**United States Department of Agriculture**

**Natural Resources Conservation Service**

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**Subject:** SOI -- Geophysical Assistance

**Date:** 15 October 2001

**To:** Allan Green
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**Purpose:**
The purpose of this investigation was to explore the potential of using ground-penetrating radar (GPR) and electromagnetic induction (EMI) to help characterize soils in the Southern Rocky Mountains region.

**Participants:**
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Alan Price, Soil Data Quality Specialist, USDA-NRCS, Lakewood, CO
Alan Stuebe, MLRA Project Leader, USDA-NRCS, San Luis, CO
Lorenz Sutherland, Agronomist, USDA-NRCS, La Junta, CO
Tim Wheeler, Soil Scientist (TSS), USDA-NRCS, Lakewood, CO

**Activities:**
Field activities were completed in Teller and Park counties during the period of 10 to 14 September 2001. Field activities were completed in Costilla County during the period of 17 to 21 September 2001.

**Conclusions:**

1. The GPR was found to be a suitable tool for soil investigations in areas of non-calcareous, coarse and coarse-loamy soils formed in materials weathered from granite, quartz-monzonite, gneiss, schist, or sandstone. In these materials, GPR can provide satisfactory observation depths to support soil survey operations.

2. Studies demonstrated that the EM38DD meter produces non-reproducible and unreliable data in areas of low to high conductivity soils. These results are possibly related to design flaws in the meter's coil orientations. In all soils examined, the EM38 meter produced stable and replicable results. In areas of very highly conductive saline soils, the EM38DD produced data and spatial patterns similar to those of the EM38 meter. Based on these studies the use of the EM38DD meter within USDA-NRCS is not recommended.

3. Multifrequency soundings in an area of Traveler soil at six frequencies with the GEM300 sensor operated in the vertical dipole orientation produced similar spatial patterns. As these patterns are similar, it is assumed that the depth of observation for GEM300 sensor at each of the six frequencies is also comparable. Interpretations were neither changed nor improved with multifrequency soundings. For most soil investigations with the GEM300 sensor, the use of one frequency with measurements in both dipole orientations will provide as much information as multifrequency soundings.

4. Hands on training were provided to all participants on the operation of the EM38 and EM38DD meters, and GEM300 sensor. Participants completed comparative field tests that evaluated the suitability and reliability of these devices.

**Recommendations:**

1. The Soil Staff in Colorado is commended for their initiative in independently evaluating and developing the use of EMI within USDA-NRCS. Through extensive fieldwork, professional development, and workshops, the staff has assumed a leadership role in the use of EMI for soil salinity appraisals. Working closely with the USDA-ARS Salinity Laboratory in Riverside, California, the staff in Colorado has helped to validate the ESAP-95 model (statistical package for estimating field scale spatial salinity patterns from electromagnetic induction response) and have fostered the use of EMI methods in adjoining states. The Soil Staff has demonstrated initiative by independently exploring the use of EMI to estimate soil properties and depths to bedrock.

2. The Geophysical Initiatives Program of the Soil Survey Division has recommended the placement of suitable geophysical tools in Colorado. Based on the results of field studies and the enthusiasm and commitment of the Soil Staff in Colorado, I recommend the immediate purchase of a GEM300 sensor ($15,025). This sensor is easy to set up and is more efficient than the EM38 meter for surveying large areas. It was repeatedly demonstrated that soil scientists prefer to conduct fieldwork with the GEM300 sensor. The sensor can be used throughout the Southern Rocky Mountain Region.

3. I would also recommend the placement by NHQ of Dualem 2/4 meters ($28,400) in Colorado. The Soil Staff in Colorado has the knowledge and the expertise to use and develop these meters for soil salinity appraisals, precision farming initiatives, high intensity soil surveys, groundwater contamination studies and archaeological investigations in Colorado and Major Land Resources Area (MLRA) Office 6.

4. Though results from this field investigation with GPR are positive, the areas of potential application within Colorado and MLRA Office 6 are limited. In many soils, GPR provided adequate observation depths for soil survey investigations. However, as the soil/bedrock interfaces were often obscured and poorly or discontinuously expressed, the interpretative quality of radar profiles was at best fair.

I wish to commend the enthusiasm and efforts of Alan Price, Laura Craven, and Alan Stuebe. Their knowledge of the soils, geology, and landscapes were of great valuable to this investigation. The assistance of Mike Petersen was also greatly appreciated.

With kind regards,

James A. Doolittle
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**Summary:**

During this investigation, a large number of soils and field sites were surveyed with both GPR and EMI in Teller, Park and Costilla counties. This report discusses some of the major findings of these investigations. At many sites both GPR and EMI data were obtained. Some of this data was collected without adequate ground-truth verifications and will not be covered in this report. In cases where adequate ground-truth verifications were not obtained, working models based on EMI responses were validated based on knowledge of soils and soil-landscape relationships. The results of these investigations were partially corroborated by visual observations of soils and soil-landscape positions. In general, results of these investigations improved or validated soil-mapping concepts of soil survey project leaders. In addition, because of the shear number of radar transects completed in this study, only a select number of representative radar profiles have been shown in this report.

**Table 1**
**Taxonomic Classification of Investigated Soils and Their Observed EMI Response**

| Series | Classification | Apparent Conductivity (mS/m) |
|---|---|---|
| Alamosa | Fine-loamy, mixed, frigid Typic Argiaquolls | 4.8 to 125.5♣ |
| Blackhall | Loamy, mixed, superactive, calcareous, frigid, shallow Ustic Torriorthents | |
| Catamount | Loamy-skeletal, paramicaceous, shallow Ustic Dystrocryepts | 0.2 to 7.5 |
| Cathedral | Loamy-skeletal, paramicaceous, frigid Lithic Haplustolls | |
| Chittum | Loamy, mixed Argic Lithic Cryoborolls. | 4.2 to 15.3 |
| Garita | Loamy-skeletal, mixed, superactive, frigid Typic Haplocalcids | 0.9 to 7.6♠ |
| Ivywild | Loamy-skeletal, paramicaceous Ustic Dystrocryepts | 0.2 to 7.5 |
| Raleigh | Loamy-skeletal, paramicaceous, shallow Ustic Haplocryolls | 0.7 to 5.5 |
| Rogert | Loamy-skeletal, mixed, superactive Lithic Haplocryolls | -0.7 to 4.5 |
| Roster | Loamy-Skeletal, mixed Lithic Haplocryolls | 2.3 to 8.7 |
| Sawcreek | Coarse-loamy, mixed, superactive Ustic Haplocryolls | 2.3 to 8.7 |
| Scout | Loamy-skeletal, mixed, superactive Ustic Eutrocryepts | 0.7 to 4.2 ♠ |
| Sphinx | Sandy-skeletal, mixed, frigid, shallow Typic Ustorthents | |
| Travelers | Loamy-skeletal, mixed, active, frigid Lithic Ustic Haplocambids | 0.6 to 12.6♠ |
| Ula | Fine-loamy, mixed, superactive Ustollic Haplocryalfs | 0.4 to 12.0 |
| Vega | Fine-silty, mixed, mesic Cumulic Haplustolls | 21.9 to 81.5♣ ♠ |
| Vorsid | Loamy, mixed Lithic Haplocryolls | 2.3 to 8.7 |
| Woosley | Fine-loamy, mixed, superactive Ustic Argicryolls | 4.2 to 15.3 |

**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. The SIR System-2000 consists of a digital control unit with keypad, VGA video screen, and connector panel. A 12-volt battery powered the system. This unit is backpack portable and, with an antenna, requires two people to operate. The 400 and 200 MHz antennas were used in this study. The range gain and filtration settings, and scanning times (70 to 110 nanoseconds (ns)) were varied based on desired observation depth and resolution of subsurface features. Hard copies of the radar data were printed in the field on a model T104 printer. All radar profiles have been stored on a CD.

Geonics Limited manufacturers the EM38, EM38DD, and the EM31 meters.[1] These meters are portable and require only one person to operate. McNeill (1980) and Geonics Limited (1998 and 2000) have described principles of operation for the EM31, EM38, and EM38DD meters, respectively. No ground contact is required with these meters. The depth of penetration is geometry limited. Lateral resolution is approximately equal to the intercoil spacing. The EM38 and the EM38DD meters have a 1 m intercoil spacing and operate at a frequency of 14,600 Hz. They have effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). The EM38DD meter consists of two EM38 meters bolted together and electronically coupled. One unit acts as a master unit (the meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one unit acts

♣ Map unit contained soils other than named series.

♠ Data obtained with GEM300 sensor

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

as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on). The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9,810 Hz. It has theoretical penetration depths of about 3.0 and 6.0 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980).

The GEM300 multifrequency sensor is manufactured by Geophysical Survey Systems, Inc.[2] 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, penetration depth is considered "skin depth limited" rather than "geometry limited." The skin-depth represents the maximum depth of penetration and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signal. Theoretical penetration depths of the GEM300 sensor are dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequencies. Multifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

The coordinates of field sites were obtained with Garman 2 GPS Receivers.[2] The receiver was operated in the continuous and the mixed satellite modes. Horizontal datum was the North American 1983.

**Study Areas:**
The suitability of a number of soils for GPR and EMI was examined during this field assignment. These soils formed in materials weathered from different lithologies and parent materials. Table 1 lists the taxonomic classifications of the soils profiled with GPR and EMI. Also shown in Table 1 are the ranges in apparent conductivity values found in these soils or representative map units. The use of GPR and EMI for soil investigations was explored at the following sites:

Chapman's Ranch, Teller County:
The study area was located south of the town of Cripple Creek. Two sites were located in open areas along roadside cuts that exposed the underlying bedrock. One site was located in an area of Cathedral very gravelly sandy loam, 20 to 50 % slopes. This shallow, well drained or somewhat excessively drained soil formed in slope alluvium, colluvium, and residuum weathered from granite or gneiss. At this site, soils formed in materials weathered from the Cripple Creek quartz-monzonite. The coordinates of this site are 38° 42′ 18.9″ N and 105° 11′ 42.9″ W. The site is at an elevation of about 8600 feet.

One site was located in an area of Rogert-Rock Outcrop complex, 20 to 60 % slopes. The shallow, well-drained Rogert soil formed in a thin layer of noncalcareous, very gravelly or channery materials weathered from granite, sandstone, gneiss, or tuff. At this site, soils formed in materials mostly weathered from the Cripple Creek quartz-monzonite. However, conspicuous outcrops of schist and gneiss occurred near this site. Large quantities of muscovite, hornblende, and some hematite were found in the soils. The coordinates of this site are 38° 42′ 59.8″ N and 105° 10′ 52.7″ W. The site is at an elevation of about 9000 feet.

Mueller State Park, Teller County:
Three sites were located in Mueller State Park. All sites are underlain by Pike Peak granite. This pink granite contains white and pink feldspar, with an abundant amount of hornblende and mica. One site was located in an open grassland area of Raleigh very gravelly sandy loam, 5 to 55 % slopes. This shallow, somewhat excessively drained soil formed in materials derived from weathered granitic rocks. The coordinates of this site are 38° 52′ 56.2″ N and 105° 10′ 26.3″ W. The site is at an elevation of about 9400 feet.

Two sites were located in forested areas of Ivywild-Catamount very gravelly sandy loam, 30 to 70 % slopes. The moderately deep, somewhat excessively drained Ivywild soil formed in colluvium, slope alluvium, or glacial till derived from granitic and metamorphic rocks. The shallow, excessively or somewhat excessively drained Catamount soil formed in residuum weathered from granite, gneiss, and schist. Large quantities of micas and hornblende were found in local deposits. The coordinates of these sites are 38° 52′ 43.7″ N and 105° 10′ 33.9″ W, and 38° 52′ 41.6″ N and 105° 10′ 34.1″ W. These sites are at an elevation of about 9500 feet.

Forest Service Site, Teller County:
This site was located about 5 miles north of the town of Divide. The site is forested and underlain by Pike Peak granite. It is located in an area of Sphinx gravelly coarse sandy loam, 15 to 40 % slopes. The shallow, somewhat excessively

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

drained Sphinx soil formed in materials derived from weathered granite. At this site, the bedrock was highly and deeply weathered and the soil contained numerous rock fragments (pebbles). The coordinates of this site are 39° 00′ 08″ N and 105 ° 09′ 52.3″ W. The site is at an elevation of about 9082 feet.

<u>Grainger's Ranch Site, Teller County:</u>
This site was located south of the town of Victor. The site is underlain by granodiorite and in an area of Raleigh very gravelly sandy loam, 5 to 55 % slopes. The coordinates of this site are 39° 00′ 08″ N and 105 ° 09′ 52.3″ W. The site is at an elevation of about 9082 feet.

<u>High Chaparral Turner Gulch, Park County:</u>
The site is in an area of Vorsid-Roster-Sawcreek complex, 3 to 20 % slopes. The shallow, well drained Vorsid and Roster soils formed in materials weathered from quartz-monzonite. The moderately deep, well to somewhat excessively drained Sawcreek soil formed in moderately coarse textured slightly acid parent materials weathered from brown or grayish brown noncalcareous soft sandstone. The coordinates of this site are 39° 02′ 39.8″ N and 105 ° 33′ 17.1″ W. The site is at an elevation of about 9120 feet.

<u>Antero Reservoir, Park County:</u>
The site is on the flood plain of the South Platte River. It is in an area of fine-loamy, mixed, superactive Typic Halaquepts. Soils are saline. The coordinates of this site are 38° 59′ 53.4″ N and 105 ° 52′ 14.7″ W. The site is at an elevation of about 8800 feet. Because of saline conditions, only EMI was used at this site.

<u>Salt Ranch, Park County:</u>
The site is in an area of Chittum-Woosley sandy loam, 5 to 20 % slopes. The shallow, well-drained Chittum soil formed in material weathered from sandstone. The moderately deep, well-drained Woosley soil formed in residuum and colluvium weathered from limestone or calcareous fine-grained sandstone. The coordinates of this site are 38° 55′ 42.4″ N and 105 ° 57′ 40.4″ W. The site is at an elevation of about 9140 feet.

<u>Arrowhead Ranch, Park County:</u>
The site is underlain by sandstone and shale of the Minturn and Belden formations. The Miniturn formation contains beds of red and gray shale, sandstone, conglomerate, and limestone. The Belden formation consists of dark gray shale, sandstone, and limestone. The site is in an area of Ula variant, 15 to 40 % slopes. The moderately deep, well drained Ula soil formed in material weathered from sandstone. Base saturation ranges from 60 to 100 percent. Rock fragments range from 15 to 35 percent and are mostly angular cobbles and pebbles. The coordinates of this site are 39° 4′ 45″ N and 106 ° 0′ 0.01″ W. The site is at an elevation of about 9340 feet.

<u>Neukirch Ranch, Park County:</u>
The site is underlain by limestone of the Minturn and Belden formations. The site is in an area of Chittum-Woosley sandy loam, 5 to 20 % slopes. The coordinates of this site are 39° 6′ 14.7″ N and 106 ° 00′ 1.2″ W. The site is at an elevation of about 9480 feet.

<u>Indian Mountain, Park County:</u>
The site is in an area of Rogert very gravelly sandy loam, 10 to 40 % slopes. The shallow, well-drained Rogert soil formed in thin layer of noncalcareous, very gravelly or channery materials weathered from quartz-monzonite. The coordinates of this site are 39° 16′ 14.5″ N and 105 ° 46′ 57.2″ W. The site is at an elevation of about 9600 feet.

<u>Alamosa soils, Costilla County:</u>
Two sites were located in areas that had been mapped as Alamosa soils. The deep, poorly to somewhat poorly drained Alamosa soil formed in moderately fine-textured alluvium on flood plains and alluvial fans. A fine-loamy, mixed, superactive, frigid Pachic Argiustolls dominated the first site. The coordinates of this site are 37° 21′ 24.1″ N and 105 ° 39′ 7.4″ W. A fine-loamy, mixed, superactive, frigid Typic Natrustolls dominated the second site. The coordinates of this site are 37 ° 20′ 47.3″ N and 105 ° 40 ′ 52.2″ W.

<u>Sangre de Cristo Mountains, Costilla County:</u>
Three sites were located within the Sangre de Cristo Mountains. The first site was located in an area of Blackhall soil. The very shallow and shallow, well drained Blackhall soil formed in material weathered from sandstone. The site is

underlain by Santa Fe sandstone. The coordinates of this site were lost. The site is located in the foothills of the Sangre de Cristo Mountains.

The second and third sites were forested and underlain by Sangre de Cristo gneiss. These sites are located in areas of Scout soil. The very deep, somewhat excessively drained Scout soil formed in colluvium, slope alluvium, and residuum weathered from sandstone, conglomerate, basalt, quartzite, rhyolite, andesite, and/or tuff. Scout soils are on mountain slopes, mesa summits, broad ridge tops, and spur ridges. The coordinates of the second site are 37 ° 17' 28.0" N and 105 ° 16 ' 43.5" W. The coordinates of third site are 37 ° 17' 9.6" N and 105 ° 16 ' 3.7" W.

Travelers and Garita soils, Costilla County:
Reconnaissance EMI surveys were conducted in areas of Travelers very stony loam, 3 to 9 % slopes, Travelers-Garita gravelly loam, 3 to 9 % slopes, and Garita gravelly sandy loam, 9-15 % slopes. The shallow, excessively drained Travelers soil formed in material weathered from basalt. Traveler soils are on basalt flows, or mesas capped by basalt. The deep, well-drained Garita soil formed in thick, calcareous, very gravelly, medium to moderately fine textured sediments weathered from basalt. Garita soils are on alluvial fans. Random traverses were conducted in these areas with the GEM300 sensor operating at a frequency of 14790 Hz. Multiple traverses were conducted in each map unit. Traverses were begun at the following coordinates 37.366331 N and 105.524063 W, 37.348173 N and 105.524883 W, and 37.334633 N and105.550563 W.

Vega Soils, Costilla County:
The study site was located on a flood plain near the town of San Luis. The very deep, well and moderately well drained, Vega soil formed in alluvium on narrow valleys and flood plains. A traverse line was extended across the flood plain. Saline soils and Histosols were observed along this traverse line. The origin of this traverse line was 37.196354 N and 105.42061 W. The traverse was conducted with the GEM300 sensor operating at a frequency of 14790 Hz.

**Field Procedures:**
Traverse lines were established across each site. Pulling the 400 and/or 200 MHz antenna along each traverse line completed the radar surveys. Multiple runs along the same traverse line were completed with each antenna at various range, filtration, and gain settings. Upon completion of each survey, radar profiles were printed and reviewed in the field. At each site, soil borings were conducted at several observation points to confirm radar interpretations.

At most sites, apparent conductivity was measured with the EM38 meter or the GEM300 sensor at observation points along each radar traverse line. Comparative EMI studies were completed at several sites. At these sites, grids were established on representative areas of the map unit. Grid dimensions and intervals varied with site conditions. Survey flags were inserted in the ground at each grid intersection and served as observation points. For comparative studies, as measurements were obtained in both the horizontal and vertical dipole orientations and precise positioning of instruments were required, the EM38 and EM38DD meters, and the GEM300 sensors were operated in a station-to-station rather than a continuous mode. Measurements were taken with the EM38 and EM38DD meters placed on the ground surface in both the horizontal and vertical dipole orientations. Measurements were taken at hip-height, in both the horizontal and vertical dipole orientations with the GEM300 sensor.

**Results:**
**GPR**
In areas of non-calcareous, coarse and coarse-loamy soils formed in materials weathered from granite, quartz-monzonite, gneiss, schist, or sandstone, GPR provides satisfactory observation depths to support soil survey operations. In areas underlain by schist, gneiss, and granite observation depths ranged from 3 to 4 m with the 200 MHz, and 1.5 to 2 m with the 400 MHz antennas. In these soils, with the exception of areas underlain by highly weathered saprolite, the soil/bedrock interface was discernible on radar profiles. In areas underlain by highly weathered Cr materials, reflections from the soil/bedrock interface were too weak to be reliably detected. Depth of penetration is directly associated with the clay and soluble salt contents of the soil. The GPR is unsuited to use in calcareous, saline, or, moderately fine and fine textured soils. Depth of penetration was comparable in upland areas of Mollisols, Inceptisols, and Entisols and did not appear to be adversely affected by the supposed higher base saturation of Mollisols. High contents of mica and hornblende were associated with the more rapid attenuation of the radar signals. These minerals were associated with more restricted GPR penetration depths.

In areas of Cathedral and Rogert soils, although intermittent reflections were evident to depths greater than 2.5 meters, well-expressed and continuous reflectors were generally restricted to depths of 1 to 1.5 m. In these soils, the soil/bedrock interface varied in amplitude and was difficult to consistently trace on radar profiles. In some areas numerous, chaotic point reflectors, believed to represent rock fragments in the soil and/or anomalies (phenocrysts, migmatites) within the bedrock, masked the soil/bedrock interface. Figure 1 is a representative profile from an area of Cathedral soils. The soil/bedrock interface has been highlighted with a dark line. This interface is highly interpretative and difficult to detect and trace laterally across this profile. Numerous sub-parallel, inclined reflectors frequently occur in sedimentary, meta-sedimentary and metamorphic rock (green lines in Figure 1 indicate some of these reflectors). These reflectors often represent bedding, fractures, or shear planes, or veins of dissimilar materials.

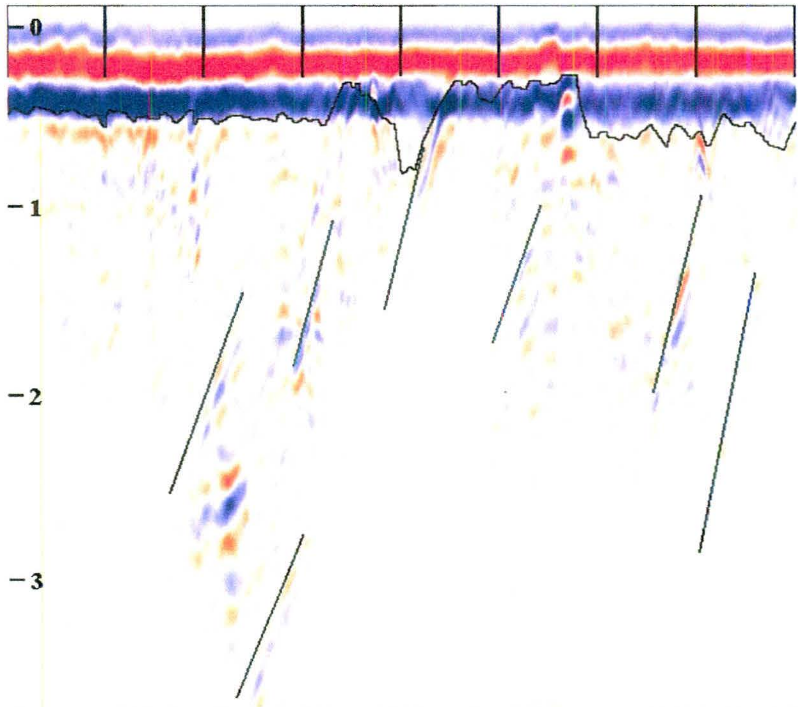


Figure 1. GPR profile obtained with 200 MHz antenna in an area of Cathedral very gravelly sandy loam, 20 to 50 % slopes. Depth scale is in m. The soil/bedrock interface has been identified with a dark line. Note sub-parallel reflectors in the quartz-monzonite bedrock.

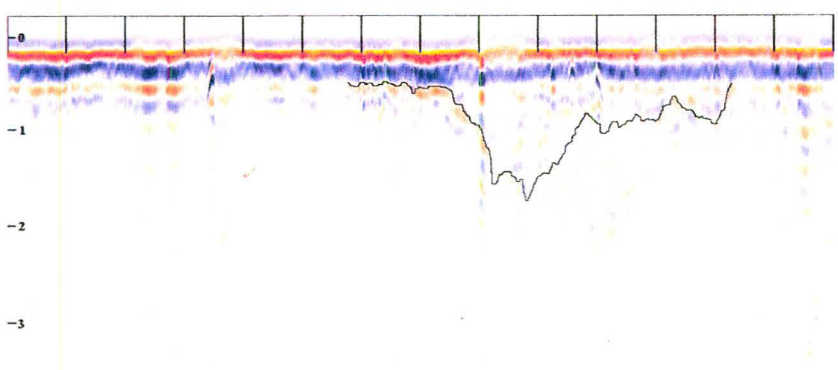


Figure 2. GPR profile obtained with 200 MHz antenna in an area of Ivywild-Catamount very gravelly sandy loam, 30 to 70 % slopes. Depth scale is in m. Note the general absence of reflectors in the Pike Peak granite bedrock.

In areas of deeply weathered Pike Peak granite (Catamount, Ivywild and Sphinx soils) the soil/bedrock interface was indistinct and often undetectable. The soil/bedrock interface was not uniformly expressed or easily detected on radar profiles. In some areas, reflections from this interface were too weak to be reliably detected. In other areas, coarse fragments in the overlying soil materials or inhomogeneities in the bedrock produced undesired reflections. These features produced spurious, chaotic reflections that often obscured the soil/bedrock interface. Figure 2 is a representative profile from and area of Catamount and Ivywild soils. The soil/bedrock interface is difficult to define and to trace laterally. The Pike Peak granite typically lacks noticeable reflectors.

In areas underlain by granodiorite (Raleigh soil), radar reflectors were generally intermittent below depths of about 2 m. In an area underlain by quartz-monzonite and grandiorite (Rogert, Roster and Vorsid soils) the maximum observation depth with the 200 MHz antenna ranged from 2 to 3 m. However, most reflectors were intermittent below depths of about 1.5 m. Numerous, chaotic point and planar reflectors made the soil/bedrock interface exceedingly difficult to identify on radar profiles. Soil bedrock interface was often defined by the upper boundary of dipping reflectors believed to represent stress plains or veins of dissimilar materials in the bedrock.

In areas underlain by shale, mudstone and limestone (of Chittum and Woosley soils), the maximum observation depth of the 200 MHz antenna was less than 1 m. However, shallow and moderately deep bedrock surfaces produced good reflectors that were traceable across radar profiles. In areas underlain by sandstone and conglomerate (Ula variant), the maximum observation depth of the 200 MHz antenna was about 2 m. However, reflectors were intermittent below depths of about 1.5 m. In addition, signal amplitudes were very weak along portions of the radar profile making interpretations difficult and more interpretative.

Results form these GPR investigations were encouraging. In many soils, GPR provided adequate observation depths for soil survey investigations. However, as the soil/bedrock interfaces were often obscured and poorly or discontinuously expressed, the interpretative quality of radar profiles was at best fair.

## **EMI**

*Comparative Studies with the EM38 and EM38DD Meters:*
Electromagnetic induction is being used increasingly for soil and agronomic studies. Electromagnetic induction has been used to assess depths to claypans (Doolittle et al., 1994; Stroh et al., 1993; Sudduth and Kitchen, 1993; and Sudduth et al., 1995), and to 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 also been used as a soil-mapping tool to assist precision farming (Jaynes, 1995; Jaynes et al., 1993; Sudduth et al., 1995).

For years, Geonics Limited has been the leader in EMI. Meters developed by Geonics Limited are widely used and accepted as standards by the research and applied geophysics community. The EM38 meter has been used extensively in soil survey investigations, salinity appraisals, and more recently for high intensity soil surveys and precision farming initiatives. High intensity soil surveys require mechanized EMI platforms that expedite fieldwork. These platforms provide a greater number of geo-referenced, apparent conductivity measurements that afford more comprehensive coverage of sites. In many soil investigations, responses from both dipole orientations are required. The horizontal dipole orientation is more sensitive to changes in apparent conductivity that occur near the surface. The vertical dipole orientation is more sensitive to changes in apparent conductivity that occurs at greater soil depths. Having both measurements greatly improve interpretations.

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 precludes the collection of data in both dipole orientations in the continuous mode. 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 has been recently developed (Geonics, 2000) to operate in the *continuous* mode and to simultaneously measure both dipole orientations without having to rotate or re-calibrate the meter.

In a comparative study with the EM38 meter in Illinois, 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, and Ohio, significant differences in measurements and resulting spatial patterns were obtained from data collected at the same observation points with the EM38 and EM38DD meters. This is of great concern, as closely matching results should be obtained with these meters.

Calibration errors and system noise are believed to be responsible for the incongruous 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 most sensitive to slight changes in the placement and orientation of the meter on the ground surface. As a consequence, slight changes in placement or orientation can cause significant changes in the measured response. These changes were most evident over resistive ground suggesting that much of the variability arises from the instrument itself rather than from the conductivity of the soil. It is believed that the amount of orientation variability can be lessened if the EM38DD is transported in a mechanically stable way. However, noise that is internal to the instrument will still appear in resistive terrain.

To test these assumptions, four comparative studies were conducted with the EM38 and EM38DD meters in areas of low to very high conductivity soil.

**Antero Reservoir, Parks County:**
The first comparative study was conducted in an area of saline soils near Antero Reservoir in Parks County. The study site was located in an area of fine-loamy, mixed, superactive Typic Halaquepts. Soils were saline. A 125 by 125 foot grid was established across the site. The grid interval was 25 ft. Survey flags were inserted in the ground at each grid intersection and served as observation points. This procedure provided 36 observation points. At each observation point measurements were obtained in both dipole orientations with the EM38 and EM38DD meters placed on the ground surface. Two surveys were completed with the EM38DD meter.

Basic statistics for the EM38 and EM38DD data are listed in Table 1. For the EM38 meter, apparent conductivity averaged 219.8 and 209.4 mS/m in the horizontal and vertical dipole orientations, respectively. For the first survey conducted with the EM38DD meter, apparent conductivity averaged 186.2 and 205.6 mS/m in the horizontal and vertical dipole orientations, respectively. For the second survey conducted with the EM38DD meter, apparent conductivity averaged 182.7 and 212.4 mS/m in the horizontal and vertical dipole orientations, respectively. Correlations between measurements obtained with the EM38DD meter in the two surveys were high (r = 0.92 and 0.94 in the horizontal and vertical dipole orientations, respectively).

**Table 1**
**Basic Statistics**
**Comparative EMI Surveys**
**Antero Reservoir, Park County**
(All values are in mS/m)

| | EM38DD-V | EM38DD-H | EM38DD-V | EM38DD-H | EM38V | EM38H |
|---|---|---|---|---|---|---|
| **Average** | 205.6 | 186.2 | 212.4 | 182.7 | 209.4 | 219.8 |
| **Minimum** | 132.0 | 84.0 | 124.0 | 71.0 | 139.0 | 105.0 |
| **Maximum** | 370.0 | 339.0 | 384.0 | 344.0 | 375.0 | 386.0 |
| **First** | 168.8 | 145.8 | 178.0 | 132.5 | 172.8 | 175.0 |
| **Third** | 234.5 | 215.5 | 251.5 | 242.8 | 225.5 | 250.3 |
| **Std. Deviation** | 52.5 | 66.3 | 54.8 | 67.4 | 50.9 | 65.6 |

In very highly conductive and saline soils at the Antero Reservoir site, measurements obtained with the EM38DD meter were, in general, similar to those obtained with the EM38 meter. The correlation between measurements obtained with EM38DD (first survey) and EM38 meters were 0.76 and 0.83 for measurements obtained in the horizontal and vertical dipole orientations, respectively. Correlations of 0.80 and 0.75 were obtained with the EM38DD (second survey) in the horizontal and vertical dipole orientations, respectively. With both meters, measurements obtained in the horizontal dipole orientation were more variable than measurements obtained in the vertical dipole orientation.

Figure 3 shows the spatial distribution of apparent conductivity collected with the EM38 meter. Patterns resulting from data collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 20 mS/m. The locations of the 36 observation points are shown in each plot. At a majority of observation points, apparent conductivity decreased and becomes less variable with increase depth (measurements obtained in horizontal dipole orientation were higher and more variable than measurements obtained in the vertical dipole orientation (see Table 1)). Values of apparent conductivity were very high throughout the site. In each plot, a band of higher conductivity extends across the western portion of the site from north to south. Lower values of apparent conductivity occur in the slightly higher-lying eastern portion and along the western boundary of the site.

Figure 4 shows the spatial distribution of apparent conductivity collected with the EM38DD meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. The left- and right-hand plots represent results from the two separate surveys. In each plot, the isoline interval is 20 mS/m. The locations of the 36 observation points are shown in each plot. Contrary to the results of the survey conducted with the EM38 meter, at a majority of observation points, apparent conductivity increased with increase depth (measurements obtained in vertical dipole orientation are higher than measurements obtained in the horizontal dipole orientation (see Table 1)). For both surveys completed with the EM38DD meter, spatial patterns were comparable and similar to those obtained with the EM38 meter. In each plot of Figure 4, a band of higher conductivity extends from north to south in the western portion of the site. Lower values of apparent conductivity occur in the slightly higher-lying eastern portion and along the western boundary of the site.

In this area of saline and very highly conductive soils, gross values of apparent conductivity (see Table 1) and spatial patterns are similar for the surveys conducted with the EM38DD (see Figure 4) meter and the EM38 meter (see Figure 3). Though exceptions can be noted, spatial patterns are similar for each meter and survey.

**Arrowhead Ranch, Park County:**
The Antero Reservoir site demonstrated the similarity of apparent conductivity values and spatial patterns obtained with the EM38 and EM38DD meters in an area of saline and very highly conductive soils. A second site was selected in Park County for comparative studies of the EM38 and EM38DD meters. This site was located at Arrowhead Ranch. The study site was located in an area that had been mapped as Ula variant, 15 to 40 % slopes. The moderately deep, well-drained Ula soil formed in material weathered from sandstone and has low apparent conductivity. A 100 by 60 foot grid was established across the site. The grid interval was 10 ft. Survey flags were inserted in the ground at each grid intersection and served as observation points. This procedure provided 77 observation points. At each observation point, measurements were obtained with the EM38 and EM38DD meters placed on the ground surface in both dipole orientations.

**Table 2**
**Basic Statistics**
**Comparative EMI Surveys**
**Arrowhead Ranch, Park County**
(All values are in mS/m)

| | EM38DD-V | EM38DD-H | EM38-V | EM38-H |
|---|---|---|---|---|
| **Average** | 22.5 | 10.5 | 4.6 | 2.8 |
| **Minimum** | 9.6 | -15.7 | 1.7 | 0.4 |
| **Maximum** | 31.5 | 35.1 | 12.0 | 10.2 |
| **First** | 18.9 | 3.4 | 3.7 | 1.7 |
| **Third** | 26.3 | 16.5 | 5.5 | 3.1 |
| **Std. Deviation** | 4.9 | 9.0 | 1.6 | 1.7 |

Basic statistics for the EM38 and EM38DD data are listed in Table 2. For the EM38 meter, apparent conductivity averaged 2.8 and 4.6 mS/m in the horizontal and vertical dipole orientations, respectively. For the EM38DD meter, apparent conductivity averaged 10.5 and 22.5 mS/m in the horizontal and vertical dipole orientations, respectively. In this area of low conductivity soils, values of apparent conductivity measured with the EM38DD meter were noticeably higher and more variable than those obtained with the EM38 meter. The higher measurements obtained with the EM38DD meter may reflect errors in calibration and the presence of two meters in close proximity to one another. The greater variability in measurements was attributed to coil misalignment on the more sloping terrain of this site.

At the Arrowhead Ranch site no to very weak correlations were found between measurements obtained with the EM38DD and EM38 meters ($r = 0.0349$ and $-0.1163$ for measurements obtained in the horizontal and vertical dipole orientations, respectively). Even though slight misplacement of the meters may have occurred, the lack of correlation between the two meters and the higher and more variable responses of the EM38DD meter were disturbing.

The upper and lower plots in Figure 5 show the spatial distribution of apparent conductivity collected at Arrowhead Ranch with the EM38 and the EM38DD meters, respectively. For each meter, the spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 4 mS/m. The locations of the 77 observation points are shown in the two upper plots (EM38 data).

A road cut adjacent to the south boundary of this site and rock outcrops revealed that the bedrock strike trends in a southeast to northwest direction. The bedrock was composed of different colored sandstone beds. In Figure 5, it is obvious from the spatial patterns that both the EM38 and EM38DD meters were insensitive to the bedrock strike or subtle changes in lithology.

The EM38 meter characterized the site as having low and comparatively invariable apparent conductivity (see Table 2). The site was characterized by the EM38 meter as consisting of fairly homogenous earthen materials. Spatial patterns evident in the data collected with the EM38 meter do not correspond to observed topographic or bedrock patterns. In Figure 5, faint, east-west trending patterns are expressed in the plots of the EM38 data. These features may represent variations in the depth to bedrock. Higher values of apparent conductivity were associated with higher clay contents, thicker soil columns, and greater depths to bedrock.

**Table 3**
**Stability of EMI Responses over Five Observation Point**
**Arrowhead Ranch, Park County**
(All values are in mS/m)

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 2.0 | 14.4 | 3.1 | 5.0 |
| 45 | 6.9 | 16.7 | 4.1 | 4.9 |
| 90 | 2.4 | 14.9 | 3.4 | 5.1 |
| 135 | 15.7 | 23.1 | 3.2 | 5.3 |
| 180 | 23.6 | 27.5 | 3.0 | 5.1 |
| **SD** | 9.34 | 5.74 | 0.44 | 0.15 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 18.2 | 4.7 | 4.7 | 4.9 |
| 45 | 21.6 | 14.5 | 6.1 | 6.2 |
| 90 | 31.0 | 40.0 | 5.1 | 5.5 |
| 135 | 22.9 | 20.4 | 2.6 | 4.7 |
| 180 | 21.3 | 2.7 | 2.3 | 5.5 |
| **SD** | 4.79 | 15.01 | 1.65 | 0.59 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 8.3 | 20.5 | 3.0 | 6.4 |
| 45 | 11.1 | 21.6 | 4.3 | 6.8 |
| 90 | -0.4 | 15.7 | 4.2 | 6.5 |
| 135 | 1.4 | 14.5 | 2.8 | 6.1 |
| 180 | -6.1 | 11.1 | 2.8 | 6.3 |
| **SD** | 6.90 | 4.35 | 0.76 | 0.26 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | -8.1 | 12.8 | 2.4 | 6.6 |
| 45 | -4.4 | 13.6 | 5.1 | 6.5 |
| 90 | 3.1 | 17.8 | 4.9 | 6.8 |
| 135 | 8.6 | 20.5 | 3.0 | 7.0 |
| 180 | 2.1 | 17.7 | 3.4 | 6.7 |
| **SD** | 6.57 | 3.21 | 1.19 | 0.19 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 2.2 | 17.4 | 2.8 | 5.8 |
| 45 | 10.0 | 20.8 | 3.9 | 6.0 |
| 90 | 1.7 | 15.6 | 5.7 | 6.6 |
| 135 | 1.6 | 19.3 | 2.4 | 6.6 |
| 180 | 3.4 | 17.4 | 2.3 | 6.0 |
| **SD** | 3.55 | 2.00 | 1.42 | 0.37 |

In contrast with the response of the EM38 meter, the EM38DD meter characterized the site as having higher and more variable apparent conductivity. In Figure 5, chaotic patterns of high and low apparent conductivity values suggest the presence of highly contrasting and anomalous subsurface features. Limited probing with a soil auger did not support these deviant values or spatial patterns.

During measurements, it was observed that slight changes in the orientation of the EM38DD meter produced significant changes in the meter's response. A test was conducted at five observation points to test the stability of measurements obtained with slight shifts in the orientation and position of the two meters. It is generally assumed that soil properties should not change radically within one meter of an observation point and that rotating a meter 180° should not significantly change a meter's response unless an anomalous feature such as a metallic object or artifact underlies it. At the five points, each meter was rotated in 45° increments through 180° over a known spot (survey flags were removed for this test). The results of this study are shown in Table 3.

At a given point, by rotating the meters, values of apparent conductivity varied by as much as 37.3 mS/m with the EM38DD meter and 3.8 mS/m with the EM38 meter. The average standard deviation for measurements obtained by rotating the EM38DD meter through five orientations at five points was about 6.2 and 6.1 mS/m in the horizontal and vertical dipole orientations, respectively. In comparison, the average standard deviation for measurements obtained by rotating the EM38 meter through five orientations at five points was only about 1.1 and 0.3 mS/m in the horizontal and vertical dipole orientations, respectively. The maximum range in apparent conductivity that was observed by rotating the EM38DD meter at a given point (see Table 3) exceeded the range observed across the entire site (see Table 2). It was concluded from this study that in areas of low conductivity soils, the EM38DD meter produced non-reproducible and unreliable data.

**Alamosa Soil, Costilla County:**
Site 1
Two study sites were selected in Costilla County to further compare the results of measurements obtained with the EM38 and EM38DD meters. Both sites were located in areas that had been mapped as Alamosa soil. The first site was located in an area of a fine-loamy, mixed, superactive, frigid Pachic Argiustolls. A 140 by 140 foot grid was established across the selected site. The grid interval was 20 ft. Survey flags were inserted in the ground at each grid intersection and served as observation points. This procedure provided 64 observation points.

Basic statistics for the EM38 meter are listed in Table 4. The EM38 meter characterized the site as having a low and exceedingly invariable (both spatially and vertically) apparent conductivity. For the first survey conducted with the EM38 meter, apparent conductivity averaged 7.6 and 7.4 mS/m in the horizontal and vertical dipole orientations, respectively. For the second survey conducted with the EM38 meter, apparent conductivity averaged 7.5 and 7.4 mS/m in the horizontal and vertical dipole orientations, respectively. The Pearson correlation coefficients for measurements obtained with the EM38 meter in the two surveys were 0.73 and 0.58 in the horizontal and vertical dipole orientations, respectively.

**Table 4**
**Basic Statistics**
**EM38DD and EM38 Meters**
**Area of Pachic Argiustolls, Costilla County**
(All values are in mS/m)

| | EM38DD-V | EM38DD-H | EM38DD-V | EM38DD-H | EM38-V | EM38-H | EM38-V | EM38-H |
|---|---|---|---|---|---|---|---|---|
| **Average** | 10.8 | 8.6 | 14.4 | 3.2 | 7.4 | 7.6 | 7.4 | 7.5 |
| **Minimum** | 0.7 | -2.9 | 4.4 | -5.8 | 4.9 | 5.5 | 4.8 | 4.7 |
| **Maximum** | 21.2 | 23.1 | 22.2 | 14.6 | 9.7 | 12.7 | 9.5 | 12.4 |
| **First** | 8.0 | 4.7 | 11.4 | -0.1 | 6.7 | 6.6 | 6.5 | 6.5 |
| **Third** | 14.5 | 13.1 | 17.7 | 5.7 | 8.1 | 8.1 | 8.1 | 8.6 |
| **SD** | 4.7 | 5.7 | 4.3 | 4.8 | 1.0 | 1.4 | 1.1 | 1.5 |

Figure 6 shows the spatial distribution of apparent conductivity collected with the EM38 meter. The upper and lower sets of plots represent the two separate surveys. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left- and right-hand plots, respectively. In each plot, the isoline interval is 4 mS/m. The locations of the 64 observation points are shown in the upper, left-hand plot. Other than showing relatively low and invariable conductivities, the plots are not similar. This was not unexpected. The low range in apparent conductivity (about 4 to 8 mS/m) coupled with the small isoline interval (4 mS/m) used in these plots, and the modest drift (1 to 2 mS/m) in the EM38 meter measurements at these low induction numbers produce the seemingly divergent spatial patterns.

Basic statistics for the EM38DD meter are also listed in Table 4. Data obtained with the EM38DD meter characterized the site as having low, but more variable (both spatially and vertically) apparent conductivity than did data obtained with the EM38 meter. For the first survey conducted with the EM38DD meter, apparent conductivity averaged 8.6 and 10.8 mS/m in the horizontal and vertical dipole orientations, respectively. For the second survey conducted with the EM38DD meter, apparent conductivity averaged 3.2 and 14.4 mS/m in the horizontal and vertical dipole orientations, respectively. Correlations between measurements obtained in the two surveys with the EM38DD meter were 0.50 and 0.38 in the horizontal and vertical dipole orientations, respectively. These values were lower than those obtained with the EM38 meter.

Figure 7 shows the spatial distribution of apparent conductivity collected with the EM38DD meter. The upper and lower sets of plots represent the two different surveys. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left- and right-hand plots, respectively. In each plot, the isoline interval is 4 mS/m. The locations of the 64 observation points are shown in the upper, left-hand plot. For an area of low conductivity soil, the spatial patterns are exceedingly complex and chaotic. No repeating or similar patterns can be discerned from these plots. Once again, the operator noticed conspicuous changes in the meter's response with slight changes in the alignment of the meter.

**Table 5**
**Stability of EMI Responses over Six Observation Point**
**Area of Pachic Argiustolls, Costilla County**
(All values are in mS/m)

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 0.5 | 8.5 | 9.6 | 8.3 |
| 45 | 5.0 | 11.4 | 9.8 | 10.6 |
| 90 | 4.7 | 8.5 | 10.4 | 11.8 |
| 135 | 4.4 | 8.5 | 10.4 | 8.7 |
| 180 | 1.1 | 8.0 | 10.6 | 8.9 |
| **SD** | 2.18 | 1.37 | 0.43 | 1.48 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 4.0 | 9.3 | 5.3 | 9.2 |
| 45 | 7.4 | 11.7 | 6.4 | 8.4 |
| 90 | -1.0 | 6.4 | 6.7 | 8.4 |
| 135 | 1.1 | 4.1 | 6.6 | 8.4 |
| 180 | 9.8 | 12.5 | 5.8 | 8.4 |
| **SD** | 4.42 | 3.54 | 0.59 | 0.36 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 5.2 | 8.2 | 5.4 | 8.1 |
| 45 | 11.4 | 11.5 | 8.4 | 7.7 |
| 90 | 10.3 | 11.4 | 9.0 | 7.7 |
| 135 | 6.1 | 7.5 | 9.3 | 7.5 |
| 180 | 14.1 | 12.1 | 9.4 | 7.8 |
| **SD** | 3.72 | 2.12 | 1.67 | 0.22 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 4.1 | 7.2 | 8.6 | 8.6 |
| 45 | 3.8 | 5.2 | 7.5 | 8.8 |
| 90 | 10.7 | 10.6 | 7.6 | 8.8 |
| 135 | 10.2 | 14.8 | 7.7 | 8.6 |
| 180 | 2.1 | 7.5 | 7.8 | 8.8 |
| **SD** | 3.98 | 3.74 | 0.44 | 0.11 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 8.2 | 11.1 | 7.2 | 9.9 |
| 45 | -0.4 | 4.6 | 7.6 | 9.0 |
| 90 | 7.9 | 11.8 | 8.0 | 9.5 |
| 135 | 10.0 | 12.0 | 7.6 | 9.8 |
| 180 | 3.8 | 10.4 | 8.1 | 9.7 |
| **SD** | 4.19 | 3.07 | 0.36 | 0.36 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | -1.5 | -0.6 | 10.1 | 9.8 |
| 45 | 25.9 | 20.0 | 10.4 | 9.3 |
| 90 | 14.2 | 12.5 | 7.8 | 8.9 |
| 135 | 5.2 | 7.8 | 7.6 | 8.8 |
| 180 | -0.1 | 3.4 | 11.0 | 9.6 |
| **SD** | 11.40 | 8.02 | 1.57 | 0.43 |

Another test was conducted to test the stability of measurements obtained with slight shifts in the orientation and position of the two meters. At six observation points, each meter was rotated in 45° increments through 180° over a known spot. The results of this study are shown in Table 5. At a given point, by rotating the meters, values of apparent conductivity varied by as much as 27.4 mS/m with the EM38DD meter and 3.9 mS/m with the EM38 meter. The average standard deviation for measurements obtained by rotating the EM38 meter through five orientations at six points was only about 0.8 and 0.5 mS/m in the horizontal and vertical dipole orientations, respectively. In comparison, the average standard deviation for measurements obtained by rotating the EM38DD meter through five orientations at six points was about 5.0 and 3.75 mS/m in the horizontal and vertical dipole orientations, respectively. Once again, the maximum range in apparent conductivity that was observed by rotating the EM38DD meter at a given observation point (see Table 5) exceeded the range observed across the entire site (see Table 4). Once again, in this area of low conductivity soils, the EM38DD meter produces non-reproducible and unreliable data.

Site 2
The second site was located in an area that had also been mapped as Alamosa soil. However, at this site the dominant soil was a fine-loamy, mixed, superactive, frigid Typic Natriustolls. A 140 by 140 foot grid was established across the site. The grid interval was 20 ft. Survey flags were inserted in the ground at each grid intersection and served as observation points. This procedure provided 64 observation points.

Basic statistics for measurements obtained with the EM38 meter are listed in Table 6. The EM38 meter characterized the site as having a low to very high apparent conductivity. For the first survey conducted with the EM38 meter, apparent conductivity averaged 35.7 and 45.9 mS/m in the horizontal and vertical dipole orientations, respectively. For the second survey conducted with the EM38 meter, apparent conductivity averaged 36.4 and 43.9 mS/m in the horizontal and vertical dipole orientations, respectively. The Pearson correlation coefficients for measurements obtained with the EM38 meter in the two surveys were 0.95 and 0.93 in the horizontal and vertical dipole orientations, respectively.

**Table 6**
**Basic Statistics**
**EM38DD and EM38 Meters**
**Area of Typic Natriustolls, Costilla County**
(All values are in mS/m)

| | EM38DD-V | EM38DD-H | EM38DD-V | EM38DD-H | EM38-V | EM38-H | EM38-V | EM38-H |
|---|---|---|---|---|---|---|---|---|
| **Average** | 55.6 | 43.6 | 55.5 | 43.3 | 45.9 | 35.7 | 43.9 | 36.4 |
| **Minimum** | 23.0 | 5.3 | 28.0 | 11.5 | 18.0 | 10.5 | 16.2 | 10.5 |
| **Maximum** | 106.5 | 125.5 | 99.3 | 108.9 | 103.5 | 133.5 | 94.4 | 110.6 |
| **First** | 43.1 | 32.0 | 43.7 | 31.3 | 33.7 | 24.2 | 31.5 | 26.5 |
| **Third** | 66.0 | 53.2 | 64.2 | 52.1 | 53.0 | 39.1 | 51.7 | 43.3 |
| **SD** | 17.7 | 20.0 | 16.8 | 18.3 | 16.5 | 20.4 | 16.8 | 19.8 |

Figure 8 shows the spatial distribution of apparent conductivity collected with the EM38 meter. The upper and lower sets of plots represent the two separate surveys. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left- and right-hand plots, respectively. In each plot, the isoline interval is 10 mS/m. The locations of the 64 observation points are shown in the upper, left-hand plot. Plots of data collected with the EM38 meter in the same dipole orientation are similar. The wide range in apparent conductivity coupled with the relatively large isoline interval (10 mS/m) combined to produce these similar spatial patterns.

Basic statistics for measurements obtained with the EM38DD meter are listed in Table 6. The EM38DD meter also characterized the site as having low to very high apparent conductivity. For the first survey conducted with the EM38DD meter, apparent conductivity averaged 43.6 and 55.6 mS/m in the horizontal and vertical dipole orientations, respectively. For the second survey conducted with the EM38DD meter, apparent conductivity averaged 43.3 and 55.5 mS/m in the horizontal and vertical dipole orientations, respectively. Correlations between measurements obtained with the EM38DD meter in the two surveys were 0.81 and 0.75 in the horizontal and vertical dipole orientations, respectively.

Figure 9 shows the spatial distribution of apparent conductivity collected with the EM38DD meter. The upper and lower sets of plots represent data obtained in the two separate surveys. For each survey, the spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left- and right-hand plots, respectively. In each plot, the isoline interval is 10 mS/m. The locations of the 64 observation points are shown in the upper, left-hand plot.

In Figure 9, the spatial patterns are exceedingly complex and chaotic. While the gross spatial patterns of measurements collected in the same dipole orientation are vaguely similar, responses vary greatly from one observation point to the next resulting in a large number of isolated delineations that surround individual observation points. This trend reflects the changes in response that were observed with slight changes in the alignment of the EM38DD meter.

Previous studies indicate that measurements obtained with the EM38DD meter will vary substantially depending on its placement on the ground surface. To further confirm this observation, another stability test was performed. At each observation point, each meter was placed on the ground surface and measurements recorded in both dipole orientations, as the meter was rotated 0, 45, 90, 135, and 180 degrees over a known spot. Table 7 is a summary of the standard deviations observed at each point with each meter and dipole orientation. It is apparent from Table 7 that measurements obtained with the EM38 meter are fairly stable and replicable. Measurements obtained with the EM38DD meter, especially in the horizontal dipole orientation, were highly variable at each point.

At a given point, by rotating the meters, values of apparent conductivity varied by as much as 46.0 mS/m with the EM38DD meter and 7.2 mS/m with the EM38 meter. The average standard deviation for measurements obtained by rotating the EM38DD meter through five orientations at six points was 12.8 and 7.0 mS/m in the horizontal and vertical dipole orientations, respectively. In comparison, the average standard deviation for measurements obtained the EM38 meter through five orientations at six points was only 1.3 and 0.75 mS/m in the horizontal and vertical dipole orientations, respectively. These test confirm that the EM38DD meter produces non-reproducible and therefore unreliable data.

**Table 7**
**Stability of EMI Responses over Six Observation Point**
**Area of Typic Natriustolls, Costilla County**
(All values are in mS/m)

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 13.0 | 40.9 | 33.2 | 48.7 |
| 45 | 16.3 | 43.3 | 34.9 | 47.8 |
| 90 | 7.6 | 42.1 | 35.0 | 48.7 |
| 135 | 50.8 | 61.9 | 35.5 | 49.6 |
| 180 | 51.1 | 43.3 | 33.9 | 48.8 |
| **SD** | 21.40 | 8.78 | 0.93 | 0.64 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 54.5 | 70.5 | 53.3 | 60.2 |
| 45 | 57.5 | 72.1 | 53.4 | 61.1 |
| 90 | 63.2 | 75.3 | 60.5 | 63.2 |
| 135 | 52.1 | 70.6 | 57.2 | 61.8 |
| 180 | 25.2 | 52.9 | 54.4 | 60.6 |
| **SD** | 14.74 | 8.81 | 3.08 | 1.18 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 27.0 | 47.3 | 30.3 | 47.5 |
| 45 | 33.3 | 55.2 | 29.0 | 47.6 |
| 90 | 7.2 | 42.8 | 32.9 | 50.3 |
| 135 | 9.3 | 42.5 | 32.1 | 49.8 |
| 180 | 53.5 | 64.4 | 32.0 | 47.2 |
| **SD** | 18.99 | 9.34 | 1.58 | 1.45 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 16.2 | 37.0 | 26.9 | 39.3 |
| 45 | 24.2 | 42.1 | 26.9 | 39.2 |
| 90 | 7.4 | 32.4 | 26.4 | 39.2 |
| 135 | 21.6 | 39.4 | 27.2 | 39.6 |
| 180 | 24.6 | 44.1 | 29.9 | 40.8 |
| **SD** | 7.20 | 4.56 | 1.39 | 0.68 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 17.9 | 23.0 | 16.5 | 20.4 |
| 45 | 18.2 | 20.4 | 16.4 | 20.4 |
| 90 | 26.9 | 26.5 | 15.2 | 19.8 |
| 135 | 25.7 | 27.1 | 16.6 | 19.7 |
| 180 | 23.3 | 24.1 | 17.5 | 20.1 |
| **SD** | 4.18 | 2.72 | 0.82 | 0.33 |

| Rotation | 38DD-H | 38DD-V | 38-H | 38-V |
|---|---|---|---|---|
| 0 | 24.1 | 24.3 | 10.2 | 15.2 |
| 45 | 2.8 | 7.4 | 10.4 | 14.7 |
| 90 | 15.3 | 18.5 | 10.0 | 14.6 |
| 135 | 26.4 | 25.7 | 10.2 | 14.7 |
| 180 | 8.3 | 13.0 | 10.2 | 14.9 |
| **SD** | 10.07 | 7.69 | 0.14 | 0.24 |

*Multifrequency Sounding with GEM300 Sensor:*
The GEM300 sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.6 m). By using multiple frequencies, multiple depths can supposedly be profiled with one pass of the sensor. However, the use of up to sixteen frequency can create an unreasonable amount of time devoted to data processing

interpretations and displays. We must ask the question: is the amount of EMI data collected needed and commensurate with the desired depth of observation and the availability of adequate ground-truth data?

Most soil scientists prefer working with the GEM300 sensor to the EM38 meter. The GEM300 sensor is keypad operated and therefore quick and easy to setup, it does not require re-nulling when measurements in two dipole orientations are recorded, and data is stored on a hard drive and can quickly be downloaded into a PC. In addition, surveys are preformed with the sensor held at waist height and not placed on the ground surface.

Does the use of multiple frequencies with the GEM300 sensor provide multiple depths and interpretation? To find out, a 150 by 150 ft was established in an area of Traveler soil in Costilla County. The grid interval was 25 feet. Survey flags were inserted in the ground at each grid intersection and served as observation points. This procedure resulted in 49 observation points. The grid was surveyed with the GEM300 sensor using six different frequencies: 6030, 7650, 9810, 12330, 14790, and 19950 Hz. Negative numbers occurred in the measurements as the sensor was not zero adjusted

Basic statistics for the GEM300 sensor are shown in Table 8. The GEM300 sensor characterized the site as having low and comparatively invariable apparent conductivity.

**Table 8**
**Basic Statistics**
**GEM300 Sensor – Vertical Dipole Orientation**
**Area of Traveler Soil, Costilla County**
(All values are in mS/m)

| | 6030V | 7650V | 9810V | 12330V | 14790V | 19950V |
|---|---|---|---|---|---|---|
| **Average** | 0.74 | 2.61 | -0.13 | 3.63 | 4.42 | 5.36 |
| **Minimum** | -6.69 | -3.15 | -5.94 | -2.22 | -0.46 | 0.92 |
| **Maximum** | 15.04 | 15.34 | 12.11 | 13.61 | 14.46 | 15.01 |
| **SD** | 4.82 | 4.24 | 3.93 | 3.59 | 3.21 | 2.93 |

The effective penetration depth of the GEM300 sensor is dependent upon the apparent conductivity of the profiled material(s) and the operating frequency. With the GEM300 sensor, the depth of penetration is considered "*skin depth limited.*" Skin depth represents the maximum depth of penetration for an EMI instrument operating at a specific frequency and sounding a medium of known conductivity. The skin depth (D) can be estimated using the following equation (McNeill, 1996):

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

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

According to equation [1], skin depth is inversely proportional to the operating frequency and the apparent conductivity of the profiled materials. In a specified soil, greater penetration depths can be achieved by decreasing the frequency. Low frequency signals have longer periods of oscillation and lose energy less rapidly than high frequency signals. As a consequence, low frequency signals travel farther through conductive mediums than high frequency signals.

At the Traveler site, with the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 0.74, 2.61, -0.13, 3.63, 4.42, and 5.36 mS/m at frequencies of 6030, 7650, 9810, 12330, 14790, and 19950 Hz, respectively. Based on equation [1], the selected frequencies and these averaged conductivities, the estimated skin depths were 237 m at 6030 Hz, 112 m at 7650 Hz, 442 m at 9810 Hz, 75 m at 12330 Hz, 62 m at 14790 Hz and 48 m at 19950 Hz. These depths are hypothetical and a bit absurd. While the induced magnetic fields may achieve these depths, the strengths of the response from these depths are undoubtedly too weak to be sensed by the GEM300.

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. Others have made a distinction between the *depth of observation* and the *depth of penetration.* The depth of penetration or the skin depth is the maximum depth that an electromagnetic field will attain in a

medium of known conductivity at a given frequency. The *depth of observation* is 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, the contribution from the *depth of observation* is the largest. The *depth of observation* is a good deal shallower than the depth of penetration.
Figure 10 shows the spatial distribution of apparent conductivity collected with the GEM300 sensor operating at six frequencies and in the vertical dipole orientation. Negative values appear, as zero adjustments were not made to the data set. In each plot, the isoline interval is 3 mS/m. The locations of the 49 observation points are shown in the upper, left-hand plot. The plots appearing in Figure 10 are remarkably similar. In each plot, values of apparent conductivity are highest in the lower part and in lower left-hand corner of the survey area. These portions of the survey area were the lowest lying and had the greatest thickness of colluvium overlying the bedrock. In each plot, values of apparent conductivity are lowest in the upper part and in the upper right-hand corner of the survey area. These portions of the survey area were the highest lying and had basalt outcrops or thin layers of colluvium overlying the bedrock.

Multifrequency soundings at six frequencies with the GEM300 sensor operated in the vertical dipole orientation produced similar spatial patterns. As these patterns are similar, it is assumed that the depth of observation for GEM300 sensor at each of the six frequencies is also comparable. Spatial patterns displayed in each plot reflect soil/bedrock patterns observed in the field and do confirm interpretive models. Interpretations were neither changed nor improved with multifrequency soundings. While slightly different spatial patterns are evident in the six plots in Figure 10, these differences are not considered significant. With anticipated backhoe observations relationships between bedrock depths and apparent conductivity will be confirmed.

Table 9 shows the correlation coefficients for measurements obtained with the GEM300 sensor operating at different frequencies and in the vertical dipole orientation. Correlations are extraordinarily high and all are significant at the .001 level. These relationships suggest that the GEM300 sensor does have different penetration depth but is most sensitive to changes in apparent conductivity that occurs at shallow depths, or is measuring similar depths and volumes of soil materials at the different frequencies.

**Table 9**

**Correlation Between Apparent Conductivity Measurements obtained with the GEM300 Sensor Operating at Different Frequencies and in the Vertical Dipole Orientations.**

| | 6030V | 7650V | 9810V | 12330V | 14790V | 19950V |
|---|---|---|---|---|---|---|
| **6030V** | 1.000 | 0.990 | 0.989 | 0.979 | 0.974 | 0.957 |
| **7650V** | | 1.000 | 0.992 | 0.984 | 0.985 | 0.967 |
| **9810V** | | | 1.000 | 0.988 | 0.986 | 0.973 |
| **12330V** | | | | 1.000 | 0.985 | 0.986 |
| **14790V** | | | | | 1.000 | 0.986 |
| **19950V** | | | | | | 1.000 |

The GEM300 sensor appears to be most sensitive to soil properties that occur at shallow depths. The depth of observation is restricted. For most soil investigations with the GEM300 sensor, the use of one frequency with measurements in both dipole orientations will provide as much information as multifrequency soundings. If the GEM300 sensor does achieve greater depths of observation and dissimilar spatial patterns are displayed at lower frequencies, we do not have the tools to physically investigate these greater depths.

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# EMI SURVEY - ANTERO RESERVOIR
# PARK COUNTY, COLORADO
# EM38 METER
# Typic Halaquepts

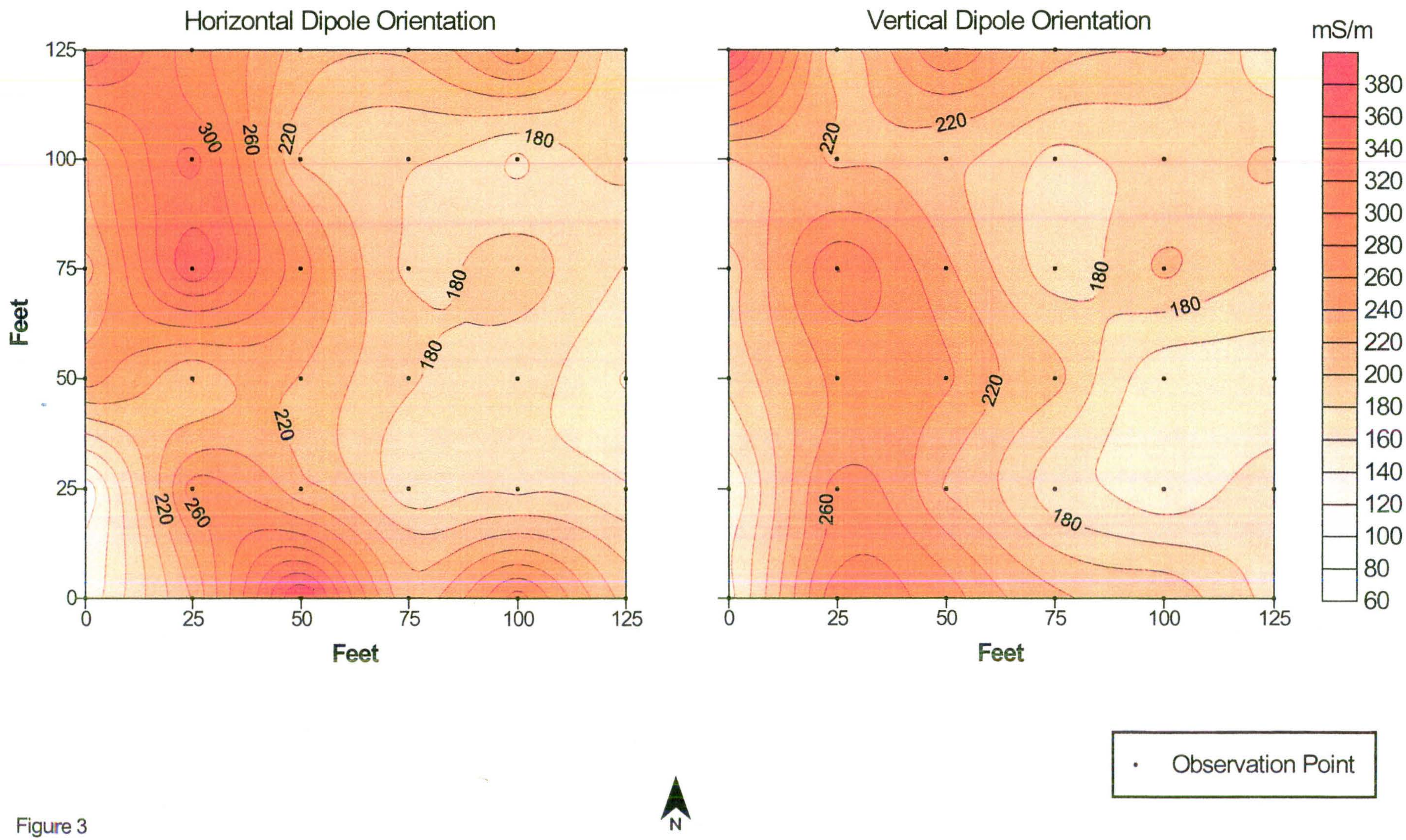


Figure 3

# EMI SURVEY - ANTERO RESERVOIR
# PARK COUNTY, COLORADO
# EM38-DD METER
# COMPARISON OF TWO SURVEYS
# Typic Halaquepts

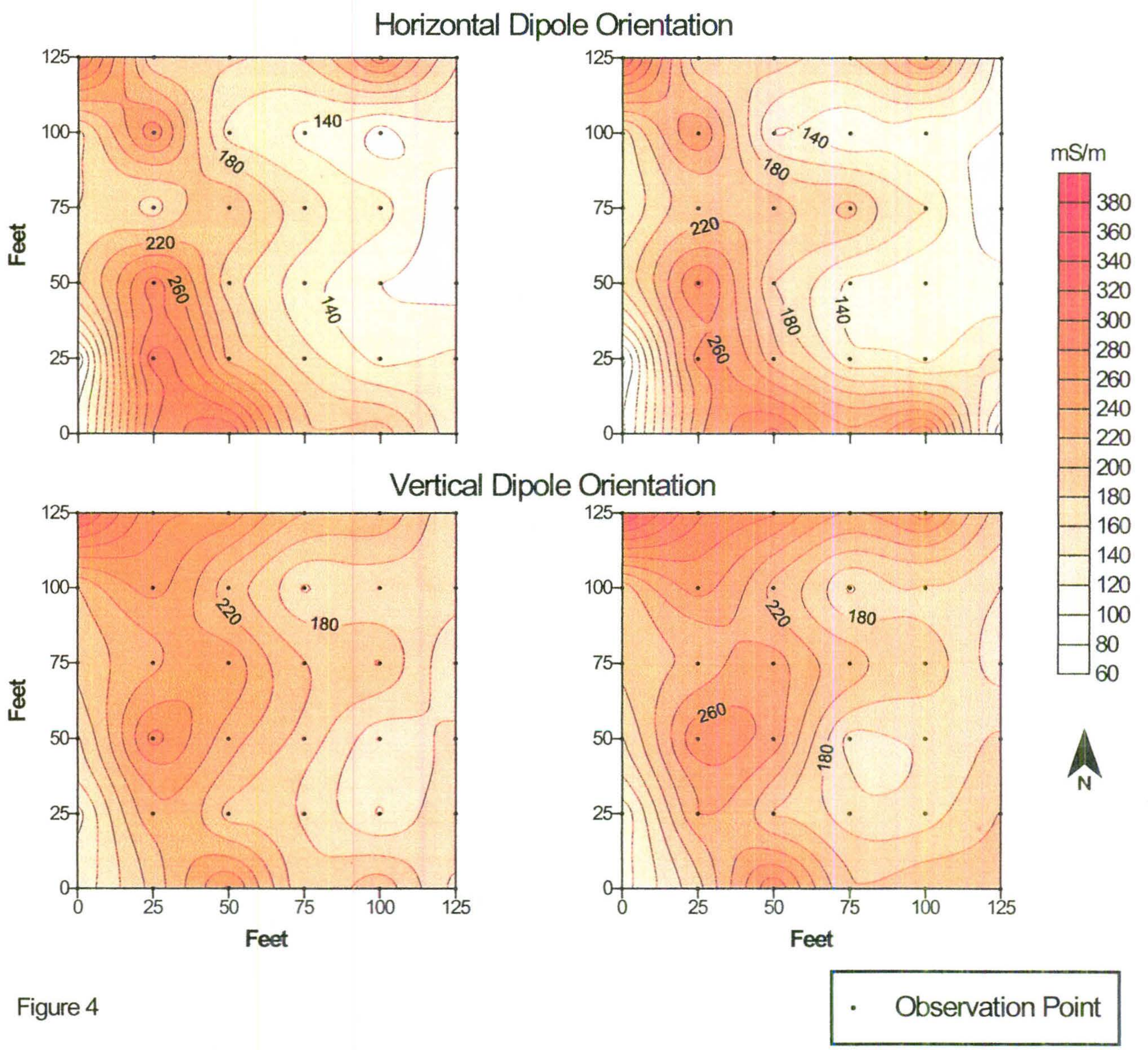


Figure 4

# COMPARISON OF EM38 & EM38DD METERS
# AREA OF ULA VARIANT

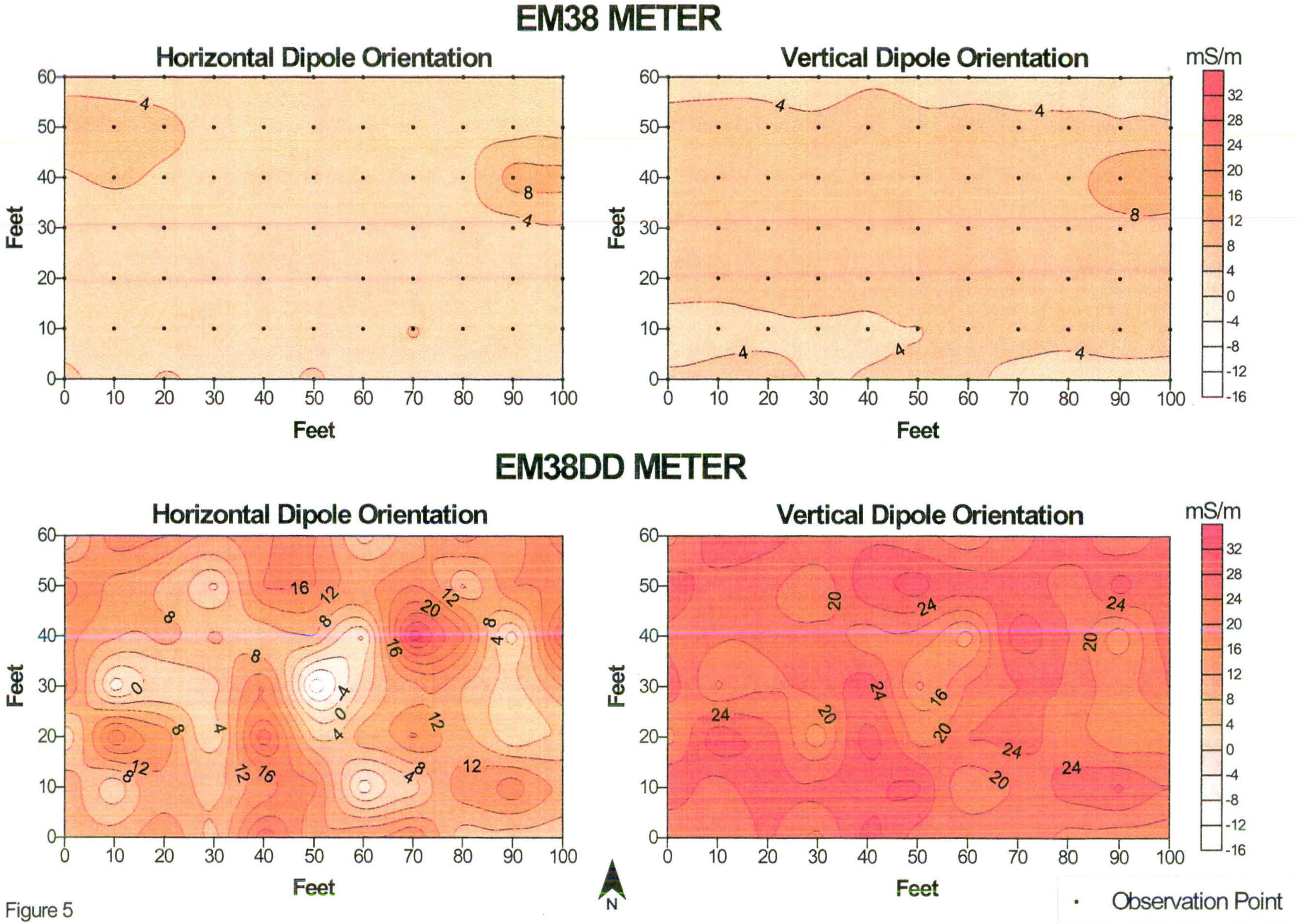


Figure 5

# COMPARISON OF EMI DATA FROM TWO SURVEYS CONDUCTED WITH EM38 METER
# Pachic Argiustolls

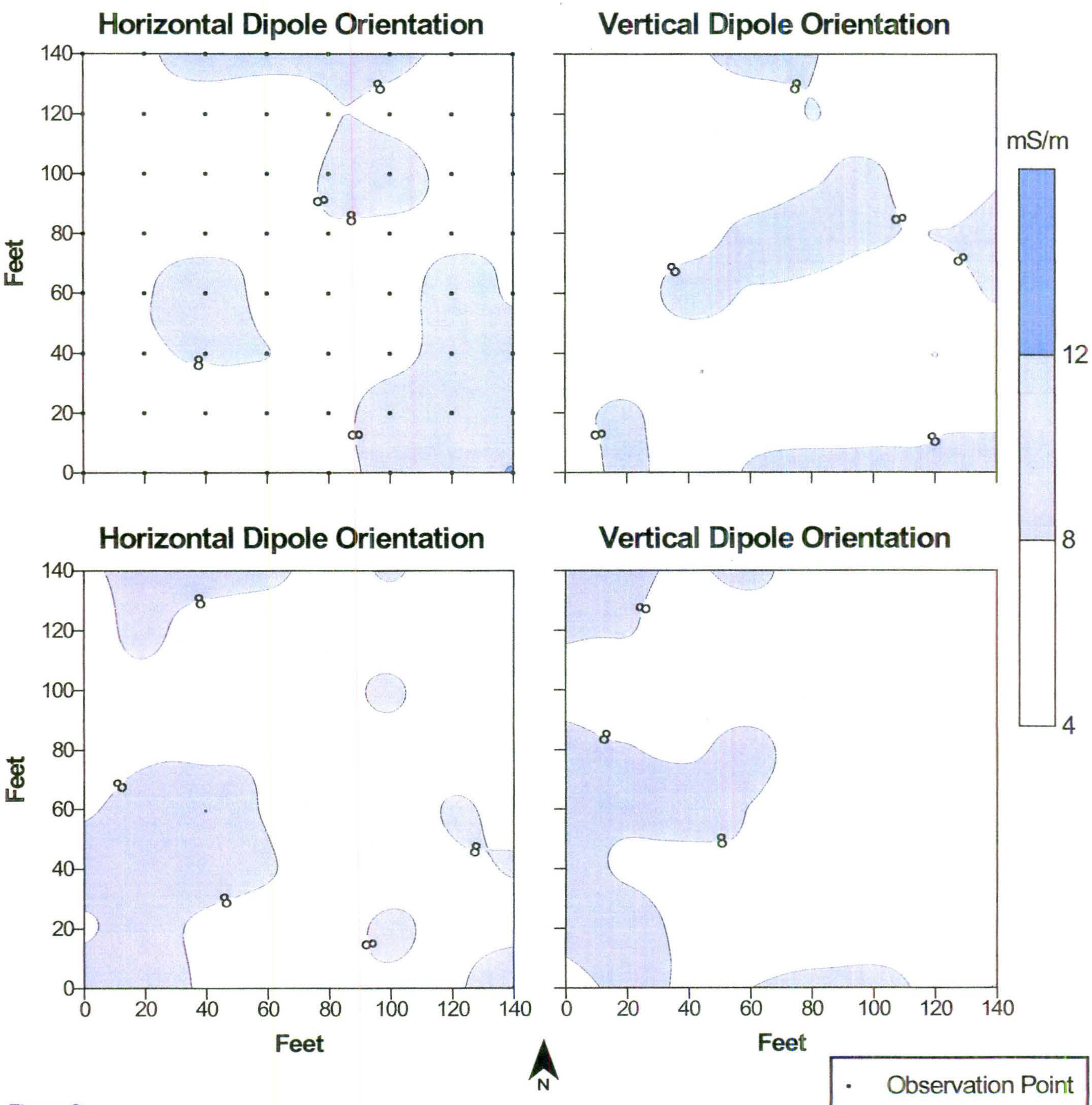


Figure 6

# COMPARISON OF EMI DATA
# TWO SURVEYS CONDUCTED WITH
# EM38DD METER
# Pachic Argiustolls

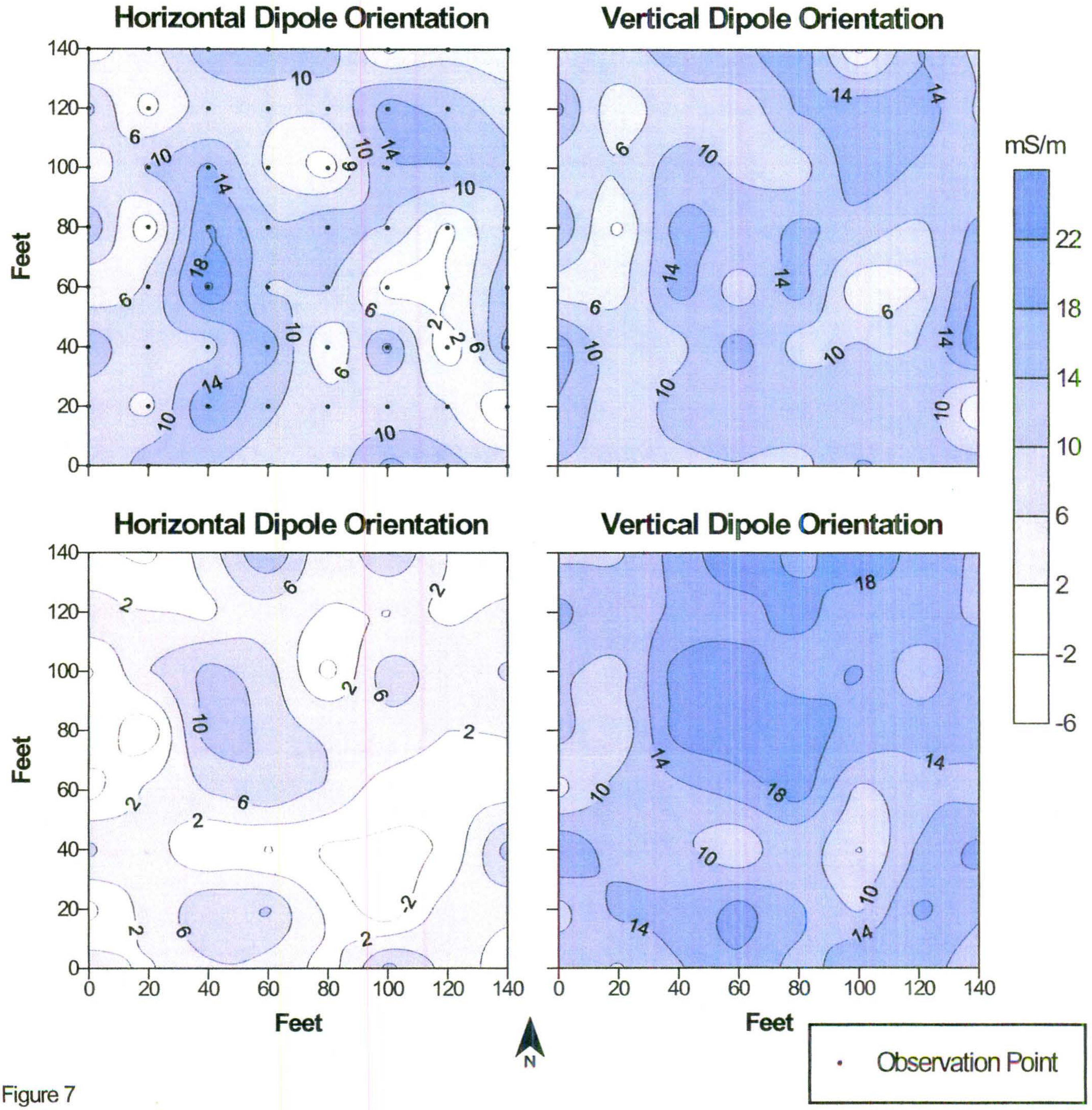


Figure 7

# COMPARISON OF EMI DATA TWO SURVEYS CONDUCTED WITH EM38 METER Typic Natrustolls

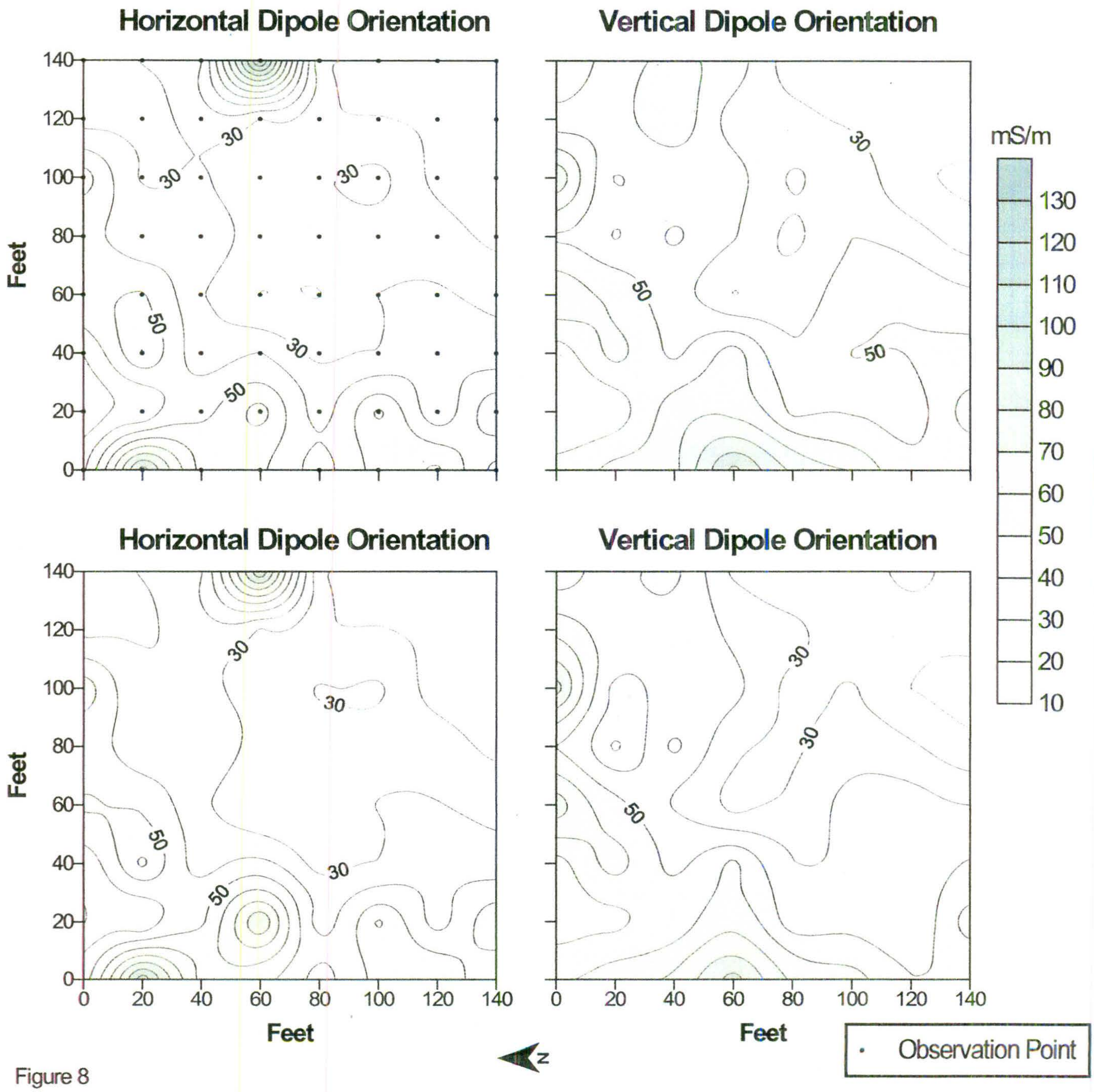


Figure 8

# COMPARISON OF EMI DATA
# TWO SURVEYS CONDUCTED WITH
# EM38DD METER
# Typic Natrustolls

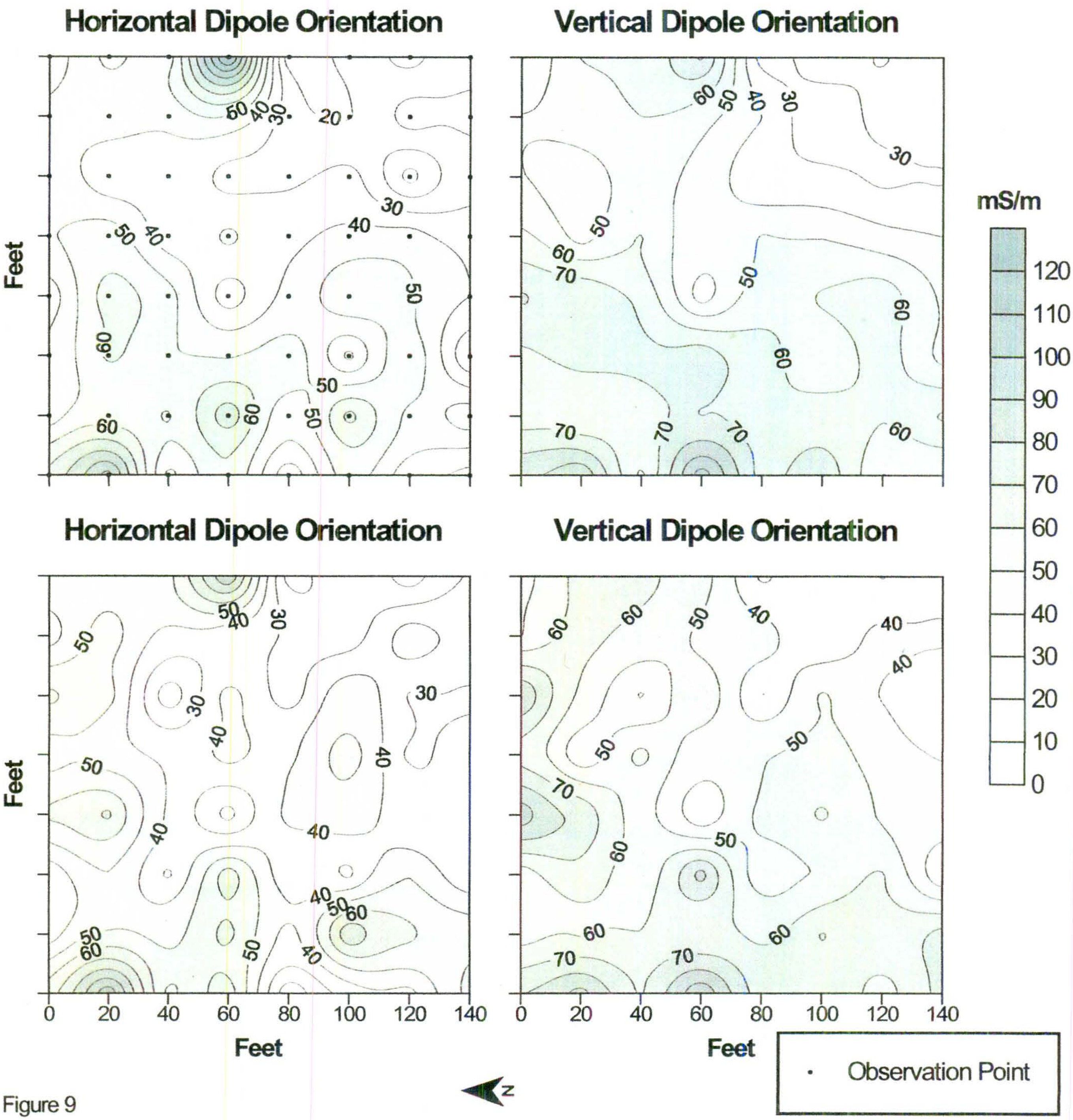


Figure 9

# GEM300 SENSOR
# VERTICAL DIPOLE ORIENTATION
# Area of Traveler Soil

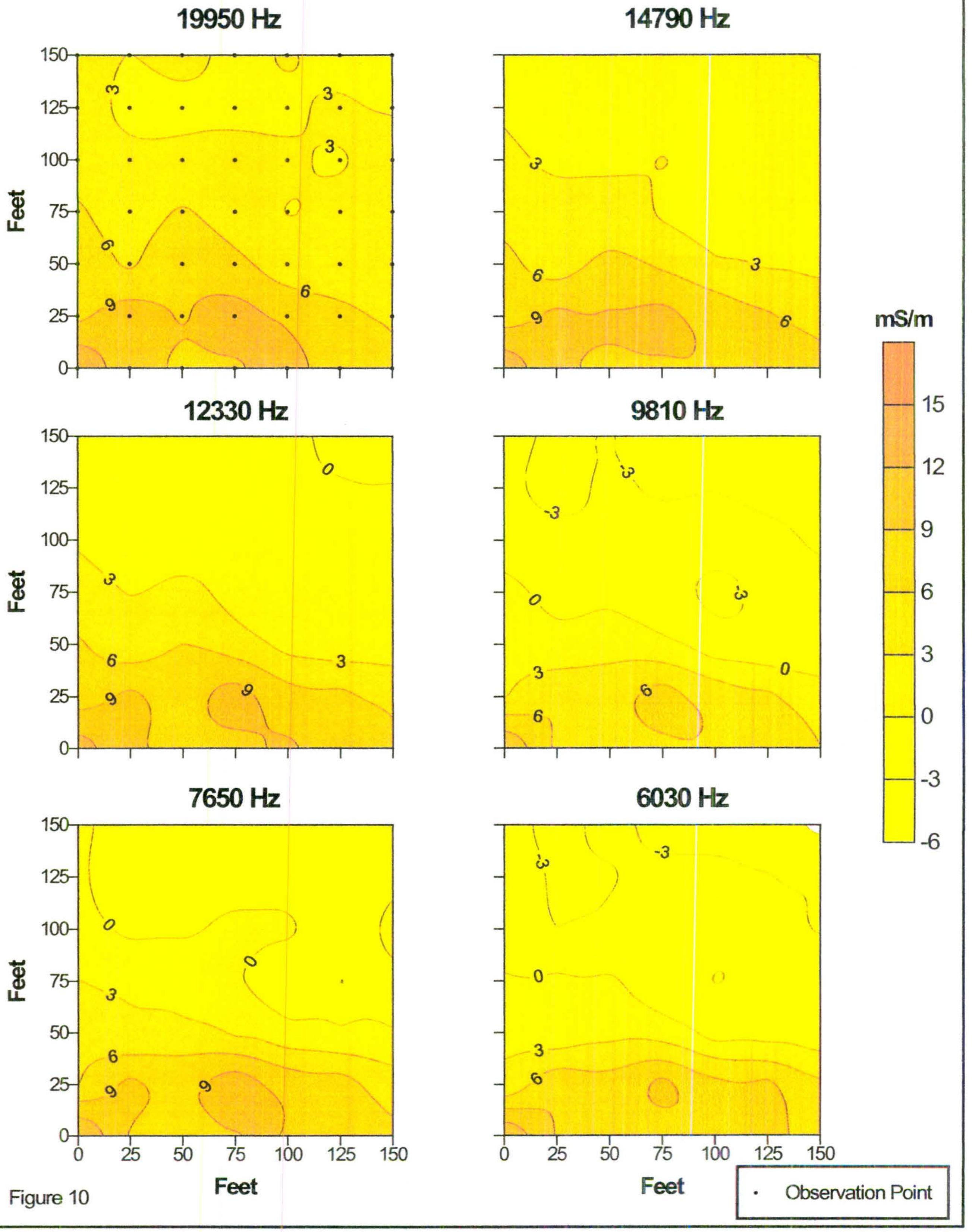


Figure 10