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Survey design to maximize the volume of exploration of the InfiniTEM system when looking for discrete targets

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ABSTRACT

A discrete conductor model was used to estimate the volume of influence of a dual transmitter loop ground time-domain electromagnetic system (the InfiniTEM system). A sphere model in locally uniform field was used to calculate the signal from a subsurface target where the currents are constrained to flow vertically. The noise was determined from two field surveys. The signal-to-noise ratio was determined at each subsurface target location and each receiver location. The sensitivity of the InfiniTEM system at each target location was defined as the maximum of the absolute value of the signal-to-noise ratio for the ensemble of receiver positions in the survey. The volume of influence is defined as the volume where all targets have a sensitivity greater than one.

The manner in which volume of influence varies can be used to determine the optimal design parameters of an InfiniTEM survey. Our analysis reveals that the InfiniTEM system should be operated with a loop separation distance of 1.5 times the loop width (where width and separation are measured parallel to the traverse lines); and that there should be 4 traverse lines between the loops, corresponding to a traverse line spacing of 250 m for a loop width of 1000 m. For the purposes of delineating highly conductive targets, the optimal waveform parameters are a high duty cycle (in our case 0.75), a low base frequency (in our case 10 Hz), and measurements should be made in the *B* field domain. For the purposes of finding less conductive targets, the base frequency should be high (in our case 30 Hz), the duty cycle should be low (in our case 0.25), and measurements should be made in the $\partial B/\partial t$ domain. Our study confirms that the InfiniTEM system can detect a 100 m radius sphere at up to 925 m depth. We have determined that electromagnetic systems are most sensitive to bodies striking perpendicular to the traverse line. As well, we have confirmed that the InfiniTEM system is most effective at detecting vertical targets.

1. Introduction

TDEM systems work on the principles of electromagnetic induction. A time-varying electric current is passed through a transmitter loop producing a time-varying magnetic field in space. According to Faraday's law, this magnetic field induces electric currents in nearby conductors (Nabighian and Macnae, 1991). The induced currents produce a secondary magnetic field which is sensed by a receiver coil.

There are a number of applications of TDEM methods including environmental protection and hydrology, in which the mobility of subsurface fluids is monitored. Such surveys allow for the detection of permafrost and groundwater, the delineation of pollution plumes and saline intrusions in aquifers, the depiction of leakage from tailings dams, and the characterization of acid mine drainage (Keller, 1997; Sheard et al., 2005; Brakni, 2011). Mapping applications have become especially important in shallow environmental surveys (Sheard et al., 2005). The TDEM method also has important applications in the discovery and delineation of ore bodies and the characterization of unexposed conductive objects in civil engineering studies (Brakni, 2011). The method is also commonly used as a supplement to the magnetic method in geological mapping, where it provides depth information.

The focus of our interest is mineral exploration, where TDEM methods have had extensive application (Nabighian and Macnae, 1991). One weakness of the TDEM method is a result of the large horizontal loop that is normally used, which does not produce strong horizontal primary magnetic fields. In Archean terranes, diapirical plutonism has rendered volcanic strata vertical (Van Kranendonk et al., 2004), so syngenetic ore bodies, which are generally stratabound are often vertically dipping. Faraday's law predicts that horizontal primary magnetic fields will couple strongly with vertically dipping bodies. Thus, horizontal primary magnetic fields are required when exploring for vertically dipping Archean syngenetic mineralization. This type of mineralization includes volcanogenic Zn–Cu, Zn–Cu–Au deposits, magmatic Ni–Cu–PGE deposits, and syngenetic Au deposits (Thurston et al., 2008). As these mineralizing styles account for a large portion of the mineral resources within the Canadian Shield, the need for a TDEM

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system capable of producing a strong horizontal primary magnetic field is apparent. This need for a horizontal field inspired the development of the InfiniTEM system.

The InfiniTEM system was developed in a research project initiated in 2003 by Abitibi Geophysics, a geophysical contracting company (Malo-Lalande, 2007). The transmitter configuration is inspired by the dual-loop moving configuration of the transient electromagnetic method described by Spies (1975) (Malo-Lalande, 2007; Boivin, 2007). The transmitter loop consists of two half-loops of reverse polarity that are connected in series in a figure-eight-shaped loop design (Bérubé et al., 2006; Malo-Lalande, 2007; Brakni, 2011). The receiver is moved over the survey area along traverse lines, within and outside the confines of the transmitter loop. The receiver data are used to infer the conductivity structure of the subsurface.

The InfiniTEM system is relatively new and little is known about its full potential with regard to specific target detection, as well as which survey and target parameters will optimize the volume of exploration. Field testing has enabled the empirical determination of survey parameters required for operation of the InfiniTEM system. However, a knowledge gap exists because of the uncertainties and practical limitations associated with field testing. As a result, theoretical modeling may yield information otherwise unobtainable from field tests. Optimization of the InfiniTEM survey parameters may result in the discovery of deeper mineralizing horizons in Archean terranes, and ensure that no shallow targets are left unrecognized within a survey area.

In this contribution, we seek to shed some light onto the effectiveness of the InfiniTEM system and its potential for finding economic targets (ore bodies). In particular we determine the transmitter waveform base frequency, duty cycle, array geometry, and survey line spacing which guarantees most effective coverage of a survey area. The optimal parameters will vary depending on the size and orientation of the targets and their conductivities. We hope that our study motivates the use of the concept of volume of influence to determine the optimal parameters of other systems, and when using more complex models (e.g., conductive host or conductive overburden).

The term "footprint" is used by geophysical practitioners to denote the surface area of the ground that is affected by an EM system (Liu and Becker, 1990; Kovacs et al., 1995). This concept was extended to the depth dimension in a half-space by Reid and Macnae (1999) and Beamish (2003, 2004). The coupling of the transmitter with a specific target was taken into account by Reid and Vrbancich (2004). The term "volume of influence" takes into account the coupling of the transmitter to the target and the coupling of the target to the receiver to estimate the volume of exploration (Smith and Wasylechko, 2012). Quantification of the effectiveness of various survey parameters of the InfiniTEM system will be assessed using this concept of the volume of influence.

Smith and Wasylechko (2012) used the sphere model of Smith and Lee (2001) to determine sensitivity cross sections of AEM exploration systems. The cross sections were generated by evaluating the response of a sphere in free space excited by an elevated magnetic dipole. A sphere in free space is a good assumption in resistive environments (e.g., the Canadian and Scandinavian Shields). More complex models would be required in other environments. The sphere was moved to different subsurface locations within the section. The sensitivity of the AEM system was defined as the maximum of the absolute value of the signal-to-noise ratio for all system positions on a profile. In their study, it was found that the sensitivity of an AEM systems depended heavily on the orientation of the induced currents at the subsurface target.

In this paper, the approach of Smith and Wasylechko (2012) is extended to ground EM systems. The sphere model of Smith and Lee (2001) for EM modeling is used to determine the optimal survey parameters for an airborne EM system by calculating sensitivity cross sections. In contrast to the previous approach, sensitivity cross-sections are not calculated. Rather, we probe the sensitivity of the InfiniTEM system by discretizing the subsurface inside some volume of interest.

2. Methodology

2.1. Sphere model

Smith and Lee (2001) derived the analytic expressions required for computing the impulse response of a sphere in free space excited by a dipolar field that is assumed to be locally uniform at the sphere. An impulse response is defined as the magnetic-field response of the target once it has been subjected to an impulse in current in the transmitter. In reality, time variation of the current in the transmitter is represented by a more complex waveform.

The primary field $\boldsymbol{H_0}$ of an infinitesimal dipole transmitter at the sphere can be computed using the expression (Smith and Lee, 2001):

$$\boldsymbol{H}_0 = \frac{1}{4\pi r^3}\left(\frac{3\boldsymbol{m_{Tx}} \cdot \boldsymbol{r}}{r^2}\boldsymbol{r} - \boldsymbol{m_{Tx}}\right), \tag{1}$$

where $\cdot$ denotes the dot product operator, $\boldsymbol{m_{Tx}}$ is the dipole moment of the transmitter vector, $\boldsymbol{r}$ is the vector offset from the transmitter to the sphere and r is the magnitude of $\boldsymbol{r}$. This dipole formula is defined in a Cartesian coordinate reference frame, with its origin at the transmitter.

For computing the primary field of the InfiniTEM transmitter, we follow the approach of Reid and Macnae (1999) and numerically integrate expression (1) over the area of the two transmitter loops, placing an infinitesimal magnetic dipole at multiple locations within the transmitter loop. Equivalently electric dipoles could have been integrated around the loop, but the Smith and Wasylechko (2012) formulation was for magnetic dipoles, so we chose to use this approach. Using electric dipoles may be faster, but we traded this off with a reduction in coding time as the coding was already done.

To determine the number of magnetic dipoles required for generating an accurate primary field, a convergence test was performed. The subsurface was discretized in intervals of 32 m, 20 m and 20 m, in the x, y, and z directions respectively. The convergence test consisted of monitoring the spatial composition of the primary field 20 m below surface as a function of the number of magnetic dipoles used to approximate the loop. The spatial composition is the percentage of the field that belongs to a particular Cartesian component. For example, if the field at a subsurface location lies in the y direction, its spatial composition is $x = 0\%$, $y = 100\%$, $z = 0\%$. If the field at a subsurface location lies diagonally in the y–z plane, its spatial composition is $x = 0\%$, $y = 50\%$, $z = 50\%$.

Fig. 1 shows the variation of the spatial composition of the primary field at 20 m depth below the transmitter loops during computation of the surface integral. The fields lying below the two transmitter loops plot on top of each other, as a result of the symmetry of the configuration. The fields reach a stable spatial composition when the transmitter loops are discretized as ~4624 magnetic dipoles.

To determine the robustness of this approximation, the spatial composition of the primary field at 100 m depth is shown in Fig. 2. In contrast to the shallower fields, this time convergence is reached with about eight hundred magnetic dipoles. We can therefore safely approximate the primary field of the InfiniTEM loop with 4624 magnetic dipoles to ensure convergence of the fields at depths greater than 20 m. The 4624 magnetic dipoles ensure convergence of the fields for a loop size of 800 m in the x direction and 800 m in the y direction. For loops of different dimensions, the amount of dipoles needed to approximate the loops is scaled proportionately.

An example section of the primary field computed is displayed in Fig. 3. The characteristic horizontal primary field located between the two transmitter loops is readily seen. Small irregularities can be observed in the near-surface fields. However, the fields at depth vary continuously, proving that the surface integral has been approximated