Development of an angular scanning system for sensing vertical profiles of soil electrical conductivity

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DEVELOPMENT OF AN ANGULAR SCANNING SYSTEM FOR SENSING VERTICAL PROFILES OF SOIL ELECTRICAL CONDUCTIVITY

V. I. Adamchuk, A. S. Mat Su, R. A. Eigenberg, R. B. Ferguson

ABSTRACT. Apparent soil electrical conductivity (ECa) is typically mapped to define soil spatial variability within an agricultural field. Knowledge of the vertical variability of ECa is desired to define the site-specific behavior of the soil profile. A pneumatic angular scanning system (PASS) was developed to sense horizontal and vertical changes of ECa on-the-go with an electromagnetic induction (EMI) instrument using an angular scanning method. This sensor system consists of a sled with a rotating mechanism, an EMI sensor, an inclinometer, and a pneumatic actuator. The system was evaluated at the University of Nebraska-Lincoln Agricultural Research and Development Center (ARDC) near Mead, Nebraska. The PASS was towed by an all-terrain vehicle (ATV) and operated from a field computer with specially designed data acquisition software. Rotation of the instrument allowed continuous transition between horizontal and vertical modes of operation. Nine discrete field locations with different soil conditions were used to compare PASS estimates with measurements obtained using a manual ECa probe. With the assumption of two fixed-depth layers, the R² value was 0.91 for the linear regression between corresponding measured and predicted ECa values, and R² was 0.54 for the difference between the ECa of deep and shallow soil. Unfortunately, solving the system of linear equations for a more complex model of a soil profile required inversion of an ill-conditioned (close to singularity) matrix, which was not feasible without regularization and an inversion procedure with non-negative constraints to be pursued in the future.

Keywords. Angular scanning, Apparent electrical conductivity, Electromagnetic induction, On-the-go soils sensing.

Sustainable agriculture ensures a well-balanced food supply under conditions of growing demand, environmental concerns, economic struggles, and long-term maintenance of land resources. Information-based management of agricultural fields has the potential to optimize production with carefully matched quantities of inputs to minimize waste to the environment. Precision agriculture combines a set of technologies specifically focused on the optimized management of agricultural inputs according to economically justified local needs (Gebbers and Adamchuk, 2010). Optimized distribution of agricultural inputs requires detailed information on soil variability across a field and at various depths in the soil. Soil sampling and laboratory analysis are the traditional approaches to define soil profiles at various field locations; however, these methods are costly, labor intensive, and time consuming. Alternatively, on-the-go proximal soil sensing has been used to map soil attributes when moving across a field (Adamchuk et al., 2004). The concept of mapping apparent soil electrical conductivity (ECa), using geophysical methods, is the most popular proximal soil sensing technique in agriculture (Corwin and Lesch, 2003; Heiniger et al. 2003; Lesch et al., 2005; Sudduth et al., 2005).

Typical ECa measurements represent the ability of soil media to conduct an electrical charge and characterize soil profiles to a depth defined by the geometry of the measuring instrument. Sensors suitable for ECa measurements on-the-go are based on three different methods: galvanic contact resistivity, capacitive coupled resistivity, and electromagnetic induction (EMI). These methods differ in the way in which a current is introduced to the soil (Allred et al., 2006; Corwin et al., 2008). However, each system contains at least one transmitting and one receiving component; these can be coulter electrodes, coaxial cables, or electromagnetic coils.

With the galvanic contact approach, at least two pairs of electrodes (typically in Wenner array configuration) must maintain stable contact with the soil surface (Allred et al., 2008). One pair of electrodes is used to create a low-frequency alternating current while another pair measures the change in electrical potential, which is directly related to soil resistivity. By increasing the distance between pairs of sensing and current-injecting electrodes, it is possible to obtain a signal response affected by deeper soil layers.

With the capacitively coupled resistivity method, a current is injected into the soil using a coaxial cable serving as a large capacitor (Allred et al., 2008). The metal shield of the
coaxial cable is one of the capacitor plates, the outer insulation of the cable provides the dielectric material, and the soil under the cable is the other plate. The transmitter applies an alternating current to the coaxial cable, which causes an electric current in the soil. On the receiver side, the current in the soil causes a current inside the coaxial cable. The difference in electric potential between the transmitter and the receiver is related to soil resistivity. As with the galvanic contact method, varying the distance between the transmitter and an array of receivers is used to obtain measurements representing variable depths.

Popular in geophysical applications, the EMI method is also used to determine soil apparent electrical conductivity (McNeill, 1980; Daniels et al., 2008). Unlike galvanic contact and capacitively coupled resistivity methods, sensor systems based on electromagnetic induction do not require contact with the soil. Instead, a transmitting inductor (coil of wire with high-frequency (>1 kHz) alternating current creates a magnetic field that causes a secondary (eddy) current in the soil. As is the case with the capacitively coupled approach, an electrical current is formed by the reverse process in the receiving inductor (the current induced by the magnetic field from this secondary eddy current). From a number of parameters relating alternating current in the transmitting and receiving inductors (amplitude, time delay, and relative orientation), the measurements obtained can be used to quantify EC_a.

As examples of EMI application, Kitchen et al. (1999), Dabas and Tabbagh (2003), Corwin and Lesch (2005), Carter et al. (1993), Freeland et al. (2002), and Triantafilis et al. (2002) used an EM-38 (Geonics Limited, Mississauga, Ontario, Canada) sensor to characterize soils of an agricultural field with respect to different soil properties, including soil texture and salinity. The EM-38 has the ability to make measurements in both horizontal and vertical modes of operation by physically rotating the instrument. The instrument needs calibration over a relatively homogeneous area before it is ready for use. This is done by placing it 1.5 m above the ground and adjusting readings to ensure that the EC_a detected in vertical mode is twice the reading of the EC_a registered in the horizontal mode (Lesch et al., 2005). The presence of metal must be avoided since it alters the calibration and can bias the mapping processes. Sudduth et al. (2001) discussed uncertainties and external factors that affect EM-38 measurements. Soil temperature that affects the measurements can be accounted for, as shown by McKenzie et al. (1989).

Over the last three decades, EMI sensors have been used to predict changes in EC_a and related soil properties with depth (e.g., Corwin and Rhoades, 1982, 1984; Slavich, 1990; Cook et al., 1989; Cook and Walker, 1992; Rhoades et al., 1989; Lesch et al., 1995; Hendrickx et al., 2002; Gebbers et al., 2007; Saey et al., 2009; Sudduth et al., 2010). This can be accomplished by: (1) using multiple receiving coils at different distances from the transmitting coil, (2) using multiple operation frequencies, (3) using vertical, horizontal, or hybrid (one coil vertical and one horizontal) modes of operation, or (4) raising the instrument to different heights above the ground.

A number of commercial instruments such as upgrades of EM-38 or DUALEM (Dualem, Inc., Milton, Ontario, Canada) have been equipped with more than two coils to simultaneously map EC_a using different distances and orientations between transmitting and receiving coils. These options typically result in more expensive instruments. While the spacing between receiving and transmitting coils, their relative orientation, and the operating frequency have been restricted by the instrument’s design, altering vertical and horizontal modes of operation has become a standard practice.

To increase the number of different depth response curves, “vertical sounding” involves raising the instrument in vertical and/or horizontal modes of operation above ground (e.g., Hendrickx et al., 2002; Rhoades et al., 1989; Borchers et al., 1997; Abdu et al., 2007). Analytically, soil EC_a profiles were predicted using second-order Tikhonov regularization to solve a singular matrix of soil EC_a data (Inman et al., 1973). To facilitate automatic vertical sounding, Carter et al. (1993) and later Triantafilis et al. (2002) and Hendrickx et al. (2002) designed mechanisms for raising an EMI sensor above the ground.

The vertical sounding technique has typically been conducted in a stationary position, which limits the ability to map agricultural fields. As an alternative to vertical sounding with a fixed mode of operation, this study focuses on continuous change of the mode of operation while relying on a fixed height above ground. Such an “angular scanning” approach involves repeated rotations (change of the operation mode from vertical to horizontal and back). The main objective of this study was to develop an instrumented system for angular EC_a scanning using an EMI sensor. Accomplishment of this objective included the development of a theoretical basis for describing the system’s response and preliminary validation of the prototype developed.

**Materials and Methods**

**Background Theory**

The electromagnetic induction method includes at least two inductors (coils) with fixed spacing and orientation between them. A high-frequency (>1 kHz) current in the first (primary) coil produces a primary magnetic field. According to Lenz’s law, the induced magnetic field generates an eddy current through the soil media. Subsequently, this current creates a secondary magnetic field in the receiving coil. The relationship between the primary and secondary currents is related to the electrical conductivity of soil media (mS m⁻¹).

The linear method was initially presented by McNeil (1980) and is illustrated using equations 1 through 5. However, this model is appropriate when measurements are below 100 mS m⁻¹ (Borchers et al., 1997). Thus, when an EM-38 instrument with 1 m separation between transmitting and receiving coils parallel to each other is placed on the ground, each measurement (denoted EM) is given by:

\[
EM = \int_0^{\infty} \phi(z) \sigma(z) dz
\]

where \( \phi(z) \) = sensitivity functions

\[
\phi(z) = \begin{cases} 
\frac{2}{\sqrt{4z^2 + 1}} & \text{for horizontal operation} \\
\frac{4z}{\left(4z^2 + 1\right)^{3/2}} & \text{for vertical operation}
\end{cases}
\]
\[ E_M (h) = \int_0^\infty \phi(z + h) \sigma(z) \, dz \]  

where \( h \) is the height of the instrument above ground.

In this case, the sensitivity and cumulative response (most frequently used for computation) functions can be rewritten as:

\[ \phi(z + h) = \begin{cases} 
2 & \text{for horizontal operation} \\
\frac{4(z + h)}{(4(z + h)^2 + 1)^{1/2}} & \text{for vertical operation} 
\end{cases} \]  

The cumulative response function, which is most commonly used to define sensitivity of response for a particular layer of soil, is calculated using:

\[ R(z + h) = \int_z^\infty \phi(z + h) \, dz = \begin{cases} 
\left( \frac{4(z + h)^2 + 1}{2(z + h)} - 2(z + h) \right) & \text{for horizontal operation} \\
\frac{1}{2 - 2(z + h)} & \text{for vertical operation} 
\end{cases} \]  

where \( R(z + h) \) is the cumulative response function for soil below \( z \) depth when the instrument is placed at \( h \) height.

Assuming that \( \sigma \) is a column vector of discrete true \( EC_a \) representing multiple homogeneous layers of soil:

\[ \sigma = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_M \end{bmatrix} \]  

where \( M \) is the number of soil layers with discrete values of \( EC_a \).

Therefore, \( m(\sigma) \) is a column vector that represents an array of expected measurements that corresponds to the vector \( \sigma \) if the instrument is placed at different heights:

\[ m(\sigma) = \begin{bmatrix} m_1(\sigma) \\ m_2(\sigma) \\ \vdots \\ m_N(\sigma) \end{bmatrix} \]  

where \( N \) is the number of measurements at different instrument heights.

The vectors \( m(\sigma) \) and \( \sigma \) can be related through the following equation:

\[ m(\sigma) = K \sigma \]  

where \( K \) is a matrix of coefficients, which is obtained by integrating the response function according to discrete depth intervals:

\[ K = \begin{bmatrix} 
\int_z^{z_1} \phi(z + h) \, dz \\
\int_z^{z_2} \phi(z + h) \, dz \\
\vdots \\
\int_z^{z_M} \phi(z + h) \, dz 
\end{bmatrix} \]  

Using the cumulative response function, each \( K_{ij} \) can be defined as:

\[ K_{ij} = \begin{cases} 
R(z_j + h_i) - R(z_{j+1} + h_i) & \text{for } j < M \\
R(z_j + h_i) & \text{for } j = M 
\end{cases} \]  

Borchers et al. (1997) described the details of the inversion procedure for a linear model. In their case, both horizontal (\( H \)) and (\( V \)) vertical sounding scans were performed in each location. Therefore, the vector \( m(\sigma) \) was a combination of \( m_H(\sigma) \) for horizontal scanning and \( m_V(\sigma) \) for vertical scanning:

\[ m(\sigma) = \begin{bmatrix} m_H(\sigma) \\ m_V(\sigma) \end{bmatrix} \]  

Naturally, matrix \( K \) was a combination of \( K_H \) and \( K_V \):

\[ K = \begin{bmatrix} K_H \\ K_V \end{bmatrix} \]  

In this case, the same equation (eq. 8) can be used to relate vectors \( m(\sigma) \) and \( \sigma \). However, in the case of any measurement error, the vector of the actual EM instrument measurements \( \mathbf{d} \) is not equal to \( m(\sigma) \).

\[ \mathbf{d} = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix} \neq m(\sigma) \]  

Therefore, instead of equation 8, the following equation has to be solved for \( \sigma \):

\[ K \sigma = \mathbf{d} \]  

It is obvious that \( N \) should be greater than or equal to \( M \) for a single mode of operation, and \( 2N \) should be greater than or equal to \( M \) for the dual (vertical and horizontal) mode. However, when the square \( K \) matrix is used (\( N = M \) for single mode and \( 2N = M \) for dual mode), its determinant is close to zero (near singular) when \( M \) is greater than 2. This means that...
K’-1 (inverse matrix) cannot be defined. The overdetermined solution (N > M for single mode and 2N > M for dual mode) also does not allow solving equation 14 for \( \sigma \).

The most common solution to overcome this problem is to use the least mean square principle to find \( m(\sigma) \) that would satisfy the objective \( \min_{\sigma} \| m(\sigma) - d \|^2 \) with \( \sigma \geq 0 \) constraint. A number of relatively complex methods (including regularization) to accomplish this task have been presented (Inman et al., 1973; Lesch et al., 1995; McBratney et al., 2000; Hendrickx et al., 2002; Gebbers et al., 2007).

**PRINCIPLE OF THE ANGULAR SCANNING APPROACH**

Angular scanning is an alternative to vertical sounding and relies on repeated 90° rotations of the EMI (e.g., EM-38) instrument. In figure 1, \( h \) is the height of the EM-38 instrument above the ground, \( z_1,2,\ldots,M-1 \) are the depths of the bottoms of \( M \)-1 homogeneous layers of soil (the \( M \)th layer is assumed to stretch to infinity), and \( \sigma_1,2,\ldots,M \) are corresponding values of soil ECa.

Based on equation 5, the horizontal and vertical distances at which the cumulative signal level \( R \) is the same for the vertical and horizontal modes of operation can be found as:

\[
z_{V} = \frac{\sqrt{1-R^2} - h}{2R} \quad (15)
\]

\[
z_{H} = \frac{1-R^2}{4R} - h \quad (16)
\]

Assuming \( \alpha \) is the angle of rotation, which is 0° in the horizontal and 90° in the vertical mode of operation, the values of \( z_{V} + h \) and \( z_{H} + h \) can be used as semi-major and semi-minor axes of an ellipsoid, respectively (fig. 2):

\[
\frac{x^2}{(z_{H}+h)^2} + \frac{y^2}{(z_{V}+h)^2} = 1 \quad (17)
\]

where

\[
\begin{align*}
x &= \text{distance from the instrument in horizontal direction (m)} \\
y &= \text{distance from the instrument in vertical direction (m)}.
\end{align*}
\]

In polar coordinates:

\[
x = r \cos \alpha, \quad y = r \sin \alpha \quad (18)
\]

where \( r \) is the distance in direction \( \alpha \) that has a constant value of the cumulative response.

With substitution of equation 18 into equation 17, this allows determining distance \( r \), so that \( R(r) \) is equal to \( R(z_{H}+h) \) and \( R(z_{V}+h) \) when the instrument is placed horizontally and vertically, respectively. This distance can be found using:

\[
r = \frac{z_{H}z_{V}}{\sqrt{z_{V}^2 \cdot \cos^2 \alpha + z_{H}^2 \cdot \sin^2 \alpha}} \quad (19)
\]

After substituting equations 15 and 16 into equation 19, the fourth-order polynomial can be solved to determine the only applicable value of \( R(r) \), or \( R(z + h) \) at any angle \( \alpha \) and depth \( z \):

\[
R = \sqrt{\frac{B + \sqrt{B^2 + 4A}}{2A}} \quad (20)
\]
\[ A = -1 - 4(\varepsilon + h)^2 \sin^2 \alpha \quad (21) \]

\[ B = 2 + 4(\varepsilon + h)^2 \sin^2 \alpha + 16(\varepsilon + h)^2 \cos^2 \alpha \quad (22) \]

This produces results similar to the conventional equation (eq. 5) that are special cases of equation 20 with the parameters defined by equations 21 and 22 (fig. 3a). After numeric differentiation, the generic function \( \phi = (\varepsilon + h, \alpha) \) can be obtained (fig. 3b). Again, equation 4 is a partial case with \( \alpha = 0^\circ \) (horizontal mode) and \( \alpha = 90^\circ \) (vertical mode).

Finally, \( \mathbf{m}(\alpha) \), in this case, represents the array of EC\(_a\) measurements obtained at different rotation angles. The inverse theory to determine vector \( \alpha \) with all non-zero elements is the same as for the vertical sounding problem.

With an assumption of two different arbitrary shapes of EC\(_a\) profiles (A and B) shown in figure 4a, theoretically predicted angular scans \( \mathbf{m}(\alpha) \) obtained using an EM-38 instrument are shown in figure 4b (based on eq. 8 with matrix \( \mathbf{K} \) built from eq. 20). Despite similar ranges of EC\(_a\) values for both profiles, EM measurements follow scan lines with different magnitudes and shapes, which implies the ability to use angular scans to differentiate the behavior of the original EC\(_a\) profiles.

**PASS DEVELOPMENT**

Figure 5 illustrates the pneumatic angular scanning system (PASS) that was developed. It was comprised of a sled with a rotating mechanism, EM-38 sensor, pneumatic system, and a data acquisition system. The PASS weighs about 20 kg and is approximately 1.7 m long, 0.6 m wide, and 0.3 m high. The sled (JSX, Shappell Corp., Grand Ledge, Mich.) provided a strong and rigid base. A PVC tube with two roller supports was designed to allow for a 90° rotation and quick EM-38 installation capability; this allowed for detachment of the instrument for calibration. Electromagnetic sensors are sensitive to nearby metals, so the use of an electric motor as actuator was dismissed and a pneumatic system was designed instead. Most of the system’s components were made of plastic or nylon to minimize signal interference to the measurement instrument. The exceptions...
Figure 5. Pneumatic angular scanning system (PASS) with remote air supply.

were the EM-38 sensor itself, an inclinometer to measure the angle of rotation, and the rod of the air actuator used to rotate the sensor. The sled was pulled over the field using a nylon rope. A white-colored wood cover was placed on top of the sled to prevent dust and minimize temperature fluctuations.

The main function of the pneumatic cylinder (actuator) was to rotate the sensor support as well as the EM-38 sensor from vertical at 90° to horizontal at 0°. This was achieved by converting the linear motion of the actuator's rod extension to rotary motion of the tube holding the EM-38 sensor. Compressed airflow was generated using a 12 VDC air compressor (Gast Manufacturing, Inc., Benton Harbor, Mich.). The air cylinder was a single-action type, and a rubber band was used to rotate the instrument in the reverse direction. Two single-pole double-throw (SPDT, push on-push off) switches (MPA-103D ALCO, Newark, Chicago, Ill.) controlled the airflow using an on/off solenoid valve installed at a distance. When the sensor reached the horizontal position, it latched the switch to release the air pressure. After reaching the vertical position, the second SPDT switch latched and engaged the air compressor again. Thus, the solenoid valve was on (rotating from the vertical to the horizontal position) only when both switches were on or both switches were off. An open air solenoid released the air pressure, which allowed the sensor to return from a horizontal to a vertical position.

An inclinometer (CXTILT02E, Crossbow Technology, Inc., San Jose, Cal.) was used to track the angle of rotation and was calibrated within 0.1° accuracy when the entire instrument was placed on level ground. A 45° mounting of the inclinometer with respect to the sled allowed it to operate in a ±45° range to represent the 0° to 90° range of the instrument’s rotation. A handheld GPS receiver (eTrex Legend, Garmin International, Inc., Olathe, Kans.) was used to obtain the geographic coordinates.

The PASS was assumed to travel at 2.5 km h⁻¹ while being pulled 1.5 m behind an ATV. The average angular speed of the instrument was about 7.5 rpm, which corresponded to 2 s per complete cycle. This resulted in a new scan in both directions of rotation (vertical to horizontal and horizontal to vertical) every 1.4 m of travel.

PASS data acquisition software was developed using LabVIEW 8.2 (National Instruments Corp., Austin, Tex.). The software was developed to combine digital data output from the EM-38 instrument, inclinometer, and GNSS receiver in a delimited text file. All three sensors were connected to a laptop computer using serial communication through serial/USB converters. The EM-38 instrument provided data at a rate of 10 to 14 Hz, while a 40 to 55 Hz data stream was obtained from the inclinometer. Finally, most GNSS receivers provide their output with a 1 to 10 Hz frequency using a common NMEA-0183 communication protocol. Each sensor was operated in continuous transmit mode.

SENSOR EVALUATION

Initially, several tests were performed to compare manual versus automatic scans as well as to analyze the effect of the metal components. Automatic scanning was evaluated in terms of time alignment between the angle of rotation and the logged values of EM. To test the effect of metal components, angular scanning was performed manually with and without the air cylinder and inclinometer installed. This test was replicated three times.

Field evaluation was performed at the University of Nebraska-Lincoln Agricultural Research and Development Center (ARDC) near Mead, Nebraska, on October 28, 2009. ARDC Field 1.14 is a 37 ha no-till irrigated field under corn-soybean rotation (fig. 6). The soil series at this site included...
The experimental site selected was used for research on site-specific water management, and nine discrete field locations, denoted as “nodes,” were used to monitor changes in the soil matric potential and soil temperature through the growing season. These locations were selected due to their diversity in texture and, therefore, water storage potential (Adamchuk et al., 2009). Table 1 lists certain soil properties at each node. Using the manual probe, three ECa profiles were obtained at each of these locations. Then, three angular scans were obtained using the PASS in three different spots around each node. Each scan represented three complete cycles from the vertical to the horizontal mode of operation and back.

The Field Scout ECa probe was capable of making measurements at 76 mm (3 in.) increments down to a maximum of 457 mm (18 in.) depth of operation, which is one of the main drawbacks of this test. Because of variable soil conditions around each node, analysis involved comparison of the averages of three soil ECa profiles obtained using the manual probe with the averages of three corresponding angular scans.

As stated earlier, solving equation 14 for $\sigma$ is not trivial and was not accomplished in this research. However, continuous reduction of the size of square matrix $K$ (assuming the number of scanned angles is the same as the number of distinct homogeneous soil layers) increased $\text{det}(K)$, which became a definitely non-singular matrix with $2 \times 2$ dimension. This allowed solving for $\sigma$ using the following equation:

<table>
<thead>
<tr>
<th>Location</th>
<th>Depth (cm)</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>Texture</th>
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<tbody>
<tr>
<td>Node 1</td>
<td>0-30</td>
<td>41</td>
<td>39</td>
<td>20</td>
<td>Loam</td>
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<tr>
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<td>30-60</td>
<td>34</td>
<td>40</td>
<td>26</td>
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<tr>
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<td>60-90</td>
<td>39</td>
<td>37</td>
<td>24</td>
<td>Loam</td>
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<tr>
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<td>90-120</td>
<td>45</td>
<td>34</td>
<td>21</td>
<td>Loam</td>
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<td>4</td>
<td>Sand</td>
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</table>
\[ \sigma = K^{-1}d \]  

In this case, matrix \( K \) was defined as:

\[
K = \begin{bmatrix}
R_{z=0, \alpha=10^\circ} - R_{z=0, \alpha=0^\circ} & R_{z=0, \alpha=10^\circ} \\
R_{z=0, \alpha=20^\circ} - R_{z=0, \alpha=0^\circ} & R_{z=0, \alpha=20^\circ} \\
R_{z=0, \alpha=90^\circ} - R_{z=0, \alpha=0^\circ} & R_{z=0, \alpha=90^\circ}
\end{bmatrix}
\]  

\[
d = \begin{bmatrix}
EM \text{ Average for } 0^\circ - 20^\circ \\
EM \text{ Average for } 70^\circ - 90^\circ
\end{bmatrix}
\]

\[
\sigma = \begin{bmatrix}
EC_a_{0-0.3 \text{ m}} \\
EC_a_{\text{below } 0.3 \text{ m}}
\end{bmatrix}
\]

Simple linear regression was used to investigate the correlation between the values of EC\(_a\) measured using the manual probe and the values predicted using PASS scans and the difference between EC\(_a\) values corresponding to the top 0.3 m of soil versus below it. The 0.3 m topsoil layer was selected since, according to figure 3b, this is the approximate depth where the value of relative response function is constant regardless of the angle of rotation.

**RESULTS AND DISCUSSION**

**PRELIMINARY TEST RESULTS**

Figure 7 illustrates the difference between angular scans (stationary 0\(^\circ\), 20\(^\circ\), 45\(^\circ\), 70\(^\circ\), and 90\(^\circ\) angles of rotation) with and without the presence of metal components. An approximate 2 mS m\(^{-1}\) bias was introduced by the inclinometer and metal rod of the cylinder, but this bias did not change with the angle of rotation. Therefore, as long as the instrument configuration is consistent, bias can be accounted for by data processing.

Figure 8a illustrates a sample response of the EM-38 and the inclinometer with relatively slow (7 s) scans. EM measurements lagged behind inclinometer data, which created a lag between EM and angle measurements. The data were analyzed to find that an approximate 250 ms difference existed between the timing of the two instrument’s output. Apparently, both the EM-38 and the inclinometer have lag times associated with serial data communication. However, the lag of the EM-38 sensor was greater. A relative lag was added to the software to compensate for the EM-38 sensor data delay (fig. 8b), which corrected the angular scans.

**FIELD EVALUATION**

Figure 9 illustrates soil EC\(_a\) profiles obtained using the manual probe in the nine locations throughout the experimental site. These profiles indicate some heterogeneity at individual nodes (e.g., node 1). On the other hand, the nine locations indicate very different conditions. Manual probe outputs varied from under 50 mS cm\(^{-1}\) for nodes 2 and
4 to over 100 mS cm\(^{-1}\) for node 5. In addition, the shapes of the soil EC\(_a\) profiles varied from constant to continuously increasing, to those with a local maximum. Unfortunately, the available manual probe was not able to measure EC\(_a\) deeper than 0.5 m, but depths below 0.5 m contributed about 1/3 of the EM-38 sensor response in the horizontal mode of
operation and over half of the sensor response when the sensor was vertical. This depth limitation resulted in the average ECa representing the soil profile below 0.3 m being calculated using 0.35 to 0.45 m manual probe data.

Figure 10 illustrates all the scans obtained. Some node locations (e.g., 5, 8, and 6) had less consistent scans than other locations. However, there was no obvious change of the shape, which indicates that soil may change the overall electrical conductivity, but the shape of the ECa profile in the upper 0.5 m of soil remained similar at each of the node locations. Equation 23 was applied to the angular measurements, and the results were compared with measured values (fig. 11). Linear regression equations for the two depths of investigation (0 to 0.3 m and below 0.3 m) had identical R². When fitting different polynomial models to the angular scans obtained, it appears that some scans may be described using a significant fourth-order polynomial, which means that ECa profile models with four parameters can be calculated using 0.35 to 0.45 m manual probe data.

The relatively high correlation between ECa values measured using the manual probe and predicted using PASS scans indicates overall applicability of the instrument. However, high values of R² relate to diverse soil conditions rather than the change in soil ECa with depth, which is the ultimate quest of this research. Moderate correlation between the measured and predicted differences in ECa for the two assumed soil layers is also a positive indicator. However, such a comparison has limited applicability since the manual probe was not capable of measuring soil ECa below 0.5 m depth.

In addition, using a 2 x 2 K matrix inversion does not benefit from a continuous angular scan and resembles double mode (vertical and horizontal) operation. The only benefit is that an instrument with only one pair of coils operated at a constant frequency can be used. This suggests the need to investigate a more complex inversion with regularization. When fitting different polynomial models to the angular scans obtained, it appears that some scans may be described using a significant fourth-order polynomial, which means that ECa profile models with four parameters can be predicted. Ultimately, this may lead to detecting the depth at which the soil ECa profile changes its behavior originating from the boundary of the soil horizons, clay pans, or other phenomena ultimately affecting soil productivity.

The on-the-go test indicated PASS robustness and suitability for field mapping. However, the inclinometer measured the angle of rotation with respect to the surface based on a gravitational response. The data show a relatively high data sampling rate and restricted boundaries of rotation, allowing flexible definition of the orientation (i.e., sensor measurements that correspond to 0° and 90° angles of rotation are assigned for each scan). Alternatively, a simple device such as an angular potentiometer could be used to measure the angle of rotation with respect to the sled.

Finally, development of ECa maps produced using the PASS is not trivial. This procedure may require an assumption of relatively homogeneous conditions for the soil represented by a whole angular scan. When inverted, the scan should produce three to four parameters of local soil ECa profiles that can be interpolated to obtain surfaces representing the field. A thematic map showing the depth of the soil profile capable of storing water accessible to plants may be a practical product obtained using the PASS instrumentation.

**CONCLUSIONS**

The PASS with LabVIEW interface was developed to measure ECa when continuously changing the mode of operation of an EMI sensor from vertical to horizontal and back. It was tested in both static conditions and during on-the-go mapping. At this time, only the results of the static test were compared to soil ECa profiles obtained using a manual probe. Furthermore, the inversion technique was applied to only two hypothetical soil layers (0 to -0.3 m and below 0.3 m). A more involved solution will require inversion of an ill-conditioned matrix; this will be pursued in the future. With the two-layer solution, R² values of 0.88 and 0.91 were found for regression between average ECa using the manual probe and using PASS for nine locations in an agricultural field. The difference between shallow and deep ECa measurements predicted using the PASS produced R² = 0.54 when related to the comparable estimates of ECa profiles obtained using a manual probe. Development of a more complex inversion solution and stated improvements in the data acquisition process should allow potential users to predict a set of
parameters indicating the change in soil ECₐ with depth at each field location, which ultimately would lead to 3-D soil modeling at a relatively low cost.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


