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Subject: SOI – Geophysical Field Assistance **Date:** 5 May 2009

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Purpose:
Multiple, detailed surveys were conducted across two small grids located within the Shale Hills Catchment (Huntingdon County) to further evaluate the effectiveness of GPR for detecting the infiltration of water in natural settings. In addition, a high-intensity electromagnetic induction (EMI) survey was completed at Pennsylvania State University's Klepler Farm in Centre County.

Activities:
Field activities were completed during the period of 23 to 24 April 2009.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Henry Lin, Assistant Professor of Hydropedology/Soil Hydrology, Department of Crop & Soil Sciences, PSU, University Park, PA
Jun Zhang, PhD Student, Department of Crop & Soil Sciences, PSU, University Park, PA
Qing Zhu, PhD Student, Department of Crop & Soil Sciences, PSU, University Park, PA

Summary:

1. Detailed, repetitive GPR surveys of an "*infiltration grid site*" were conducted with a 400 MHz antenna. The *infiltration grid site* (2.5 by 1 m) is located in an area of Weikert soils within the Shale Hills Catchment. Ten and fourteen separate GPR surveys of this grid site were completed on days 1 and 2, respectively. Each GPR survey consisted of 11 separate radar records (total of 264 radar records). Over this period, 85 liters of water were emptied into a shallow (about 15 cm deep) trench (1-m long) located immediately (about 10 cm) upslope of the grid area. Water was emptied into the trench in five, 17-liter sequences over the two day period. Fifteen Decagon 5TE soil moisture sensors were inserted in the downslope trench to measure changes in soil moisture. At no time during this experiment was water observed seeping into the downslope trench or across the surface of the *infiltration grid site*.

2. A very large number of radar records were collected over the *infiltration grid site*. These records have been turned-over to the principal investigator, Jun Zhang, for analysis. As part of his research project, Jun is responsible for the analysis of the collected two-dimensional (2D) radar records and the construction and

interpretation of three-dimensional (3D) pseudo-images. Data collected during this two-day period are essential to Jun's research on the infiltration of water in shallow soils underlain by highly fractured shale.

3. Two radar grid surveys were also conducted across a "permanent grid site" located in a swale and area of Rushtown soils. Data have been turned over to Jun Zhang, but are not discussed in this report.

4. This was the first time that reflections from the underlying and dipping bedding and cleavage planes were apparent on radar records collected at *infiltration grid site*. Soils were exceptionally moist at the time of this investigation. The increased moisture contents in bedding and/or cleavage planes are believed to be responsible for the greater reflections from these interfaces on the radar records. These results suggest that that fractures, bedding and/or cleavage planes in shale (as well as other rock types) are best profiled with GPR when the parent rock is optimally moistened.

5. A high-intensity EMI survey was completed across Qing Zhu's research site at Klepler Farm. Unlike earlier surveys, which were completed with an EM38DD meter, the present survey was completed with the newly developed EM38MK2-2 meter. Both meters are manufactured by Geonics Limited. The results of this survey have been turned over to Qing for analysis and incorporation into his research.

It was my pleasure to participate in these studies and to work with Dr. Henry Lin and his graduate students at Pennsylvania State University.

With kind regards,

James A. Doolittle
Research Soil Scientist
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Equipment:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (SIR-3000), manufactured by Geophysical Survey Systems, Inc. (GSSI; Salem, NH).[1] The SIR-3000 consists of a digital control unit (DC-3000) with keypad, SVGA video screen, and connector panel. A 10.8-volt lithium-ion rechargeable battery powers the system. The SIR-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. Antennas with center frequency of 400 and 200 MHz were used in this investigation. With an antenna, the SIR-3000 requires two people to operate. Daniels (2004) and Jol (2008) discuss the uses and operation of GPR.

The RADAN for Windows (version 6.6) software program (GSSI) was used to process the radar records shown in this report.[1] Processing included: header editing, setting the initial pulse to time zero, color table and transformation selection, distance normalization, range gain adjustments, signal stacking, and migration, (see Daniels (2004) and Jol (2008) for discussions of these techniques).

The EM38-MK2 meter, manufactured by Geonics limited (Mississauga, Ontario), was used in the high intensity survey at Klepler Farm.[1] The EM38-MK2 meter weighs about 2.8 kg (6.2 lbs) and requires only one person to operate. The EM38-MK2 meter consists of one transmitter coil and two receiver coils, and operates at a frequency of 14,500 Hz. The receiver coils are separated from the transmitter coil at distances of either 100 or 50 cm. This configuration provides nominal penetration depths for the 100 and 50 cm coil spacings of 150 and 75 cm in the vertical dipole orientation (VDO) and 75 and 38 cm in the horizontal dipole orientation (HDO), respectively. Operating procedures for the EM38-MK2 meter are described by Geonics Limited (2008). The EM38-MK2 meter can provide simultaneous measurements of both quadrature-phase (conductivity) and in-phase (susceptibility) components within the two depth ranges.

Calibration of GPR:
Ground-penetrating radar is a time scaled system. The system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., bedrock, soil horizon, stratigraphic layer) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (D), two-way pulse travel time (T), and velocity of propagation (v) are described in equation [1] (after Daniels, 2004):

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

The velocity of propagation is principally affected by the relative dielectric permittivity (E_r) of the profiled material(s) according to equation [2] (after Daniels, 2004):

$$E_r = (C/v)^2 \qquad [2]$$

Where C is the velocity of propagation in a vacuum (0.298 m/ns). Velocity is expressed in meters per nanosecond (ns). In soils, the amount and physical state (temperature dependent) of water have the greatest effect on the E_r and v. At the time of these studies, soils were relatively moist.

Based on the measured depth and the two-way pulse travel time to a known subsurface reflector (metal plate buried at 50 cm), the velocity of propagation and the relative dielectric permittivity through the upper part of soil profiles were estimated using equations [1] and [2]. In an area of Rushtown soils, the estimated E_r was 14.3. This permittivity resulted in a v 0.0788 m/ns.

Field Methods:
The Shale Hills Catchment is underlain by fractured rock. In this study, GPR and frequency-domain reflectometry (FDR) are used to better understand and characterize ground-water flow paths in shallow soils over fractured bedrock, at scales of one to several meters.

The infiltration grid (200 by 100 cm) is located in an area of Weikert soils. To complete a GPR survey, eleven, 200-cm traverses are completed across the grid with a 400 MHz antenna. Traverse lines are orientated essentially orthogonal to

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

the slope. The interval between successive traverse lines is 10 cm. Ten and fourteen separate GPR surveys of the *infiltration grid site* were completed on days 1 and 2, respectively. Each survey consisted of 11 parallel GPR traverses across the grid site. All traverses were conducted from west to east across the grid site. Over this two-day period, 85 liters of water were emptied into a shallow (about 15 cm deep) trench located immediately upslope of the grid. Water was emptied into the trench in five, 17-liter sequences over the two day period. At no time during this experiment was water observed seeping into the downslope trench or across the surface of the *infiltration grid site*.

Fifteen Decagon 5TE sensors (Pullman, Washington) were installed in the downslope trench.[2] These sensors were inserted into the upslope sidewall at depths of 5, 10 and 20 cm. These sensors are designed to measures soil moisture, soil temperature, and bulk electrical conductivity (EC).

To complete the high-intensity EMI survey at Klepler Farm, the newly developed EM38MK2-2 meter was used. This meter was operated in the VDO and continuous mode. The EM38MK2-2 meter was placed in a plastic sled with its long axis orientated parallel to the direction of travel, and towed behind an all-terrain vehicle (ATV) at speeds of 1 to 3 m/sec. The EMI survey of Klepler Farm was completed by driving the ATV at a uniform pace along rows of stubble, in a random or back and forth manner.

A Trimble AgGPS 114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to georeferenced the EMI data.[2] An Allegro CX field computer (Juniper Systems, North Logan, UT) was used to record both EMI and position data.[2] Using the recently marketed RTmap38 program (Geomar Software, Inc. (Mississauga, Ontario)), both GPS and apparent conductivity (EC_a) data are simultaneously recorded and displayed on the Allegro CX field computer.[1] The color display for the RTmap38 program (see Figure 1) allows researchers to immediately track, observe, and interpret the results of EMI surveys. With this software program, researchers can visually correlate EMI data with soil and landscape patterns, and move directly to sites of different EC_a for sampling and verifications of the factors influencing the EC_a. In Figure 1, the left-hand plot shows the display during data recording; the right-hand plot shows the screen when data collection is paused and the *hidden menu* appears.

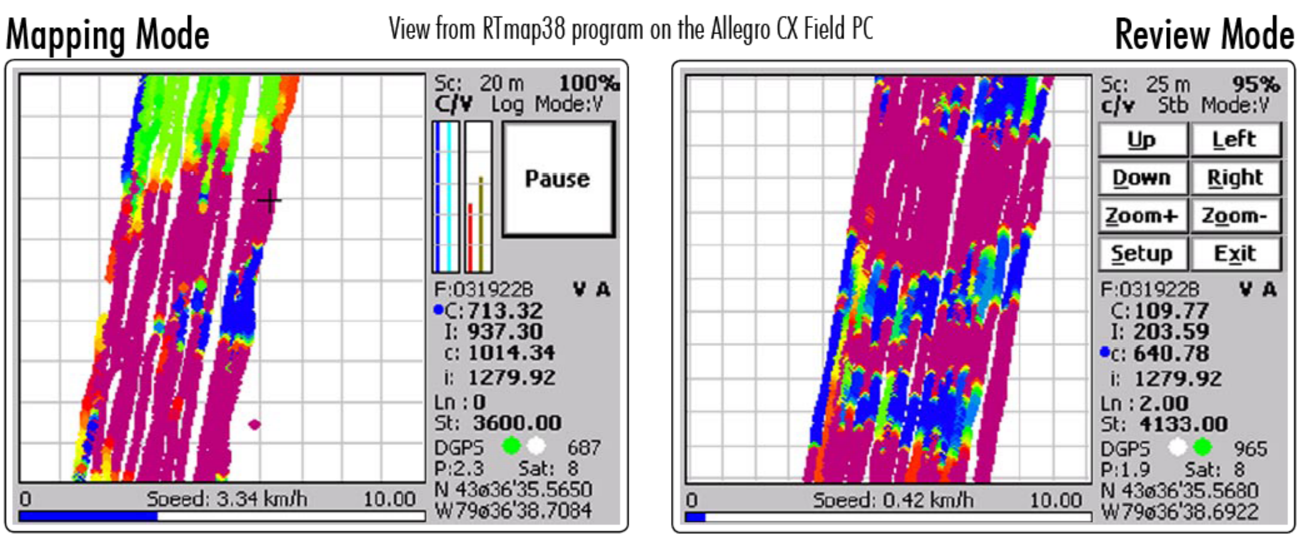

Figure 1. The RTmap38 program provides an instaneous track of each traverse and EC_a measurements displayed as a colored image on the Allegro field computer (courtesy of Geomar Software, Inc.).

Results:

GPR Survey of Infiltration Grid:

Repetitive GPR surveys were conducted across the small *infiltration grid site* to observe temporal differences in subsurface reflections associated with the flow of water through profiles of Weikert soils. Figure 2 contains nine radar

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

records that were collected during the course of these surveys along the first traverse line of the *infiltration grid site*. The first traverse line is closest to the trench into which the water was poured, and should, therefore, be the most affected by the water. The trench parallels this line and is situated immediately upslope of the 0.5 to 1.5 distance marks that appear on each of the radar records.

All radar records shown in Figure 2 were subjected to the same processing. Processing procedures include: header editing, setting the initial pulse to time zero, color table and transformation selection, and distance normalization. All radar records shown in Figure 2 are displayed with the same display range gain adjustments. In the lower portion (below 75 cm) of each of the radar records, inclined reflection patterns are evident. These reflectors vary in amplitude and expression, mostly dip in the same direction, and are believed to mimic some of the bedding and/or cleavage planes in the underlying shale bedrock. This was the first time that these reflectors were apparent on radar records collected at *infiltration grid site*. The increased moisture contents in bedding and/or cleavage planes are believed to be responsible for the greater reflections from these interfaces on the radar records. These results suggest that that fractures, bedding and/or cleavage planes in shale (as well as other rock types) are best profiled with GPR when the parent rock is optimally moistened.

In Figure 2, similar spatial patterns appear in the time-lapsed radar records from traverse line 1. As no significant changes in signal amplitudes and reflection patterns are evident on these radar records, there exists no clear indication of the movement of water through these vertical radar slices. Based on these radar images, it must be assumed that the majority of the water that was poured into the adjoining trench has infiltrated the subsurface through fractures that underlie the trench. On the radar records shown in Figure 2, variations in spatial patterns and signal amplitudes are slight and essentially indistinguishable. Though highly subjective, signal amplitudes in the underlying bedrock appear to be slightly greater immediately and shortly after the pouring of 17- liters of water into the nearby trench (Figure 2-B, -C, -F, and -G) than at later time intervals. This suggests that GPR may be detecting some additions of water into the soil and bedrock. An amplitude analysis of the radar records is needed to confirm this wishful speculation. On each radar record, slight difference in reflection geometries and patterns can be observed. These differences are attributed to slight disparity in the track, tilt, and speed of the antenna as it was moved along the traverse line.

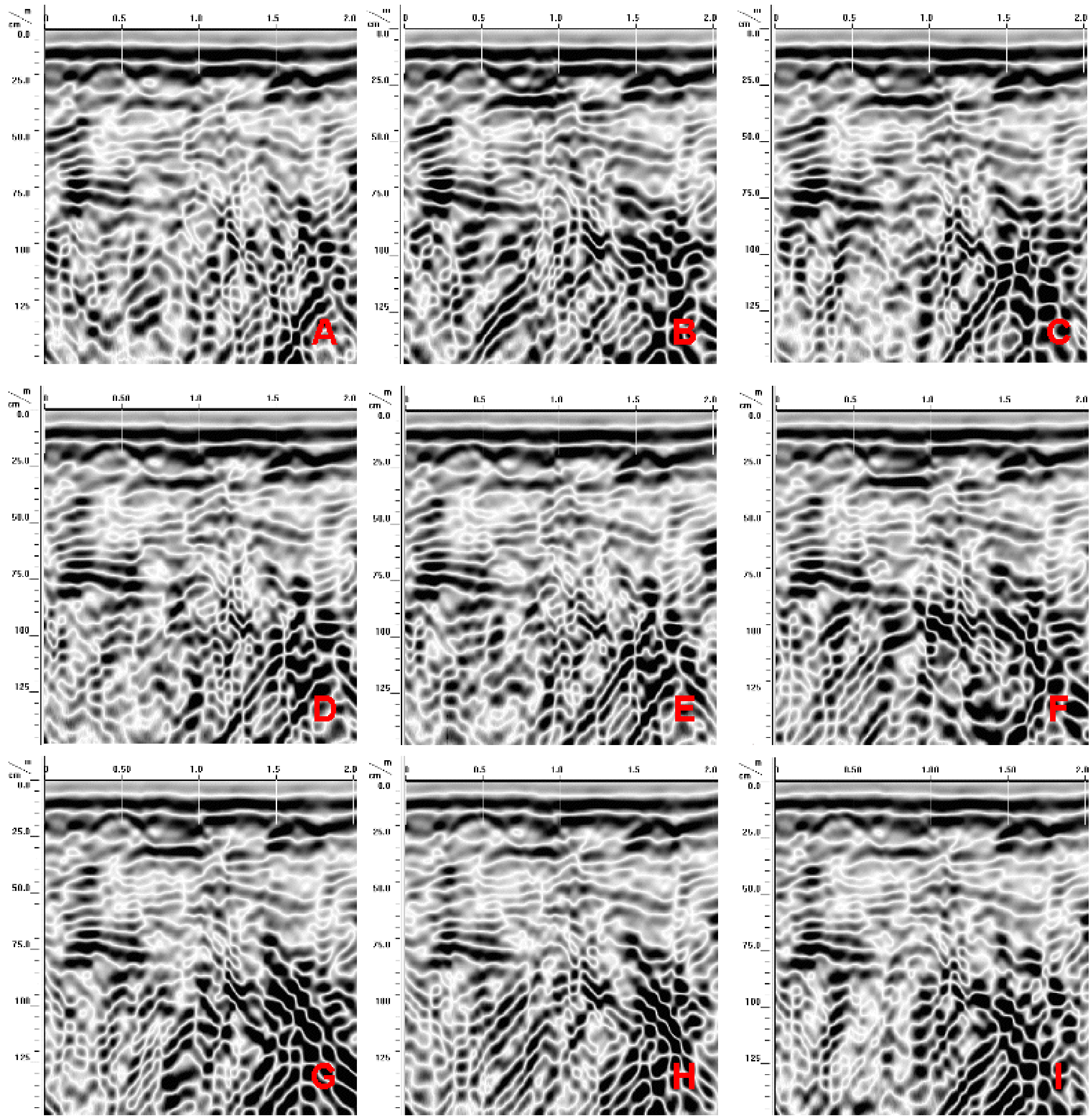

Figure 2. These 2D radar records were collected along the first line of the infiltration grid site. These records represent the following radar traverses: the initial dry traverse (A), immediately after the first wetting (FW) (B), 5 minutes after FW (C), 15 minutes after FW (D), 25 minutes after FW,(E), immediately after the second wetting (SW)(F), 5 minutes after SW (G), 15 minutes after SW (H), AND 25 minutes after SW(I).

The same radar records that are shown in Figure 2 are shown again in Figure 3. In Figure 3, the radar records have been migrated. Migration algorithms are often used to improve signal to noise ratios and to reconstruct and properly align inclined interfaces. The effects of migration are evident in the removal of some inclined reflectors and diffraction tails. In addition, deeper soil interfaces have been reconstructed and are theoretically more properly align through migration. While migration may have resulted in the more proper positioning of these inclined reflectors, the unmigrated radar records (see Figure 2) are preferred as reflector patterns within the shale bedrock are more clearly expressed and approximate the observed and expected orientation of bedding and/or cleavage planes.

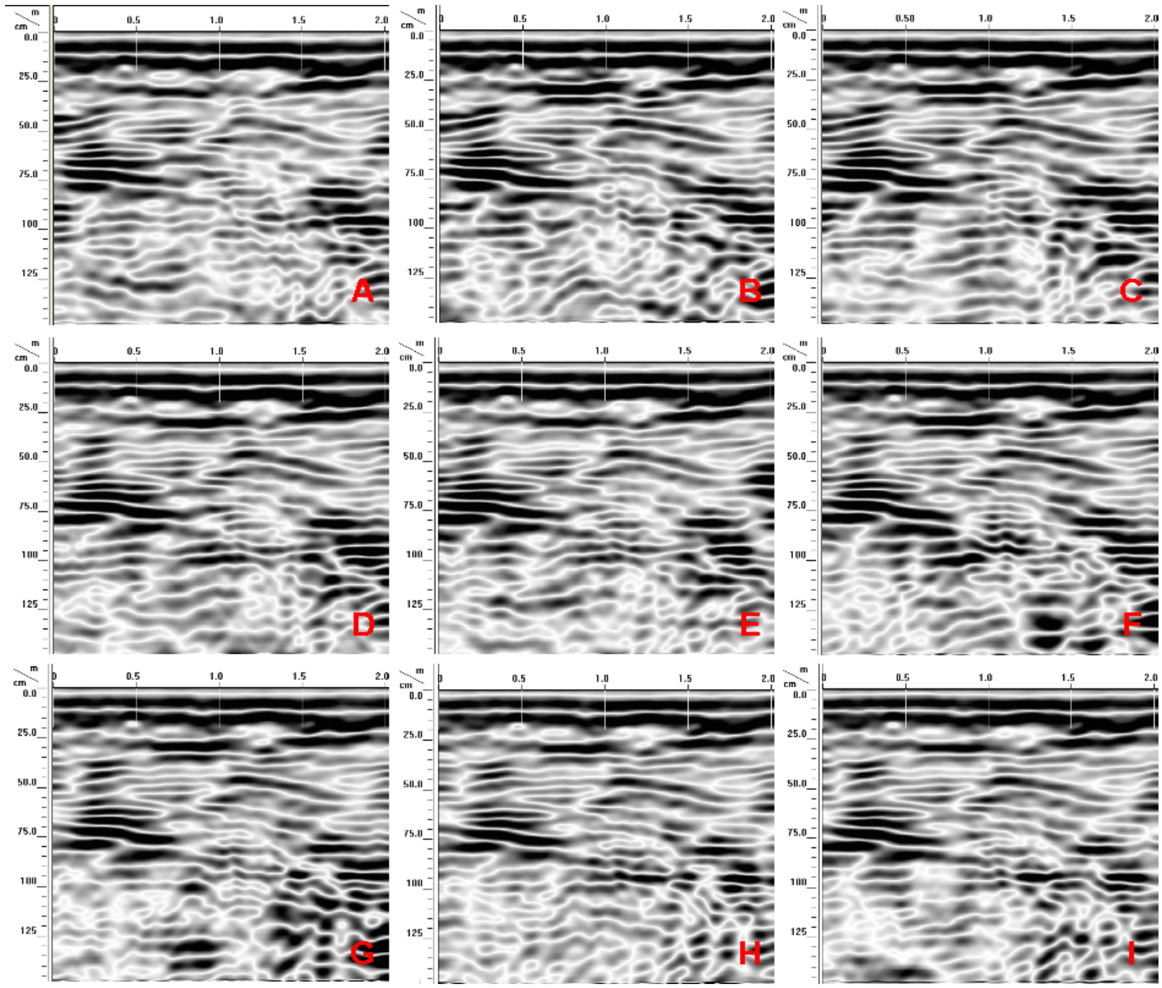

Figure 3. These 2D radar records, which were collected along the first line of the infiltration grid site, have been migrated. These records represent the following radar traverses: the initial dry traverse (A), immediately after the first wetting (FW) (B), 5 minutes after FW (C), 15 minutes after FW (D), 25 minutes after FW,(E), immediately after the second wetting (SW)(F), 5 minutes after SW (G), 15 minutes after SW (H), AND 25 minutes after SW(I).

EMI Survey of Klepler Farm:

Table 1 summarizes the results of the EMI survey that was completed on Qing Zhu's research fields at Klepler Farm. All EC_a data shown in this table have been temperature corrected. For the shallower-sensing (0 to 75 cm) 50 cm intercoil spacing, EC_a ranged from about -207 to 600 mS/m. The large range in EC_a values reflects the presence of buried utility lines and artifacts scattered across the fields. However, across most portions of these fields, EC_a is less variable with a large number (one-half) of the measurements between about 2.8 and 9.6 mS/m. For the 50 cm intercoil spacing, EC_a averaged only 6.5 mS/m with a rather large standard deviation of 11.2 mS/m. For the deeper-sensing (0 to 150 cm) 100 cm intercoil spacing, EC_a ranged from about -389 to 68 mS/m. Once again, the large range in EC_a reflects the presence of buried utility lines and scattered artifacts. For the 100 cm intercoil spacing, EC_a averaged 15.5 mS/m with a standard deviation of 7.8 mS/m. One-half the EC_a measurements were between about 13.0 and 18.4 mS/m. Compared with the shallower sensing 50-cm intercoil spacing, EC_a measured in the deeper sensing 100-cm intercoil spacing is higher and less variable. As the maximum response of the 100-cm intercoil spacing occurs at a depth of about 40 cm, this trend is assumed to principally reflect the higher clay and moisture contents of the Bt horizon.

Table 1

Basic EMI Statistics for the EMI survey that was conducted at the Klepler Farm Research Site on 23 April 2009. (Other than the number of observations, all values are expressed in mS/m)

Intercoil Spacing	100 cm	50 cm
Number	6752	6752
Minimum	-389.04	-206.96
25%-tile	12.99	2.78
75%-tile	18.43	9.57
Maximum	68.22	600.19
Average	15.54	6.50
Standard. Deviation	7.85	11.22

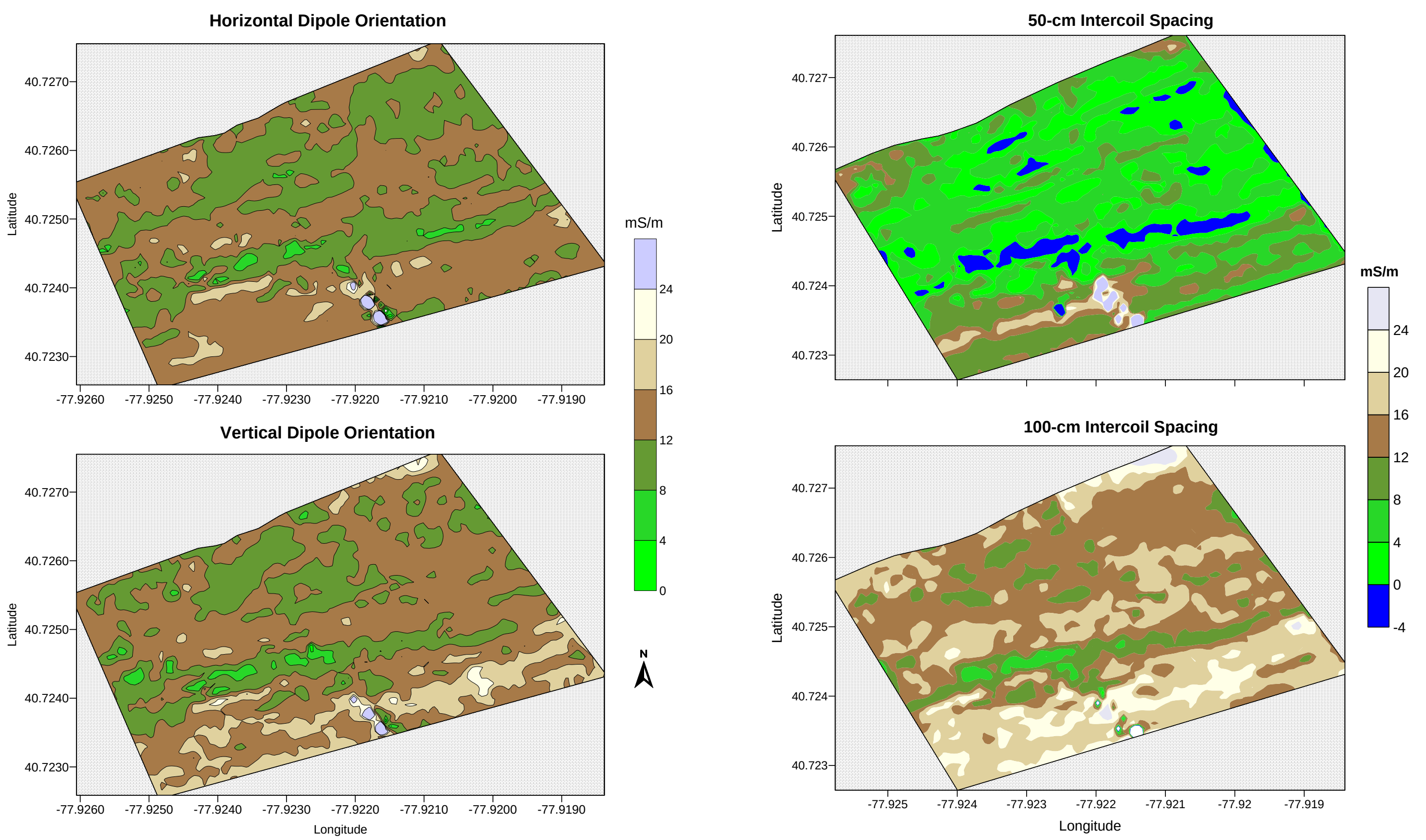

Figure 4. These plots show the EC_a data collected with the EM38DD (left-hand plots) and the EM38MK2-2 (right-hand plots) meters. Nominal depths of penetration are 75 (HDO and 50-cm intercoil spacing) and 150 (VDO and 100-cm intercoil spacings) cm, respectively.

In general, EC_a is relatively low across most of the site. The relatively low EC_a reflects the electrically resistive nature of soils and underlying limestone bedrock. The large range in recorded EC_a reflects the presence of buried utility lines within portions of the fields. Buried power cables entered the south-central portion of the study site along a farm road. These utilities produced electromagnetic interference resulting in anomalous EMI responses. Other anomalous EC_a measurements reflect metallic artifacts that were either discarded or shallowly-buried in the field and crossed or closely approached with the meter during the survey.

Figure 4 contains four, two-dimensional plots of EC_a data that were collected with an EM38DD meter (left-hand plots) in the horizontal (upper plot) and vertical (lower plot) dipole orientations, and with the EM38MK2-2 meter (right-hand plots) for the 50 (upper plot) and 100-cm (lower plot) intercoil spacings. The EM38DD data are for the EMI survey that was conducted in the fall of 2008. In each plot, the isoline interval is 4 mS/m and the same color ramp is used. As the broad spatial EC_a patterns evident in these plots are similar, these patterns are considered temporally stable and are presumed to reflect differences in stable soil properties (e.g., clay content and soil depth). These spatial similarities suggest the presence of spatially stable hydropedologic functional units that are defined with EMI. While broad spatial patterns are similar on all plots, differences in EC_a values are evident between the two EMI instruments and among dipole orientations and intercoil spacings. The intricacies of the spatial patterns are highly variable. These differences reflect, in part, differences in soil moisture contents, as well as the volume of soil measured with each meter and configuration, calibration, numbers and spacings of observations, and the tracks of the mobile platform.

Spatial EC_a patterns appearing in Figure 4 are assumed to be principally related to differences in soil depth and wetness. Areas with lower EC_a are on higher-lying, more sloping, better drained landscape components. In general, these areas have thinner caps of residuum and shallower depths to limestone bedrock. Areas with higher EC_a are on lower-lying, more imperfectly drained plane and concave slope components. In general, these areas are wetter, and have thicker caps of residuum and deeper depths to bedrock.

In the plots shown in Figure 4, the approximate locations of buried utility lines can be identified by anomalous EC_a values plotted in the extreme south central portion of the research fields. The northern portion of the research site also contains buried utility lines, but this area was avoided.

References:

Daniels, D. J., 2004. Ground Penetrating Radar; 2nd Edition. The Institute of Electrical Engineers, London, United Kingdom.

Geonics Limited, 2008. EM38-MK2 ground conductivity meter operating manual. Geonics Limited, Mississauga, Ontario.

Jol, H., 2009. Ground Penetrating Radar: Theory and Applications. Elsevier Science, Amsterdam, The Netherlands.