



Application note

Temperature-dependent hysteresis effects on EM induction instruments: An example of single-frequency multi-coil array instruments



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ABSTRACT

Non-invasive electromagnetic (EM) induction has been used in agriculture, earth science and archaeology. This is because the apparent electrical conductivity (EC_a or quadrature response – $mS\ m^{-1}$) and the apparent magnetic susceptibility (in-phase response – ppt) which they measure are related to soil properties such as clay, soil mineralogy, salinity and soil moisture as well as buried metal objects. Although the accuracy issues of the single-coil array EM38 meter have been widely discussed, the accuracy issues of the next generation, multi-coil (perpendicular-PRP and horizontal-HCP) array DUALEM meter, particularly the instrument drift, have little been reported. In this study, the diurnal drifts of a DUALEM-421S and a DUALEM-21S were studied at single locations (for a 24 h period) and along a 480-m transect (at five typical operation times). Based on the experiment results of the two DUALEM instruments, it was found that the EC_a readings of the PRP arrays were more stable than those of the HCP arrays. The reverse was true for in-phase measurements. Specifically, during the diurnal cooling and heating phases, EC_a measurements of the HCP arrays and in-phase PRP arrays showed different correlations with ambient temperature, which can be defined as instrument-specific and temperature-dependent hysteresis effects. In addition, the stability of EC_a and in-phase measurements increased with array length and was much less compared to the theoretical values. It was suggested a similar experiment should be conducted for the DUALEM instruments before the DUALEM surveys and repeated DUALEM surveys for mapping the spatio-temporal variations in soil properties should be carried out at the similar temperature (i.e., similar ambient temperature and within the same warming or cooling phase). In addition, shading the instruments with non-conductive thermal insulation should be adopted and drift correction procedures should be applied to improve the quality of the measurements of the EM instruments.

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1. Introduction

Non-invasive electromagnetic (EM) induction techniques have been used in agriculture, ecology, hydrology, environmental science, earth science and archaeology (Doolittle and Brevik, 2014). This is because the apparent electrical conductivity (EC_a or quadrature response – $mS\ m^{-1}$) and the apparent magnetic susceptibility (in-phase response – ppt) which they measure are related to soil properties such as clay, soil mineralogy, salinity and soil moisture (Corwin and Lesch, 2005) as well as buried metal objects (De Smedt et al., 2013).

In order to provide reliable measurements to the end-users, a number of researchers have studied the accuracy issues of the EM instruments, including instrument and data acquisition system

accuracies, mobile system effects, calibration of EC_a readings to soil physical properties, the effects of varying ambient temperature and magnetic conditions as well as the varying resistance, inductance and capacitance of the transmitter and receiver coils (Sudduth et al., 2001; Robinson et al., 2004; dos Santos and Porsani, 2011; Ma et al., 2011; Mester et al., 2014).

However, most of the studies were focused on the single-frequency, single-coil array EM instrument, such as the Geonics EM38 (Geonics Limited, Mississauga, Ontario). The measurement errors of the EM instruments can be classified into two categories, namely, systematic or random errors and a number of noise reduction procedures have been proposed (Minsley et al., 2012; White and Beamish, 2015).

Recently, the multi-coil array DUALEM-21S and DUALEM-421S meters (Duaem, Inc., Milton, Ontario) have become popular because they enable multiple sets of EC_a data to be collected simultaneously. The advantage is that in a single pass different depths of

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soil ECa can be measured and therefore the possibility of generating 2-d and 3-d models of electromagnetic conductivity images (EMCI) by EM inversion and akin to electrical resistivity tomography (ERT) are being realised (Triantafyllis and Monteiro Santos, 2010, 2013; Saey et al., 2013).

Although the accuracy issues of this type of EM instrument have been previously reported by several researchers (Abdu et al., 2007; Taylor and Holladay, 2013), the diurnal temperature effects on the instruments have not been well studied. Recently, Delefortrie et al. (2014) and De Smedt et al. (2016) established different calibration procedures to remove the drift of DUALEM-21S due to various sources of noise. However, their assumption that the EC_a dataset collected within a short period of time did not suffer from drifts remains to be confirmed because EC_a measurements may be affected by varying physical properties of the transmitter and receiver coils due to the varying ambient temperature as demonstrated by Robinson et al. (2004) and Mester et al. (2014). In addition, they also found that the drifts of the EC_a and in-phase measurements of the DUALEM-21S were different for different coil arrays.

To further investigate the novel single-frequency multi-coil array EM instrument, we aim to explore the effect of diurnal temperature influences on the drifts of (i) a DUALEM-421S and (ii) a DUALEM-21S at single locations during a 24 h period, and (iii) a DUALEM-421S along a 350 m long transect at five time steps of a day. We also seek to determine the effect of shielding on the drifts of DUALEM-421S and DUALEM-21S. The experiments are important because they can provide guidance for minimising the instrument drifts when mapping the spatio-temporal variation in soil moisture content and other soil properties at multiple depths using this type of EM instrument (Huang et al., 2017, in press).

2. Materials and methods

2.1. Study site

The study field is located on an experimental farm of the Plant Breeding Institute of The University of Sydney, Cobbitty, New South Wales, Australia (34°01'22.86"S, long. 150°39'54.96"E). The study area has mean annual maximum and minimum temperatures of 23.7 and 10.2 °C with a mean annual precipitation of 789 mm (BOM, 2016). The soil is predominantly non-saline across the study area (electrical conductivity of the 1 part soil: 5 parts water <2 dS m⁻¹). Detailed information about the variation in soil properties across the study field can be found in Huang et al. (2017).

2.2. DUALEM-421S and DUALEM-21S configuration

The DUALEM-421S (DUALEM Inc., Milton, ON, Canada) simultaneously measures soil apparent electrical conductivity (EC_a or quadrature response, mS m⁻¹) and the apparent magnetic susceptibility (in-phase response – ppt) to six different depths. It consists of a transmitting coil (Tx) that operates at 9.0 kHz and three pairs of receiver coils (Rx). The Tx and one Rx pair have horizontal windings which form a horizontal coplanar array (HCP). The distance between the Tx and the coplanar Rx are 1, 2, and 4 m. The notation 1mHcon, 2mHcon, and 4mHcon represent EC_a and correspond to depths of exploration (DOE) of 1.5, 3.0, and 6.0 m, respectively. The other coils in each Rx pair have vertical windings and with the Tx forms perpendicular arrays (PRP). The distances between the Tx and the Rx are 1.1, 2.1, and 4.1 m, respectively. The respective EC_a measurements are represented by 1mPcon, 2mPcon, and 4mPcon with DOE corresponding to approximately 0.5, 1.0, and 2.0 m, respectively. The DUALEM-421S also collected the in-phase (ppt)

measurements of the EM fields. The notations 1mHip, 2mHip and 4mHip represent in-phase measurements by HCP coil arrays and 1mPip, 2mPip and 4mPip represent in-phase measurements by PRP coil arrays. The DUALEM-421S has a built-in sensor which measures the internal temperature of the instrument and allows for temperature compensation of the measurement.

The configuration of the DUALEM-21S (DUALEM Inc., Milton, ON, Canada) is similar to that of the DUALEM-421S. Instead of three pairs of the Rx, DUALEM-21S only has two pairs of Rx. The distances between Tx and HCP Rx are 1 and 2 m, and the distances between Tx and PRP Rx are 1.1 and 2.1 m.

After personal communication with DUALEM Inc., we were informed that each DUALEM sensor was unique at the time of calibration, and compensation parameters might become less effective for a given array as a sensor aged.

2.3. Experiment I: stationary DUALEM-421S measurements

A site was selected in the middle of a bare field (150°39'48.16"E, 34°1'36.30"S). Four temperature probes (Thermocouples, Unidata Pty Ltd, WA, Australia) were installed at the site at depths of 0.15, 0.30, 0.45 and 0.60 m, respectively. To avoid the interference of change in soil temperature on the EC_a and in-phase data, three layers of thermal insulation earth wool were placed on the surface of the selected site. The insulation was made of recycled glass (Knauf Insulation Pty Ltd, Murarrie, Queensland, Australia) and was 6 m long, 1.2 m wide and ~0.27 m thick. A temperature probe was also placed in the middle of the insulation. A DUALEM-421S was then placed on top of the insulation. The age of this instrument was eight years. This information is useful as the transmitter and receiver coils age with time, so do physical properties of the coils. To avoid direct sunlight, a plastic shade cloth was installed 20 cm above the DUALEM-421S which was fixed by a number of wooden pegs and a PVC pipe. It is noted that the wires of the temperature probes were placed close to the centre of the DUALEM-421S to minimise the interference with the EM field. The experiment at the single location began 30 min after the instrument was turned on. That is, the EC_a and in-phase measurements started at 16:30 on 4 May 2016. This was suggested in the DUALEM User Manual to minimise the instrument drift caused by the temperature change of the sensors during the instrument start-up. Approximately a day and three-quarters later and at 9:15 on 6 May 2016, the soil insulation was removed with the DUALEM-421S continuing logging under the shade for a further 24 h to study the effect of soil temperature.



Fig. 1. The instrument setup for experiment II.

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