Journal of Applied Geophysics 90 (2013) 119–125

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Broadband soil susceptibility measurements for EMI applications

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ARTICLE INFO

Article history:
Received 29 November 2012
Accepted 21 January 2013
Available online 30 January 2013

Keywords:
Electromagnetic induction
Soil
Magnetic susceptibility
Remanent magnetization

ABSTRACT

When seeking low-metal targets, the success rate of an electromagnetic induction (EMI) system is often determined by the susceptibility of the soil near the object. In this paper, we begin the process of characterizing a random soil in terms of its effect on EMI sensor readings. After providing a brief review of the theory behind how soil susceptibilities affect EMI measurements, we measure the susceptibilities of 43 samples of soil from the United States, Puerto Rico, Iraq, and Afghanistan using a custom susceptibility sensor. We define a set of metrics and give the distribution of values for how magnetically active the soils are, how dispersive they are, and how well the commonly used log model fits to their susceptibility as a function of frequency. All measurements taken in the study are consistent with the log model of susceptibility if one accounts for the noise floor of the sensor. The sensor used for the measurements is described briefly and validated using a set of magnetic salts.

1. Introduction

Electromagnetic induction (EMI) sensors are frequently used to detect buried objects. These sensors come in two basic varieties: continuous-wave (CW) and pulsed-induction (PI). The simplest CW systems produce a single frequency on the transmit coil and seek variations on the receive coil voltage at this frequency to detect a buried target. Simple PI systems produce a pulse of transmitted current and at some time delay later, take a sample of the receive coil's response, or sample an integrated version of that response. A sensor that takes a single data point at each location will generally have a fairly low ability to discriminate between target types.

Modern EMI sensors work on the same principle as simple sensors, but take multiple data samples at each scan location. In CW sensors, this corresponds to multiple frequencies applied in a multisine. In the time-domain this corresponds to multiple time samples taken after the transmit current is turned off. A multiple sample approach allows the sensor to provide some discrimination ability and reduce the tendency to false alarm over a simple detector (Candy, 1996; Collins et al., 1999; Gao et al., 2000; Keiswetter et al., 2000; Sower and Cave, 1995). In both cases, the improvement in discrimination is related to the ability to more accurately measure the impulse response of the ground below the sensor. One way to understand this improvement is to consider this impulse response in the frequency domain.

The improvement observed in these systems can be related to the tendency of discrete metallic targets to have a frequency response that varies more than the magnetic response of the surrounding soil. When this is the case, very simple signal processing methods can be used to distinguish a change in the magnetic properties of the soil from a buried target. However, multiple authors have noted that when seeking low-metal targets, the frequency-dependent properties of the soil can be a major source of error (Buselli, 1982; Dabas et al., 1992; Das, 2006; Shamatava et al., 2007). This frequency dependence is often referred to as a viscous remanent magnetization, magnetic viscosity, or magnetic relaxation. These terms refer to the time-domain behavior of the mechanism. In this paper we work solely in the frequency domain and so adopt the more general term for a frequency-varying material property of “dispersion”.

The environmental factors that create this dispersion are still an area of research in the geomagnetics community (Dearing et al., 1996), but it does seem to be well established that the dispersion is created by a distribution of magnetic particles consisting of a single domain. Each particle introduces a Debye-like relaxation into the susceptibility, χ. This relaxation model originated in Néel's work on superparamagnetism (Néel, 1950), and was adopted to assemblies of single-domain particles in Vincenz (1965). It was initially applied to soils in Mullins and Tite (1973). Extensive measurements over a range of temperatures in Dunlop and West (1969) validated the theory also.

If one assumes that the particles have a log-uniform distribution of relaxations over the full bandwidth tested, an expression for the complex susceptibility as a function of frequency, ω, can be obtained (Dabas et al., 1992; Das, 2006),

$$\chi(\omega) = c(\ln(\omega/\omega_0) + j\pi/2) \quad (1)$$

where c and ω_0 are unknown real constants.

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http://dx.doi.org/10.1016/j.jappgeo.2013.01.009

This model of dispersive susceptibility is of interest to us because of its simplicity. We will refer to it as the log model. In Bailey and West (2005), Dabas et al. (1992) and Mullins and Tite (1973), a set of soil samples were tested and appear to fit the log model qualitatively.

While the theory of how soil susceptibility produces changes in the voltages on a receive coil is fairly well understood (Das, 2006), this does not tell the entire story of how soil affects an EMI sensor. This is because it neglects the signal processing portion of the sensor that translates the sequence of measured voltages into a decision on the presence of a target. In any practical sensor, the voltage on the coil is processed through several stages, some of which even incorporate the log-model described above (Candy, 1996; Lhomme et al., 2008; Pasion et al., 2007; Wei et al., 2011). Given that a sensor will incorporate some model of soil susceptibility into its processing, the question of how soil susceptibility affects an EMI sensor comes down to the question, "How well can we model the susceptibility of an unknown soil as a function of frequency?"

To our knowledge, the work to most closely address this question is Dabas et al. (1992), where a variety of soils from sites where the author had noticed anomalous magnetic responses are measured using a CW sensor over the frequencies from 80 Hz to 10 kHz. For our purposes, this work has limited applicability however, because it does not provide quantitative statements that would allow it to be applied in a sensor design context. Ideally, we would like to know the answers to the following questions about a random sample of soil,

- How magnetically active is it?
- How well does a constant fit its susceptibility?
- How well does the log-model fit its susceptibility?

In this paper, we begin to provide quantitative answers to these questions by defining a metric associated with each question and providing the statistics seen for these metrics for a wide variety of soils. In addition, we extend the upper frequency range measured by Dabas et al. (1992) from 10 kHz to 90 kHz.

In outline, the paper is as follows. First, we provide an overview of the well-known theory behind how soil susceptibilities produce a voltage on the receive coil of an EMI detector and why it is important to focus on the frequency-dependent part of that voltage. Since we work with CW sensors, we will describe the importance of the frequency-dependent part in terms of a simple CW system, but this component is also of importance in a PI system (Buselli, 1982). After that, we describe a custom susceptibility sensor designed to work on the same frequency range as a CW system we work with Scott (2007). We validate the sensor by measuring the permeability of a set of magnetic salts and showing a good agreement to the published values of these permeabilities. Next, we define a set of metrics that will allow us to relate measured soil susceptibilities to the questions posed above quantitatively. Finally, we test the susceptibilities of a set of 43 soil samples and discuss the distribution of the metrics seen for these soils.

2. Background

In this section, we give a brief review of the EMI sensing problem and the way that soil can cause false alarms. To do so, we will provide the form of the response seen on a simplified CW sensor and discuss how the susceptibility can be mistaken for a metallic object. In Fig. 1, we show a schematic of a transmit and a receive coil in the vicinity of a region of soil with susceptibility, χ, and a buried target of interest with polarizability dyadic, $\bar{\bar{\mathbf{c}}}$. In this analysis, we ignore the clutter problem. We assume that any point source will be a target of interest for examination by further signal processing, although in reality many point sources will simply be magnetic rocks or buried debris. We also treat the problem magneto-quasistatically, so all capacitive effects are ignored here. A voltage, V_x, is applied to the two inductors depicted in series in Fig. 1. These are, from left to right, the reference and transmit inductors. A reference voltage, V_{REF}, is recorded by the top amplifier. We are interested in the transfer function to the receive voltage, V_{RECV}/V_{REF}, and how it is affected by the region of susceptibility and discrete target.

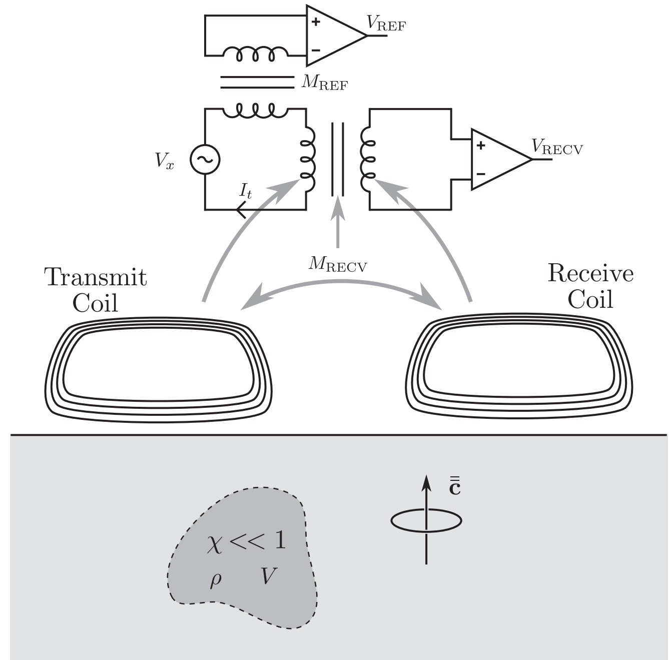

Fig. 1. Schematic of a generic EMI sensor over a body of non-magnetically active ground. Two types of targets are shown in the ground: a volume, V, of magnetically active soil, and a discrete target with polarizability, $\bar{\bar{\mathbf{c}}}$.

Let $\mathbf{H}^t$ and $\mathbf{H}^r$ be the magnetic fields produced by the transmit coil and receive coil, respectively, when no secondary sources are present and a current of I_t is driven through each. If we assume a small induced current, we can write the response of the system when the secondary sources are present as

$$\frac{V_{RECV}}{V_{REF}} = -\frac{\mu_0}{M_{REF} I_t^2}\left(\mathbf{H}^t(\mathbf{r})\cdot\bar{\bar{\mathbf{c}}}\cdot\mathbf{H}^r(\mathbf{r}) + \int_V \rho\chi\mathbf{H}^t\left(\mathbf{r}'\right)\cdot\mathbf{H}^r\left(\mathbf{r}'\right)d\mathbf{r}'\right) + \left(\frac{M_{RECV}}{M_{REF}}\right), \quad (2)$$

where χ is the mass susceptibility of the soil in the region, V, and ρ is the density there. M_{RECV} and M_{REF} are the mutual inductances of the transmit–receive pair and the reference transformer respectively. For the purposes of this paper, we assume χ and ρ are constant over the extent of the sample volume. The argument for this expression is essentially the argument used in Scott and Larson (2010) but here we introduce an additional term for the region of distributed susceptibility. Additional details on the use of reciprocity to compute contributions to a voltage from dipole sources can be found in Casey and Baertlein (1999) and Vesselle and Collin (1995).

The terms in this expression are, in order, caused by the metallic object being sought, the soil, and the mutual coupling between the coils. In many CW sensors, the coils can be designed to make M_{RECV} nearly zero. This means that the detection problem comes down to determining whether the voltage measured is caused by a sought target or soil (a false alarm). Here we will discuss three methods for making this decision. Each method is based on a different model of the soil susceptibility.

In the first case, we simply assume that χ is sufficiently near zero that we can classify large voltages as targets and smaller voltages as soil anomalies. In the second case, we note that a large portion of