APPENDIX 4

Improving electromagnetic induction detector technology in humanitarian demining

R.C. Bailey, University of Toronto, Departments of Geology and Physics, Toronto, Canada
G.F. West, University of Toronto, Department of Physics, Toronto, Canada

SUMMARY

A variety of metal detectors using electromagnetic induction (EMI) are available for the detection of buried metallic targets in general and for humanitarian demining in particular. Detector designs suitable for humanitarian demining must be simple, robust and cheap. No one detector is optimal in all environments: variations in soil conductivity, and more importantly, frequency dependent soil magnetic susceptibility can favor one design over another. In particular, soils containing magnetic minerals can have as a result, a frequency dependent magnetic susceptibility which overlaps or coincides with the frequency range used for mine detection. Such soils are common enough that appropriate technology to understand and deal with these effects can make the dangerous job of humanitarian demining somewhat safer.

The Geophysics Lab of the University of Toronto is attempting to improve the technology in two ways. (supported by the Canadian Centre for Mine Action Technologies (CCMAT)) is aimed at investigating how EMI field instruments for humanitarian demining might be improved. The first is by constructing a better laboratory instrument to make measurements of the electromagnetic properties of difficult soils, in particular of frequency dependent magnetic susceptibility, and by finding semi-analytic representations of these responses suitable for modeling purposes. Based on experiments with a prototype, two production versions of this EMI spectrometer instrument are being built, with noise levels of the order of a few times $10^{-5}$ S.I. units, over a frequency range of 100 Hz to about 70 kHz. The second approach is by coding the software to allow such data to be used effectively in the simulation of detector performance. This involves assembling a number of induction algorithms into a single simulation code with a straightforward GUI, intended to be public domain as a MATLAB code. The final version of the code, when completed, is to handle single or multiple transmitter and receiver coils of circular or polygonal shape, general transmitter current waveforms, arbitrary transmitter orientations and survey paths, small targets with frequency-dependent anisotropic responses (permitting both magnetic and inductive responses to be calculated), embedded in multi-layered half spaces with both conductivity and frequency-dependent susceptibility (so-called `difficult soils`).

Keywords: Electromagnetic induction, Humanitarian Demining, Frequency-dependent susceptibility

INTRODUCTION

With support from Defense Research and Development Canada's program on humanitarian demining, we are developing software tools to help simulate the performance of electromagnetic induction (EMI) metal detectors of arbitrary design. In order to make valid simulations, we need quantitative descriptions of the induction response of mine-like target objects and of the electromagnetic properties of the soils in which the mines may be hidden. The information must be valid in the spectral range employed in typical mine detectors, 1 to 100 kHz, and should preferably cover from 0.1 kHz to 1 MHz. Unfortunately, with the exception of a few susceptibility amplitude measurement at two frequencies (465 and 4650 Hz) using the Bartlington susceptibility meter (ref), few spectral data are available in the scientific literature.

Modern anti-personnel mines typically contain only a few grams or less of electrically conductive metal; often only ~ 1 mm to ~ 1 cm in extent. Thus, it has become necessary to increase the basic sensitivity of mine detectors to a level where discrimination between the desired EMI response from a significant target object and the unwanted responses from magnetic minerals naturally present in the soil is often
the key issue --- not just simple target detectability. Furthermore, in wet locales such as marine beaches, the bulk electrical conductivity of the environment may possibly generate significant interference. Therefore, most modern detectors are designed to be unresponsive to ideally permeable, non-conductive materials and they use a spectral window below about ~100 kHz to minimize possible response from the bulk conductivity of the soil.

**Figure 1.** EMI detector for humanitarian demining use.

Although experience with the best modern EMI metal detectors has been relatively favourable, it has also revealed that many naturally magnetic soils do not behave as ideally permeable materials. Some may exhibit a frequency dependent, complex, magnetic susceptibility capable of confusing most detectors (sometimes termed *viscous magnetization* or VM, (Dunlop, D.J. and O. Ozdemir, 1997)). In the few cases where the effect has been investigated seriously, it usually is attributed to the presence of very fine grained ferromagnetic material close to the Neel superparamagnetic transition (Mullins and Tite, 1973). The problem was first noticed in Australia where EMI metal detectors are widely used in prospecting for gold nuggets in weathered soil, and at least one manufacturer there (MineLab) offers an instrument that can be trained to reject a VM background signal (Candy, 1996).

It is, of course, possible to estimate by theoretical methods (*e.g.* Das, 2005) the EMI response characteristics of conductive and permeable objects like those present in mines. However, the metal objects in actual mines may have poorly known compositions and odd shapes, so direct experimental confirmations seem necessary. Likewise, the volume magnetic susceptibility of typical soils (real or complex) can be estimated from the limited available studies, and electrical conductivity can be estimated from porosity and water salinity data. However, because reality often differs from prior expectations, we believe that direct observation would be better.

**THE EMI SPECTROMETER**

The spectrometer (West and Bailey, 2005) uses a pair of transmitter coils in a Helmholtz configuration and a pair of receiver coils also in a Helmholtz configuration, to achieve uniform sensitivity over as large a volume as possible. Samples of standard paleomagnetic size (12.9 ml) are easily accommodated, and even over twice this sample volume, the sensitivity does not vary by more than about 5%. An additional pair of reference coils is used to null the directly coupled signal. A small number of turns in the coils keeps self-resonances above about 0.5 MHz. The signal is locally preamplified before sending to a PC computer for processing.

Signal acquisition is done with a high-end commercial sound card in a PC, driven by MATLAB. A wide-band signal generated with this card is used to drive the transmitter. Current input to the transmitter coils is used. The received signal is sampled at 192 kHz; a frequency-dependent susceptibility is computed by correlation and spectral division. A null (sample-free) measurement run is incorporated to reduce the effects of instrument drift. Measurement of a sample can take as little as 30 seconds, including loading and unloading. Tensor measurements for anisotropic samples are also possible, utilizing a rotating sample holder and a more complex measurement protocol.

**Figure 2.** Prototype of wideband EMI spectrometer. The prototype does not have a case. Not shown are the...
preamplifier, the transmitter unit or the computer used for signal acquisition.

Magnetic soils that present a serious problem for mine detection usually have susceptibilities of 1 mSIU or greater. Thus the sensitivity objective for the instrument was an ability to delineate accurately the susceptibility spectrum of a standard 12.9 ml specimen with a susceptibility of about 1 mSIU. Therefore, base level drifts and noise should not much exceed 0.01 mSIU over the measurement bandwidth of 100 Hz to about 70 kHz.

**Figure 3.** Wide-band susceptibility response of a "problem soil" from Bosnia, in milliSI units. In-phase as blue crosses; quadrature response (emulating an induction response) of about $-3 \times 10^{-4}$ SI as red circles.

**Figure 4.** Wideband noise floor of the instrument a measurement, from an empty sample holder, close to $10^{-5}$ SI units. Colors and symbols as in Figure 3.

**Figure 5.** Induction response of a small metal object (Canadian penny) in two orthogonal directions, expressed as an equivalent susceptibility of a sample volume of 12.9 ml. Colors and symbols as in Figure 3.

**SIMULATION CODE**

The main challenge in preparing the simulation code is not the computation of electromagnetic responses of soils and targets. In general, targets are small, so point target responses are appropriate (that is, the inducing field can be assumed uniform over the region of the target, and the fields of the target at the receiver can be assumed to be those of a point dipole). With targets typically buried less than 10 cm, shielding by overlying soil is typically small and often negligible. Standard algorithms for calculating fields in a layered environment have been available in the literature for some time (e.g. Grant and West, 1965; Wait, 1982; Ward, S and Hohmann, 1987; GuptaSarma and Singh, 1997). The primary goal in coding was to achieve usability by instrument designers on a wide range of instrument designs, with arbitrary coil arrangements, transmitter waveforms, and signal acquisition and processing, as well as the ability to use target and soil response data based on both theoretical models and experimental data such as produced by the spectrometer above.
Figure 6. Components of the detection simulation model used by the code.

Accordingly, effort has been directed towards an effective GUI and flexible methods of describing instrument configuration and target characteristics (Bailey and West, 2006). Target responses are characterized in terms of a pole-zero description (West and Bailey, 2006) in the complex frequency plane, a separate response for each principal axis of the target if required. The exponential decays associated with each pole can be pre-processed with the instrument signal processing algorithms. This permits a simple sum over these decay modes to be performed at each instrument location in a simulated survey, in which only the instrument-target coupling amplitudes need be recomputed at each location, not the full frequency or waveform dependence.

The final suite of models which the code is planned to handle are summarized in Table 1. The code is written in MATLAB. This facilitated several important features: users can enter theoretical responses as MATLAB formulae, which the code will understand; all of MATLAB’s editable plotting facilities are available, and the GUI permits exporting numerical results to the MATLAB workspace, where users can do any further analysis of them with their own code.

<table>
<thead>
<tr>
<th></th>
<th>HCC</th>
<th>HPC</th>
<th>TPD</th>
<th>TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS</td>
<td>U,S</td>
<td>U</td>
<td>U,S</td>
<td>U</td>
</tr>
<tr>
<td>LHS</td>
<td>U,S</td>
<td>U</td>
<td>U,S</td>
<td></td>
</tr>
<tr>
<td>FD3DS</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Design goals of the code. Sensor abbreviations are HCC - horizontal circular coils; HPC - horizontal polygonal coils; TPD - tilted point dipoles; TPC - tilted polygonal coils. Target and host abbreviations are: UFDPT - unshielded frequency-dependent point target; SFDPT - shielded frequency-dependent point target; FS - free space; LHS - conductive layered half-space with conductivity and frequency-dependent susceptibility specified in each layer; FD3DS - 1, 2, or 3D weak susceptibility distribution with global frequency-dependence.

CONCLUSIONS

We have developed an instrument for wideband measurements of magnetic susceptibility over the frequency range 100 Hz to 70 kHz. We have developed code for utilizing this data in the calculation of the induction response of small metal targets embedded in soils with frequency dependent magnetic permeability. These two tools should be useful in producing better designs for field instruments for humanitarian demining, which can distinguish between the quadrature response of the desired metal targets and the quadrature response caused by the frequency-dependent magnetic susceptibility of problem soils.

ACKNOWLEDGEMENTS

This work was supported by the Canadian Centre for Mine Action Technologies (CCMAT) of Defense Research and Development Canada (DRDC) as part of contract No. W7702-03R942/001/EDM. We gratefully acknowledge the assistance and guidance provided by DRDC personnel in at Suffield, Alberta, and especially the help from Dr.Yoga Das, technical authority for the contract. We also acknowledge the assistance provided by Dr Rob Moucha.

REFERENCES


