**United States Department of Agriculture**

**Natural Resources Conservation Service**

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**Subject:** SOIL -- Geophysical Assistance

**Date:** 21 September 2000

**To:** M. Denise Doetzer
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1606 Santa Rosa Road, Suite 209
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**Purpose:**
Ground-penetrating radar (GPR) and electromagnetic induction (EMI) methods were used to characterize soils on mine benches in Buchanan County, VA.

**Participants:**
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA
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Glenn Graham, District Conservationist, USDA-NRCS, Clintwood, VA
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Dave Wagner, Soil Survey Project Leader, USDA-NRCS, Vansant, VA
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**Activities:**
All field activities were completed during the period of 12-14 September 2000.

**Study Areas:**
The principal study areas were located at an active mining site near the Grundy Airport (Motivation Mine) and in an area of Kaymine soil near the town of Lee Master. The very deep, well drained Kaymine soil formed in nonacid regolith from the surface mining of coal. The regolith consists of partially weathered fine earth and rock fragments. The rock fragments are principally siltstone and sandstone with minor amounts of shale and coal. Kaymine is a member of the loamy-skeletal, mixed, active, nonacid, mesic Typic Udorthents.

**Conclusions:**

1. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations are interpretive and do not substitute for direct ground-truth observations (soil borings). The use of geophysical methods can reduce the number of coring observations, direct their placement, and supplement their interpretations.

2. Because of restricted observation depths and low interpretative quality, ground-penetrating radar was found to be an inappropriate tool to characterized the selected areas of mixed mine spoil materials. However, in regolith composed predominantly of sandstone (Fiveblock series), the use of GPR may be more appropriate and beneficial to the soil survey project.

3. Based on results from the Lee Master site, EMI appears to be a promising tool for the characterization and mapping of areas of mine spoil. At the Lee Master site, in areas of Kaymine soil, EMI successfully mapped and

discriminated a "low" from a "high" fertility area. The "low" fertility area had significantly lower values of apparent conductivity than the "high" fertility area. In addition, areas dominated by sandstone had lower apparent conductivity than areas predominated by siltstone and shale. These relations and the use of EMI should be investigated more fully by researchers knowledgeable of mine spoil areas and supported by chemical and mineralogical characterizations.

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

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
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**Equipment:**
The radar unit is the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc.[1] Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. A 12-volt battery powered the system. This unit is backpack portable and, with an antenna, requires two people to operate. The 120, 200, and 400 MHz antennas were used in this study. Scanning times ranged 60 or 100 nanoseconds (ns); the scanning rate was 32 scan/second. Radar data were stored on disc and printed in the field on a model T-104 printer.

The electromagnetic induction instrument used in this study was the GEM300 sensor. The GEM300 sensor is manufactured by Geophysical Survey Systems, Inc.[1] Won and others (1996) have described the use and operation for the GEM300 sensor. The GEM300 sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed intercoil spacing of 1.3 m. The sensor records both in-phase and quadrature measurements. Output is the mutual coupling ratio in parts per million or apparent conductivity (mS/m).

The coordinates of each observation points were obtained with Rockwell Precision Lightweight GPS Receivers (PLGR)[1]. The receiver was operated in the continuous mode. The mixed satellite mode was used. The Universal Transverse Mercator (UTM) coordinate system was used. Horizontal datum was the North American 1983. The horizontal zone was 17S. Horizontal units were expressed in meters.

To help summarize the results of this study, the SURFER7 for Windows program, developed by Golden Software, Inc.,[1] was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search.

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

**Field Procedures:**
Radar surveys were completed at the Motivation Mine and the Lee Master sites. The Motivation Mine is an active mountain top removal site. Radar traverses were conducted across a mine bench and a more sloping area that had been restored to original contours. The Lee Master site is a reclaimed mine site. The Lee Master site has been mapped as map unit 501C (Kaymine soil). Soils at this site are very deep to restricting layer or rock. This site was divided into a "low" and a "high" fertility site based on observed plant growth. Both sites are being used for hay.

Traverse lines were established at each site. Survey flags were inserted in the ground at intervals of about 5 to 20 feet along each traverse line (only one interval per line) and served as observation points. Pulling the antenna across selected areas completed radar surveys. At each observation point, the radar operator impressed a dashed, vertical line on the radar profile. This line identified an observation point (flagged reference point) on the radar record. Although, GPR provides a continuous profile of subsurface conditions, interpretations were restricted to observation points.

Electromagnetic induction surveys were conducted at the Lee Master site. Random traverses were made across both a "low" and "high fertility" areas of this site. Traverses were made in accessible areas away from potential interference from fence lines and farm structures. However, both sites contained buried mining equipment and metallic debris that produced anomalous apparent conductivity readings. Wherever possible, the observation point was relocated to avoid these sources of interference. While most traverses were located in hay land, several traverse were conducted in wooded or overgrown, bushy areas. Electromagnetic induction surveys of the sites were conducted with the GEM300 sensor in the manual mode. Measurements were taken with the GEM300 sensor held at hip-height in the horizontal and vertical dipole orientations. In-phase, quadrature phase, and conductivity data were recorded at frequencies of 14790 and 19050 Hz. Along each traverse line, measurements were taken at a distance of about 15 paces. This process provided a total of 223 and 100 observation points within the "low" and "high fertility" areas, respectively. The coordinates of each observation point were obtained with a Rockwell PLGR.

Within the "high fertility" site, a 100 by 100 ft grid was established with a Rockwell PLGR. Eleven survey lines were established across the study site at intervals of 10 ft. The length of each survey line was 100 ft. The GEM300 sensor was operated in the continuous mode. The location of each observation point recorded with the GEM300 sensor was processed and adjusted by the MAGMAP96 software program.[2] The GEM300 sensor was configured to record an observation every 2 seconds. Walking at a uniform pace along each of the eleven parallel survey lines resulted in 288 observations. Separate surveys were completed with the sensor held in either the horizontal or vertical dipole orientation. Measurements were taken with the GEM300 sensor held at hip-height. In-phase, quadrature phase, and conductivity data were recorded at frequencies of 14790 and 19050 Hz.

**GPR:**

Background:
Ground-penetrating radar has been used extensively to locate potential hazards in advance of underground mining (Cook, 1973, Coon et al., 1981, Pittman et al. 1984, and Molinda et al., 1996). However, in these studies, results of radar surveys varied with the electrical properties of the scanned lithology. Recently, GPR has been used in surface mined areas of South Africa (Paterson and Laker, 1999, Paterson, 2000). Reclaimed materials often have a sufficiently high conductivity to cause the rapid attenuation of the radar signal and limit observation depths. Radar profiles from surface mined areas are typically noisy and difficult to interpret.

Calibration of GPR
Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from the antenna to an interface (e.g., soil horizon, fracture, 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 the following equation (Morey, 1974):

$$v = 2d/t \qquad [1]$$

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

The velocity of propagation is principally affected by the dielectric permittivity (e) of the profiled material(s) according to the equation:

$$e = (c/v)^2 \qquad [2]$$

Where c is the velocity of propagation in a vacuum (0.3 m/nanosecond). Velocity is expressed in meters per nanosecond (ns). A nanosecond is one billionth of a second. The amount and physical state of water (temperature dependent) have the greatest effect on the dielectric constant of a material.

At the Motivation Mine site, the depth to bedrock was measured (0.91 and 0.30 m) at two observation points. Based on these depths and equation [1], the velocity of propagation was estimated to be about 0.067 m/ns through the mine spoil materials. Using equation [2], the dielectric permittivity was 20.

Results:

The depth of penetration was severely restricted (<70 cm), image quality was generally poor, and interpretations ambiguous in most investigated reclaimed areas. The poor response of GPR was attributed to high signal loss in the mixed regolith from surface mining. These materials were moist, compacted, and consisted of a mixture of crushed sandstone, shale, siltstone, and coal. Shale, siltstone and coal are considered high loss materials for GPR.

Figure 1 is a representative radar profile from the Lee Master site. This profile was obtained with the 200 MHz antenna. The segmented vertical lines at the top of the radar profile are event markers that represent observation point spaced about 3 m apart. In Figure 1, the vertical scale is in meters and is shown along the left margin. A scanning time of 60 ns was used in this study. Using equation [1], a scanning time of 60 ns, and a propagation velocity of 0.067 m/ns, the maximum depth of penetration was estimated to be about 2 m. However, interpretable reflections are restricted to the upper 70 cm of the profile. These reflections represent layers of weathered fine earth and rock fragments. As these reflections are discontinuous, numerous soil borings would be required to confirm their identities. Below 70 cm, high levels of background noise mask desired reflections. The use of image processing programs will improve imagery only slightly and may not warrant the extra time and costs. Even after processing, data will remain ambiguous and, because of the restricted penetration depth, the bedrock surface will remain undefined.

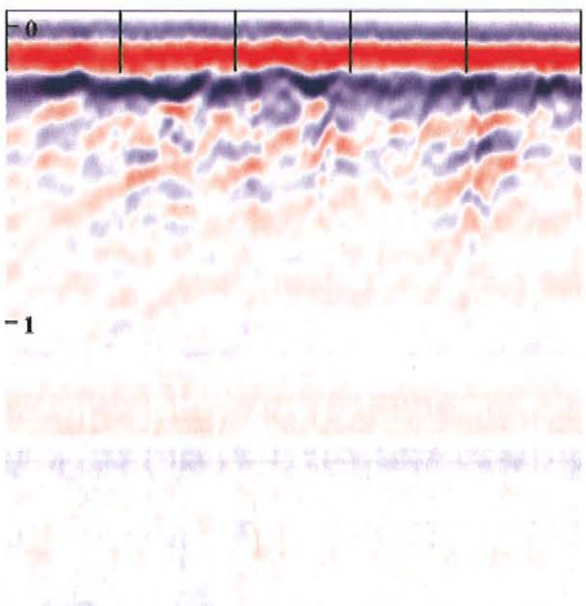


Figure 1 – Representative radar profile from an area of Kaymine soil.

The most favorable results were obtained in a non-compacted embankment composed predominantly of crushed, well-oxidized (brown color) sandstone at the Motivation Mine Site (see Figure 2). In Figure 2, the segmented vertical lines at the top of the radar profile are event markers that represent observation point spaced about 5 m apart. A scanning time of 70 ns was used in this study. Using equation [1], a scanning time of 70 ns, and a propagation velocity of 0.067 m/ns, the maximum depth of observation was estimated to be about 2.3 m. The bedrock surface is apparent in this figure and has been highlighted with a dark line. Beneath this interface, the radar signal is severely attenuated and little further information can be discerned. Numerous discontinuous planar reflectors are evident in the regolith. In addition, point reflectors, presumably representing rock fragments of varying sizes, are also apparent in these materials. While the depth of penetration and the amount of subsurface information that can be gleaned from Figure 2 is considered good, these results are considered an exception to an otherwise dismal performance of GPR in areas of regolith from surface mines. Based on the poor results of this survey, ground-penetrating radar is not considered an appropriate geophysical tool for the investigations of most mixed regolith from surface mines.

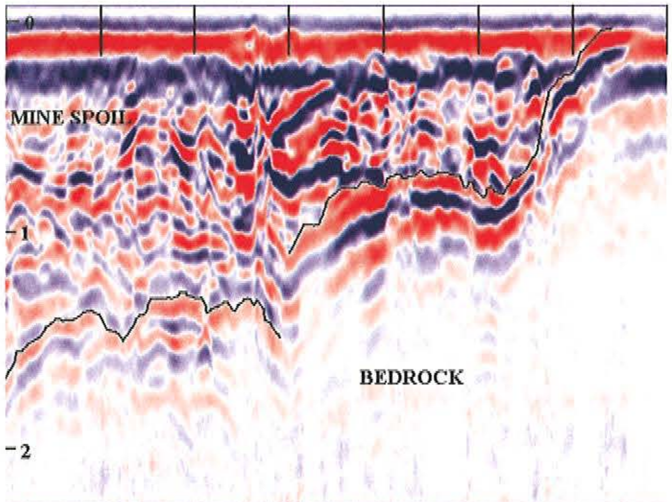


Figure 2 – Representative radar profile from an embankment area at the Motivation Mine.

## EMI:

Background:

At surface mine sites, EMI has been used mostly to map the extent of acid leachate and detect sources of ground water contamination (King and Sartorelli, 1991, and Ladwig, 1982). No reference to the use of EMI for mapping the depth to bedrock or characterizing the nature of the reclaimed soil materials is known.

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific penetration depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the volumetric water content, type and concentration of ions in solution, temperature and phase of the soil water, and amount and type of clays in the soil matrix (McNeill, 1980). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction measures vertical and lateral variations in apparent electrical conductivity. Values of apparent conductivity are seldom diagnostic in themselves, but lateral and vertical variations in these measurements can be used to infer changes in earthen materials. Interpretations are based on the identification of spatial patterns within data sets. To assist interpretations, computer simulations are normally used

Depth of Observation:

With the GEM300 sensor, the depth of penetration or the "skin depth" is estimated 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). Within the "high" fertility area of the Lee Master site, with the GEM300 sensor held in the vertical dipole orientation, apparent conductivity averaged 17.6 and 14.9 at frequencies of 14790, and 19050 Hz, respectively. Based on equation [1], the selected frequencies and these averaged conductivities, the estimated skin depths were about 31 m at 14790 Hz, and 30 m at 19050 Hz. Within the defined skin depth, earthen materials from all depths contribute, in varying degrees, to the measured response. With increasing depth, the relative contribution from various depth layers passes through a maximum. While the induced magnetic fields may achieve these estimated skin depths, the strengths of the response diminish with increasing depth and are too weak to be sensed by the GEM300 sensor.

The *depth of observation* is often defined as the depth that contributes the most to the total EMI response measured on the ground surface. Although contributions to the measured response come from all depths, the contribution from the *depth of observation* is the largest (Roy and Apparao, 1971). As noted by Roy and Apparao (1971), for any system, the depth of observation is a good deal shallower than is generally assumed or reported. As no depth-weighting functions are presently available for the GEM300 sensor, it is unclear what depth is providing the maximum response.

In many EMI studies, negative conductivity values are removed by electronic nulling of the data set. The negative offset was not taken out of the GEM300 data. As a consequence, negative apparent conductivity values appear in the data and simulated plots. Negative values are also associated with "metallic" cultural features such as buried mining equipment and metallic debris.

Results:

Figures 3 and 4 show the results of the survey conducted with the GEM300 sensor within the "low fertility" area. The spatial distributions of apparent conductivity collected at frequencies of 14790 and 19050 Hz are shown in figures 3 and 4 respectively. In each figure, measurements of apparent conductivity obtained in the shallower-sensing horizontal and deeper-sensing vertical dipole orientations are shown in the upper and lower plots, respectively. The isoline interval is 5 mS/m. In Figure 3, the locations of the 100 observation points recorded with the GEM300 sensor are shown in the upper plot.

Figures 5 and 6 show the results of the survey conducted with the GEM300 sensor within the "high fertility" area. The spatial distributions of apparent conductivity collected at frequencies of 14790 and 19050 Hz are shown in figures 5 and 6 respectively. In each figure, measurements of apparent conductivity obtained in the shallower-sensing horizontal and deeper-sensing vertical dipole orientations are shown in the upper and lower plots, respectively. The isoline interval is 5 mS/m. In each figure, the locations of the 223 observation points recorded with the GEM300 sensor are shown in the upper plot. Also shown in each plot is the location of the site of a more detailed EMI survey (see figures 7 and 8).

**Table 1**
**Basic Statistics for EMI Survey of**
**The "High" Fertility Area**
**Of the Lee Master Site**

All measurements are in mS/m

| | 14790v | 14790H | 19050V | 19050H |
|---|---|---|---|---|
| **Average** | 17.6 | 11.7 | 14.9 | 10.2 |
| **Minimum** | -96.5 | -182.7 | -131.4 | -272.4 |
| **Maximum** | 117.9 | 33.9 | 64.9 | 22.2 |
| **First** | 15.7 | 11.0 | 14.3 | 9.8 |
| **Second** | 18.5 | 12.7 | 17.1 | 11.7 |
| **Third** | 20.7 | 14.5 | 19.5 | 13.4 |

Tables 1 and 2 summarize the results of this survey. Basic statistics for the EMI survey that was conducted in the "high" fertility area of the Lee Master site are shown in Table 1. As shown in figures 5 and 6, values of apparent conductivity were variable across the site. Extreme positive and negative values are attributed to the presence of buried mining equipment and metallic debris. For each frequency, average and medium values of apparent conductivity were higher in the deeper-sensing vertical dipole orientation than in the shallower-sensing horizontal dipole orientation. In addition, apparent conductivity increased with decreasing frequency. Both of these trends suggest that apparent conductivity increases with increasing observation depths. At a frequency of 19050 Hz, apparent conductivity averaged 14.9 and 10.2 mS/m in the vertical and horizontal dipole orientation, respectively. At a frequency of 19050 Hz, one half the observations had values of apparent conductivity between 14.3 and 19.5 mS/m in the vertical dipole orientation, and between 9.8 and 13.4 mS/m in the horizontal dipole orientation. At a frequency of 14790 Hz, apparent conductivity averaged 17.6 and 11.7 mS/m in the vertical and horizontal dipole orientation, respectively. At a frequency of 14790 Hz, one half the observations had values of apparent conductivity between 15.7 and 20.7 mS/m in the vertical dipole orientation, and between 11.0 and 14.5 mS/m in the horizontal dipole orientation.

Basic statistics for the EMI survey that was conducted in the "low" fertility area of the Lee Master site are shown in Table 2. Extreme positive and negative values are attributed to the presence of buried mining equipment and metallic debris. Values of apparent conductivity were lower in the "low" fertility than in the "high" fertility area of the Lee Master site. Within the "low" fertility area, for each frequency, average values of apparent conductivity were slightly higher in the deeper-sensing vertical dipole orientation than in the shallower sensing horizontal dipole orientation. In addition, apparent conductivity increased with decreasing frequency. Once again, these trends suggest that apparent conductivity increases with increasing observation depths. At a frequency of 19050 Hz, apparent conductivity averaged 6.2 and 5.6 mS/m in the vertical and horizontal dipole orientation, respectively. At a frequency of 19050 Hz, one half the observations had values of apparent conductivity between 1.1 and 12.0 mS/m in the vertical dipole orientation, and between 1.6 and 10.1 mS/m in the horizontal dipole orientation. At a frequency of 14790 Hz, apparent conductivity averaged 8.7 and 7.5 mS/m in the vertical and horizontal dipole orientation, respectively. At a frequency of 14790 Hz, one half the observations had values of apparent conductivity between 4.3 and 13.1 mS/m in the vertical dipole orientation, and between 4.5 and 11.5 mS/m in the horizontal dipole orientation.

**Table 2**
**Basic Statistics for EMI Survey of**
**The "Low" Fertility Area**
**Of the Lee Master Site**

All measurements are in mS/m

| | 14790v | 14790H | 19050V | 19050H |
|---|---|---|---|---|
| **Average** | 8.7 | 7.5 | 6.2 | 5.6 |
| Minimum | -9.6 | -21.3 | -18.9 | -31.7 |
| **Maximum** | 29.5 | 26.5 | 32.1 | 29.0 |
| **First** | 4.3 | 4.5 | 1.1 | 1.6 |
| **Second** | 9.7 | 7.8 | 7.6 | 6.4 |
| **Third** | 13.1 | 11.3 | 12.0 | 10.1 |

Values of apparent conductivity were lower in the "low" fertility than in the "high" fertility area of the Lee Master site. These differences are believed to reflect differences in the composition of the underlying mine spoil materials. Lower values of apparent conductivity are associated with a greater amount of materials derived from sandstone. Higher values of apparent conductivity are associated with a greater amount of materials derived from siltstone and shale. Shale and siltstone are more conductive than sandstone. Palacky (1987) observed conductivity ranges 1 to 35 mS/m for sandstone and 40 to 425 mS/m for shale. To confirm these observations and the effect of the regolith composition on apparent conductivity, several additional sites were visited. These sites were characterized as being predominantly underlain by either debris from sandstone (6 observations) or siltstone and shale (24 observations). Sites predominated by sandstone had average conductivity (vertical dipole orientation) of 11.43 and 10.57 mS/m at frequencies of 14790 Hz and 19050 Hz, respectively. Values of apparent conductivity ranged from 7.8 to 14.8 mS/m and from 7.9 to 14.3 mS/m at frequencies of 14790 Hz and 19050 Hz, respectively. Sites predominated by siltstone and shale had average conductivity (vertical dipole orientation) of 22.14 and 21.20 mS/m at frequencies of 14790 Hz and 19050 Hz, respectively. Values of apparent conductivity ranged from 11.8 to 30.6 mS/m and from 9.6 to 30.5 mS/m at frequencies of 14790 Hz and 19050 Hz, respectively. An analysis of variance was performed on the two data sets (sandstone versus siltstone and shale) and a significant difference in variance was found (F value of 22.132, significant at the 0.001 level) between the two groups. With additional work, the predominant composition of mixed mine spoil materials may be estimated and map with EMI.

A small 100 by 100 foot area within the "High" fertility area of the Lee Master site was more intensively surveyed with the GEM300 sensor. For this survey the sensor was operated in the continuous mode and recorded 288 observations. Figures 7 and 8 show the spatial patterns of apparent conductivity that resulted from this more intensive survey. In each plot the isoline interval is 5 mS/m. In general, conductivity increased towards the upper portion (north) of each plot. Comparing figures 5 and 6 with figures 7 and 8, we see that the smaller scale map has described a greater variability of apparent conductivity over short distances. The basic statistics for this survey are shown in Table 3.

**Table 3**
**Basic Statistics for EMI Survey for the detailed Grid located within the "High" Fertility Area of the Lee Master Site**

All measurements are in mS/m

| | 14790V | 14790H | 19050V | 19050H |
|---|---|---|---|---|
| **Average** | 19.6 | 12.8 | 17.4 | 11.6 |
| **Minimum** | -1.5 | -13.4 | -12.2 | -16.4 |
| **Maximum** | 117.9 | 33.9 | 64.9 | 22.2 |
| **First** | 15.9 | 11.1 | 14.6 | 9.9 |
| **Second** | 18.5 | 12.7 | 17.2 | 11.8 |
| **Third** | 20.7 | 14.5 | 19.5 | 13.5 |

**References:**

Cook, J. C. 1973. Radar exploration through rock in advance of mining. Transactions of the Society of Mining Engineers. 254: 140-254.

Coon, J. B., J. C. Fowler, and C. J. Schafers. 1981. Experimental uses of short pulse radar in coal seams. Geophysics. 46(8): 1163-1168.

Daniels, D. J. 1996. Surface-Penetrating Radar. The Institute of Electrical Engineers, London, United Kingdom. 300 p.

Doolittle, J. A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. pp. 11-32. In: Reybold, W. U. and G. W. Peterson (eds.) Soil Survey Techniques, Soil Science Society of America. Special Publication No. 20. p. 98

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

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

King, A. and A. N. Sartorelli. 1991. Theory and application of electromagnetic geophysics to minesite contaminant mapping. Paper No. 160. 93 Annual Meeting of the Canadian Institute of Mining and Metallurgy. April 28 – May 2, 1991. Vancouver. British Columbia.

Ladwig, K. J. 1982. Electromagnetic induction methods for monitoring acid mine drainage. Ground Water Monitoring Review III: 46-52.

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

McNeill, J. D. 1996. Why doesn't Geonics Limited build a multifrequency EM31 or EM38 meter? Technical Note TN-30. Geonics Limited, Mississauga, Ontario. 5 p.

Molinda, G. M., W. D. Monaghan, G. L. Mowrey, and G. F. Persetic. 1996. Using ground penetrating radar for roof hazard detection in underground mines. US Dept. of Energy. Report of Investigation 9625. 14 p.

Morey, R. M. 1974. Continuous subsurface profiling by impulse radar. pp. 212-232. In: Proceedings, ASCE Engineering Foundation Conference on Subsurface Exploration for Underground Excavations and Heavy Construction, held at Henniker, New Hampshire. Aug. 11-16, 1974.

Palacky, G. J. 1987. Clay mapping using electromagnetic methods. First Break 5(8): 295-306.

Paterson, D. G. 2000. Mapping rehabilitated mine spoils in South Africa using GPR. 298-302 pp. IN: (Noon, D. ed.) Proceedings Eight International Conference on Ground-Penetrating Radar. May 23 to 26, 2000, Goldcoast, Queenland, Australia. The University of Queensland. 908 p.

Paterson, D, G., and M. C. Laker. 1999. Using ground-penetrating radar to investigate spoil layers in rehabilitated mine spoils. S. Afr. J. Plant Soil. 16 (3): 131-134.

Pittman, W. E., R. H. Church, W. E. Webb, and J. T. McLendon. 1984. Ground penetrating radar; A review of its application in the mining industry. USDI-Bureau of Mines. Bureau of Mines Information Circular 8964. 23 p.

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

Roy, A. and A. Apparao. 1971. Depth of investigation in direct current methods. Geophysics 36:943-959.

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

# EMI SURVEY OF LEE MASTER SITE, VA
# LOW FERTILITY AREA
# GEM300 SENSOR
# 14790 Hz

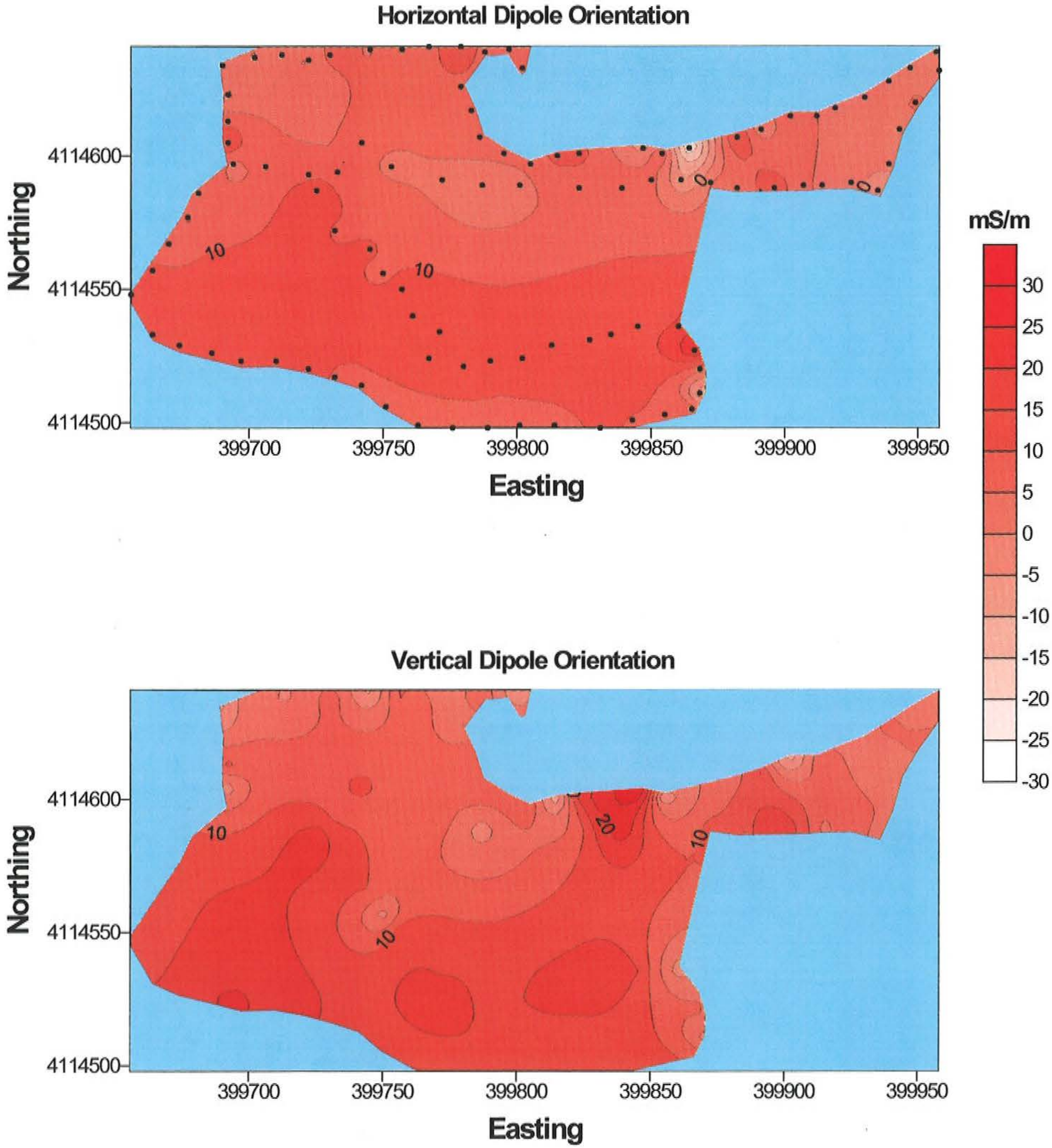


Figure 3

# EMI SURVEY OF LEE MASTER SITE, VA
# LOW FERTILITY AREA
# GEM300 SENSOR
# 19050 Hz

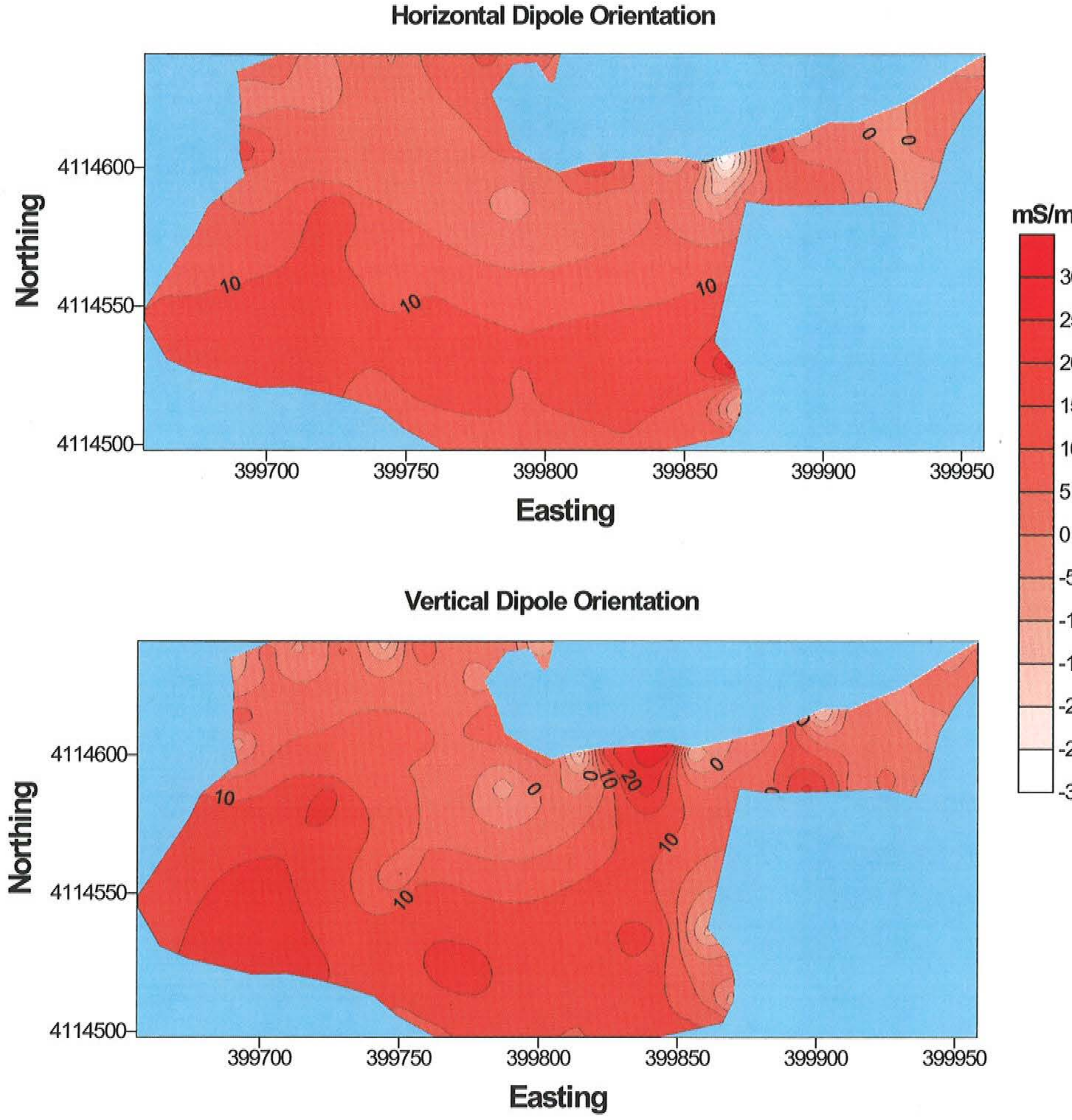


Figure 4

# EMI SURVEY OF LEE MASTER SITE, VA
# HIGH FERTILITY AREA
# GEM300 SENSOR
# 14790 Hz

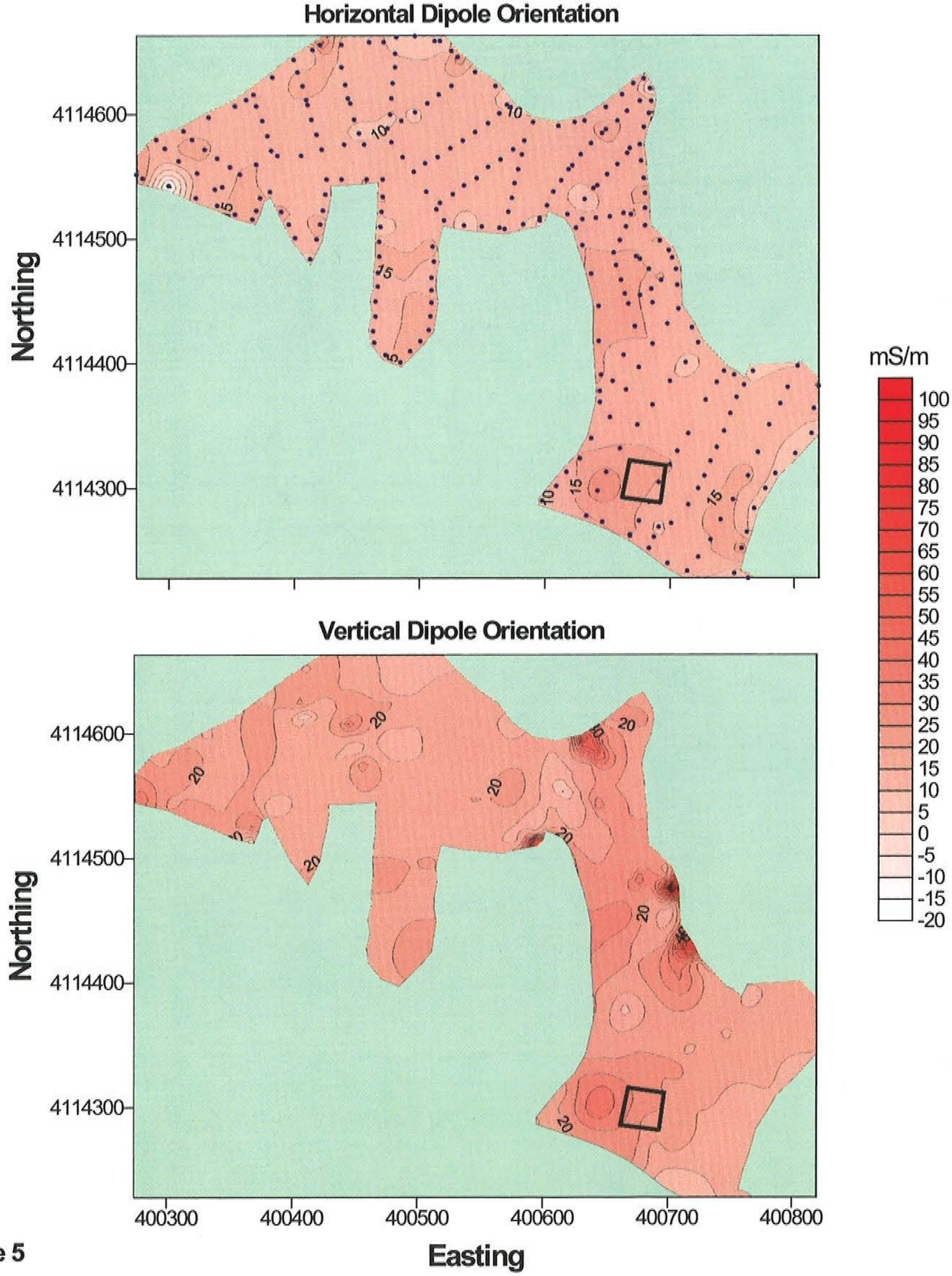


Figure 5

# EMI SURVEY OF LEE MASTER SITE, VA
# HIGH FERTILITY AREA
# GEM300 SENSOR
# 19050 Hz

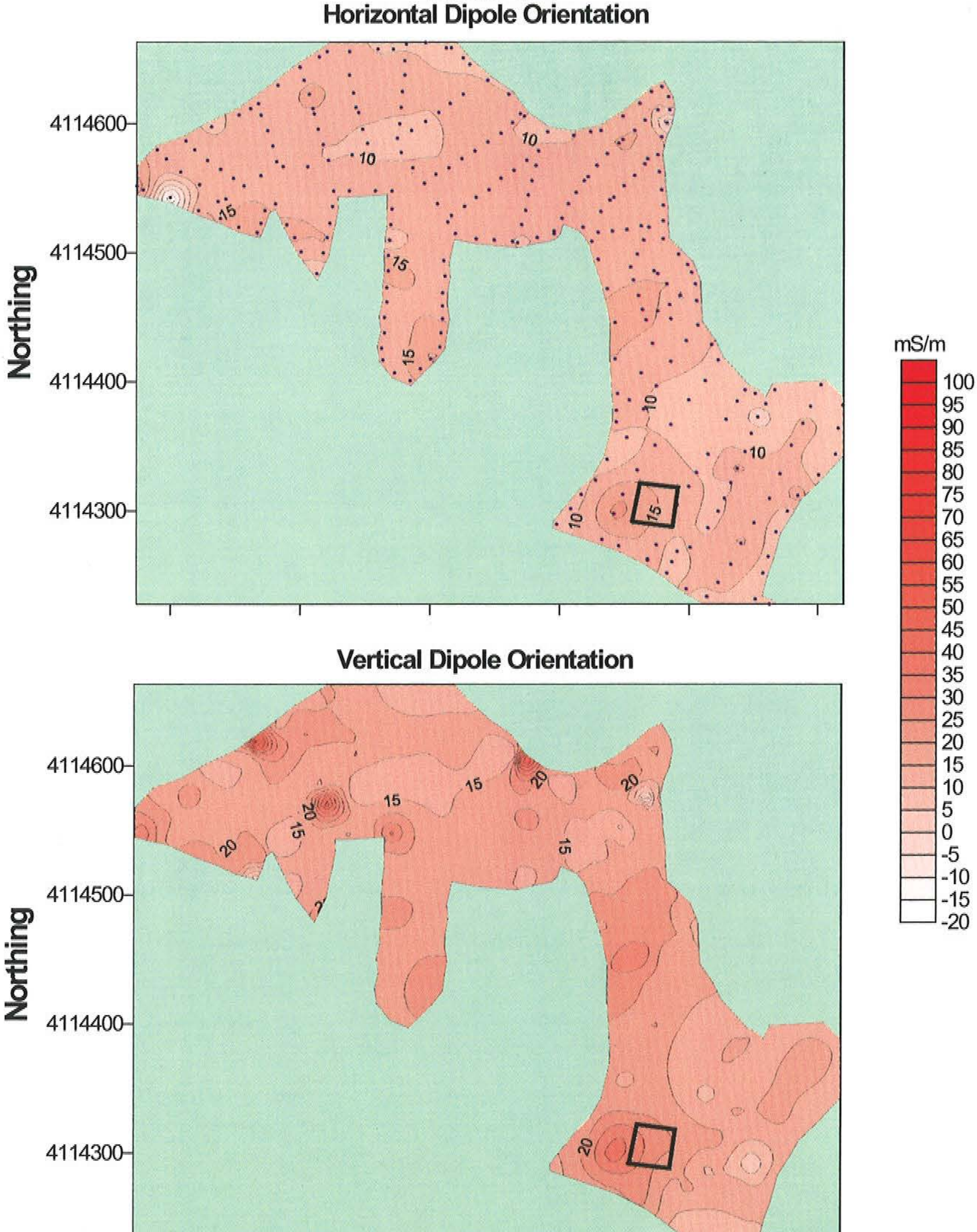


Figure 6

# EMI SURVEY OF LEE MASTER SITE, VA
# DETAIL GRID
# GEM300 SENSOR
# 14790 Hz

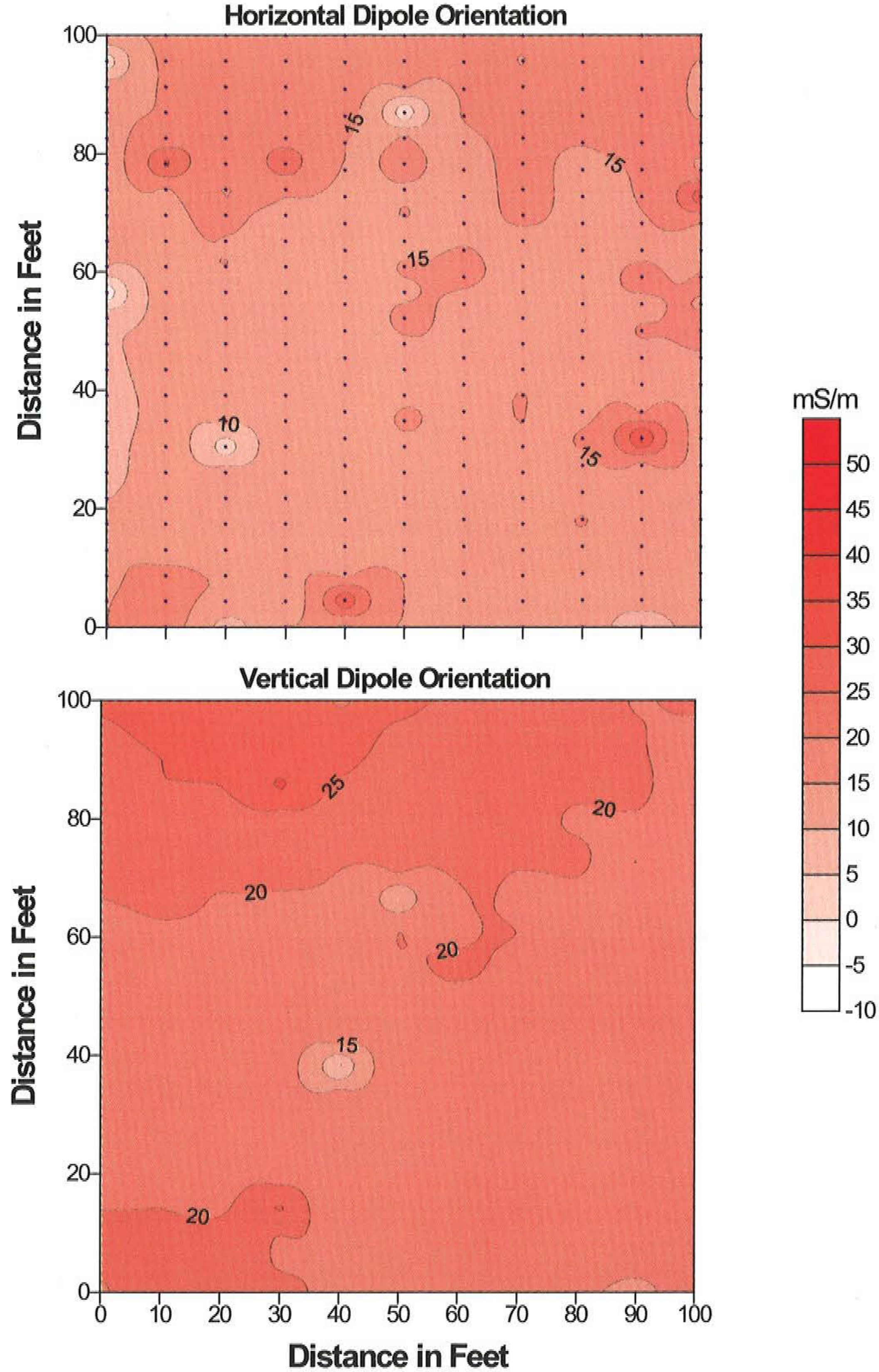


Figure 7

# EMI SURVEY OF LEE MASTER SITE, VA
## DETAIL GRID
## GEM300 SENSOR
## 19050 Hz

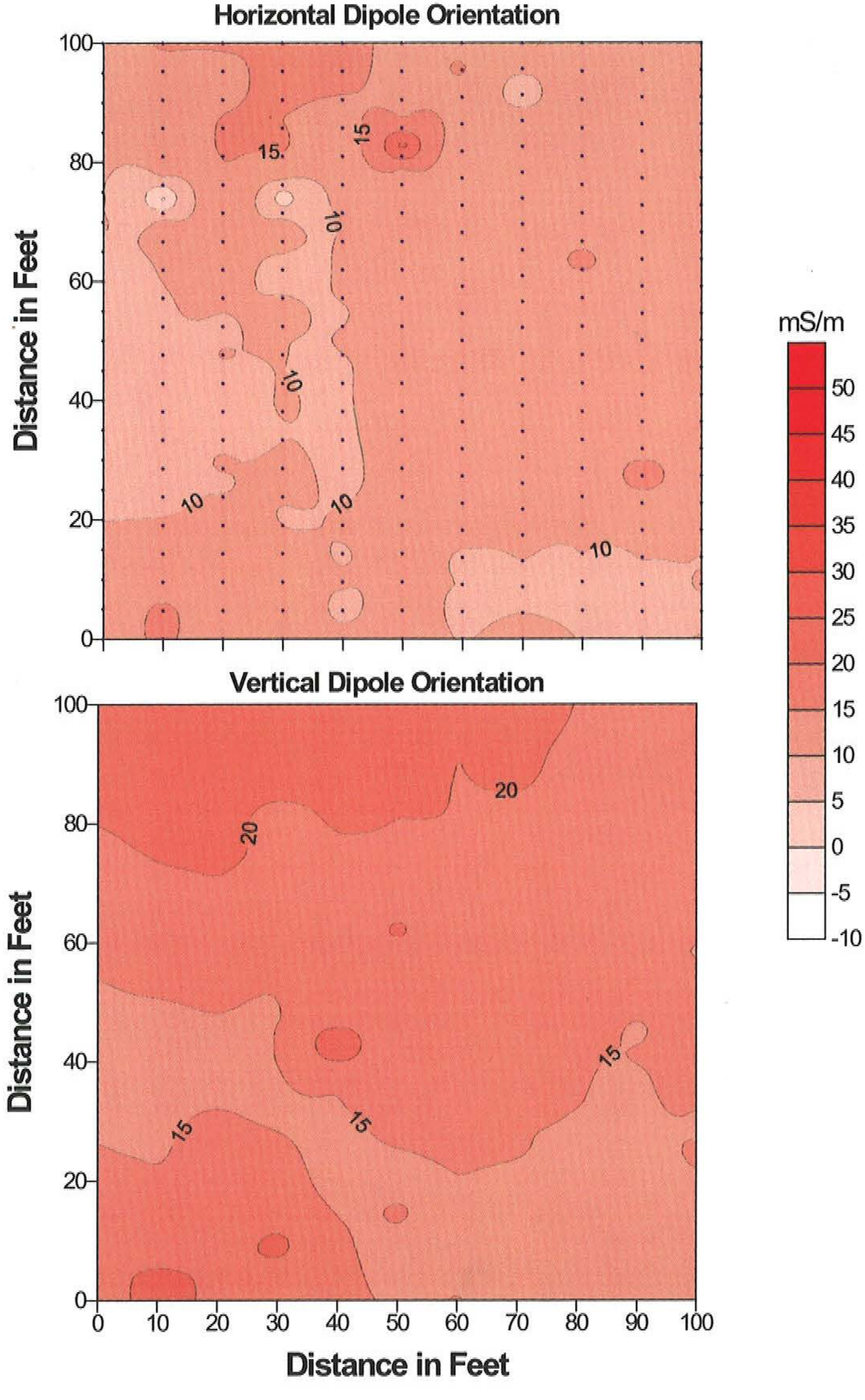


Figure 8