United States
Environmental Protection
Agency

Land And
Emergency Management
5401R

EPA 510-B-16-004
October 2016
www.epa.gov/ust

Expedited Site Assessment Tools For Underground Storage Tank Sites

A Guide For Regulators

Printed on Recycled Paper

Chapter III

Surface Geophysical Methods

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Exhibits

Chapter III
Surface Geophysical Methods

Geophysical methods provide information about the physical properties of the earth's subsurface. There are two general types of methods: Active, which measure the subsurface response to electromagnetic, electrical, and seismic energy; and passive, which measure the earth's ambient magnetic, electrical, and gravitational fields. Information provided by these tools can be applied to UST sites by helping to locate buried objects, to determine geologic and hydrogeologic conditions, and, occasionally, to locate residual or floating product.

Geophysical methods can also be subdivided into either surface or borehole methods. Surface geophysical methods are generally non-intrusive and can be employed quickly to collect subsurface data. Borehole geophysical methods require that wells or borings be drilled in order for geophysical tools to be lowered through them into the subsurface. This process allows for the measurement of *in situ* conditions of the subsurface. In the past, using borehole geophysical methods had not been cost-effective for most UST site investigations; however, in recent years, direct push (DP) technology probe rods have been fitted with geophysical sensors that can provide geophysical information rapidly. Although many geophysical methods are not available with DP technologies, the methods that are available can often provide information more cost effectively than traditional borehole geophysical methods. As a result, borehole geophysics will be mentioned only briefly in this chapter. Geophysical sensors available with DP equipment are discussed in Chapter V, Direct Push Technologies.

Data collected with geophysical tools are often difficult to interprete because a given data set may not indicate specific subsurface conditions (*i.e.*, solutions are not unique). Instead, data provided by these tools indicate anomalies which can often be caused by numerous features. As a result, geophysical methods are most effectively used in combination with other site information (*e.g.*, data from different geophysical methods, sampling and analytical tools, geological and historic records, anecdotal information). A combination of these sources is often necessary to resolve ambiguities in geophysical plots (*i.e.*, the graphical representation of data produced by a specific method).

Geophysical methods can be important tools both in the implementation of cost-effective expedited site assessments (ESAs) and in the remediation design and monitoring phases. When they are used as part of an ESA, geophysical methods are, typically, best used in the initial phase of an investigation to help focus resources for the remainder of the assessment.

Exhibit III-1 provides a general guide to the applicability of the most appropriate geophysical methods for UST site investigations. The six technologies are ground penetrating radar, electromagnetic methods, electrical resistivity, metal detection, seismic methods, and magnetometry. All geophysical methods have limitations that will affect their applicability at specific sites. This chapter is designed to provide the reader with a basic understanding of when to consider using geophysical methods and which methods are applicable for specific conditions. It is beyond the scope of this chapter to discuss all geophysical methods that are potentially useful for the applications discussed below. There are numerous geophysical methods that are only marginally applicable for UST site investigations because of the interferences from cultural objects (*e.g.*, buildings, pipes) or because of the cost. In addition, there are numerous configurations for applying geophysical methods that can be used to minimize interferences and improve resolution. These specific configurations are also beyond the scope of this chapter and are best resolved by discussing specific site assessment objectives with an expert geophysicist. The reader may also refer to Dobecki (1985) and Daily (1995) for more information on these configurations.

In addition to this chapter, there are several documents developed by the U.S. EPA that provide useful information for the lay reader. A complete overview of available geophysical methods is provided in *Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites* (EPA, 1993b). The *Geophysical Advisor Expert System* (Olhoeft, 1992) is a software program that can help the user determine the most applicable geophysical methods for specific site conditions. Information about a specific site is entered in response to questions asked by the program. *Geophysical Techniques for Sensing Buried Wastes and Waste Migration* (Benson, *et al.*, 1984) is also a useful resource that provides a more complete discussion of the most applicable geophysical methods for environmental site assessment purposes.

The remainder of this chapter is divided into two sections. First, a methodology section provides general information about the applicability, operating principles, advantages and limitations of the geophysical methods listed in Exhibit III-1. Because many of these methods have multiple applications at UST sites, application sections have been developed to make comparisons between methods for specific tasks. The applications fall into three categories also presented in Exhibit III-1: Locating buried objects, assessing geologic and hydrogeologic conditions, and delineating residual and floating product. For the convenience of the reader a list of equipment manufacturers and a matrix of their products are included at the end of the chapter.

Exhibit III-1
Summary Of Surface Geophysical Method Applicability

Applications	**Ground Radar**	**magnetic**	**Electrical**	**Metal**	**Seismic**	**Magnetometry**
USTs		1		1		1a
	1		3		N/A	
Trench and backfill		2		N/A		3
Hydrogeologic Condition						
	2		1		1	
Mapping lateral variation	2		2		2	
Depth to groundwater		2		N/A		N/A
Floating Product	[1]		R	N/A		N/A

a=ferrous objects only
N/A=Not Applicable

R=Methods currently being researched and developed
Research methods that are well documented

The following section provides overviews of the geophysical methods that are most likely to be useful at UST sites. The discussions summarize the uses of the method, its operating principles, and its advantages and limitations. Schematic drawings of the operating principles of these methods are also provided.

Ground Penetrating Radar

Ground penetrating radar (GPR) can be a very useful geophysical method for UST sites because it is appropriate for a broad range of investigations and is only rarely affected by cultural interferences (*e.g.*, buildings, fences, power lines). GPR can be helpful in:

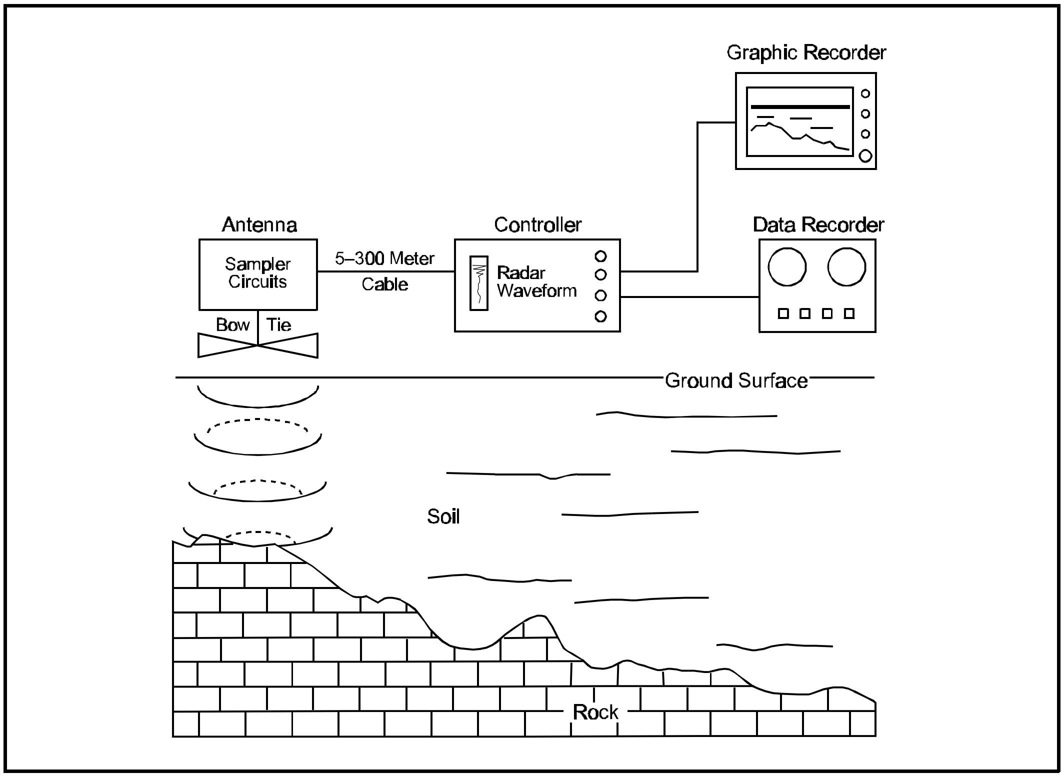
- Locating USTs, utilities, and backfilled areas;
- Determining geologic and hydrogeologic conditions; and
- Occasionally, delineating floating product.

GPR uses high frequency electromagnetic waves (*i.e.*, radar) to acquire subsurface information. The waves are radiated into the subsurface by an emitting antenna. When a wave strikes a suitable object, a portion of the wave is reflected back to a receiving antenna. Measurements are continuously recorded with a resolution that is significantly higher than most other surface geophysical methods, providing a profile (*i.e.*, cross-section) of subsurface conditions. Exhibit III-2 provides a schematic drawing of the GPR operating principles.

The GPR method utilizes antennas that emit a single frequency between 10 and 3000 MHz. Higher frequencies within this range provide better subsurface resolution at the expense of depth of penetration. Lower frequencies in this range allow for greater penetration depths but sacrifice subsurface target resolution. In UST investigations, the working frequency range is generally 100 to 900 MHz. Frequencies above 900 MHz are typically used for investigations less than 2 feet below ground surface (bgs).

In addition to the antenna frequency, the depth of wave penetration is controlled by the electrical properties of the media being investigated. In general, the higher the conductivity of the media, the more the induced radar wave is attenuated (absorbed), lessening the return wave. Electrically conductive materials (*e.g.*, many mineral clays and soil moisture rich in salts and other free ions) rapidly attenuate the radar signal and can significantly limit the usefulness

Exhibit III-2
Schematic Drawing Of Ground Penetrating Radar Operating Principles



Source: Benson et al., 1984

of GPR. For example, in shallow, wet clays with high conductivity values (30 millimhos per meter or greater), the depth of penetration may be less than 2 feet. In contrast, in dry materials that have electrical conductivity values of only a few millimhos per meter, such as clay-free sand and gravel, penetration depths can be as great as 90 feet. Penetration depths typically range between 3 and 15 feet bgs. As a result, it is important to research the likely subsurface materials in an area before deciding to use this method. Test surveys are also commonly used to help predict the success of GPR.

The depths to reflecting interfaces can be calculated from the two-way travel times of the reflected waves. Travel times are measured in nanoseconds (*i.e.*, 1 billionth of a second). Because the velocity of electromagnetic radiation through various materials is well established, one can calculate the depth of penetration with various techniques. Estimations can also be made if the nature of the subsurface materials is only generally known.

GPR measurements are usually made along parallel lines that traverse the area of interest. The spacing of the lines depends on the level of detail sought and the size of the target(s) of interest. Traverse rates can vary greatly depending on the objective of the survey. Typically, an average walking pace of 2 to 3 miles per hour is used. Some very detailed investigations can be as slow as 0.1 mile per hour, and newer systems can be mounted on vehicles and used at speeds up to 65 miles per hour for reconnaissance of the shallow subsurface. The data can be recorded for processing off-site, or they can be produced in real-time for analysis in the field.

GPR is relatively unaffected by above surface cultural interferences if the GPR antennas are shielded. For antennas that are not shielded, an experienced operator can often distinguish and ignore reflections from overhead objects. Subsurface cultural interferences include densely packed rebar used in reinforced concrete (the density at which rebar is a problem is site specific), wire mesh (often used for concrete floors in buildings), and pipes and utilities (if geology is the target).

Electromagnetic Methods

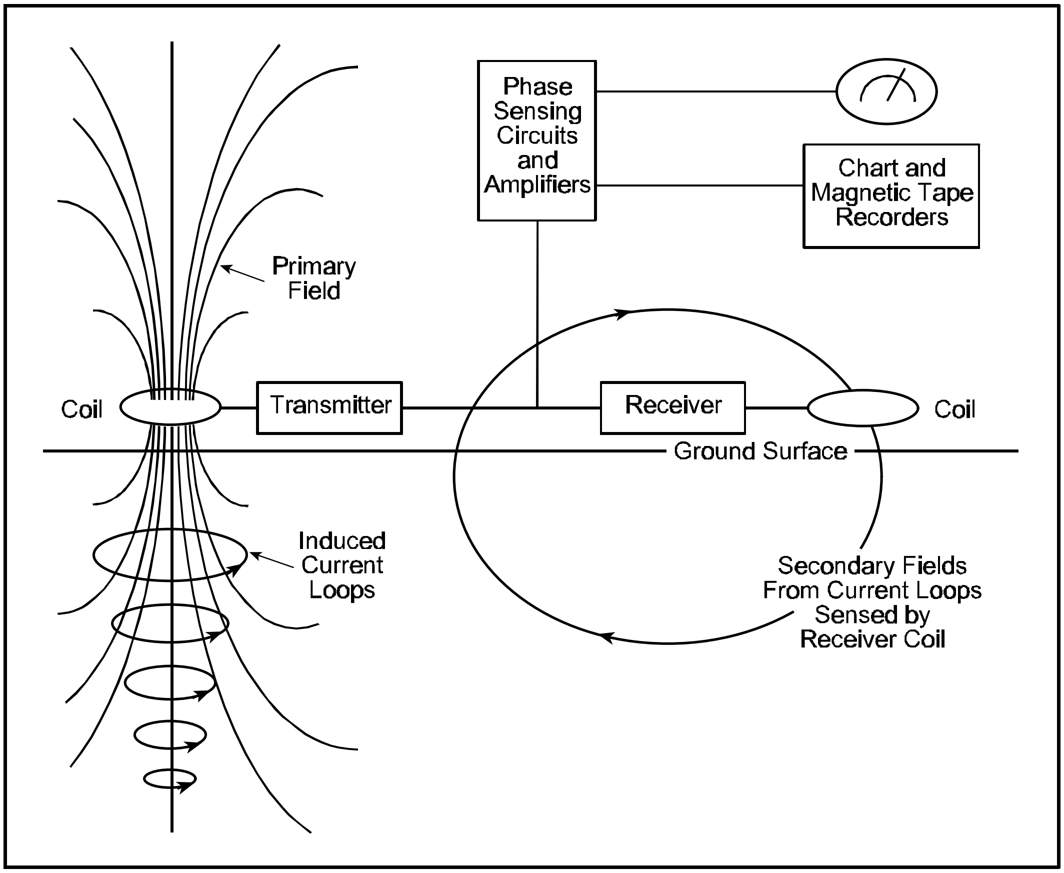
Electromagnetic (EM) methods, also referred to as electromagnetic induction methods, are some of the most diverse and useful geophysical techniques. Although they are commonly subject to cultural interferences, they can:

- Locate buried objects (metal and non-metal);
- Obtain geologic and hydrogeologic information; and
- On rare occasions, delineate residual and floating product.

Although both GPR and metal detectors utilize electromagnetic radiation, EM methods in this chapter refer to the measurement of subsurface conductivities by low frequency electromagnetic induction. A transmitter coil radiates an electromagnetic field which induces eddy currents in the subsurface. The eddy currents, in turn, induce a secondary electromagnetic field. The secondary field is then intercepted by a receiver coil. The voltage measured in the receiver coil is related to the subsurface conductivity. These conductivity readings can then be related to subsurface conditions. Exhibit III-3 presents a schematic drawing of EM operating principles.

The conductivity of geologic materials is highly dependent upon the water content and the concentration of dissolved electrolytes. Clays and silts typically exhibit higher conductivity values because they contain a relatively large number

Exhibit III-3
Schematic Drawing Of Electromagnetic Operating Principles



Source: U.S. EPA, 1993a

of ions. Sands and gravels typically have fewer free ions in a saturated environment and, therefore, have lower conductivities. Metal objects, such as steel USTs, display very high conductivity measurements which provide an indication of their presence.

There are two basic types of EM methods--frequency domain (FD) and time domain (TD). FDEM measures the electrical response of the subsurface at several frequencies (different separation distances between the transmitter and receiver can also be used) to obtain information about variations of conductivity (or its reciprocal, resistivity) with depth. TDEM achieves the same results by measuring the electrical response of the subsurface to a pulsed wave at several time intervals after transmission, longer time intervals measure greater depths. Both methods have overlapping applicabilities.

The EM receiver and transmitter coils can be configured in many different ways, depending on the objectives of the survey. One common configuration for shallow environmental investigations utilizes transmitter and receiver coils that are attached to the ends of a rigid fiberglass rod at a fixed distance (*i.e.*, fixed-coil separation). The equipment is then moved across the area of investigation. This configuration is particularly suitable for detection of USTs and metal pipes.

The limitations of EM methods are primarily a result of the interferences, typically caused when this method is applied within 5 to 20 feet of power lines, buried metal objects (including rebar), radio transmitters, fences, vehicles, or buildings. In addition, its success depends upon subsurface conductivity contrasts. For example, the difference in conductivity between an UST and surrounding natural or fill material is typically adequate for detection. However, mapping more subtle targets, such as fine versus coarse material or contamination, is less predictable. Consequently, pilot studies can be conducted to determine if an adequate conductivity contrast exists for the objective of the study.

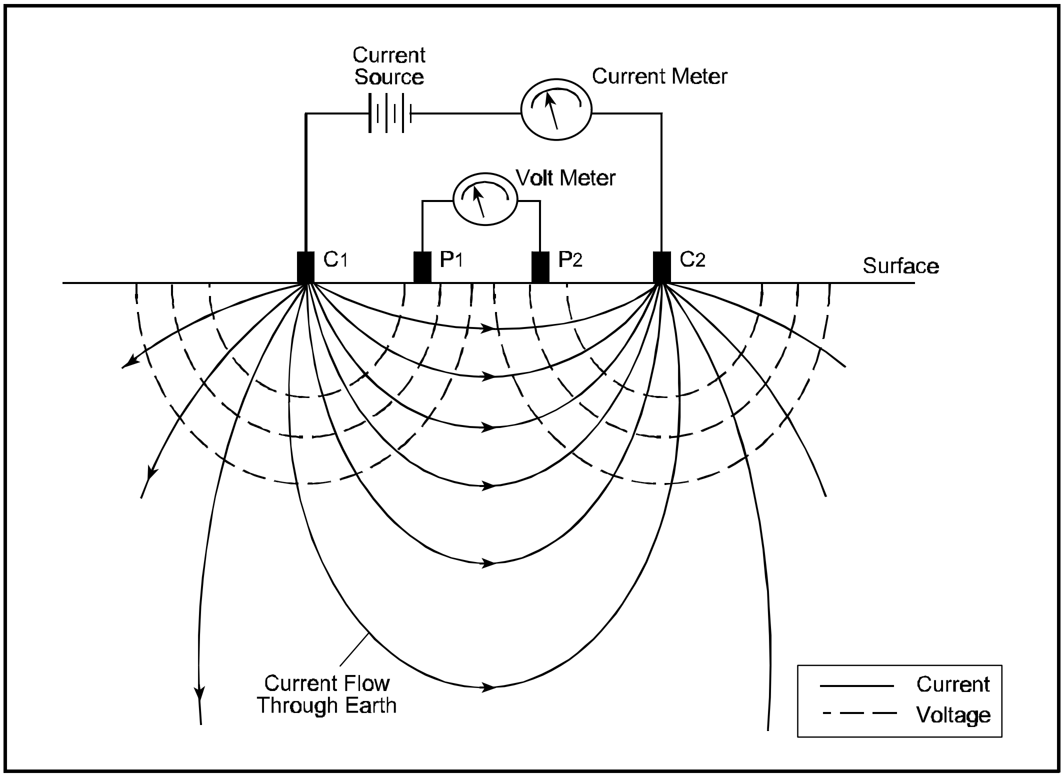
Electrical Resistivity

Electrical resistivity, also referred to as galvanic electrical methods, is occasionally useful at UST sites for determining shallow and deep geologic and hydrogeologic conditions. By measuring the electrical resistance to a direct current applied at the surface, this geophysical method can be used to:

- Locate fracture zones, faults, karst, and other preferred groundwater/contaminant pathways;
- Locate clay lenses and sand channels;
- Locate perched water zones and depth to groundwater; and
- Occasionally, locate large quantities of residual and floating product.

A variety of electrode configurations or arrays (*e.g.*, Wenner, Schlumberger, dipole-dipole) can be used depending on the application and the resolution desired. Typically, an electrical current is applied to the ground through a pair of electrodes. A second pair of electrodes is then used to measure the resulting voltage. The greater the distance between electrodes, the deeper the investigation. Because various subsurface materials have different, and generally understood, resistivity values, measurements at the surface can be used to determine the vertical and lateral variation of underlying materials. As with EM, success depends upon subsurface resistivity contrasts. Exhibit III-4 presents a schematic drawing of electrical resistivity operating principles using the Wenner array.

Exhibit III-4
Schematic Drawing Of Electrical Resistivity Operating Principles



Source: Benson et al., 1984

Although resistivity is subject to interferences from the same objects as EM, it is less affected by them. In addition, if the location of metal pipes and utilities is known, electrode arrays can often be arranged to minimize interferences. Furthermore, resistivity resolution is comparable to, and sometimes better than, EM.

Electrical resistivity, however, has a number of limitations. The following is a list of the most significant issues that should be considered when selecting this method:

- Electrodes must be in direct contact with soil; if concrete or asphalt are present, holes must be drilled for inserting the electrodes and then refilled when the survey is complete.

- For deep investigations, electrode arrays can be quite long. The distance between outside electrodes must be 4 to 5 times the depth of investigation.

- Measurements may be limited by both highly conductive or highly resistive surface soils. If shallow clays and extremely shallow groundwater are present, most of the current may concentrate at the surface. Although the condition is very rare, the presence of thick, dry, gravelly material (or massive dry material) at the surface may prevent the current from entering the ground.

Metal Detection

Metal detectors, also referred to as pipeline and cable detectors, are widely used at UST sites for the specific application of locating buried metal objects, both ferrous and non-ferrous in a process called metal detection (MD). MD can be used at UST sites to locate:

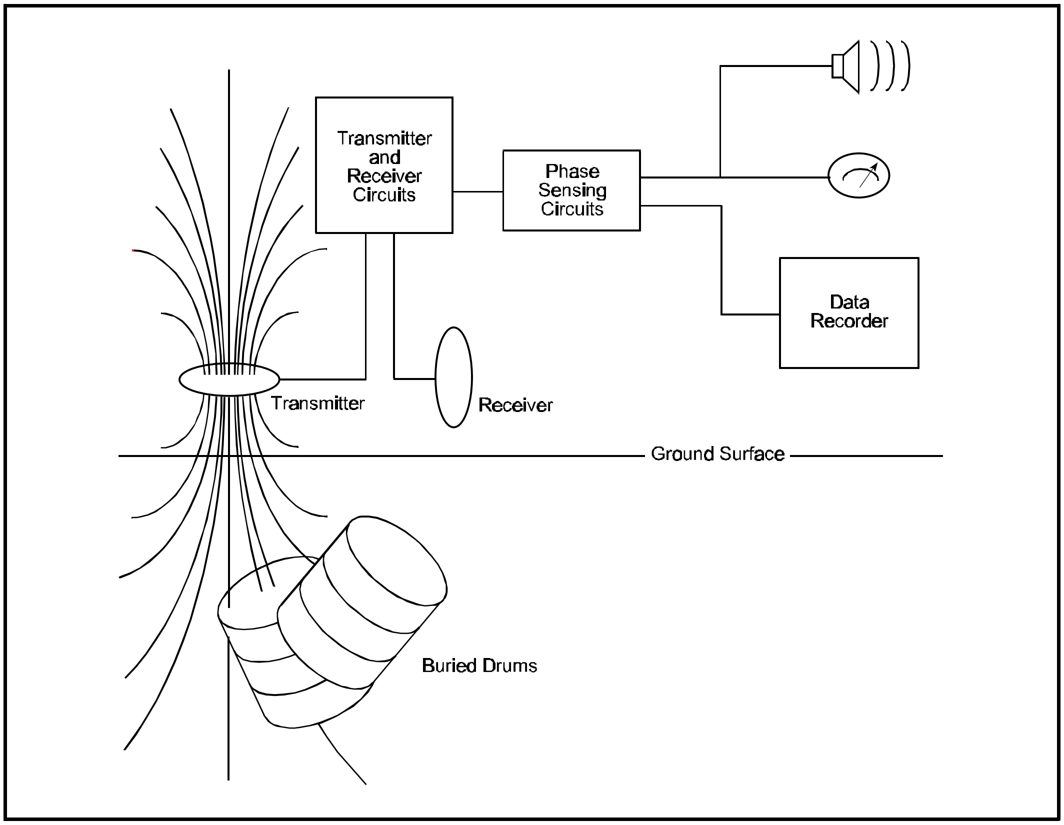
- Steel and composite (*i.e.*, fiberglass-coated steel) tanks;
- Metal piping; and
- Utilities.

There are two types of MD--frequency domain and time domain. Frequency-domain metal detectors are typically used for locating shallow metals (less than 2 feet) and for tracing piping and cables at UST sites. Time-domain metal detection is useful for investigations from 0 to 15 feet and for locating USTs or buried drums. Both types provide good response to all metal objects.

Metal detectors operate by the same principles as EM methods, but they are adapted to the specific purpose of locating metal objects. When the subsurface current is measured at a specific level, the presence of metal is indicated with a meter reading, with a sound, or with both. Commercial metal detectors used for locating USTs also have data recording capabilities although stakes or paint marks are typically placed over targets as the survey proceeds. Exhibit III-5 presents a schematic drawing of MD operating principles.

The depth of investigation with MD surveys is dependent primarily on the surface area and the depth of the object. The response of MD decreases dramatically with depth. As a target depth is doubled, the response decreases by a factor of as much as 64 (the response to small objects decreases more rapidly than the response to large objects). However, metal detectors are very appropriate for UST sites because they are capable of detecting metal utilities up to 3 feet bgs, a 55-gallon metal drum up to 10 feet bgs, or a 10,000-gallon steel tank up to 20 feet bgs.

Exhibit III-5
Schematic Drawing Of Metal Detection Operating Principles



Source: Benson et al., 1984

MD is less sensitive to surface and subsurface interferences than EM methods, but care must be taken to minimize noise from metal fences, vehicles, buildings, and buried pipes. Rebar in concrete is perhaps the most common problem for this method at UST sites. The electrical conductivity of the soil does not cause significant interferences for MD methods; however, mineralized soils and iron-bearing minerals can provide significant natural interference with surveys.

Seismic Methods

Seismic methods provide stratigraphic information by measuring how acoustic waves travel through the subsurface. They can be used at UST sites to:

- Determine depth and thickness of geologic strata;

- Determine depth to groundwater;
- Estimate soil and rock composition; and
- Help resolve fracture location and orientation.

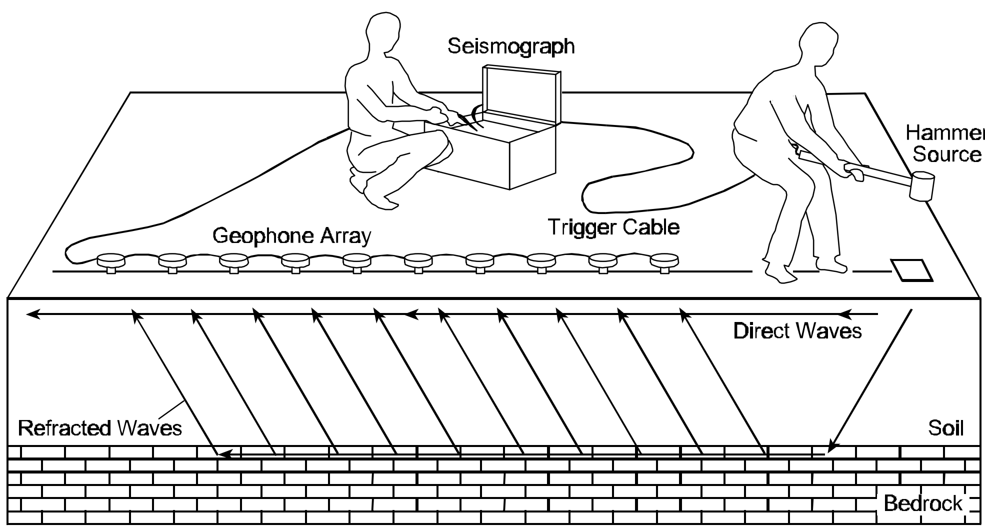
There are primarily two types of seismic method applications—refraction and reflection. Seismic refraction measures the travel times of multiple sound (*i.e.*, acoustic) waves as they travels along the interface of two layers having different acoustic velocities. Seismic reflection, on the other hand, measures the travel time of acoustic waves in the subsurface as they reflect off of these interfaces. Traditionally, seismic reflection has been used for deep geological investigations (up to 3000 feet), and seismic refraction has been used for shallow investigations (up to 100 feet). Although recent developments have blurred the applications of the two methods, seismic refraction remains more commonly used for shallow investigations because it is less expensive and easier to use for resolving stratigraphy less than 50 feet bgs. This chapter will focus on seismic refraction.

Seismic refraction utilizes an energy source, such as a sledge hammer or small explosives, to create acoustic waves in the subsurface. When there is a change in the seismic velocity of the waves traveling from one layer to the next, refracted waves are created. These waves are recorded by geophone sensors (*i.e.*, seismic wave receivers) arranged in a direct line from the energy source. The time it takes the waves to refract is dependent on the composition, cementation, density, and degree of weathering and fracturing of the subsurface materials. Exhibit III-6 presents a schematic drawing of seismic refraction operating principles.

The advantage of seismic refraction is that it can resolve three to five layers of stratigraphy and provide good depth estimates. Furthermore, it is fairly easy to implement, and the energy source can be as simple as a 10-pound sledge hammer. Seismic refraction, however, has a number of limitations that should be considered:

- Geophone spreads may be as much as five times as long as the desired depth of investigation, therefore limiting its use in congested locations.
- If velocity contrasts do not exist between sediment layers they will not be resolved.
- Thin layers cannot be resolved.
- If numerous buried utilities are in the vicinity of the seismic profiles, they may interfere with the collection of usable data by creating a false layer near the surface.
- For surveys in paved areas, holes need to be drilled in order to provide a firm contact between the geophones and the soil.

Exhibit III-6
Schematic Drawing Of Seismic Refraction Operating Principles



Source: Benson et al., 1984

- Seismic velocities of geologic layers must increase with depth. Although this situation is typical, conditions such as frozen soil or buried pavement will prevent detection of underlying formations.
- Seismic methods are sensitive to acoustic noise and vibrations; however, there are a number of ways to minimize this noise, including using data filtering software or taking profiles (*i.e.*, geophysical subsurface cross-sections) when there is no traffic (*e.g.*, taking measurements during red lights or at night).

Although seismic refraction can be used for depths below 300 feet, it is usually used for depths less than 100 feet because of the very long geophone spreads required and the energy sources (*e.g.*, a 500 lb. drop weight, explosives) necessary to reach these depths.

Magnetic Methods

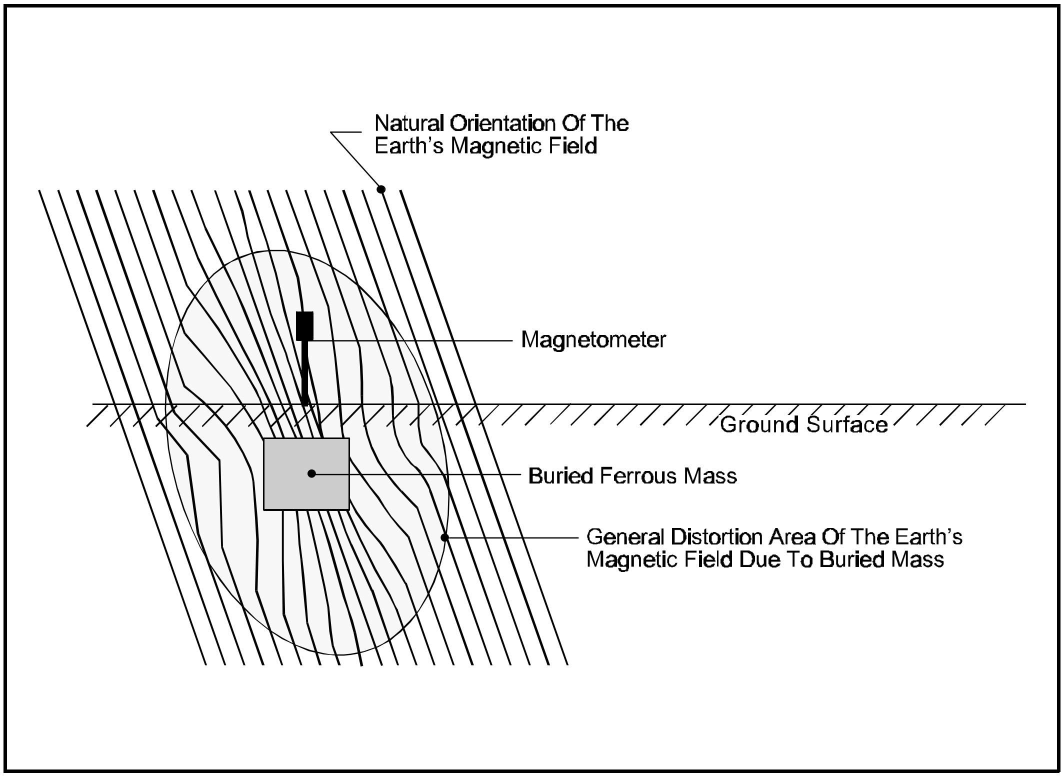
Magnetometers are useful at UST sites for locating tanks and piping made of ferrous materials. Although highly sensitive magnetometers have been developed that can detect the void space within large buried objects of any material (*e.g.*, fiberglass tanks), this technology is not often used in UST investigations because many cultural interferences present at UST sites will mask the affect.

Magnetometers that are commonly used at UST sites work by measuring the earth's total magnetic field at a particular location. Buried ferrous materials distort the magnetic field, creating a magnetic anomaly. There are two methods for measuring these anomalies--the total field method and the gradient method. The total field method utilizes one magnetic sensing device to record the value of the magnetic field at a specific location. The gradient method uses two sensors, one above the other. The difference in readings between the two sensors provides gradient information which helps to minimize lateral interferences. Total field magnetic methods are often used at sites with few cultural features. Gradiometer methods can be used in culturally complex areas. As a result, gradiometers are more applicable for UST sites. Exhibit III-7 presents a schematic drawing of magnetometry operating principles.

Magnetometers may be useful for reconnaissance surveys of UST sites because they are very fast and relatively inexpensive. Potential cultural interferences include steel fences, vehicles, buildings, iron debris, natural soil minerals, and underground utilities. Gradiometer methods are useful for minimizing these interferences. Power lines are an additional source of interference that can be neutralized with the use of very sophisticated equipment that synchronizes readings with the oscillating electrical current.

Some magnetometers are very simple and do not have a data recording or processing ability. They indicate the presence of iron with a sound or meter and can be used as a rapid screening tool. Magnetometers that record data can, with the aid of data processing software, be used to estimate the size and depth of ferrous targets.

Exhibit III-7
Schematic Drawing Of Magnetometry Operating Principles



Source: Modified from U.S. EPA, 1993a

There are three general applications for geophysical tools in the assessment of UST sites: Locating buried objects; assessing geological and hydrogeological conditions; and, to a lesser extent, delineating residual or floating product. The following text contains discussions of the geophysical methods that are most applicable for these activities. Specific information about each method and a comparison chart of all methods are provided to help the reader decide which method to use under various conditions.

Each of the following discussions includes a summary table highlighting the parameters that affect the applicability of the described methods. Only information that is relevant to the specific application is presented for each of the methods. Some of the parameters discussed in the previous section that affect the applicability of a method are presented in the tables but not repeated in the text.

The summary tables include cost estimates which are presented as low, moderate, or high. More accurate estimates are not possible because there are an enormous number of site-specific factors that affect cost (*e.g.,* survey objectives, survey size, spacing between traverse lines, mobilization costs). Furthermore, the expense of a survey will be greatly affected by who conducts the investigation (*e.g.*, a consultant or an individual renting equipment directly from the manufacturer), how much data processing will be required, and whether a written report is necessary.

Similar to cost estimates, time requirements for a geophysical survey are presented as fast, moderate, and slow. Geophysical methods can be ranked by how quickly they can be used, but the specific time that a survey will take varies considerably depending on the level of detail required and the size of the area to be investigated. In general, all of the methods presented in this chapter can be completed within one day at a typical UST site (*i.e.*, less than 2 acres); in some cases, a survey can be completed within half a day. Sometimes, no data processing will be necessary beyond what is immediately presented; or, additional data processing may be completed in the field; in other situations, extensive off-site data processing will be necessary.

Locating Buried Objects

Many times the initial step to a site assessment is to determine the location of USTs, associated piping, and/or utilities. This type of activity is ideally suited to geophysical tools. If the location of these structures has not been recorded, the use of geophysical methods can save an enormous amount of time and money.

There are four primary methods used for locating buried objects: Ground penetrating radar (GPR), time-domain metal detection (MD), magnetometry (MAG), and electromagnetic methods (EM). Exhibit III-8 provides a summary of the information presented in this discussion.

Ground Penetrating Radar

Ground penetrating radar is effective for locating buried objects, whether metal or non-metal. Targets of investigation include:

- Steel, fiberglass, composite, and steel-reinforced concrete USTs;
- Utilities;
- Rebar; and
- Backfill.

When site conditions are favorable, GPR provides the best resolution of any geophysical method for locating buried objects. Although the exact resolution depends on the frequency of the antenna used and the depth of penetration required, GPR can generally locate a tank to within a foot, both vertically and horizontally. However, because GPR is typically used at much slower rates and with more dense traverse lines than MAG, MD, and EM, it is often more cost-effective to use GPR for focused investigations. When the location of an object is only suspected or estimated, other (*i.e.*, reconnaissance) methods may be more appropriate. Exhibit III-9 is an example of a plot and interpretation of GPR being used to locate buried USTs. The hyperbolic shape of the radar wave reflections is a typical profile of a buried object.

Metal Detection

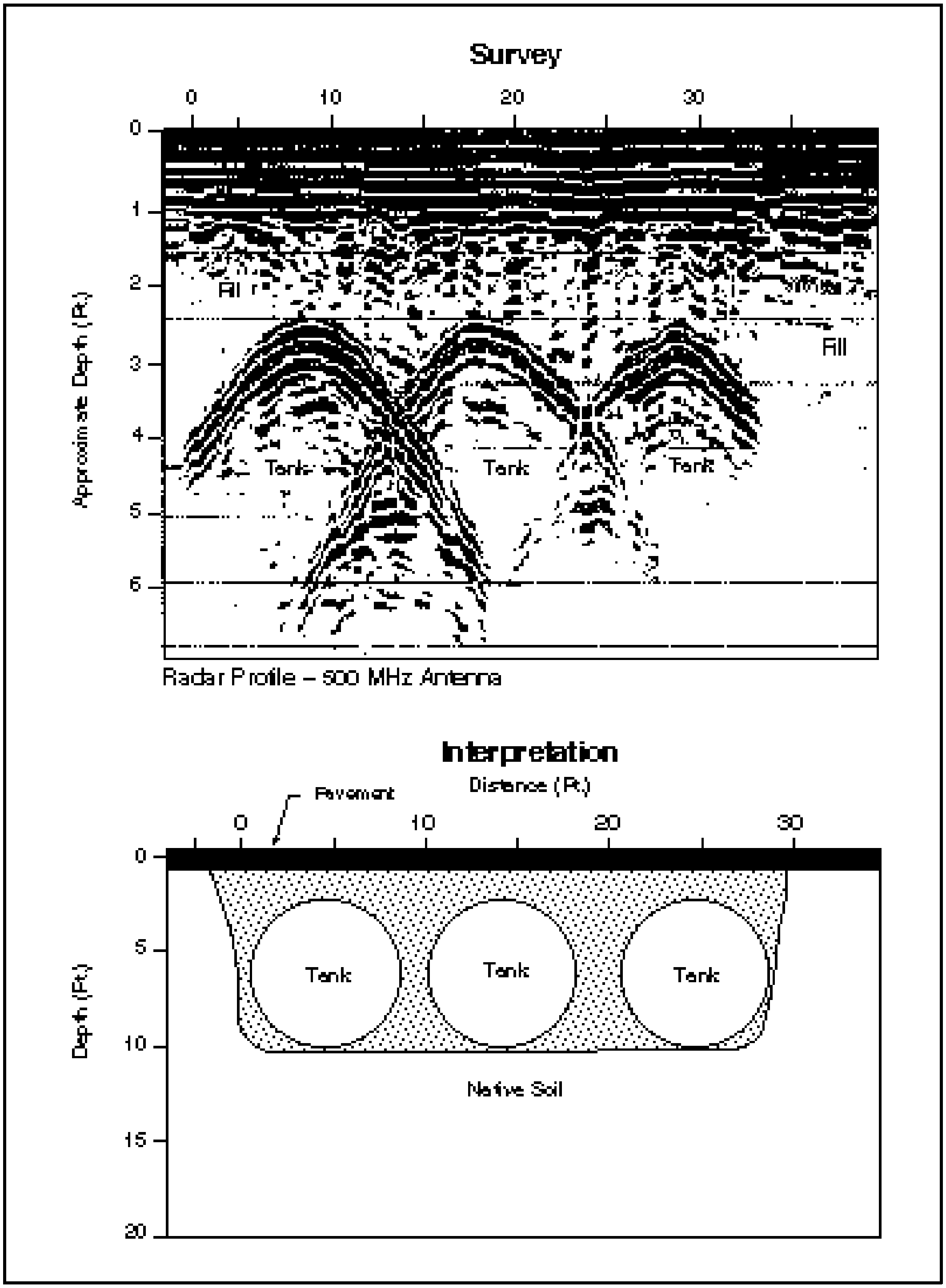
Metal detection (MD) surveys are useful for locating only metal objects, both ferrous and non-ferrous. Investigations at UST sites include:

- Steel, composite, and steel-reinforced concrete USTs;
- Reinforced concrete covering fiberglass USTs; and
- Utilities composed of any metal.

Exhibit III-8
Summary Of Geophysical Methods For Locating Buried Objects

	Ground Penetrating Radar	Metal Detection	Magnetometry	Electromagnetic Methods
Purpose	Focused investigation	Reconnaissance survey	Reconnaissance survey	Reconnaissance survey
Typical Depth Of Penetration	3 to 15 ft	10 to 12 ft (55-gal. drum)	10 to 15 ft (55-gal. drum)	8 to 10 ft
Materials Detected	Metal and non-metal	Metal	Ferrous materials	Metal and non-metal
Cultural Interferences	Densely packed rebar, wire mesh	Metal surface structures, power lines	Metal surface structures, power lines	Metal surface structures, power lines
Natural Interferences	Conductive soils (*e.g.*, silts, clays)	Mineralized soils	Mineralized soils, iron deposits	Highly conductive saline soils
Resolution	0.1 to 4 ft	20% vertically and horizontally	10 to 15% vertically and horizontally	Vertical resolution is between 4 and 12 ft; 4 ft horizontally
Produces Usable Field Data	Yes	Yes	Yes	Yes
Time	Slow to Moderate	Moderate to Fast	Fast	Moderate to Fast
Cost	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate

Exhibit III-9
Ground Penetrating Radar Survey And Interpretation Of Buried USTs



Source: NORCAL Geophysics Consultants, Inc.

MD provides excellent horizontal resolution. Utilities can be traced better than with magnetometry, however, resolution of depth can only be defined to within 20 percent of the actual depth. If better resolution is required, a follow-up survey with GPR may be appropriate. Exhibit III-10 presents an example of a survey plot and interpretation using a very sophisticated MD that was able to locate the UST and associated piping.

Magnetometry

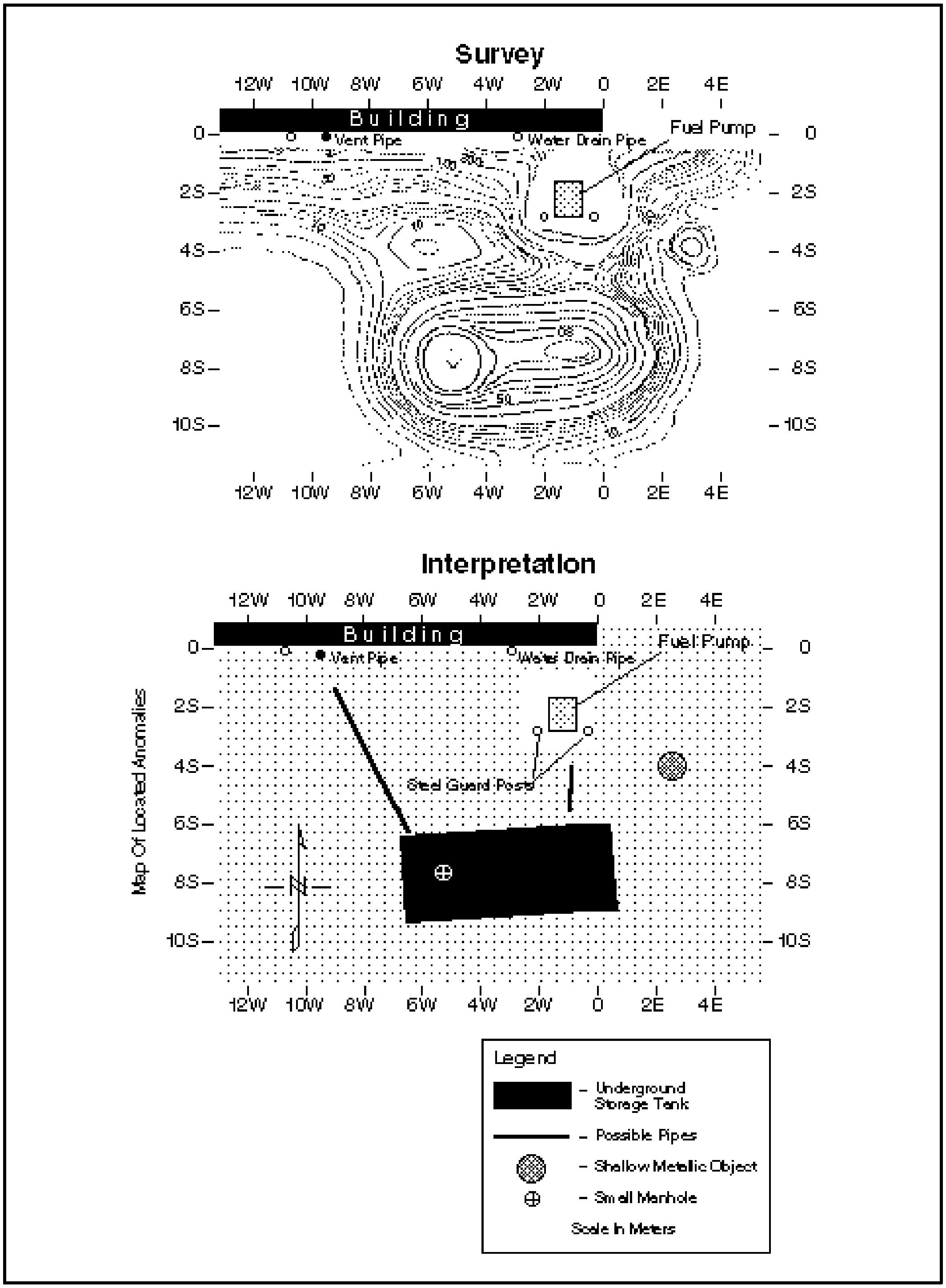
Magnetometry (MAG) methods are well suited for reconnaissance surveys because they collect data rapidly, they give large responses for buried ferrous objects, and they are cost-effective. As described in the method overviews, MAG surveys can be useful at UST sites for detecting:

- Steel, composite, and steel-reinforced concrete USTs;
- Utilities composed of ferrous materials; and
- Trenches.

In addition to being able to detect ferrous materials, very sensitive MAG equipment can also detect the void space in a large container of any material. However, because fiberglass tanks are typically covered with reinforced concrete, the magnetic response will be dominated by the presence of the reinforcing steel. Highly sensitive magnetometers can be more useful in detecting backfilled trenches because their iron content often contrasts with the surrounding soils. Depth of penetration is as deep as necessary for most UST sites. For example, a 55-gallon drum can be detected at 10 to 15 feet (depending on the sensitivity of the magnetometer), and a 10,000-gallon tank can be detected much deeper. The resolution of the data is also good when processed with the appropriate software, the vertical and horizontal location of an object can be determined to within 10 to 15 percent.

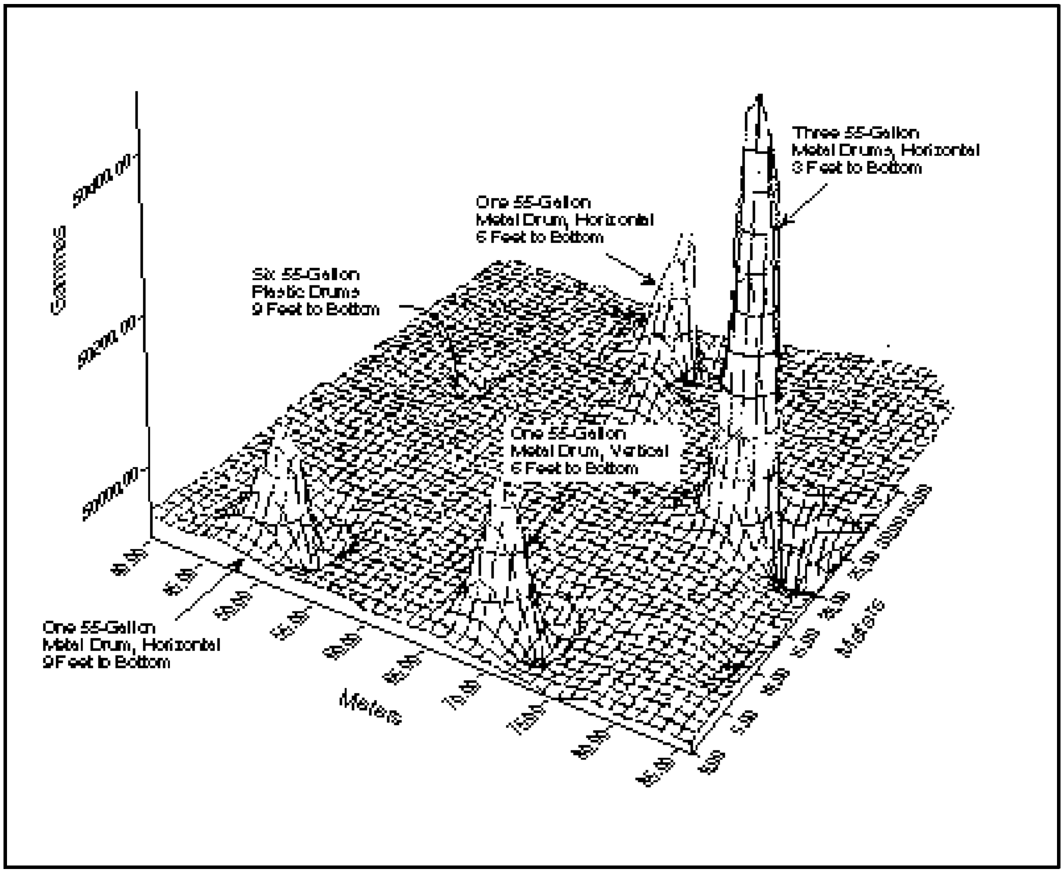
Exhibit III-11 provides an example of a MAG survey at a Stanford University test site. This section of the test site contained metal and non-metal objects, all of which were detected with the highly sensitive magnetometer. The large mounds indicate the location of metal drums buried at various depths and positions. Also of interest is the negative anomaly that is caused by six plastic drums buried 9 feet bgs.

Exhibit III-10
Metal Detection Survey And Interpretation At UST Site



Source: Geonics Limited

Exhibit III-11
Magnetometry Survey At Stanford University Test Site



Source: Geometrics, Inc.

Electromagnetic Methods

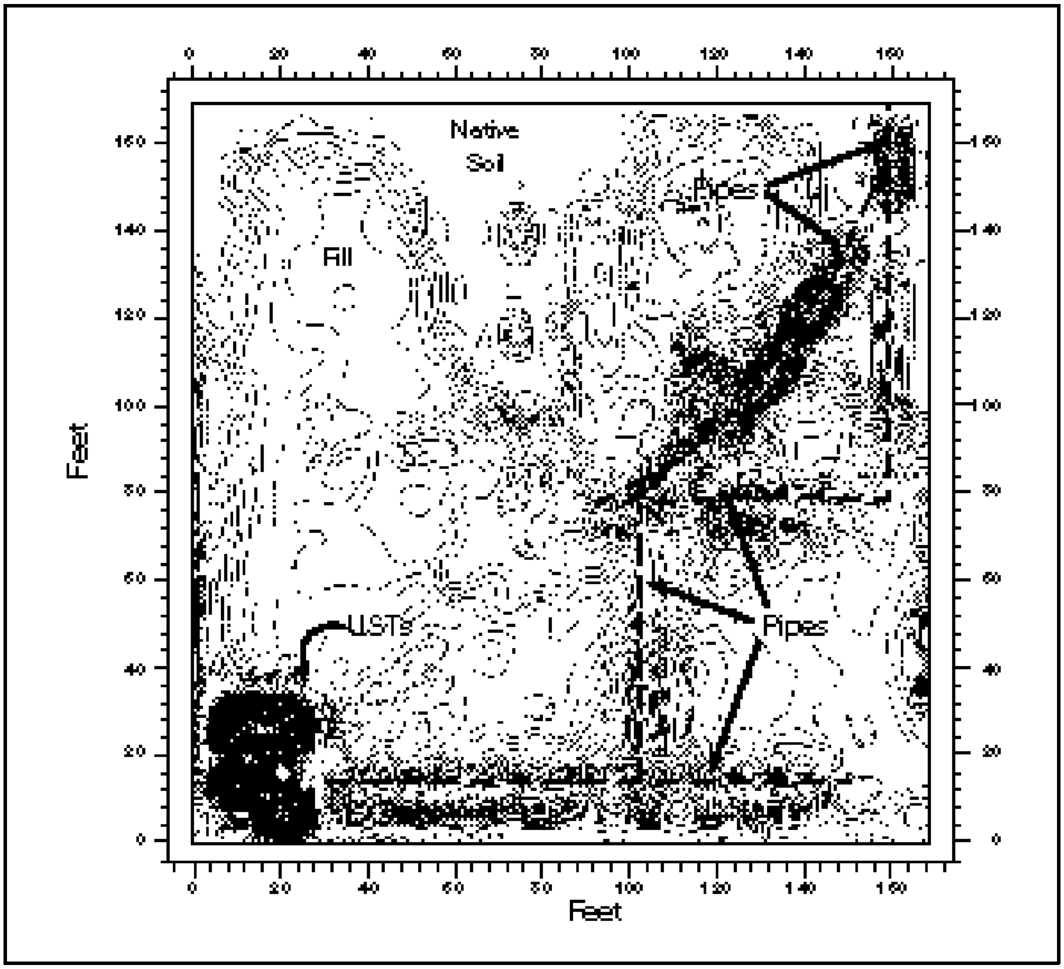
The most widely used EM method for UST investigations is frequency-domain fixed-coil EM (the distance between transmitter and receiver coils is fixed). It is useful for locating buried objects, whether metal or non-metal. This method can be used at UST sites to locate:

- Steel, composite, and steel-reinforced concrete USTs;
- Utilities; and
- Backfill soils.

EM methods are well suited for reconnaissance of large open areas because data collection is rapid, and a large variety of subsurface anomalies be located, whether metal or non-metal, including backfill of former USTs. Because EM methods can indicate the location of many types of buried objects, follow-up investigations with GPR are often applicable.

For EM instruments commonly used at UST sites for assessment of buried objects, the depth of investigation is limited to 12 feet or less, regardless of the size of the object detected. Horizonal resolution with EM is approximately 4 feet, and vertical resolution is between 4 and 12 feet. Exhibit III-12 is an example of contoured EM data and an interpretation map at an UST site. The survey was able to locate several USTs and associated piping as well as to delineate the area of backfill.

Exhibit III-12
Electromagnetic Survey And Interpretation At UST Site



Source: NORCAL Geophysical Consultants, Inc.

Assessing Geological And Hydrogeological Conditions

All geophysical methods are capable of providing information about geologic and/or hydrogeologic conditions. By assessing the subsurface, investigators can make judgements about where contamination is likely to be located and the direction it is likely to migrate. This information is also critical in the design of appropriate remediation technologies. Geophysical methods are, of course, not always necessary for determining the geologic and hydrogeological conditions of UST sites; however, when adequate background information does not exist and site geology is complicated, geophysical methods may be a cost-effective means of supplementing intrusive methods of characterization (*e.g.*, soil logging).

Geophysical methods can be helpful in resolving depth to groundwater; determining depth, thickness, and composition of soil and rock layers; and mapping local features such as permeable zones, joints, faults, karst, and buried stream channels. The following text summarizes the most useful methods for these tasks and explains their applicability. The geophysical methods most likely to be useful at UST sites include ground penetrating radar (GPR), seismic refraction (SR), electrical resistivity (ER), and electromagnetics (EM). Although all of these methods may on occasion be useful in determining the depth to the saturated zone, they all require sharp boundaries to be successful. As a result, when there is a large capillary fringe, they may not distinguish the saturated zone from the vadose zone.

Magnetometry, very low frequency electromagnetics (VLF-EM), self-potential (SP), and seismic reflection are other surface geophysical methods that may provide additional information; however, they are not discussed in detail because they are rarely useful at UST sites for assessing geologic and hydrogeologic conditions because of sensitivities to cultural interferences, cost, or applicability for rare conditions. Magnetometry and VLF-EM methods can be useful for delineating faults and large fracture zones. SP surveys, although sensitive to interferences, can be used to assess karst, fractures, and groundwater recharge. Borehole methods may also be useful for logging soil types and fracture characterization. Borehole methods that have been adapted to direct push technologies are discussed in the Chapter V. Exhibit III-13 summarizes the application of each of the major surface geophysical methods used for subsurface characterization of geologic and hydrogeologic conditions.

Exhibit III-13
Summary Of Geophysical Methods For Assessing Geologic And Hydrogeologic Conditions

	Seismic Refraction	Electromagnetic Methods	Ground Penetrating Radar	Electrical Resistivity
Depth Of Penetration	>100 ft	>100 ft	3 to 15 ft (up to 90 ft in clean sands and gravels)	>100 ft
Features Detected	Sediment thickness, bedrock, fractures, faults, groundwater	Distribution of sand and clays, bedrock, fractures, faults, groundwater	Sediment thickness, bedrock, fractures, faults, groundwater (rarely)	Distribution of sands and clays, bedrock, fractures, faults, groundwater
Cultural Interferences	Urban noise (*e.g.*, construction, traffic), buried concrete	Metal surface structures, radio transmitters, power lines, buried pipes and cables	Densely packed rebar	Concrete, metal surface structures
Natural Interferences	Frozen soil		Conductive soils	Highly conductive soils
Resolution	2 to 3 ft	Variable	<1 ft	Vertical: 5 ft Horizontal: 5 ft
Produces Usable Field Data	If required	Depends on the specific method	Yes	No
Time	Slow to Moderate	Moderate to Fast	Slow to Fast	Slow to Moderate
Cost	Moderate to High	Low to Moderate	Low to Moderate	Moderate to High

Seismic Refraction

Seismic refraction is typically the most applicable seismic method for assessing subsurface conditions at UST sites. It can be used to resolve:

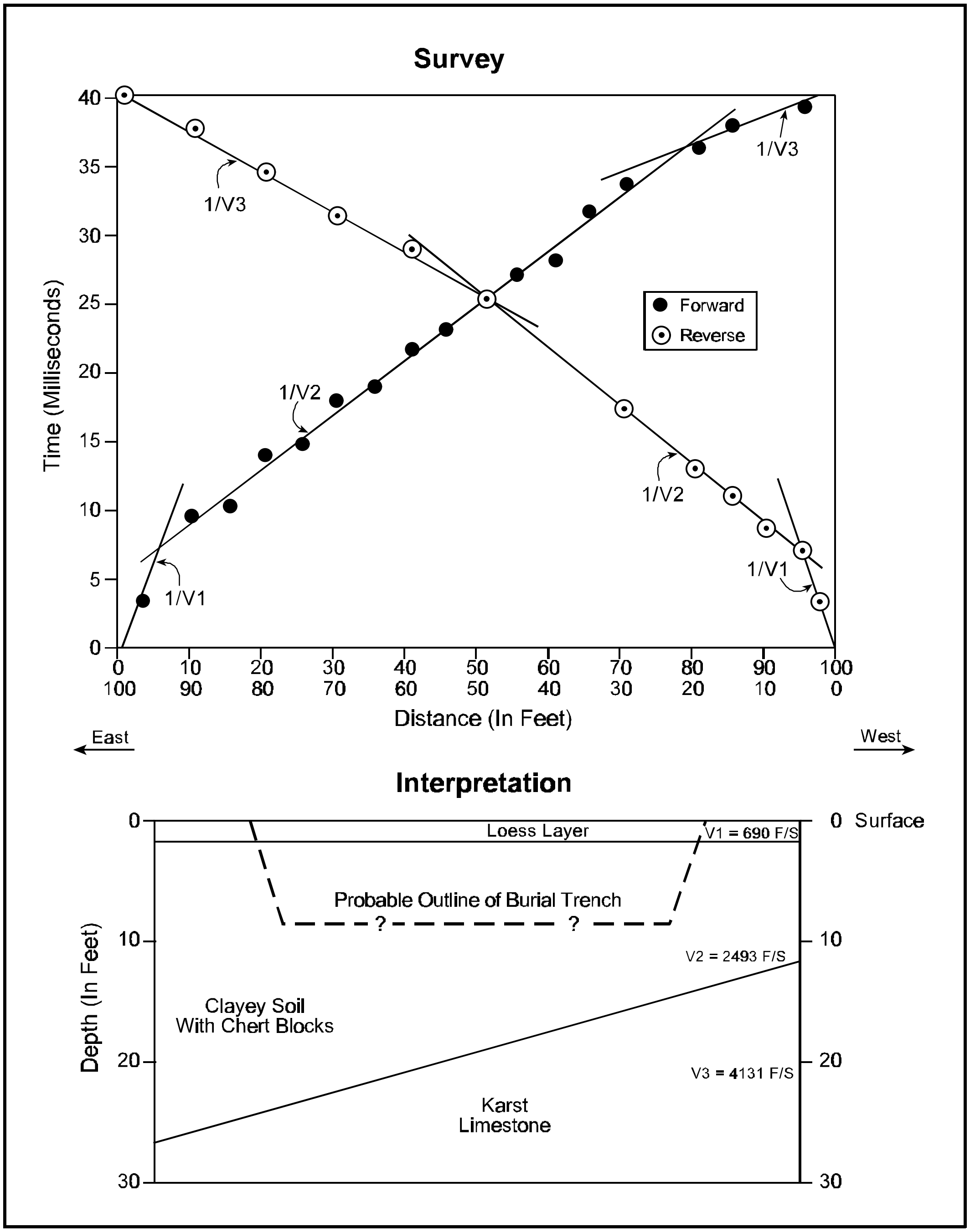
- Sediment depth and thickness;
- Karst, fractures, and faults;
- Depth to bedrock; and
- Occasionally, depth to groundwater.

Seismic refraction supplies semi-continuous data which, in combination with borings and other sampling techniques, can be extrapolated to resolve localized geologic features over the entire area of investigation. It is possible to resolve three to five distinct soil or rock layers and penetrate depths over 100 feet.

Occasionally, this method can be helpful in determining the depth to groundwater. In order to be successful, the velocity of the saturated zone must be significantly greater than the overlying formation. Because consolidated formations typically have very fast seismic velocities that are not significantly affected by groundwater, if the water table is located in a consolidated formation, it will not likely be discernable. Seismic velocities will typically increase significantly in unconsolidated formation; however, if the boundary is sharp (*e.g.*, as in course sands), a refraction survey will not be capable of determining if the layer is groundwater or another formation. Additional seismic tests, which are beyond the scope of this document, can be used to determine if the refraction is water or soil/rock.

Exhibit III-14 provides an example of a seismic refraction survey and interpretation used to resolve the depth to bedrock at a hazardous waste site. Each dot and circle represents the measured response of a geophone. Its placement on the graph is determined by the geophone location in the array and the time between energy release and the seismic wave arrival to the geophone. Measurements are taken in two directions (*e.g.*, forward and reverse) in order to resolve dipping (*i.e.*, inclined) stratigraphy. Because distance divided by time equals velocity, the inverse of the slope of the lines equals the seismic velocity of the subsurface material. Therefore, a change in the slope represents a change in the material. This survey was able to resolve three separate velocity layers (V_1, V_2, and V_3). The depth to bedrock throughout the area of investigation was resolved with V_3. The buried trench depicted in the interpretation was based on historical site information and was not resolved with seismic refraction.

Exhibit III-14
Seismic Refraction Survey And Interpretation



Source: Benson et al., 1984

Electromagnetic Methods

EM methods can be useful for assessing both the shallow subsurface and deep geological features. At some UST sites, it can provide information about:

- Stratigraphy;
- Preferred groundwater pathways;
- Fracture zones and faults; and
- Occasionally, depth to groundwater.

There are various EM methods that are useful for both shallow and deep geological and hydrogeological investigations. The frequency-domain fixed-coil separation EM method is the most practical EM approach for the shallow subsurface (less than 12 feet) at UST sites because its lateral resolution and speed of operation is superior to other EM methods. For collecting data from deeper than 12 feet, there are time-domain (TDEM) and other frequency-domain equipment available that can reach depths below 100 feet.

Exhibit III-15 is a schematic drawing of a TDEM survey. The black vertical lines are soundings (*i.e.*, vertical measurements) of subsurface electrical conductivity. The information between the lines is interpolated. By comparing information from the TDEM soundings with boring logs, it is possible to extrapolate the geology over a wide area. In this example, the approximate location of sediments is measured to a depth of 200 feet bgs.

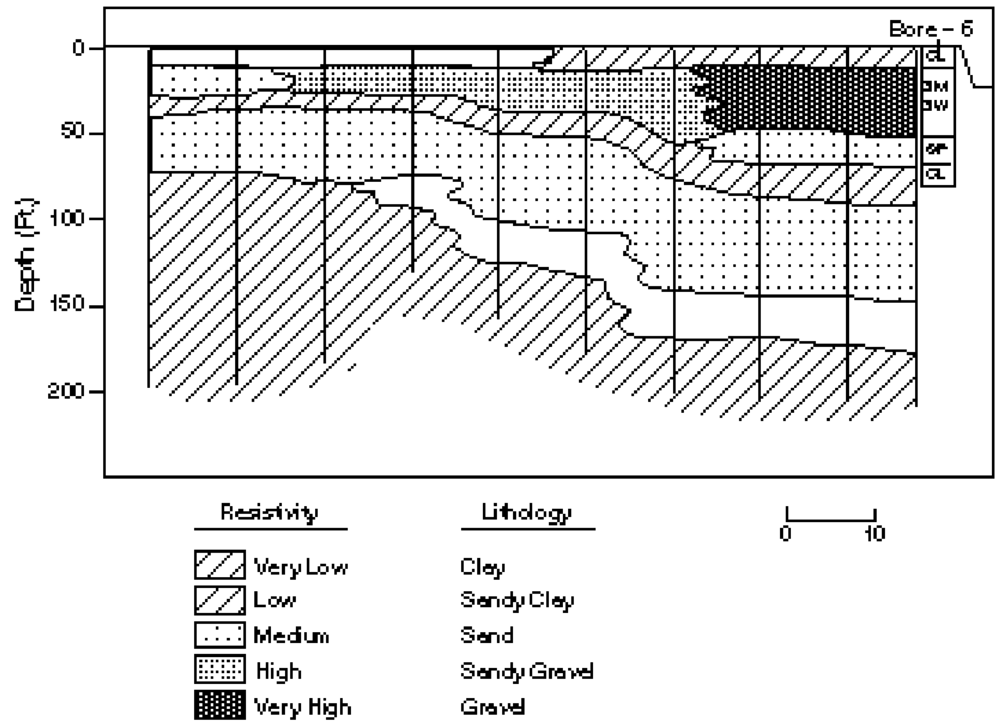
The resolution provided by EM methods is often not as good as other geophysical methods. Horizontal resolution may indicate the location of features to within 4 feet; vertical resolution can only be approximated. However, general indication of stratigraphy can be presented. The direction and general location of fractures and faults can also be presented.

Ground Penetrating Radar

When soil conditions are favorable, GPR can be very effective for assessing shallow, localized subsurface conditions. The geologic and hydrogeologic features that can be detected with GPR include:

- Karst, fractures, and faults;
- Depth and thickness of shallow sediments and bedrock; and
- Occasionally, depth to groundwater.

Exhibit III-15
Time-Domain Electromagnetic Survey Of Stratigraphy



Source: NORCAL Geophysical Consultants, Inc.

GPR provides excellent resolution; however, interpretation of plots can be very difficult and require an experienced practitioner. Because it is not generally used as a reconnaissance tool, it is best used to clarify the existence and location of suspected features within a specific area. In addition, GPR is typically only useful for delineating shallow geological features because its depth of penetration can be significantly limited by site conditions. However, when soil conductivities are very low (*e.g.*, in sand, gravel), geologic features can be resolved up to 90 feet bgs.

GPR can be used to estimate the depth and thickness of soil and rock layers to within one foot. Occasionally, depth to groundwater can be determined, but the site must be above shallow, well-sorted sands that produce a water table with a small (less than 1 foot) capillary fringe.

Exhibit III-16 presents an example of a GPR survey and interpretation of karst. Although GPR did not provide good resolution in zones of solid limestone, the karst could be mapped because the radar signal is not attenuated as much in the sand that fills the karst.

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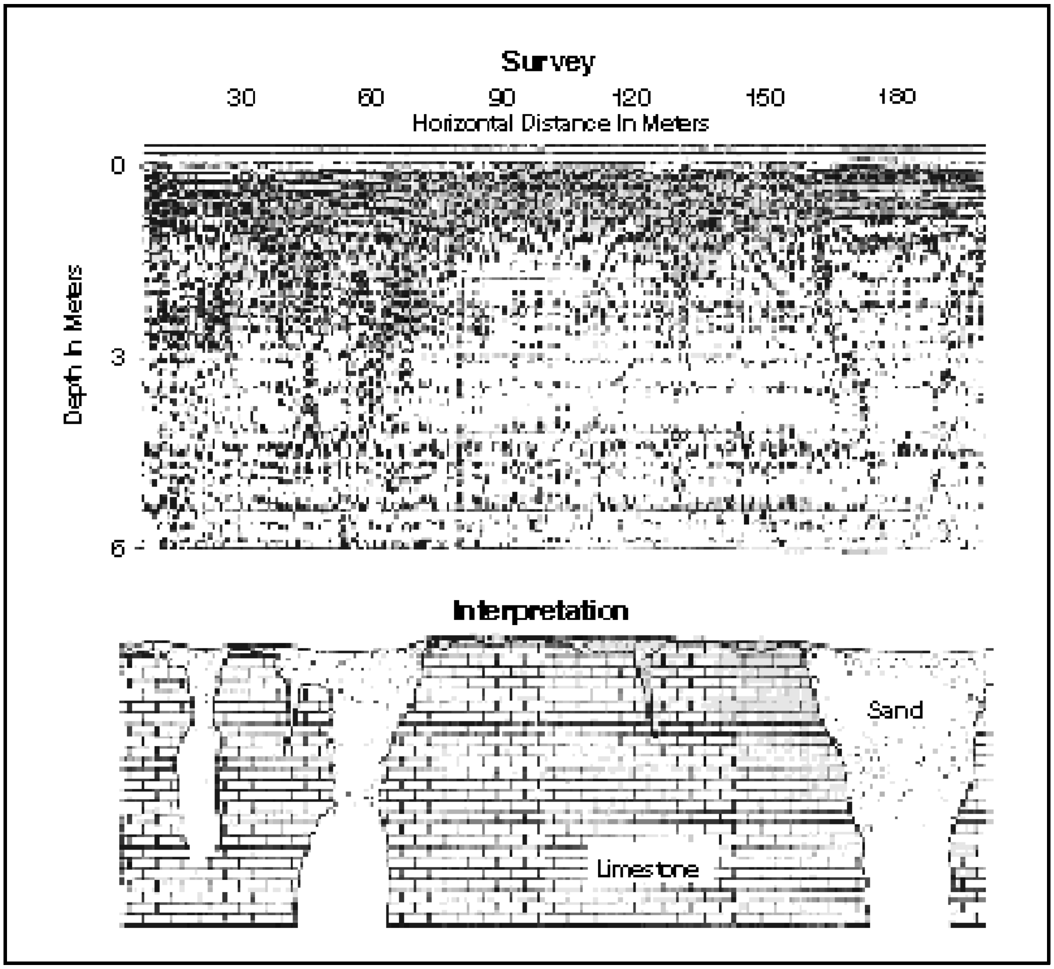
Exhibit III-16
Ground Penetrating Radar Survey And Interpretation Of Karst



Source: Benson et al., 1984

Electrical Resistivity

Electrical resistivity can occasionally be used at UST sites to provide information about subsurface conditions. When used for this purpose, resistivity measurements can help resolve:

- Sediment depth and thickness;
- Karst, fractures, and faults;
- Depth to bedrock; and
- Depth to groundwater.

ER can easily collect data beyond 100 feet bgs, however, geologic features less than approximately 5 feet may not be resolved. Depths of these features can be estimated to within 5 feet if additional subsurface data (*e.g.*, boring logs) are available. The accuracy of depth estimates decreases with depth.

Delineating Residual Or Floating Product

One of the most difficult aspects of a site assessment is delineating the extent of contamination. Although geophysical tools are not helpful in mapping the extent of dissolved product at a site, in some situations they can play an important role in mapping the location of residual product in the vadose zone and floating product above groundwater. This is an area of active research and many issues involved with the uses of appropriate methods remain unresolved.

In general, hydrocarbons are difficult to detect because they are resistive compounds that often cannot be distinguished from the surrounding soils and rock layers. However, among the hydrocarbons, light non-aqueous phase liquids (LNAPLs) (*e.g.*, gasoline, jet fuel, diesel fuel) are the most likely hydrocarbons to be detected because they float and form a distinct layer above the groundwater. For some geophysical methods, the LNAPL layer must be several feet thick for detection. Some detection methods may detect older spills more easily than newer spills because the natural rise and fall of a water table will “smear” the product over a greater area. In addition, the natural lateral geologic variations will interfere with the interpretation of geophysical plots for all methods because distinguishing between changes due to geology or LNAPLs may be difficult.

There are several surface geophysical methods that have the potential to detect LNAPLs in the subsurface. Ground penetrating radar (GPR) and electrical resistivity (ER) are currently the best documented methods and are discussed in the following text. A summary of the effectiveness of these two methods for delineating residual or floating product is presented in Exhibit III-17.

Exhibit III-17
Summary Of Geophysical Methods For Delineating Residual And Floating Product

	Ground Penetrating Radar	Electrical Resistivity
Depth Of Detection	3 to 15 ft	10 to 15 ft
Cultural Interferences	Densely packed rebar	Concrete, metal surface structures
Natural Interferences	Conductive soils (*e.g.*, clays), lateral geologic variations	Highly conductive soils (*e.g.*, wet dense clays), lateral geologic variations
Produces Usable Field Data	Yes	No
Detection Limit (Quantity Of Product)	Unknown	Unknown
Cost	Low to Moderate	Moderate to High

Other methods that are undergoing research but that are not yet appropriate for inclusion, include electromagnetic methods (EM), induced polarization (Olhoeft, 1986; also known as complex resistivity), and ultrasonic imaging (Geller, 1995; a type of seismic method). Borehole methods are extremely useful for the purpose of determining the thickness of floating product because they provide exact, *in situ* measurements that cannot be accomplished with any other means. These methods are discussed in detail in Direct Push Technologies, Chapter V.

Ground Penetrating Radar

Occasionally, GPR can provide an indication of the presence of hydrocarbons although success may be difficult to predict, and the reasons for its occurrence are not yet completely understood. There are several observations reported in scientific literature. In most cases, interpretation requires a boring log to compare reflection depths with actual soil types.

One study (Daniels, 1995) reports that in areas of petroleum hydrocarbon contamination, radar waves will not necessarily reflect back to the GPR receiver.

This effect causes a "halo" (*i.e.*, decrease in reflection) over the area of contamination which contrasts with neighboring areas of reflection. A similar result was observed in a controlled kerosene spill in Canada (DeRyck, 1993). However, in another controlled spill experiment (Campbell, 1996), a bright spot (*i.e.*, an increase in the reflected GPR signal) was observed. The reason for these contradictory results has not yet been adequately explained.

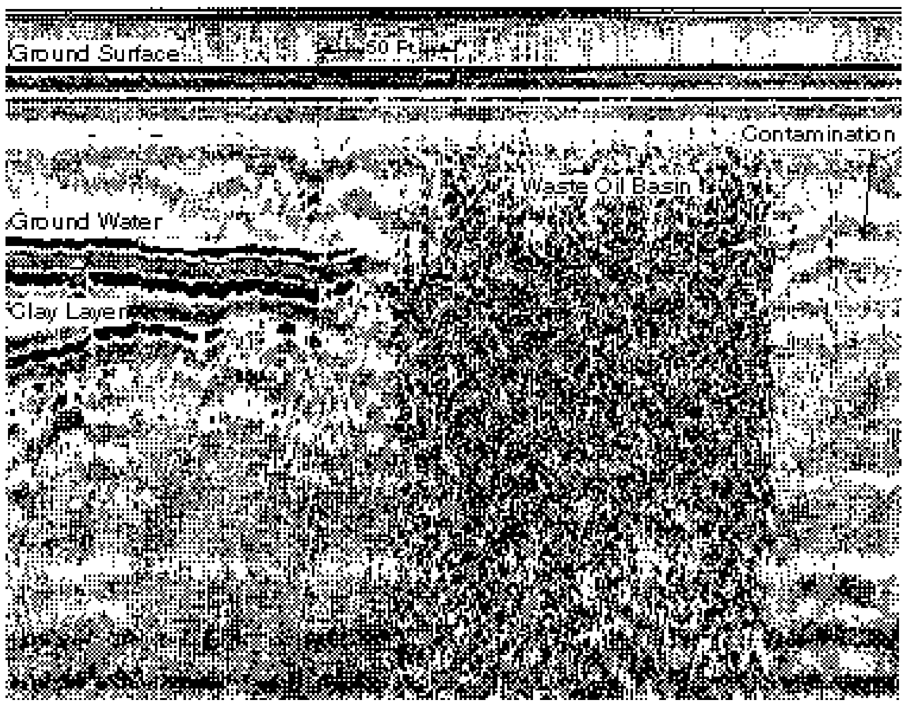
In addition (Benson, 1995) observed that, on occasion, a small amount of petroleum can cause the groundwater capillary fringe to collapse. If the water table is located in a zone of low permeability soils that create a large capillary fringe (*e.g.*, clays), then a drop in the location of the groundwater reflection compared with the surrounding area may be observed. Exhibit III-18 provides an example of this phenomenon.

The amount of floating product required for these observations, and the conditions that cause them requires further research. As a result, the use of GPR to detect contamination is still experimental.

Electrical Resistivity

Electrical resistivity surveys are primarily used for determining site stratigraphy. On occasion, as a secondary aspect of the survey, this method may present evidence of LNAPL contamination (DeRyck, 1993). In order for this method to be successful, a number of conditions must exist at a site. Groundwater must be no more than 15 feet deep, conductive soils must be present in the contaminated zone, and floating product must exist (although the minimum quantity is unknown). Because this method is relatively expensive and success in locating hydrocarbon contamination is not predictable, it is not typically used for the sole purpose of locating petroleum plumes.

Exhibit III-18
Petroleum Contamination Detected With Ground Penetrating Radar



Source: U.S. EPA, 1995

Geophysical Equipment Manufacturers

A list of geophysical equipment manufactures is included below in Exhibit III-19 and a matrix of their products is presented in Exhibit III-20. The equipment has not been evaluated by the EPA and inclusion in this manual in no way constitutes an endorsement. These vendors are listed solely for the convenience of the reader.

Exhibit III-19
Geophysical Equipment Manufacturers

Bison Instruments, Inc. 5708 West 36th Street Minneapolis, MN 55416-2595 Tel: (612) 931-0051 Fax: (612) 931-0997	Geometrics 395 Java Dr. Sunnyvale, CA 94089 Tel: (408) 734-4616 Fax: (408) 745-6131
Geonics Limited 8-1745 Meyerside Dr. Mississauga, Ontario Canada L5T 1C6 Tel: (905) 670-9580 Fax: (905) 670-9204	Geophysical Survey Systems, Inc. 13 Klein Dr. North Salem, NH 03073-0097 Tel: (603) 893-1109 Fax: (603) 889-3984
GeoRadar, Inc. 19623 Vis Escuela Dr. Saratoga, CA 95070 Tel: (408) 867-3792 Fax: (408) 867-4900	GeoStuff, Inc. 19623 Vis Escuela Dr. Saratoga, CA 95070 Tel: (408) 867-3792 Fax: (408) 867-4900
GISCO 900 Broadway Denver, CO 80203 Tel: (303) 863-8881 Fax: (303) 832-1461	Oyo-Geosciences, Inc. 7334 North Gessner Houston, TX 77040 Tel: (800) 824-2319 Fax: (713) 849-2595
Phoenix Geophysics, Ltd. 3871 Victoria Park Ave. Unit No.3 Scarborough, Ontario Canada M1W 3K5 Tel: (416) 491-7340	Scintrex, Ltd. 222 Snidecroft Rd. Concord, Ontario Canada L4K 1B5 Tel: (905) 669-2280 Fax: (905) 669-6403
Sensors and Software, Inc. 5566 Tomken Rd. Mississauga, Ontario Canada L4W 1P4 Tel: (905) 624-8909 Fax: (905) 624-9365	Zonge Engineering and Research Organization, Inc. 3322 East Fort Lowell Rd. Tucson, AZ 85716 Tel: (602) 327-5501 Fax: (602) 325-1588

Exhibit III-20
Matrix Of Manufacturers And Equipment[1]

	Borehole	Electro-magnetic Methods	Electrical Resistivity	Ground Penetrating Radar	Metal Detection	Magnetometry	Seismic Methods
Bison	✓		✓			✓	✓
Geometrics		✓				✓	✓
Geonics	✓	✓			✓		
GSSI				✓			
GeoRadar				✓			
GeoStuff	✓						✓
GISCO		✓	✓			✓	✓
Oyo	✓	✓	✓	✓	✓	✓	✓
Phoenix		✓					
Scintrex	✓		✓			✓	
SSI				✓			
Zonge		✓	✓		✓		

[1] This matrix presents only a general list of the equipment manufactured that is discussed in this chapter. These manufactures may manufacturer other geophysical equipment in addition to what is listed here. In addition, these manufacturers may only supply specialized equipment for the listed methods, and not necessarily all the equipment that is needed.

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