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

Subject: -- Geophysical Assistance -- **Date:** 15 April 2003

To: William J. Gradle
State Conservationist
USDA - NRCS
2118 W. Park Court
Champaign, Illinois 61821

Purpose:
To explore the potential of using geophysical tools to assist in the soil surveys updates of Crawford and Douglas counties, Illinois.

Participants:
Chris Cochran, MLRA Project Leader, USDA-NRCS, Charleston, IL
Ron Coleman, Soil Scientist, USDA-NRCS, Charleston, IL
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA
Troy Fehrenbacher, Soil Scientist, USDA-NRCS, Charleston, IL
John Pierce, District Conservationist, USDA-NRCS, Robinson, IL
Sam Werner, Soil Scientist, USDA-NRCS, Charleston, IL
Roger Windhorn, Resource Soil Scientist, USDA-NRCS, Champaign, IL
Dan Withers, Cartographic Technician, USDA-NRCS, Champaign, IL

Activities:
All field activities were completed during the period of 25 to 26 March 2003.

Equipment:
The Veris 3100 soil EC mapping system was used in this study. This system is a towed-array, multi-electrode resistivity unit manufactured by Veris Technologies.[1] Operating procedures are described by Veris Technologies (1998). In isotropic materials, conductivity is the reciprocal of resistivity. The Veris 3100 soil EC mapping system converts measurements of apparent resistivity (ohm-m) into apparent conductivity (mS/m). The Veris system provides two depths of penetration: one for the upper 0 to 30 cm (shallow) and one for the upper 0 to 90 cm (deep) of the soil. The depth of penetration is dependent upon the spacing and type of electrode array. The electrode array is a modified Wenner array with 6 unequally spaced electrodes (rotating discs). Voltage is applied to discs number 2 and 5. The wider-spaced discs (number 1 and 6) measure the current across the 0 to 90 cm depth interval; the more closely spaced discs (number 3 and 4) measure the current across the 0 to 30 cm depth interval. The Veris 3100 implement is pulled behind a pickup truck at speeds of about 5 to 10 m/hr. A Trimble 132 GPS receiver is used to geo-reference the measurements made with this system.[1]

The electromagnetic induction meter used in this study was the EM38DD, manufactured by Geonics Limited.[1] Operating procedures are described by Geonics Limited (2000). The EM38DD meter is portable and requires only one person to operate. No ground contact is required with this meter. The EM38DD operates at a frequency of 14,600 Hz. It has effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively. The EM38DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master unit (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on).

[1] Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

The Geonics DAS70 Data Acquisition System was used to record and store both EMI and GPS data.[1] The acquisition system consists of the EM38DD meter, an Allegro field computer, and a Trimble AG114 GPS receiver. With the logging system, the EM38DD meter is keypad operated and measurements can either be automatically or manually triggered.

To help summarize the results of this study, the SURFER for Windows, version 8.0 (developed by Golden Software, Inc.) was used to construct two-dimensional simulations.[2] Grids were created using kriging methods with an octant search.

The radar unit is the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc.[2] Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. The SIR System-2000 consists of a digital control unit (DC-2000) with keypad, VGA video screen, and connector panel. A 12-volt battery powers the system. This unit is backpack portable, and with an antenna, requires two people to operate. The 200 MHz antenna was used in this study.

The RADAN NT (version 2.0) software program was used to process the radar profiles (Geophysical Survey Systems, Inc, 2001).[2] Processing included color transformation, marker editing, distance normalization, and range gain adjustments.

Results:

1. A significant difference exists in the apparent conductivity of Hickory and Alford soils. Apparent conductivity averaged 24.7 mS/m with a range of 20.0 to 33.4 mS/m over Alford soils. Apparent conductivity averaged 9.5 mS/m with a range of 7.1 to 16.4 mS/m over Hickory. An analysis of variance revealed a significant difference (at 0.001 level) in apparent conductivity between the two map units. The results of this survey suggest that areas of Alford and Hickory soils can be differentiated based on EMI responses. Within each soil delineation, slight variations in EMI responses were observed in each map unit. Differences in EMI response were attributed to differences in the depth to bedrock and the soil moisture content.

2. In general, within the Douglas County sites, apparent conductivity was moderate to high (typically less than 20 mS/m) and spatially variable. With both EMI instruments, apparent conductivity increased and became more variable with increasing penetration depths. The vertical response of these EMI devices can be attributed to the comparatively low clay and moisture contents of the surface layers, the higher clay and water contents of the subsoil and the amount of free carbonates in the lower part of the solum and in the substratum. In general the surface layers were lighter textured and drier than the underlying, heavier textured subsoil. In the absence of topographic, soil, and crop yield data; spatial patterns of apparent conductivity cannot be fully assessed over so large (110 acres) and diverse a site.

Recommendations:

1. In order to provide continuous, geo-reference coverage of sites, GPS must be integrated with EMI. ArcView GIS has become accessible to many soil scientists and field offices. Integration of EMI and ArcView GIS techniques provides a more expedient and cost-effective method for soil mapping and alternative methods for displaying multiple data sets.

2. To maximize the efficiency of EMI, mobile operations, such as the Veris 3100 soil EC mapping system, are recommended for open farmlands. Hand carrying EMI instruments while walking over large sites is slow, labor intensive, and inefficient. In open fields, mobile surveys results in larger amounts of data collected, more comprehensive coverage of sites, greater acquisition efficiency, and less operator fatigue. The National Soil Survey Center must develop a mobile platform for its EMI equipment.

It was my pleasure to work again in Illinois and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
B. Ahrens, Director, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
C. Cochran, MLRA Project Leader, USDA-NRCS, 683 Castle Drive, Charleston, IL 61920-7471
W. Maresch, Acting Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250
R. McLeese, State Soil Scientist, USDA-NRCS, 2118 W. Park Court, Champaign, IL 61821
T. Neely, State Soil Scientist/MO Leader, 6013 Lakeside Blvd., Indianapolis, Indiana 46278
C. Olson, National Leader, Soil Investigation Staff, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
W. Tuttle, Soil Scientist (Geophysical), USDA-NRCS-NSSC, P.O. Box 974, Federal Building, Room 206, 207 West Main Street, Wilkesboro, NC 28697

Study Site:

Crawford County:

Two radar traverses were conducted in an area of Hickory silt loam, 10 to 15 percent slopes, eroded (Awalt, 1996). The site was located along a drainageway in a wooded area in the northeast quarter, Section 15, T 5 N., R. 12 W. The very deep, well drained Hickory soil formed in till that can be capped with up to 20 inches of loess. Hickory is a member of the fine-loamy, mixed, active, mesic Typic Hapludalfs family. GPR traverses were also conducted in areas of Alford silt loam, 1 to 5 percent slopes, and 5 to 10 percent slopes, eroded (Awalt, 1996). The Alford site was located along a drainageway in an open area in the southeast quarter, Section 14, T 6 N., R. 11 W. The very deep, well drained Alford soil formed in loess. Alford is a member of the fine silty, mixed, superactive, mesic Ultic Hapludalfs family.

Douglas County:

EMI surveys were completed on two 80-acre fields located in the northeast quarter of section 7, T. 15 N., R. 10 E. (Field 1), and the northwestern quarter of Section 26, T. 15 N., R. 9 E. (Field 2). Both fields are on a level to nearly level, glacial lake plain. These fields include areas that have been mapped as: Milford silty clay loam, 0 to 1 percent slopes (map unit (M.U.) 69); Brenton silt loam, 0 to 1 percent slopes (M.U. 149); Drummer silty clay loam, 0 to 2 percent slopes (M.U. 152); Flanagan silt loam, 0 to 2 percent slopes (M.U. 154A); and Rutland silt loam, 0 to 2 percent slopes (M.U. 375A). The very deep, poorly drained and very poorly drained Milford soil formed in lacustrine sediments on glacial lake. Milford is a member of the fine, mixed, superactive, mesic Typic Endoaquolls family. The very deep, somewhat poorly drained Brenton soil formed in silty materials that overlie loamy stratified outwash. Brenton is a member of the fine-silty, mixed, superactive, mesic Aquic Argiudolls family. The very deep, poorly drained Drummer soil formed in silty materials that overlie loamy stratified outwash. Drummer is a member of the fine-silty, mixed, superactive, mesic Typic Endoaquolls family. The very deep, somewhat poorly drained Flanagan soil that formed in silty materials that overlies loamy calcareous till. Flanagan is a member of the fine, smectitic, mesic Aquic Argiudolls. The somewhat poorly drained Rutland soil that formed in silty materials that overlies clayey till or lacustrine sediments. Rutland soil is deep to a densic contact. Rutland is a member of the fine, smectitic, mesic Aquic Argiudolls family.

Field Procedures:

The Veris 3100 soil EC mapping system was towed behind a 4WD vehicle. Measurements were continuously recorded and geo-referenced with a GPS receiver. An observation (two apparent conductivity measurements (shallow and deep) with coordinates) is recorded every second. By varying the speed of advance, the number and density of observation points can be varied. Moving across the fields at a speed of about 5 mph, the Veris 3100 implement recorded 2806 and 1827 geo-referenced observations in fields 1 and 2, respectively. The actual operating time was about 45 and 30 minutes for fields 1 and 2, respectively. During the survey, the Veris 3100 soil EC mapping system maintained fairly good ground contact and only a few negative values were recorded. Negative values are attributed to buried metallic objects or poor ground contact of coulter-electrodes. These values were removed from the data sets.

The EM38DD meter was operated in the continuous mode with measurements recorded at 1-sec intervals. The EM38DD was held about 3 inches above the ground surface with its long axis parallel to the direction of traverse. Generally following the tracks of the Veris 3100 implement in field 1 and walking at a fairly brisk and uniform pace, the EM38DD meter recorded 5837 geo-referenced measurements in about 1.6 hours of actual recording time. The actual time of the pedestrian survey was over 3 hours as the operator required periods for rest, data entry, and equipment adjustments at the end of each traverse. Because of the relatively slow speed of advance, the number of EM38DD observations was closely spaced. The close spacing of observations along traverse lines resulted in some spatial aliasing of the data.

In Crawford County, GPR traverses were completed in areas of Hickory and Alford soils. Along each traverse line, survey flags were inserted in the ground at intervals of about 3.0-m (10 feet). The survey flags served as reference points. Pulling the 200 MHz antenna along each traverse line completed a radar survey file. As the radar antenna was pulled passed each flagged reference point, the operator impressed a vertical reference line on the radar profile to identify the reference point.

Results:

Crawford County:

GPR Survey:

Calibration:

Ground-penetrating radar is a time scaled system. The system measures the time it takes electromagnetic energy to travel from an antenna to an interface (i.e., soil horizon, bedrock, stratigraphic layer) and back. To convert travel time into a depth scale requires knowledge of the velocity of pulse propagation. Several methods are available to determine the velocity of propagation. These methods include use of table values, common midpoint calibration, and calibration over a target of known depth. The last method is considered the most direct and accurate method to estimate propagation velocity (Conyers and Goodman, 1997). The procedure involves measuring the two-way travel time to a known reflector that appears on a radar record and calculating the propagation velocity by using the following equation (after Morey, 1974):

$$V = 2D/T \qquad [1]$$

Equation [1] describes the relationship between the propagation velocity (V), depth (D), and two-way pulse travel time (T) to a subsurface reflector. During this study, the two-way radar pulse travel time was compared with measured depths to a known metallic reflector buried at each site. Though slight variations did occur, the estimated velocity of propagation through the upper part of the soils was about 0.07 m/ns. The dielectric permittivity was 18. These values were used to scale the radar records. Using a propagation velocity of 0.07 m/ns and a scanning time of 70 and 110 ns, the maximum penetration depth was about 2.4 and 3.8 m.

Hickory silt loam, 10 to 15 percent slopes, eroded

Two 33.5-m (110-foot) traverse lines with 12 equally spaced, flagged reference points were established across this unit. In general, the radar records were of good interpretative quality. Based on radar interpretation, the depth to bedrock averaged 1.75 m with a range of 0.76 to 2.87 along radar traverse 1. The depth to bedrock averaged 1.86 m, with a range of 0.81 to 3.61 m along radar traverse 2. Table 1 provides the frequency distribution of observation based on soil depth classes. Along each traverse line, soils were dominantly deep (1.0 to 1.5 m) and very deep (> 1.5 m) with minor inclusions of moderately deep (0.5 to 1.0 m) soils on side slopes to drainageways.

Table 1. Frequency Distribution of Observations
(Based on Soil Depth Classes)

	GPR Traverse	
	#1	**#2**
Shallow	0.00	0.00
Moderately Deep	0.25	0.25
Deep	0.33	0.00
Very Deep	0.42	0.75

EMI Survey:

As shown in Figure 1, a significant difference exists in the apparent conductivity measurements obtained over Hickory and Alford soils. Apparent conductivity averaged 24.7 mS/m with a range of 20.0 to 33.4 mS/m over Alford soils. Apparent conductivity averaged 9.5 mS/m with a range of 7.1 to 16.4 mS/m over Hickory. An analysis of variance revealed a significant difference (at 0.001 level) in apparent conductivity between the two map units. The results of this survey indicate that areas of Alford and Hickory soils can be differentiated based on EMI responses. Both soils are medium textured and members of the Hapludalfs great group. Alford soil belongs to the active and Hickory soil belongs to the semiactive activity class. Differences in the activity classes of these soils correspond with observed differences in apparent conductivity (higher values associated with active and lower values associated with semiactive activity class).

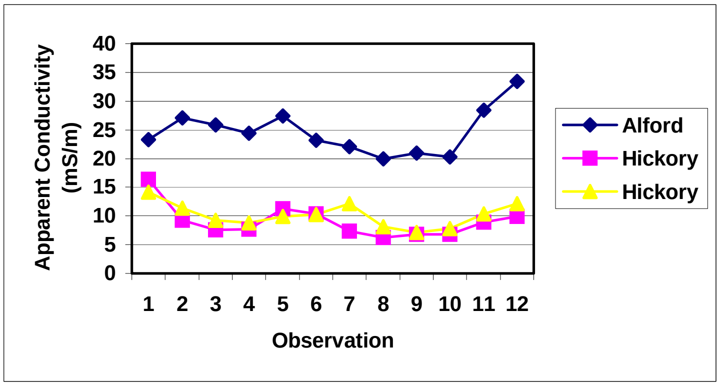

Figure 1. Apparent conductivity measured with the EM38 meter in areas of Alford and Hickory soils.

Slight variations in EMI responses were observed in each map unit. In general, EMI responses were higher on summits and lower-lying drainageways, and lower on higher-lying, better drained, side slopes that were shallower to bedrock. In the Hickory soil site, based on five soil cores to bedrock (ranging in depth from 36 to 67 inches), a moderate positive correlation (r = 0.581) was found to exist between the EMI response and the measured depth to bedrock. The lack of a stronger correlation was attributed to differences in soil moisture content of the soils. Because of the very deep depth to bedrock, no comparison was made between depth to bedrock and EMI response at the Alford site.

Douglas County

Field 1

In Field 1, data collected with the Veris 3100 soil EC mapping system and the EM38DD meter were noticeably disparate in absolute values but similar in spatial distribution. For each instrument, data were recorded at a rate of one measurement/sec. The faster speed at which the mobile Veris unit completed the survey resulted in a smaller number of observations (N = 2806 versus 5837). Data recorded with the Veris unit were higher and more variable than data recorded with the EM38DD meter (see Table 2). For both instruments, apparent conductivity increased with increasing observation depths. With the Veris system, apparent conductivity averaged 30.3 and 55.6 mS/m for shallow and deep measurements, respectively. With the EM38DD meter, apparent conductivity averaged 16.8 and 37.9 mS/m for measurements obtained in the horizontal and vertical dipole orientations, respectively. In all previous surveys using both the Veris 3100 soil EC mapping system and the EM38DD meter, measurements were more closely alike in absolute values. No explanation for this observed difference in measurement between the two devices is possible at this time.

Table 2.
Apparent Conductivity Data collected with the Veris 3100 implement and the EM38DD meter in Field 1.
(All values are in mS/m)

	Veris Implement		EM38DD	
	Shallow	**Deep**	**Horizontal**	**Vertical**
Average	30.3	55.6	16.8	37.9
Standard Deviation	6.8	8.6	4.8	5.9
Minimum	9.1	10.1	2.0	17.7
Maximum	51.3	80.0	48.3	70.0
25% Quartile	25.7	49.6	13.5	33.6
75% Quartile	34.7	61.1	19.9	41.7

With the Veris 3100 soil EC mapping system, apparent conductivity ranged from about 9 to 51 mS/m with a standard deviation of 6.8 mS/m for the shallow (0 to 30 cm) measurements. Apparent conductivity ranged from about 10 to 80 mS/m with a standard deviation of 8.6 mS/m for the deep (0 to 90 cm) Veris measurements. With the EM38DD meter, apparent conductivity ranged from about 2 to 48 mS/m with a standard deviation of 4.8 mS/m in the shallower-sensing (0 to 0.75 m) horizontal dipole orientation. Apparent conductivity ranged from about 18 to 70 mS/m with a standard deviation of 5.9 mS/m in the deeper-sensing (0 to 1.5 m) vertical dipole orientation.

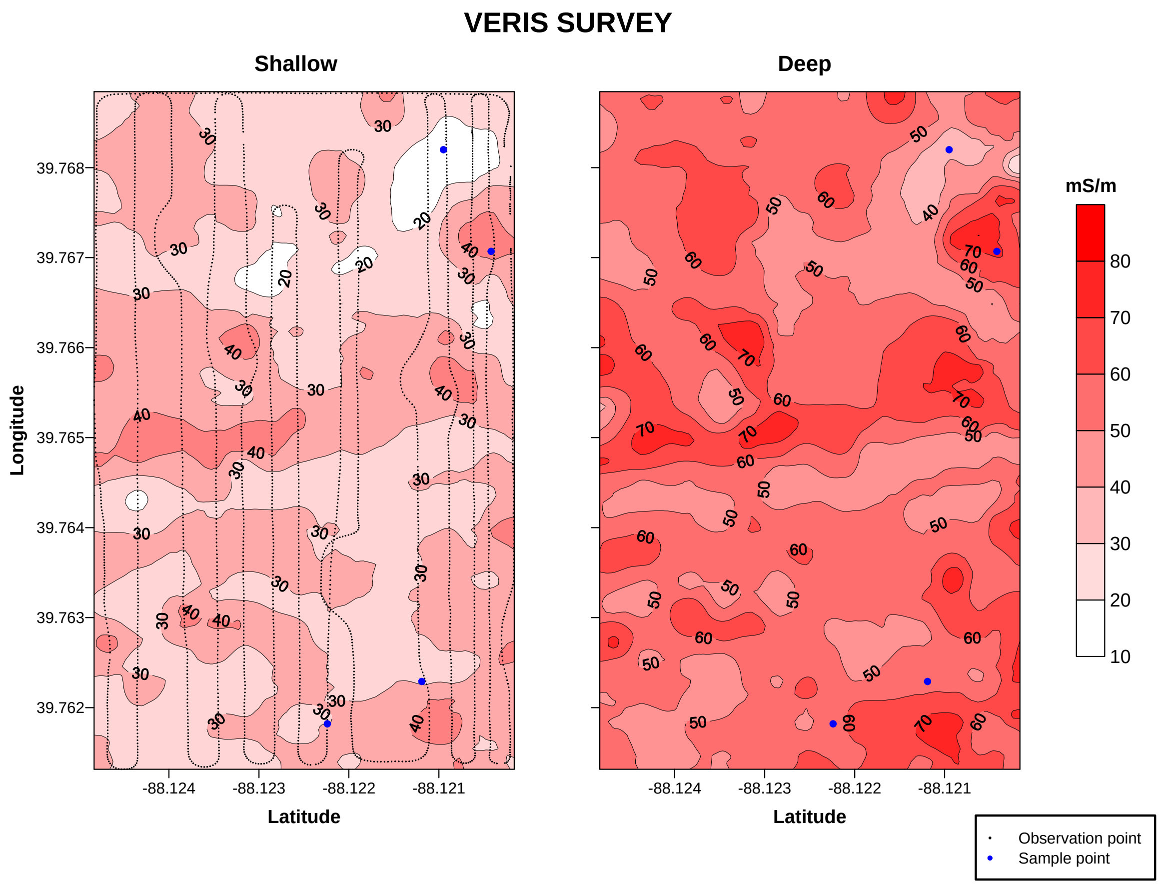

Figure 2 Plots of apparent conductivity collected in Field 1 with the Veris 3100 soil EC mapping system.

Figure 2 contains choropleth maps showing the spatial distribution of apparent conductivity collected with the Veris 3100 soil EC mapping system. In each map, color variations have been used to show the distribution of apparent conductivity. In each plot the isoline interval is 10 mS/m. To remove spurious measurements and lines, the *grid node editor* of Surfer 8 was used to blank or make slight changes (0.1 to 0.2 mS/m) to some of the measured EMI responses. In Figure 2, the locations of four soil core sites that were excavated and described during this survey are shown in each map.

Figure 2 reveals that the apparent conductivity spatially variable and contrasting within Field 1. Isolated areas of lower apparent conductivity (shallow measurements < 20 mS/m) correspond to slightly higher-lying, better-drained knobs. Areas of higher apparent conductivity (>35 mS/m) extend as a ribbon (from west to east) across the central portion or as concentrated areas in the northwest and eastern portions of the field.

Figure 3 contains choropleth maps showing the spatial distribution of apparent conductivity collected with the EM38DD meter. In each map, color variations have been used to show the distribution of apparent conductivity. In each plot the isoline interval is 10 mS/m. To remove spurious measurements and lines, the *grid node editor* of Surfer 8 was used to blank or make slight changes (0.1 to 0.2 mS/m) to some of the measured EMI responses. In Figure 3, the locations of four soil core sites that were excavated and described during this survey are shown in each plot.

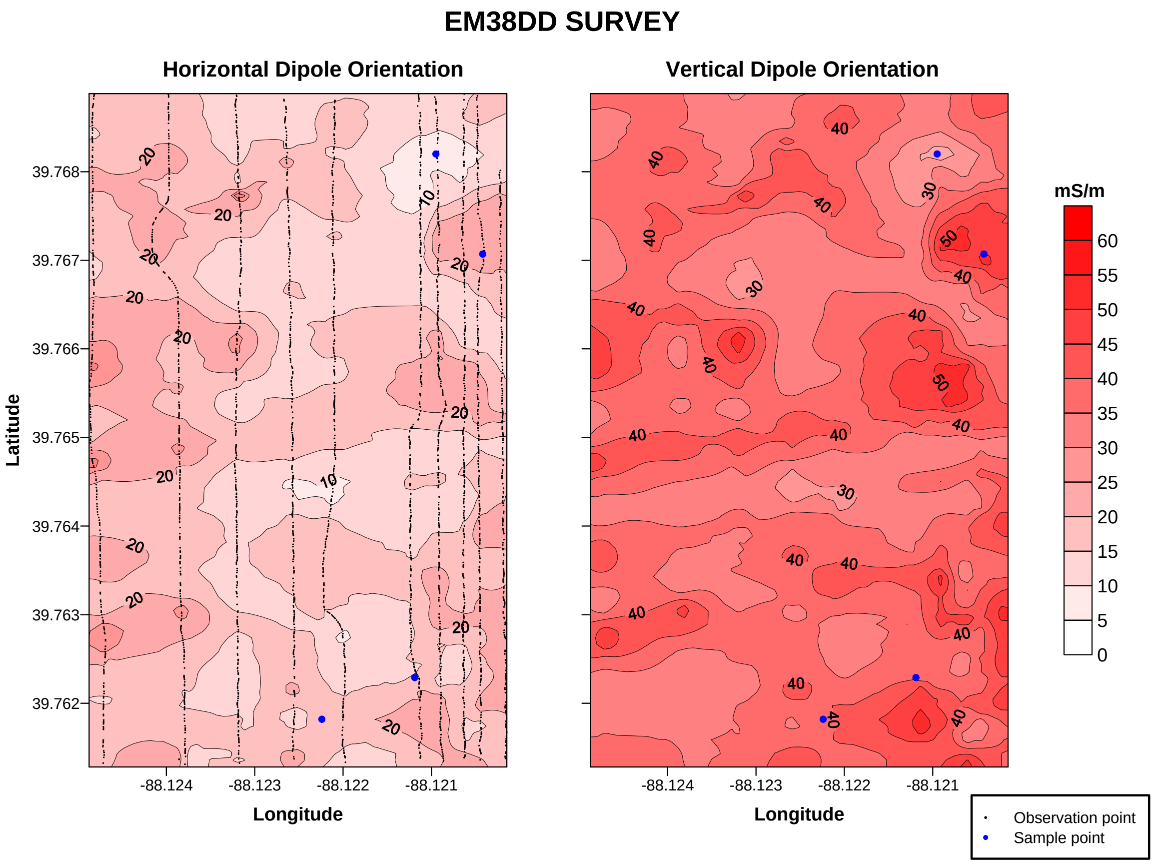

Figure 3 Plots of apparent conductivity collected in Field 1 with the EM38DD meter.

Though absolute values of apparent conductivity are different, spatial patterns expressed in the choropleth maps of figures 2 and 3 are similar. Areas of lower apparent conductivity (< 10 mS/m in the horizontal dipole orientation) correspond to slightly higher-lying, better-drained knobs. Both the Veris system and the EM38DD meter identified a knob of relatively low conductivity near the northeast corner of the field. Other areas of low apparent conductivity were not consistently identified possibly due to the location (tracks of the two EMI tools were not identical) and number of observation points, and the effects of computer processing of the EMI data. In general, with both the Veris system and the EM38DD meter, similar areas of higher apparent conductivity (>35 mS/m with EM38DD meter operated in the vertical dipole orientation) extend as a ribbon (from west to east) across the central portion or as concentrated areas in the northwest and eastern portions of the field.

Coring Sample Sites
Four cores sites were selected based on variations in the EMI responses recorded with the Veris 3100 soil EC mapping system (deep). At these core sites, the recorded apparent conductivity ranged from 28.2 to 71.4 mS/m. Following the completion of the survey, these sites were located with another GPS unit (Garmin) and cores were extracted and described. This procedure is flawed, as it is impossible to return to the exact site of EMI measurement. Additional EMI measurements should have been obtained at the time of coring.

Though significantly different EMI responses were recorded at the 4 core sites, the extracted soil profiles were remarkably similar. Three of the four profiles outwardly appeared identical and were classified as being members of the fine, mixed, mesic Typic Epiaquolls family. The fourth core (located on a slightly higher lying position and having the lowest measured EMI response), though very similar in outward appearance to the other three, was classified as being a member of the fine, mixed, mesic Aquic Hapludolls family. For the four cores, depths to the fine-textured (silty clay) Bt horizons ranged from 8 to 11 inches. Thickness of the fine-textured Bt horizon ranged from 18 to 25 inches. These measured parameters were not appreciably different and, in themselves, cannot explain the variations observed in EMI responses across Field 1. No correlation was found to exist between EMI response and the depth to (r ranged from -0.150 to 0.002) or thickness (r ranged from 0.032 to 0.334) of the Bt horizon. In this field, based on core observations and EMI responses, no correlation is possible based on clay content or soil type. Differences in moisture content, though not measured, is suspected to contribute most to the difference in EMI responses observed in this level to nearly level field located on a glacial lake plain. In addition, underlying the Bt horizon were stratified deposits that ranged in texture from loamy sands to silty clay.

For precision agriculture more detailed and accurate soil maps are needed that show the "cause and effect" relationship between soil physical and chemical properties and crop yields. Although the choropleth maps of this field show high and consistent patterns of variability, the cause(s) of this variability is not obvious nor has it been properly characterized by the EMI survey. It is often said that EMI provides greater information to growers whose fields show high soil variability rather than fields with more uniform and invariable soils conditions. If the variability in EMI response is low within a unit of management, the use of EMI may not be warranted. Electromagnetic induction responses were highly variable in Field 1. While EMI responses were contrasting and spatial patterns were consistent within this field, the determination of causal relationship between soil properties and EMI responses remains elusive. Unless the parameters that cause this variability can be understood the use of EMI is also unwarranted.

Field 2

Compared with Field 1, apparent conductivity data recorded with the Veris 3100 soil EC mapping system in Field 2 were lower and less variable. In Field 2, data recorded with the Veris system averaged 27.6 and 51.0 mS/m for shallow and deep measurements, respectively. With the Veris system, apparent conductivity ranged from about 10 to 40 mS/m with a standard deviation of 4.6 mS/m for the shallow (0 to 30 cm) measurements. Apparent conductivity ranged from about 27 to 69 mS/m with a standard deviation of 5.8 mS/m for the deep (0 to 90 cm) Veris measurements.

Table 3. Apparent Conductivity Data collected with the Veris 3100 implement in Field 2.
(All values are in mS/m)

	Shallow	Deep
Average	27.6	51.0
Standard Deviation	4.6	5.8
Minimum	10.0	26.7
Maximum	39.9	69.4
25% Quartile	24.9	47.5
75% Quartile	30.8	54.9

Figure 4 contains choropleth maps showing the spatial distribution of apparent conductivity collected with the Veris 3100 soil EC mapping system. In each map, color variations have been used to show the distribution of apparent conductivity. In each plot the isoline interval is 10 mS/m. To remove spurious measurements and lines, the *grid node editor* of Surfer 8 was used to blank or make slight changes (0.1 to 0.2 mS/m) to some of the measured EMI responses.

Figure 4 reveals that the apparent conductivity spatially variable and contrasting within Field 2. Isolated areas of lower apparent conductivity (shallow measurements < 20 mS/m) correspond to slightly higher-lying, better-drained knobs. Areas of higher apparent conductivity (>60 mS/m) are inextensive and are restricted to small limited inclusions scattered across the field.

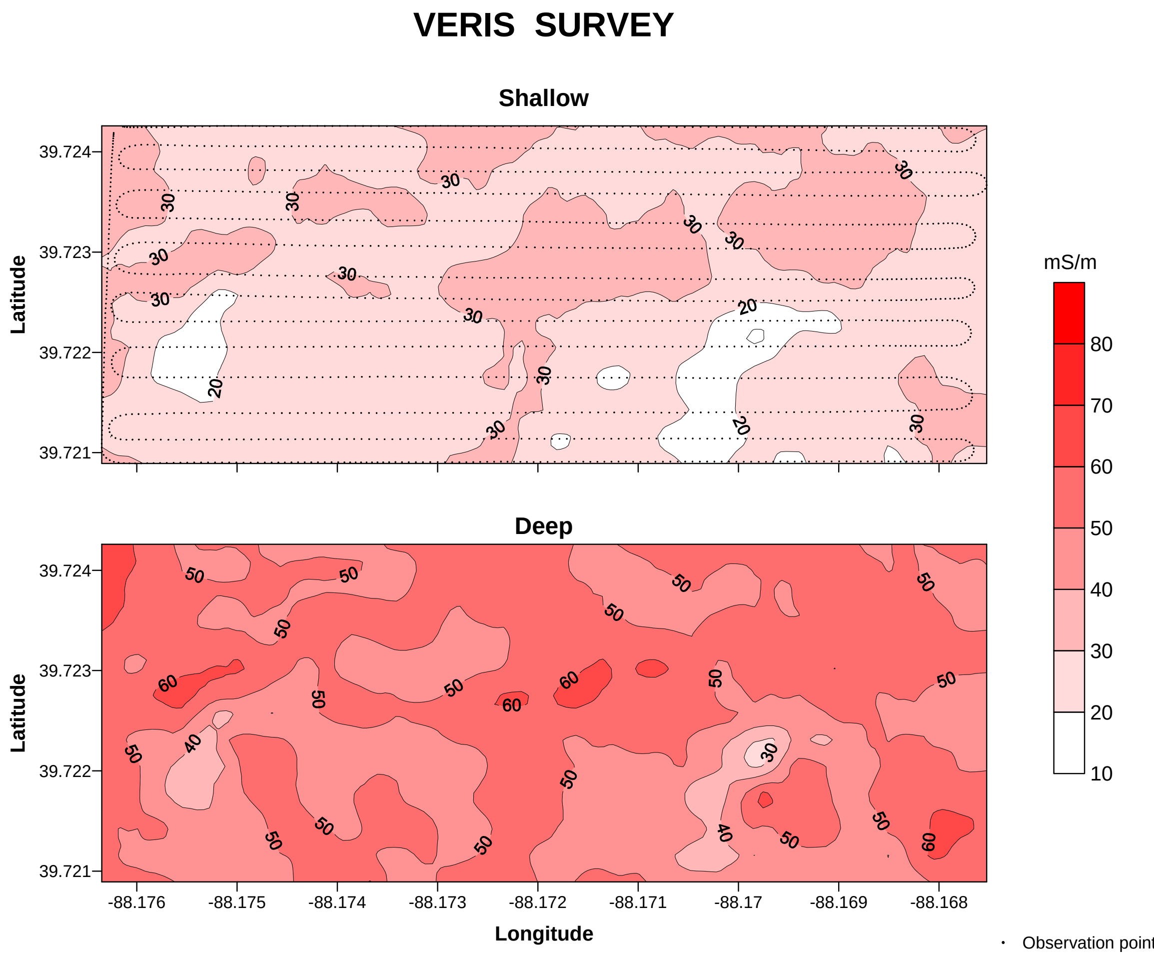

Figure 4 Plots of apparent conductivity collected in Field 2 with the Veris3100 soil EC mapping system

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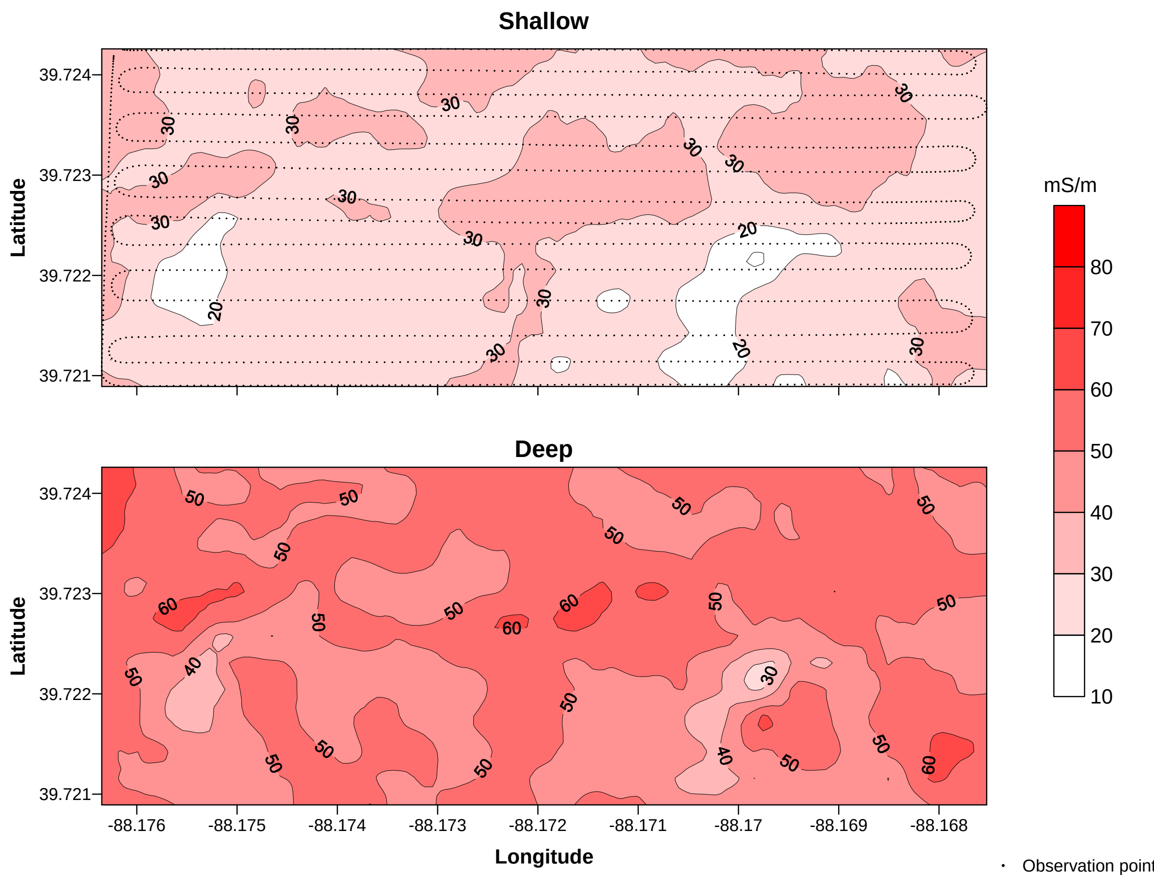
These studies in Douglas County reinforced the need for mobile platforms to conduct EMI surveys of large units of management. To maximize the efficiency of EMI, mobile operations, such as the Veris 3100 soil EC mapping system are recommended for open farmlands. Pedestrian EMI surveys are labor intensive and impractical for surveying large management units. The use of field vehicles with EMI and GPS permits greater flexibility and the rapid surveying of large tracts of land (Freeland et al. 2002). Cannon and other (1994) reported that mobile EMI surveys increased productivity by a factor of five over traditional pedestrian surveys. Freeland and others (2002) recommend the use of mobile EMI surveys over pedestrian EMI surveys for larger areas or whenever the total number of observations exceeds 1600 data points. In open fields, mobile surveys results in larger amounts of data collected, more comprehensive coverage of sites, greater acquisition efficiency, and less operator fatigue. However, in many terrains, mobile EMI surveys are impractical and pedestrian surveys must be carried out.

The collection of EMI data does not require knowledge of soils or soil survey techniques. Lesser-trained technicians can collect EMI data. However, as illustrated at this site, an intensive sampling scheme is need to unravel the factors that are influencing the EMI response and a qualified soil scientist is required to properly interpret and correlate the data.

VERIS SURVEY



Ground-Penetrating Radar (GPR):
A GPR survey was conducted with the 400 MHz antenna in an area of Elpaso silty clay loam, 0 to 1 percent slopes. The purpose of this survey was to confirm whether GPR could be used to assess soil compaction and the development of traffic pans. A 10 by 10 meter grid was established near the location of the excavated Elpaso pit. Survey procedures were modified to facilitate the construction of 3-D images and the interpretation of near surface soil features. To construct three-dimensional displays, the imagery between adjoining radar profiles is interpolated. As a consequence, the quality and detail of a three-dimensional display will increase as the spacing between survey lines is decreased (Geophysical Survey Systems, Inc., 2001b). As a general rule, lines should be spaced so that the radar beams from adjacent lines overlap at the depth of interest (Geophysical Survey Systems, Inc., 2001b). Generally these lines should be closely spaced (0.5 to 1 m apart).

Radar traverse were conducted at 0.5 m intervals along 21, parallel, 10-m lines. Traverses were conducted in a south-north direction. This direction was orthogonal to the direction of tillage. Surveys were conducted by moving the 400 MHz antenna along the ground surface in a back and forth manner along grid lines that were parallel to the x-axis. Along each line, a measuring line, with marks spaced at 1-m intervals, was stretched between the end points. As the antenna was towed passed each mark, a vertical mark was impressed on the radar profile. The origin (X = 0, Y = 0) of the grid was located in the southeast corner of the survey area. Each line number refers to the y coordinate.

Interpretations:
Figure 1 is a representative radar profile from an area of Elpaso soil. A scale (in nanoseconds) is located along the left-hand side of the radar profile. This scale represents the two-way travel time of the radar pulse. For the upper part of the soil profile, with the 400 MHz antenna, the velocity of propagation was estimated to be about 0.10 m/ns (based on tabled values). Based on this velocity of propagation, a two-way travel time of 30 ns provides a

maximum penetration depth of about 1.6-m. The segmented vertical lines at the top of the radar profile represent equally spaced (1 m) reference marks.

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