United States Department of Agriculture
Natural Resources Conservation Service
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Subject: -- Geophysical Assistance -- **Date:** March 26, 2002

To: William J. Gradle
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Purpose:
The objectives of this investigation were to conduct comparative studies with the EM38 and EM38-DD meters and the GEM300 sensor and to assess the relative suitability of each device in an area of sodium-affected soils.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA
Sam Indorante, MLRA Project Leader, USDA-NRCS, Carbondale, IL
Matt McCauley, Zone Soil Scientist, USDA-NRCS, Benton, IL
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Activities:
All field activities were completed on 12 to 14 March 2002.

Recommendations and Conclusions:

1. All three EMI instruments produced similar data sets, spatial patterns, and interpretations. Any one of these devices can be recommended for the appraisal of sodium-affected soils. Surveys conducted with these EMI instruments in different areas of southern Illinois or at different times (provided that differences in temperature are compensated for) should be comparable. Final conclusions and recommendations must await processing of laboratory results at the National Soil Survey Laboratory, NSSC, Lincoln, Nebraska.

2. A major drawback of the EM38 meter is the device's inability to simultaneously record measurements in both dipole orientations. With the EM38 meter, surveys can either be completed in a station-to-station mode (with measurements taken in one or both dipole orientations at each observation point), or in a continuous mode (with measurements obtained in only one dipole orientation). In the station-to-station mode, to obtain measurements in both dipole orientations, a measurement is made in one dipole orientation, then the meter is rotated and re-nulled prior to obtaining the measurement in the other dipole orientation. This tedious operation slows survey speeds and often precludes the simultaneous collection of data in both dipole orientations. For surveys conducted with the EM38 meter operating in the continuous mode, the device cannot be rotated and measurements can only be taken in one dipole orientation. Consequently, two separate surveys are required to obtain measurements in both dipole orientations. The EM38DD meter can be operated in the continuous mode and simultaneously measure both dipole orientations without having to be rotated or re-calibrated. Simultaneous measurements and the lack of the requirement to repeatedly re-nulling the EM38DD meter decreases survey time and improve field efficiency.

3. In previous studies significant differences in measurements and resulting spatial patterns were obtained from data collected at the same observation points with the EM38 and EM38DD meters. Coil misalignment, calibration errors, and system noise are believed to be responsible for the inconsistent

measurements obtained with the EM38DD meter. Last fall, Geonics Limited , aware of the EM38DD meter's instability advised all users to return their EM38DD meters for additional modifications. Results of a comparative test with the EM38 meter at the study site have demonstrated the stability of measurements that are presently obtainable with the modified EM38DD meter.

4. In each of the two survey grids, plots of apparent conductivity collected with the GEM300 sensor are remarkably similar. In particular, data collected in the same dipole orientation, but at different frequencies, are remarkably alike. In each set of plots, patterns are similar, but signal amplitudes vary with frequency. High correlations were found among apparent conductivity measurements obtained at different frequencies and/or dipole orientations.   Correlations are extraordinarily high, suggesting that the GEM300 sensor is measuring similar volumes of soil materials at different frequencies.   The GEM300 sensor appears to be most sensitive to soil properties that occur at shallow depths and that the depth of observation is restricted. The use of multiple frequencies adds time to the processing of field data, but does not appear to provide any additional information in areas of alkaline soils. In areas of sodium-affected soils characterized by moderately high apparent conductivity, the use of a single frequency and two dipole orientations appears to provide sufficient information to select sampling points and characterize spatial patterns.

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

With kind regards,

James A. Doolittle
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cc:
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Background:
Nettleton and others (1994) used EMI to identify sodium-affected soils in south-central Illinois. They found that soils with natric horizons have an apparent conductivity greater than 45 or 55 mS/m in the horizontal and vertical dipole orientations, respectively. Sodium-affected soils that lacked natric horizons had apparent conductivities ranging from 20 to 45 mS/m and 30 to 55 mS/m in the horizontal and vertical dipole orientations, respectively. In their investigation, Nettleton and others (1994) only used an EM38 meter. Dissimilarities in apparent conductivity measurements have been observed in studies using different EMI devices. These dissimilarities in measurement have been attributed to differences in manufacturer's calibration, intercoil spacing, depth and volume of soil profiled, and frequencies. This study will reevaluate the results obtained by Nettleton and others (1994) and compare data obtained with the EM38 and EM38DD meters and the GEM300 sensor.

Equipment:
Geonics Limited manufactures the EM38 and the EM38DD meters.[1] Both meters are portable and require only one person to operate. No ground contact is required with either meter. Lateral resolution is approximately equal to the intercoil spacing. These meters have a 1 m intercoil spacing and operate at a frequency of 14,600 Hz. These meters have effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). The EM38-DD meter consists of two EM38 meters bolted together and electronically coupled. One unit acts as a master unit (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one unit acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on). Data was stored in an Omnidata 720 polycorder.[1] With the polycorder, measurements can be either automatically or manually triggered.

The GEM300 sensor, developed by Geophysical Survey Systems, Inc.,[1] was also used in this study. Won and others (1996) have described the use and operation of this sensor. This sensor is portable and requires only one person to operate. No ground contact is required with the GEM300 sensor. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 19,950 Hz with a fixed coil separation (1.3 m). The GEM300 sensor is keypad operated. Measurements can be either automatically or manually triggered. Multifrequency sounding with the GEM300 sensor theoretically allows multiple depths to be profiled with one pass of the sensor.

The position of all observation points was obtained with Rockwell Precision Lightweight GPS Receivers (PLGR).[1] The GPS receiver was operated in the continuous and the mixed satellite modes. The Universal Transverse Mercator (UTM) coordinate system was used. Horizontal datum was the North American 1983. Horizontal units were expressed in meters.

To help summarize the results of this study, the SURFER for Windows program (version 7.0), developed by Golden Software, Inc.,[2] was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search.

Study Area:
The study site was located near DuQuoin, Illinois. The site was located principally in an area of Hoyleton-Darmstadt silt loams, 0 to 2 percent slopes but included an area of Tamalco silt loam, 1 to 5 percent slopes, eroded, (Grantham and Indorante, 1988). The somewhat poorly drained Darmstadt and Hoyleton soils and the moderately well drained Tamalco soil formed in loess and underlying silty or loamy deposits that overlie a strongly weathered paleosol in Illinoian till. Darmstadt is a member of the fine-silty, mixed, superactive, mesic Albic Natraqualfs family. Hoyleton is a member of the fine, smectitic, mesic Aquertic Hapludalfs family. Tamalco is a member of the fine, smectitic, mesic Typic Natrudalfs family.

Survey Procedures:
Two, 50 by 50 m grids were established at the study site. The grid interval was 10 m. Survey flags were inserted in the ground at each grid intersection and served as observation points. This procedure provided 36 observation points in each grid. The coordinates of each observation point were determined with GPS.

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[1] Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.
[2] Trade names have been used in this report to provide specific information. Their use does not constitute endorsement.

As measurements were obtained in both the horizontal and vertical dipole orientations and precise positioning of instruments were required, all EMU instruments were operated in a station-to-station rather than a continuous mode. Measurements were taken with the EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations. Measurements were taken with the EM38DD meter placed on the ground surface. Measurements were taken at hip-height with the GEM300 sensor in both the horizontal and vertical dipole orientations.

Soil samples were collected at six observation points. The sampling sites were selected to span the observed range in apparent conductivity and to provide reasonable coverage of the study site. At each sampling site, soil samples were acquired in 30-cm intervals down to a depth of 120 cm.

Interpretation of Data:

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a depth-weighted, average conductivity measurement for a column of earthen materials to a 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 will increase with increased soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Interpretations of EMI data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in apparent conductivity are used to infer changes in soils and soil properties. EMI integrate the bulk physical and chemical properties of soils within a defined depth into a single value. 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. As a consequence, measurements can be associated with changes in soils and soil map units (Doolittle et al., 1996; Hoekstra et al., 1992; and Jaynes et al., 1993).

Electromagnetic induction has been used to assess and map depths to claypans (Doolittle et al., 1994; Stroh et al., 1993; Sudduth and Kitchen, 1993; and Sudduth et al., 1995), estimate topsoil depth (Sudduth et al., 1999), and measure soil water contents (Kachanoski et al., 1988), cation exchange capacity (McBride et al., 1990), field-scale leaching rates of solutes (Jaynes et al., 1995; Slavich and Yang, 1990) and herbicide partition coefficients (Jaynes et al., 1995). Electromagnetic induction has been used as a soil-mapping tool to assist precision farming (Jaynes, 1995; Jaynes et al., 1993; Sudduth et al., 1995).

Instrument Stability Test:

In an earlier comparative study with the EM38 meter in Illinois, efficiency of the EM38DD meter was demonstrated. The capacity to simultaneous measure responses in both dipole orientations and the lack of the requirement to repeatedly re-nulling the EM38DD meter decrease survey time by 56 percent. However, in studies conducted in Illinois, Iowa, Ohio, and Colorado significant differences in measurements and resulting spatial patterns were obtained when data were collected at the same observation points with the EM38 and EM38DD meters. This is of great concern, as it is imperative that closely matching results are obtained with these meters. Coil misalignment, calibration errors, and system noise are believed to be responsible for the inconsistent measurements obtained with the EM38DD meter. With the EM38DD meter, the vertical dipole transmitter coil (master unit) and horizontal dipole receiver coil (slave unit) are sensitive to slight changes in the placement and orientation of the meters on the ground surface. As a consequence, slight changes in placement or orientation can cause significant changes in the measured response. These changes are most evident over resistive ground suggesting that much of the variability arises from the instrument rather than from the conductivity of the soil.

In the fall of 2001, Geonics Limited, aware of the EM38DD meter’s instability advised all users to return their EM38DD meters for additional modifications. This study represents the first comparative study conducted by USDA since the modification of the EM38DD meter.

A test was conducted to evaluate the stability of measurements obtained with slight shifts in the orientation and position of the EM38 and EM38DD meters. At four observation points, each meter was rotated in 45^{o} increments through 360^{o} over a known spot. The results are shown Table 1. At a given point, by rotating the EM38DD meter on the ground surface, values of apparent conductivity varied by as much as 5.1 and 3.0 mS/m in the horizontal and vertical dipole orientations, respectively. At the same points, by rotating the EM38 meter, values of apparent conductivity varied by as much as 12.6 and 7.8 mS/m in the horizontal and vertical dipole orientations, respectively. However, the average standard deviation for measurements obtained with the EM38 meter rotated over each of four observation points was only 1.4 and 1.9 mS/m in the horizontal and vertical dipole orientations, respectively. Similarly, the average standard deviation for measurements obtained with the EM38DD meter rotated over each of four observation points was 1.3 and 1.1 mS/m in the horizontal and vertical dipole orientations, respectively. The modifications of the EM38DD meter has resulted in stable measurements.

Table 1.Stability of EMI Responses for the EM38 and EM38DD Meters

(All values are in mS/m)

EM38 Meter

	VDO	HDO		VDO	HDO		VDO	HDO		VDO	HDO
0	39.5	29.0	0	49.3	34.1	0	49.2	32.2	0	48.6	31.5
45	39.5	29.4	45	49.0	35.1	45	50.1	34.2	45	48.7	32.5
90	35.2	32.1	90	49.3	35.4	90	49.5	33.8	90	48.2	31.6
135	39.8	28.1	135	48.9	35.2	135	49.3	32.8	135	46.7	31.2
180	39.7	29.3	180	49.2	36.8	180	49.5	33.7	180	48.5	31.4
225	39.0	28.6	225	49.5	35.5	225	50.0	33.4	225	48.5	31.5
270	27.4	28.4	270	50.0	36.5	270	49.8	33.6	270	48.0	32.5
315	40.0	35.9	315	48.6	35.3	315	49.4	33.3	315	48.1	31.8
360	39.5	28.9	360	49.4	36.4	360	49.4	33.9	360	48.5	32.6
Average	37.7	30.0	**Average**	49.2	35.6	**Average**	49.6	33.4	**Average**	48.2	31.8
Minimum	27.4	28.1	**Minimum**	48.6	34.1	**Minimum**	49.2	32.2	**Minimum**	46.7	31.2
Maximum	40.0	35.9	**Maximum**	50.0	36.8	**Maximum**	50.1	34.2	**Maximum**	48.7	32.6
SD	4.1	2.5	**SD**	0.4	0.8	**SD**	0.3	0.6	**SD**	0.6	0.5

EM38DD Meter

	VDO	HDO		VDO	HDO		VDO	HDO		VDO	HDO
0	35.1	24.3	0	43.7	29.8	0	43.7	29.3	0	42.5	27.4
45	36.4	23.0	45	44.6	28.8	45	44.5	29.5	45	42.0	27.2
90	36.6	25.5	90	44.9	28.8	90	41.0	31.4	90	41.6	28.2
135	36.8	25.4	135	44.8	28.6	135	45.0	29.2	135	41.1	30.0
180	36.7	25.2	180	44.2	30.2	180	44.7	30.0	180	42.2	29.7
225	36.8	23.9	225	44.9	29.8	225	46.1	28.6	225	44.2	28.2
270	36.8	25.8	270	44.8	30.1	270	44.8	28.4	270	41.9	30.0
315	36.4	25.3	315	44.1	29.0	315	43.9	30.6	315	41.6	29.5
360	36.3	24.5	360	43.6	31.1	360	43.9	29.5	360	41.1	29.0
Average	36.4	24.8	**Average**	44.4	29.6	**Average**	44.2	29.6	**Average**	42.0	28.8
Minimum	35.1	23.0	**Minimum**	43.6	28.6	**Minimum**	41.0	28.4	**Minimum**	41.1	27.2
Maximum	36.8	25.8	**Maximum**	44.9	31.1	**Maximum**	46.1	31.4	**Maximum**	44.2	30.0
SD	0.5	0.9	**SD**	0.5	0.8	**SD**	1.4	0.9	**SD**	0.9	1.1

Comparison of EMI Data:

Data collected at the seventy-two observation points within the two grids with the three different EMI instruments were compared. Strong (r = 0.786 to 0.994) and significant (0.001 level) relations were found among all instruments, dipole orientations, and frequencies. Consistently high correlations (r = 0.93 to 0.99) were found among measurements collected with the GEM300 sensor operating at different frequencies (6030, 9810, and 14790

Hz) and dipole orientations. Lower correlations were found between measurements collected with the GEM300 sensor and the EM38 meter (r= 0.786 to 0.924) or the EM38DD meter (r = 0.855 to 0.957). Correlations were high between measurements collected with the EM38 meter and the EM38DD meter (r = 0.906 to 0.958). The strengths of these correlations suggest that these devices are responding to similar column of earthen materials and have similar observation depths.

Table 2. EMI Response at Seventy-two Observation Points
Correlations between Different Instruments, Dipole Orientations, and Frequencies.[♣]

	6030V	6030H	9810V	9810H	14790V	14790H	EM38V	EM38H	EM38DD-V	EM38DD-H
6030V	1.000	0.979	0.981	0.927	0.993	0.972	0.828	0.786	0.863	0.855
6030H		1.000	0.979	0.964	0.984	0.992	0.881	0.858	0.915	0.910
9810V			1.000	0.970	0.994	0.977	0.885	0.845	0.922	0.887
9810H				1.000	0.954	0.973	0.924	0.908	0.957	0.931
14790V					1.000	0.980	0.864	0.822	0.899	0.878
14790H						1.000	0.884	0.865	0.915	0.916
EM38V							1.000	0.905	0.955	0.906
EM38H								1.000	0.954	0.949
EM38DD-V									1.000	0.958
EM38DD-H										1.000

Results:

EM38 and EM38DD Meters

Basic statistics for EM38 and EM38DD data collected in Grid #1 are listed in Table 3. Apparent conductivity increased and became more variable with depth (measurements obtained in the vertical dipole orientation are higher and more variable than those obtained in the horizontal dipole orientation). With the EM38 meter operated in the horizontal dipole orientation, apparent conductivity averaged 31.2 mS/m with a standard deviation of 8.5. With the EM38DD meter operated in the horizontal dipole orientation, apparent conductivity averaged 26.4 mS/m with a standard deviation of 6.6. A paired t-test (t value of 10.20) revealed a significant difference in the means when these two meters were operated in the horizontal dipole orientation. With the EM38 meter operated in the vertical dipole orientation, apparent conductivity averaged 47.6 mS/m with a standard deviation of 12.0. With the EM38DD meter operated in the vertical dipole orientation, apparent conductivity averaged 46.8 mS/m with a standard deviation of 10.6. A paired t-test (t value of 1.24) revealed no significant difference in means when these two meters were operated in the vertical dipole orientation. The significant difference in the measured means measured with the EM38 and the EM38DD meter in the horizontal dipole orientation was attributed to calibration errors.

Table 3. Basic Statistics
EM38 AND EM38DD Meters
Grid Site #1
(All values are in mS/m)

	EM38-H	EM38-V	EM38DD-H	EM38DD-V
Average	31.2	47.6	26.4	46.8
Minimum	16.8	23.5	14.6	25.8
Maximum	59.0	75.7	47.9	73.5
First	26.7	40.3	22.2	39.8
Second	31.2	49.1	26.5	48.4
Third	35.3	53.5	29.4	52.4

When operated in the horizontal dipole orientation, the correlation coefficient (r) between measurements obtained at the thirty-six observation points with the EM38 meter and measurements obtained with the EM38DD meter was

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[♣] All significant at the .001 level.

0.97 (significant at 0.001 level). When operated in the vertical dipole orientation, the correlation coefficient (r) between measurements obtained at the thirty-six observation points with the EM38 meter and measurements obtained with the EM38DD improved to about 0.96 (significant at 0.001 level).

Figure 1 shows the spatial distribution of apparent conductivity collected with the EM38DD (upper plots) and the EM38 (lower plots) meters. For each meter, the spatial distributions of apparent conductivity collected in the vertical and horizontal dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 5 mS/m. Though exceptions can be noted, spatial patterns are similar in each plot. Relative values are most similar in plots of data collected in the same dipole orientation. A conspicuous band of relatively high apparent conductivity extends across the survey area from the northwest to the southeast corners with the highest conductivity measured in the southeast quarter of each plot. These areas are believed to have soils with higher sodium absorption ratios.

Basic statistics for EM38 and EM38DD data collected in Grid #2 are listed in Table 4. Here also, apparent conductivity increased and became more variable with depth (measurements obtained in the vertical dipole orientation are higher and more variable than those obtained in the horizontal dipole orientation). With the EM38 meter operated in the horizontal dipole orientation, apparent conductivity averaged 30.3 mS/m with a standard deviation of 4.8. With the EM38DD meter operated in the horizontal dipole orientation, apparent conductivity averaged 23.96 mS/m with a standard deviation of 3.98. A paired t-test (t value of 24.93) revealed a significant difference in the means obtained when these two meters were operated in the horizontal dipole orientation. With the EM38 meter operated in the vertical dipole orientation, apparent conductivity averaged 45.8 mS/m with a standard deviation of 6.8. With the EM38DD meter operated in the vertical dipole orientation, apparent conductivity averaged 44.97 mS/m with a standard deviation of 6.23. A paired t-test (t value of 3.2) revealed a significant difference in the values obtained with these two meters in the vertical dipole orientation. This difference was attributed to calibration and placement errors.

Table 4. Basic Statistics
EM38 AND EM38DD Meters
Grid Site #2
(All values are in mS/m)

	EM38-H	**EM38-V**	**EM38DD-H**	**EM38DD-V**
Average	30.3	45.9	24.0	45.0
Minimum	19.6	31.6	16.0	31.8
Maximum	38.0	56.9	30.6	55.3
First Quartile	26.8	41.3	20.8	40.6
Second Quartile	29.6	45.7	23.5	44.0
Third Quartile	34.4	51.3	27.0	50.0

When operated in the horizontal dipole orientation, the correlation coefficient (r) between measurements obtained at the thirty-six observation points with the EM38 meter and measurements obtained with the EM38DD meter was 0.97 (significant at 0.001 level). When operated in the vertical dipole orientation, the correlation coefficient (r) between measurements obtained at the thirty-six observation points with the EM38 meter and measurements obtained with the EM38DD improved to about 0.98 (significant at 0.001 level). Both meters measured similar spatial patterns and trends.

Figure 2 shows the spatial distribution of apparent conductivity collected with the EM38DD (upper plots) and the EM38 (lower plots) meters. For each meter, the spatial distributions of apparent conductivity collected in the vertical and horizontal dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 5 mS/m. Though exceptions can be noted, spatial patterns are similar in each plot. Relative values are most similar in plots of data collected in the same dipole orientation. A conspicuous band of relatively high apparent conductivity extends across the northwest portion of survey area. This band is believed to be associated with soils having higher sodium absorption ratios.

GEM300 Sensor:

As shown in Table 2, strong (r = 0.93 to 0.99) and significant (0.001 level) correlations were found among measurements collected with the GEM300 sensor operating at different frequencies (6030, 9810, and 14790 Hz) and dipole orientations. The strengths of these correlations are believed to reflect the restricted and closely similar observation depths that were obtained at the selected frequencies.

Basic statistics for GEM300 data collected in Grid #1 are listed in Table 5. Measurements of apparent conductivity collected with the GEM300 were comparable with those collected with the EM38DD and the EM38 meters. Apparent conductivity increased and became more variable with depth (measurements obtained in the vertical dipole orientation are higher and more variable than those obtained in the horizontal dipole orientation). With the GEM300 sensor operated in the horizontal dipole orientation, apparent conductivity averaged 30.1, 26.5, and 29.7 mS/m at frequencies of 6030, 9810, and 14790 Hz, respectively. With the GEM300 sensor operated in the vertical dipole orientation, apparent conductivity averaged 56.4, 53.2, and 56.7 mS/m at frequencies of 6030, 9810, and 14790 Hz, respectively.

Table 5. Basic Statistics
GEM300 Survey
Grid Site #1
(All values are in mS/m)

	Frequency (Hz)					
	6030V	**6030H**	**9810V**	**9810H**	**14790V**	**14790H**
Average	56.4	30.1	53.2	26.5	56.7	29.7
Minimum	34.1	16.6	30.5	13.2	33.3	16.4
Maximum	75.5	43.3	73.2	39.4	76.0	43.4
First Quartile	49.0	26.5	45.4	22.4	48.8	25.5
Second Quartile	59.4	31.4	56.3	27.8	59.6	30.9
Third Quartile	63.5	34.4	60.1	30.2	63.7	33.6

Figure 3 shows the spatial distribution of apparent conductivity collected with the GEM300 sensor at different operating frequencies and dipole orientations. Data collected at frequencies of 6030, 9810, and 14790 Hz are shown in the left-hand, middle, and right-hand plots, respectively. Data collected in the vertical and horizontal dipole orientations are shown in the upper and lower plots, respectively. In each plot, the isoline interval is 5 mS/m. Though exceptions can be noted, spatial patterns are similar in each plot. Relative values are most similar in plots of data collected in the same dipole orientation. These spatial patterns are closely similar to patterns obtained with the EM38 and EM38DD meters (see Figure 1). A conspicuous band of relatively higher apparent conductivity extends across the study area from the northwest to the southeast corner. This band is believed to be associated with soils having higher sodium absorption ratios.

Table 6. Basic Statistics
GEM300 Survey
Grid Site #1
(All values are in mS/m)

	6030V	**6030H**	**9810V**	**9810H**	**14790V**	**14790H**
Average	45.9	25.0	46.6	24.2	47.9	24.8
Minimum	32.1	16.0	33.4	15.0	34.1	15.5
Maximum	55.3	31.9	55.5	30.9	57.4	31.6
First Quartile	42.3	23.0	43.3	21.6	44.9	22.2
Second Quartile	46.5	24.8	46.9	24.1	48.3	24.9
Third Quartile	49.1	27.4	50.1	27.3	51.7	27.9

Basic statistics for GEM300 data collected in Grid #2 are listed in Table 6. Measurements of apparent conductivity collected with the GEM300 were comparable with those collected with the EM38DD and the EM38 meters.

Apparent conductivity increased and became more variable with depth (measurements obtained in the vertical dipole orientation are higher and more variable than those obtained in the horizontal dipole orientation). With the GEM300 sensor operated in the horizontal dipole orientation, apparent conductivity averaged 25.0, 24.2, and 24.8 mS/m at frequencies of 6030, 9810, and 14790 Hz, respectively. With the GEM300 sensor operated in the vertical dipole orientation, apparent conductivity averaged 45.9, 46.6, and 47.9 mS/m at frequencies of 6030, 9810, and 14790 Hz, respectively.

Figure 4 shows the spatial distribution of apparent conductivity collected with the GEM300 sensor in Grid #2, at different operating frequencies and dipole orientations. Data collected at frequencies of 6030, 9810, and 14790 Hz are shown in the left-hand, middle, and right-hand plots, respectively. Data collected in the vertical and horizontal dipole orientations are shown in the upper and lower plots, respectively. In each plot, the isoline interval is 5 mS/m. Major spatial patterns are similar in each plot. Relative values are most similar in plots of data collected in the same dipole orientation. Apparent conductivity varies significantly with dipole orientation. Spatial patterns are similar in plots obtained from measurements collected at different frequencies, but identical dipole orientations. These spatial patterns are closely similar to patterns obtained with the EM38 and EM38DD meters (see Figure 2). A conspicuous band of relatively higher apparent conductivity extends across the northwest portion of survey area.

Theories of EMI Operations:

In a theoretical discussion on EMI, McNeill (1980) noted that apparent conductivity is a function of instruments calibration, coil separation, coil orientation, and frequency. Furthermore, McNeill noted that the depth of penetration is dependent on coil separation, coil orientation, and frequency. Larger coil separations and lower frequencies are used to achieve greater depths of penetration. The orientation (either vertical or horizontal) of the transmitter and receiver coil axis with respect to the ground surface affects the response from materials at different depths (McNeill, 1985). In the horizontal dipole orientation, these instruments are more sensitive to near surface materials. In the vertical dipole orientation, these instruments are more sensitive to deeper materials.

For meters developed by Geonics Limited, the depth of penetration is considered to be "*geometry limited*" (McNeill, 1980). With these meters, the use of greater intercoil spacings and lower frequencies will result in greater depths of penetration. Under conditions of low induction numbers, the depth-response functions of meters developed by Geonics Limited are assumed to be independent of soil conductivity. Conditions of low induction numbers are usually satisfied in soils having relatively low conductivities (McNeill, 1980). However, these conditions may not be satisfied in all areas of alkaline soils. de Jong and others (1979) reported that the depth of observation would vary depending on the bulk electrical conductivity of the profiled material(s). Greenhouse and others (1998) have recently commented that the electrical conductivity of soils plays a critical role in the depth of observation. Under conditions of low induction numbers, in the horizontal dipole orientation, 64 percent of the measured response of the EM38 meter comes from the upper 60 cm of the soil profile and 20 percent comes from depths greater than 120 cm (McKenzie et al., 1997; McNeill, 1980; and Wollenhaupt et al., 1986). In the vertical dipole orientation, 51 percent of the measured response comes from the upper 90 cm of the soil profile and 27 percent comes from depths greater than 180 cm (McKenzie et al., 1997; McNeill, 1980; and Wollenhaupt et al., 1986).

With the GEM300 sensor, the depth of penetration is considered "*skin depth*" limited rather than "*geometry limited*" (Won, 1980 and 1983, Won et al., 1996). Skin depth represents the maximum depth of penetration for an EMI instrument operating at a specific frequency and sounding a medium of known conductivity. Penetration depth or skin depth is inversely proportional to frequency (Won et al., 1996). Lower frequency signals have longer periods of oscillation and loose energy less rapidly than higher frequency signals. As a consequence, lower frequency signals travel farther through conductive mediums than higher frequency signals, and greater depths of penetration can be achieved by decreasing the frequency. At a given frequency, the depth of penetration is greater in a low conductivity soil than in a high conductivity soil.

The skin depth (depth of penetration) can be estimated for the GEM300 sensor using the following formula (McNeill, 1996):

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

Where s is the ground conductivity (mS/m) and f is the frequency (kHz).

At the DuQuoin study site, with the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 51.2, 49.9, and 52.3 mS/m at frequencies of 6,030, 9,810, and 14,790, respectively. Using equation [1], the estimated skin depths are about 28 m at 6,030 Hz, 22 m at 9,810 Hz, and 18 m at 14,790 Hz. However, results from this and other investigations suggest that these skin depths are unrealistic and pointless.

For each EMI instrument, response is not uniform with depth; surface and shallow layers contribute more to the overall response than deeper layers. Greenhouse and others (1998) noted that the electrical conductivity of soils plays a critical role in defining the depth of penetration that can be obtained with EMI. Furthermore, these authors noted that EMI instruments do not penetrate a fixed distance under all circumstances. The *depth of observation* is defined as the depth that contributes the largest part to the total EMI response measured on the ground surface. Although contributions to the measured response come from all depths within the effective depth of penetration or skin depth, the contribution from the *depth of observation* is the largest (Roy and Apparao, 1971). As noted by Roy and Apparao (1971), for any EMI instrument, the depth of observation is a good deal shallower than is generally assumed or reported. In alkaline soils, the high conductivity of the surface and near surface horizons contributes greatly to the depth-weighted response of EMI instruments and limits the depth of observation. In areas of moderately and highly conductive soils, manufacturer's specifications or the skin depth estimations may provide a fairly accurate measure of the depth of penetration, but grossly overestimates the depth of observation.

Doolittle and others (2000) used the GEM300 sensor in an area of saline soils with averaged apparent conductivities ranging from about 154 to 158 mS/m and from about 98 to 104 mS/m in the vertical and horizontal dipole orientations, respectively. They noted that, in saline soils, the use of multiple frequencies provided little additional information and did not improve interpretations. Similar conclusions can be drawn from this study of alkaline soils with averaged apparent conductivity that ranged from about 46 to 48 mS/m and from about 24 to 25 mS/m in the vertical and horizontal dipole orientations, respectively. At the DuQuoin study site, multifrequency sounding with the GEM300 sensor was found to provide no additional information and did not improve interpretations over single frequency sounding.

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EMI SURVEY
IN AN AREA OF
HOYLETON - DARMSTADT SILT LOAMS
GRID #1

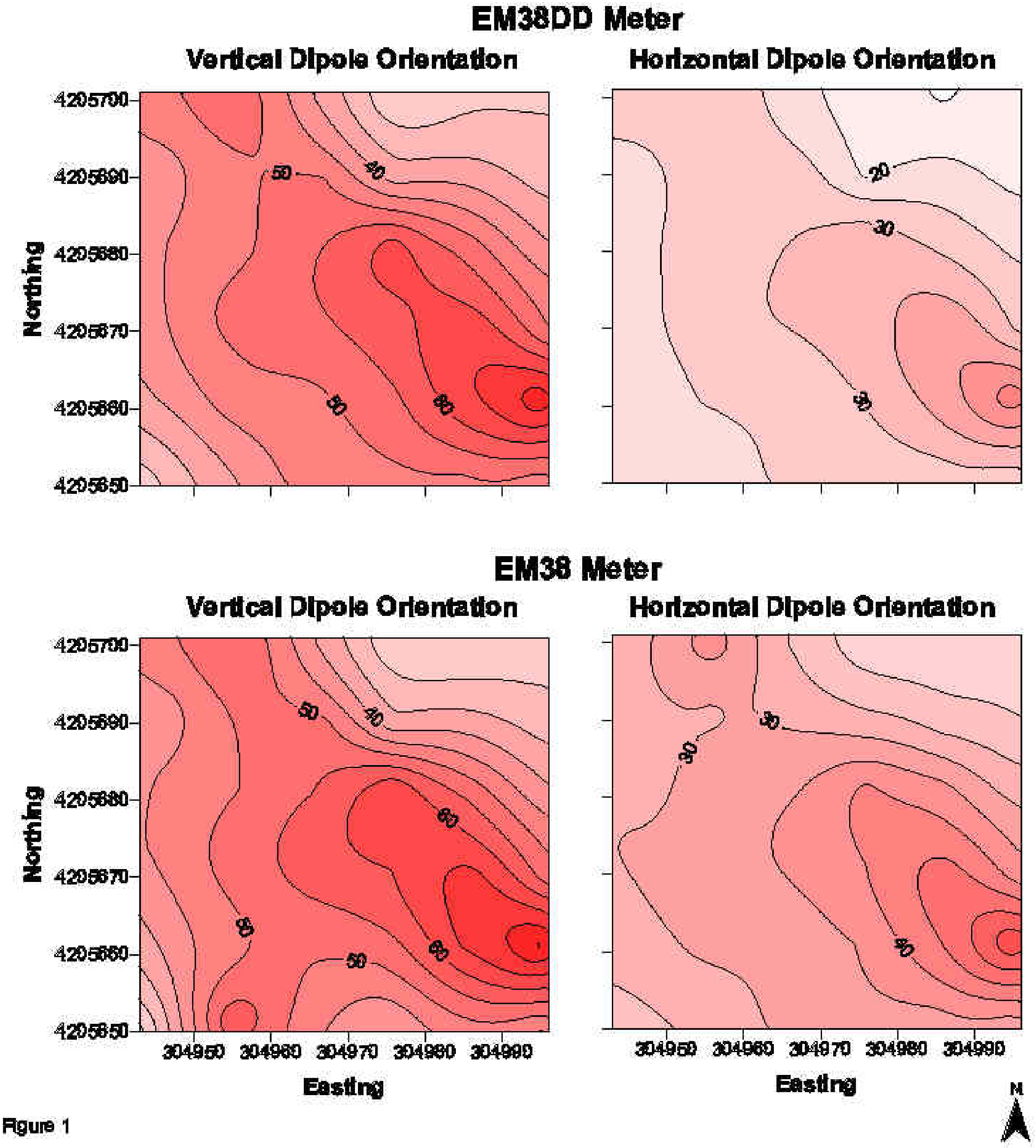

Figure 1

EMI SURVEY
IN AN AREA OF
HOYLETON - DARMSTADT SILT LOAMS
GRID #2

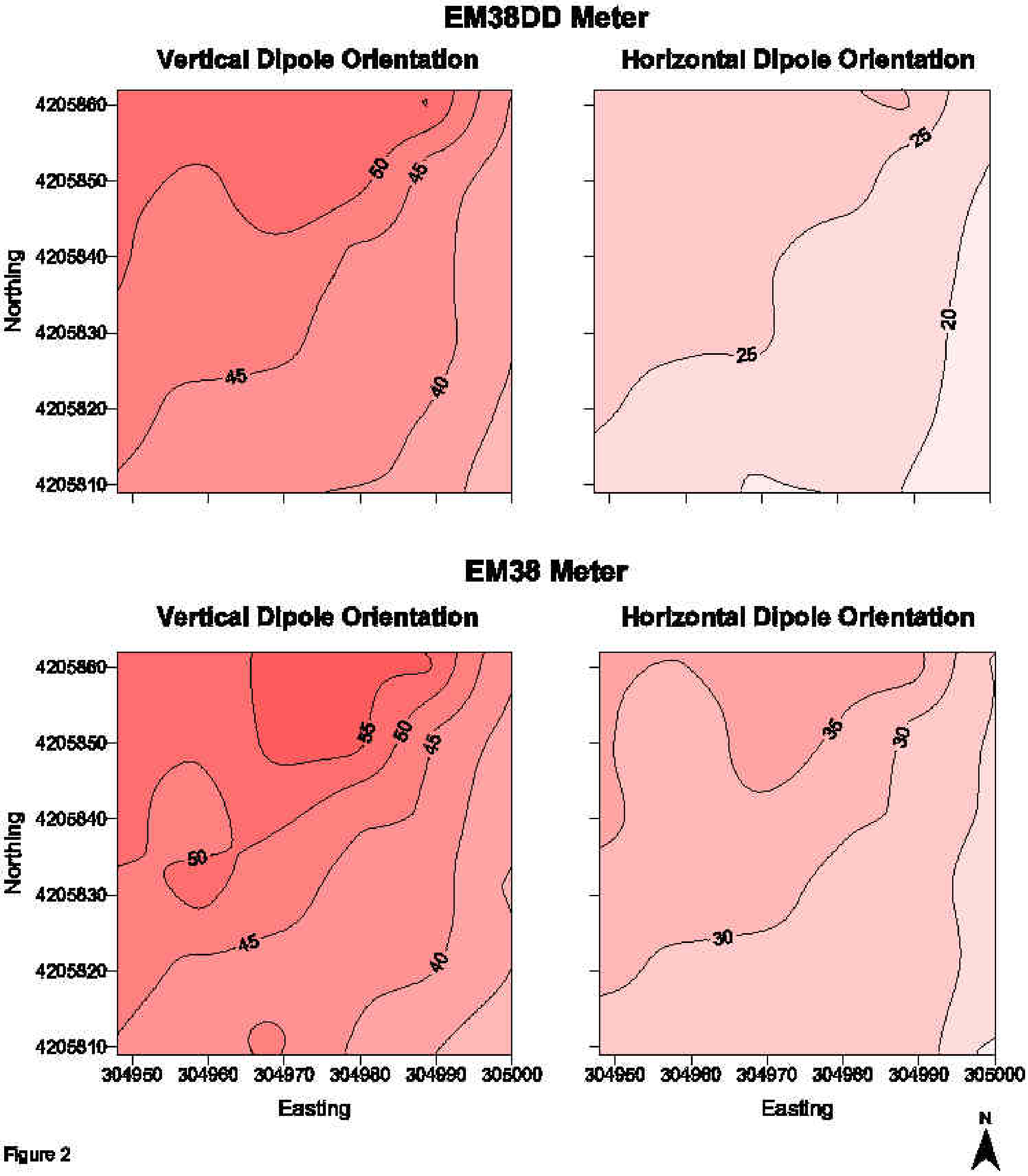

Figure 2

EMI SURVEY
IN AN AREA OF
HOYLETON - DARMSTADT SILT LOAMS
GRID #1 - GEM300 SENSOR

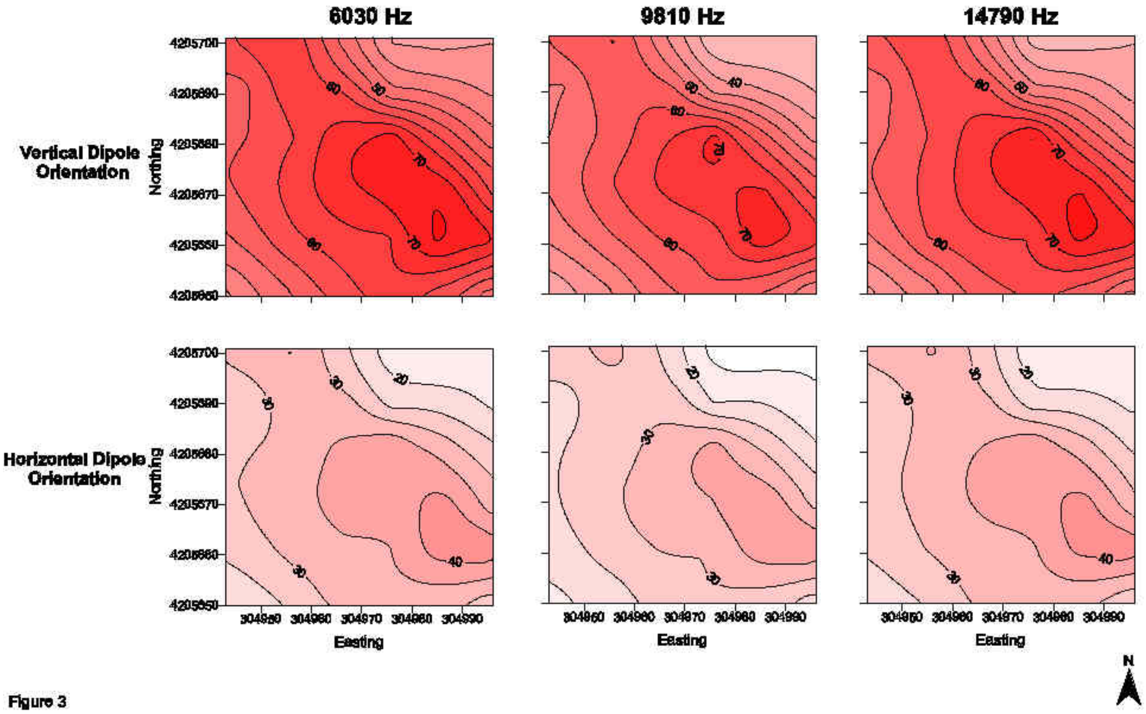

Figure 3

EMI SURVEY
IN AN AREA OF
HOYLETON - DARMSTADT SILT LOAMS
GRID #2 - GEM300 SENSOR

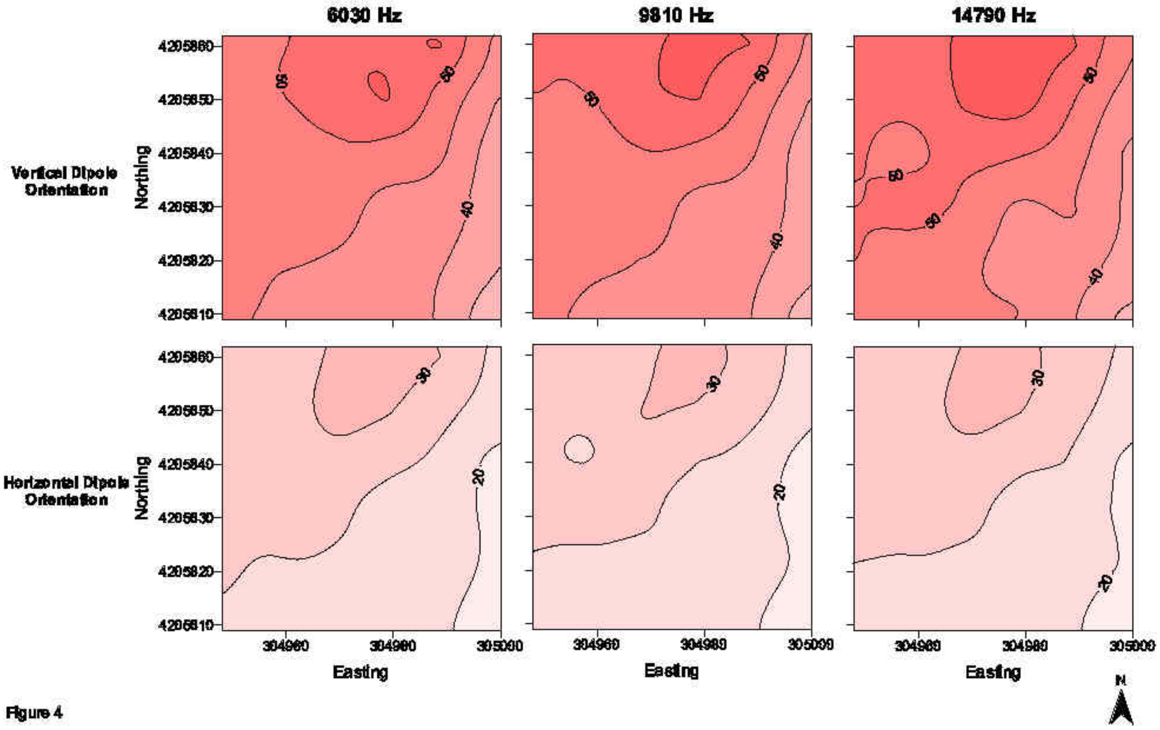

Figure 4