EVALUATION OF THE TEMPORAL AND OPERATIONAL STABILITY OF APPARENT SOIL ELECTRICAL CONDUCTIVITY MEASUREMENTS

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ABSTRACT

Measuring apparent soil electrical conductivity (EC_a), using galvanic contact resistivity (GCR) and electromagnetic induction (EMI) techniques is frequently used to implement site-specific crop management. Various research projects have demonstrated the possibilities for significant changes in the measured quantities over time with relatively stable spatial structure representations. The objective of this study was to quantify the effects of temporal drift and operational noise for three popular EC_a mapping instruments. The sensors were placed in stationary positions approximately 5 m apart in an area with relatively low EC_a. Temporal drift was assessed using a series of 4.5-h data logs recorded under different weather conditions (from extremely hot to near freezing temperatures). Both EMI instruments were also used to quantify the effect of minor changes in the height, pitch and roll of the sensor with respect to the ground. These operation noise tests were replicated over several days. GCR measurements of EC_a, along with perpendicular coplanar (PRP) EMI measurements, have shown relatively strong stability over time. Each operational effect introduced measurement uncertainties comparable to the impact of a change in temperature and soil water content.

Keywords: apparent soil electrical conductivity, galvanic contact resistivity, electromagnetic induction

INTRODUCTION

Site-specific crop management has been implemented to increase profitability and reduce the negative environmental impact of modern farming. The application of proximal soil sensing (PSS) facilitates a better understanding of spatial crop growing conditions and accounts for local needs. Thus, maps of soil EC_a reveal soil heterogeneity related to various physical characteristics affecting the ability of the soil profile to conduct an electrical charge. Soil EC_a has been related to salinity (De Jong et al., 1979; Williams and Hoey, 1987; Lesch et al., 1995), texture (Slavich and Petterson, 1993; Corwin and Lesch, 2003), and soil water content (Kachanoski et al., 1988, Sheets and Hendrickx, 1995; Corwin and Lesch, 2001).

The most popular methods in measuring soil EC_a are using the GCR and EMI techniques. Both involve at least one element resulting in a current in the soil and at least one element sensing resistance/conductance of soil media. For GCR, a set of contact (typically rolling) electrodes has been used to inject the current and to sense a change in the potential at a fixed distance. These electrodes have been configured in a Schlumberger, Wenner, Dipole-dipole, and other array configurations (Allred et al., 2006). Alternatively, EMI offers a non-destructive method, according to which alternating current in the transmitter coil generates a primary electromagnetic field causing an eddy current within the soil matrix. An eddy current, in its turn, generates a secondary electromagnetic field within the receiving coil. The relationship between currents created from both the primary and the secondary electromagnetic fields allow for the detection of the conducting characteristics of the soil.

Several studies have reported on different levels of EC_a observed using the same instrumentation (Abdu et al., 2007; Saey et al., 2009; Urdanoz and Aragüés, 2012). These studies did not focus on the sensitivity of these instruments to temporal and operational noise, which can have a remarked affect on the measurements. The differences in ambient and soil conditions (McNeill, 1992) may cause the signal to change over time (drift). For example, heat builds in the instrument directly exposed to sunlight and this reduces the soil EC_a (Sudduth et al., 2001; Sudduth et al., 2011). In contrast, cold weather also may significantly reduce measured soil EC_a due to a reduction in electrolyte mobility (Allred et al., 2005). Taylor and Holladay (2013) found 1 mS/m offset due to the temporal drift. The soil EC_a measurements also could be affected by the internal thermal drift of the instrument (Robinson et al., 2004). In addition, EC_a measurements were shown to be altered due to small changes in the height above ground (Sudduth et al., 2010), or as a result of roll and pitch of the measuring instrument (Doolittle et al., 1994; Simpson et al., 2009; Adamchuk et al., 2011).

Since service providers have to consider a combination of factors causing temporal and operational noise when mapping agricultural fields, the objective of this study was to quantify the deviation of the stationary EC_a measurements produced using different instruments over time (both, short-term and long-term), and due to different operational uncertainties (height, roll and pitch).

MATERIALS AND METHODS

Tested Instruments

Three different instruments were used to simultaneously measure soil EC_a (mS/m) at the same time within the same area. Those included a GCR sensor Veris Quad 1000[1] (Veris Technologies, Inc., Salina, Kansas, USA) shown in

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[1] Mention of a trade name, proprietary product, or company name is for presentation clarity and does not imply endorsement by the authors, the Universiti Putra Malaysia, McGill University, nor does it imply exclusion of other products that may also be suitable.

Figure 1 and two EMI instruments: DUALEM-21S (Dualem, Inc., Milton, Ontario, Canada) and EM-38 (Geonics Limited, Mississauga, Ontario, Canada) shown in Figure 2. Table 1 summarizes the main parameters for these instruments.

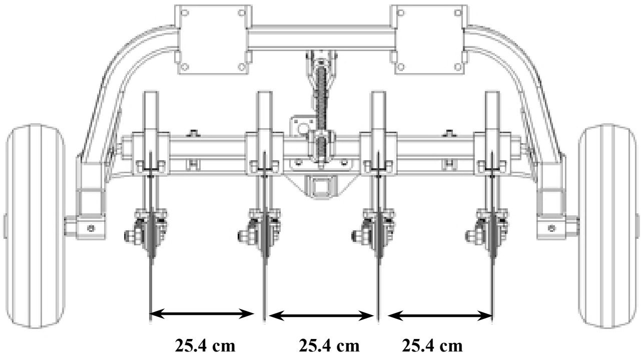

Figure 1. GCR sensor Veris Quad 1000 (http://www.veristech.com).

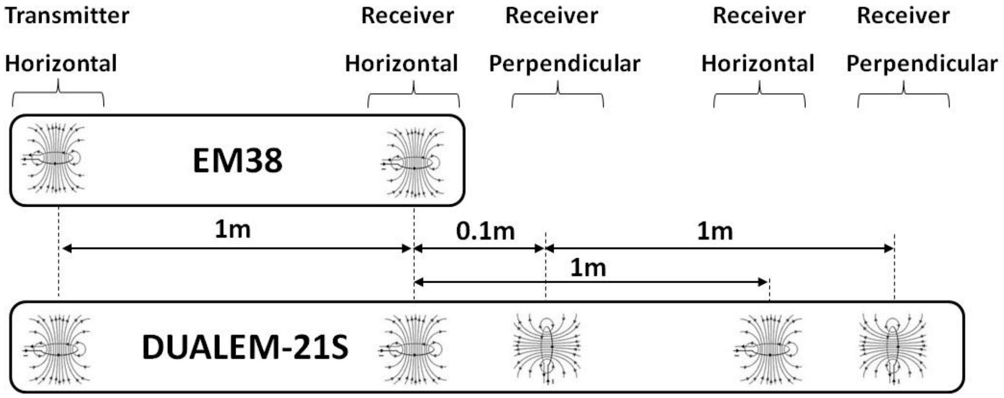

Figure 2. EMI sensors EM-38 (above) and DUALEM-21S (below), modified from Simpson et al. (2009).

Table 1: GCR and EMI type of instrument specification

Specification	Veris Quad 1000	EM-38	DUALEM-21S
Method	GCR	EMI	EMI
Dimensions, m	1.43 x 1.50 x 0.69	1.06 x 0.15 x 0.13	2.41 x 0.09 x 0.09
Mass, kg	136	3	5
Power supply	12 V DC external	9 V DC internal	12 V DC external
Number of depths	1	2	4
Operating frequency	20 Hz	14.6 kHz	9 kHz
Data output rate	1 Hz	14 Hz	5 Hz

The Veris Quad 1000 used in this study consisted of four rolling coulters and provided output related to shallow (0-30cm) soil EC_a (Lund et al., 1999). The EM-38 had only one pair of coplanar coils 1 m apart. The unit can be positioned in horizontal (HCP) or vertical (VCP) coplanar mode producing EC_a measurements related to 0.75 and 1.5 m deep soil profiles, respectively. This unit was calibrated before each use according to the manufacturer's recommendations.

Finally, the DUALEM-21S had two pairs of coplanar coils (HCP) 1 and 2 m from the transmitting coil, and two perpendicular (PRP) coils at 1.1 and 2.1 m from the transmitting coil. Both coil distances produced peak signal at 1.5 and 3 m deep soil profiles.

A LabView application (National Instruments, Cor., Austin, Texas, USA) has been developed to automatically log data from the three sensors at individual data rates. In addition, a Watch Dog 2700 weather station (Spectrum Technologies, Inc., Aurora, Illinois, USA) was used to record ambient conditions that might affect instrument performances. Monitored parameters were logged with a 5-min interval and included: air temperature and humidity, wind speed and direction, as well as rainfall. The same station was used to monitor soil temperature, and water content 30 cm below the surface using a stationary installed probe SMEC 300 (Spectrum Technologies, Inc., Aurora, Illinois, USA).

Experimental Procedure

The instruments were placed in stationary positions approximately 5 m apart, as shown in Figure 3. The test area at Macdonald Farm of McGill University, Quebec, Canada, was a lawn with relatively low EC_a (less than 15 mS/m) located away from any infrastructure. The soil type at the test location was identified as Chicot series, sandy loam soil with moderate a moisture holding capacity, and moderate to poor drainage (Paul, 1960).

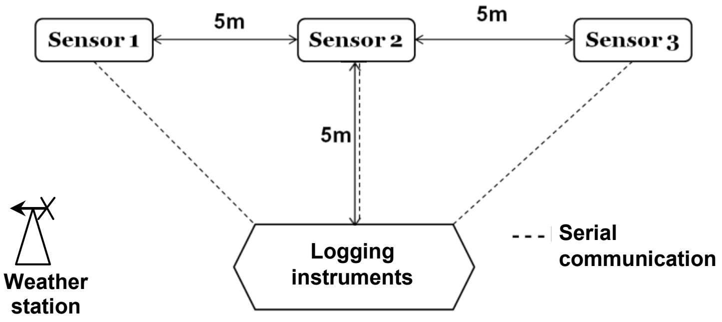

Figure 3. Experimental setup.

A series of five 4.5-h data recordings were conducted from August to October 2013. Each time, the instruments were placed in the same marked locations. The GCR coulter disks were pushed gently to ensure good contact with the soil. The EMI instruments were placed on the flat ground with the roll of the instruments as close to 0º as possible.

Another set of 5-min data recordings was conducted with artificially introduced EMI instruments operation noise. Evaluated factors included: i) 0 and 10 cm height above the ground (H_0 and H_{10}) simulating inconsistence distance between the instrument and soil surface, ii) +10º, 0º, and -10º pitch (P_{+10°, P_{0°, and P_{-10°) simulating potential raze of one side of the instrument, and iii) +10º, 0º, and -10º roll (R_{+10°, R_{0°, and R_{-10°) simulating deviation of the instrument from its vertical orientation. Since the EM-38 instrument has only one pair of coils separate tests were performed for both vertical and horizontal position measurements. Since EM-38 measurements did not compensate for temperature, both raw measurements and estimated measurements at 25 ºC (EC_{25}) were used when analysing EM-38 instrument data. Based on Corwin and Lesch (2005), and Ma et al., (2010), EC_{25} estimates were calculated using:

$$EC_{25} = \left(0.4470 + 1.4034e^{-t/26.815}\right) \cdot EC_t \tag{1}$$

where EC_t = soil EC_a measured at a particular soil temperature
t = soil temperature, ºC

Preliminary data analysis was based on a comparison of raw (unfiltered) data distributions obtained at the highest possible data rate for 1) individual 4.5-h logging under normal operation ($H_0 + R_{0^\circ} + P_{0^\circ}$) and 2) individual operational uncertainties: height, pitch and roll. While the temporal tests quantify the potential data drift from the beginning to the end of a single mapping exercise, the operational tests reveal the influence of typical uncertainties of the position of the instrument with respect to the ground. In addition, the test replicates show the influence of soil temperature and moisture superimposed with possible uncertainties of sensor repositioning or other unexpected effects.

RESULTS AND DISCUSSIONS

Figure 4 illustrates the timeline of all of the tests and Figure 5 demonstrates the range of air and soil temperatures, relative humidity and soil water content during each 4.5-h temporal test. These tests generally cover all reasonable operational conditions when EC_a data are normally collected.

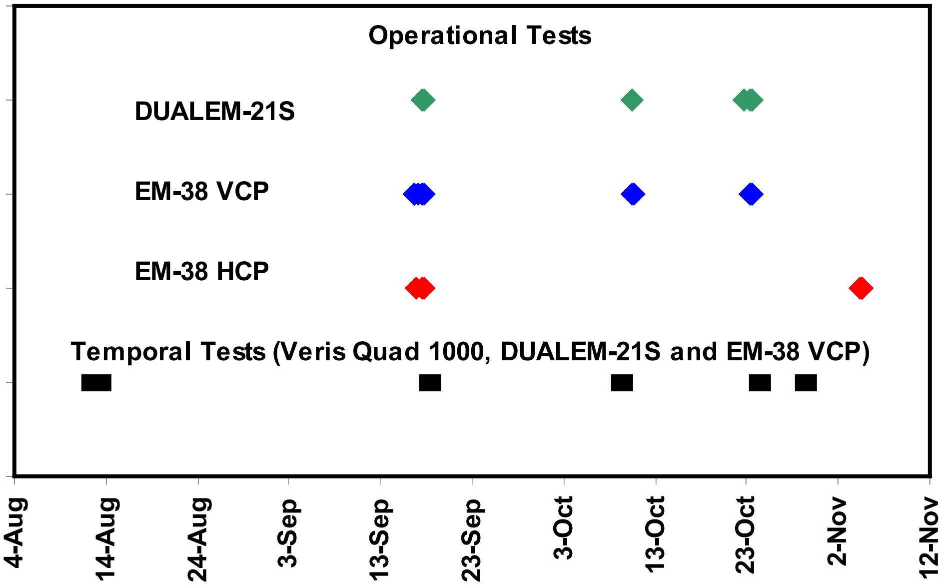

Figure 4. Experimental timeline.

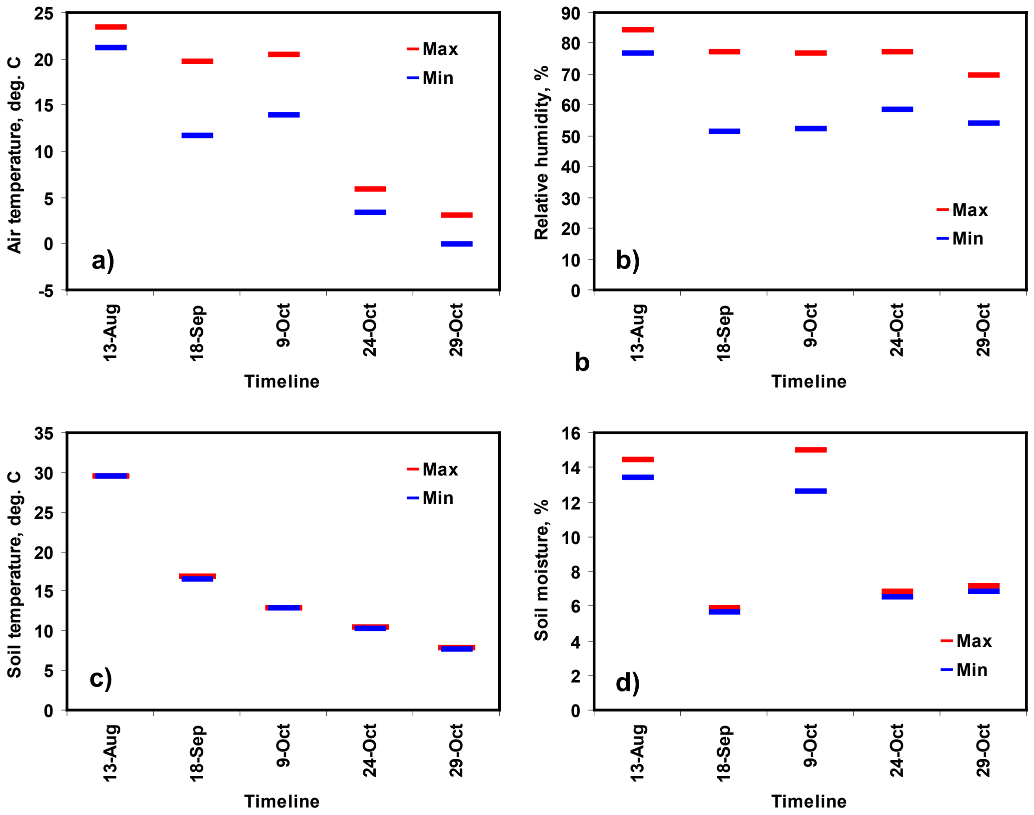

Figure 5. Environmental conditions, including a) air temperature, b) relative humidity, c) soil temperature, and d) soil moisture during temporal tests.

Figure 6 illustrates the results of the temporal test. It is apparent that the GCR instrument had negligible data variations during each 4.5-h test and minor differences from day to day, which includes the difference due to sensor reinstallation. DUALEM-21S PRP measurements were also relatively stable during each test as well as from day to day followed by DUALEM-21S HCP data and EM-38 VCP measurements. For unknown reason, on September 18, DUALEM-21S measurements obtained with the 1-m coil separation (both HCP and PRP) presented negative values. This was not the case with the remaining four days of testing. Also, it was interesting to observe that applying equation 1 to compensate for the difference in soil temperature did not decrease the variance of EM-38 measurements, despite the expectations. On the contrary, EM_{25} estimates have shown greater variance as compared to unprocessed EM_t measurements.

Figures 7 and 8 show the results of the operational test for both EMI sensors. Each 5-min data log represented a particular test configuration that was repeated on three different occasions during at least two different days in random order. Since normal operation (zero height, pitch and roll) was a part of each part of the operational tests, this configuration has been replicated nine times. A roll test was not preformed for the EM-38 instrument operated in HCP mode. All the charts have the same EC_a scale.

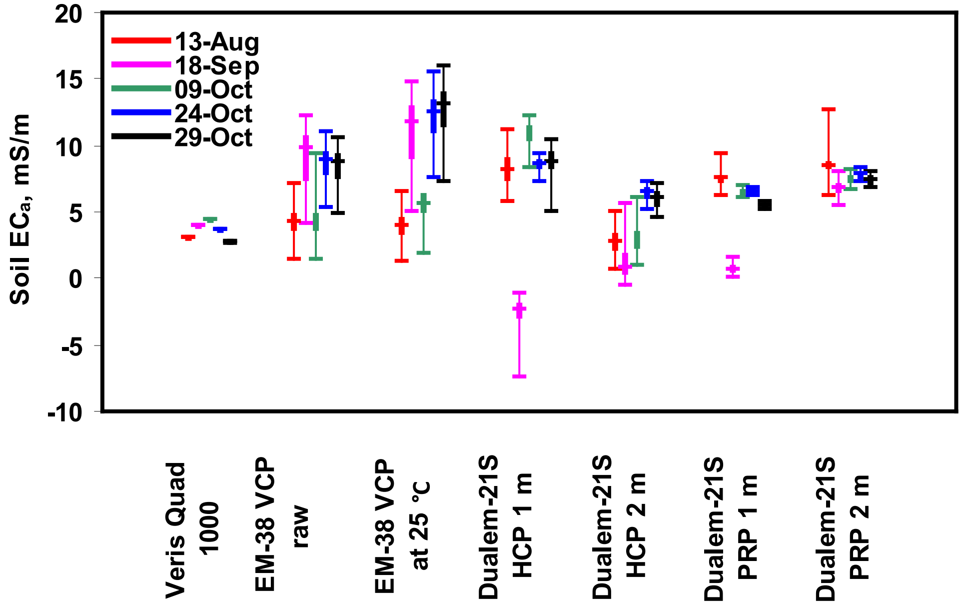

Figure 6. Boxcar plot of EC_a measurements during the temporal test.

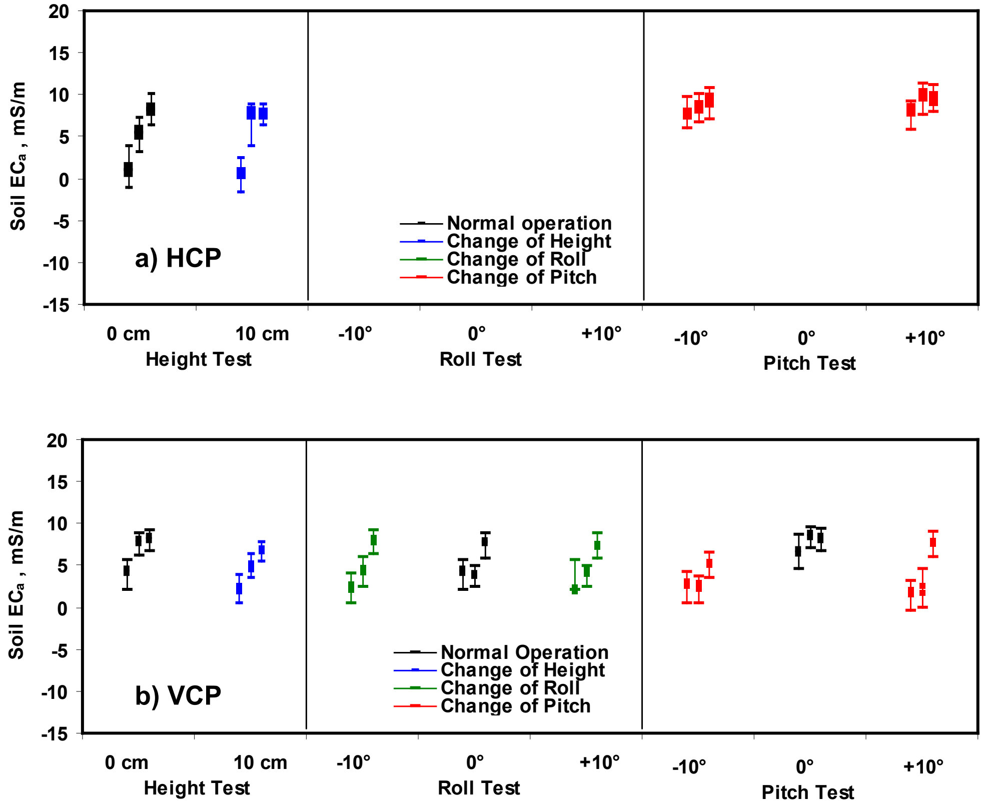

Figure 7. Results of EM-38 operational test for a) HCP and b) VCP.

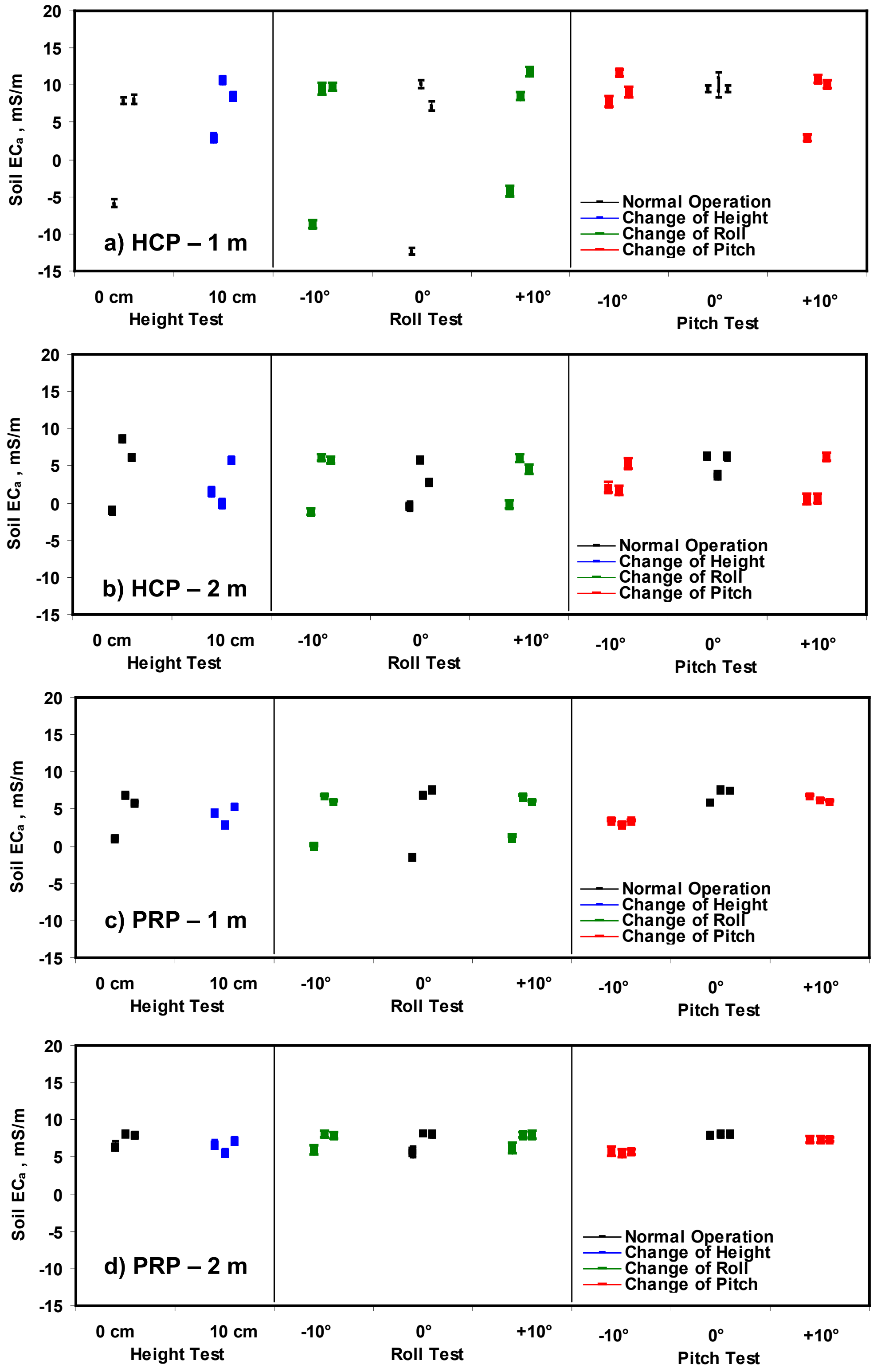

Figure 8. Results of DUALEM-21S operational test for a) HCP – 1m, b) HCP – 2 m, c) PRP – 1 m, and d) PRP – 2 m.

Based on the preliminary data analysis, it follows that the DUALEM-21S had significantly lower data fluctuations during 5-min log intervals in each configuration as compared to EM-38. Further, HCP mode operation produced greater data fluctuations as compared to the VCP or PRP mode. A significant difference between the replicated tests was observed for each type of measurement. DUALEM-21S PRP – 2 m measurements were the most stable from test event to test event as well as during each 5-min log interval.

During each test, the effect of height, pitch and roll differences was lower than the effect of the replicated test. Minor reductions in EC_a measurements have occurred when raising the unit or raising one end of the unit. Change of pitch effect was most noticeable for DUALEM-21S PRP measurements, when data fluctuation during individual log intervals was minimal. Finally, the effect of ±10º roll did not make a significant contribution to the measurements recorded. In general, these results indicate that random replication of the same stationary test had greater effect on the measurements than any specific operational treatments in this study.

SUMMARY

A set of stationary tests of one GCR and two EMI instruments has revealed the degree of temporal and operation-induced variation on observed measurements. While the GCR instrument was relatively immune to long-term data drift, repositioning of EMI instruments on the soil surface during different times of year (different soil temperature) provided more noticeable differences, Furthermore, EMI measurements were less stable during 4.5-h log periods. Longer distance between the transmitting and receiving coil and the PRP rather than the HCP operation provided more stable results. The same applies to the operational tests. The effects of the instrument height (10 cm versus placed on the ground), ±10º roll and ±10º pitch were smaller than the difference from test event to test event, which could be attributed to a number of uncontrolled factors, including exact position of the instrument and different environment parameters. From a practical point of view, it appears that restricting the operational effects below tolerances tested in this study may be unnecessary as the key factors / be controlled and should considered when interpreting EC_a maps of agricultural fields.

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