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SUBJECT: SOI – Geophysical Assistance

November 22, 2011

TO: Ronnie Taylor
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File Code: 330-7

Purpose:
The purpose of this field work was to provide introductory training on the use of a newly acquired Profiler sensor. In addition, results from the Profiler were compared with those of an EM31 meter to better understand the profiling depths of the multifrequency electromagnetic induction instrument (Profiler).

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Edwin Muñiz, Assistant State Soil Scientist, USDA-NRCS, Somerset, NJ
Fred Schoenagel, Resource Soil Scientist, USDA-NRCS, Clinton, NJ
Claire Steager, Civil Engineering Technician, USDA-NRCS, Woodstown, NJ
Uziel Torres, Soil Conservationist, USDA-NRCS, Woodstown, NJ
Rob Tunstead, MLRA Soil Survey Office Leader, USDA-NRCS, Hammonton, NJ

Activities:
Field activities were completed on 10 May 2011.

Summary:

1. Based on the findings of Brosten et al. (2011) and this study, I accept the Profiler as being a *geometry limited* instrument like the EM31 meter, rather than a *skin depth limited* device. The Profiler has a coil separation of 121 cm. Compared to the EM31 meter, because of its smaller intercoil spacing, the Profiler will profile the soil to lesser depths in both dipole orientations. In the VDO and HDO, the depths of exploration for the Profiler are accepted as being approximately 1.8 and 0.9 m, respectively.

2. The Profiler has been most accurately calibrated at 15 kHz. This frequency should be used to measure the apparent conductivity (EC_a) of soils.

It was my pleasure to work with your staff and take part in this study.

Jim Doolittle

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Technical Report on the Use of Geophysical Methods for the Evaluation of the Surface Water Contamination from a livestock holding area , Woodstown, New Jersey, 10 May 2011.

James A. Doolittle

Equipment:
A Profiler EMP-400 sensor (Geophysical Survey Systems, Inc. (GSSI)) was used in this study (see Figure 1)[1]. The sensor has a 1.22 m intercoil spacing and operated at frequencies ranging from 1000 to 16000 Hz. The Profiler EMP-400 sensor (henceforth referred to as the Profiler) is a multifrequency EMI meter that can simultaneously collect data at three separate frequencies between 1 and 16 kHz. For each frequency, data are recorded for both the in-phase and the quadrature phase components, and apparent conductivity. Although the Profiler sensor outputs a data column for magnetic susceptibility, these data are not correct (Dan Delea, personal communication 27 April 2011). Correctly estimated data on magnetic susceptibility have not been implemented yet and the units are presently "grayed out" (disabled). A rechargeable Li-ion battery pack powers the sensor. Surveys can be conducted with this sensor held in either the vertical (VDO) or horizontal dipole orientation (HDO). The sensors electronics are controlled via Bluetooth communications with a TDS RECON-400 Personal Data Assistant (PDA). To collect geo-referenced data, the PDA is configured with an integral 12-channel WAAS (Wide Area Augmentation System) GPS.

Figure 1. Edwin Muñiz, Assistant State Soil Scientist completes an EMI survey of a livestock loafing area near Woodstown, New Jersey, with a Profiler sensor held in the vertical dipole orientation.

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

An EM31 meter (Geonics Limited, Mississauga, Ontario) was also used in this study[1]. Like the Profiler, this meter needs no ground contact, is portable; and requires one person to operate. McNeill (1980) has described the principles of operation for the EM31 meter. The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9.8 kHz. When placed on the soil surface, the EM31 meter has effective exploration depths of about 3.0 and 6.0 meters in the HDO and VDO, respectively (McNeill, 1980). The Geonics DAS70 Data Acquisition System was used to record and store both EM31 and GPS data[2]. The acquisition system consists of an EM31 meter, Allegro CX field computer, and Trimble AG114 GPS receiver[2]. With this logging system, the EM31 meter is keypad operated and measurements can either be automatically or manually triggered.

To help summarize the results of the EMI surveys, the SURFER for Windows (version 9.0) software (Golden Software, Inc., Golden, CO) was used to construct the simulations shown in this report[2]. Grids were created using kriging methods with an octant search.

Depth of Exploration for the EM31 meter and the Profiler sensor:
McNeill (1980) describes how the measured apparent conductivity (EC_a) is a function of an EMI instrument's calibration, coil separation, coil orientation, and frequency. Larger coil separations and lower frequencies are used to achieve greater depths of exploration. The EM31 meter has a coil separation of 366 cm; the Profiler has a coil separation of 122 cm. For multifrequency EMI sensors, Won et al. (1996) observed that changing the transmitter frequency will change the depth of exploration. Won (1980 and 1983) makes clear that the exploration depths of a multifrequency EMI instrument are governed by the *skin-depth effect*: low frequency signals travel farther through conductive mediums than high frequency signal. The Profiler can operate at multiple frequencies ranging from 1000 to 16000 Hz.

With the EM31 meter and all meters developed by Geonics Limited, the depth of exploration is considered *geometry limited* (coil spacing and orientation) rather than *skin depth limited* (McNeill, 1980). Under conditions of low induction numbers, the depth-response functions of these meters are assumed to be independent of soil conductivity. Conditions of low induction numbers have been assumed to be satisfied in soils having relatively low conductivities ($EC_a < 100$ mS/m) (McNeill, 1980). Slavich (1990) and de Jong et al. (1979) reported that the depth of exploration will vary depending on the bulk electrical conductivity of the profiled material(s). Greenhouse et al. (1998) also commented that the electrical conductivity of soils play a critical role in the depth of exploration that can be obtained with all EMI instruments.

With the Profiler, the depth of exploration is considered *skin depth limited* rather than *geometry limited* (Won, 1980 and 1983, Won et al., 1996). *Skin depth* represents the maximum depth of exploration for the Profiler operating at a specific frequency and sounding a medium of known conductivity. Exploration depth or *skin depth* is inversely proportional to frequency (Won et al., 1996). Low frequency signals have longer periods of oscillation and loose energy less rapidly than high frequency signals. As a consequence, low frequency signals travel farther through conductive mediums than high frequency signals. Greater depths of exploration can supposedly be achieved with the Profiler by decreasing the frequency. At a given frequency, the depth of exploration is greater in soils having lower conductivity than in soils having a higher conductivity. However, because of other factors, such as the geometry of the sensor, the depth of observation may be less than the *skin depth* (Greenhouse et al., 1998). Multifrequency sounding with the Profiler supposedly allows multiple depths to be profiled with one pass of the sensor.

Dan Delea (GSSI) noted that values for apparent conductivity data collected between 14 and 16 kHz will be in effect the same (personal communication 27 April 2011). He also noted that at lower frequencies the values will actually increase.

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

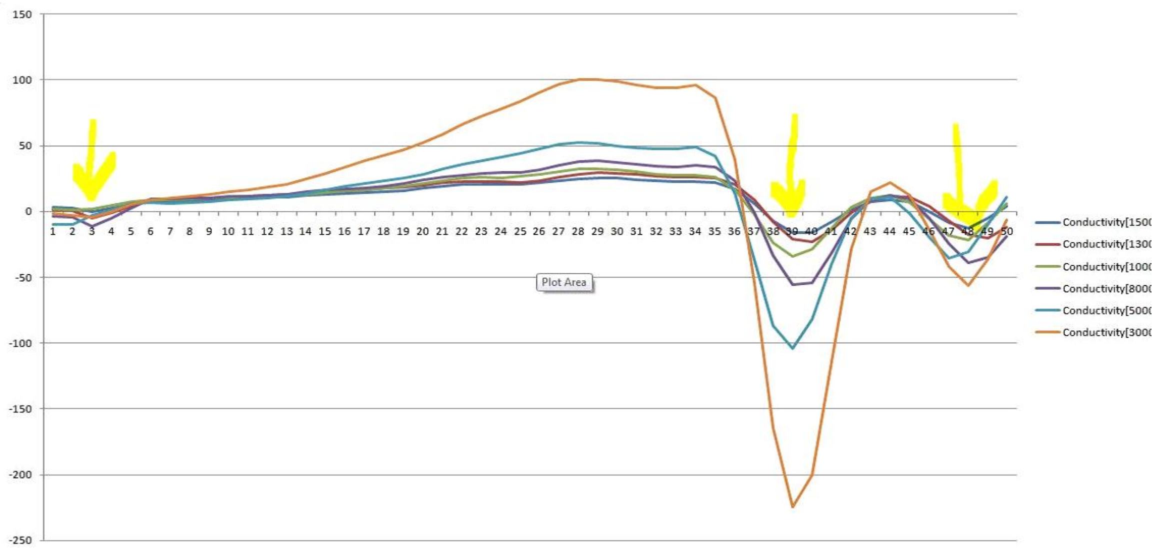

Figure 2. Data collected at different frequencies with the Profiler-EMP-400 sensor from a line across GSSI's test pit (courtesy of GSSI, Salem, NH).

Figure 2 shows the distribution of EC_a measured with the Profiler sensor along a 24-yard long line across GSSI's test pit. The negative excursions are cause by metallic strips on the surface at the beginning and end of the line and a metal plate 2 feet down at 40 feet. The lowest conductivity (i.e., 15 kHz) is actually the correct one (Dan Delea, personal communication 27 April 2011).

Brosten et al. (2011) note how multifrequency EMI sensors continue to challenge practitioners. While some researchers (Huang and Won, 2000; Won, 1980 and 1983; Won et al., 1996) argue that data recorded by multifrequency sensors provide useful information, McNeill (1996) contends that the data recorded is redundant because the sensitivity of these instruments is strongly controlled by their low frequency range and coil spacings. Brosten et al. (2011) used synthetic modeling methods and determined that with a GEM-2 multifrequency sensor, in a medium that had an estimated skin depth of 23.4 m, the actual depth of exploration ranged from only 1.8 to 2.7 m.

The depth of exploration for the Profiler appears to be *geometry limited* rather than *skin depth limited*. Based on the findings of Brosten et al. (2011) and this study, I accept the Profiler as being a *geometry limited* instrument like the EM31 meter. The Profiler has a coil separation of 122 cm. Compared to the EM31 meter (with a coil spacing of 366 cm), because of its smaller intercoil spacing, the Profiler will profile the soil to lesser depths in both dipole orientations. In the VDO and HDO, the depths of exploration for the Profiler are accepted as being approximately 1.8 and 0.9 m, respectively.

Field Site:

The site (about 75.769 N. latitude and 41.551 W. longitude) is located in animal loafing areas and adjoining fields that are downs lope from farm structures. Within the survey site, soils are mapped as Alloway loam on 2 to 5 % slopes (AhpB) and Othello, Fallsington and Trussum soils on 0 to 2 % slopes (OTMA). These very deep soils formed in marine sediments on the Northern Atlantic Coastal Plain. The moderately well drained Alloway soils formed in silty and clayey sediments. The poorly drained Fallsington soils formed in loamy sediments. The poorly drained Othello and Trussum soils formed in silty and clayey sediments, respectively. The taxonomic classifications of these soils are listed in Table 1.

Table 1. - Taxonomic Classification Of The Soils Recognized At Site in Salem County.

Soil Series	Taxonomic Classification
Alloway	Fine, mixed, active, mesic Aquic Paleudults
Fallsington	Fine-loamy, mixed, active, mesic Typic Endoaquults
Othello	Fine-silty, mixed, active, mesic Typic Endoaquults
Trussum	Fine, mixed, active, mesic Typic Paleaquults

Field Methods:
Pedestrian surveys were made with both the EM31 meter and the Profiler across the site. Both devices were operated in the deeper-sensing, vertical dipole orientation (VDO). Both instruments were operated in the continuous mode with measurements recorded at a rate of 1/sec. The long axis of each device was orientated parallel to the direction of traverse. The EM31 meter was held at hip-height; the Profiler was held about 10 cm above the ground surface. For the Profiler, EC_a data were recorded at 16, 10, and 3 kHz. Apparent conductivity was not temperature corrected to a standard temperature of 75^o F.

Results:
In Table 2, the data obtained at three different frequencies with the Profiler are presented and can be compared with the data collected with the EM31 meter. The data set collected with the Profiler at 10 and 16 kHz are, for all intents and purposes, identical and suggest similar exploration depths. These data sets imply that the use of only one frequency (preferably 15 kHz) will sufficed for soil investigations. The use of additional frequencies requires added processing and interpretation time, with no supplementary soil information. Data recorded at 3 kHz with the Profiler are exceptionally variable with anomalously high positive and negative values. These values are assumed to represent high levels of instrument noise at lower frequency settings. Data recorded with the EM31 meter are lower and less variable than the data recorded with the Profiler. The greater exploration depth of the EM31 meter results in lower average EC_a, suggesting that the area is perhaps underlain by coarser-textured (more electrically resistive) materials.

Table 2. Apparent Conductivity Data from the Study Site

	Profiler 16 kHz	Profiler 10 kHz	Profiler 3 kHz	EM31 9.8 kHz
Number	2457	2457	2457	1953
Minimum	-60.8	-71.8	-773.5	25.8
25%-tile	43.1	43.2	37.6	35.0
75%-tile	63.0	63.5	70.2	44.4
Maximum	117.6	104.4	640.3	135.3
Average	53.2	53.4	49.8	40.1
Std. Dev.	13.9	13.6	43.8	8.0

Figure 3 contains plots of the EC_a data collected with the Profiler at three different frequencies. The same color scales and ramps have been used in each plot shown in Figure 2. Spatial patterns and values of EC_a are very similar in the plots of EC_a data collected at 10 and 16 kHz. As a consequence, it is felt that only one frequency would have sufficed to characterize the spatial EC_a patterns. The plot of EC_a data recorded at 3 kHz is more dissimilar, with noticeably high positive and negative excursions. These inconsistent readings are suspected to reflect greater levels instrument noise and interference (resulting in anomalously high and low excursions) at lower frequencies, and more unreliable data.

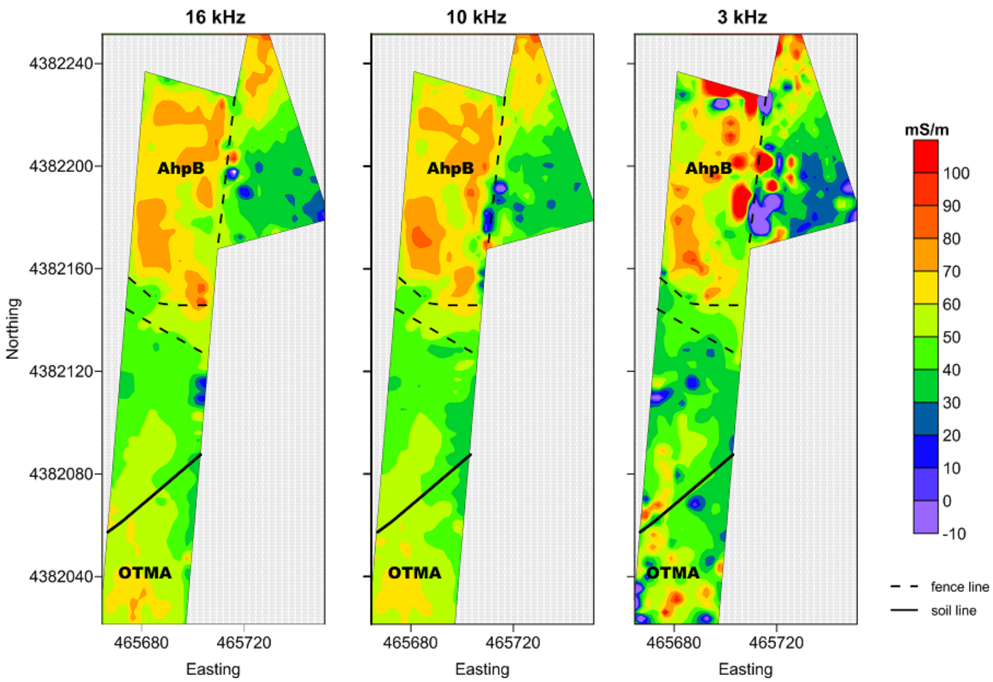

Figure 3. Apparent conductivity data measured with the Profiler at frequencies of 16 kHz (left), 10 kHz (center), and 3 kHz (right). Segmented and solid lines represent fence and soil boundary line, respectively.

Figure 4 is a plot of the data collected with the EM31 meter operated in the VDO. The same color scales and ramps used in Figure 3 for the Profiler data have been used in this plot. While EC_a values are lower and less variable, spatial patterns are remarkably similar to those measured with the Profiler at frequencies of 10 and 16 kHz. As the EM31 meter profiles the soil to deeper exploration depths than the Profiler (366 versus 122 cm), the lower EC_a measured suggest that meter is profiling deeper, coarser-textured and more electrically resistive materials.

Figure 5 contains a three-dimensional (3D) wireframe simulation of the site with a superimposed contour plot of the EC_a data measured with EM31 meter in the VDO. In this simulation, segmented and solid lines represent fence and soil boundary line, respectively. An ill-defined zone of higher EC_a is evident on the higher-lying, northern portions of the study site. This portion of the study site adjoining the farm structures used to house and feed cows. Here, the higher conductivity is attributed to the flow and accumulation of animal wastes in the soil. An area of anomalously high EC_a occurs near the base of the slope along an intermittent stream channel that is located between two of the fence lines shown in this plot. This is a wetter area, which may serve as a collection area for contaminants. The higher conductivity in this area can be attributed to higher moisture and soluble salt contents. However, these assumptions need to be verified with further ground-truth observations and measurements.

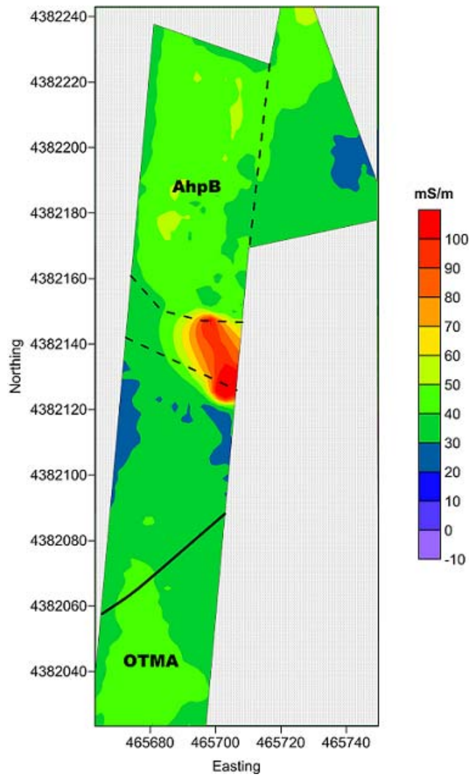

Figure 4. Apparent conductivity data measured with the EM31 meter in the VDO. Segmented and solid lines represent fence and soil boundary line, respectively.

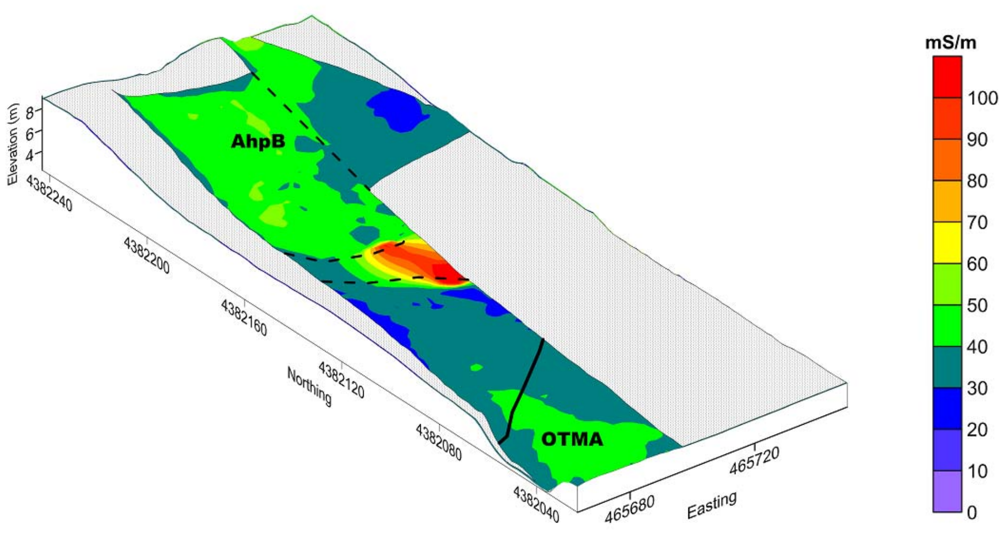

Figure 5. This three-dimensional representation of the Woodstown site shows the spatial distribution of EC_a across the surveyed area as measured with the EM31 meter operated in the VDO. Segmented and solid lines represent fence and soil boundary line, respectively.

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