**United States Department of Agriculture** | **Natural Resources Conservation Service** | **11 Campus Boulevard Suite 200 Newtown Square, PA 19073**

**Subject:** **--** Geophysical Assistance **--** **Date:** 29 July 2001

**To:** Marcia K. Schulmeister, Ph.D.
The University of Kansas
Kansas Geological Survey
1930 Constant Ave., Campus West
Lawrence, KS 66047

**Purpose:**
The purpose of this investigation was to further evaluate results obtained with various electromagnetic induction (EMI) tools for site-specific and high intensity soil surveys.

**Participants:**
Jim Butler, Senior Scientist, University of Kansas, Kansas Geological Survey, Lawrence, KS
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA
Bruce Evans, Soil Scientist, USDA-NRCS, Lawrence, KS
Marcia K. Schulmeister, Post-Doctoral Associate, University of Kansas, Kansas Geological Survey, Lawrence, KS
Margaret Townsend, Research Associate, University of Kansas, Kansas Geological Survey, Lawrence, KS
Doug Wysocki, Research Soil Scientist, USDA-NRCS, Lincoln, NE

**Activities:**
All field activities were completed during the period of 27 to 28 July 2001.

**Equipment:**
The EM31 meter and the GEM300 sensor were used in this study. Geonics Limited manufacturers the EM31 meters. This meter is portable and requires only one person to operate. McNeill (1980) has described principles of operation for the EM31meter. No ground contact is required with this meter. The depth of penetration is geometry limited. Lateral resolution is approximately equal to the intercoil spacing. The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9,810 Hz. It has theoretical penetration depths of about 3.0 and 6.0 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980).

The GEM300 multifrequency sensor is manufactured by Geophysical Survey systems, Inc. [1]This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.6 m). Won and others (1996) have described the use and operation of this sensor. With the GEM300 sensor, the penetration depth is considered "skin depth limited" rather than "geometry limited." The skin-depth represents the maximum depth of penetration and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signal. Theoretical penetration depths of the GEM300 sensor are dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequencies. Multifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

[1] Manufacturer's names are provided for specific information; use does not constitute endorsement.

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,[2] was used to construct two- and three-dimensional simulations. Grids were created using kriging methods with an octant search.

**Recommendations:**

1. Soil maps prepared by the USDA are not intended for precision agriculture. However, soil surveys do provide valuable information to precision agriculture. It is incumbent upon the Soil Survey Division to promote the use of soil information as a key component of precision agriculture and to ensure that soil surveys are used within their designed limits.

2. Results from different instruments produce similar but not identical results. Differences in measured values and spatial patterns of apparent conductivity are attributed to differences in the frequency, depth and volume of soil sounded, and depth-response functions of each instrument, as well as variations in soils and soil properties. Differences in sampling intensity and survey design also affect results.

3. Within each grid area, similar spatial patterns of apparent conductivity were obtained with most instruments. While measured values varied among instruments, these differences reflect variations in the volume and depth of materials sounded. The correlations among several instruments suggest that they are measuring similar volumes of earthen materials and provide comparable results.

4. Geophysical interpretations are considered preliminary estimates of site conditions. The results of all geophysical investigations are interpretive and do not substitute for direct soil borings. The use of geophysical methods can reduce the number of soil observations, direct their placement, and supplement their interpretations. Interpretations should be verified by ground-truth observations.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
R. Ahrens, Director, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
C. Olson, National Leader for Soil Investigations, USDA-USDA, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
H. Smith, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14$^{th}$ & Independence Ave. SW, Washington, DC 20250

**Electromagnetic Induction:**
Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a

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specific depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are caused by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the type and concentration of ions in solution, the amount and type of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976). While EMI does not measure specific ions or compounds, it can provide a measure of the bulk ionic concentration or nutrient levels in soils.

Electromagnetic induction has been used to assess and map soil salinity (Cook and Walker, 1992; Corwin and Rhoades, 1982 and 1990; Slavich and Petterson, 1990), sodium-affected soils (Ammons et al., 1989; Nettleton et al., 1994), depths to claypans (Doolittle et al., 1994; Stroh et al., 1993; Sudduth and Kitchen, 1993; and Sudduth et al., 1995), and edaphic properties important to forest site productivity (McBride et al., 1990). Kitchen and others (2000) used EMI to estimate topsoil thickness and clay content, which were associated with soil profile nutrient pools. Electromagnetic induction has been used to estimate soil water contents (Kachanoski et al., 1988; Sheets and Hendrickx, 1995), cation exchange capacity and exchangeable Ca and Mg (McBride et al., 1990), and leaching rates of solutes (Jaynes et al., 1995b). Recently, EMI has been used as a soil-mapping tool to assist precision agriculture (Jaynes, 1995; Jaynes et al., 1995b; Sudduth et al., 1995). Jaynes and others (1995a) compared EMI measurements with yield data and found that relationship between yield and EMI response varied from site to site and was not consistent from year to year.

Electromagnetic induction is not suitable for use in all soil investigations. Generally, the use of EMI has been most successful in areas where subsurface properties are reasonably homogeneous and one property (e.g. salt, clay, or water content) exerts an overriding influence over soil electrical conductivity. In these areas, variations in apparent conductivity can be directly related to changes in the dominant property (Cook et al., 1989). In studies conducted in Iowa (Jaynes et al., 1995, 1995b), variations in more than one property weakened and obscured relationships. In these studies, collective changes in the moisture, clay, and carbonate contents weakened relationships between apparent conductivity and moisture stress or drainage classes.

**Study Area:**

The study area is located in Douglas County, Kansas, about farm about 2 miles northeast of Lawrence. The area had been mapped as Kennebec silt loam and Wabash silty clay loam (Dickey et al., 1977). The Kennebec series consists of deep, moderately well drained, soils formed in alluvium on flood plains. Kennebec soil is a member of the fine-silty, mixed, superactive, mesic Cumulic Hapludolls family. The Wabash series consists of very deep, poorly and very poorly drained soils formed in alluvium on flood plains. Wabash soil is a member of the fine, smectitic, mesic Cumulic Vertic Endoaquolls family.

**Field Procedures:**

An irregularly shaped grid was established across the study area. The grid interval was 50 feet. Survey flags were inserted in the ground at each grid intersection and served as observations points. This procedure provided 164 observation points.

As measurements were obtained in both the horizontal and vertical dipole orientations and, as precise positioning of instruments were required, the EM31 meter and GEM300 sensors were operated in a station-to-station rather than a continuous mode. Measurements were taken at hip-height in both the horizontal and vertical dipole orientations with the EM31 meter and the GEM300 sensor.

**Results:**

**Discussion:**

Interpretations of EMI or resistivity data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in apparent conductivity have been used to infer changes in soils and soil properties. Electrical resistivity and EMI integrate the bulk physical and chemical properties for a defined observation depth into a single value. As a consequence, measurements can be associated with changes in soils and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993; Doolittle et al., 1996). For each soil, intrinsic physical and chemical properties, as well as temporal variations in soil water and temperature, establish a unique or characteristic range of apparent conductivity values.

Electromagnetic induction is useful to precision agriculture when apparent conductivity can be associated with soil properties that are related to crop productivity and where spatial patterns of apparent conductivity correspond to patterns of crop yield variation. Patterns of apparent conductivity do not tend to vary significantly over time. Doerge and others (1999) noted that once an apparent conductivity map is prepared, it remains relatively accurate unless some significant soil modification occurs (e.g. accelerated erosion, land leveling, terrace construction, flood deposition or erosion). However, temporal variations in apparent conductivity do occur as a consequence of changes in soil moisture content and temperature. Values of apparent conductivity increase with increased soil moisture content and/or temperature (about 2 % per degree Centigrade) (McNeill, 1980).

Table 1 summarizes the data collected with the EM31 meter and the GEM300 sensor. In general, values of apparent conductivity increased with increasing depth of observation. For both instruments, measurements obtained in the deeper sensing vertical dipole orientation were greater than those obtained in the shallower sensing horizontal dipole orientation. For the GEM300 sensor, in the horizontal dipole orientation, apparent conductivity decreased and became more variable at lower frequencies. However, in the vertical dipole orientation, apparent conductivity was essentially invariable at different frequencies.

**HORIZONTAL DIPOLE ORIENTATION**

| | EM31 | 3030 Hz | 6390 Hz | 9810 Hz | 14790 Hz |
|---|---|---|---|---|---|
| **Average** | 57.3 | 34.8 | 44.8 | 49.6 | 51.4 |
| **Minimum** | 9.8 | -2.5 | -50.0 | 16.1 | 17.7 |
| **Maximum** | 84.6 | 379.4 | 324.3 | 272.0 | 206.1 |
| **First Quartile** | 51.2 | 22.2 | 33.8 | 39.4 | 42.4 |
| **Second Quartile** | 7.7 | 32.9 | 44.5 | 50.0 | 52.4 |
| **Third Quartile** | 3.5 | 41.7 | 51.2 | 56.0 | 58.9 |

**VERTICAL DIPOLE ORIENTATION**

| | EM31 | 3030 Hz | 6390 Hz | 9810 Hz | 14790 Hz |
|---|---|---|---|---|---|
| **Average** | 83.1 | 93.6 | 92.1 | 93.3 | 93.4 |
| **Minimum** | 47.4 | 36.5 | 39.3 | 40.8 | 42.9 |
| **Maximum** | 141.2 | 149.0 | 147.7 | 142.0 | 131.1 |
| **First Quartile** | 74.5 | 83.6 | 80.0 | 80.5 | 81.7 |
| **Second Quartile** | 81.3 | 94.7 | 93.6 | 94.6 | 94.9 |
| **Third Quartile** | 89.6 | 103.1 | 102.7 | 104.0 | 104.7 |

Table 1. Basic statistic for apparent conductivity measured with the EM31 meter and the GEM300 sensor in the horizontal and vertical dipole orientations. For the GEM300 sensor, measurements were obtained at frequencies of 3030, 6390, 9810, and 14790 Hz.

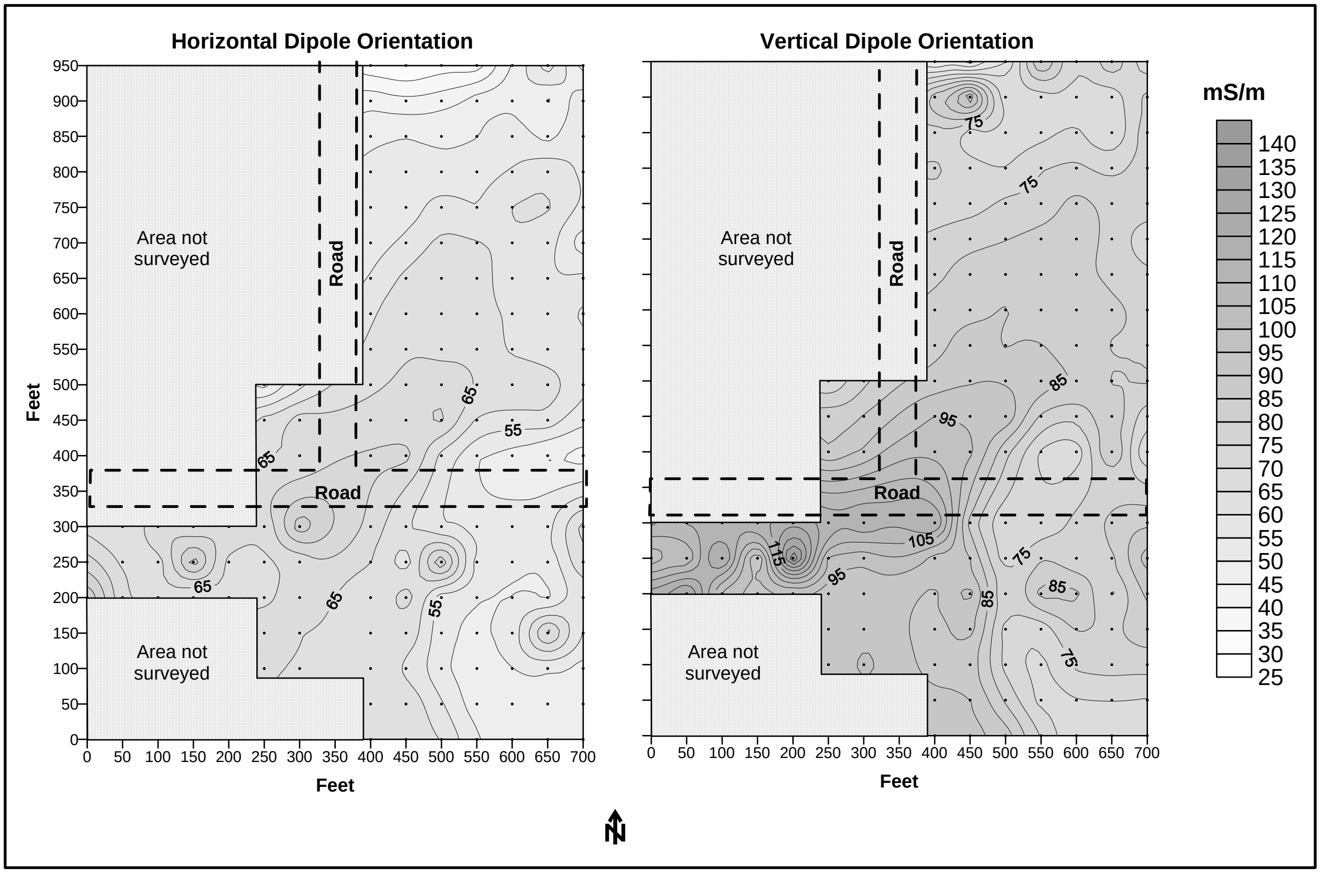


*Figure 1. Spatial distribution of apparent conductivity measured with the EM31 meter in the horizontal (0 to 2 m) and vertical (0 to 5 m) dipole orientations.*

Figure 1 shows the spatial distribution of apparent conductivity as measured with the EM31 meter in the horizontal (left-hand plot) and vertical (right-hand plot) dipole orientations. In each plot, the isoline interval is 5 mS/m. The approximate locations of the two intersecting roads have been shown. Conductivity increases with depth of observation. This trend suggests the presence of more conductive materials in the subsurface. In each plot, a broad linear band of higher conductivity crosses the study area from southwest to northeast. Buried utility lines cross the study area. When observation points were located close to these features, anomalous values were produced. In both plots, several point anomalies, each having conspicuously higher apparent conductivity, are believed to represent interference from these utilities. Lines can be drawn between several of these points to indicate the positions of the utility lines.

Figure 2 shows plots of apparent conductivity as measured with the GEM300 sensor at four different frequencies and in the horizontal dipole orientation. In each plot, the isoline interval is 10 mS/m. While slight differences in spatial patterns can be observed at different frequencies, the plots are remarkably similar. In the plot of the 6390 Hz data, a prominent anomaly is evident in the northeast corner of the study area. As this feature is not apparent in any other plot, it may represent random system noise. In each plot, a broad linear band of higher conductivity crosses the study area from southwest to northeast.

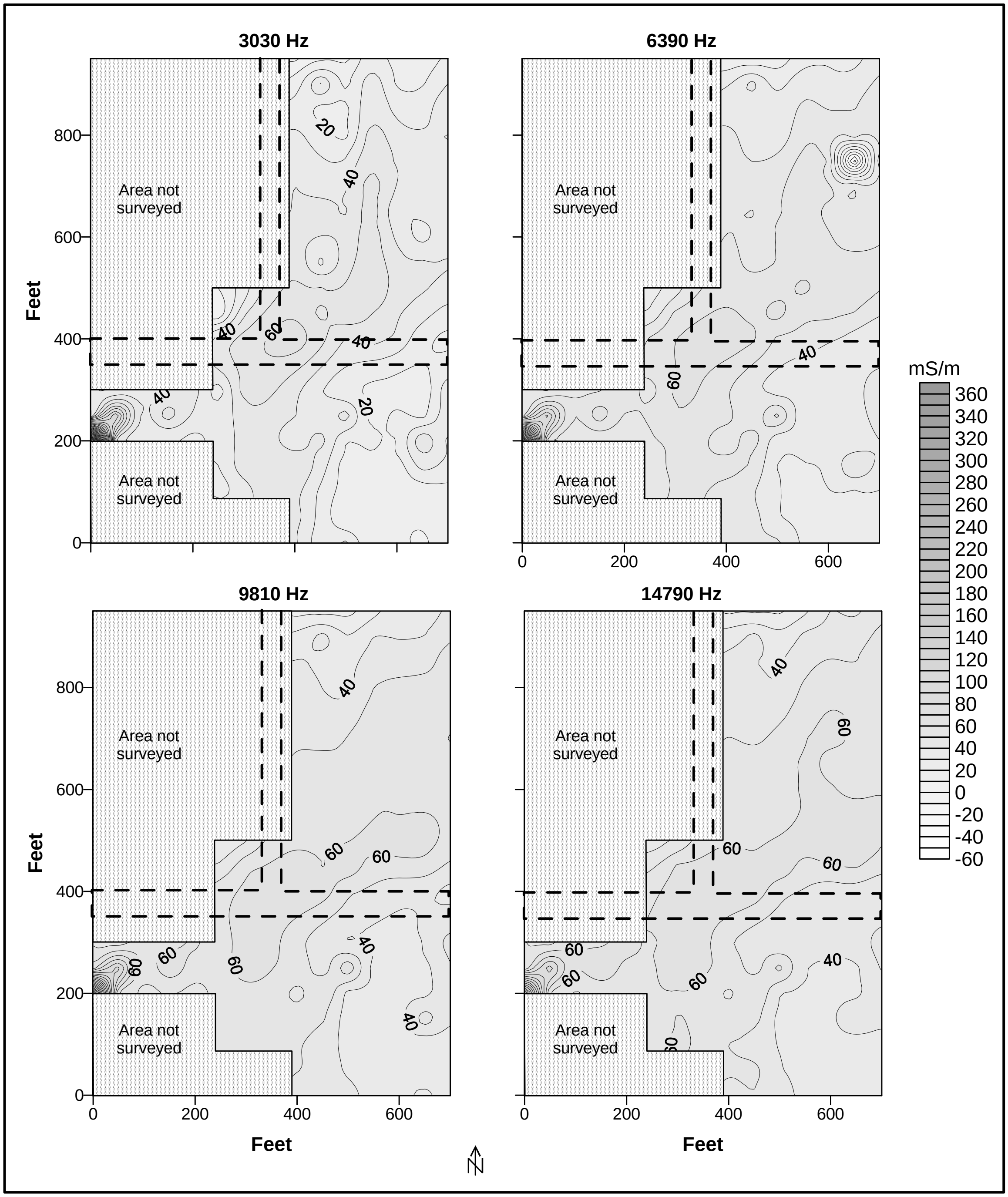


*Figure 2. Spatial distribution of apparent conductivity measured with the GEM300 sensor at different frequencies and in the horizontal dipole orientation.*

Figure 3 shows plots of apparent conductivity as measured with the GEM300 sensor at four different frequencies and in the vertical dipole orientation. In each plot, the isoline interval is 10 mS/m. While slight differences in spatial patterns can be observed at different frequencies, the plots are remarkably similar. In each plot, a broad linear band of higher conductivity crosses the study area from southwest to northeast.

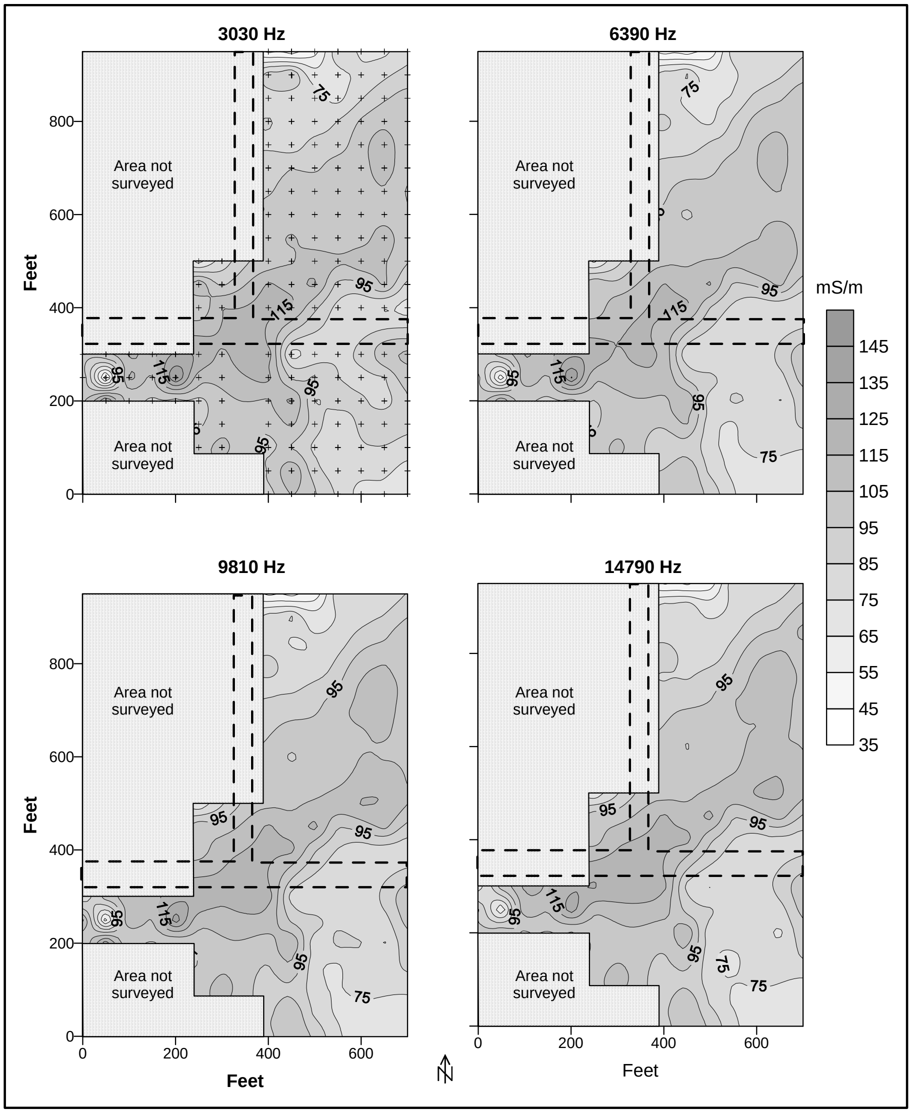


*Figure 3. Spatial distribution of apparent conductivity measured with the GEM300 sensor at different frequencies and in the vertical dipole orientation.*

**Depth of Observation of the GEM300 sensor:**

The theoretical penetration depth of the GEM300 sensor is dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency of the sensor. Penetration depths are governed by the "skin-depth" effect (Won, 1980 and 1983). Skin-depth is the maximum depth of penetration for an EMI sensor operating at a particular frequency and sounding a medium with a known conductivity. Penetration depth or "skin-depth" is inversely proportional to frequency (Won et al., 1996). Low frequency signals travel farther through conductive mediums than high frequency signal. Lowering the frequency will extend the depth of penetration. At a given frequency, the depth of penetration is greater in low conductivity soil than in high conductivity soils. Multifrequency sounding with the GEM300 provides the potential for multiple depths to be profiled with one pass of the sensor.

The theoretical depth of penetration or the "skin depth" can be estimated with the following formula given by McNeill (1996):

$$D = 500/(s*f)^{-2} \qquad [1]$$

Where s is the ground conductivity (mS/m) and f is the frequency (kHz). With the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 93.6, 92.1, 93.3, and 93.0 mS/m at frequencies of 3030, 6390, 9810, and 14790Hz, respectively. Based on equation [1], the selected frequencies, and these averaged conductivities, the estimated skin depths were about 30, 20, 16, and 14 m at 3030, 6390, 9810, and 14790 Hz, respectively. While the induced magnetic fields may achieve these depths, the strengths of the response from these depths are too weak to be sensed by the GEM300 sensor. The actual depth of observation is much shallower and is defined by the depth-weighting function of the sensor and the conductivity of shallower soil horizons. As no depth-weighting functions are presently available for the GEM300 sensor, it is unclear what feature(s) or depth is providing the observed response.

The depth of observation may be defined as the depth that contributes the most to the total EMI response measured on the ground surface. Although contributions to the measured response come from all profiled depths, the contribution from the *depth of observation* is the largest (Roy and Apparao, 1971). As noted by Roy and Apparao (1971), for any system, the depth of observation is a good deal shallower than generally assumed or reported penetration depth.

Although no depth-weighting functions are available for the GEM300 sensor, measurements obtained in the horizontal dipole orientation are more sensitive to changes in apparent conductivity that occur at shallower soil depths. Measurements obtained in the vertical dipole orientation are more sensitive to changes in apparent conductivity that occurred at greater soil depths. At each frequency, the averaged measurements taken in the deeper-sensing, vertical dipole orientation were higher than those obtained in the shallower-sensing, horizontal dipole orientation. This relationship suggests the presence of more conductive layers in the subsurface than at the surface. The similarity in spatial patterns and data sets collected with the GEM300 sensor in the same dipole orientation but at different frequencies, suggest similar observation depths. Multifrequency sounding with the easier to operate GEM300 sensor was found to provide no additional information and did not improve interpretations over single frequency sounding.

**References:**

Ammons, J. T., M. E. Timpson, and D. L. Newton. 1989. Application of aboveground electromagnetic conductivity meter to separate Natraqualfs and Ochraqualfs in Gibson County, Tennessee. Soil Survey Horizons 30(3): 66-70.

Cook, P. G., M. W. Hughes, G. R. Walker, and G. B. Allison. 1989. The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies. Journal of Hydrology 107:251-265.

Cook, P. G. and G. R. Walker. 1992. Depth profiles of electrical conductivity from linear combinations of electromagnetic induction measurements. Soil Sci. Soc. Am. J. 56:1015-1022.

Corwin, D. L., and J. D. Rhoades. 1982. An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements. Soil Sci. Soc. Am. J. 46:517-520.

Corwin, D. L., and J. D. Rhoades. 1990. Establishing soil electrical conductivity - depth relations from electromagnetic induction measurements. Communications in Soil Sci. Plant Anal. 21(11&12): 861-901.

Dickey, H. P., J. L. Zimmerman, R. O. Plinsky, and R. D. Davis. 1977. Soil Survey of Douglas County, Kansas. USDA-Soil Conservation Service and the Kansas Agricultural Experiment Station. U. S. Government Printing Office, Washington DC. 73 p.

Doolittle, J., R. Murphy, G. Parks, and J. Warner. 1996. Electromagnetic induction investigations of a soil delineation in Reno County, Kansas. Soil Survey Horizons 37:11-20.

Doolittle, J. A., K. A. Sudduth, N. R. Kitchen, and S. J. Indorante. 1994. Estimating depth to claypans using electromagnetic inductive methods. J. Soil and Water Conservation 49(6):552-555.

Geonics Limited. 2000. EM38-DD ground conductivity meter: Dual dipole version operating manual. Geonics Ltd., Mississauga, Ontario. 33 pp.

Greenhouse, J. P., and D. D. Slaine. 1983. The use of reconnaissance electromagnetic methods to map contaminant migration. Ground Water Monitoring Review 3(2):47-59.

Hoekstra, P., R. Lahti. J. Hild, R. Bates, and D. Phillips. 1992. Case histories of shallow time domain electromagnetics in environmental site assessments. Ground Water Monitoring Review. 12(4):110-117.

Jaynes, D. B. 1995. Electromagnetic induction as a mapping aid for precision farming. pp. 153-156. IN: Clean Water, Clean Environment, 21st Century: Team Agriculture. Working to Protect Water Resources. Kansas City, Missouri. 5 to 8 March 1995.

Jaynes, D. B. 1996. Improved soil mapping using electromagnetic induction surveys. 169-179. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Precision Agriculture: Proceedings of Third International Conference. Minneapolis, Minnesota. June 23-26, 1996. American Society of Agronomy, Madison, Wisconsin.

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1993. Soil type and crop yield determination from ground conductivity surveys. 1993 International Meeting of American Society of Agricultural Engineers. Paper No. 933552. ASAE, St. Joseph, MI. pp. 6.

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1995a. Yield mapping by electromagnetic induction. pp. 383-394. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Proceedings of Second International Conference on Precision Management for Agricultural Systems. Minneapolis, Minnesota. March 27-30, 1994. American Society of Agronomy, Madison, Wisconsin.

Jaynes, D. B., J. M. Novak, T. B. Moorman, and C. A. Cambardella. 1995b. Estimating herbicide partition coefficients from electromagnetic induction measurements. J. Environmental Quality. 24:36-41.

Kachanoski, R. G., E. G. Gregorich, and I. J. Van Wesenbeeck. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. Soil Sci. 68:715-722.

Kitchen, N. R., K. A. Sudduth, and S. T. Drummond. 1999. An evaluation for determining site-specific management zones.

Kitchen, N. R., K. A. Sudduth, and S. T. Drummond. 2000. Characterizing soil physical and chemical properties influencing crop yields using soil electrical conductivity. Second International Geospatial Information in Agriculture and Forestry Conference. Lake Buena Vista, Florida. January 10-12, 2000. 11 p.

McBride, R. A., A. M. Gordon, and S. C. Shrive. 1990. Estimating forest soil quality from terrain measurements of apparent electrical conductivity. Soil Sci. Soc. Am. J., 54:290-293.

McNeill, J. D. 1980. Electrical Conductivity of soils and rocks. Technical Note TN-5. Geonics Ltd., Mississauga, Ontario. p. 22.

Mulla, D. J. 1993. Mapping and managing spatial patterns in soil fertility and crop yields. pp. 15-26. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Proceedings of Second International Conference on Precision Management for Agricultural Systems. Minneapolis, Minnesota. March 27-30, 1994. American Society of Agronomy, Madison, Wisconsin.

Nettleton, W. D., L. Bushue, J. A. Doolittle, T. J. Endres, and S. J. Indorante. 1994. Sodium-affected soil identification in south-central Illinois by electromagnetic induction. Soil Sci. Soc. Am. J. 58:1190-1193.

Olson, J. 2000. New soil maps spark change. Farm Industry News March 2000. 78-82.

Rhoades, J. D., P. A. Raats, and R. J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 40:651-655.

Sheets, K. R., and J. M. H. Hendrickx. 1995. Noninvasive soil water content measurement using electromagnetic induction. Water Resources Research 31: 2401-2409.

Slavich, P. G. and G. H. Petterson. 1990. Estimating average rootzone salinity from electromagnetic induction (EM-38) measurements. Australian J. Soil Res. 28:453-463.

Sorensen, K. 1994. Pulled array continuous electrical profiling. pp. 977-983. IN: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems. Boston, MA.

Stroh, J., S. R. Archer, L. P. Wilding, and J. Doolittle. 1993. Assessing the influence of subsoil heterogeneity on vegetation patterns in the Rio Grande Plains of south Texas using electromagnetic induction and geographical information system. College Station, Texas. The Station (Mar 93): 39-42.

Sudduth, K. A. and N. R. Kitchen, 1993. Electromagnetic induction sensing of claypan depth. Paper No. 93-1550. Presented at the December 1993, Winter Meetings of the American Society of Agricultural Engineers. St. Joseph, Michigan. pp. 18.

Sudduth, K. A., N. R. Kitchen, D. H. Hughes, and S. T. Drummond. 1995. Electromagnetic induction sensing as an indicator of productivity on claypan soils. pp. 671-681. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Proceedings of Second International Conference on Precision Management for Agricultural Systems. Minneapolis, Minnesota. March 27-30, 1994. American Society of Agronomy, Madison, Wisconsin.

Taylor, R. S. 2000. Development and applications of geometric-sounding electromagnetic systems. Dualem Inc., Milton Ontario. 4 pp.

Veris Technologies. 1998. 3100 Soil EC Mapping System Operations Manual. Publication No. AN 1CM02-02. Veris Technologies, Salina, KS.

Veris Technology. 2001. USDA Soil Maps. Veris Technologies, Salina, KS. Retrieved April 19, 2001, from the World Wide Web: http://www.veristech.com/cor_usda.htm.

Won, I. J., Dean A. Keiswetter, George R. A. Fields, and Lynn C. Sutton. 1996. GEM-2: A new multifrequency electromagnetic sensor. Journal of Environmental & Engineering Geophysics 1:129-137.