DEPARTMENT OF TOXIC SUBSTANCES CONTROL
CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

APPLICATION OF SURFACE GEOPHYSICS AT CONTAMINATED SITES

Guidance Manual for Groundwater Investigations

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FOREWARD

The California Environmental Protection Agency (Cal/EPA) is charged with the responsibility of protecting the state's environment. Within Cal/EPA, the Department of Toxic Substances Control (DTSC) has the responsibility of managing the State's hazardous waste program to protect public health and the environment. The State Water Resources Control Board and the nine Regional Water Quality Control Boards (RWQCBs), also part of Cal/EPA, have the responsibility for coordination and control of water quality, including the protection of the beneficial uses of the waters of the state. Therefore, RWQCBs work closely with DTSC in protecting the environment.

The DTSC is issuing this guidance on the application for surface geophysics for immediate use in investigations and cleanups at contaminated sites. This document supersedes previous DTSC issued guidance dated July 1995, *Application of Surface Geophysics at Hazardous Substance Release Sites,* and is one in a series of DTSC guidance documents pertaining to the characterization and cleanup of contaminated sites.

This document was prepared by staff in the Geological Services Unit (GSU) within DTSC. The GSU provides geologic assistance, training and guidance to DTSC and outside stakeholders. This document has been prepared to provide guidelines for the characterization and remediation of contaminated sites. It should be used in conjunction with the companion reference for groundwater characterization activities:

Guidelines for Planning and Implementing Groundwater Characterization of Contaminated Sites (DTSC, 2012).

Please note that within this document, the more commonly used terms, *hazardous waste site* and *toxic waste site*, are used synonymously with the term hazardous substance release site. However, it should be noted that any unauthorized release of a substance, hazardous or not, that degrades or threatens to degrade water quality may require corrective action to protect its beneficial use.

Comments and suggestions for improvement of this revised guidance, *Application of Surface Geophysics at Contaminated Sites,* should be submitted to:

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ABBREVIATIONS AND ACRONYMS

ASTM	ASTM International (formerly known as American Society of Testing and Materials)
bgs	below ground surface
Cal/EPA	California Environmental Protection Agency
DTSC	Department of Toxic Substances Control
EM	electromagnetic
FEM	frequency-domain electromagnetic
GPR	ground penetrating radar
GPS	global positioning system
GSU	Geological Services Unit
IP	induced polarization
kHz	kiloHertz
QA/QC	quality assurance/quality control
RWQCB	Regional Water Quality Control Board
SP	spontaneous potential
TDEM	time-domain electromagnetic
TEM	transient electromagnetic
USEPA	United States Environmental Protection Agency
UXO	unexploded ordnance
VLF	very low frequency

1.0 INTRODUCTION

1.1 Purpose

This document has been written to provide guidelines for the application of surface geophysical techniques in the characterization of contaminated sites. This manual aids in the selection of surface geophysical methods, provides recommended quality assurance and quality control (QA/QC) procedures, and presents a standardized approach to the presentation of the resulting data. This document discusses the following surface geophysical methods: electromagnetics (EM), very-low frequency (VLF) electromagnetics, electrical resistivity, magnetometry, ground penetrating radar, gravimetry, seismic reflection, and seismic refraction. Induced polarization (IP) and spontaneous potential (SP) geophysical methods are briefly discussed as less frequently used techniques at contaminated sites.

The DTSC intends for these guidelines to incorporate relevant technical publications and documents. These guidelines will be updated as new techniques become available and existing methods refined to meet the state of the science.

This guidance manual was developed in conjunction with other investigative documents as outlined in *Guidelines for Planning and Implementing Groundwater Characterization of Contaminated Sites* (DTSC, 2012).

1.2 Application

Surface geophysical surveys provide critical information on subsurface features and can be applied in all stages of hazardous waste investigations. When applied early in site characterization, surface geophysics provides valuable information that usually leads to significant cost savings for site investigation and remediation. Surface geophysical surveys reveal areas of disturbed soil, evidence of waste disposal, location of waste containers (i.e. drums), ordnance related items, and other cultural features. Additionally, surface geophysics can be used to locate monitoring wells, correlate geologic stratigraphy, and in some cases locate underground contaminant plumes. Cultural features such as underground utilities can be avoided during well installation or soil removal actions. Also, leaky water pipes, sewer or waste lines can be located with surface geophysics aiding in determining contaminant migration pathways.

1.3 Limitations

The recommendations presented identify the minimal criteria necessary to obtain quality data that assures reasonable and independently verifiable interpretations, while some sites may require investigative efforts above and beyond the scope of this document. The qualified professionals performing site investigations and their clients remain responsible for meeting pertinent regulatory requirements and observing proper technical judgment.

This document broadly discusses surface geophysical methods and instruments that can be used in contaminated site investigations. The guidance does not provide specific operating procedures for geophysical surveys or for interpreting their results, and does not present every geophysical method and instrument available. The qualified professional in charge remains responsible for deciding specific geophysical methods, procedures, and interpreting results. Departures from the workplan that were necessary during the course of the investigation should be identified by the geophysicist.

The guidelines presented herein are applicable to the use of surface geophysics to define natural conditions and man-made features that may contain hazardous waste or influence the movement of contaminants.

This document does not supersede existing statutes and regulations. Federal, state and local regulations, statutes, and ordinances should be identified when required by law, and site characterization activities should be performed in accordance with the most stringent of these requirements where applicable, relevant and appropriate.

2.0 RECOMMENDED PRACTICES AND SPECIFICATIONS

2.1 Personnel Qualifications

Conducting surface geophysical surveys and interpreting results requires specialized education and training in geology, geophysics, and physics. Understanding each method’s theory, procedures for the proper collection of data, and interpretation techniques, as well as knowledge of the site geology is necessary for successful completion of a survey. Personnel planning field surveys or interpreting geophysical data should possess adequate certification of such training. Specialized geophysical education is not required for field crews conducting geophysical surveys; however, these personnel should be under the supervision of a professional geophysicist who should ensure field crews are adequately trained and qualified.

The Geologist and Geophysicist Act defines the scope of practice and qualifications for conducting geophysical surveys in California. Section 7835.1 of the Act which states, "All geophysical plans, specifications, reports or documents shall be prepared by a professional geophysicist . . . professional geologist . . . or by a subordinate employee under his or her direction." In addition, the professional accepts responsibility for the contents by affixing his or her signature or seal. However, possession of a license as a Professional Geologist in California does not, in and of itself, qualify a person to practice geophysics. Therefore, the following criteria should be considered for defining qualified geophysical personnel: a Professional Geophysicist for the State of California, or a Professional Geologist for California who is also a qualified geophysicist, defined in Section 7807.1 of the Geologist and Geophysicist Act, as a person who meets required education and experience qualifications for, but does not possess registration as a geophysicist. The DTSC recommends that all geophysical studies be supervised and directed by Professional Geophysicists.

2.2 Quality Control Parameters

2.2.1 Feasibility Assessment and Method Selection

Every surface geophysical technique has specific advantages and limitations. The success or failure of any particular geophysical technique is dependent upon many factors, including geologic conditions, atmospheric disturbances, and urban development. It is necessary to evaluate these site-specific factors to assess the viability of surface geophysical techniques and, if possible, select the techniques that will best suit field conditions. This evaluation should include the following elements:

- Determine the data quality objectives of the study,
- Identify potential sources of interference with the geophysical signal, and
- Describe the targets of interest (including composition and depth of burial) and an assessment of sensitivity of the chosen techniques to the targets of interest.

A summary of the geophysical techniques discussed in this document is provided in Table 1.

Table 1 - Common Surface Geophysics Techniques for Contaminated Sites

Method	Description and Purpose
Electromagnetics (EM)	Uses induced electrical currents to measure the bulk conductivity of subsurface materials. Also used to map buried steel drums, tanks, pipelines, and unexploded ordnance (UXO).
Very Low Frequency (VLF) Electromagnetics	Uses low frequency radio signals to detect magnetic fields and electrical conductors, particularly long, straight, electrically charged conductors.
Electrical Resistivity	Uses induced electrical current to measure the bulk resistivity of subsurface materials to provide estimates of depth, thickness, and resistivity of subsurface geology and fluids.
Magnetometry	Measures magnetic field of subsurface anomalies such as underground pipelines and buried metal debris, drums, and other metallic debris.
Ground Penetrating Radar (GPR)	Uses high-frequency electromagnetic waves to map depth to bedrock, depth to the water table, depth and thickness of soil strata, subsurface cavities, and fractures in bedrock. Also used to locate buried objects, such as pipes, drums, tanks, cables, and boulders as well as to map landfill and trench boundaries
Gravimetry	Measures variations in the earth’s gravitational field to delineate geologic structures and large-scale features such as faults, landfills, and groundwater basins.
Seismic Reflection	Uses sound wave reflections to identify subsurface stratigraphy and structural features.
Seismic Refraction	Uses sound wave refractions to identify subsurface stratigraphy.
Induced Polarization (IP)	Measures bulk electrical characteristics of subsurface materials to map contaminant plumes or confining layers.
Spontaneous Potential (SP)	Measures the difference in potential to detect movement of ionic fluids to or within groundwater.

The amount and quality of existing site-specific geologic information should also be considered. The number and types of geophysical surveys and measurement locations should be determined by, or in consultation with, qualified geophysical personnel.

A discussion of the feasibility evaluation and its results should be included in an appropriate workplan and geophysical report. This discussion need not be comprehensive: a concise summary may be sufficient for most evaluations. However, the amount of detail should be dependent on site-specific factors and the objectives of the investigation.

2.2.2 Data Processing

Producing interpretable data from geophysical measurements may require some degree of data or signal processing, to reduce interference caused by noise and enhance the signals of interest. Care should be used during processing to ensure data of interest to the study are adequately preserved. To this end, data needs should be balanced with processing requirements so that, whenever possible, the amount of processing is kept to a minimum. The processing methods used to produce any final interpretations should be documented in an appropriate geophysical report. Proprietary techniques should be described, although commonly available methods may be documented by reference to published literature.

2.2.3 Measurement Locating

A basic requirement for any site characterization study is that sampling or measurement points are located and mapped accurately. The degree of care and accuracy needed to locate and map geophysical measurements will vary, depending on data requirements and the purpose for their use. For example, gravity measurement stations usually require professional surveying or use of a Global Positioning System (GPS) collecting detailed location coordinates; whereas electromagnetic [EM] measurement stations could be located by simple sighting to a permanent datum, if only qualitative analysis were needed. The techniques and precision of location surveys should be appropriate to the required precision and purpose of the data. If professional surveying is required, civil engineers or surveyors licensed by the State of California should be used. Surveyed points should be recorded using the California State Plane coordinate system. Locations of all measurements should be presented in all appropriate workplans and geophysical reports.

2.2.4 Correlation with Geology

When site-specific subsurface lithologic and hydrologic data are available, the geophysical models should be correlated with the subsurface information. This does not imply that geophysical models may be used by themselves (see Section 2.2.5). If subsurface data are not available, they should be collected whenever feasible. The results of this correlation should be included in the interpretation section of an appropriate geophysical report.

2.2.5 Reconnaissance Studies

No geophysical technique yields a unique solution. However, by adding an additional geophysical method to the survey, the number of possible solutions that could fit both data sets is significantly reduced. Without site-specific geologic data, an accurate geophysical interpretation cannot be obtained with confidence. The use of more than one method adds constraint to the geologic interpretation of geophysical data. Therefore, where geophysical techniques are used as part of a reconnaissance study, more than one geophysical technique should be used. For the purposes of this document, a reconnaissance study is defined as a study undertaken in the early stages of a site investigation, a survey to plan well or boring installations, as survey to enhance removal actions, or further investigations at a site where little or no site-specific stratigraphic or hydrostratigraphic information is available.

2.2.6 Calibration and Field Checks

The quality of data from geophysical instruments should be assured through regular calibration and by conducting field checks prior to each survey. All geophysical instruments should be tested and calibrated on a regular basis. Calibration and field checks should be conducted according to manufacturer's recommendations; if none exist, the owner should establish and follow a regular schedule for both calibration and field checks. Appropriate standards for field checks vary depending on the type of instrument, but can include built-in standards, external calibrators, or an established baseline area on the ground. In any case, a description of calibration and field check methods used should be documented and included in an appropriate geophysical report.

2.2.7 Documentation

QA/QC procedures for surface geophysical surveys should be addressed in an appropriate geophysical workplan and report. The workplan should identify the objectives of the study and outline the rationale for the selection of the geophysical methods to be used. The final report should present an interpretation of the geophysical data, and should discuss any problems encountered in the field and any deviations from the workplan that were needed to solve those problems. Geophysical report guidelines and suggested report contents are provided in the *Guidelines for Geophysical Reports for Environmental and Engineering Geology* (California Board for Geologists and Geophysicists, 1998).

As discussed in the preceding sections, the feasibility assessment (Section 2.2.1), measurement locations (Section 2.2.3), and calibration information (Section 2.2.6) should be recorded and presented in an appropriate document. It is equally important that the interpretation of the geophysical data be fully documented and substantiated, for verification and possible extension of the survey. The field methods used to conduct the surveys (Section 2.2.1), techniques used for data processing (Section 2.2.2) and interpretation should be documented in an appropriate geophysical report. All data used to interpret surface geophysical surveys should be presented as part of the interpretation, including a description of regional and (if available) site-specific geology (Section 2.2.4), graphs and tables of geophysical data, and the names and descriptions of any computer software used for data reduction and interpretation. Raw data and data files used for computer modeling need not be included in the final report. However, such data should be kept on file and made available at the request of regulatory agencies. The data and interpretations should be included in one or more deliverables (i.e., workplans and site characterization reports), as described in *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA* (U.S. Environmental Protection Agency, 1988).

2.3 Electromagnetics (EM)

2.3.1 Fundamentals

EM is the technique of inducing and detecting electrical currents in the subsurface. Currents are induced in the subsurface by the application of time-varying magnetic fields which measure the bulk conductivity (the inverse of resistivity) of subsurface materials. EM can be used to locate pipes, utility lines, cables, buried steel drums, trenches, buried waste, and concentrated contaminant plumes. The method can also be used to map shallow geologic features such as lithologic changes, clay layers, and fault zones (Benson, 1982).

2.3.2 Instrumentation

The most common type of EM equipment used at contaminated sites consists of coplanar transmitter and receiver coils with fixed separation. Most of these systems have only a few discrete coil separations in order to internally process the data for the output to be in conductivity units (millimhos per meter). Some systems produce an output in units of secondary field as a percentage of the primary field. Increasing the coil separation increases the depth of exploration (ASTM D6820-02).

The frequency-domain electromagnetic (FEM) systems are more commonly used in contaminated sites investigations. With FEM systems, the electrical current flowing in the transmitter coil is sinusoidal with time, running at a fixed frequency. Most FEM equipment allows measurement of both the “in-phase” (or “real”) component and 90 degree “out-of-phase” (or “quadrature”) components of the induced magnetic field (ASTM D6639-01).

Another type of EM equipment operates in the time domain and is used more for detection of buried metallic objects. Operation of this “transient” or “time-domain” electromagnetic (TEM or TDEM) equipment involves a transmitted current that is kept on long enough to create a steady-state magnetic field in the earth, and is then shut off. The resulting induced currents then dissipate with time. The secondary magnetic field associated with decaying currents is sampled at a remote receiver as a function of time after transmitter shut-off (ASTM D6820-02).

2.3.3 Data Collection

EM data can be acquired in two configurations, either along a traverse or in a rectangular grid pattern. Each configuration has its advantages and disadvantages, which are dependent upon variables such as the site conditions, size and orientation of the target, et cetera.

With both grid and traverse data, the spacing of data acquisition points is important. To ensure detection of targets of interest, station intervals must be close enough for the EM instrument to detect the smallest-sized target. If an electrically conductive contaminant plume is to be investigated, the station interval should ensure that several stations are within the area corresponding to the contaminant plume. Station intervals can be increased away from the area of anomalous readings if there is low variability in the data. Data acquisition should extend beyond target boundaries so that background levels can be obtained and to understand background variability.

Depth of penetration is greater in the vertical dipole configuration than in the horizontal dipole configuration; therefore, the vertical dipole configuration is more commonly used. Depth of penetration is generally considered to be one-half the coil separation, but in actuality is a complex function of subsurface conductivity, coil separation and orientation, and transmitter frequency (ASTM D6429-99).

Grid or traverse coordinates can be located use Global Positioning System (GPS) or, alternatively, can be surveyed from fixed locations, such as buildings, property corners, or other features that can be resurveyed at a future date. Features such as buildings, roads, monitoring wells, property lines, and potential sources of cultural interference should be noted. General features of the topography should also be noted because the instrument readings are often influenced by water-table depth and overburden thickness.

2.3.4 Quality Assurance/Quality Control

Sources of cultural noise should be avoided to the extent possible. These include large metal objects, buried cables, pipes, buildings, metal fences, and other electrically conductive materials (ASTM D6639-01). Instrument readings should be considered compromised (unless known to be otherwise) when the midpoint between the transmitter and receiver coils is within four coil separations from a source of cultural noise, such as a metal fence, pipeline, power line, or other source noise. Instrument readings in proximity to sources of cultural interference should be noted by the field operator so that the interpreting geophysicist can compensate for the effects of these features.

2.3.5 Interpretation

Instrument readings in millimhos per meter do not need additional data reduction because they are already in units corresponding to the bulk conductivity of the subsurface. Data acquired along traverses can be qualitatively interpreted by comparison to published modeling results or computer modeling programs. Layer determinations require a different field procedure than profiling or aerial mapping (ASTM D6639-01). Detailed descriptions of these procedures are available in existing literature.

2.3.6 Presentation of Findings/Conclusions

Data acquired in a grid configuration should be displayed as profiles and contour map(s), with reference to the contour interval and scale of the profile plots. Traverse data should be presented in profile form, and include the scale of the plots. Location of grids and traverses should be indicated on a site map. Areas of probable buried metallic targets or contaminant plumes should also be indicated on the contour map, along with physical and cultural features. The geophysical report should contain information pertinent to the instrumentation, field operations, and interpretation techniques used.

2.3.7 Advantages

The EM method is commonly used on contaminated site investigations and many geophysicists are familiar with EM data acquisition procedures and interpretation techniques. Most EM equipment used is lightweight and easily portable and field measurements can be acquired rapidly and with a minimum number of field personnel.

2.3.8 Limitations

The main limitation of the EM method when used for contaminated site investigations is cultural noise which may include large metal objects, buried cables, power lines, pipes, buildings, and metal fences. However, in some site investigations, these objects may be targets of interest in their own right. Therefore, electromagnetics can successfully be used to map buried steel drums, tanks, pipelines, unexploded ordnance (UXO), and other metal objects, although the presence of these objects will effectively mask the more subtle response of most geologic features.

2.4 Very Low Frequency (VLF) Electromagnetics

2.4.1 Fundamentals

The very-low frequency (VLF) electromagnetic method detects magnetic fields and electrical conductors by utilizing radio signals in the 15 to 30 kiloHertz (kHz) range that are generated by military communication transmitters (USEPA, 1993). The VLF method is useful for detecting long, straight electrical conductors, such as conductive faults and fracture zones, especially water-bearing fracture zones in hard rock. Due to the availability of limited frequency, VLF measurements are interpreted mostly qualitatively and it is difficult to derive depth information from VLF data. This method provides data of sufficient quality for use in many environmental applications (Tezkan, 1999).

The VLF instrument compares the magnetic field of the primary signal (the transmitted signal) to that of the secondary signal (induced current flow within the subsurface electrical conductor). In the absence of subsurface electrical conductors, the transmitted signal is horizontal and linearly polarized. When a subsurface conductor is crossed, the magnetic field becomes elliptically polarized and the major axis of the ellipse tilts with respect to the horizontal axis (McNeill, 1988; Paterson and Ronka, 1971).

A number of VLF transmitting stations are operated by the United States military on a worldwide basis; the most commonly used stations in North America are located at Annapolis, Maryland; Cutler, Maine; Seattle, Washington; and Lualualei, Hawaii. VLF systems utilize one or more of these transmitting stations for survey applications.

For more complete discussion of the VLF method, readers are referred to McNeill and Labson (1991).

2.4.2 Instrumentation

All VLF instruments measure two components of the electromagnetic field or equivalently the “tilt angle” and ellipticity of the field. The more recent instruments measure both in-phase and quadrature components of the ratio of horizontal-to-vertical magnetic field. Some instruments have real-time interpretive capability for use while still collecting data. The induced electrical field is measured by inserting two probes in the ground, spaced about five meters apart, and measuring the potential difference at the transmitter frequency. The induced field provides additional information about the overburden thickness and conductivity (Hutchinson and Barta, 2002).

2.4.3 Data Collection

VLF data are usually collected along traverses and anomalies are correlated between traverses. Lines of data acquisition must be located perpendicular to the strike of the intended target so anomalous zones can be compared to background levels. Lines should be oriented parallel to one another and spaced 25 to 50 feet apart and should be placed to avoid areas of cultural features that may interfere with instrument readings and mask the intended target. Data should be acquired along traverses of adequate length to cover the entire anomaly caused by the target and the readings return to a background level.

2.4.4 Quality Assurance/Quality Control

The VLF receiver antenna should be properly oriented to consistently collect data facing the same direction. Field notes should be kept regarding the location of cultural features, such as buried utility lines, buildings, metal fences, overhead high voltage power lines, and concrete structures. To ensure data quality and to assist with interpretations, instrument readings be taken along a traverse using more than one transmitting station.

2.4.5 Interpretation

VLF interpretation is generally qualitative or subjective in nature. Data collected in the field can be interpreted without further data reduction. By plotting data components versus distance along a traverse, an experienced geophysicist can often interpret where fractures or zones of high electrical conductivity are located. Some simple modeling may be carried out for simple geometric structures.

2.4.6 Presentation of Findings/Conclusions

The most common way to present VLF data is to plot the “real” and “imaginary” component values on the y-axis and distance along a traverse on the x-axis of a plot. Plots should be drafted at the same vertical and horizontal scales for consistency and ease of comparison. Interpreted zones of interest and locations of cultural features should be indicated on annotated plots. The locations of the traverses should be shown on a base map along with anomalies interpreted as zones of interest.

The geophysical report should include explanations for the transmitting station used, the traverse station spacing, and field procedures implemented. Problems encountered during data collection (such as a transmitting station shutting down or excessive atmospheric interference) should be noted.

2.4.7 Advantages

Advantages of the VLF method are ease of use, rapid deployment, simple processing and low cost. The method requires a field crew of only one or two people. It is an effective geophysical method for detecting long, straight, electrically charged conductors, such as water-filled fractures and faults within bedrock (Hutchinson et. al., 2010).

2.4.8 Limitations

One important limitation of the VLF method is the lack of source control; available transmitters are operated by the military and are often shut down for scheduled and unscheduled maintenance. Also, the method is sensitive to ferrous and nonferrous cultural noise and has only a relatively shallow depth of investigation (no greater than 75 meters). Interpretation is generally qualitative in nature; quantitative modeling requires a high data density and a well constrained model. Topographic effects can bias the data, are difficult to remove, and are model dependent (Hutchinson and Barta, 2002).

2.5 Electrical Resistivity

2.5.1 Fundamentals

Electrical resistivity methods measure bulk resistivity of geologic materials and are used to map the electrical resistivity structure of the subsurface. Geophysicists use electrical resistivity data to interpret geologic structure and/or physical properties of subsurface geologic materials. In the electrical resistivity method, current is induced in ground through surface electrodes. Electrical resistivity of a geologic unit or feature is a function of porosity, permeability, water saturation and the concentration of dissolved solids in pore fluids within the subsurface (ASTM D6431-99).

2.5.2 Instrumentation

Instrumentation for electrical resistivity systems consist of a transmitter and receiver; the transmitter supplies an electrical current that is applied across the electrodes. The power requirements for the most commonly used electrode arrays, such as Schlumberger and Wenner arrays, are minimal with power usually supplied by a battery pack. Other electrode configurations, such as dipole-dipole arrays, generally require additional power, often necessitating the use of an electrical generator. The complexity of receivers range from simple analog voltmeters to computer-controlled systems capable of signal enhancement, stacking, and digital data storage.

2.5.3 Data Collection

The three most common surveying methods used with electrical resistivity are profiling, sounding, and profiling-sounding. For the purpose of mapping depths and thickness of stratigraphic units, electrical resistivity data should be collected in sounding mode. Lateral electrical resistivity contrasts, such as lithologic contacts, are usually mapped in the profiling mode. In situations where the electrical resistivity is expected to vary both vertically and horizontally, such as in contaminant plume mapping, the preferred mode is profiling-sounding (Ward, 1990).

2.5.4 Quality Assurance/Quality Control

The two most common sources of errors in electrical resistivity surveying are errors associated with the positioning of electrodes, electrical noise from power lines, and poor electrical contact. The errors in positioning electrodes most often occur when moving electrodes. These distance measurement errors can be detected on apparent electrical resistivity versus electrode separation curves. The field geophysicist should recognize these errors and direct the field crew to check the location of the electrodes. To reduce electrical noise generated by power lines, the contact electrical resistance at the potential electrodes should be minimized. This can be accomplished by using non-polarizing potential electrodes along with wetting soils under the electrode with water. Electrical contact can be monitored by observing instrument readings and trends in collected data.

2.5.5 Interpretation

Once electrical resistivity data are acquired, apparent electrical resistivity should be calculated by dividing the measured voltages by the applied current. The resultant is then multiplied by the geometric factor specific to the electrode array used in the acquisition of data. Subsequently, the geophysicist should model the data to interpret subsurface geologic structure.

The methods used to model apparent electrical resistivity data differ according to each mode of data acquisition. Sounding data, acquired using either the Wenner or Schlumberger array, can be modeled using master curves or computer modeling algorithms. Modeling profiling-sounding data requires a more complicated computer simulation due to electrical resistivity variations both laterally and vertically. Detailed discussion of various modeling methods and techniques is beyond the scope of this guidance. Additional details are available in existing literature (ASTM D6431-99).

2.5.6 Presentation of Findings/Conclusions

The geophysical report should provide a list of data acquisition parameters, including electrode separations, current amplitudes, measured voltages, and reduced apparent resistivities. Information regarding the manner in which the data were reduced or modeled should be included in the report.

Electrical resistivity data acquired in sounding mode should be presented on a bilogarithmic plot of electrical resistivity versus the distance from the current electrodes to the center of the electrode array. If data are modeled, the modeled apparent electrical resistivities should be presented on the bilogarithmic plot along with the observed apparent electrical resistivities. Also, the model should be presented in a section plot.

Data collected in profiling mode should be displayed in a plot of apparent electrical resistivity versus distance. Any modeling results should be presented and include an explanation of parameter values.

Data collected in the profiling-sounding mode should be presented in psuedosection format with the apparent electrical resistivity plotted as a function of position and electrode separation. Any modeling results presented should include an explanation of parameter values (ASTM D6431-99).

2.5.7 Advantages

A main advantage of the electrical resistivity method is that quantitative modeling is possible; modeling can provide relatively accurate estimates of depth, thickness and electrical resistivity of subsurface layers. The layered electrical resistivities can then be used to estimate the electrical resistivities of subsurface fluids.

2.5.8 Limitations

Limitations of the electrical resistivity method in contaminated sites are mostly due to site conditions, rather than any inherent limitations of the method. Sites frequently are located in industrial areas which contain numerous sources of electrical noise. Electrical resistivity surveys require a relatively large area, far removed from power lines and grounded metallic structures such as metal fences, pipelines, railroad tracks, and steel buildings. Another potential limitation is fieldwork can be labor intensive; a minimum of three crewmembers are required for field work (ASTM D6431-99).

2.6 Magnetometry

2.6.1 Fundamentals

Magnetometry has limited practicality for geologic investigations conducted at contaminated sites. Because of the extreme sensitivity of the Earth's magnetic field to micro-scale anomalies, magnetometry works best in rural or unpopulated areas. Urban development introduces innumerable sources of noise: fences, power lines, underground pipes, and small pieces of buried metal debris can cause local perturbations in the magnetic field. However, these sources of magnetic noise are themselves often items of interest because localized magnetic anomalies at hazardous waste sites are often directly associated with hazardous waste disposal. This is typically not caused by the waste itself, but by the containers in which the waste was placed. Buried steel drums and pipelines, as well as metal debris associated with waste, can be readily detected by magnetometry. Thus, magnetic noise that masks the geologic signal is often a valuable target for geophysical surveys at hazardous waste sites.

Magnetometers measure the intensity of earth's magnetic field strength in units of gammas or nanoteslas (1 gammas = 1 nanotesla = 0.00001 gauss). Magnetometers measure either the intensity of the total magnetic field or gradients in the magnetic field. Local variations in the earth's magnetic field (anomalies) are caused mostly by variations in concentrations of ferromagnetic material in proximity to the magnetometer's sensor. A buried ferrous metal objects, such as steel drums or other ferrous metal containers, locally distort the earth's magnetic field and results in a magnetic anomaly. (USEPA, 1993)

The common objective of conducting a magnetic survey at contaminated sites is to map these anomalies and delineate the area of burial of the sources of these anomalies. For most hazardous waste studies, magnetic anomalies of interest are often one to two orders of magnitude greater than the natural variations in the magnetic field (diurnal variations and micropulsations).

2.6.2 Instrumentation

Several types of magnetometers are used in contaminated site investigations. These include the total-field proton-precession magnetometer, the fluxgate magnetometer, and the cesium vapor magnetometer. The specific operation and construction of these various instruments may be found in the literature.

The type of magnetometer most commonly used in hazardous waste site investigations is the total field proton-precession magnetometer. This instrument measures the earth's total magnetic field. The major advantages of the proton precession magnetometer are the ease of operation and the rapid cycling rate of the instrument. This rapid cycling rate allows the operator to take a reading of the magnetic field strength in about one to two seconds (Breiner, 1973).

The fluxgate magnetometer is another type of magnetometer that may be used to locate buried ferrous objects. This instrument usually measures the vertical component of the earth's magnetic field and are typically configured as gradiometers (USEPA, 1993).

Cesium vapor magnetometers exhibit high sensitivity and have the capability for continuous data acquisition, allowing detection of smaller targets and data collection at walking speed.

Magnetometers can be configured as vertical magnetic gradiometers which measure the vertical gradient of the earth's total magnetic field. A vertical gradient configuration involves two or more magnetometer sensors mounted on a staff, with a constant distance of vertically separation between sensors, usually one or one-half meter (larger separation of sensors provide greater sensitivity to the gradiometer) (Breiner, 1973). Gradiometers takes readings from both sensors and measures the difference between the two magnetic field measurements. Gradient measurements enhance magnetic anomalies resulting from shallow sources (Benson, 2006).

2.6.3 Data Collection

In most contaminated site investigations, magnetic anomalies of interest are often one to two orders of magnitude greater than the natural variations in the magnetic field (diurnal variations and micropulsations). However, if the signal associated with buried wastes is expected to be within the range of the natural field variation, two magnetometers are needed: one to record field information, the other to record baseline measurements. The data from this base station should be used to check for magnetic storms, measure diurnal variations and correct the field data.

Magnetic data can be collected along traverses or in a rectangular grid pattern. In both traverse and grid configurations, the distance between magnetic readings should be close enough to detect the expected sources of magnetic anomalies. If large ferrous metal objects are expected to be buried on a site, such as steel underground storage tanks or several 55-gallon steel drums buried together, the distance between readings (station spacing) can be large, sometimes as much as 20 to 25 feet. If the buried target is a single 55- gallon steel drum or similar sized object, a smaller station spacing of five to 10 feet is needed.

Traverses should be aligned with magnetic north in order to define the asymmetric anomaly usually associated with buried ferromagnetic material and for more effective use of various methods for estimating depths to the sources of magnetic anomalies.

Grid or traverse coordinates can be located use Global Positioning System (GPS) or, alternatively, can be surveyed from fixed locations, such as buildings, property corners, or other features that can be resurveyed at a future date. Non-magnetic survey markers should be used to mark grid or traverse coordinates. Large cultural features (e.g., buildings and roads), as well as potential sources of electromagnetic interference (e.g., high voltage power lines, metal fences, and areas of surface debris) should be noted on the magnetometer survey map.

2.6.4 Quality Assurance/Quality Control

Undertaking magnetometric surveys at contaminated sites requires a considerable degree of care and preparation. Wherever possible, the locations of all utility lines (both above and underground) should be determined beforehand. It is important that a site being investigated has little or no ferrous metal debris on the ground surface; the presence of surface metal and cultural interference which cannot be removed from the site prior to the magnetometer investigation should be noted in the field investigator's notes. Evaluation of the field notes by the geophysicist during the interpretation allows for a qualitative compensation for the effects of these features.

In addition, if the anomalies of interest are expected to be of similar magnitude to the natural field variation, it is necessary to assess site-specific noise and instrument repeatability by taking at least two readings at each measurement station. Repeated measurements should agree to within 1 gamma or nanotesla (or the minimum accuracy of the instrument). Field measurements that do not repeat to within this value should be averaged. Values that do not repeat to within 10 gammas or nanotesla should not be used. During magnetic storms, when large variations in the magnetic field occur, such repeatability is usually not possible. While these conditions persist, magnetic surveys should not be undertaken.

Note: These guidelines were developed for ground-based, total field instruments. The above guidelines do not generally apply to the use of gradient-type magnetometers (gradiometers). Airborne magnetometers have been extensively used for resource exploration, but except for very large, remote sites where regional geology or isolated cultural features (e.g., landfills, buried wells) are of interest, aerial magnetometry is not suited for contaminated site investigations.

2.6.5 Interpretation

The geophysicist should plot magnetic anomalies on a location map of the area investigated. The source of plotted anomalies should be identified (interpreted) as representing areas most likely containing buried ferrous metal objects or being the result of features other than buried ferrous materials. It is sometimes possible to determine the approximate depth of burial of the material based on the magnetic data; graphical and computer-based modeling techniques are available for estimating the depth of burial. After examination collected data, the geophysicist should outline areas of probable buried ferrous materials.

2.6.6 Presentation of Findings/Conclusions

The results of a magnetometer survey can be presented as both contour map(s) and profiles. Profiles are usually oriented in the north-south direction, although this is not mandatory. The orientation of the field traverses should be indicated on plots and areas interpreted to contain buried ferrous materials should be marked on the contour map. Cultural and natural physical features should also be shown on contour maps. A listing of the magnetic data, including background readings should be included in a geophysical report. The geophysical report must also contain relevant information regarding instrumentation, field operations, data quality, corrections, and unusual magnetic events from base station recordings, data reduction, and interpretation techniques used in the investigation.

2.6.7 Advantages

The advantages of using magnetometry to investigate contaminated sites include relatively low costs, ease and speed of data collection, and the relatively short amount of time needed to complete the geophysical survey. Site preparation is minimal, requiring removal of as many surface ferrous metal objects as possible and noting potential sources of instrument interference. Surveying requirements are not ridged and can be completed with a transit or Brunton-type compass and measuring tape.

2.6.8 Limitations

The main limitation with magnetometer surveys is interference from cultural objects. Man-made structures constructed with steel or iron materials have magnetic susceptibility which interferes with instrument responses to buried ferrous metal materials. Features that should be avoided include steel structures, metal fences, steel reinforced concrete, surface metal, pipelines, and underground utilities. In addition, electromagnetic fields generated by local electrical power sources (i.e., overhead high voltage power lines, electrical generators, and electrical transmission lines) can cause instrument interference that renders magnetometer readings useless for interpretation. When these features cannot be avoided, their locations should be noted by field personnel and on the site contour map.

Another limitation is the inability to differentiate between buried ferrous metal objects. While detection and depth estimates associated with magnetic anomalies are part of standard interpretations, it is not possible to determine if an anomaly is in response to buried 55-gallon steel drums, buried accumulations of discarded automobile parts, or buried kitchen appliances.

2.7 Ground Penetrating Radar (GPR)

2.7.1 Fundamentals

Ground Penetrating Radar (GPR) is a valuable tool for surface geophysical investigations. With GPR, data can be collected rapidly and interpreted while still in the field, and its ease of interpretation is matched only by seismic reflection techniques.

The GPR method uses a transmitter to emit pulses of high-frequency electromagnetic waves into the subsurface and the electromagnetic energy is reflected back to the surface-receiving antenna; data are recorded as a function of time. The transmitter can be moved either slowly across the ground surface or at fixed station intervals. The penetrating electromagnetic waves are scattered at changes in the complex dielectric permittivity, which is a property of the subsurface material dependent primarily upon the bulk density, clay content, and water content of the subsurface (Olehoft, 1984).

The GPR method is used to map geologic conditions that include depth to bedrock, depth to the water table, depth and thickness of soil strata, subsurface cavities, and fractures in bedrock. GPR is also used locate buried objects, such as pipes, drums, tanks, cables, and boulders as well as mapping landfill and trench boundaries (ASTM D6432-99).

The depth of GPR penetration is dependent on soil/rock properties and radar frequency transmitted into the ground. In general, 3 to 30 feet of penetration with GPR is common, although depths exceeding 100 feet have been reported (Benson, 2006). The optimum penetration occurs in dry, sandy, or rocky areas, while poor penetration occurs in moist, clayey, or conductive soils.

2.7.2 Instrumentation

GPR equipment used in subsurface investigations usually consists of a transmitter and receiver antenna, a radar control unit, and data storage and display devices (ASTM D6432-99). The frequency of the transmitting antenna can be selected to achieve either greater depth penetration using a lower frequency antenna, or increased resolution using a higher frequency antenna. There is a large variety of GPR system configurations; the description provided here is generalized. Readers are referred existing literature if a more detailed description is needed.

2.7.3 Data Collection

Data should be collected to meet the objectives of the survey and in consideration of the characteristics of the site. Factors worth considering include geology, desired depth of penetration, geometry of the target, electromagnetic properties of the target, geologic materials containing the target, the presence of sources of noise, and site access. In addition, the level of detail desired should be considered. Reconnaissance surveys should have large spacing between radar lines with relative few transects, while detail surveys should have relatively close spaced transects (ASTM D6432-99).

2.7.4 Quality Assurance/Quality Control

GPR traverses should be positioned and spaced appropriately to resolve and locate targets of interest. Notes regarding traverse intersections, objects on the ground surface, buildings, monitor wells, property lines, and sources of cultural interference should be included on field notes, GPR profiles, and/or maps. Beginning and end points of traverses must be surveyed from a known location, which can be recovered at a future date.

Interference can be caused by electromagnetic transmissions from power lines and radio transmitters, or by the presence of man-made or natural objects above the ground surface. Rough terrain along traverse lines can cause the antenna unit to transmit signals at deflecting angles, causing inaccuracies and interference. A shielded antenna should be used when such objects and conditions exist at the site. Also, back-scattered interference of electromagnetic waves by objects near the transmitter and/or receiver units may preclude the use of vehicles or all-terrain vehicles to tow the field instrument(s). If vehicles are used, a comparison traverse (towed by hand versus by vehicle) should be conducted at the site (NJDEP, 2005).

The manufacturer’s recommendations should be followed for instrument calibration and standardization. An operational check of equipment before each project and before starting fieldwork each day should be conducted. A routine check of equipment should be made periodically and after each problem encountered (ASTM D6432-99).

2.7.5 Interpretation

GPR profiles are commonly qualitatively interpreted, although it is also possible to computer process digital data (i.e., use various digital and velocity filters, stack data, deconvolve data, and other processes). Data may be converted to depth values and corresponding profiles generated. Capable interpreters can often define shallow stratigraphy, soil horizons, bedrock fractures, and the water table when evaluating profiles. Areas of artificial fill and soil disturbance, buried man-made features (such as drums, tanks, and pipelines), and non-metallic structures (such as concrete vaults, voids or concrete and ceramic pipes) can also be inferred or identified.

2.7.6 Presentation of Findings/Conclusions

Data are usually presented as a continuous profile display with the horizontal axis as distance units (feet or meters) along the GPR traverse and the vertical axis as two-way time units in nanoseconds (ASTM D6432-99). However, some GPR systems will present the data as a depth profile; caution must be used when viewing data displayed as depth profiles because depths are determined by conversion factors assigned by the equipment operator. Accurate depth determinations must be derived from recorded features which are calibrated using actual depth measurements from nearby boreholes or from other geophysical investigations.

2.7.7 Advantages

Under optimal site conditions, the GPR method can result in a continuous profile that provides the greatest resolution of all commonly used surface geophysical methods (USEPA, 1993). Under such conditions, GPR data can resolve geological features, water-insoluble contaminants, man-made buried objects, voids, and hydrologic features such as water table.

Most GPR systems can provide a continuous display of data along a traverse which may be interpreted qualitatively in the field. The real-time capability of the GPR method results in a rapid turnaround and allows interpreters to quickly evaluate subsurface site conditions.

2.7.8 Limitations

The depth of penetration and resolution of GPR data depend on surface and subsurface conditions. Most GPR field instruments are towed across the ground surface; therefore the ground surface should be flat, dry, and clear of any brush or debris. The quality of the data can be degraded by a variety of factors such as an uneven ground surface or various cultural noise sources (such as strong electromagnetic fields, nearby vehicles, or buildings). Consequently, costs associated with site preparation necessary prior to performing the survey may be a limiting factor to site investigations. In addition, all stratigraphic information available, such as borehole data and information on the depth to water table and lithology, should be evaluated in the survey area prior to GPR data acquisition.

Depth penetration of the GPR method is severely limited by attenuation and/or absorption of the transmitted electromagnetic (radar) waves into the ground. In general, penetration of radar waves is reduce by a shallow water table, high clay content of the subsurface, and in areas where the electrical resistivity of the subsurface is less than 30 ohm-meters (Olehoft, 1986). GPR has the most favorable results in dry sandy soil where a deep water table exists. Under optimal conditions, depth penetration is between one and ten meters (Benson et. al., 1982).

Because the depth of penetration is adversely affected by increasing moisture content, GPR surveys are usually not feasible during or shortly after rainstorms. To minimize the effects of near-surface moisture, GPR should not be performed after any measurable precipitation until the ground has sufficiently dried.

Additionally, GPR is susceptible to external interference. Trees, power lines, radio transmissions, and surface debris can significantly affect radar images (Benson et al., 1982). These factors should be evaluated prior to any GPR study and accounted for during data interpretation.

2.8 Gravimetry

2.8.1 Fundamentals

Gravimetry is not routinely used for contaminated site investigations, primarily because gravimetric techniques are typically not sensitive enough to detect buried hazardous waste or waste-related features. Microgravity methods exist that increase resolution of small shallow targets, but these methods are difficult to implement or costly when compared to other geophysical methods of equal effectiveness. Therefore, guidelines for microgravity surveys will not be developed. However, gravimetry can be a useful tool for larger scale investigations related to contaminated sites. As a result, guidelines presented here are applicable to the use of gravity methods to delineate geologic structures and other large-scale features, such as faults, landfills, and ground water basins potentially contributing to or affected by pollution.

Gravimetrics involves measuring variations in the intensity of the earth’s gravitational field. These variations depend upon changes in the density of the subsurface in vicinity of the location where gravity measurements are acquired.

2.8.2 Instrumentation

Three principle classes of instruments are used in conventional gravity measurements: torsion balance, pendulum, and gravity meter (gravimeter) (USEPA, 1993). The most commonly used gravimeter is the Relative Gravimeter. This is spring-based instrument which measures the amount stretch in a spring as produced by a known weight. Gravimeters may also be used and directly measure the acceleration of a mass during free fall in a vacuum. A more complete description of these instruments is available in existing literature.

Gravity meters should be capable of taking measurements to the nearest 0.001 milligal.

2.8.3 Data Collection

Considerable care needs to be exercised when conducting gravity surveys and reducing the acquired data. Gravimeters are susceptible to erratic changes in instrument readings (tares) if improperly handled or jarred. In addition, gravimeters are prone to instrument drift due to aging and temperature changes. The degree to which these effects occur depends on the design of the gravimeter. Careful handling and assuring a constant instrument temperature are essential to the success of any gravity survey.

If during the course of a survey a gravimeter is subjected to a jarring force beyond that which occurs during normal handling, the operator should check for instrument tares by repeating gravity measurements at the last station prior to the suspected tare. In spite of this precaution, tares may not be detected until drift between stations is checked. An unusually large drift indicates a tare has occurred. This condition requires re-measurement of the appropriate locations. The corrections applied to the measurements and the amount of tide-corrected drift should be documented in an appropriate geophysical report.

Gravity data can be acquired in either a grid configuration or along a traverse; grid data may not be regularly spaced due to inaccessibility of planned station locations. Data should be acquired beyond the area of interest to determine the regional gravity field.

The elevation and latitude of each gravity station should be surveyed to an accuracy of ±0.1 foot and ±40 feet, respectively. To ensure accurate gravity measurements, consecutive readings at each station should be taken until satisfactory duplication is obtained.

2.8.4 Quality Assurance/Quality Control

Numerous survey methods exist that allow for tare checks and drift correction. All follow some variation of a technique presented in Telford et al. (1976), in which stations are measured along a loop, resulting in a periodic remeasurement at selected stations. We recommend, as proposed in Telford et al. (1976), that stations be reoccupied at intervals not to exceed two hours. To permit data correction, the time of each gravity measurement should be recorded. Drift data will contain components of both instrument drift and tidal effects. In addition, if a spring-based relative gravimeter is used, the strength of the spring must be calibrated by placing the gravimeter in a base station where the gravitational acceleration is known.

Field data must be corrected for elevation, rock density, latitude, earth-tide variations, and the influence of surrounding topographic variations (USEPA, 1993).

2.8.5 Interpretation

Gravity measurements need to be reduced to simple Bouguer gravity anomalies. Reduction of gravity data involves the correction for tidal effects, instrumental drift, latitude, elevation, and terrain (Dobrin, 1976 and Telford et. al., 1976). Removal of the regional gravity from simple Bouguer gravity anomalies is necessary to obtain residual gravity; this is an important aspect of gravity interpretation because residual gravity data is the dataset used in final gravity interpretation. Interpretations must be made with care because a variety of geologic situations can be represented by residual gravity data. Details regarding data reduction, corrections, removal of regional gravity of effects, and interpretation using model-based computer programs are available in existing literature.

2.8.6 Presentation of Findings/Conclusions

Gravity data should be displayed as model-based interpreted gravity profiles as well as gravity anomaly maps (both Bouguer and residual gravity anomaly maps). Interpreted features should be indicated on the anomaly maps.

The final geophysical report should include a listing of the gravity data collected, the type of gravity meter used along with its accuracy and calibration requirements, the accuracy of the surveying methods used for both elevation and location at each station, a discussion regarding the data reduction, calculations completed during interpretation, and modeling and interpretation computer programs used.

2.8.7 Advantages

Gravity surveys can be undertaken in areas where cultural effects preclude the use of other geophysical methods. Gravity measurements can be made inside buildings and structures and in heavily populated areas (ASTM D6429-99).

2.8.8 Limitations

Gravity measurements are susceptible to natural and man-made vibrations (ASTM D6429-99). Also, each gravity station must be precisely surveyed for elevation and location, which can be time consuming and costly.

2.9 Seismic Reflection

2.9.1 Fundamentals

In the seismic reflection method, sound waves (both compressional and shear waves) travel down to a geologic interface and reflect back to the surface. Seismic waves are reflected from geologic interfaces where there is a contrast in acoustic properties between the layers of geologic materials above and below the interface (Benson, 2006). The travel-times of waves reflected from interfaces are measured; times are converted to depth measures using wave velocity calculations derived during seismic investigations. Depths to geologic interfaces and determinations of general categories of subsurface geologic materials are included in interpretation of seismic reflection data.

Seismic reflection data can be acquired and processed as 2-dimensional lines or 3-dimensional data volumes, depending on the objectives of the site investigation, geologic conditions at the site, and project budget.

2.9.2 Instrumentation

Seismic reflection data are acquired using energy sources that generate acoustic waves through mechanical impact: explosions, or vibrations to the ground. The arrival of reflected seismic waves are recorded using a seismograph and are recorded with respect to time and location. The reflected waves are detected at the surface by geophone receivers which transform mechanical energy into electrical voltages. The voltages are relayed along cables to the seismograph, which records the voltage output versus time.

Engineering seismographs are the most common types used in investigations at contaminated sites. Seismographs record data (responses to reflected acoustic waves) along “channels;” each channel records the response of a geophone or array of geophones. Seismographs are available in multichannel systems which commonly contain 24, 48, or 96 channels. Multichannel systems have geophone stations located at predetermined distances along the seismic cable. Single channel systems have the geophone moved to the next station after each shot.

2.9.3 Data Collection

Selection of data acquisition parameters for seismic reflection surveys is site dependent; each contaminated site must be evaluated separately for selection of optimum data acquisition parameters. There are several different seismic energy sources, geophone and shotpoint array configurations and offset distances, and survey plans that can be used at any site. The geophysicist must use experience and documentation of case histories to choose parameters. Field testing of instrument response to selected data acquisition parameters should be completed prior to data acquisition in production-mode.

Geophone coupling to the ground involves pushing a small spike attached to the bottom of the geophone into the soil or using adhesive materials to “glue” the geophone baseplate to a hardened surface (asphalt or concrete). Geophone placement is important; each geophone gives optimum response when the axis of the geophone is positioned vertically with the geophone attached firmly into the ground. Geophones are manufactured to record different natural frequencies depending upon the desired result. High natural frequency geophones (usually greater than 30 hertz) are used when collecting shallow reflection data (Dobrin, 1976). Shotpoint and geophone locations should be along as straight of a line as possible and surveyed for elevation control.

More complete discussions of survey design and field procedures are available in existing literature.

NOTE: California law requires a person to be specifically trained and licensed to handle explosives. Therefore, when explosives are deemed necessary for use as an energy source for reflection surveys, all handling of explosives should be performed by a blaster licensed by the California Office of the State Fire Marshal.

2.9.4 Quality Assurance/Quality Control

Prior to data acquisition, all instruments and cables should be checked for proper functionality. During data acquisition, the seismic crew observer should note any irregularities in equipment operation (i.e., dead geophones, replacement of cables or geophones, variation in seismic energy source output, or seismograph malfunction) as well as noteworthy field conditions (i.e., excessive noise from wind or vehicular traffic). The quality of seismic reflection data is extremely dependent upon local geology and physical conditions of the site, therefore a comprehensive evaluation of the area to be surveyed should be completed, including a site visit and review of all available geologic data.

2.9.5 Interpretation

Prior to the interpretation of seismic reflection data, extensive processing of that data must be completed. This includes demultiplexing, static elevation corrections, normal moveout corrections, gain control, and numerous other processing steps that are beyond the scope of this guidance. Complete description of the various processing steps is available in existing literature.

The interpretation of seismic data includes calculating subsurface velocity information, which is dependent upon the acoustic properties of subsurface geologic materials. Acoustic properties or velocities can categorize various geologic materials. Depth to geologic interfaces can be calculated using the velocities derived from seismic investigations.

A complete discussion of the many methods of data reduction and interpretation is beyond the scope of this guidance, but can be found in Dobrin (1976), Coffeen (1978), and Telford et.al. (1990).

2.9.6 Presentation of Findings/Conclusions

The final geophysical report should include the elements described in the *Guidelines for Geophysical Reports for Environmental and Engineering Geology (*California Board for Geologists and Geophysicists, 1998). Displays of data must, at a minimum, include profiles of processed data along each line of data. When multiple lines of data are acquired, a map should be generated that shows the locations of traverses and other pertinent site information. Pertinent site information should include the locations roads, buildings, property lines, and other cultural and physical features. When 3-D seismic reflection data is acquired, a map showing the grid of acquired data must be generated.

Profiles, at a minimum, should include details showing fixed positions, surface landmarks intersected by the traverse, labeled interpretations, and a vertical time/depth scale. The final geophysical report should include details regarding data acquisitions procedures, instrumentation, data processing steps, and interpretation procedures.

2.9.7 Advantages

The seismic reflection method can provide more detail on subsurface stratigraphy and structural features compared with other methods. The high resolution and depth of investigation capability make this geophysical method useful for evaluation of subsurface geology at depths beyond approximately 40 feet below ground surface at contaminated sites.

2.9.8 Limitations

One limitation to seismic reflection data is in the absence of definitive geologic and geophysical information near the seismic reflection survey area (i.e., borehole lithologic and seismic wave velocity data), precise depth determinations cannot be made. In a typical seismic reflection survey, the correlation of seismic data to stratigraphic units, such as depth to top of bedrock, requires geologic information from borehole(s).

Another limiting factor is cost. Seismic reflection surveys require significant resources (field personnel, equipment, data reduction and processing programs, experienced geophysicist interpreters, etc.). As a result, reflection can be one of the more expensive geophysical methods.

2.10 Seismic Refraction

2.10.1 Fundamentals

Seismic refraction is defined as the travel path of compressional sound waves through an upper layer of geologic materials and along an interface at the base of the upper layer and then back to the surface. It is the travel-time of compressional waves that are refracted along the acoustic interface that are measured. At contaminated sites, the seismic refraction method is most commonly used to determine the thickness and depth of soil and rock layers, their physical properties, and the depth to bedrock. This geophysical method can also be used to detect and locate large features associated with contaminated sites, such as landfills and burial pits.

2.10.2 Instrumentation

The equipment used to acquire seismic reflection surveys is fundamentally the same as that used for seismic reflection data. A seismograph is used to record geophone responses to refracted compressional acoustic waves returning to the ground surface. The most common seismic energy source used to generate acoustic waves for refraction surveys is mechanical impact devices, such as a sledge hammer or accelerated weight drop.

2.10.3 Data Collection

Seismic refraction data are acquired along lines which must be planned so geometry of the geophone spread (the distance between each geophone and the total length of all geophone stations combined) will allow the subsurface target to be resolved. The overall line length should be three to five times the maximum depth of interest. The closer the spacing of geophone stations are within the overall geophone spread, the higher the resolution of shallow targets.

As with seismic reflection surveys, geophone placement is important; each geophone gives optimum response when the axis of the geophone is positioned vertically with the geophone attached firmly into the ground. For refraction surveys, the natural frequency of geophones is 8 to 14 hertz (ASTM D5777-00).

Shotpoint and geophone locations should be along as straight of a line as possible and surveyed for elevation control.

More complete discussions of survey design and field procedures are available in existing literature.

2.10.4 Quality Assurance/Quality Control

All instruments and cables should be checked for proper functionality prior to the start of a refraction survey. Irregularities in equipment operation during data acquisition should be noted in by the seismic crew observer’s log in addition to noteworthy field conditions.

2.10.5 Interpretation

Seismic refraction data can be interpreted graphically or with the aid of computer programs. Arrival times of compressional seismic waves as detected by surface geophones are first determined and then time-distance plots are constructed. Straight line segments of the plots (along with each segment’s slope) correspond to the number of subsurface geologic layers and the velocity of seismic waves associated with each layer. Breaks in straight line segments of the time-distance plots and each geologic layer’s seismic wave velocity are used to calculate depth of the layer. Seismic refraction data should be acquired from one end of the line of geophones, and then again starting from the opposite end of the line of geophones (referred to as forward and reverse data) so that the geophysicist can interpret true velocities, depth to layers, and dip of each layer.

As discussed in Section 2.10.3 above, refraction data should be acquired in a straight line; corrections are required whenever the line deviates for straight-line geometry. In addition, elevation corrections must be made when there are significant changes in topographic relief along the line of data acquisition.

There are several analytical interpretation methods for seismic refraction data. Details of each interpretation algorithm are beyond the scope of this guidance but are available in existing literature.

2.10.6 Presentation of Findings/Conclusions

The final geophysical report should include the elements described in the *Guidelines for Geophysical Reports for Environmental and Engineering Geology* (California Board for Geologists and Geophysicists, 1998). Displays of data should, at a minimum, include profiles of interpreted data and a topographic contour map with the locations of all lines of acquired data. In addition to locations of the lines of acquired data, the map should show other pertinent site information including roads, buildings, property lines, and other cultural and physical features. Profiles, at a minimum, should include details showing fixed positions, surface landmarks intersected by the traverse, labeled interpretations, and a vertical time/depth scale. The final geophysical report should include details regarding data acquisitions procedures, instrumentation, data processing steps, and interpretation procedures.

2.10.7 Advantages

Seismic refraction data can provide subsurface information along a continuous traverse for a relative low cost. Depth and thickness of geologic layers can be determined if subsurface conditions are conducive to seismic refraction methods. Depth to the water table and bedrock may also be determined.

Seismic velocities of geologic layers can be calculated from refraction data. Velocity information can be related to various physical properties of subsurface layers which allow geophysicists to assign layers to general categories of rock type. It should be noted that rock types have a range of velocities and these velocities do not always correspond to specific types of rock.

2.10.8 Limitations

A significant limitation of the seismic refraction method is long refraction traverses are sometimes required. Lines of data acquisition need to be three to five times the length of the maximum depth of interest. Also, refraction data is susceptible to vibrations (noise) from natural and cultural sources.

The seismic refraction method requires certain site conditions to be successful. These conditions include:

- The seismic velocities of the geologic layers increase with depth;
- The seismic velocity of layers is assumed to be uniform and isotropic;
- The seismic velocity contrasts between layers is sufficient to resolve their interface;
- The geometry of the geophones in relation to the refracting layers will permit the detection of thin geologic layers; and
- The apparent dip of layers is less than ten to fifteen degrees.

If these conditions are not met, accurate depth information will not be obtained (ASTM D5777-00 and NJDEP, 2005).

2.11 Other Surface Geophysical Methods

2.11.1 Induced Polarization (IP)

Induced polarization (IP) is a lesser-used surface geophysical method at contaminated sites. The induced polarization method measures the bulk electrical characteristics of geologic materials; these characteristics are related to the mineralogy, geochemistry and grain size of the subsurface materials through which electrical current passes. IP surveys have been successfully used in ground water studies to map clay and silt layers that serve as confining units separating unconsolidated sediment aquifers, and in contaminant plume mapping.

Detailed discussions of the IP method, and its advantages and limitations, are available in existing literature.

2.11.2 Spontaneous Potential (SP)

Spontaneous Potential (SP) is another less frequently used geophysical method at contaminated sites. This method measures the difference in potential between any two points on the ground produced by the small, naturally produced currents that occur beneath the Earth's surface. The SP method is passive, non-intrusive and does not require the application of an electric current. At contaminated lease sites, SP data may be used to detect movement of ionic fluids to or within groundwater (USEPA, 2011).

Detailed discussions of the SP method, and its advantages and limitations, are available in existing literature.

3.0 SUMMARY OF GUIDELINES

PERSONNEL QUALIFICATIONS

1. Personnel in responsible charge of geophysical projects must be a licensed Professional Geophysicist or a licensed Professional Geologist with the required education and experience.
2. Field personnel working under the supervision of a licensed professional must adequately trained and qualified.

QUALITY CONTROL PARAMETERS

FEASIBILITY ASSESSMENT AND METHOD SELECTION

1. Determine data quality objectives of the study.
2. Identify potential sources of interference.
3. Select techniques best suited for site-specific geology, field conditions, and potential sources of interference.

DATA PROCESSING

1. Preserve data of interest.
2. Minimize amount of processing whenever possible.

MEASUREMENT LOCATING

1. Obtain appropriate level of precision for project.
2. Professional surveyors should be licensed by the State of California.

CORRELATION WITH GEOLOGY

1. Use site-specific lithologic and hydrologic data.

RECONNAISSANCE STUDIES

1. Use multiple geophysical methods to enhance geological interpretations.

CALIBRATION AND FIELD CHECKS

1. Test and calibrate instruments regularly.
2. Conduct field checks prior to each survey.
3. Follow manufacturer instructions.
4. Use built-in standards, external calibrators, or established baselines, as appropriate.

DOCUMENTATION

1. Document QA/QC procedures in workplan and report.
2. Include problems encountered in the field in the report.
3. Describe any deviations from the workplan in the report.
4. Document interpretation of geophysical data in the report.
5. Provide supporting information in the report.

ELECTROMAGNETICS

1. Electrical current is induced to locate pipes, utility lines, cables, buried steel drums, trenches, buried waste, and contaminant plumes.
2. Uses either frequency-domain or time-domain systems.
3. Surveys configured in either rectangular grid pattern or along a traverse.
4. Depth of penetration is greater with the vertical dipole configuration.
5. Avoid sources of cultural noise when possible.

VERY LOW FREQUENCY (VLF) ELECTROMAGNETICS

1. Useful for detecting long, straight electrical conductors such as conductive faults, fracture zones, and water-bearing fracture zones in hard rock.
2. Utilizes radio signals in the 15 to 30 kHz range.
3. Generally utilize qualitative interpretation.
4. Difficult to derive depth information.

ELECTRICAL RESISTIVITY

1. Provides estimates of depth, thickness, and electrical resistivity of subsurface layers.
2. Current is induced at the ground surface with electrodes.
3. Use profiling, sounding, or profiling-sounding methods.
4. Errors generally occur with electrode positioning and electrical noise from power lines and other metallic structures.

MAGNETOMETRY

1. Measures the intensity or gradients of earth’s magnetic field strength.
2. Can delineate area of buried ferrous metal objects such as drums and underground storage tanks.
3. Data collected along traverses or in a rectangular grid pattern.
4. Avoid sources of cultural noise when possible.

GROUND PENETRATING RADAR (GPR)

1. High-frequency electromagnetic waves are used to identify depth to bedrock, depth to water table, depth and thickness of soil strata, subsurface cavities, fractures in bedrock, buried objects, and landfill/trench boundaries.
2. Ground should be flat, dry, and clear of any brush or debris.
3. Avoid sources of cultural noise when possible.

GRAVIMETRY

1. Typically not sensitive enough to detect buried hazardous waste or waste-related features.
2. Useful to delineate large-scale features such as faults, landfills, and groundwater basins.
3. Measures variations in the intensity of earth’s gravitational field.
4. Gravimeters must be handled carefully.
5. Surveys configured in either grid pattern or along a traverse.

6. Can be used in areas where cultural effects preclude use of other geophysical methods.
7. Each measurement location must be precisely surveyed.

SEISMIC REFLECTION

1. Seismic waves reflect from geologic interfaces to provide estimate of depth to geologic interfaces and general subsurface geologic material.
2. Can provide detail on structural features.
3. Use tool for depths greater than 40 feet below ground surface.
4. Can be two-or three dimensional.

SEISMIC REFRACTION

1. Seismic waves refract along interfaces between different geologic materials to provide estimate of depth to geologic interfaces and general subsurface geologic material.
2. For accurate depth information, certain criteria regarding site geology need to be met.

INDUCED POLARIZATION (IP)

1. Lesser-used method.
2. Measures the bulk electrical characteristics of materials.

SPONTANEOUS POTENTIAL (SP)

1. Lesser used method.
2. Passive method that measures differences in small, naturally produced currents that occur beneath the Earth’s surface.

4.0 REFERENCES

American Society of Testing Material Standards (ASTM). ASTM D5777-00 (Reapproved 2006). *Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation*. West Conshohocken, Pennsylvania.

American Society of Testing Material Standards (ASTM). ASTM D6429-99 (Reapproved 2006). *Standard Guide for Selecting Surface Geophysical Methods*. West Conshohocken, Pennsylvania.

American Society of Testing Material Standards (ASTM). ASTM D6431-99 (Reapproved 2010). *Standard Guide for Using the Direct Current Resistivity Method for Subsurface Investigation*. West Conshohocken, Pennsylvania.

American Society of Testing Material Standards (ASTM). ASTM D6432-99 (Reapproved 2005). *Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation*. West Conshohocken, Pennsylvania.

American Society of Testing Material Standards (ASTM). ASTM D6639-01 (Reapproved 2008). *Standard Guide for Using the Frequency Domain Electromagnetic Method for Subsurface Investigations*. West Conshohocken, Pennsylvania.

American Society of Testing Material Standards (ASTM). ASTM D6820-02 (Reapproved 2007). *Standard Guide for Use of the Time Domain Electromagnetic Method for Subsurface Investigation*. West Conshohocken, Pennsylvania.

Benson, R.C., R.A. Glaccum, and M.R. Noel. 1982. *Geophysical Techniques for Sensing Buried Wastes and Waste Migrations*, Technos Inc. Published by National Ground Water Association.

Benson, R.C. 2006. *Remote Sensing and Geophysical Methods for Evaluation of Subsurface Conditions*. In: David M. Nielsen (editor), *Practical Handbook of Ground Water Monitoring*. Lewis Publishers, Inc. Chelsea, Michigan. pp. 249-296.

Breiner, S. 1999. *Applications Manual for Portable Magnetometers*, Geometrics, pp. 1-58.

California Board for Geologists and Geophysicists. 1998. *Guidelines for Geophysical Reports for Environmental and Engineering Geology*. http://www.geology.ca.gov/forms-pubs/geophysical.pdf

Coffeen, J.A. 1978. *Seismic Exploration Fundamentals.* The Petroleum Publishing Company. Tulsa, Oklahoma, pp. 1-277.

Department of Toxic Substances Control (DTSC). 2012. Guidelines for Planning and Implementing Groundwater Characterization of Contaminated Sites.

Dobrin, M.B. 1976. *Introduction to Geophysical Prospecting*, 3rd ed. McGraw-Hill, New York, New York, pp. 357-403.

Hutchinson, P.J. and L.S. Barta. 2002. VLF surveying to delineate longwall mine-induced fractures. *Leading Edge*, pp. 491-493.

Hutchinson, P.J., M.H. Beird, and M. Mitchell. 2010. Groundwater Purveying Using Very Low Frequency Fracture Delineation Methods, Proceedings from the 2010 Symposium on the Application of Geophysics to Engineering and Environmental Problems, pp. 294-301. http://geo-image.com/documents/30.pdf

McNeill, J.D. 1988. Electromagnetics, in *Proceedings on the Application of Geophysics to Engineering and Environmental Problems*, pp. 251-348.

McNeill, J.D. and V.F. Labson. 1991. Geological mapping using VLF radio fields, in Nabighian, M.N., Ed., Electromagnetic methods in applied geophysics II: Society of Exploration Geophysics, pp. 521-640.

New Jersey Department of Environmental Protection (NJDEP). 2005. Field Sampling Procedures Manual, Chapter 8, Geophysical Techniques, pp. 1-46.

Olehoft, G.R. 1984. Applications and Limitations of Ground Penetrating Radar, Expanded Abstracts, Society of Exploration Geophysicists 54th Annual Meeting, Atlanta, GA.

Olehoft, G.R. 1986. Direct Detection of Hydrocarbon and Organic Chemicals with Ground Penetrating Radar and Complex Resistivity, Proceedings of the NWWA Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, Houston, Texas, pp. 1-22.

Paterson, N.R. and V. Ronka. 1971. Five Years of Surveying with Very Low Frequency – Electromagnetics Method. *Geoexploration*, Vol. 9, Issue 1, 7-26.

Telford, W.M., L.P. Geldart, R.E. Sheriff and D.A. Keys. 1976. *Applied Geophysics*. Cambridge University Press, Cambridge, England, pp. 7-103.

Telford, W.M., Geldart, L.P., Sheriff, R.E. 1990. *Applied Geophysics*. Cambridge University Press, Cambridge, England, pp. 214-233.

Tezkan, B. 1999. A Review of Environmental Applications of Quasi-Stationary Electromagnetic Techniques. *Surveys in Geophysics*, 20, pp. 279–308.

United States Environmental Protection Agency (USEPA). 1988. *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA.* EPA/540/G-89/004. pp.1-1 through 6-15.

United States Environmental Protection Agency (USEPA). 1993. *Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide*. EPA/625/R-92/007. pp.1-1 through 6-15.

United States Environmental Protection Agency (USEPA). 2011. United States Environmental Protection Agency, Self-Potential (SP) Method, Environmental Geophysics website http://www.epa.gov/esd/cmb/GeophysicsWebsite/index.html

Ward, Stanley H. 1990. Resistivity and Induced Polarization Methods *in Geotechnical and Environmental Geophysics,* Investigations in Geophysics No. 5, Society of Exploration Geophysics, pp. 147-189.