**COMPARISON OF ELECTROMAGNETIC INDUCTION, CAPACITIVELY-COUPLED RESISTIVITY, AND GALVANIC CONTACT RESISTIVITY METHODS FOR SOIL ELECTRICAL CONDUCTIVITY MEASUREMENT**

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**ABSTRACT.** In situ measurement of apparent soil electrical conductivity (ECa) is an important precision agriculture tool useful for determining spatial changes in soil properties. Three near-surface geophysical methods are available for rapid, continuous measurement of ECa in agricultural fields. These methods are electromagnetic induction (EMI), capacitively coupled resistivity (CCR), and galvanic contact resistivity (GCR). Acceptance for using geophysical methods to gauge spatial changes in soil properties hinges to a significant degree on there being consistency of the measured ECa spatial pattern between geophysical methods. Testing of all three methods was conducted on two adjacent test plots having fine-grained soils and during two time periods with dissimilar shallow hydrologic conditions. Different operational modes for each of the three geophysical methods were evaluated, including three primary electromagnetic field frequencies (8190, 14610, and 20010 Hz) used for the EMI method, four spacing distances (0.625, 1.25, 2.5, and 5.0 m) between the two dipoles employed with the CCR method, and two different Schlumberger electrode array lengths (0.7 and 2.1 m) utilized for the GCR method. Therefore, a total of nine geophysical method − operational mode combinations were tested.

Based on spatial correlation analysis, the areal ECa patterns measured by the nine method − operational mode combinations showed substantial similarity to each other, with one exception. The exception was the short electrode array mode of the GCR method that when paired with the various modes of the other two geophysical methods, exhibited an average correlation coefficient, r, that ranged between only 0.30 and 0.45. All other average r values for pairs of different geophysical method − operational mode combinations ranged between 0.62 and 0.97. Spatial correlation coefficients, for both test plots, between the same method − operational mode combination, but at two different times in which hydrologic conditions varied, ranged from 0.35 to 0.95 for eight of the nine method − operational mode combinations, with the GCR short electrode array having values of 0.32 and 0.58. Regarding the test plot ECa average or median, there were substantial differences in values obtained by the three geophysical methods. Electromagnetic vertical sounding measurements along with results obtained by CCR, and GCR surveying, when combined, indicate that for both test plots, from the surface to a depth of a little over 2 m, soil electrical conductivity generally increased first and then decreased. Most importantly, although the measured ECa magnitudes vary between the three geophysical methods, results show that EMI, CCR, and GCR all provide useful and consistent information on soil electrical conductivity spatial patterns.

**Keywords.** Apparent soil electrical conductivity (ECa), Electromagnetic induction (EMI), Capacitively-coupled resistivity (CCR), Galvanic contact resistivity (GCR).

**P**recision agriculture combines geospatial datasets, state-of-the-art farm equipment technology, and global positioning system (GPS) receivers to support spatially variable field application of fertilizer, soil amendments, pesticides, herbicides, and tillage. The benefits of precision agriculture to farmers are maximized crop yields and/or reduced input costs. There is an important environmental benefit as well. Over-application of agrochemicals and soil tillage is fairly common. Since precision agriculture operations result in optimal amounts of fertilizer, soil amendments, pesticides, herbicides, and tillage being applied to different parts of the field, potentially less agrochemicals and sediment enter waterways from runoff.

Geospatial information on soil fertility aids determination of appropriate agrochemical application rates and tillage effort. Various soil profile properties, such as salinity, organic matter content, cation exchange capacity, grain size distribution, clay mineralogy, claypan/fragipan depth, etc., all influence soil fertility. These same soil profile properties affect measured apparent soil electrical conductivity (ECa). Consequently, spatial patterns of soil fertility can potentially be inferred from mapped ECa. However, to ensure confidence among farm managers that ECa mapping can indeed be used...
to gauge spatial changes in soil fertility, the different geophysical methods for measuring EC$_a$ need to demonstrate spatially consistent results relative to one another. (Farm managers will view the overall EC$_a$ measurement approach with skepticism if the spatial EC$_a$ patterns change dramatically depending on which near-surface geophysical method is employed.)

EC$_a$ is generally electrolytic in nature, thereby depending on the concentration and mobility of dissolved ions present within the soil pore water (McNeill, 1980a). As one would expect, the EC$_a$ effect due to the concentration of exchangeable, mobile ions in the soil environment is influenced by or related to soil profile properties including salinity, organic matter content, cation exchange capacity, grain size distribution, clay mineralogy, etc. Ion mobility is affected by the size, shape, tortuosity, and interconnectedness of the pores; the temperature and phase state of the pore water; the extent to which the pores are filled with water; and the dynamics of precipitation, dissolution, and ion activity. Consequently, the grain size distribution that governs the pore geometry; the temperature level, frozen ground conditions; the presence of claypans or fragipans that keep more water in the root zone by reducing drainage; surface wetness related to timing and intensity of rainfall/irrigation events; depth to the water table; and the types of exchangeable ions present, can all influence ion mobility in the shallow soil environment, and hence, the measured EC$_a$.

Near-surface geophysical methods, particularly those capable of mapping EC$_a$, are gaining more widespread use in agriculture. An increasing amount of research within this area continues to document possible uses and limitations for employing geophysical methods to map EC$_a$. Corwin and Lesch (2005) list soil related properties that have been either directly or indirectly assessed by EC$_a$ measurement. For example, there has been a substantial amount of study to date focused on demonstrating that EC$_a$ mapping with electromagnetic induction (EMI) or galvanic contact resistivity (GCR) methods is an effective way to judge the magnitude and spatial variability of soil salinity (Hendrickx et al., 1992; Lesch et al., 1992; Doolittle et al., 2001).

Research results are mixed concerning the value of using EC$_a$ geophysical measurement techniques to monitor soil moisture conditions. Scanlon et al. (1999) evaluated EC$_a$ measured with EMI methods as a reconnaissance technique to characterize unsaturated flow in an arid setting and determined that the magnitude of the impact of water content on EC$_a$ was dependent on the geomorphic setting. An investigation conducted by Sheets and Hendrickx (1995) in an arid region of southern New Mexico discovered a positive linear relationship to exist between EMI EC$_a$ and water content in the top 1.5 m of the soil profile. At a site in Minnesota, Khakural et al. (1998) also verified a positive linear relationship between EMI EC$_a$ and soil profile water storage. Research by Kachanoski et al. (1990) indicated that EMI EC$_a$ explained more than 80% of the variation in soil water storage at scales larger than 40 m. Sudduth et al. (2001) concluded that soil moisture and soil temperature need to be taken into account when using EMI EC$_a$ to estimate topsoil depth. Lund et al. (1999), using resistivity methods, showed that variable soil moisture and temperature conditions did not significantly affect the EC$_a$ spatial pattern of a Kansas wheat field. Interestingly, in a field study near Quebec City, Quebec, Canada carried out with traditional resistivity methods, Banton et al. (1997) found that neither the EC$_a$ mean or spatial pattern changed significantly between wet and dry soil conditions. Johnson et al. (2001), for a test site located in the Colorado portion of the semiarid Central Great Plains, found a modest negative correlation (r = -0.33) between GCR EC$_a$ and soil water content.

In addition to salinity and water content, previous research has focused on the effects of other soil characteristics on EC$_a$. The study by Banton et al. (1997) also determined that EC$_a$ was moderately correlated with soil texture and organic matter, but not with porosity, bulk density, or hydraulic conductivity. Johnson et al. (2001), found a positive correlation at their Colorado test site between GCR EC$_a$ and bulk density, percentage clay, laboratory measured soil electrical conductivity, and pH; but a negative correlation between GCR EC$_a$ and total and particulate organic matter, total carbon, total nitrogen, extractable phosphorous, microbial biomass carbon, microbial biomass nitrogen, potentially mineralizable nitrogen, and surface residue mass. Doolittle et al. (1994) determined a way to estimate claypan depths in a Missouri soil based on EC$_a$ values obtained with EMI methods. Furthermore, Fraise et al. (2001) were able to define claypan soil management zones with a combination of topographic elevation and EMI EC$_a$ data. Kravchenko et al. (2002) likewise employed this combination of topographic elevation and EC$_a$ (obtained with GCR methods) to map soil drainage classes. Inman et al. (2002) found that EMI EC$_a$ and ground penetrating radar data when used together can be a promising soil survey technique. Jaynes et al. (1995) estimated herbicide partition coefficients based on EMI EC$_a$ measurements. Additionally, Eigenberg and Nienaber (1998) established that EMI EC$_a$ could be used as a way to detect field areas with high soil nutrient build-up due to manure applications.

To date, there has been only a limited amount of research focused on comparing EC$_a$ measurement results obtained from different near-surface geophysical methods or with the same method but different equipment. Buchleiter and Farahani (2002) compared EMI and GCR methods on sandy loam soil and found that the measurements of both exhibited similar areal and vertical EC$_a$ trends. Doolittle et al. (2001), for the purpose of salinity assessment, compared a single-frequency EMI ground conductivity meter with a multi-frequency EMI ground conductivity meter and concluded, with respect to areal EC$_a$ patterns, that multi-frequency EMI data provided little additional information beyond what was obtained with single-frequency EMI data. Doolittle et al. (2002) compared GCR, single-frequency EMI, and multi-frequency EMI and determined, for mapping textural changes in alluvial soils of southeast Missouri, that all three produced similar areal EC$_a$ patterns. Sudduth et al. (2003) compared EMI and GCR on two fields in Illinois and two fields in Missouri and found that both methods produced similar results with respect to areal EC$_a$ patterns and EC$_a$ relationships to soil physical and chemical properties. Dabas and Tabbagh (2004) used numerical simulations to highlight the advantages and disadvantages of EMI and GCR. Research related to the use of capacitively-coupled resistivity (CCR) methods for agricultural purposes has at best been minimal.

Consequently, there is a strong need for a comparison of all three methods together under the same field conditions, particularly in regard to fine-grained soils common to the
Midwest United States that are derived from weathering of glacially deposited sediments. Therefore, this research focused on evaluating EMI, CCR, and GCR methods under variable shallow hydrologic conditions at two adjacent test plots having loam to silt loam to clay loam soils. The governing hypothesis of the project can be stated as, "Electromagnetic induction, capacitively-coupled resistivity, and galvanic contact resistivity methods all produce consistent results with respect to the measured soil electrical conductivity spatial patterns within fine-grained glacial sediment derived soils."

**MATERIALS AND METHODS**

**ELECTROMAGNETIC INDUCTION METHOD: GEM-2**

Three different near-surface geophysical techniques for measuring the apparent soil electrical conductivity (ECa) were evaluated, including electromagnetic induction (EMI), capacitively-coupled resistivity (CCR), and galvanic contact resistivity (GCR). An instrument called a ground conductivity meter (GCM) is commonly employed for shallow subsurface EMI investigations. The GCM principle of operation begins with an alternating electrical current that is passed through one of two small electric wire coils spaced a set distance apart and housed within the GCM. This transmitting coil current generates an electromagnetic (EM) field above the surface, a portion of which propagates into the ground. This EM field, called the primary field, induces an alternating electrical current within the ground, in turn generating a secondary EM field. A portion of the secondary field propagates back to the surface and the air above. The second wire coil acts as a receiver measuring the amplitude and phase components of both the primary and secondary EM fields. The amplitude and phase differences between the primary and secondary fields are then used, along with the inter-coil spacing, to calculate an “apparent” value for soil electrical conductivity (ECa).

The Geophex, Ltd. GEM-2 (Raleigh, N.C.) was the GCM used exclusively in this study (fig. 1a). The GEM-2 is a multi-frequency GCM and the three primary EM field frequencies employed in this research were 8,190, 14,610, and 20,010 Hz. The lower two frequencies were chosen to be similar to frequencies employed by other commonly used shallow investigation GCMs, such as the 9000-Hz Dualem Inc. DUALEM-1S (Milton, Ontario, Canada) and the 14,600-Hz Geonics Ltd. EM38 (Mississauga, Ontario, Canada). The 20,010-Hz frequency was chosen because it is near the upper frequency limit for this particular GCM. The GEM-2 has a transmitter/receiver intercoil spacing of 1.66 m, and for ECa mapping purposes, it was operated at a height of 1 m above the ground surface (fig. 1a) in the vertical dipole mode (horizontal coplaner transmitter/receiver coil configuration). Data processing software provided by the manufacturer corrected ECa readings for instrument height above the ground surface. The sampling rate for GEM-2 in this study was approximately 7 measurements per second for each of the three frequencies (8,190, 14,610, and 20,010 Hz). The distance between ECa sampling points was considered to be uniform along any transect for the GEM-2 based on the assumption that the walking pace at which this GCM was carried remained relatively constant.

The actual depth of investigation is an important issue regarding ECa measurement with EMI methods. The skin depth, \( \delta \), occurs at the level beneath the GCM where the...
amplitude of the primary EM field is reduced to 1/e, or 37%, of the value generated at the transmitting coil (Reynolds, 1997; Sharma, 1997). The skin depth is sometimes used as an indication of the investigation depth for EMI measurement and its value (in meters) is expressed:

$$\delta = 504\left(\frac{1}{\sigma f}\right)^{0.5}$$  \hspace{1cm} (1)

where $\sigma$ is the soil electrical conductivity in siemens per meter (S/m), and $f$ is the primary EM field frequency in Hz. At $f$ values of 8,190, 14,610, and 20,010 Hz along with a typical test site $\sigma$ value equal to 0.025 S/m, the calculated $\delta$ numbers are respectively, 35.2, 26.4, and 22.5 m. These large values are unlikely to reflect the true EMI depth(s) of investigation obtained in this study, because $\delta$ calculations do not take into account instrument noise, near-surface electrical conductivity variations, etc.

Huang (2004) developed a procedure, based on $\delta$ and the separation distance between the transmitting and receiving coils, $s$, to better determine the actual EMI depth of investigation. The approach described by Huang (2004) is founded on the investigation depth being proportional to the square root of $\delta$, with the proportionality constant a function of $s$. Using this procedure, the previously calculated $\delta$ values, a GEM-2 intercoil spacing, $s$, of 1.66 m, the depths of investigation at 8,190, 14,610, and 20,010 Hz are 14.0, 12.1, and 11.2 m, respectively. These values are still rather large and do not take into account impacts due to geologic and/or soil environment complexity; atmospheric conditions; EM noise from power lines, telephone lines, or machinery in operation; etc.

A more commonly used approximation for the EMI investigation depth is discussed in detail by McNeill (1980b). For this method, given operation at low values of the induction number and assuming horizontal flow of electric current within the soil, the EMI depth of investigation is largely determined by $s$. Low induction number conditions occur where the primary EM field frequency is low enough that the ratio of $s$ to $\delta$ is substantially less than 1 (Sharma, 1997). McNeill (1980b) shows that, in the vertical dipole mode of operation (horizontal coplaner transmitter/receiver coil configuration), approximately 70% of the EMI response is obtained within a distance beneath the GCM of 1.5 m. The GEM-2 has an $s$ value of 1.66 m, and during use for $E_Ca$ mapping purposes, it was held 1 m above the ground surface in the vertical dipole mode of operation, thereby giving it a more realistic soil investigation depth of 1.5 m beneath the ground surface ([1.5 × 1.66 m] – 1 m = 1.5 m) based on McNeill (1980b).

Comparison of GEM-2 $E_Ca$ measurement results among the three frequencies and electromagnetic vertical sounding techniques (Dualem Inc., 2004) provided insight into the GEM-2 investigation depth. Electromagnetic vertical sounding involved collecting $E_Ca$ measurements (uncorrected for height) as the GEM-2 was raised in 0.2-m increments from the ground surface to a height of 2.4 m. A total of 160 $E_Ca$ measurements were averaged at each GEM-2 vertical position for each of the three EM frequencies (8,190, 14,610, and 20,010 Hz). As the EMI sensor is raised, more and more of the instrument response is governed by the zero electrical conductivity air layer between the sensor and ground surface.

Therefore, with increasing height, measured GEM-2 $E_Ca$ should decrease. The height at which measured $E_Ca$ was reduced to a fraction of the $E_Ca$ value obtained at ground surface corresponded to the GEM-2 depth of investigation.

**CAPACITIVELY-COUPLED RESISTIVITY METHOD: OHMMAPPER TR1**

Capacitively-coupled resistivity (CCR) was the second near-surface geophysical method tested. As the name implies, CCR employs capacitive coupling to introduce electric current into the ground. This capacitive coupling is accomplished using coaxial cables. Essentially, a large capacitor is formed by the coaxial cable and the soil surface. The metal shield of the coaxial cable is one of the capacitor plates, and soil surface is the other capacitor plate, with the outer insulation of the coaxial cable acting as the dielectric material separating the two plates. For the transmitter, application of alternating current to the coaxial cable side of the capacitor results in an alternating current being generated in the soil on the other side of the capacitor. With regard to the receiver, the same thing happens, except in reverse, the current starts in the ground and charges up the capacitance of the coaxial cable, where it is measured to determine the voltage generated by the current flowing in the soil. Two transmitter coaxial cables are incorporated into the transmitter dipole and two receiver coaxial cables are incorporated into the receiver dipole, thereby allowing the CCR method to mimic the dipole-dipole electrode array of the more traditional galvanic contact resistivity (GCR) method. This similarity to a GCR dipole-dipole electrode array enables the CCR method to calculate apparent soil resistivity, and then its inverse, apparent soil electrical conductivity ($E_Ca$) using the measured electric current, measured voltage, coaxial cable dipole lengths, and the spacing distance between the two dipoles. The spacing between the two dipoles governs the soil investigation depth, given that the dipole lengths are kept constant.

The CCR device used for this project was a Geometrics, Inc. OhmMapper TR1 (San Jose, Calif.) (fig. 1b). The OhmMapper TR1 is a capacitively-coupled, towed dipole-dipole array resistivity measurement system capable of continuous data collection at time intervals as short as 0.5 s. The transmitter and receiver dipoles were each 5 m in length and comprised of coaxial cables and transmitter/receiver electronics. The transmitter generates a 16,000 Hz alternating current. The OhmMapper TR1 also has a battery power supply, a data logger console, and rope separates the two dipoles from one another (fig. 1b). Four rope length separation distances between the dipoles (0.625, 1.25, 2.5, and 5 m) were tested. Based on 5-m dipoles, the separation distances between them of 0.625, 1.25, 2.5, and 5.0 m that were used correspond to respective soil investigation depths of approximately 0.5, 0.8, 1.3, and 2.1 m, as determined by extrapolation of data presented by Loke (2003a). The distance between $E_Ca$ sampling points was considered to be uniform along any transect for the OhmMapper TR1 based on the assumption that the walking pace at which this CCR device was pulled remained relatively constant.

Geophysical inverse modeling techniques (Parker, 1994) are very powerful tools and can be easily applied to the type of data collected by the OhmMapper TR1 to produce a depth profile showing the vertical distribution of soil electrical conductivity beneath a particular measurement transect. A
resistivity inverse modeling computer program, RES2DINV, developed by Loke (2003b), was used with OhmMapper TR1 data to produce the electrical conductivity depth profiles. Using least-squares optimization methods (Loke, 2003b), RES2DINV combined data collected along a particular transect at all four dipole to dipole separation distances (0.625, 1.25, 2.5, and 5.0 m) in order to generate an electrical conductivity depth profile beneath that transect.

**Galvanic Contact Resistivity Method: Veris 3100**

The third near-surface geophysical ECa measurement method evaluated in this study was galvanic contact resistivity (GCR). With traditional GCR, an electrical current (direct or low frequency alternating) is supplied between two electrodes staked directly into the ground while voltage is concurrently measured between one or more separate pairs of staked electrodes. The electric current, voltage, and electrode configuration are then used to calculate a value for apparent soil resistivity, which is then converted to ECa.

The GCR device used for this project was a Veris Technologies Veris 3100 Soil EC Mapping System (Salina, Kans.) (figs. 1c and 1d). With this unit, the electrodes are mounted on a steel frame (fig. 1d) and comprised of 43-cm diameter steel coulters (disks) that cut through the soil to depths of approximately 2.5 to 7.5 cm as they are pulled along behind a vehicle at field speeds of up to 25 km/h (fig. 1c). The data-logging interval is 1 s and measurement locations are determined using an integrated global positioning system (GPS). These GPS coordinates were then converted to local test plot coordinates in order to be consistent with the EMI and CCR data. The Veris 3100 Soil EC Mapping System that was used in this study has six coulters with non-adjustable spacing (two for electric current application and four for voltage measurement), thereby providing two Schlumberger electrode array configurations, a shorter one (0.7 m) for mapping the top 0.3 m of the soil profile and a longer one (2.1 m) for mapping the top 0.9 m of the soil profile.

**Characteristics of the Two Test Plots**

The three near-surface geophysical methods (EMI, CCR, and GCR) were compared at two test plots, which for simplicity will be referred to at Test Plot No. 1 and Test Plot No. 2. The two test plots are located side-by-side on a portion of the Ohio State University – Waterman Agricultural and Natural Resources Laboratory near the intersection of Lane Avenue and Kenny Road in Columbus, Ohio. A schematic map of the research site is provided in figure 2 showing that both test plots have an active corrugated polyethylene tubing (CPT) subsurface drainage system. In addition, both test plots have an inactive clay tile subsurface drainage system. The active CPT subsurface drainage system is buried at depths of 0.6 to 1.2 m and offset 0.3 to 1.8 m south of the inactive clay tile subsurface drainage system, which is 0.5 to 1 m beneath the surface.

The active CPT subsurface drainage system in Test Plot No. 1 is connected to a hydraulic control structure (fig. 2). This hydraulic control structure contains a height-adjustable weir, and water when added on the upstream side of the weir backs up into the functioning drainage pipes beneath Test Plot No. 1, in turn raising the water table in the field to a specific stabilized level above the drain lines. Test Plot No. 1 can be set to uncontrolled drainage mode by removing the weir from the hydraulic control structure. The active CPT subsurface drainage system in Test Plot No. 2 is routed directly to a main collector pipe, which diverts water off site (fig. 2). Consequently, Test Plot No. 2 is always in uncontrolled drainage mode, and unlike Test Plot No. 1, does not have the capability for maintaining the water table at a position above the drain lines.

With respect to dimensions, Test Plot No. 1 is 42.6 m north-south by 39.6 m east-west, while Test Plot No. 2 is 42.6 m north-south by 33.5 m east-west. The separation distance between the two test plots is 4.9 m. The soil series present at the test plots are Crosby (fine, mixed, mesic Aeric Ochraqualfs) and Kokomo (fine, mixed, mesic Typic Argiaquolls). Average soil properties from both test plots are presented in table 1. To obtain the test plot soil property averages listed

![Figure 2. Schematic map of the test plots on which apparent soil electrical conductivity (ECa) data were collected. CPT = corrugated polyethylene tubing.](image-url)
in table 1, five soil samples were collected at widely spaced locations in each test plot from 4-in. diameter boreholes augered to a depth of 1 m. These soil samples, composited from the surface to a depth of 1 m, were analyzed using standard methods (ASA and SSSA, 1982; Wray, 1986) at Ohio State University laboratories for % sand, % silt, % clay, salinity as indicated by the electrical conductivity of a 1/1 by weight soil/water slurry, pH, % organic matter, cation exchange capacity, and concentration of the dominant exchangeable cation (Ca\(^{2+}\)). The soil types present at both test plots, based on the grain size analysis (Wray, 1986) of the individual composited samples, ranged from loam to silt loam to clay loam, all of which are typical of material derived from weathering of Midwest U.S. glacial till deposits. A short grass cover was maintained on both test plots during periods that geophysical surveys were conducted.

**FIELD CONDITION MONITORING**

To assess shallow hydrologic conditions during periods that geophysical surveys were conducted, ten shallow observation wells were installed in Test Plot No. 1 and five shallow observation wells were installed in Test Plot No. 2 for measurement of water table depths. On average, the observation wells were emplaced to a depth of 0.87 m. A Solinst Canada Ltd. Mini 101 water level meter (Georgetown, Ontario, Canada) was used to measure the observation well water table depths. Furthermore, whenever water table depths were measured, soil surface volumetric water content values were also obtained near the observation well locations using a Spectrum Technologies, Inc. Field Scout TDR-300 (Plainfield, Ill.) time domain reflectometry probe.

Monitoring of field conditions during periods of geophysical surveying additionally involved collecting air and soil temperature data. The ambient air temperature was measured using a Spectrum Technologies, Inc. Crop TRAK infrared thermometer (Plainfield, Ill.). Air temperature readings were taken approximately 30 cm above the ground surface at points near the top of wooden stakes partially inserted into the soil at the southwest and northeast corners of the test plots. Soil temperatures were measured near the southwest and northeast corners of the test plots at depths of 15 to 20 cm with Weksler soil thermometers (Stratford, Conn.).

**GEOPHYSICAL DATA COLLECTION AND ANALYSIS**

A comparison of all three geophysical methods for measuring EC\(a\) was conducted once in the late summer 2002 during a period from 5 to 14 August and once in the middle of fall 2002 during a period from 2 to 5 October. EMI, CCR, and GCR were tested within the time period from 5 to 14 August in hopes of evaluating the technologies under drier shallow hydrologic conditions. (August in Ohio is often a month with limited rainfall and high evapotranspiration rates.) To help achieve these shallow hydrologic conditions, Test Plot No. 1 had been kept in uncontrolled drainage mode in the six months prior to the 5 to 14 August time period. (Again, Test Plot No. 2 is always in uncontrolled drainage mode.) The second round of testing, 2 to 5 October, was conducted to assess the three geophysical methods under wetter shallow hydrologic conditions. (Significant rainfall is not uncommon for Ohio in October, and cooler temperatures reduce evapotranspiration rates.) Attempts to make Test Plot No. 1 as wet as possible during 2 to 5 October involved subirrigating the field by adding water on the upstream side of the weir within the hydraulic control structure that was connected to the Test Plot No. 1 active subsurface drainage system. This subirrigation began approximately one month prior to 2 October 2002.

Each separate geophysical survey involved taking EC\(a\) measurements along a set of parallel transects that covered one of the test plots. The lines of measurement were oriented north-south and were 42.6 m in length. The spacing distance between adjacent measurement transects was 3.05 m. For each of the EMI, CCR, and GCR test plot surveys, EC\(a\) average, EC\(a\) median, EC\(a\) standard deviation, and EC\(a\) coefficient of variation were calculated from the raw EC\(a\) data, followed by generation of EC\(a\) contour maps. EC\(a\) statistics and map contour line values are reported in millisiemens per meter (mS/m). To produce the EC\(a\) contour maps, geostatistical kriging techniques were employed, in which a linear function with nugget effect model or a power function with nugget effect model proved to be the best fits to the variograms of the data. The interpolated EC\(a\) grids produced by kriging used a unit cell size of 0.43 \(\times\) 0.43 m, therefore 9300 interpolated data points were used to generate the Test Plot No. 1 EC\(a\) contour maps, and 7900 interpolated data points were used to generate the Test Plot No. 2 EC\(a\) contour maps. Kriging was utilized for interpolation of the raw data because it tends to be an exact interpolator, or simply, when the coordinates of an interpolated data point and raw data point coincide, the value of the interpolated point equals that of the raw data point.

Spatial correlation analysis between pairs of these interpolated grids was used to quantify the similarity in areal EC\(a\) trends measured by the three geophysical methods and their different operational modes. There are nine geophysical method – operational mode combinations.

- **Electromagnetic Induction (EMI)**
  - GEM-2 8190 Hz
  - GEM-2 14620 Hz
  - GEM-2 20010 Hz
- **Capacitively-Coupled Resistivity (CCR)**
  - OhmMapper TR1 0.625-m dipole spacing
  - OhmMapper TR1 1.25-m dipole spacing
  - OhmMapper TR1 2.5-m dipole spacing
  - OhmMapper TR1 5.0-m dipole spacing
- **Galvanic Contact Resistivity (GCR)**
  - Veris 3100 short electrode array
  - Veris 3100 long electrode array

Spatial correlation coefficients were computed by comparing EC\(a\) values at all locations on one interpolated grid with the corresponding EC\(a\) values at all locations on a second interpolated grid. For any test plot (No. 1 or 2) and survey period (5 to 14 August or 2 to 5 October) permutation, there were nine interpolated grids, based on the different

<table>
<thead>
<tr>
<th>Test Plot</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>EC(LM)[a] (mS/m)</th>
<th>pH</th>
<th>OM[b] (meq/100g)</th>
<th>CEC[c] (g/g)</th>
<th>DEC[d] (µg/g)</th>
</tr>
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<tr>
<td>1</td>
<td>29.6</td>
<td>57.2</td>
<td>13.2</td>
<td>21.7</td>
<td>7.43</td>
<td>3.25</td>
<td>18.5</td>
<td>2723</td>
</tr>
<tr>
<td>2</td>
<td>32.9</td>
<td>43.2</td>
<td>23.9</td>
<td>20.4</td>
<td>7.35</td>
<td>3.06</td>
<td>18.9</td>
<td>2758</td>
</tr>
</tbody>
</table>

[a] ECLM = laboratory measured electrical conductivity of a 1:1 soil/water mixture (representative of soil salinity).
[b] OM = organic matter percent by weight.
[c] CEC = Cation exchange capacity.
[d] DEC = Dominant exchangeable cation (Calcium – Ca\(^{2+}\)).
method – operational mode combinations, which were then compared to one another in this manner to quantify similarities in areal spatial trends. Consequently, given a particular test plot and survey period, there were 36 spatial correlation coefficients computed, which is a number representing all the possible pairs of different method – operational mode combinations. Furthermore, to evaluate hydrologic condition impacts, spatial correlation coefficient values for each test plot were calculated between the same geophysical method – operational mode combination, but with respect to the two different periods of investigation. Statistics from the EC_a surveys, GEM-2 electromagnetic vertical sounding, and inversion of the OhmMapper TR1 data all provided insight on changes in EC_a with depth.

**TIMELINE OF EVENTS**

**FIRST PHASE OF THE GEOPHYSICAL INVESTIGATION:**
5 TO 14 AUGUST 2002

- Weather conditions were fairly dry the week prior, and the amount of rainfall during this preceding period was only 3 mm.
- In the early morning hours on 5 August there was 24 mm of rainfall. During the rest of this period over which geophysical surveying was conducted, no additional rainfall occurred.
- 5 August: Data was collected on Test Plot No. 1 with the OhmMapper TR1.
- 7 August: Field condition measurements were obtained. At this time, there were ten observation wells in Test Plot No. 1, and the five observation wells for Test Plot No. 2 were not installed until later in this month. On this day, 7 August, seven out of the ten Test Plot No. 1 observation wells were dry, and the other three had water table depths of 0.72, 0.81, and 0.78 m. The average soil surface volumetric water content was 40.5% for Test Plot No. 1 and 50.4% for Test Plot No. 2. Air temperatures averaged 24°C and soil temperatures averaged 22°C.
- 8 August: Data was collected on Test Plot No. 2 with the OhmMapper TR1.
- 12 August: Data was collected on Test Plot No. 1 and Test Plot No. 2 with the GEM-2. On this day, seven out of the ten Test Plot No. 1 observation wells were dry, and the other three had water table depths of 0.79, 0.80, and 0.78 m. The average soil surface volumetric water content was 32.4% for Test Plot No. 1 and 38.6% for Test Plot No. 2. Air temperatures averaged 31°C and soil temperatures averaged 27°C.
- 14 August: Data was collected on Test Plot No. 1 and Test Plot No. 2 with the Veris 3100.

**SECOND PHASE OF THE GEOPHYSICAL INVESTIGATION:**
2 TO 5 OCTOBER 2002

- Weather conditions were quite wet the week prior, and the amount of rainfall during this preceding period was 107 mm. Test Plot No. 1 had been in subirrigation mode for approximately a month before this phase of the geophysical investigation. The water level in the Test Plot No. 1 weir-type hydraulic control structure was maintained at a position 0.76 m above the bottom of the control structure on its upstream side.
- 2 October: Data was collected on Test Plot No. 1 and Test Plot No. 2 with the OhmMapper TR1. The average water table depth in Test Plot No. 1 was 0.58 m. The water table in Test Plot No. 1 was not level, but rather undulating, it typically being 0.4 m higher over the drain lines than it was at locations midway between them. The average water table depth for Test Plot No. 2 was 0.87 m. Soil surface volumetric water contents averaged 47.0% for Test Plot No. 1 and 47.4% for Test Plot No. 2. Air temperatures averaged 24°C and soil temperatures averaged 18°C.
- 4 October: There was approximately 33 mm of rainfall, 20 mm occurred in the early morning hours and another 13 mm in the evening. Data was collected on Test Plot No. 1 and Test Plot No. 2 with the Veris 3100.
- 5 October: Data was collected on Test Plot No. 1 and Test Plot No. 2 with the GEM-2. Soil surface volumetric water contents averaged 57.4% for Test Plot No. 1 and 55.8% for Test Plot No. 2. Air temperatures averaged 14°C and soil temperatures averaged 16°C.

It is rather apparent from the shallow hydrologic measurements for both test plots that the electromagnetic induction (EMI) GEM-2 and galvanic contact resistivity (GCR) Veris 3100 surveys were conducted under wetter conditions in 2 to 5 October than in 5 to 14 August. The capacitive-coupled resistivity (CCR) OhmMapper TR1 surveying, Test Plot No. 1 had moderately wetter conditions in 2 to 5 October than in 5 to 14 August. However, with respect to the OhmMapper TR1 and Test Plot No. 2, shallow hydrologic conditions were marginally drier in 2 to 5 October than in 5 to 14 August. It is no surprise that, on the whole, air and soil temperatures were higher in 5 to 15 August than 2 to 5 October. TDR volumetric water content measurements were sometimes greater than 50%, which is probably somewhat higher than could be reasonably expected. Regardless, the TDR measurements still proved useful, in the relative sense, for assessment of near-surface soil moisture conditions.

**RESULTS AND DISCUSSION**

**SOIL ELECTRICAL CONDUCTIVITY SPATIAL PATTERNS**

Examples of areal apparent soil electrical conductivity (EC_a) spatial patterns detected by the nine geophysical method – operational mode combinations are depicted in figures 3 and 4. The EC_a contour interval is 6 mS/m in both figures, and relative grayscale shading is used to distinguish areas with low EC_a values (darkest shades) from areas with high EC_a values (lightest shades). Figure 3 shows EC_a contour maps produced from data collected 2 to 5 October 2002 for Test Plot No. 1. Generally, all the maps in figure 3, with one exception, depict the same overall EC_a trends. The lowest EC_a values are found along the southern boundary and southwest corner of Test Plot No. 1. Higher EC_a values for Test Plot No. 1 are present in a swath extending from the northeast corner to the center of the western boundary. The only map showing extensive divergence from these general Test Plot No. 1 EC_a trends is the one produced from data collected by the Veris 3100 short electrode array.

Figure 4 shows EC_a contour maps produced from data collected 2 to 5 October 2002 for Test Plot No. 2. As with figure 3, all the maps in figure 4 generally have the same overall EC_a trends, with one exception. The lowest EC_a values are found along the southern and northern boundaries.
Figure 3. Test Plot No. 1 EC\textsubscript{a} contour maps for the 2 to 5 October 2002 geophysical surveying phase, (a) GEM-2 8190 Hz, (b) GEM-2 14610 Hz, (c) GEM-2 20010 Hz, (d) OhmMapper TR1 0.625-m dipole spacing, (e) OhmMapper TR1 1.25-m dipole spacing, (f) OhmMapper TR1 2.5-m dipole spacing, (g) OhmMapper TR1 5.0-m dipole spacing, (h) Veris 3100 short electrode array, and (i) Veris 3100 long electrode array. The contour interval is 6 mS/m and lighter grayscale shading represents higher EC\textsubscript{a} values while darker shading represents lower EC\textsubscript{a} values.

Higher EC\textsubscript{a} values for Test Plot No. 2 are present in a swath extending from the center of the eastern boundary to the center of the western boundary. Again the map produced from the Veris 3100 short electrode array data is the only one showing extreme divergence from these general Test Plot No. 2 EC\textsubscript{a} trends.

Figures 3 and 4 show test plot areal EC\textsubscript{a} spatial patterns from data collected during the 2 to 5 October phase of the geophysical investigation. The Test Plot No. 1 and Test Plot No. 2 areal EC\textsubscript{a} spatial trend results for the 5 to 14 August phase proved to be similar to those of the 2 to 5 October phase. Areal EC\textsubscript{a} spatial pattern comparisons between the different geophysical methods and their various operational modes are quantified for the complete project in table 2, which provides a matrix of average spatial correlation coefficients. Each value in the matrix, representing a specific pair of different geophysical method – operational mode combinations, is the average of the Test Plot No. 1, 5 to 14 August; Test Plot No. 2, 5 to 14 August; Test Plot No. 1, 2 to 5 October; and Test Plot No. 2, 2 to 5 October spatial correlation coefficients for this same pair of different geophysical method – operational mode combinations. As discussed in the Materials and Methods section, the spatial correlation coefficients used in calculating this average are the result of a statistical correlation analysis between two kriged interpolated EC\textsubscript{a} grids, generated from raw data collected by two, in this case different, geophysical method – operational mode combinations.

Table 2 emphasizes some of the results depicted in figures 3 and 4. In particular, the Veris 3100 short electrode array (GCR method), which when paired with the various modes of the GEM-2 (EMI method) and OhmMapper TR1 (CCR method), exhibited an average correlation coefficient, \( r \), that ranged between only 0.30 and 0.45. The Veris 3100 short electrode array and the Veris 3100 long electrode areal EC\textsubscript{a} spatial patterns compared better, having an average
correlation coefficient of 0.64. All other average $r$ values for pairs of different geophysical method – operational mode combinations ranged between 0.62 and 0.97, indicating that the GEM-2, OhmMapper TR1, and Veris 3100 long electrode array consistently detected the same areal $E_{Ca}$ spatial trends.

Overall results comparing the different geophysical method – operational mode combinations to one another did not vary appreciably based on the test plot or the period that data were collected. This conclusion is based on averaging the 36 spatial correlation coefficients for each test plot and survey period permutation. This 36 spatial correlation coefficient average equals 0.65 for Test Plot No. 1 – 5 to 14 August, 0.65 for Test Plot No. 2 – 5 to 14 August, 0.70 for Test Plot No. 1 – 2 to 5 October, and 0.73 for Test Plot No. 2 – 2 to 5 October. With a range of only 0.65 to 0.73, these four averaged spatial correlation coefficients are not extremely different.

Table 3 provides spatial correlation coefficient values for each test plot calculated between the same geophysical method – operational mode combination, but with respect to different periods of investigation. Not including the Veris 3100 short electrode array results and with the exception of the GEM-2 8190 Hz on Test Plot No. 2 ($r = 0.55$), all other $r$ values in table 3 were quite substantial ($0.65 \leq r \leq 0.95$), even the GEM-2 8190 Hz on Test Plot No. 1 ($r = 0.91$),
indicating a significant amount of consistency between one time period and the next for almost all of the geophysical method – operational mode combinations. The correlation coefficient is 0.58 between the Veris 3100 short electrode array for Test Plot No. 1 in 5 to 14 August and the Veris 3100 short electrode array for Test Plot No. 1 in 2 to 5 October. The correlation coefficient is only 0.32 between the Veris 3100 short electrode array for Test Plot No. 2 in 5 to 14 August and the Veris 3100 short electrode array for Test Plot No. 2 in 2 to 5 October. Therefore, the areal ECa spatial trends measured by the Veris 3100 short electrode array were not, at least in this study, strongly consistent from one time period to the next. The Veris 3100 short electrode array has the shallowest soil investigation depth for any of the geophysical method – operational mode combinations tested, and the disparity in its results compared to the other method – operational mode combinations that are presented in tables 2 and 3, could be due to the greater impact on the Veris 3100 short electrode array of near surface features and conditions, which may differ significantly from those at greater depth.

Differences in test plot water table depths and soil surface volumetric water content between 5 to 14 August and 2 to 5 October and the results presented in table 3 imply that changing shallow hydrologic conditions do not have an overwhelming impact on areal ECa spatial trends in a fine-grained soil derived from glacial material. The conclusion just stated is strengthened by considering that the Test Plot No. 1 water table was not uniform during 2 to 5 October. The water table in Test Plot No. 1 for 2 to 5 October was on average 0.4 m higher over the drain lines than it was at locations midway between them (see fig. 2), but this non-uniform water table does not appear to have impacted the ECa trends depicted in figure 3 or to have reduced the Test Plot No. 1 spatial correlation coefficients given in table 3. In fact, spatial correlation coefficient values calculated between the same geophysical method – operational mode combination, but with respect to different periods of investigation, were typically greater for Test Plot No. 1 with an average value of 0.85 than Test Plot No. 2 with an average of 0.72.

To obtain detailed information on the vertical ECa spatial pattern beneath a transect, RES2DINV, the resistivity inverse modeling computer program developed by Loke (2003b), was used with the OhmMapper TR1 data to produce electrical conductivity depth profiles, of which two examples are shown in figure 5. Figure 5a is a depth profile produced from OhmMapper TR1 data collected on 2 October 2002 along a north-south transect, 18.3 m east of the Test Plot No. 1 west boundary. Figure 5b is a depth profile produced from OhmMapper TR1 data collected on 2 October 2002 along a north-south transect, 15.3 m east of the Test Plot No. 2 west boundary.

Grayscale shading in figure 5 provides a very basic representation of the electrical conductivity distribution to a depth of 2.1 m. In the most general sense, soil electrical conductivity is higher in the first meter beneath the surface than the second meter beneath the surface. Contour lines help depict the complexity of the electrical conductivity pattern within approximately 1.4 m of the surface. As shown in figures 5a and 5b, progressing from the surface down to a depth of around 1 m, electrical conductivity often increases and then decreases.

### Table 2. Average areal ECa spatial correlation coefficient matrix.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Test Plot No. 1 − August/02</th>
<th>Test Plot No. 1 − October/02</th>
<th>Test Plot No. 2 − August/02</th>
<th>Test Plot No. 2 − October/02</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1[c]</td>
<td>0.97</td>
<td>0.70</td>
<td>0.80</td>
<td>0.78</td>
</tr>
<tr>
<td>G2[c]</td>
<td>0.97</td>
<td>0.70</td>
<td>0.80</td>
<td>0.78</td>
</tr>
<tr>
<td>G3[d]</td>
<td>0.87</td>
<td>0.81</td>
<td>0.82</td>
<td>0.79</td>
</tr>
<tr>
<td>O1[e]</td>
<td>0.85</td>
<td>0.81</td>
<td>0.71</td>
<td>0.30</td>
</tr>
<tr>
<td>O2[f]</td>
<td>0.87</td>
<td>0.81</td>
<td>0.31</td>
<td>0.68</td>
</tr>
<tr>
<td>O3[g]</td>
<td>0.88</td>
<td>0.33</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>O4[h]</td>
<td>0.88</td>
<td>0.33</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>V1[i]</td>
<td>0.75</td>
<td>0.65</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>V2[j]</td>
<td>0.75</td>
<td>0.65</td>
<td>0.75</td>
<td>0.65</td>
</tr>
</tbody>
</table>

### Table 3. Areal ECa spatial correlation coefficient values for each test plot between the same geophysical method – operational mode combination, but with respect to different periods of investigation.

<table>
<thead>
<tr>
<th>Geophysical Method − Operational Mode Combination</th>
<th>Test Plot No. 1 − 5−12 Aug. vs. 2−5 Oct.</th>
<th>Test Plot No. 2 − 5−12 Aug. vs. 2−5 Oct.</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1[b]</td>
<td>0.91</td>
<td>0.55</td>
</tr>
<tr>
<td>G2[c]</td>
<td>0.94</td>
<td>0.75</td>
</tr>
<tr>
<td>G3[d]</td>
<td>0.95</td>
<td>0.77</td>
</tr>
<tr>
<td>O1[e]</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>O2[f]</td>
<td>0.87</td>
<td>0.77</td>
</tr>
<tr>
<td>O3[g]</td>
<td>0.86</td>
<td>0.87</td>
</tr>
<tr>
<td>O4[h]</td>
<td>0.90</td>
<td>0.87</td>
</tr>
<tr>
<td>V1[i]</td>
<td>0.58</td>
<td>0.32</td>
</tr>
<tr>
<td>V2[j]</td>
<td>0.85</td>
<td>0.89</td>
</tr>
</tbody>
</table>

[a] Based on a pooled t-test (Snedecor and Cochran, 1967), all the r values in this table are statistically significant (null hypothesis, $r = 0$, rejected, $P < 0.001$).

[b] G1 = GEM-2 with primary EM field frequency of 8190 Hz.
[c] G2 = GEM-2 with primary EM field frequency of 14610 Hz.
[d] G3 = GEM-2 with primary EM field frequency of 20010 Hz.
[e] O1 = OhmMapper TR1 with 0.625 m separation between dipoles.
[f] O2 = OhmMapper TR1 with 1.25 m separation between dipoles.
[g] O3 = OhmMapper TR1 with 2.5 m separation between dipoles.
[h] O4 = OhmMapper TR1 with 5.0 m separation between dipoles.
[i] V1 = Veris 3100 Soil EC Mapping System with short electrode array.

### Table 4. SOIL ELECTRICAL CONDUCTIVITY MEASUREMENTS

<table>
<thead>
<tr>
<th>Geophysical Method − Operational Mode Combination</th>
<th>Test Plot No. 1 − 5−12 Aug. vs. 2−5 Oct.</th>
<th>Test Plot No. 2 − 5−12 Aug. vs. 2−5 Oct.</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1[b]</td>
<td>0.91</td>
<td>0.55</td>
</tr>
<tr>
<td>G2[c]</td>
<td>0.94</td>
<td>0.75</td>
</tr>
<tr>
<td>G3[d]</td>
<td>0.95</td>
<td>0.77</td>
</tr>
<tr>
<td>O1[e]</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>O2[f]</td>
<td>0.87</td>
<td>0.77</td>
</tr>
<tr>
<td>O3[g]</td>
<td>0.86</td>
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</tr>
<tr>
<td>O4[h]</td>
<td>0.90</td>
<td>0.87</td>
</tr>
<tr>
<td>V1[i]</td>
<td>0.58</td>
<td>0.32</td>
</tr>
<tr>
<td>V2[j]</td>
<td>0.85</td>
<td>0.89</td>
</tr>
</tbody>
</table>

[a] Based on a t-test (Snedecor and Cochran, 1967), all the r values in this table are statistically significant (null hypothesis, $r = 0$, rejected, $P < 0.001$).

[b] G1 = GEM-2 with primary EM field frequency of 8190 Hz.
[c] G2 = GEM-2 with primary EM field frequency of 14610 Hz.
[d] G3 = GEM-2 with primary EM field frequency of 20010 Hz.
[e] O1 = OhmMapper TR1 with 0.625 m separation between dipoles.
[f] O2 = OhmMapper TR1 with 1.25 m separation between dipoles.
[g] O3 = OhmMapper TR1 with 2.5 m separation between dipoles.
[h] O4 = OhmMapper TR1 with 5.0 m separation between dipoles.
[i] V1 = Veris 3100 Soil EC Mapping System with short electrode array.
Figure 5. Soil electrical conductivity depth profiles produced from inverse modeling with RES2DINV of OhmMapper TR1 data collected 2 October 2002, (a) line of measurement is 18.3 m east of the west boundary of Test Plot No. 1, and (b) line of measurement is 15.3 m east of the west boundary of Test Plot No. 2.

variation were largest for the OhmMapper TR1 data with 0.625- and 1.25-m dipole to dipole spacing distances. This increased variability for the OhmMapper TR1 data collected with 0.625- and 1.25-m dipole to dipole spacing distances may be a result of the electrical fields between the ends of the transmitter and receiver dipoles becoming distorted when they are close together, which in conjunction with bouncing of the dipole ends that occurs as the array is towed can produce poorer quality, noisier, ECa measurements (Geometrics, Inc., 2004). Trend-wise, table 4 shows a decrease in ECa test plot standard deviations and coefficients of variation for the OhmMapper TR1 as its dipole to dipole spacing is increased from 0.625 to 5.0 m for a particular test plot and survey period.

The observed trend for the GEM-2, given a particular test plot and survey period permutation, was a decrease in ECa test plot standard deviations and coefficients of variation as the primary electromagnetic (EM) field frequency increased from 8190 to 14610 to 20010 Hz, indicating that under the circumstances tested, lower frequencies generate noisier data. The Veris 3100 short electrode array almost always had the lowest ECa test plot standard deviation and coefficient of variation values, confirming that ECa values were fairly

Table 4. Test plot ECa averages, medians, standard deviations, and coefficients of variation for the different geophysical method − operational mode combinations.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Plot No. 1, 5-14 August 2002</td>
<td>21.3 (21.7)</td>
<td>18.4 (18.7)</td>
<td>21.1 (21.5)</td>
<td>59.4 (57.5)</td>
<td>56.2 (54.6)</td>
<td>50.2 (49.7)</td>
<td>34.1 (33.8)</td>
<td>15.5 (15.2)</td>
</tr>
<tr>
<td>Test Plot No. 1, 2-5 October 2002</td>
<td>33.7 (34.3)</td>
<td>31.1 (31.9)</td>
<td>33.8 (34.7)</td>
<td>47.6 (48.1)</td>
<td>44.5 (43.9)</td>
<td>39.4 (39.6)</td>
<td>31.8 (31.9)</td>
<td>38.7 (38.7)</td>
</tr>
<tr>
<td>Test Plot No. 2, 5-14 August 2002</td>
<td>17.5 (17.0)</td>
<td>14.4 (13.9)</td>
<td>17.0 (16.5)</td>
<td>43.0 (42.8)</td>
<td>38.9 (39.3)</td>
<td>35.2 (35.6)</td>
<td>30.7 (31.3)</td>
<td>16.3 (16.0)</td>
</tr>
<tr>
<td>Test Plot No. 2, 2-5 October 2002</td>
<td>29.2 (29.4)</td>
<td>26.5 (26.7)</td>
<td>28.9 (29.3)</td>
<td>34.7 (34.3)</td>
<td>33.0 (33.1)</td>
<td>30.3 (30.3)</td>
<td>26.7 (27.1)</td>
<td>37.9 (37.7)</td>
</tr>
</tbody>
</table>

| Standard Deviation − mS/m, (Coefficient of Variation − dimensionless) of Test Plot ECa |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Test Plot No. 1, 5-14 August 2002 | 8.5 (0.40) | 5.9 (0.32) | 5.5 (0.26) | 16.4 (0.28) | 16.1 (0.29) | 12.7 (0.25) | 8.8 (0.26) | 2.8 (0.18) | 7.0 (0.20) |
| Test Plot No. 1, 2-5 October 2002 | 6.6 (0.20) | 5.8 (0.19) | 5.7 (0.17) | 12.0 (0.25) | 11.0 (0.25) | 9.7 (0.25) | 6.4 (0.20) | 3.8 (0.10) | 5.9 (0.12) |
| Test Plot No. 2, 5-14 August 2002 | 8.5 (0.49) | 5.1 (0.35) | 4.0 (0.24) | 8.6 (0.20) | 7.2 (0.19) | 5.5 (0.16) | 4.8 (0.16) | 3.0 (0.18) | 6.8 (0.23) |
| Test Plot No. 2, 2-5 October 2002 | 4.7 (0.16) | 3.7 (0.14) | 3.6 (0.12) | 7.4 (0.21) | 5.8 (0.18) | 4.4 (0.15) | 3.6 (0.13) | 3.3 (0.09) | 5.6 (0.12) |

[a] G1 = GEM-2 with primary EM field frequency of 8190 Hz.
[b] G2 = GEM-2 with primary EM field frequency of 14610 Hz.
[c] G3 = GEM-2 with primary EM field frequency of 20010 Hz.
[d] O1 = OhmMapper TR1 with 0.625-m separation between dipoles.
[e] O2 = OhmMapper TR1 with 1.25-m separation between dipoles.
[f] O3 = OhmMapper TR1 with 2.5-m separation between dipoles.
[g] O4 = OhmMapper TR1 with 5.0-m separation between dipoles.
[h] V1 = Veris 3100 Soil EC Mapping System with short electrode array.
[i] V2 = Veris 3100 Soil EC Mapping System with long electrode array.
uniform across each of the two test plots when measured with the Veris 3100 short electrode array (see figs. 3h and 4h). The average and median ECa values in table 4 are very similar, indicating that the ECa measurement distributions tend to be symmetrical. Because the average and median ECa values are quite similar, discussion of results will focus only on average ECa values. Test plot ECa averages in table 4 exhibit a wide range, from 14.4 mS/m for the GEM-2 14,610-Hz frequency on Test Plot No. 2 in 5 to 14 August to 59.4 mS/m for the OhmMapper TR1 0.625 m dipole-dipole spacing on Test Plot No. 1 in 5 to 14 August. For a particular test plot and survey period permutation, the variation in average ECa for the different geophysical method – operational mode combinations is quite substantial, indicating significant dissimilarities between the different geophysical method – operational mode combinations with respect to soil volume influencing the instrument response, magnitude of effects due to small-scale features, sensitivity to changes in field conditions, relative impact of unwanted electromagnetic signal (noise), procedures for calculating ECa, etc. Consequently, care and caution definitely need to be exercised when integrating ECa results from different geophysical methods in order to draw specific conclusions, for example, on changes in transient conditions (nutrient levels, soil wetness, etc.) of an agricultural field or distinctions in soil texture between two locations.

There are some distinct trends in the test plot ECa averages presented in table 4. All three geophysical methods generally exhibit Test Plot No. 1 ECa averages that are greater than Test Plot No. 2 ECa averages for comparable survey periods. The corresponding ECa averages for the EMI GEM-2 and GCR Veris 3100 are considerably larger in the 2 to 5 October surveys than the 5 to 14 August surveys on both test plots. This result is not unexpected because fairly wet shallow hydrologic conditions existed during the days within the 2 to 5 October period that the GEM-2 and Veris 3100 surveys were conducted, and dry shallow hydrologic conditions existed during the days within the 5 to 14 August period that the GEM-2 and Veris 3100 surveys were conducted. ECa typically increases as shallow hydrologic conditions become wetter (larger soil surface volumetric water content values and reduced depth to the shallow water table), so the GEM-2 and Veris 3100 ECa averages should have been greater, which is what occurred for the 2 to 5 October period compared to the 5 to 14 August period.

The impact of shallow hydrologic conditions on CCR OhmMapper TR1 measurements is somewhat puzzling. Corresponding OhmMapper TR1 ECa averages were larger for the 5 to 14 August survey period than the 2 to 5 October survey period on both test plots. These OhmMapper TR1 results may make some sense for Test Plot No. 2, which had marginally wetter shallow hydrologic conditions during the day surveyed in the 5 to 14 August period than on the day surveyed in the 2 to 5 October period. However, Test Plot No. 1 had moderately wetter conditions and lower average ECa values on the day OhmMapper TR1 surveying was conducted within the 2 to 5 October period as compared to the day OhmMapper TR1 surveying was conducted within the 5 to 14 August period. This result is opposite the normal relationship of an increase in ECa as shallow hydrologic conditions become wetter. The reason for this discrepancy in regard to the OhmMapper TR1 Test Plot No. 1 data is at present unclear.

The table 4 GEM-2 ECa averages, given a particular test plot and survey period, are quite similar regardless of the primary EM field frequency. This result could indicate one of two possibilities. First, if GEM-2 soil investigation depth is in some manner related to skin depth, then similar ECa averages over a frequency range of 8,190 to 20,010 Hz imply that soil electrical conductivity is fairly uniform with depth. The second possibility is that the GEM-2 soil investigation depth is based solely on the 1.66-m transmitter/receiver intercoil spacing, and the depth of soil investigation (based on operating the GEM-2 at 1 m above the ground surface) is around 1.5 m for all three frequencies; therefore it would be expected that the ECa averages were similar for the three frequencies employed.

The OhmMapper TR1 ECa averages, given a particular test plot and survey period, decrease as the spacing distance between dipoles is increased. The OhmMapper TR1 depth of soil investigation increases from approximately 0.5 to 0.8 to 1.3 to 2.1 m as the dipole-to-dipole spacing is increased from 0.625 to 1.25 to 2.5 to 5.0 m. Therefore, the OhmMapper TR1 trend of decreasing ECa averages with increasing dipole spacing implies that soil electrical conductivity values become smaller with depth. The figure 5 soil electrical conductivity depth profiles generated from OhmMapper TR1 data using inverse modeling methods indicate that the electrical conductivity trend with depth is somewhat more complicated. The figure 5 profiles show a layer with higher electrical conductivity values overlying a layer with lower values, and for the overlying layer, soil electrical conductivity often increases and then decreases from the surface downwards. The Veris 3100 ECa averages, given a particular test plot and survey period, are smaller for the short electrode array compared to the large electrode array. The Veris 3100 soil investigation depth is around 0.3 m for the short electrode array and 0.9 m for the long electrode array. Consequently, smaller ECa averages for the Veris 3100 short electrode array compared to the Veris 3100 long electrode array indicates that soil electrical conductivity increases from the surface down to a depth of about 0.9 m.

**Electromagnetic Vertical Sounding Implications**

To gain further insight on the GEM-2 investigation depth and soil electrical conductivity trends with depth, two electromagnetic vertical soundings were conducted with the GEM-2 on 1 December 2004, one in the center of Test Plot No. 1 and one in the center of Test Plot No. 2. The electromagnetic vertical sounding results, with ECa uncorrected for the height above the ground surface, are provided in figure 6 for both test plots and all three GEM-2 primary EM field frequencies. Figure 6 shows a substantial decrease in uncorrected ECa values for all frequencies and at both test plots as the GEM-2 is raised from the surface to a height of 2.4 m. In fact, averaged over the three GEM-2 frequencies and both test plots, the uncorrected ECa at 2.4 m is approximately 15% of its value at the ground surface. In addition, evaluating both test plots separately, the relationships between uncorrected ECa and GEM-2 height are remarkably similar for all three primary EM frequencies employed, even taking into account the 8190-Hz measurement instabilities.

As the GEM-2 is repeatedly raised from one level to the next, more and more of its response is affected by the air between the GEM-2 and the ground surface. The electrical
conductivity of air is 0 mS/m. Because the figure 6 GEM-2 uncorrected ECₐ values at a height of 2.4 m are on average only 15% of their corresponding values at the ground surface, it can be concluded that the ECₐ response at 2.4 m is virtually dominated by the 0 mS/m air. If at a 2.4-m height above the ground surface, the GEM-2 response is almost completely governed by air and not the soil, then the GEM-2 total investigation depth is somewhere around 2.4 m. This 2.4-m value is very near the 1.5 s investigation depth proposed by McNeill (1980b) for low induction number considerations of EMI surveying. (The s value is the transmitter/receiver intercoil spacing, which for the GEM-2 equals 1.66 m, and 1.5 × 1.66 m = 2.5 m.) Consequently, the overall figure 6 results indicate that the GEM-2 soil investigation depth, at all three primary EM field frequencies employed, was 1.5 m [(1.5 × 1.66-m intercoil spacing) – 1-m GEM-2 height above surface] for the ECₐ mapping surveys conducted during 5 to 14 August and 2 to 5 October. Therefore, it is not at all surprising that the table 4 GEM-2 ECₐ averages, based on the three primary EM field frequencies, were very similar given a particular test plot and survey period, simply because the GEM-2 investigation depth was essentially the same at 8,190, 14,610, and 20,010 Hz. Although a multi-frequency ground conductivity meter (GCM) was not an advantage in this case with respect to depth of investigation, it does have a possible benefit for reducing the impact of unwanted EM signal (noise). If the unwanted EM signal is limited to a short band of frequencies, then using a GCM with several widely separated primary EM field frequencies allows useful data to still be obtained outside the EM noise band.

Figure 7 displays the electromagnetic vertical sounding results with ECₐ values corrected for the GEM-2 height above the ground surface. Because of instabilities in the 8190-Hz measurements, only the 14,610- and 20,010-Hz GEM-2 data are shown. The corrected values representing apparent soil electrical conductivity are calculated as follows (Dualem Inc., 2004):

$$ EC_{a-corrected} = \frac{EC_{a-uncorrected}}{1 - h(z)} $$  \hspace{1cm} (2)

where the cumulative response function, $h(z)$, of an EMI GCM in the vertical dipole mode of operation (horizontal coplaner transmitter/receiver coil configuration) is expressed:

$$ h(z) = \frac{1}{\sqrt{4z^2 + 1}} $$  \hspace{1cm} (3)

with

$$ z = \frac{d}{s} $$  \hspace{1cm} (4)

where $d$, in this case, equals height of the GCM above the ground surface and $s$ is the transmitter/receiver intercoil spacing.

Figure 7 shows, for both test plots and both primary EM field frequencies, a modest increase in corrected ECₐ as the GEM-2 is raised from the ground surface to a height of 0.4 m. Beyond 0.4 m, as the GEM-2 is raised to greater and greater height, corrected ECₐ values continually decrease, with the largest ECₐ reductions occurring between heights of 1.6 and 2.4 m for Test Plot No. 1 and 2.0 and 2.4 m for Test Plot No. 2. With a GEM-2 total investigation depth of approximately 2.5 m, the large ECₐ reductions that occur as the GEM-2 is raised from 1.6 to 2.4 m on Test Plot No. 1 and 2.0 to 2.4 m on Test Plot No. 2 may be indicative of a low electrical conductivity layer just beneath the ground surface.

As shown in figure 7 and described in the preceding paragraph, maximum values for the corrected ECₐ are found when the GEM-2 is 0.4 m above the ground surface, implying that soil electrical conductivity first increases with depth beneath the surface, and then at some level begins to decrease. There is another possibility. If the proportional contribution of a low electrical conductivity layer just beneath the ground surface to the total soil EMI response decreases as the GEM-2 is raised 0.4 m above the ground,
then this scenario would account for the corrected ECa maxima at a 0.4-m height. However, this alternative explanation relying on the reduced proportional EMI response to a near-surface, low electrical conductivity soil layer does not hold up to scrutiny, because simple calculations indicate that the proportional contribution to the total soil EMI response of a 0.4- to 0.6-m layer directly beneath the surface actually increases as the GEM-2 is raised from the surface to a 0.4-m height. Consequently, the most likely explanation for the corrected ECa maxima at a GEM-2 height of 0.4 m remains a situation in which soil electrical conductivity first increases with depth beneath the surface, and then at some level begins to decrease.

Due to the complexity of the vertical dipole mode cumulative response function, the actual depth at which the soil electrical conductivity trend reversal takes place is difficult to estimate, based on the figure 7 electromagnetic vertical sounding data. As previously stated, for any test plot and survey period, the Veris 3100 short electrode array ECa average was less than that of the Veris 3100 long electrode array, indicating for both test plots an overall increase in soil electrical conductivity from the surface to a depth of 0.9 m. These GEM-2 electromagnetic vertical sounding and Veris 3100 survey results taken together indicate an electrical conductivity trend reversal within the soil profile, probably somewhere below 1 m, in which the trend of a continuous electrical conductivity increase from the surface downwards changes over to a trend in which soil electrical conductivity decreases with depth. Furthermore, the corrected ECa electromagnetic vertical sounding results (fig. 7) point to a vertical soil electrical conductivity reversal at depth that is more pronounced in Test Plot No. 2 than Test Plot No. 1.

The Test Plot No. 1 electromagnetic vertical sounding location is positioned only 1.5 m east of the center point for the measurement transect along which OhmMapper TR1 data were collected to produce the figure 5a soil electrical conductivity depth profile. Likewise, the Test Plot No. 2 electromagnetic vertical sounding location is positioned only 1.5 m east of the center point for the measurement transect along which OhmMapper TR1 data were collected to produce the figure 5b soil electrical conductivity depth profile. At a line center distance of 21.3 m on both figure 5 depth profiles, soil electrical conductivity first increases and then decreases with depth, with the trend reversal occurring approximately 1 m beneath the surface.

**SUMMARY AND CONCLUSIONS**

There are three near-surface geophysical methods available for rapid, continuous measurement of apparent soil electrical conductivity (ECa) in agricultural fields. These methods are electromagnetic induction (EMI), capacitively-coupled resistivity (CCR), and galvanic contact resistivity (GCR). The EMI method was tested with a Geophex, Ltd., GEM-2 multi-frequency ground conductivity meter (GCM), CCR was evaluated using the Geometrics, Inc., OhmMapper TR1, and GCR was assessed with a Veris Technologies, Veris 3100 Soil EC Mapping System. Each of the three geophysical methods had different operational modes which were evaluated, included three primary electromagnetic (EM) field frequencies (8,190, 14,610, and 20,010 Hz) used for the EMI method (GEM-2), four spacing distances (0.625, 1.25, 2.5, and 5.0 m) between the two dipoles employed by the CCR method (OhmMapper TR1), and two different Schlumberger electrode array lengths (0.7 and 2.1 m) utilized for the GCR method (Veris 3100). Consequently, a total of nine geophysical method − operational mode combinations were assessed.

Testing of all three methods under variable shallow hydrologic conditions was conducted at two adjacent test plots having loam to silt loam to clay loam soils. (These soils were derived from weathering of glacially deposited material, and in this regard, are typical examples of soil common throughout the Midwest United States.) Similarities and differences between the nine method − operational mode combinations were examined with respect to measured areal ECa patterns for the two agricultural test plots and in regard to test plot ECa averages, medians, standard deviations, and coefficients of variation. To evaluate hydrologic condition
impacts, spatial correlation coefficient values for each test plot were calculated between the same geophysical method – operational mode combination, but with respect to the two different periods of investigation. In addition, electrical conductivity variation as a function of soil depth was assessed from OhmMapper TR1 and Veris 3100 geophysical survey data along with GEM-2 electromagnetic vertical sounding measurements.

The four major findings of this research investigation are listed as follows.

• All the geophysical method – operational mode combinations, except the Veris 3100 short electrode array, detected similar areal ECₐ patterns for both test plots. The important implication of this result is that EMI, CCR, and GCR are all capable of determining, in a consistent manner, the areal ECₐ patterns present in farm fields. Consequently, each of the three geophysical methods is a viable option for precision agriculture ECₐ mapping purposes.

• Changes in shallow hydrologic conditions (soil surface volumetric water content and shallow water table depth) were not found to have a significant impact on the areal ECₐ patterns measured by the different geophysical method – operational mode combinations, again with the possible exception of the Veris 3100 short electrode array. Consequently, this result strongly indicates that areal ECₐ patterns are most likely governed by spatial changes in soil profile properties, at least for fine-grained glacial sediment derived soils common throughout the Midwest United States.

• For a particular test plot and survey period, substantial variability was exhibited in the average values of the ECₐ measurements obtained by each of the nine geophysical method – operational mode combinations. Therefore, care and caution are definitely warranted when integrating ECₐ results from different geophysical methods in order to make certain assessments, for example, evaluating changes in agricultural field transient conditions (nutrient levels, soil wetness, etc.) or determining the similarity in soil texture between two farm locations.

• Electromagnetic vertical soundings with the GEM-2, inverse modeling of OhmMapper TR1 measurements, and Veris 3100 short and long electrode array data, when they are all combined, point to a general vertical soil electrical conductivity trend common for both test plots in which soil electrical conductivity from the surface down to a depth of around 2 m first increases and then decreases. The reversal in the vertical electrical conductivity trend probably occurs somewhere below a depth of 1 m. This assessment for both test plots of the overall soil electrical conductivity change with depth served to demonstrate that EMI, CCR, and GCR can all provide some manner of useful information on vertical soil electrical conductivity trends.

The EMI, CCR, and GCR methods all appear capable of delineating areal ECₐ spatial patterns along with offering some insight on soil electrical conductivity change with depth. The findings of this investigation are applicable to glacial sediment derived soils typical of the Midwest United States. Further research is certainly needed comparing EMI, CCR, and GCR methods together on a variety of soils in different regions of the United States or elsewhere in the world.

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