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Standard Guide for Using the Frequency Domain Electromagnetic Method for Subsurface Site Characterizations[1]

This standard is issued under the fixed designation D6639; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 *Purpose and Application:*

1.1.1 This guide summarizes the equipment, field procedures, and interpretation methods for the assessment of subsurface conditions using the frequency domain electromagnetic (FDEM) method.

1.1.2 FDEM measurements as described in this standard guide are applicable to mapping subsurface conditions for geologic, geotechnical, hydrologic, environmental, agricultural, archaeological and forensic site characterizations as well as mineral exploration.

1.1.3 The FDEM method is sometimes used to map such diverse geologic conditions as depth to bedrock, fractures and fault zones, voids and sinkholes, soil and rock properties, and saline intrusion as well as man-induced environmental conditions including buried drums, underground storage tanks (USTs), landfill boundaries and conductive groundwater contamination.

1.1.4 The FDEM method utilizes the secondary magnetic field induced in the earth by a time-varying primary magnetic field to explore the subsurface. It measures the amplitude and phase of the induced field at various frequencies. FDEM instruments typically measure two components of the secondary magnetic field: a component in-phase with the primary field and a component 90° out-of-phase (quadrature component) with the primary field (Kearey and Brook 1991). Generally, the in-phase response is more sensitive to metallic items (either above or below the ground surface) while the quadrature response is more sensitive to geologic variations in the subsurface. However, both components are, to some degree, affected by both metallic and geologic features. FDEM measurements therefore are dependent on the electrical properties of the subsurface soil and rock or buried man-made objects as well as the orientation of any subsurface geological features or man-made objects. In many cases, the FDEM measurements can be used to identify the subsurface structure or object. This method is used only when it is expected that the subsurface soil or rock, man-made materials or geologic structure can be characterized by differences in electrical conductivity.

1.1.5 The FDEM method may be used instead of the Direct Current Resistivity method (Guide D6431) when surface soils are excessively insulating (for example, dry or frozen) or a layer of asphalt or plastic or other logistical constraints prevent electrode to soil contact.

1.2 *Limitations:*

1.2.1 This standard guide provides an overview of the FDEM method using coplanar coils at or near ground level and has been referred to by other names including Slingram, HLEM (horizontal loop electromagnetic) and Ground Conductivity methods. This guide does not address the details of the electromagnetic theory, field procedures or interpretation of the data. References are included that cover these aspects in greater detail and are considered an essential part of this guide (Grant and West, 1965; Wait, 1982; Kearey and Brook, 1991; Milsom, 1996; Ward, 1990). It is recommended that the user of the FDEM method review the relevant material pertaining to their particular application. ASTM standards that should also be consulted include Guide D420, Terminology D653, Guide D5730, Guide D5753, Practice D6235, Guide D6429, and Guide D6431.

1.2.2 This guide is limited to frequency domain instruments using a coplanar orientation of the transmitting and receiving coils in either the horizontal dipole (HD) mode with coils vertical, or the vertical dipole (VD) mode with coils horizontal (Fig. 2). It does not include coaxial or asymmetrical coil orientations, which are sometimes used for special applications (Grant and West 1965).

1.2.3 This guide is limited to the use of frequency domain instruments in which the ratio of the induced secondary magnetic field to the primary magnetic field is directly proportional to the ground's bulk or apparent conductivity (see 5.1.4). Instruments that give a direct measurement of the apparent ground conductivity are commonly referred to as Ground Conductivity Meters (GCMs) that are designed to operate within the "low induction number approximation." Multi-frequency instruments operating within and outside the low induction number approximation provide the ratio of the

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***A Summary of Changes section appears at the end of this standard**

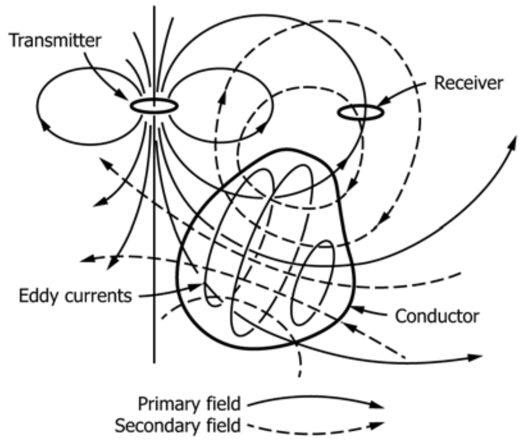

FIG. 1 Principles of Electromagnetic Induction in Ground Conductivity Measurements (Sheriff, 1989)

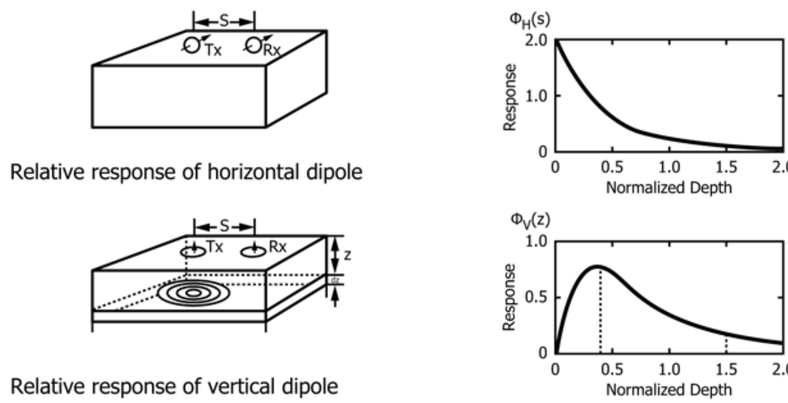

FIG. 2 Relative Response of Horizontal and Vertical Dipole Coil Orientations (McNeill, 1980)

secondary to primary magnetic field, which can be used to calculate the ground conductivity.

1.2.4 The FDEM (inductive) method has been adapted for a number of special uses within a borehole, on water, or airborne. Discussions of these adaptations or methods are not included in this guide.

1.2.5 The approaches suggested in this guide for the frequency domain method are the most commonly used, widely accepted and proven; however other lesser-known or specialized techniques may be substituted if technically sound and documented.

1.2.6 Technical limitations and cultural interferences that restrict or limit the use of the frequency domain method are discussed in section 5.4.

1.2.7 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education, experience, and professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged without consideration of a project's many unique aspects. The word standard in the title of this document means that the document has been approved through the ASTM consensus process.*

1.3 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method.

1.4 *Precautions:*

1.4.1 If the method is used at sites with hazardous materials, operations, or equipment, it is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine the applicability of regulations prior to use.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the*

Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D420 Guide to Site Characterization for Engineering Design and Construction Purposes

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Groundwater (Withdrawn 2013)[3]

D5753 Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging

D6235 Practice for Expedited Site Characterization of Vadose Zone and Groundwater Contamination at Hazardous Waste Contaminated Sites

D6429 Guide for Selecting Surface Geophysical Methods

D6431 Guide for Using the Direct Current Resistivity Method for Subsurface Characterization

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms used in this standard, refer to Terminology D653.

3.1.2 The majority of the technical terms used in this document are defined in Sheriff (1991). An additional definition follows:

3.2 *apparent conductivity, σ_a*—The conductivity that would be measured by a GCM when located over a homogeneous isotropic half space that has the same ratio of secondary to primary magnetic fields (Hs/Hp) as measured by other frequency domain instruments over an unknown subsurface. Apparent conductivity is measured in millisiemens per meter (mS/m).

4. Summary of Guide

4.1 *Summary of the Guide*—An alternating current is generated in a transmitter coil producing an alternating primary electromagnetic field, which induces an alternating current in any nearby conductive material. The alternating currents induced in the earth material produce a secondary electromagnetic field, which is sensed by a nearby receiver coil (Fig. 1). Common FDEM instruments operate under the "low induction number approximation", which is a function of the separation between the transmitter and receiver, the electrical permeability and conductivity of the ground, and the frequency of the transmitter signal. Essentially, this means that, in the absence of any metallic objects in the subsurface, the ratio of the magnitude of this secondary magnetic field to the primary magnetic field is directly converted to an apparent conductivity measurement of the earth material in a GCM. The ratio of secondary to primary magnetic fields (Hs/Hp) in other frequency domain instruments can be interpreted in terms of the ground conductivity. When operating under the low induction number approximation, most of the response will be in the quadrature component. When this assumption does not hold, such as in the presence of metal, there will be a significant in-phase component to the response, and the direct correlation of the signal response to apparent conductivity breaks down.

4.1.1 The depth of the site characterization is related to the frequency of the alternating current, the distance between transmitter and receiver coils (intercoil spacing) and coil orientation. For the GCM, the depth of the site characterization is related to the distance between electrodes and the coil orientation.

4.1.2 The apparent conductivity measured by a GCM or calculated from the ratio of the secondary to primary magnetic fields is the conductivity of a homogeneous isotropic half space, as long as the low induction number condition applies and the subsurface is nonmagnetic. If the earth is horizontally layered, the apparent conductivity measured or calculated is the sum of the conductivities of each layer, weighted by its thickness and depth, and is a function of the coil (dipole) orientation (Fig. 2). If the earth is not layered, that is, a homogeneous isotropic half space, both the horizontal and vertical dipole measurements are equal. In either case, if the true conductivities of the layered earth or the homogeneous half space are known, the apparent conductivity that would be measured with a GCM can be calculated with a forward modeling program.

4.1.3 Any variation either in the electrical homogeneity of the half space, or the layers, or a physical deviation from a horizontally layered earth, results in a change in the apparent conductivity measurement from the true conductivity. This characteristic makes it possible to locate and identify many significant geological features, such as buried channels, some fractures or faults (Fig. 3) or buried man-made objects. The signatures of FDEM measurements over troughs and dikes and similar features are well covered in theory (Villegas-Garcia and West, 1983) and in practice.

4.1.4 While many ground conductivity surveys are carried out to determine simple lateral or areal changes in geologic conditions such as the variation in soil salinity or location of a subsurface conductive contaminant plume, measurements made with a GCM with several intercoil spacings or different coil orientations can be used to identify up to two or three horizontal layers, provided there is a sufficient conductivity contrast between the layers (Fig. 4), the layer thicknesses are appreciable, and the depth of the layers falls within the depth range of the instrument used for the measurement.

4.1.5 Similarly, by taking both the horizontal and vertical dipole measurements at several heights above the surface resolved with a rigid fixed transmitter-receiver configuration, two or three layers within the instrument depth of exploration can also sometimes be resolved.

4.2 *Complementary Data*—Other complementary surface (Guide D6429) and borehole (Guide D5753) geophysical data, along with non-geophysical data related to the site, may be

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

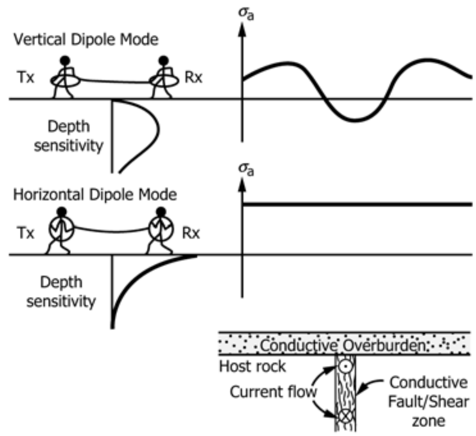

FIG. 3 Typical Vertical and Horizontal Dipole Profiles Over a Fracture Zone (McNeill, 1990)

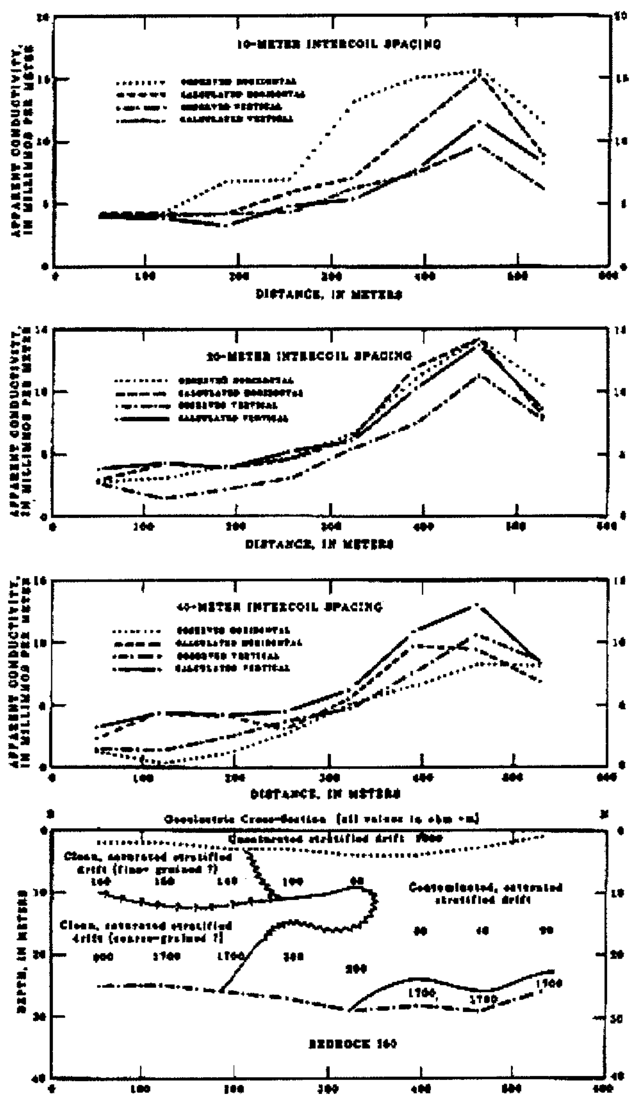

FIG. 4 Cross Section of Frequency Domain Soundings (Grady and Haeni, 1984)

necessary, and are always useful, to properly interpret the subsurface conditions from frequency domain data.

4.2.1 *Frequency Domain as Complementary Method*—In some cases, the frequency domain method is not able to provide results in sufficient detail or resolution to meet the objectives of the site characterization, although for a given depth of investigation, the EM methods usually require less space than linear arrays of the DC method. It is, however, a fast, reliable method to locate the objective of the site characterization, which can then be followed up by a more detailed resistivity or time domain electromagnetic survey (Hoekstra et al, 1992).

5. Significance and Use

5.1 *Concepts:*

5.1.1 This guide summarizes the equipment, field procedures and interpretation methods used for the characterization of subsurface materials and geological structure as based on their properties to conduct, enhance or obstruct the flow of electrical currents as induced in the ground by an alternating electromagnetic field.

5.1.2 The frequency domain method requires a transmitter or energy source, a transmitter coil, receiver electronics, a receiver coil, and interconnect cables (Fig. 5).

5.1.3 The transmitter coil, when placed on or near the earth's surface and energized with an alternating current, induces small currents in the near earth material proportional to the conductivity of the material. These induced alternating currents generate a secondary magnetic field (H_s), which is sensed with the primary field (H_p) by the receiver coil.

5.1.4 Under a constraint known as the "low induction number approximation" (McNeill, 1980) and when the subsurface is nonmagnetic, the secondary magnetic field is fully out-of-phase with the primary field and is given by a function of these variables.

$$\sigma_a = (4/\omega\mu_o s^2)(H_s/H_p) \quad (1)$$

where:

σ_a = apparent conductivity in siemens/meter, S/m,
ω = $2\pi f$ in radians/sec; f = frequency in Hz,
μ_o = permeability of free space in henrys/meter $4\pi \times 10^{-7}$, /m,
s = intercoil spacing in meters, m, and
H_s = the out-of-phase component of the secondary magnetic field, both measured by the receiver coil.
H_p = the out-of-phase component of the primary magnetic field measured by the receiver coil.

Perhaps the most important constraint is that the depth of penetration (skin depth, see section 6.5.3.1) of the electromagnetic wave generated by the transmitter be much greater than the intercoil spacing of the instrument. The depth of penetration is inversely proportional to the ground conductivity and instrument frequency. For example, an instrument with an intercoil spacing of 10 m and a frequency of 6400 Hz, using the vertical dipole, meets the low induction number assumption for earth conductivities less than 200 mS/m.

5.1.5 Multi-frequency domain instruments usually measure the two components of the secondary magnetic field: a component in-phase with the primary field and a component 90° out-of-phase (quadrature component) with the primary field (Kearey and Brook 1991). Generally, instruments do not display either the in-phase or out-of-phase (quadrature) components but do show either the apparent conductivity or the ratio of the secondary to primary magnetic fields.

5.1.6 When ground conditions are such that the low induction number approximation is valid, the in-phase component is much less than the quadrature phase component. If there is a relatively large in-phase component, the low induction number approximation is not valid and there is likely a very conductive buried body or layer, that is, ore body or man-made metal object.

5.1.7 The transmitter and receiver coils are almost always aligned in a plane either parallel to the earth's surface (axis of the coils vertical) and generally called the vertical dipole (VD) mode or aligned in a plane perpendicular to the earth surface (axis of the coils horizontal) generally called the horizontal dipole (HD) mode (Fig. 3).

5.1.8 The vertical and horizontal dipole orientations measure distinctly different responses to the subsurface material (Fig. 2). When these vertical and horizontal dipole mode measurements are made with several intercoil spacings or appropriate frequencies, they can be combined to resolve multiple earth layers of varying conductivities and thicknesses. This FDEM method is generally limited to only 2 or 3 layers with good resolution of depth and conductivity and only if there is a strong conductivity contrast between layers that are relatively thick and relatively shallow (in terms of the intercoil spacing).

5.1.9 The conductivity value obtained in 5.1.4 is referred to as the apparent conductivity σ_a. For a homogeneous and

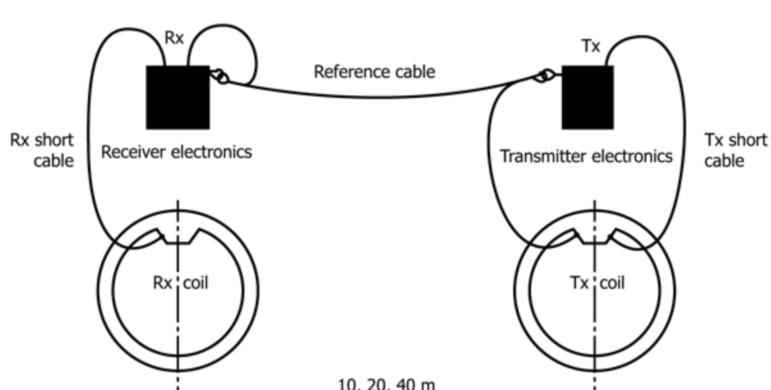

FIG. 5 Schematic of Frequency Domain Electromagnetic Instrument

isotropic earth or half space (in which no layering is present), the apparent conductivity will be the same for both the measurements. Since the horizontal dipole (HD) is more sensitive to the near surface material than the vertical dipole (VD), these two measurements can be used together to tell whether the conductivity is increasing or decreasing with depth.

5.1.10 For instruments referred to as Ground Conductivity Meters (GCMs), the system parameters and constants in 5.1.4 are included in the measurement process, giving a calculated reading of σ_a, usually in mS/m. In some instruments, the ratio of the in-phase components of the secondary to primary magnetic fields (H_s/H_{pp}) is displayed in ppt (parts per thousand).

5.1.11 For other frequency domain instruments, the measurements for both the in-phase and quadrature phase of the secondary magnetic field are given as ratios.

5.1.12 For a homogeneous horizontally layered earth, the measured apparent conductivity calculated by the instrument is the sum of each layer's conductivity weighted by the appropriate HD or VD response function (Fig. 2).

5.1.13 When the subsurface is not homogeneous or horizontally layered (such as when there is a geologic anomaly or man-made object present), the apparent conductivity may not be representative of the bulk conductivity of the subsurface material. Some anomalous features can, because of their orientation relative to the instrument coils, produce a negative apparent conductivity. While this negative value is not valid as a conductivity measurement, it is an indication of the presence of a geologic anomaly or buried object.

5.1.14 Many common geologic features such as fracture zones, buried channels, dikes and faults, and man-made buried objects, can be detected and identified by relatively well-known anomalous survey signatures (Fig. 3).

5.2 *Parameters Measured and Representative Values:*

5.2.1 The FDEM method provides a measure of the apparent electrical conductivity of the subsurface materials. For ground conductivity meters (GCMs), this apparent conductivity is read or recorded directly. For instruments not using the "low induction number approximation" the measurement is given by the ratio of the secondary magnetic field to the primary magnetic field (H_s/H_p).

5.2.2 Some GCMs also give an in-phase measurement corresponding to the in-phase component of the secondary magnetic field in parts per thousand (ppt) of the primary field. The in-phase component is especially useful for mineral exploration, detecting buried man-made metallic objects, or for measuring the soil or rock magnetic susceptibility and verifying the assumption that the subsurface is nonmagnetic (McNeill, 1983).

5.2.3 Fig. 6 shows the electrical conductivities for typical earth materials varying over five decades from 0.01 mS/m to a few thousand mS/m. Even a specific earth material (Fig. 6) can have a large variation in conductivity, which is related to its temperature, particle size, porosity, pore fluid saturation, and pore fluid conductivity. Some of these variations, such as a conductive contaminant pore fluid, may be detected by the FDEM method.

5.3 *Equipment:*

5.3.1 The FDEM equipment consists of a transmitter electronics and transmitter coil, a receiver electronics and receiver coil, and interconnect cables. Generally these vary only from one instrument to another in transmitter power, coil size, intercoil separation and transmitter frequency.

5.3.2 Some instruments are designed with a rigid, fixed intercoil separation usually less than about 4 meters and are used for relatively shallow measurements of less than 6 meters.

5.3.3 For deeper measurements of up to 100 meters, depending on the instrument, the instrument consists of separate coils interconnected by cable, (Fig. 5) and generally operates at several intercoil spacings. Instruments using the "low induction number approximation" usually have a single frequency for each intercoil spacing and are generally referred to as Ground Conductivity Meters (GCMs). Measurements of apparent conductivity, σ_a, are calculated and displayed in millisiemens per meter (mS/m).

5.3.4 FDEM instruments taking multiple frequency measurements at a fixed intercoil separation usually give their

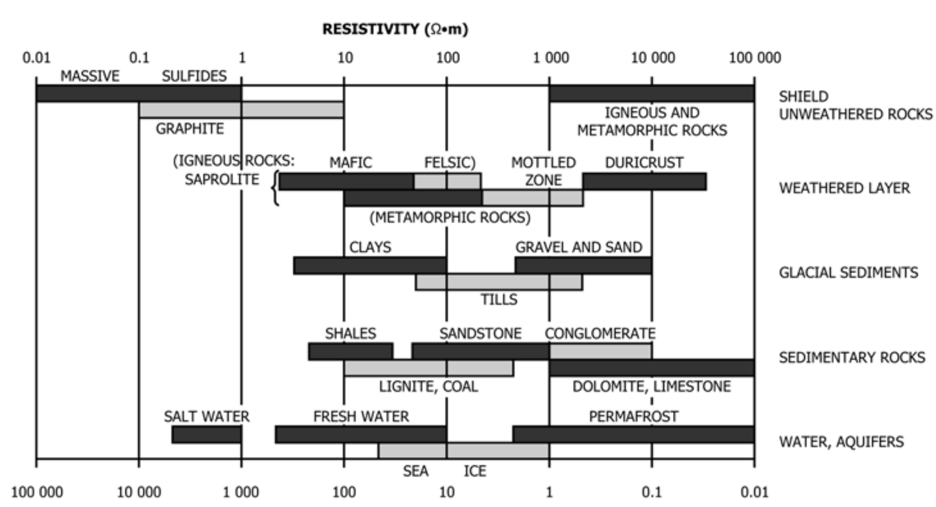

FIG. 6 Earth Material Conductivity Ranges (Sheriff, 1991)

results as a ratio of the secondary to primary magnetic fields (H_s/H_p). These instruments usually have some frequencies that satisfy the low induction number approximation from which the apparent conductivity is calculated. The larger multiple coil separation, multiple frequency instruments are mainly used for mineral exploration, whereas the smaller multiple frequency instruments are used for much the same applications as the GCMs.

5.4 *Limitations and Interferences:*

5.4.1 *General Limitations Inherent to Geophysical Methods:*

5.4.1.1 A fundamental limitation inherent to all geophysical methods lies in the fact that a given set of data cannot be associated with a unique set of subsurface conditions. In most situations, surface geophysical measurements alone cannot resolve all ambiguities, and some additional information, such as borehole data, is required. Because of this inherent limitation in geophysical methods, a frequency domain or ground conductivity survey alone can never be considered a complete assessment of subsurface conditions. It should be noted that multiple methods of measuring electrical conductivity in the earth (that is, FDEM, TDEM, DC Resistivity) will only produce the same answers for the ideal conditions of a nonmagnetic, frequency-independent, isotropic homogeneous half-space. The presence of heterogeneities (for example, layering, objects), anisotropy, magnetic materials, and frequency dependent mechanisms will result in varying geometric patterns of electrical current flow in the ground and consequent different values of measured apparent conductivity between the methods. Properly integrated with other information, conductivity surveying can be an effective method of obtaining subsurface information.

5.4.1.2 In addition, all surface geophysical methods are inherently limited by decreasing resolution with depth.

5.4.2 *Limitations Specific to the FDEM Method:*

5.4.2.1 The interpretation of subsurface conditions from frequency domain measurements assumes a nonmagnetic homogeneous horizontally layered earth. Any variation from this ideal results in variations in the interpretation from the actual subsurface. There are areas with soils that contain significant quantities of ferromagnetic or superparamagnetic minerals or metal fragments in which this assumption is no longer valid. This can be tested with electromagnetic instruments (see 5.2.2). If the assumption is incorrect, then the apparent conductivity will be higher than it should be.

5.4.2.2 Ground conductivity meters (GCMs) using a single frequency and one intercoil spacing are limited to detecting lateral variations. With two coil orientations, (horizontal and vertical dipole modes), a qualitative interpretation of whether the conductivity is increasing or decreasing with depth is available. Information as to the layering or vertical distribution of the subsurface conductivity can be derived from measurements at different heights above the surface.

5.4.2.3 For soundings, using both coil orientations and multiple intercoil separations, only two or three layers can be reasonably interpreted. There must still be a significant conductivity contrast between layers and layer thicknesses.

5.4.2.4 Equivalence problems occur when more than one layered model fits the data because combinations of layer conductivities and thicknesses produce the same sounding responses. For example, a thin highly conductive layer will look much like a thicker, less conductive layer of approximately the same conductivity thickness product. These problems are sometimes resolved by using borehole conductivity or resistivity data, knowing the general geology of the area, or by knowing what is being looked for and what response is expected. FDEM systems give the best results when searching for a conductive layer in a resistive medium. It is difficult to resolve resistive thin layers in a conductive medium even if the layers have a significant electrical contrast.

5.4.2.5 Frequency domain instruments are best used under relatively high electrical conductivity conditions (greater than 1 mS/m). For low conductivity materials (less than 1 mS/m), useful measurements are better obtained with resistivity methods (Guide D6431).

5.4.2.6 Ground conductivity meters (GCMs) have a straight-line (linear) relationship between the true bulk conductivity of a homogeneous half space and the apparent conductivity read by the instrument, provided that the true conductivity is within the region controlled by the low induction number approximation for the physical parameters of the particular instrument-intercoil separation and frequency. As the conductivity of the half space increases, making the approximation less and less valid, the apparent conductivity measured by the GCM or calculated using the low induction number approximation (5.1.4) deviates more and more from the true ground conductivity. Fig. 7 shows this nonlinearity for a short one-meter (3.3 ft) intercoil spaced instrument operating at 13 kHz, and shows that, for this spacing, nonlinearity of response is not a problem for most earth materials.

5.4.2.7 The deviation from linearity, however, can be quite significant for instruments with large intercoil spacings (upwards of 20 m) and relatively high frequency of operation. Here the nonlinearity can start at relatively low values of conductivity and can result in negative values at high values of the true conductivity (Fig. 8).

5.4.3 *Natural and Cultural Sources of Noise (Interferences):*

5.4.3.1 Sources of noise referred to here do not include those of a physical nature such as difficult terrain or man-made obstructions but rather those of a geologic, ambient, or cultural nature that adversely affect the measurements and hence the interpretation.

5.4.3.2 The project's objectives in many cases determine what is characterized as noise. If the survey is attempting to characterize geologic conditions, responses due to buried pipelines and man-made objects are considered noise. However, if the survey were attempting to locate such objects, variations in the measurements due to varying geologic conditions would be considered noise. In general, noise is any variation in the measured values not attributable to the object of the survey.

5.4.3.3 *Natural Sources of Noise*—The major natural source of noise in FDEM measurements is naturally occurring atmospheric electricity (spherics). This interference is caused by solar activity or electrical storms. Information about solar

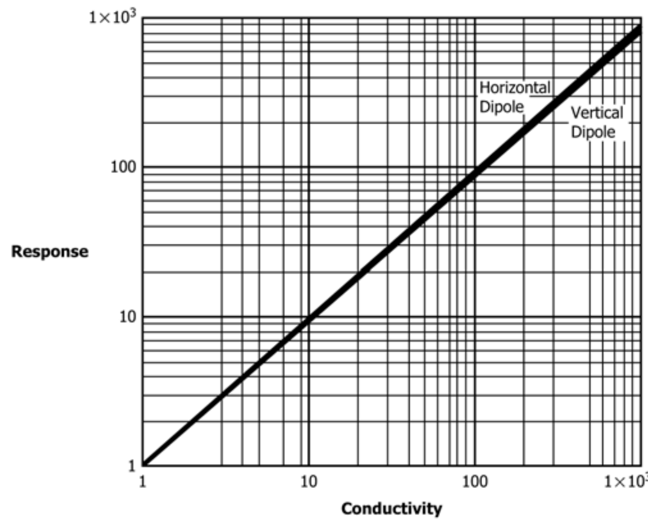

FIG. 7 Non-linearity for a Short-spaced Instrument

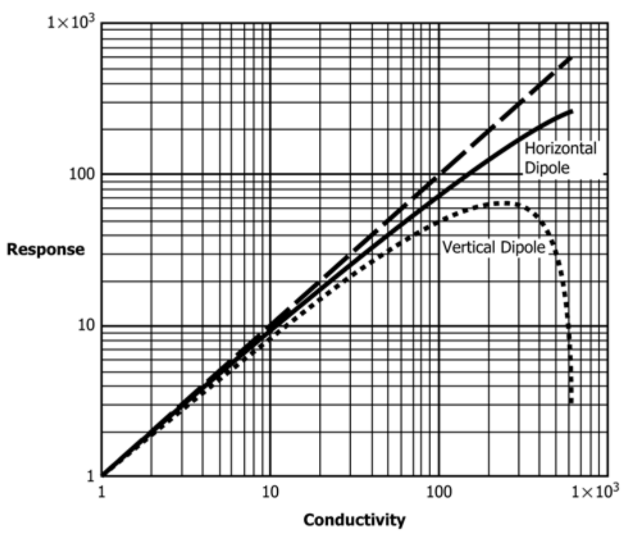

FIG. 8 Non-linearity for a Long-spaced Instrument

activity can be obtained on the Internet at the National Oceanic and Atmospheric Administration web site (http://www.noaa.gov). Electrical storms many miles away can still cause large variations in measurements. When these conditions exist, it is best to abandon the survey until a better time. Increasing the transmitter power can significantly reduce the effect of spherics. This increases the secondary field strength and hence the signal to noise ratio. Unfortunately such a process is at the expense of a larger and heavier transmitter coil.

5.4.3.4 *Cultural Sources of Noise*—Cultural sources of noise include interference from electrical power lines, communications equipment, nearby buildings, metal fences, surface or near surface metal, pipes, underground storage tanks, landfills and conductive leachates. Interference from power lines is directly proportional to the intercoil spacing and mainly only affects large intercoil spacings (greater than 15 or 20 m). Frequency domain instruments with small intercoil spacings are generally unaffected.

5.4.3.5 Surveys should not be made in close proximity to buildings, metal fences or buried metal pipelines that can be detected by frequency domain, unless detection of the buried pipeline, for example, is the object of the survey. It is sometimes difficult to predict the appropriate distance from potential noise sources. Measurements made on-site can quickly identify the magnitude of the problem and the survey design should incorporate this information (see 6.3.2.2).

5.4.4 *Alternate Methods*—In some instances, the preceding factors may prevent the effective use of the FDEM method. Other surface geophysical (see Guide D6429) or non-geophysical methods may be required to investigate the subsurface conditions. Alternate methods, such as DC Resistivity (Guide D6431) or TDEM, which may not be affected by the specific source of interference affecting the frequency domain method may be used to show an electrical contrast.

6. Procedure

6.1 *Qualification of Personnel*—The success of a FDEM survey, as with most geophysical techniques, is dependent upon many factors. Among the most important is the competency of the persons responsible for planning, carrying out the survey, and interpreting the data. An understanding of the theory, field procedures and methods of interpretation (McNeill, 1990) of conductivity or EM data, and an understanding of the site geology, is necessary. Personnel not having specialized training or experience should be cautious about using this technique or interpreting data and solicit assistance from qualified practitioners.

6.2 *Planning the Survey*—Successful use of the frequency domain method depends to a great extent on careful and detailed planning.

6.2.1 *Objectives of the Frequency Domain Survey*—Planning and design of a conductivity (FDEM) survey should be done with due consideration to both the objectives of the survey and the survey site characteristics. These factors affect the survey design, the equipment used, the level of effort required, the interpretation method selected, and the budget necessary to achieve the desired survey quality. Other important considerations include site geology, depth of site characterization, topography, and site access. The presence of noise-generating activities (on-site utilities, man-made structures) and operational constraints (restrictions to the site) that affect the quality and quantity of the measurements must also be considered. It is good practice to obtain as much relevant information as possible about the site prior to finalizing a survey design and mobilizing to the field.

6.2.2 *Support Information*—Frequency domain surveys vary in complexity. The extent to which site, hydrogeologic conditions, soil type, depth and type of rock information are required or useful depends on the objectives and complexity of the survey.

6.2.2.1 In general, for a geotechnical, geologic or hydrogeologic survey any relevant information about the site is useful when planning the survey. This includes thickness and type of soil cover, depth and type of rock, depth to water table, stratigraphy, topography and mapped fractures and fracture zones.

6.2.2.2 For surveys mapping lateral changes in conductivity or looking for buried man-made metallic objects, very little subsurface geologic information may be required.

6.2.2.3 A survey plan requires site information about buildings, fences, buried utilities and any other potential cultural interferences as well as topography and access to the site.

6.2.3 *Assess Probability of Survey Success:*

6.2.3.1 Assess whether the frequency domain method can meet the project objectives such as mapping a conductive layer, delineating subsurface geological features or detecting and mapping buried man-made materials.

6.2.3.2 The detection and mapping of a subsurface conductive layer requires an adequate conductivity contrast between the target layer and adjacent layers. With reasonable information about the local geology, the level of detectability of a given geologic condition can be determined from a forward model calculation.

6.2.3.3 When attempting to delineate subsurface features such as buried river channels and fracture zones, only qualitative results can be expected. Such features would have to be within the depth limitations of the instrument and have sufficient conductivity contrast to be detectable. Support information for this type of survey would include aerial photography, geologic maps or satellite imagery to delineate the general pattern of the structure.

6.2.3.4 Man-made buried metal objects would have to be of a size and at a depth to be detectable. Detectability of metal objects depends on size, shape, material, depth and orientation. The best assessment regarding the detectability of a metal target is to compare the target with the theoretical or measured detectability of a known similar target.

6.3 *Survey Design*—The main consideration affecting the survey design is the survey objective, which generally determines the type of FDEM instrument, the survey pattern, station density, the number and type of measurements at each station, and whether multiple frequencies, coil separations, or dipole orientations are required.

6.3.1 *Instrument Selection*—The instrument selected depends primarily on the depth of exploration required and the survey objective. For example, shallow depths of exploration as in mapping soil salinity and archaeological and forensic surveys typically require a small intercoil spacing because the targets could be quite small and at shallow depths, requiring a high resolution survey. Mapping the areal extent of a conductive layer at 20 m depth probably requires only a survey with widely spaced stations using a coil separation of 15 to 30 m. If the objective also includes locating the depth of the layer, several coil separations and orientations are required. A survey designed to locate an ore body would probably use a multi frequency instrument of relatively large intercoil spacing. The intercoil spacing selected is generally equal to the desired depth of exploration. Although the measurements can be significantly affected by very conductive subsurface material at depths up to twice the intercoil spacing, the effect of that material on the measurement is difficult to interpret.

6.3.2 *Type of Survey:*

6.3.2.1 There are as many survey designs as there are applications for the frequency domain method, however most can be categorized into one of four types, reconnaissance, profile, mapping and sounding. The first three are usually conducted with one intercoil spacing and frequency and one or two dipole orientations. Multiple intercoil spacings or frequencies are generally used when more information about the vertical distribution of conductivity is required, although the frequency domain method is rarely used for detailed soundings.

6.3.2.2 *Reconnaissance Surveys* are usually widely spaced areal surveys designed to determine whether a more detailed frequency domain survey is warranted. In some cases, the reconnaissance survey precedes a more detailed DC resistivity or time domain soundings.

6.3.2.3 *Profile Surveys* are used most often for mapping linear targets such as fracture zones, faults, pipelines or other buried linear features. Depending on the project objectives, a single profile line may be sufficient. Profile surveys are also used for mapping a bedrock profile, overburden depth, or conductivity profile for a future pipeline. When mapping linear features such as fracture zones, the survey line should be oriented perpendicular to the feature. Several profile lines may be required to accurately determine the location and orientation of the feature.

6.3.2.4 *Mapping Surveys* are simply an extension of the profile survey where the object of the survey is to determine the areal extent of the target (Fig. 9) or to detect and locate one or more small targets over the survey area. Grid size or station spacing can vary considerably for mapping surveys going from station spacing for shallow high density surveys of 0.25 m to spacings up to several tens of meters or more where a conductive clay layer or contaminant plume is being mapped.

6.3.2.5 Soundings may be made following one of the preceding types of survey or may be made independently. Sounding data add approximate depth and layer conductivity information to the survey results (Fig. 4).

6.3.3 *Location and Density of Survey Lines:*

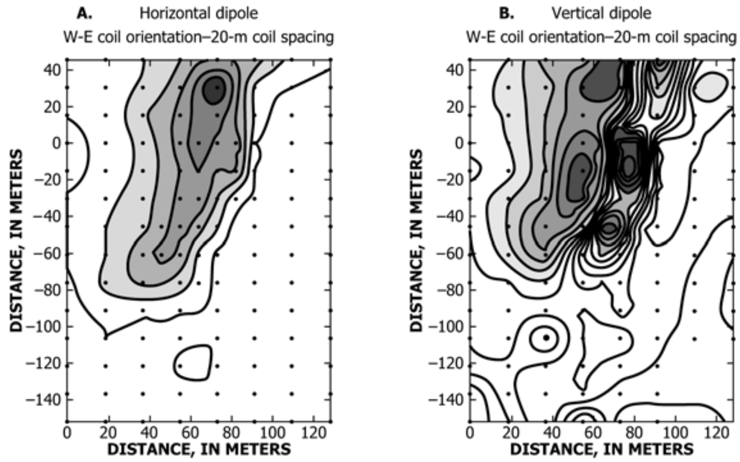

FIG. 9 Map of Inductive Terrain Conductivity Data over a Dipping Conductive Fracture (Powers et al, 1999)

6.3.3.1 Preliminary location of survey lines is usually selected with the aid of topographic maps, aerial photos and site maps showing cultural interference, such as buildings, fences and power lines. Primary consideration to the location and density of survey lines should be determined by the objectives of the survey.

6.3.3.2 The initial survey plan may be fairly coarse if the first phase of the survey is to locate a large extended target such as a conductive clay layer or contaminant plume. A more detailed grid pattern along with soundings might be used in the follow-up survey to better define the target.

6.3.3.3 Survey lines over fractures and fault zones should be as perpendicular to the feature as possible.

6.3.3.4 If the direction of the linear feature is not known or if there are linear features in different directions, it is helpful to conduct perpendicular surveys to establish the orientation of the features. The station spacing along a survey line should be small enough to ensure enough measurements are taken to define the anomaly signature if the fracture is crossed (Fig. 10).

6.3.3.5 Surveys using the same FDEM instrument might have widely varying spatial density requirements. A soil salinity survey might take measurements every 25 m, whereas an archaeological survey might have a grid spacing of 0.5 m or less, even though the same instrument (intercoil spacing) was used in each case. In these examples, the depth of exploration dictated the instrument used whereas the objectives or resolution required of the survey was the controlling factor for the grid spacing.

6.3.3.6 Other factors to consider when locating the survey lines are: the need for data at a given location; the accessibility of the area; the proximity of wells or test holes for control data; and the extent, location and impact of any man-made interferences that introduce noise or prevent measurements from being taken.

6.3.4 In all cases, the survey line or areal coverage should extend sufficiently beyond the target area to give a good reference to the normal background conditions.

6.4 *Survey Implementation:*

6.4.1 *On-site Check of Survey Plan*—A systematic visual inspection of the site should be made on arrival to determine that the site information provided was accurate and that the initial survey plan is reasonable. At this point, modifications to the survey plan may be implemented if required.

6.4.2 *Feasibility Test*—Preliminary measurements can be used to confirm the expected conductivities and conductivity contrasts. One of the preliminary measurements might be a sounding to confirm the geologic stratigraphy expected or to compare with borehole data. If only a single intercoil spacing instrument is used, preliminary measurements might include horizontal and vertical dipole measurements to determine whether the ground within the depth limitations of the instrument is homogeneous or increasing or decreasing in conductivity with depth. The same increase or decrease in conductivity can also be detected by varying the height of a rigid, single frequency instrument above the ground.

6.4.3 *Survey Line Layout*—When laying out survey lines, the following should be considered:

6.4.3.1 Mark the stations on the ground. If continuous measurements are being recorded, mark the fiducial stations. The fiducial marks reduce the measurements to spatially oriented measurements with a minimum of error. Variations in walking or vehicle speed will result in positioning errors, which are corrected for each time a fiducial mark is recorded. The closer the fiducial marks, the smaller the spatial error.

6.4.3.2 A Differential Global Positioning System (DGPS) can be used to locate the position of each measurement within the error specified for the DGPS.

6.4.4 *Data Collection*—If a survey is conducted along generally parallel lines, as in a grid survey or a profile survey over a linear anomaly, the transmitter-receiver orientation should be the same at each station and along each line and perpendicular to features such as pipes, trenches and faults.

6.4.4.1 If the orientation of the features is not known, perpendicular measurements should be taken at each station on the grid, but should be plotted separately to produce two distinct contour maps. This will assist interpretation of all

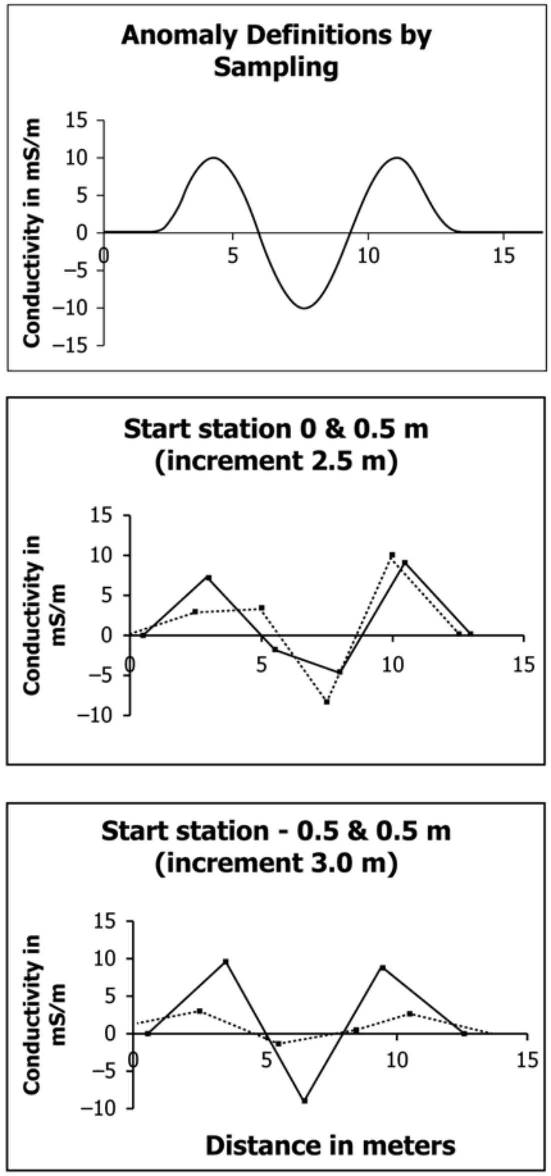

FIG. 10 Effect of Station Spacing on Target Definition

linear anomalies and generally improve detection of small anomalies, especially if located near buildings or fences.

6.5 *Interpretation of FDEM Data*—Frequency domain data can be used in a qualitative, semi- quantitative and quantitative manner depending on the purpose and objectives of the survey.

6.5.1 *Profile Interpretation:*

6.5.1.1 Profiling with FDEM instruments is used most often for locating anomalies (presence or absence of clay layers, fracture zones, faults, buried channels, pipes, conductive contaminant plumes and buried waste material). These are generally detected by a measurement signature characteristic of the anomaly and can be interpreted by visually inspecting the plotted profile line data.

6.5.1.2 Profile data are obtained usually with one frequency, one intercoil spacing and one or two coil orientations (vertical and/or horizontal dipoles). In addition to detecting anomalies, these data often can provide a qualitative indication of changes in the depth to bedrock (where there is a conductivity contrast between the overlying soil and the bedrock) from visual inspection of the profile line data. With the addition of good reference data, that is, borehole data, depth to bedrock, overburden material identification, taken at stations along or near the profile line, a value for depth to bedrock along the profile can be determined.

6.5.1.3 In some cases where more depth information is necessary, measurements using 2 or 3 intercoil spacings and both coil orientations are taken at each station along a profile line. These surveys are considerably more time-consuming than a single coil spacing, single frequency, profiling survey and are generally used only when a 2 or 3 layer profile is required. Interpretation of these data is usually done using a commercially available computer program.

6.5.2 *Areal Interpretation*—Surveys taken in a grid fashion are usually intended to map the lateral extent of some feature, a conductive clay or contaminated layer, or a buried disposal site. They can also be high-resolution surveys looking for small buried objects such as in an archaeological or forensic site characterization. In either case, the conductivity (quadrature phase), or in-phase, or both, data are plotted and contoured and interpreted visually by geometric patterns of conductivity contrasts.

6.5.3 *Frequency Domain Soundings:*

6.5.3.1 FDEM soundings can be made using multiple intercoil spacings and horizontal and vertical dipoles. They can also be made with a rigid single frequency instrument by varying the height of the instrument above the ground. With these measurements, the conductivity, depth and thickness of 2 or possibly 3 layers can be resolved. The layers can be interpreted using a set of response equations and response curves or by using an inverse modeling program. The program can also be used in the forward mode to determine, before a survey is undertaken, whether there is a sufficient conductivity contrast between the target layer and the background or to determine what the contrast should be, to be detectable.

6.5.3.2 Frequency domain soundings can also be made, where the earth materials being measured are nonmagnetic, with an instrument with a single intercoil spacing and multiple frequencies. In this method, the depth of site characterization for each frequency is limited by the skin depth (d) given by:

$$d = 500\left(\sqrt{(1/\sigma f)}\right) \tag{2}$$

where:

σ = ground conductivity, mS/m, and
f = frequency, kHz.

Forward and inverse modeling software programs are also available for this sounding method.

6.6 *Quality Control (QC)*—Quality control can be appropriately applied to FDEM conductivity measurements and is applicable to the field procedures, processing and interpretation phases of the survey. Good quality control requires that standard procedures are followed and appropriate documentation is made.

6.6.1 *Calibration and Standardization*—In general, the manufacturer's recommendation should be followed for calibration and standardization. If no such recommendations are provided, a routine check of equipment should be made on a periodic basis and after each problem and repair. An operational check of equipment along with a test measurement made in a background or test area should be carried out before each project, before the start of a new project, and before starting fieldwork each day.

6.6.2 *Survey Procedure*—The use of Differential Global Positioning Systems (DGPS) or accurate surveying systems can sometimes significantly improve the quality of the survey. DGPS systems are relatively easy to use and generally cost effective. They can provide survey locations that are operator independent. Any follow-up survey required can then be simply and accurately located with respect to the original survey.

6.6.3 Field procedure quality control should include:

6.6.3.1 Documentation of survey grid or station layout and measurements to be taken.

6.6.3.2 Documentation of any changes to the planned field procedure due to previously unknown site conditions (man-made and natural).

6.6.3.3 Any other conditions that affect the survey and measurements including topography, obstacles, weather conditions, radio frequency transmitters, concentrations of metal (including buildings, rebar in concrete, fences, pipelines, vehicles) and nearest power lines.

6.6.3.4 Profile or grid data should be plotted immediately after data acquisition to ensure that the data are of adequate quality and quantity to define the survey objectives.

6.6.3.5 Documentation of any problem with the equipment; what steps were taken to correct the problem, and how the problem could affect the data.

6.6.3.6 Establish and revisit nearby base station (background or test area) on a periodic basis.

7. Report: Test Data Sheet(s)/Form(s)

7.1 The following is a list of the key items that should be recorded. In some cases where the results will be acted upon immediately, only a simple description of the survey will be required for the records.

7.1.1 The purpose and scope of the survey.

7.1.2 The geologic setting.

7.1.3 The conditions for selecting the frequency domain method.

7.1.4 The frequency domain instrument selected and reasons, if appropriate.

7.1.5 Any assumptions that were made.

7.1.6 Any limitations relative to the frequency domain method.

7.1.7 A site map with grid or profile line layout.

7.1.8 The measurements taken at each station - horizontal or vertical dipoles, number of intercoil spacings or frequencies.

7.1.9 The method of interpretation, analysis or software programs used.

7.1.10 Final processed maps or profiles.

7.1.11 Appropriate references for any supporting data used in the interpretation.

7.1.12 Persons responsible for the survey and data processing and interpretation.

7.1.13 *Presentation of Data and Interpretation:*

7.1.13.1 Measurements made with a frequency domain instrument are usually presented as apparent conductivity values in millisiemens per meter (mS/m) for the quadrature component or parts per thousand (ppt) for the in-phase component where the frequencies used do not obey the low induction number approximation. In these cases all measurements are expressed as ratios of the secondary magnetic field to the primary magnetic field (H_s/H_p) in ppt.

7.1.13.2 The results of a profile survey are usually shown as a single or multiple profiles. Where there are multiple profiles closely spaced, the measurements can also be presented as a contour map. Where the subsurface is a fairly good approximation to a homogeneous half space or a layered earth, these plots reflect some function of the subsurface bulk conductivity. When there are man-made buried objects such as pipes or drums or geologic anomalies such as fractures, faults or buried river channels, the profile measurements over these areas will not be a measure of the subsurface conductivity but rather, a signature indicative of the anomaly.

7.1.13.3 A grid survey is generally conducted to obtain the lateral or areal extent of some subsurface conductive feature such as a conductive leachate plume, a clay layer or salt water intrusion (Fig. 9). For these objectives, satisfactory results are usually obtained with fairly large station spacing. High-resolution grid surveys are usually used when the objective of the survey is to detect and locate relatively small objects (buried man-made metal objects) or small variations in conductivity as might signify an archaeological or forensic artifact or feature. Interpretation of the contour maps produced from a survey can sometimes be further extended by using computer-enhancing features. These methods include restricting the number of colors or shades used or by using shaded relief. Even with the enhancement features, many details can only be seen and verified from the profiles. Contouring interpolates between grid points, which tend tends to blur details. By looking at the raw data in profile, one can distinguish features not apparent in the contours. Contouring, on the other hand, sometimes shows low amplitude anomalies nearly parallel to the survey lines, which are difficult to distinguish on the profiles. Whenever detail is critical, looking for difficult to detect targets or small changes in conductivity, both profile and contour plots should be examined.

7.1.13.4 Frequency domain soundings are used generally to provide a rough estimate of the depth, thickness, and conductivity of subsurface layers without expecting high bias. This is due mainly to equivalence problems, the nonlinear nature of the response function and limited field measurements. Nevertheless, with a reasonable conductivity contrast between layers, frequency domain soundings can give more than an adequate vertical electrical profile for most 2 or 3 layer situations. While these calculations can be carried out with equations and graphs, computer programs providing a rapid inversion solution along with the equivalence solutions make the interpretation considerably easier.

8. Bias, Precision and Resolution

8.1 *Bias*—For the purpose of this guide, bias is defined as a measure of the closeness to the truth.

8.1.1 The bias of a conductivity profile could be defined as its ability to determine depth to bedrock, produce an overburden conductivity profile or delineate a subsurface geologic or man-made feature.

8.1.1.1 The bias of the depth to bedrock will depend on additional information such as from borehole data, measurements near an outcrop, the conductivity of the overburden and its consistency throughout the profile. The better this information, the more accurate the depth to bedrock profile is likely to be.

8.1.1.2 The conductivity profile will likely only be as accurate as the uniformity of the overburden. If the overburden is layered, the bulk conductivity measurement will be a weighted average based on the response function appropriate for the dipole orientation. The depth calculation will vary if there are changes in the layers conductivity or thickness reducing the bias if these changes are unknown.

8.1.1.3 The bias related to delineating a subsurface feature will depend on a number of factors including: depth to feature, intercoil spacing, conductivity of the background as well as within the feature, the width of the feature, the number of measurements taken and the degree of perpendicularity to the feature. The variability in the overburden conductivity or topographic variations can cause fluctuations in the measurements. Measurement error can also be caused by not keeping the coils coplanar, and is greater for the vertical dipole than for the horizontal dipole configuration.

8.1.2 Grid or areal frequency domain surveys are usually used for mapping the areal extent of some conductive feature such as a clay layer, a conductive leachate or a buried landfill. It is also widely used for locating buried man-made objects like buried drums, pipes, utilities or artifacts. The bias of the method in these applications will depend mainly on the objectives of the survey and the suitability of the frequency domain method under the survey site conditions.

8.2 *Precision*—Precision is defined as the repeatability between measurements. That is, if a measurement is repeated at the same location in the same manner, how close will the second measurement be to the original. If the repeat frequency domain measurement were taken at exactly the same location, under exactly the same conditions as the original measurement, we would expect a high level of precision. The main factors affecting precision will be small errors in location, coil alignment and spacing as well as environmental changes in temperature, soil moisture and electromagnetic noise.

8.3 *Resolution*—Conductivity measurements are a weighted average of all the conductivities of the materials within a volume related to the intercoil spacing of the instrument. The greater the intercoil spacing, the larger the volume of earth being measured and the poorer the resolution.

8.3.1 *Vertical Resolution*—Vertical resolution for the frequency domain method is defined as how small a change in depth or in the thickness of a layer can be detected. This is a complex function of the depth, thickness, conductivities and layer conductivity contrasts and instrument used for the survey. In general, the most that can be expected from the FDEM method is conductivity thickness product ($\sigma \cdot t$) of the layer if detectable, and a qualitative estimate of depth. Forward models can be used to determine whether a layer can be detected in a specific situation. Inverse modeling can typically resolve 2 to 3 layers. One can conclude that if a conductive layer appears to be detected then it is present. Its depth, conductivity and thickness will at best be estimates.

8.3.2 *Lateral Resolution*—Lateral resolution for the frequency domain method is primarily dependent on the intercoil separation and the measurement spacing. Lateral resolution is directly proportional to the intercoil spacing. Instruments with smaller coil spacings provide better resolution for a shallower depth. Resolution can be improved by decreasing the station separation. To get the best lateral resolution available with the frequency domain instrument, the station frequency should be a minimum of five measurements per intercoil separation. Decreasing the line spacing will have little effect if the subsurface is relatively uniform or if the objective of the survey is simply to detect potential targets. Decreasing the line spacing will always provide more information on target location and size.

9. Keywords

9.1 electromagnetics; frequency domain electromagnetics; geophysics; ground conductivity; surface geophysics

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SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this standard since the last issue (2001(2008)) that may impact the use of this standard. (February 1, 2018)

(1) The standard was reinstated with only minor editorial changes and text additions in 1.1.4 and 4.1.