United States Department of Agriculture

Natural Resources Conservation Service

11 Campus Boulevard
Suite 200
Newtown Square, PA 19073

Subject: SOI-Electromagnetic Induction (EMI) Field Assistance

Date: 19 January 2000

To: Denise Doetzer
State Conservationist
1606 Santa Rosa Road
Suite 209
Richmond, VA 23229-5014

Purpose:
The purpose of this visit was to conduct an EMI survey of the area surrounding an agricultural waste-holding facility in which a sinkhole had developed. In addition field assistance and training was provided to staff and students of Radford University involved in an archaeological investigation at Saltville, Virginia.

Participants:
Clifford Boyd, Professor of Anthropology, Radford University, Radford, VA
Brendan Cox, Graduate Student, Radford University, Radford, VA
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA
Jennine Freyman, Soil Resource Specialist, USDA-NRCS, Christianburg, VA
Buddy Gilmore, Conservationist, USDA-NRCS, Abington, VA
Gene Harris, Resource Conservationist, USDA-NRCS, Wytheville, VA
Rhett Herman, Professor of Geophysics, Radford University, Radford, VA
Gregg Hornshell, Agricultural Engineer, USDA-NRCS, Warrenton, VA
Bill Moss, Conservationists, Holston SWCD, Abington, VA
Ryan Murlley, Graduate Student, Radford University, Radford, VA
Batty Skiles, Agricultural Engineer, USDA-NRCS, Christianburg, VA
John Surber, Undergraduate Student, Radford University, Radford, VA
Wayne Turley, Conservation Technician, Holston SWCD, Abington, VA
Bob Whisonat, Professor of Geology, Radford University, Radford, VA

Activities:
All activities were completed during the period of 7 and 8 January 2000. During the morning of 7 January, an animal waste-holding facility in Washington County, Virginia, was surveyed with both the EM31 meter and the GEM300 sensor. During the late afternoon of 7 January and the morning of 8 January, three archaeological sites were surveyed in Saltville, Virginia. On the afternoon of 8 January, additional survey points were collected with the GEM300 sensor at the animal waste-holding facility in Washington County.

Equipment:
The electromagnetic induction meter used in this study was the EM31 manufactured by Geonics Limited.[1] This meter is portable and requires only one person to operate. McNeill (1980) has described the principles of operation for this meter. No ground contact is required with this meter. The meter provides limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing. The EM31 meter operates at a frequency of 9,810 Hz. It has theoretical observation depths of about 3.0 and 6.0 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1980). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

A GEM300 multifrequency sensor, developed by Geophysical Survey systems, Inc., [1] was also used in this study. The GEM300 sensor is a newly developed EMI device. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.6 m). Won and others (1996) have described the use and operation of this sensor. With the GEM300 sensor, the depth of observation is considered "skin depth limited" rather than "geometry limited". The skin-depth represents the maximum depth of observation and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signal. The theoretical observation depth of the GEM300 sensor is dependent

[1] Trade names have been used in this report to provide specific information. Their use does not constitute endorsement.

upon the bulk conductivity of the profiled earthen material(s) and the operating frequency. Multifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

At the waste-holding facility in Washington County, all positions were geo-referenced with a Rockwell Precision Lightweight GPS Receiver (PLGR).[2] The receiver was operated in the continuous and the mixed satellite modes. Coordinates of each observation point were expressed in latitude/longitude. Horizontal datum was the North American 1927. Horizontal units were expressed in degrees/minute/seconds.

At Site #1 in Saltville, the GEM300 sensor was operated in the continuous mode. The locations of all observation collected with the GEM300 sensor at this site were processed and adjusted by the MAGMAP96 software program. [2] At Site # 2 and #3 in Saltville, the GEM300 sensor was operated in the station mode and the location of all observation points were based on survey grids.

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

Results:

1. Participants received training on the use and operation of the EM31 meter and the GEM300 sensor. At each site, systematic field surveys were completed using EMI techniques. Data were interpreted in the field.

2. At the waste-holding facility in Washington County, EMI survey did not reveal evidence of the pathway(s) taken by wastes products after the solution feature developed. However, the area surrounding the waste-holding facility has a complex pattern of isoconductivity lines and, based on interpretations of the EMI data, is believed to have a high probability for the collapse of additional solution cavities.

3. As revealed from survey results at Saltville, EMI is well suited to archaeological studies. This method can provide in a relatively short time the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions and for planning further investigations. A disc containing the EMI data from the Saltville sites has been mailed to Jeannine Freyman for delivery to the staff at Radford University. Data can be plotted and assessed by archaeologists and geologists involved in this project.

4. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.

5. Jeannine Freyman is commended for her leadership and excellent organization of this field assistance.

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

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:

J. Culver, Director, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
W. Nettleton, National Leader, Soil Investigation Staff, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
Greg Secrist, State Conservation Engineer, 1606 Santa Rosa Road, Suite 209, Richmond, Virginia 23229-5014
H. Smith, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250
Steve Carpenter, State Soil Scientist/MLRA Office Leader, USDA-NRCS, 75 High Street, Room 301, Morgantown, WV 26505

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Agricultural Waste Holding Facility, Washington County, Virginia

Electromagnetic Induction:
Electromagnetic induction is a noninvasive geophysical tool that uses electromagnetic energy to measure the bulk electrical conductivity of the soil below the transmitter and receiver coils. This apparent conductivity (EC_a) is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of soils. The electrical conductivity of soils is influenced by the types and concentration of ions in solution, the amount and types of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980). Apparent conductivity increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988, Rhoades et al., 1976).

Electromagnetic induction has been used to investigate the seepage of contaminants from waste sites (Brune and Doolittle, 1990, Drommerhausen et al., 1995, Eigenberg et al., 1998, Radcliffe et al., 1994, Ranjan and Karthigesu, 1995, Siegrist and Hargett, 1989, and Stierman and Ruedisili, 1988). Soils affected by animal wastes often have conspicuously higher values of apparent conductivity than adjoining soils that are unaffected by these contaminants.

Electromagnetic induction has been used to infer the relative concentration, extent, and movement of contaminants from waste-holding facilities. Electromagnetic induction does not provide a direct measurement of specific ions or compounds. However, measurements of apparent conductivity have been correlated with specific ions that are mobile in the soil and associated with animal wastes. Apparent conductivity has been correlated with concentrations of chloride, ammonia, and nitrate nitrogen in soils (Brune and Doolittle, 1990, Ranjan and Karthigesu, 1995, Eigenberg et al., 1998).

Study Site:
The site is located in Washington County about four miles southwest of Chilhowie. The waste-holding facility is located in a drainageway and surrounded on two sides by steep slopes. The area surrounding the waste-holding facility was littered with abandoned farm implements, storage facilities, farm structures, buried pipelines and drains, overhead utility lines, and fence lines. These objects inferred with the electromagnetic fields of the EMI tools and often had a noticeable affected on EMI measurements. To reduce their influence, these sources of "cultural noise" were given a wide-berth. However, despite this effort and because of the large number of artifacts, some EMI measurements were influenced by known or unknown sources of cultural noise.

Field Procedures:
On the first survey day, 101 survey flags were inserted in the ground along fourteen traverse lines. Flags were inserted in the ground at intervals varying from 25 to about 60 feet. The coordinates of each observation point were obtained with a GPS receiver. Measurements were taken at each of these observation points with an EM31 meter held at hip-height in both the horizontal and vertical dipole orientations. Measurements were also taken at each observation point with a GEM300 sensor held at hip-height in vertical dipole orientation. On the second survey day, to provide more comprehensive coverage of the site, 142 additional observations were obtained with the GEM300 sensor. Once again, measurements were taken with a GEM300 sensor held at hip-height in vertical dipole orientation.

Depth of Observation:
The electrical conductivity of soils and earthen materials plays a critical role in the depth of observation that can be obtained with EMI (Greenhouse et al., 1998). The skin depth represents the maximum depth of observation for an EMI meter or sensor operating at a specific frequency and sounding a medium of known conductivity. Observation 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. At a given frequency, the depth of observation is greater in soils having low conductivity than in soils having high conductivity. However, because of other factors, such as the geometry of the meter or sensor, the depth of observation may be less than the skin depth (Greenhouse et al., 1998).

With meters developed by Geonics Limited, the depth of observation is considered to be "geometry" limited (intercoil spacing) rather than skin depth limited (McNeill, 1980). The EM31 meter operates at a frequency of 9810 Hz. It has theoretical observation depths of about 3.0 and 6.0 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1980).

With the GEM300 sensor, the depth of observation is considered "skin depth" limited rather than "geometry' limited (Won, 1980 and 1983, Won et al., 1996). The theoretical observation depth of the GEM300 is dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency of the sensor. A nomogram was developed (Won et al., 1996) to approximate the skin depth for a given frequency and soil conductivity. Unfortunately, independent researchers have not extensively tested this nomogram. In addition, it is believed that the nomogram is off by about one order of magnitude (Dan Delea, Geophysical Survey Systems, Inc., personal communication).

Data was recorded at four frequencies with the GEM300 sensor. These frequencies were 2010, 6810, 9810, and 14610 Hz. Based on 243 measurements made at this site with the GEM300 sensor, apparent conductivity averaged 10.9, 14.0, 13.7, and 4.6 mS/m at frequencies of 2010, 6810, 9810, and 14610 Hz, respectively. Using the developed nomogram (Won et al., 1996), the average skin depths are about 10 m at 2010 Hz, 5 m at 6810 Hz, 4 m at 9810 Hz, and 2 m at 14,610 Hz.

Results:
Table 1 summarizes the apparent conductivity measurements. The number of observations was 101 and 243 for the EM31 meter and the GEM300 sensor, respectively. In general, values of apparent conductivity were highly variable across the site. The wide range in values is believed to reflect the presences of ferrous objects (high negative values) and animal wastes (high positive values).

Table 1
Basic Statistics
EMI Survey
Washington County Site
(All values are in mS/m)

	AVERAGE	MINIMUM	MAXIMUM	FIRST	MEDIAN	THIRD
EM31H	8.8	5.0	9.5	7.0	7.5	8.6
EM31V	10.2	6.5	14.0	7.4	9.0	10.6
2010 Hz	10.9	-103.0	129.1	2.1	9.5	18.1
6810 Hz	14.0	-31.6	113.1	7.0	12.3	19.0
9810 Hz	13.7	-183.3	202.1	3.2	8.2	18.1
14610 Hz	4.6	-19.9	92.5	-2.1	2.9	9.0

As a working model for the site, the overlying soil materials are considered more conductive than the underlying limestone bedrock. The higher conductivity of the soil materials is attributed to their higher clay and moisture contents. Measurements obtained with the EM31 meter increased with increasing depths of observation (measurements obtained in the vertical dipole orientation were higher than those obtained in the horizontal dipole orientation). This trend does not conform to the model and the projected conductivity profile for the site. As the meter was held at hip-height (about 1 m above the ground surface) the theoretical observation depths were about 2 and 5 meters in the horizontal and vertical dipole orientations, respectively. It is assumed that over a large portion of the survey area (mostly on lower-lying slope positions), this meter did not sense the underlying limestone bedrock, but sensed the increase in clay and moisture contents with increasing depth within the soil profile. With the GEM300 sensor, average and median values of apparent conductivity increased then decreased with increasing observation depths. Values were lowest in the surface materials (measured at 14610 Hz), increased within the soil profiles (measured at 9810 and 6810 Hz), then decreased (measured at 2010 Hz), as presumably a greater volume of the underlying, more resistive, limestone bedrock was included in the profiling depth.

Positive correlations were found between measurements made with the GEM300 sensor and the EM31 meter at the 101 observation points measured on 7 January. The strongest correlation between measurements was found between the GEM300 sensor operating frequency of 14610 Hz and the EM31 meter in horizontal ($r^2 = 0.67$) and vertical ($r^2 = 0.59$) dipole orientations. Difference in measurements were attributed to slight spatial differences in the points of measurements, the depth and volume of soil measured with each tool, and differences in calibrations provided by manufacturers.

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

Figure 1 contains two-dimensional plots showing the spatial distribution of apparent conductivity collected with the EM31 meter. The upper plot represents data collected with the EM31 meter in the horizontal dipole orientation. The lower plot represents data collected with the EM31 meter in the vertical dipole orientation. The locations of the waste-holding facility (stippled lines) and the embankment (filled rectangle) have been shown in each plot. In each plot, the isoline interval is 3 mS/m.

Areas of high apparent conductivity immediately surround the waste-holding facility. These higher values are attributed to increased concentrations of salts from animal wastes and increased soil moisture contents in the lower-lying areas surrounding the structure. In both plots, high values near A, B, and C reflect potential seepage plumes or the influence of nearby buildings on the electromagnetic fields. The area in which the solution feature formed is the indented area (see "D" in Figure 1) that extends into the waste-holding facility. This area has been recently excavated and covered with fill materials. This area was surveyed with both EMI tools.

Neither of the plots shown in Figure 1 provides information concerning the fate or pathways of the waste materials that were drained through subsurface cavities from this structure. The area surveyed was considered to be too restrictive to assess these spatial trends.

Figure 2 and 3 contain two-dimensional plots showing the spatial distribution of apparent conductivity collected with the GEM300 sensor. Figure 2 contains plots of the apparent conductivity collected at 2010 Hz (upper) and 6810 Hz (lower). The estimated skin (observation) depths are about 10 meters at 2010 Hz and 5 meters at 6810 Hz. Figure 3 contains plots of the apparent conductivity collected at 9810 Hz (upper) and 14610 Hz (lower). The estimated skin depths are about 4 meter at 9810 Hz and 2 meter at 14610 Hz. In each plot, the isoline interval is 10 mS/m.

In each of the plot shown in figures 2 and 3, a dot marks the approximate location of the former cavity that opened and drained the waste-holding facility. Also shown in each plot are the waste-holding facility (stippled lines) and embankment (filled rectangle). A pile of material removed from the waste-holding facility is labeled "A." This pile of waste-contaminated materials is more conductive than surrounding soil materials. An opening to a cavern was observed along the base of a slope near the river. The approximate location of this cavern has been labeled "B" in each plot and conforms to an area of low conductivity. In each plot, a large silage storage area forms a conspicuous rectangular pattern of high conductivity around "C."

Areas underlain by buried solution cavities have irregular depths to bedrock and variable thickness of overburden. Areas underlain by solution cavities have a more complex pattern of isoconductivity lines than areas where these subsurface features are not present or were not detectable. In the plots of apparent conductivity collected at 2010 Hz, 6810 Hz, and 9810 Hz, intricate patterns of isoconductivity lines are believe to reflect the presence of karst features and the effects of variable clay and moisture contents, overburden thickness, and depth to bedrock. In some areas, these patterns also reflect the presence of cultural features and their interference with the electromagnetic fields.

The area surrounding the waste-holding facility has a complex pattern of isoconductivity lines and, based on EMI interpretations, is believed to be at risk for the collapse of additional solution cavities. The EMI survey did not reveal evidence of the pathway(s) taken by wastes products after the solution feature developed.

Archaeological Sites at Saltville, Virginia

EMI:

Electromagnetic induction is a noninvasive geophysical tool that can be used for detailed archaeological site investigations. Advantages of EMI are its portability, speed of operation, flexible observation depths, and moderate resolution of subsurface features. Results from an EMI survey are interpretable in the field. This geophysical method can, in a relatively short time, provide the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions, planning further investigations, and locating exploratory test pits.

Electromagnetic induction measures vertical and lateral variations in magnetic and/or electrical fields associated with induced subsurface currents. Data is expressed as in-phase, quadrature phase, or apparent conductivity. The in-phase and quadrature phase responses represent the ratio of the secondary magnetic field at receiver coil to the primary magnetic field at receiver coil. In-phase refers to the part of the signal that is in phase (has zero phase shift) with the primary or reference signal. The in-phase signal is sensitive to buried metallic objects and has been referred to as the "metal detection" mode. The magnitude of the in-phase signal is proportional to the cube of a buried metallic object's surface area and is inversely proportional to its depth raised to the sixth power (Greenhouse et al., 1998). Quadrature phase refers to the part of the signal that is 90 degrees out of phase with the primary signal. The quadrature phase response is linearly related to the ground conductivity. Some highly conductive targets with small cross-sections, such as pipes, may show up better in the quadrature phase because of the channelization of current.

With the GEM300 sensor, in-phase and quadrature phase data are expressed in parts per million (ppm). Traditionally, EMI data are expressed as apparent conductivity. The GEM300 sensor automatically converts quadrature phase data into apparent conductivity data. Values of apparent conductivity are expressed in milliSiemens per meter (mS/m). Apparent conductivity is a weighted, average measurement for a column of earthen materials to a specific observation 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 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).

Values of apparent conductivity are seldom diagnostic in themselves, but lateral and vertical variations in these measurements can be used to infer changes in soils and soil properties and the locations of buried artifacts. Interpretations are based on the identification of spatial patterns within data sets. To assist interpretations, computer simulations are normally used.

Saltville, Virginia:

A sign along the road leading to Saltville declares the town as the "Salt Capital of the Confederacy." In 1864, this town provided about two-thirds (about 100,000 tons) of the salt used in the Confederate states (Whisonant, 1996). The commercial production of salt at Saltville was by brine extraction from deep wells that intercepted layers of rock salt. Brine was pumped from wells and boiled in rows of heavy iron kettles set on top of large (150 feet in length) arch furnaces (Whisonant, 1996). In 1864, the Saltville operation consisted of 38 furnaces, 2,600 kettles, and as many as 300 structures (Whisonant, 1996). The town was the site of two military engagements during the Civil War. After the second battle, many of the sheds and kettles were destroyed by Federal troops. However, within two weeks, salt production resumed at Saltville. Salt production ceased in 1906.

Field Procedures:

The Radford University staff selected three sites for investigation. Grids were established at each site. Site 1 was located along a railroad line. A 45 by 90 foot grid was established across this site. The grid interval was 15 and 5 feet. The GEM300 sensor was operated in the continuous mode, in the vertical dipole orientation, at frequencies of 9810, 13530, and 18630 Hz. Inphase and conductivity measurements were obtained for each frequency at each observation point. Measurements were made at a total of 563 observation points.

Site 2 was located on a golf course. The site contained a partially exposed iron kettle. An irregularly shaped, 80 by 100 foot grid was established across this site. The grid interval was 5 and 10 feet. The GEM300 sensor was operated in the station mode, in both the horizontal and vertical dipole orientations, at frequencies of 9810, 14610, and 18630 Hz. Inphase and conductivity measurements were obtained for each frequency at each observation point. At each observation point 12 separate measurements were made with the sensor. These measurements were made at a total of 169 observation points.

Site 3 was located in a wooded ravine. This site was suspected to be the location of a mass burial of Federal soldiers. An irregularly shaped, 95 by 30 foot grid was established across this site. The grid interval was 5 and 10 feet. The GEM300 sensor was operated in the station mode, in both the horizontal and vertical dipole orientations, at frequencies of 9810, 14610, and 18630

Hz. Inphase and conductivity measurements were obtained for each frequency at each observation point. At each observation point 12 separate measurements were made with the sensor. These measurements were made at a total of 48 observation points.

Results:

Compared with conventional EMI meters, multifrequency profiling with the GEM300 sensor provides a superior method (in terms of survey speed, spatial resolution, and data density) to characterize buried metallic and non-metallic artifacts. Contour plots are used to display the data. Spatial patterns are used to detect and, in some instances, identify buried artifacts. Depth of observation in a given medium is determined by the operating frequency of the GEM300 sensor. The response from a buried artifact is also dependent on the operating frequency. Artifacts detectable at one frequency may be unrecognizable at another frequency. The use of multiple frequencies provides multiple observation depths and improves the possibilities of detection.

Figures 4, 5, and 6 are representative plots from sites #1, #2, and #3 respectively. Each figure consists a conductivity and an in-phase plot of data collected at a single operating frequency and coil orientation. The in-phase signal is sensitive to buried metallic objects and has been referred to as the "metal detection" mode. The conductivity plots are more sensitive to changes in earthen materials and may detect differences in soils and fill materials. The conductivity plot for Site #1 (see Figure 4) reveals the presence of two rectangularly shaped areas of high conductivity. These patterns are believed to be artificial and reflect areas occupied by former structures or containing dissimilar fill materials. The in-phase plot for Site #1 (see Figure 4) reveals the presence of numerous "point anomalies" that are suspected to represent buried ferrous artifacts. Some of these anomalies appear in pairs and some are located within the rectangularly shaped areas of high conductivity evident in the upper plot.

The conductivity plot for Site #2 (see upper plot, Figure 5) reveals the presence of a buried water line that crosses the survey area (see linear pattern of negative soil conductivity in the lower part of Figure 5). Also evident in this plot is the large partially buried kettle (at the 50,55 foot grid intersection) and several addition buried point anomalies. These features are more clearly expressed in the in-phase plot for Site #2 (see lower plot, Figure 4).

The conductivity plot for Site #3 (see left-hand plot, Figure 6) reveals the presence of a conspicuous point anomaly. The in-phase plot for Site #3 (see Figure 6) also reveals this point anomalies and several more weakly expressed areas. Unless buried with metallic objects, a 136-year-old mass gravesite would be difficult to detect with EMI. The features detected in Figure 6 may be artificial, but could also represent more recent natural events associated with erosion and sedimentation. As with the preceding sites, ground-truth observations are needed to confirm the identity of these features.

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EMI SURVEY
ANIMAL WASTE HOLDING FACILITY
WASHINGTON COUNTY, VIRGINIA
EM31 METER

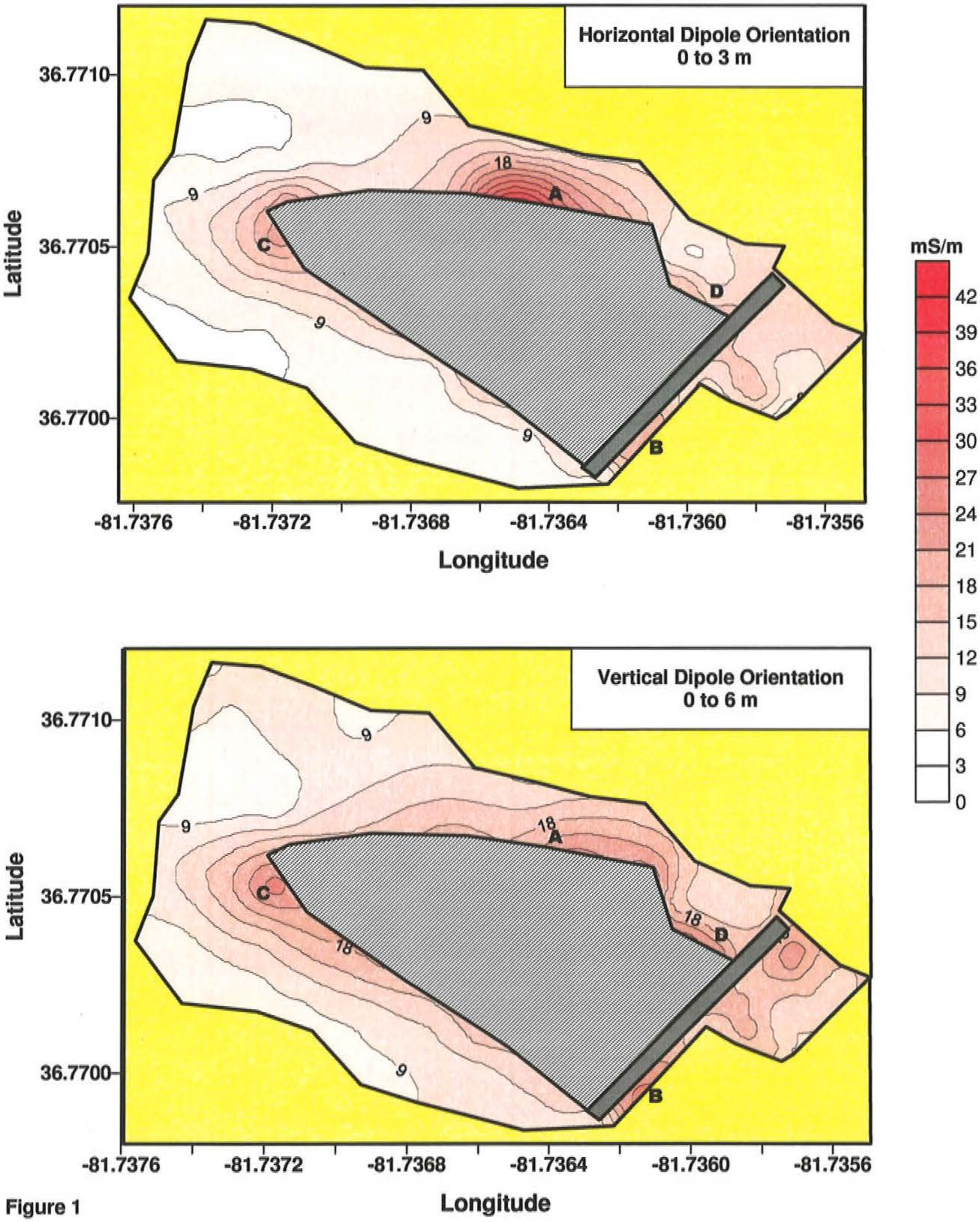


Figure 1

EMI SURVEY
ANIMAL-WASTE HOLDING FACILITY
WASHINGTON COUNTY, VIRGINIA
GEM300 SENSOR

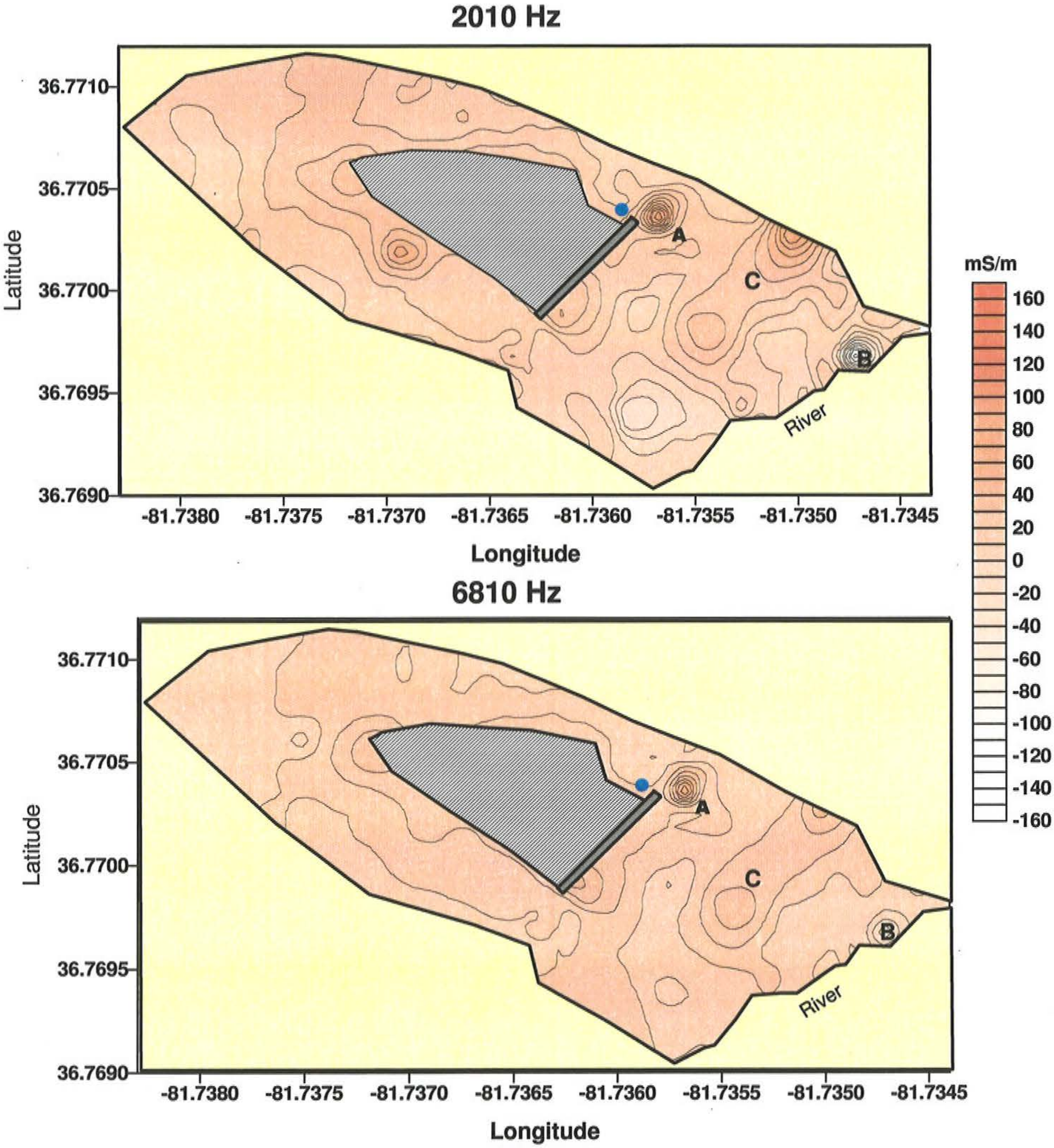


Figure 2

EMI SURVEY
ANIMAL-WASTE HOLDING FACILITY
WASHINGTON COUNTY, VIRGINIA
GEM300 SENSOR

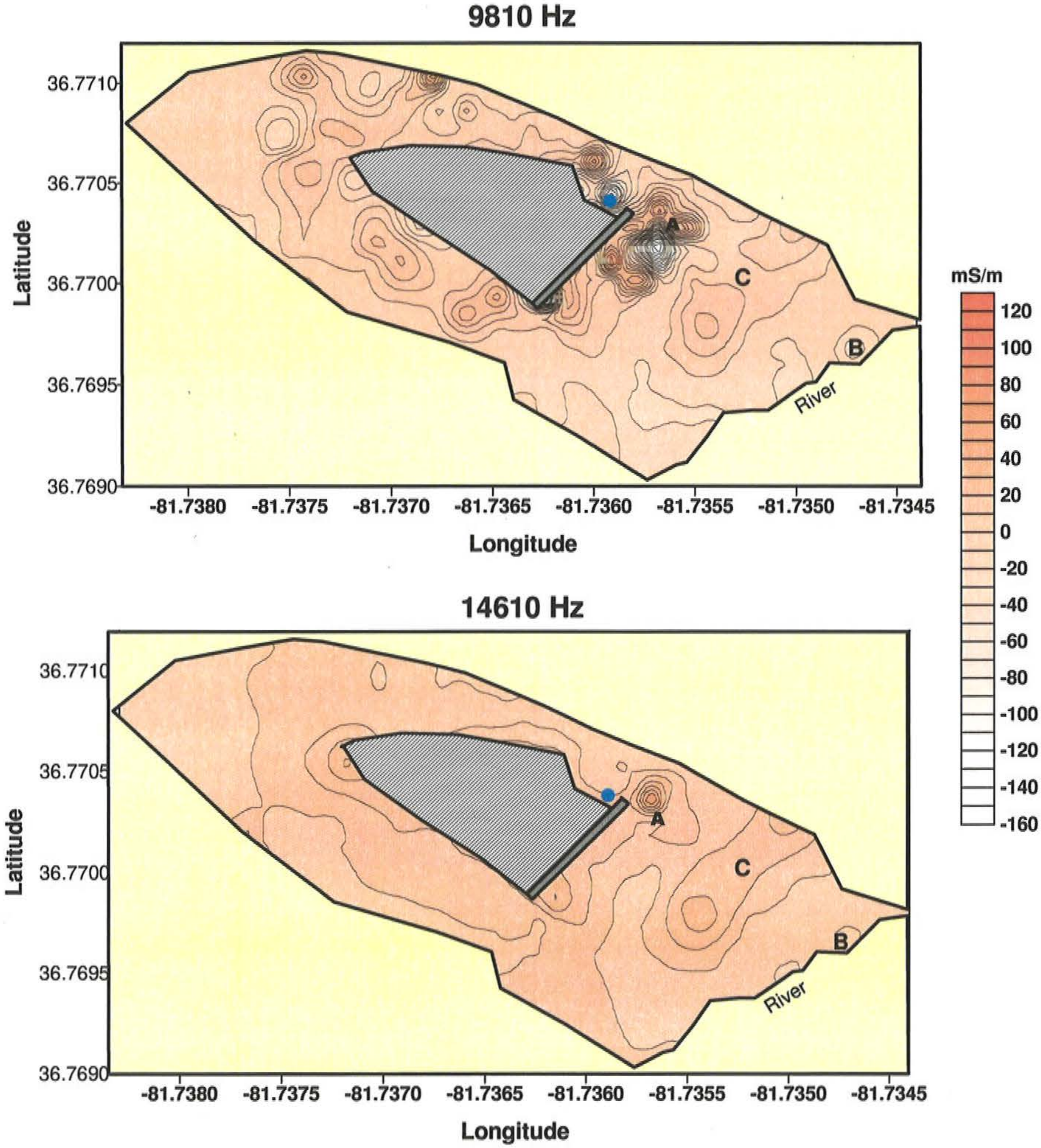
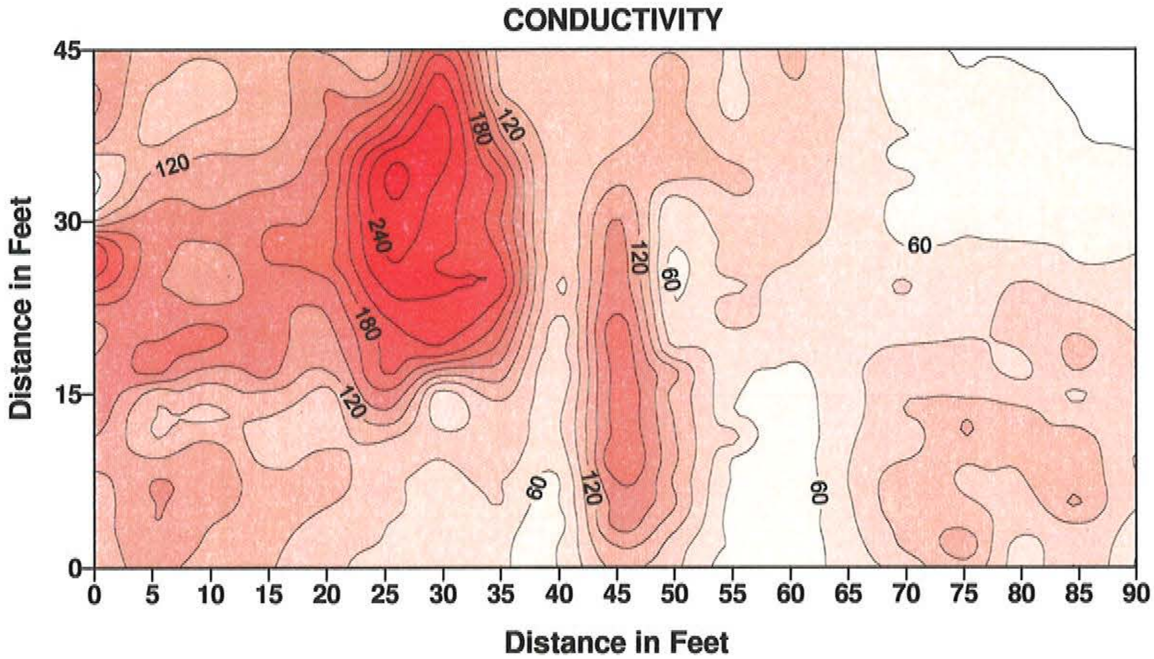


Figure 3

EMI SURVEY
SITE #1
SALTVILLE, VIRGINIA
GEM300 SENSOR
18630 HZ



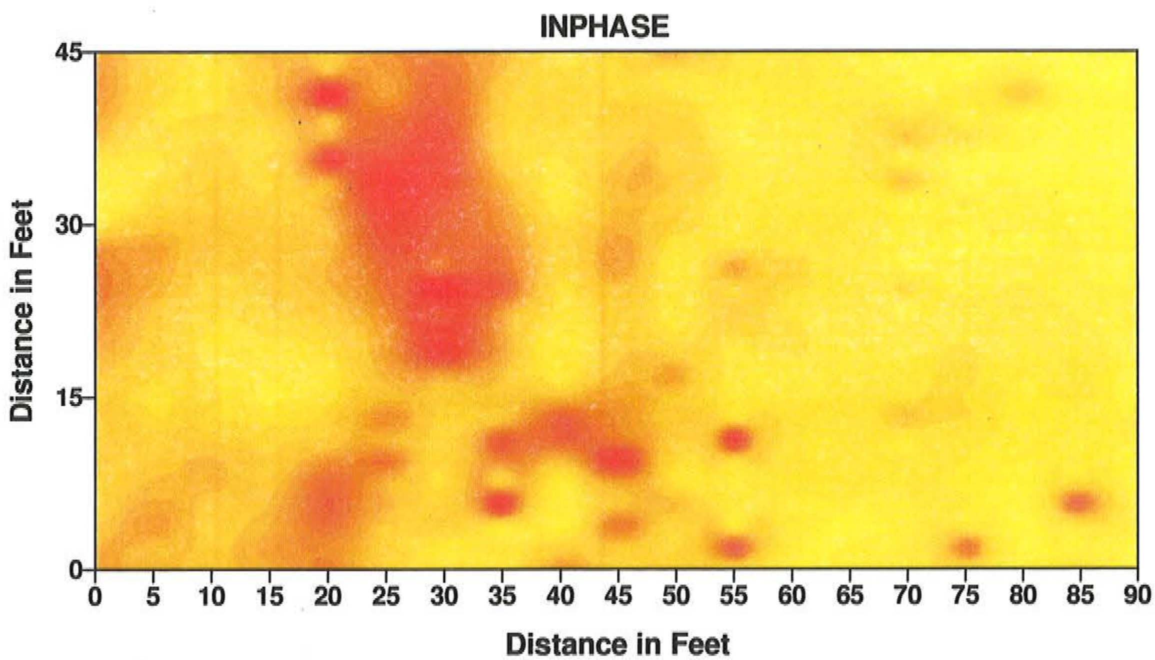
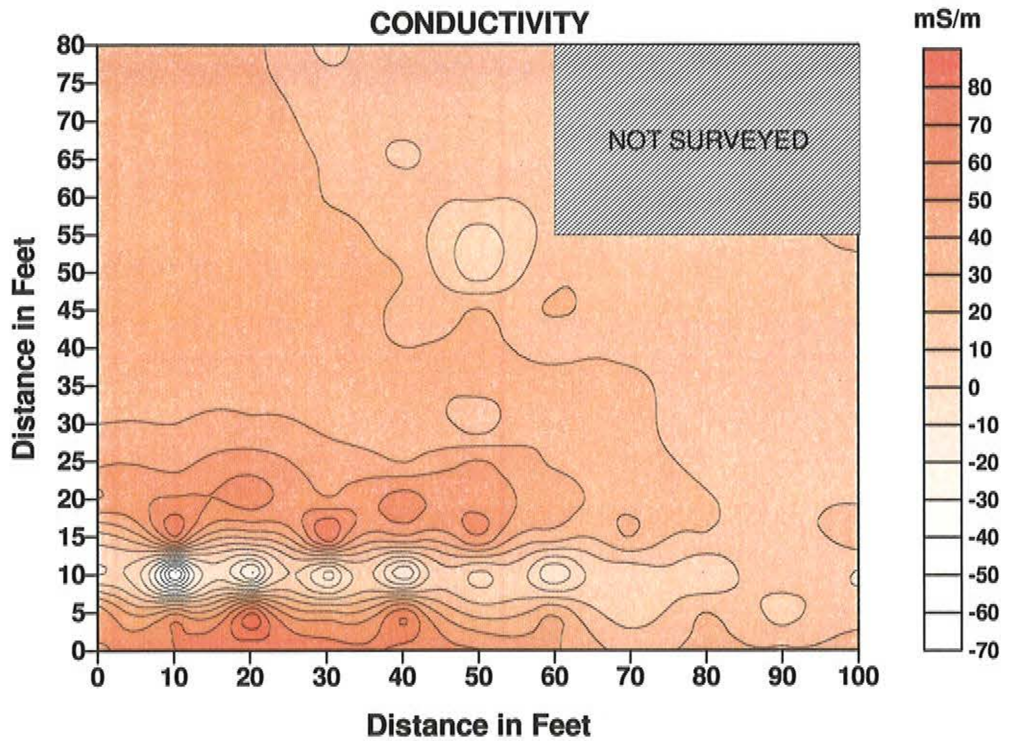


Figure 4

EMI SURVEY
SITE #2
SALTVILLE, VIRGINIA
GEM300 SENSOR
Vertical Dipole Orientation
14630 HZ



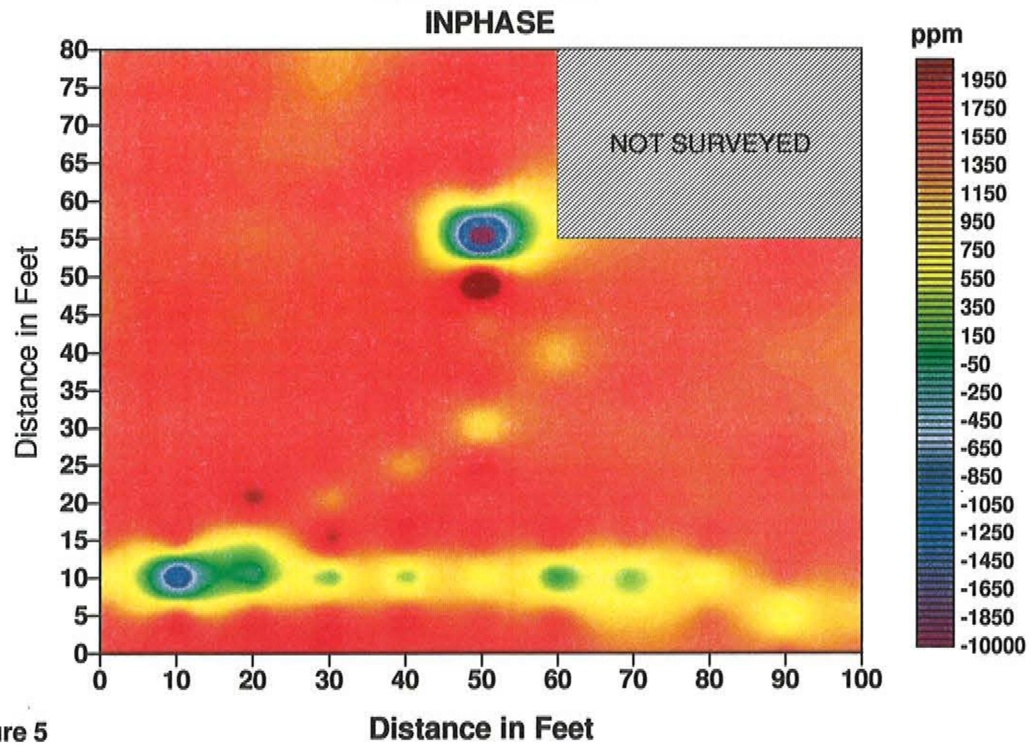


Figure 5

EMI SURVEY
SITE #3
SALTVILLE, VIRGINIA
GEM300 SENSOR
Horizontal Dipole Orientation
14630 HZ

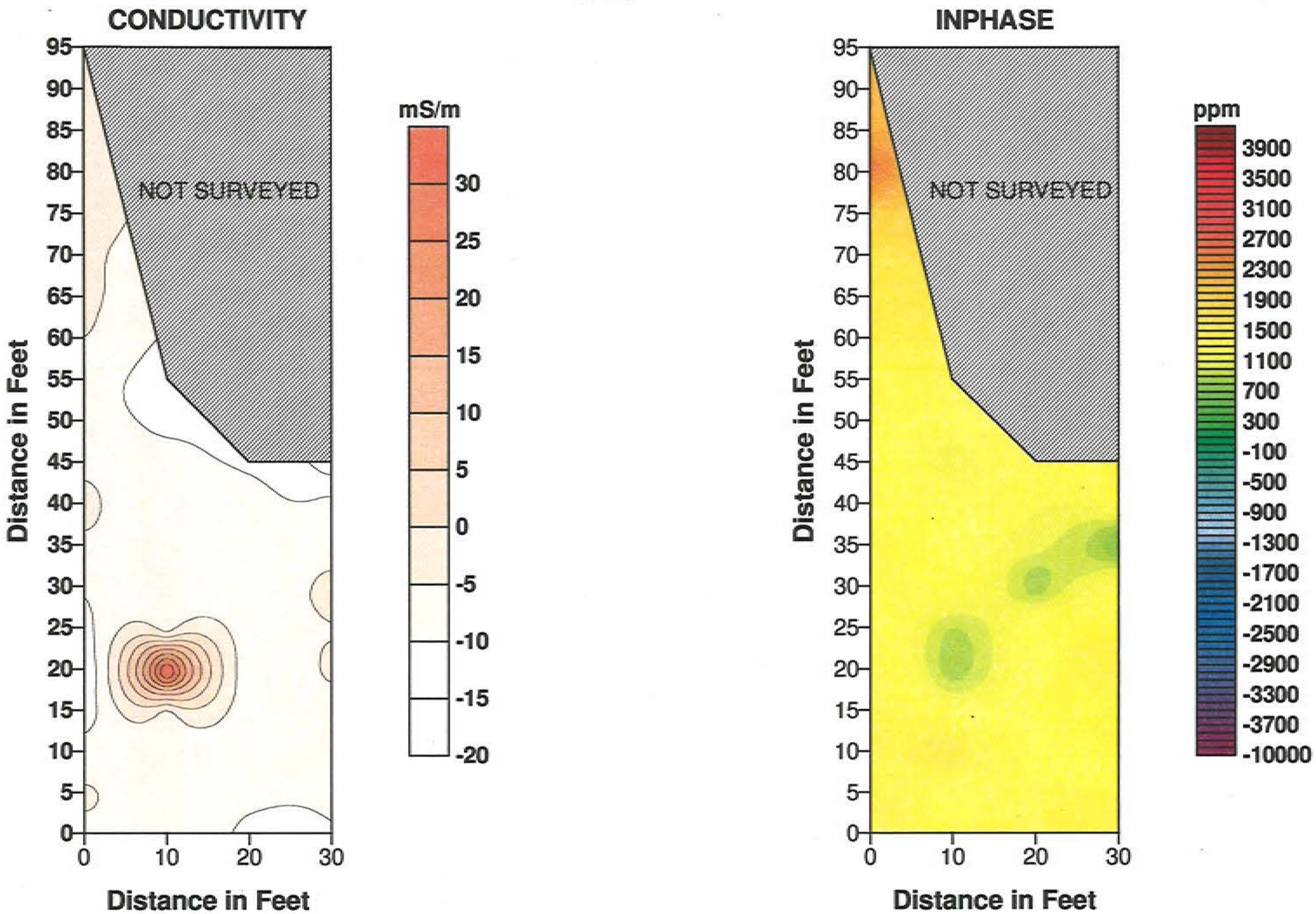


Figure 6