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Non-standard electromagnetic induction sensor configurations: Evaluating sensitivities and applicability

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ABSTRACT

For near surface geophysical surveys, small-fixed offset loop–loop electromagnetic induction (EMI) sensors are usually placed parallel to the ground surface (i.e., both loops are at the same height above ground). In this study, we evaluate the potential of making measurements with a system that is not parallel to the ground; i.e., by positioning the system at different inclinations with respect to ground surface. First, we present the Maxwell theory for inclined magnetic dipoles over a homogeneous half space. By analyzing the sensitivities of such configurations, we show that varying the angle of the system would result in improved imaging capabilities. For example, we show that acquiring data with a vertical system allows detection of a conductive body with a better lateral resolution compared to data acquired using standard horizontal configurations. The synthetic responses are presented for a heterogeneous medium and compared to field data acquired in the historical Park Sanssouci in Potsdam, Germany. After presenting a detailed sensitivity analysis and synthetic examples of such ground conductivity measurements, we suggest a new strategy of acquisition that allows to better estimate the true distribution of electrical conductivity using instruments with a fixed, small offset between the loops. This strategy is evaluated using field data collected at a well-constrained test-site in Horstwalde (Germany). Here, the target buried utility pipes are best imaged using vertical system configurations demonstrating the potential of our approach for typical applications.

1. Introduction

Loop–loop electromagnetic induction (EMI) systems with a small fixed offset (such as the EM38, EM31, or the DualEM device) allow mapping of variations in electrical conductivity within the uppermost meters of the subsurface. These systems, which are also called ground conductivity meters (GCM), are often used in archeological prospection (Tabbagh, 1986; Lück and Eisenreich, 1999; Simpson et al., 2009), soil science (Corwin and Rhoades, 1982; Abdu et al., 2007), precision farming applications (Doolittle et al., 1994; Yoder et al., 2002; Gebbers et al., 2009), as well as for soil salinity mapping (Triantafilis et al., 2000; Nogués et al., 2006) and detecting buried objects such as utility pipes (Nelson and McDonald, 2001). Most of the surveys are acquired by using one fixed loop configuration and one selected direction of data acquisition. As a consequence, often the recorded data are only interpreted in terms of apparent conductivity. Nowadays, large scale multi-configuration acquisition becomes feasible (Saey et al., 2012, 2013) and one needs to invert at least a minimum of two configurations in order to determine a heterogeneous distribution of conductivity. This has been done by joint 1D inversion of different standard configurations (Santos et al., 2010; von Hebel et al., 2014), which are known as horizontal and vertical coplanar loops (HCP and VCP), as well as the perpendicular loop (PERP) configuration as presented by Frischknecht et al. (1987). For all of these configurations, the system is placed parallel to ground surface; i.e., both loops are at the same height above ground.

In this paper, we study the pattern of the eddy currents when data are acquired with an inclined fixed-offset system (i.e., the loops are at different angles with regard to the ground). We estimate the sensitivities of such inclined ground conductivity meters and, by using spectral 3D forward modeling, we generate multi-angle synthetic data for a synthetic model consisting of various buried conductive and resistive objects. The calculated multi-angle synthetic responses are compared to two multi-angle field data examples. Resulting from the analysis of multi-angle sensitivities and our synthetic study, we suggest a new strategy for data acquisition, which allows us to obtain a more intuitive apparent conductivity map compared to standard strategies of data acquisition. Finally, the proposed method is tested and compared with the standard HCP configuration for data sets acquired across known buried utility pipes at a well-constrained test-site.

2. Theory

Electromagnetic (EM) loop–loop systems consist of one transmitter loop (Tx) emitting a time harmonic electromagnetic field, which interacts with the conductive ground, and a receiver loop (Rx), which

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measures the magnetic field resulting from this interaction. When the offset between Tx and Rx is fixed and small (typically 1 m to 3 m), such EM systems are called EMI sensors or GCM. Here, we are interested in using such EMI systems at different inclinations and, thus, we first have to derive the Maxwell equations for inclined loops. After that, we will present our approach to model data recorded using an EM38 device, which is the EMI instrument used to collect our field data examples presented later on.

2.1. EM field for an inclined magnetic dipole source

The theory of electromagnetic fields caused by an inclined loop source has been already studied by Gavril et al. (1988) and Mor et al. (1989) by solving the equation of the electrical potential vector A. In this approach, the source is modeled as a circular electrical current. Another approach is to consider the source as an equivalent magnetic dipole. This approach has been employed for correcting bird pitches in airborne harmonic electromagnetic systems (Fitterman and Yin, 2004; Yin and Fraser, 2004) by using scalar potentials (Wait, 1982). By using a potential vector formulation, the electromagnetic field of an inclined magnetic dipole can also be easily derived using the magnetic potential vector F for a magnetic dipole source. This approach is presented in Guillemoteau et al. (2015b) and is briefly presented in the following.

In order to model the electromagnetic field generated by an inclined magnetic dipole, we solve the equation of the magnetic potential vector (Ward and Hohmann, 1987, p. 146)

$$\nabla^2 \mathbf{F} + k^2 \mathbf{F} = \mathbf{J}_m^S, \tag{1}$$

where $k = \sqrt{\omega^2 \mu\varepsilon - i\omega\mu\sigma}$ is the wave number which depends on the angular frequency ω of the harmonic EM excitation and the electrical properties of the ground; i.e., on electrical conductivity σ, dielectric constant ε, and magnetic susceptibility μ. For the range of frequencies used by EMI sensors (0.5–50 kHz) and considering the range of electrical properties typically observed in the subsurface, one can use the quasi-static approximation for which the first term of the wave number is negligible. In addition, for most materials we can assume a constant magnetic susceptibility equal to the one of the vacuum ($\mu = \mu_0$). Thus, the wave number is given by $k = \sqrt{-i\omega\mu_0\sigma}$ and only depends on σ and ω. For the case of an inclined magnetic dipole with ϕ being the angle of inclination, the magnetic source term $\mathbf{J}_m^S$ is given by

$$\mathbf{J}_m^S = -i\omega\mu_0 m\delta(x)\delta(y)\delta(z)\,(\sin\phi\mathbf{x} + \cos\phi\mathbf{z}), \tag{2}$$

where m is the magnetic moment and δ is the Dirac delta function that is used to describe the spatial singularity of a dipole. We note that the source term is oriented in two directions; i.e., it is separated into a horizontal magnetic dipole (HMD) and a vertical magnetic dipole (VMD) component. Following from the linearity of Maxwell's equations, the magnetic field $\mathbf{H}^0$ measured by Rx in air (layer 0) in the presence of a conductive ground (layer 1) is simply given by

$$\mathbf{H}^0 = \sin\phi\mathbf{H}^0_{HMD} + \cos\phi\mathbf{H}^0_{VMD}, \tag{3}$$

where $\mathbf{H}^0_{HMD}$ and $\mathbf{H}^0_{VMD}$ are the magnetic fields generated by a horizontal and a vertical magnetic dipole, respectively, located in the air layer over a homogeneous ground. The formula to calculate the response as a function of the height of the source is given by Ward and Hohmann (1987). In a similar manner, the electric field $\mathbf{E}^1$ induced inside the ground (layer 1) is given by

$$\mathbf{E}^1 = \sin\phi\mathbf{E}^1_{HMD} + \cos\phi\mathbf{E}^1_{VMD}, \tag{4}$$

where $\mathbf{E}^1_{HMD}$ and $\mathbf{E}^1_{VMD}$ are the horizontal electrical fields induced inside the ground by a horizontal magnetic dipole and a vertical magnetic dipole, respectively. The formulas for each component can be found in Tølbøll and Christensen (2007) and Guillemoteau et al. (2012) and are recalled here:

$$E^1_{x,HMD} = -\frac{i\omega\mu m}{4\pi}\int_0^\infty \left[\frac{2xy}{\rho^3}J_1(\lambda\rho) - \frac{xy}{\rho^2}\lambda J_0(\lambda\rho)\right] t_{TE}^{HMD} e^{-\lambda h} e^{-u_1 z} d\lambda, \tag{5}$$

$$E^1_{y,HMD} = \frac{i\omega\mu m}{4\pi}\int_0^\infty \left[\left(\frac{1}{\rho} - \frac{2x^2}{\rho^3}\right)J_1(\lambda\rho) - \frac{x^2}{\rho^2}\lambda J_0(\lambda\rho)\right] t_{TE}^{HMD} e^{-\lambda h} e^{-u_1 z} d\lambda, \tag{6}$$

$$E^1_{z,HMD} = 0, \tag{7}$$

$$E^1_{x,VMD} = \frac{i\omega\mu m}{4\pi}\frac{y}{\rho}\int_0^\infty \frac{\lambda^2}{u_1} J_1(\lambda\rho) t_{TE}^{VMD} e^{-\lambda h} e^{-u_1 z} d\lambda, \tag{8}$$

$$E^1_{y,VMD} = -\frac{i\omega\mu m}{4\pi}\frac{x}{\rho}\int_0^\infty \frac{\lambda^2}{u_1} J_1(\lambda\rho) t_{TE}^{VMD} e^{-\lambda h} e^{-u_1 z} d\lambda, \tag{9}$$

$$E^1_{z,VMD} = 0. \tag{10}$$

Here, λ is the radial component of the wave number in cylindrical coordinates, ρ is the horizontal distance between Tx and Rx, J_n are Bessel functions of the nth order, u_1 is the vertical component of the wave number for the ground (layer 1), and $t_{TE}^{HMD} = 2\lambda/(\lambda + u_1)$ and $t_{TE}^{VMD} = 2u_1/(\lambda + u_1)$ are the coefficients of transmission for a HMD and a VMD source, respectively. Due to the high contrast in conductivity between the air and the ground, the electric field inside a flat homogeneous ground is always parallel to the surface whatever the dipole inclination. It follows that, for a horizontal ground surface, there are no vertical eddy currents (transverse electric mode only) and, therefore, it is not possible to detect the vertical anisotropy of the medium.

In Fig. 1, we show the horizontal electric field induced into the ground by a magnetic dipole source working at a frequency of f 14,600 Hz for three different inclinations. We see that a horizontal loop ($\phi = 0°$) generates circular current patterns with no preferred directions (Fig. 1a). For a loop inclination of $\phi = 45°$ (Fig. 1b), the distribution of the ground induced currents is characterized by a pronounced asymmetrical shape with increased induced currents beneath the part of the loop that is closer to the ground. The horizontal magnetic dipole ($\phi = 90°$) shows induced currents with a clear preferential direction parallel to the plain of the loop (Fig. 1c). Thus, changing the azimuth of a vertical loop would allow for detecting the horizontal anisotropy of a conductive half-space.

2.2. Modeling McNeill conductivity data

EMI sensors are sensitive to the total magnetic field $\mathbf{H}$ consisting of a primary field $\mathbf{H}_p$ propagating in air and a secondary field $\mathbf{H}_s$ induced by eddy currents in a conductive ground:

$$\mathbf{H} = \mathbf{H}_p + \mathbf{H}_s. \tag{11}$$

The primary field is real because it is in-phase (IP) with the source. The secondary field is complex because it contains a quadrature or out of phase (OP) part:

$$\mathbf{H}_s = \mathbf{H}_s^{IP} + i\mathbf{H}_s^{OP}. \tag{12}$$

In this study, we consider the apparent conductivity σ_a data which are derived from $\mathbf{H}_s^{OP}$ by using the following formula