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System stability and calibrations for hand-held electromagnetic frequency domain instruments

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ABSTRACT

There are a few multiple-frequency domain electromagnetic induction (EMI) hand-held rigid boom systems available for shallow geophysical resistivity investigations. They basically measure secondary field real and imaginary components after the system calibrations. One multiple-frequency system, the EMP-400 Profiler from Geophysical Survey Systems Inc., was tested for system calibrations, stability and various effects present in normal measurements like height variation, tilting, signal stacking and time stability.

Results indicated that in test conditions, repeatable high-accuracy imaginary component values can be recorded for near-surface frequency soundings. In test conditions, real components are also stable but vary strongly in normal surveying measurements. However, certain calibration issues related to the combination of user influence and measurement system height were recognised as an important factor in reducing for data errors and for further processing like static offset corrections.

1. Introduction

The electromagnetic induction (EMI) method is used to study electrical conductivity variations of the subsurface. The primary electromagnetic field is generated by a grounded wire, loop or small-coil, and the secondary field after the suppression of the primary field is detected and is dependent on the earth's electrical conductivity and magnetisation structure. One technique is to use hand-held systems with rigid boom installation and small intercoil spacing where transmitters and receivers behave like magnetic dipoles. Applied frequencies start from a few hundred up to tens of thousands of Hertz (Hz), where the range is limited at the lower end by a very low level of induced voltages and at the higher end by reaching the limit of quasi-stationary range (Spies and Frischknecht, 1991), and occurring displacement currents.

Normal use of EMI surveying with hand-held rigid boom instruments has coil separations between 0.5 and 6.0 m. Surveyors can utilise either the single- or multi-frequency technique or can use one or several different coil spacings and coil geometries. This study deals with multi-frequency instrument and technique using one set of coils. System output is in the form of the secondary field real and imaginary components, from which the conversion to electrical conductivities is made with the Low Induction Number (LIN) approach or with more elaborate post-processing. Depending on the electrical properties, coil separation and frequencies, the typical depth penetration varies from ground surface to 10–20 m at the highest.

For hand-held small intercoil spacing electromagnetic systems, the primary field is very strong at short distances and stability and levelling issues are more problematic than for larger scale systems. At the same time, secondary field components are relatively small and greater accuracy is required to enable reliable quantitative earth soundings. Measurement accuracy, system stability and drift have been important issues for a long time and have been studied by several authors. For example, Abraham et al. (2006) studied the use of the multi-frequency Geophex GEM-2 system using direct current (DC) resistivity stations and repeated EMI measurements to analyse the noise, drift levelling and calibration. Mitsuhata and Imasato (2009) studied on-site bias noise correction for a small intercoil spacing multi-frequency instrument. Delefortrie et al. (2014) developed a calibration procedure for drift correction using calibration tie line and time series analysis for a multiple coil-spacing instrument.

Sudduth et al. (2001) found that in field scale agricultural survey drift can form a significant fraction of on-site electrical conductivity-induced variations. They used a calibration transect to adjust for the drift in a Geonics EM38 sensor. Collection of individual datasets within each surveyed field was necessary for the best results. One major source of the drift, temperature change, was also concluded as a source in the study published by Robinson et al. (2004).

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Minsley et al. (2012) analysed both systematic and random errors in EMI measurements. They published a modelling solution to recover both multiplicative and additive calibration factors at each frequency. A minimum of two calibration locations are required with the ground truth electrical model. To filter random errors, they developed a principal component analysis-based filter. The signal level offsets can also be corrected during the data inversion stage as Sasaki et al. (2010) have shown with the developed electromagnetic 3-D inversion scheme.

The objective of this paper is to study a survey-related system and geometry parameters and stability for a multi-frequency instrument used for sounding experiments and investigations. The study aimed to push forward knowledge of measurement related factors and experimental data of factors involved. Accurate quantitative measurements are critical to reach a stage beyond EMI anomaly mapping, particularly if environmental measurement and monitoring uses are of interest. Comprehensive analysis of the frequency discrimination effect – if the electrical conductivity structure enables frequency sounding characteristics or not – is beyond the scope of this paper.

2. General electromagnetic dipolar field characteristics

Fundamental equations for a magnetic dipole as a source on a homogeneous half-space (HS) are well known. For vertically oriented magnetic dipoles (HCP, horizontal coplanar) lying on a homogeneous ground surface (height h = 0.0 m), the electromagnetic field is complex in nature and can be expressed for the secondary vertical magnetic field as the mutual coupling ratio (Spies and Frischknecht, 1991)

$$\frac{Z}{Z_0}=\frac{2}{k^2r^2}\left[\left(9+9ikr-4k^2r^2-ik^3r^3\right)e^{-ikr}-9\right] \tag{1}$$

For the horizontally oriented magnetic dipoles (VCP, vertical coplanar) lying on a homogeneous surface (h = 0.0 m), the secondary horizontal field as the mutual coupling ratio is

$$\frac{Z}{Z_0}=\frac{2}{k^2r^2}\left[3+k^2r^2-\left(3+3ikr-k^2r^2\right)e^{-ikr}\right] \tag{2}$$

where

r = distance (coil separation), m
k = $(\mu\varepsilon\omega^2+i\sigma\mu\omega)^{1/2}$ is the complex propagation constant
i = $\sqrt{-1}$
σ = electrical conductivity, S/m = $1/\rho$, where ρ = electrical resistivity, Ωm
μ = $\mu_r\mu_0$, half-space magnetic permeability, Vs/Am
ε = $\varepsilon_r\varepsilon_0$, half-space dielectric permittivity, F/m
ω = $2\pi f$, angular frequency, 1/s
f = frequency, 1/s (Hertz)
μ_0 = vacuum magnetic permeability = $4\pi\cdot10^{-7}$H/m
ε_0 = vacuum dielectric permittivity = $8.854\cdot10^{-12}$ F/m
μ_r and ε_r are relative magnetic permeability and dielectric permittivity, respectively.

In Eqs. (1) and (2) the resulting field can be separated into in-phase (real, Re) and out-of-phase (imaginary, Im) components, typically expressed as normalised percentage (%), parts per thousand (ppt) or parts per million (ppm) values. The governing parameter in the frequency domain is the induction number B,

$$B=(\sigma\mu\omega/2)^{1/2}\,r \tag{3}$$

so that the half-space response varies with B, and various combinations of electrical conductivity, magnetic permeability, excitation frequency and distance may yield identical values. This relationship forms the basis for frequency and geometric sounding alternatives used in the instrumentation.

Although the formulas look quite different, they give almost identical results for imaginary components, and for real components the HCP values are double the VCP values when B < 0.1. Above the limit, HCP values grow more rapidly than in VCP mode.

When the dipole height deviates from zero, a full analytical solution must be used to solve the electromagnetic field components (Spies and Frischknecht, 1991). The solution requires numerical integration for the homogeneous half-space model as well as for horizontally layered electrical earth models.

However, the increasing height influence and attenuation for Im-components can be derived using quasi-static formulas (Frischknecht et al., 1991) and in the LIN range, for HCP configuration as in formula (4)

$$\frac{Im_h}{Im_0}=\left[4\left(\frac{h}{r}\right)^2+1\right]^{-\frac{1}{2}} \tag{4}$$

and for VCP configuration as given in formula (5)

$$\frac{Im_h}{Im_0}=\left[4\left(\frac{h}{r}\right)^2+1\right]^{\frac{1}{2}}-2\left(\frac{h}{r}\right) \tag{5}$$

where

Im_h and Im_0 are imaginary component values at heights h and zero, respectively.

In Fig. 1 the half-space response for HCP configuration and for Re- and Im- components is shown for coil heights 0.0 m and 1.0 m over a range of induction numbers B. Zero height solid line curves can be calculated by using formula (1). The imaginary component at a height of 1.0 m is about half of the zero-level value and in the Re-component, height attenuation is very small when the induction number is <0.1 but rises abruptly above that. At zero height the Im-component turns rapidly downwards and becomes negative when B exceeds 1.0 and other curves express bending at higher B values.

For multi-frequency surveying and soundings, the depth penetration is one fundamental factor to be considered. Huang (2005) has shown in his analysis that the depth penetration is close to the square root of the skin-depth calculated for coil separations between 0.2 and 2 m. This result has several implications for the EMI technique and observable field component values:

- Frequencies and earth electrical conductivities influence the surveying depth to a limited extent. For example, in 100 Ωm resistivity ground, the depth penetration for frequency 1 kHz is approximately 12.6 m and for 10 kHz approximately 7.1 m. For 10 Ωm ground the depth penetration at 10 kHz is approximately 4.0 m correspondingly.
- Within the surveyed depth range, the responses from electrical structures sum up, so resulting differences in electrical properties detected with various frequencies in the same position are small by theory. Converted electrical conductivity or resistivity values derived from adjacent frequencies (should) correlate strongly.
- The frequency differentiation capability with short intercoil spacing multi-frequency systems is limited. A broad frequency band is required to cover a significant depth range or multiple coil-spacings can be used instead (geometric sounding).

Acquired imaginary component data is normally converted to apparent electrical conductivities by using exact half-space solution or limited range LIN approximation. The term apparent is used to describe the average nature of conductivity resulting from inhomogeneous earth.