meter below the surface. At the down-plunge end the top of the target is at three and a half m below the surface. The host material is till, with a 1 m thick sandy outwash at a depth of about 2 m. The till is moderately conductive, 60Ωm in the top few m, grading to about 20Ωm below the sandy outwash.

Numerous EM surveys have been conducted over this target, including time domain EM, resistivity, IP, VLF, maxmin, em31 and em16. The time domain EM and IP both show a strong response, resistivity shows a weak response (across the target), as does the VLF, while all the other surveys exhibit very weak or undetectable responses.

A plan view of the survey area is shown in figure 1. The square transmitter loops of the em-47,
(40 m by 40 m) and the em-37, (165 m by 165 m), are shown as thick lines, along with the projection of the target onto the surface, shown as a short solid line. The centers of the Tx loops are shown as small crosses. The survey results described here were obtained along line 89E, shown as a dotted line. All measurements are of the vertical component of $\frac{\partial B}{\partial t}$ taken at one and two meter intervals along the profile.

![Survey Plan View](image-url)

**Figure 1.** A survey plan view showing the layout of the 40 m by 40 m em-47 Tx loop, and the 165 by 165 m em-37 Tx loop.

The response of the isolated target is separated from the background response of the till by the spatial characteristics of the response along the profile, and confirmed by the temporal characteristics of the recovered background response. The background response - that due to currents circulating in the till uninfluenced by the target - should peak near the center of the Tx loop. By examining profiles where there is no known target, it has been confirmed that a quadratic is a good fit to the background response provided the sides of the Tx loop are not approached too closely. A cubic polynomial or higher order polynomial may be required otherwise. Only the far-offset stations are used to determine the background response. Since the response of the shallow target is localized around the target, far-offset in this sense means more than a few meters away from the target. Accordingly, a quadratic or cubic is fit to the far-offset stations. This procedure, shown in figure 2 for the first gate of the EM-47 (u)ltrahigh range is performed for every gate. The fitted background response is then subtracted from the observed response to yield a residual, which is presumed to be due to the response of the target alone.

At each station in the profile the background response should decay as a power law $t^{-5/2}$,
(Ward and Hohmann, 1987) and the residual responses should decay as either a power law or an exponential, depending on which mode is dominant during the interval being examined. When the recovered background responses are plotted vs gate-time, the decay is nearly a power law $t^{-5/2}$, as would be expected for a homogeneous or layered earth with moderate resistivity variations. Furthermore, the recovered residual responses decay either as exponentials with well-defined time constants, or as a power law, depending on which mode is excited.

![Figure 2](image)

**Figure 2.** A separation into background and target response. The top figure shows the raw data in ($mV \propto dB_z/dt$), as a function of station position for the first gate of the em-47 (u)ltra-high range. The solid curve is a third order polynomial fit to the response of the last four stations on either side. The bottom figure shows the residual response produced by subtracting the fitted polynomial from the observed data.

Three separate modes of excitation of the target are recovered. These are identified as: a galvanic response (mode 1), a vortex response (mode 2) and a viscous remanent magnetization (mode 3). The identification of the modes is based on their spatial characteristics and decay rates.

**MODE 1 - GALVANIC**

Mode 1 (figure 3) decays as a power law $t^{-5/2}$, suggesting that it is related to the background currents circulating in the host till, which themselves decay following this power law. The power law decay is rapid, so this is the dominant mode in the earliest gates, typically from 7 microseconds to 12
microseconds after turn-off, although it persists for about 50 microseconds before finally dropping below the noise level. The spatial form is a crossover, which would be expected for a concentration of current by a good conductor. Indeed, the crossover is at the known location of the target. The mode three response can also be seen at about 102N, however, at 6.9\( \mu \)sec after turn-off, the galvanic response dominates. The peak to valley width is 7 m, which would give a depth-to-source of 3 m for an isolated line current. This is greater than the known depth of the target. The galvanic currents however, include a return path in the host (figure 4) which would tend to make the peak-to-valley distance similar to the long dimension of the conducting target, resulting in an overestimate of the depth.

Figure 3. The galvanic response in the first gate of the em-47 (ultra-high range, 6.9\( \mu \)sec after turn-off. The mode three response can be seen at about 102 N, although at this time it is still much smaller than mode 1.

Figure 4. A schematic of the mode 1 response along the profile and the inferred current pattern in the target and host. The polarity of the current in the target is west to east. The return currents in the host are counter clockwise (viewed from above) to the north of the target and clockwise to the south of the target.
MODE 2 - VORTEX

Mode 2 (figure 5) is identified as a vortex, or induction, excitation of the target. The amplitude decays exponentially with a three millisecond time constant. This response is also a crossover, but note the change in polarity from the response in mode 1. Again, the crossover is directly over the target, but the peak-to-valley width is only 1 m. A target of these dimensions, with a late stage time constant of 3 ms, indicates a resistivity for the target of $10^{-7}\Omega m$, (Nabighian and Macnae, 1987). This is close to the resistivity of steel. The inferred current pattern in the target is a circulation in the plane of the target, probably confined to near the outer edges.

![Figure 5](image1)

**Figure 5.** The mode 2 response (3.5 ms) after turn-off.

![Figure 6](image2)

**Figure 6.** A schematic of the mode 2 response along the profile and the inferred current in the target. The current is clockwise in this view.
MODE 3 - VISCOUS REMANENT MAGNETIZATION

The mode 3 response (figure 7) is a single peak centered over the target. The amplitude decays following an exponential with a time constant of only 0.3 millisecond. This mode disappears relatively quickly and indeed it is the dominant mode only after the galvanic response has decayed. It remains the dominant response until it decays to a level below that of mode 2. It is the dominant mode from 16 microseconds to 1.4 milliseconds after turn-off. The full-width at half-height of the profile response is 1.5 m. Magnetic modeling of a target of the known dimensions, orientation and depth of this target, and the exponential decay with time, suggest that this mode is probably a viscous magnetic response. The typical range for viscous remanent relaxation time constants is $10^{-12} - 10^{-8}$s; (Bertotti, 1998) so the time constant recovered here, $3 \times 10^{-4}$s, is unexpectedly large.

Figure 7. The mode 3 response 0.3 ms after turn-off.

Figure 8. A schematic of the mode 3 response and the inferred polarity of the magnetization.
Summary

In a time domain profile over a shallow conducting target of known dimensions, three distinct responses were discernable. The identification and summary description of the three modes are:

MODE 1 - GALVANIC
- Amplitude decays as a power law
- Dominant mode from 7 to 12 microseconds
- Persists for 50 microseconds
- Crossover over target with peak-to-valley width of 7 m
- Interpreted to be a channeling or galvanic response

MODE 2 - VORTEX
- Amplitude decays as an exponential with 3 millisecond time constant
- Dominant mode from 2.8 to 28 milliseconds
- Opposite polarity to mode 1
- Crossover over target with peak-to-valley width of 2 m
- Interpreted to be an induction response

MODE 3 VISCOUS REMANENT MAGNETIZATION
- Amplitude decays exponentially with an 0.3 millisecond time constant
- Dominant mode from 0.1 milliseconds to 3 milliseconds
- Peak response over target with half-height-width 1.5 m
- Interpreted to be a viscous remanent magnetic response

Historically, the vortex response has been considered to be the dominant response, indeed the importance of the galvanic response has only begun to be appreciated relatively recently and it is not included in all modeling packages. In this case, where a shallow, conducting, high permeability target is in a moderately conducting host material, the dominant response is the galvanic response, followed by the viscous remanent magnetic response, while the vortex response is weak and only very briefly above the noise level.

VLF, em31 and maxmin surveys have also been carried out over this target with disappointing results. The VLF tilt-angle response is only a degree, while no convincing response at all is found with the maxmin, despite taking great care with Tx-Rx separation and orientation. The time domain data suggest that the galvanic and viscous remanent magnetic responses would only be large at 100kHz or higher, well above the VLF and maxmin frequencies, while the (weak) vortex response would be dominant at frequencies below 10kHz. Thus, it is probable that the frequency domain surveys were responding to the vortex mode only, which the time domain data indicates is only very weakly excited. Indeed, the peak to valley width of the VLF tilt-angle response of this target is consistent with a vortex response, but not with a galvanic response.

The identification of all three modes is extremely valuable in recovering the parameters of the source; size, depth, orientation and conductance. These are much better constrained by the joint interpretation of all three modes than they could be by the observation of only one mode. All of the recovered parameters are in excellent agreement with the known target.

Time domain em is an effective technique for the investigation of shallow conducting targets, especially in an environment such as that described here, where it is the only em technique that produces a large, interpretable response.

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References

