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Standard Guide for Use of the Time Domain Electromagnetic Method for Subsurface Investigation[1]

This standard is issued under the fixed designation D6820; 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*—This guide summarizes the equipment, field procedures, and interpretation methods for the assessment of subsurface materials and their pore fluids using the Time Domain Electromagnetic (TDEM) method. This method is also known as the Transient Electromagnetic Method (TEM), and in this guide is referred to as the TDEM/TEM method. Time Domain and Transient refer to the measurement of a time-varying induced electromagnetic field.

1.1.1 The TDEM/TEM method is applicable to investigation of a wide range of subsurface conditions. TDEM/TEM methods measure variations in the electrical resistivity (or the reciprocal, the electrical conductivity) of the subsurface soil or rock caused by both lateral and vertical variations in various physical properties of the soil or rock. By measuring both lateral and vertical changes in resistivity, variations in subsurface conditions can be determined.

1.1.2 Electromagnetic measurements of resistivity as described in this guide are applied in geologic studies, geotechnical studies, hydrologic investigations, and for mapping subsurface conditions at waste disposal sites (**1**).[2] Resistivity measurements can be used to map geologic changes such as lithology, geological structure, fractures, stratigraphy, and depth to bedrock. In addition, measurement of resistivity can be applied to hydrologic investigations such as the depth to water table, depth to aquitard, presence of coastal or inland groundwater salinity, and for the direct exploration for groundwater.

1.1.3 General references for the use of the method are McNeill (**2**), Kearey and Brooks (**3**), and Telford et al (**4**).

1.2 *Limitations:*

1.2.1 This guide provides an overview of the TDEM/TEM method. It does not provide or address the details of the theory, field procedures, or interpretation of the data. Numerous references are included for that purpose and are considered an essential part of this guide. It is recommended that the user of the TDEM/TEM method be familiar with the references cited and with the ASTM standards D420, D653, D5088, D5608, D5730, D5753, D6235, D6429 and D6431.

1.2.2 This guide is limited to TDEM/TEM measurements made on land. The TDEM/TEM method can be adapted for a number of special uses on land, water, ice, within a borehole, and airborne. Special TDEM/TEM configurations are used for metal and unexploded ordnance detection. These TDEM/TEM methods are not discussed in this guide.

1.2.3 The approaches suggested in this guide for the TDEM/TEM method are commonly used, widely accepted, and proven. However, other approaches or modifications to the TDEM/TEM method that are technically sound may be substituted.

1.2.4 *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 should be used in conjunction with 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, nor should this document be applied without consideration of a project's many unique aspects. The word standard in the title of this document means only that the document has been approved through the ASTM consensus process.*

1.3 *Precautions:*

1.3.1 It is the responsibility of the user of this guide to follow any precautions in the equipment manufacturer's recommendations and to establish appropriate health and safety practices.

1.3.2 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 any regulations prior to use.

1.3.3 This guide does not purport to address all of the safety concerns that may be associated with the use of the TDEM/TEM method. It must be emphasized that potentially lethal voltages exist at the output terminals of many TDEM/TEM

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[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Characterization.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

transmitters, and also across the transmitter loop, which is sometimes uninsulated. It is the responsibility of the user of this equipment to establish appropriate safety practices and to determine the applicability of regulations prior to use.

1.3.4 The values stated in SI units are regarded as standard. The values given in parentheses are inch-pound units, which are provided for information only and are not considered standard.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D420 Guide to Site Characterization for Engineering Design and Construction Purposes (Withdrawn 2011)[4]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D5088 Practice for Decontamination of Field Equipment Used at Waste Sites

D5608 Practices for Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites

D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Groundwater (Withdrawn 2013)[4]

D5753 Guide for Planning and Conducting 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 Investigation

D6639 Guide for Using the Frequency Domain Electromagnetic Method for Subsurface Investigations

3. Terminology

3.1 *Definitions:*

3.1.1 See Terminology D653.The majority of the technical terms used in this document are defined in Sheriff (**5**) and Bates and Jackson (**6**).

4. Summary of Guide

4.1 *Summary of the Method*—A typical TDEM/TEM survey configuration for resistivity sounding (Fig. 1) consists of a transmitter connected to a (usually single-turn) square loop of wire (generally but not necessarily insulated), laid on the ground. A multi-turn receiver coil, usually located at the center of the transmitter loop, is connected to a receiver through a short length of cable.

4.1.1 The transmitter current waveform is usually a periodic, symmetrical square wave (Fig. 2). After every second quarter-period the transmitter current (typically between 1 and 40 amps) is abruptly reduced to zero for one quarter period, after which it flows in the opposite direction to the previous flow.

4.1.2 Other TDEM/TEM configurations use triangular wave current waveforms and measure the time-varying magnetic field while the current is on.

4.1.3 The process of abruptly reducing the transmitter current to zero induces, in accord with Faraday's Law, a short-duration voltage pulse in the ground that causes a current to flow in the vicinity of the transmitter wire (Fig. 3). After the transmitter current is abruptly turned off, the current loop can be thought of as an image, just below the surface of the ground, of the transmitter loop. However, because of the resistivity of the ground, the magnitude of the current flow immediately decays. This decaying current induces a voltage pulse in the ground, which causes more current to flow at larger distances from the transmitter loop and at greater depths (Fig. 3). The deeper current flow also decays, due to the resistivity of the ground, inducing even deeper current flow. To determine the resistivity as a function of depth, the magnitude of the current flow in the ground as a function of time is determined by measuring the voltage induced in the receiver coil. The voltage is proportional to the time rate of change of the magnetic field arising from the subsurface current flow. The magnetic field is directly proportional to the magnitude of the subsurface current. By measuring the receiver coil voltage at successively later times, measurement is effectively made of the current flow, and thus the electrical resistivity of the earth, at successively greater depths.

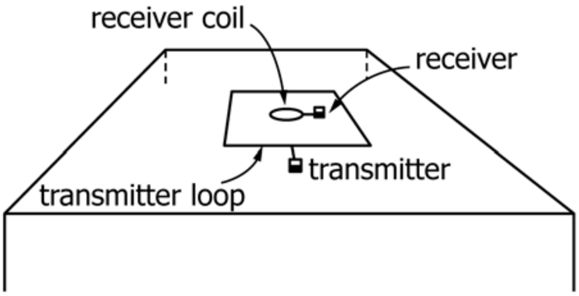

FIG. 1 Typical TDEM/TEM Survey Configuration (7)

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[3] 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.

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

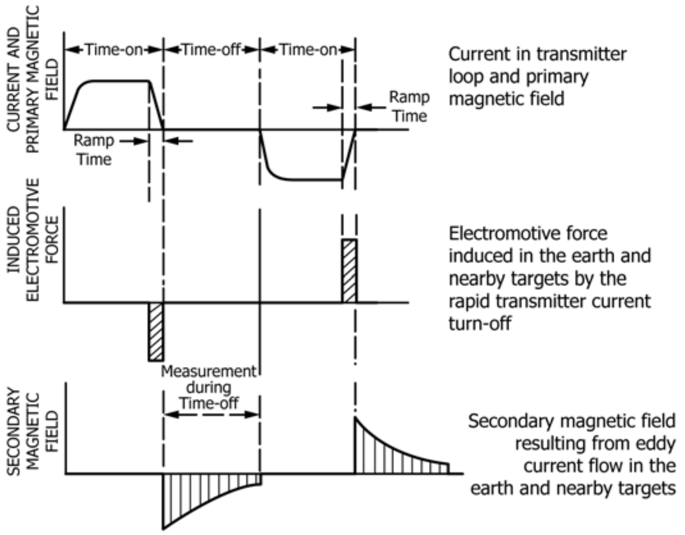


FIG. 2 Typical Time Domain Electromagnetic Waveforms (2)

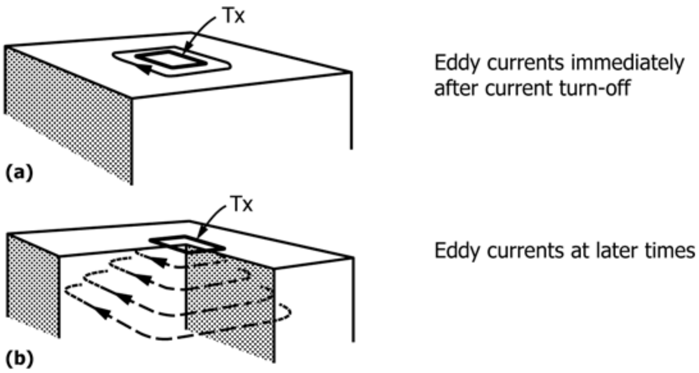


FIG. 3 Time Domain Electromagnetic Eddy Current Flow at (a) Early Time and (b) Late Time (2)

4.1.4 Data resulting from a TDEM/TEM sounding consist of a curve of receiver coil output voltage as a function of time. Analysis of this curve produces a layered earth model of the variation of earth resistivity as a function of depth. The analysis can be done graphically or with commercially available TDEM/TEM data inversion programs.

4.1.5 To determine lateral variations of resistivity in the subsurface, both transmitter and receiver are moved along profile lines on a survey grid. In this way, a three-dimensional picture of the terrain resistivity is developed.

4.1.6 TDEM/TEM surveys for geologic, engineering, hydrologic and environmental applications are carried out to determine depths of layers or lateral changes in geological conditions to a depth of tens of meters. Using larger transmitters and more sensitive receivers, it is possible to achieve depths up to 1000 m.

4.2 *Complementary Data*—Geologic and water table data obtained from borehole logs, geologic maps, data from outcrops or other geological or surface geophysical methods (Guide D6429) and borehole geophysical methods (Guide D5753) are always helpful in interpreting subsurface conditions from TDEM/TEM survey data.

5. Significance and Use

5.1 *Concepts:*

5.1.1 This guide summarizes the equipment, field procedures, and interpretation methods for using the TDEM/TEM method for determination of those subsurface conditions that cause variations in subsurface resistivity. Personnel requirements are as discussed in Practice D3740.

5.1.2 All TDEM/TEM instruments are based on the concept that a time-varying magnetic field generated by a change in the current flowing in a large loop on the ground will cause current to flow in the earth below it (Fig. 3). In the typical TDEM/TEM system, these earth-induced currents are generated by abruptly terminating a steady current flowing in the transmitter loop (**2**). The currents induced in the earth material move downward and outward with time and, in a horizontally layered earth, the strength of the currents is directly related to the ground conductivity at that depth. These currents decay exponentially. The decay lasts microseconds, except in the cases of a highly conductive ore body or conductive layer when the decay can last up to a second. Hence, many measurements can be made in a short time period allowing the data quality to be improved by stacking.

5.1.3 Most TDEM/TEM systems use a square wave transmitter current with the measurements taken during the off-time (Fig. 2) with the total measurement period of less than a minute. Because the strength of the signal depends on the induced current strength and secondary magnetic field, the depth of investigation depends on the magnetic moment of the transmitter.

5.1.4 A typical transient response, or receiver voltage measured, for a homogeneous subsurface (half-space) is shown in Fig. 4. The resistivity of the subsurface is obtained from the late stage response. If there are two horizontal layers with different resistivities, the response or receiver output voltage is similar to the curves shown in Fig. 5.

5.2 *Parameter Measured and Representative Values:*

5.2.1 The TDEM/TEM technique is used to measure the resistivity of subsurface materials. Although the resistivity of materials can be a good indicator of the type of material, it is never a unique indicator. Fig. 6 shows resistivity values for various earth materials. Each soil or rock type has a wide range of resistivity values and many ranges overlap. It is the interpreter who, based on knowledge of the local geology and other conditions, must interpret the resistivity data and arrive at a reasonable geologic and hydrologic interpretation. Very often, it is the l shape of a resistivity anomaly that is diagnostic, rather than the actual values of interpreted resistivity.

5.2.2 In the TDEM/TEM technique, the measured quantity is the time-varying voltage induced in the receiver coil and generated by the time-varying magnetic flux (field) of the decaying currents as they move to successively greater depths in the earth. This time rate of change of magnetic flux, and thus the receiver output voltage, has units of volts per square meter of receiver coil area (which area is supplied by the equipment manufacturer). Since the voltage is usually extremely small it is measured in nanovolts (nV) per square meter of receiver coil, where 1 nV = 10^{-9} volts.

5.2.3 The resistivity (usually designated in the geophysical literature by the symbol ρ) represents the absolute ability of a substance to prevent the flow of an electrical current. The reciprocal of resistivity is conductivity (usually designated by the symbol σ, where $\sigma = 1/\rho$), which represents the absolute ability of the same substance to allow the flow of electrical current. Resistive terrain has a low value of conductivity and vice versa. Throughout this guide, the term resistivity is used . The resistivity of a material depends on the physical properties of the material and is independent of the geometry. Units of resistivity are ohmmeters or ohm-ft (1 ohmmeter = 3.28 ohm ft). Units of conductivity are siemens/meter (S/m) or more commonly millisiemens/meter (mS/m), where 1 S/m = 1000 mS/m. Thus ρ (ohmmeters) = 1/ σ (siemens/meter) = 1000/σ (mS/m).

5.2.4 For most applications in engineering and hydrogeology, the pore fluid dominates the flow of electrical current and thus, the resistivity. As a general rule, materials that lack porosity show high resistivity (examples are massive limestone, most igneous and metamorphic rocks); materials whose pore space lacks water show high resistivity (examples are dry sand or gravel, ice); materials whose pore water is fresh show high resistivity (examples are clean gravel or sand, even when saturated); and materials whose pore water is saline show very low resistivity.

5.2.5 The relationship between resistivity and water saturation is not linear. The resistivity increases relatively slowly as saturation decreases from 100 % to 40 to 60 %, and then increases much more rapidly as the saturation continues to decrease.

5.2.6 Many geologic materials show medium or low resistivity if clay minerals are present (examples are clay soil, severely weathered rock). Clay minerals decrease the resistivity because they adsorb cations in an exchangeable state on their surfaces.

5.2.7 An empirical relationship known as Archie's Law describes an approximate relationship between the resistivity of a matrix material, its porosity and the resistivity of the pore fluid. For saturated sandstones and limestones and many other saturated substances, the resistivity, r, is given approximately by:

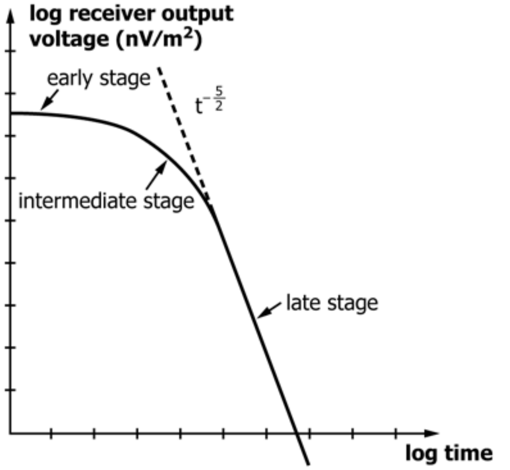


FIG. 4 Typical TEM Receiver Output Voltage Versus Time Plot (7)

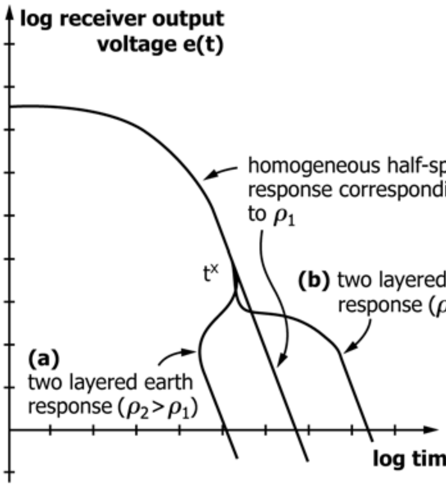


FIG. 5 TDEM Receiver Output Voltage for Various Earth Models (7)

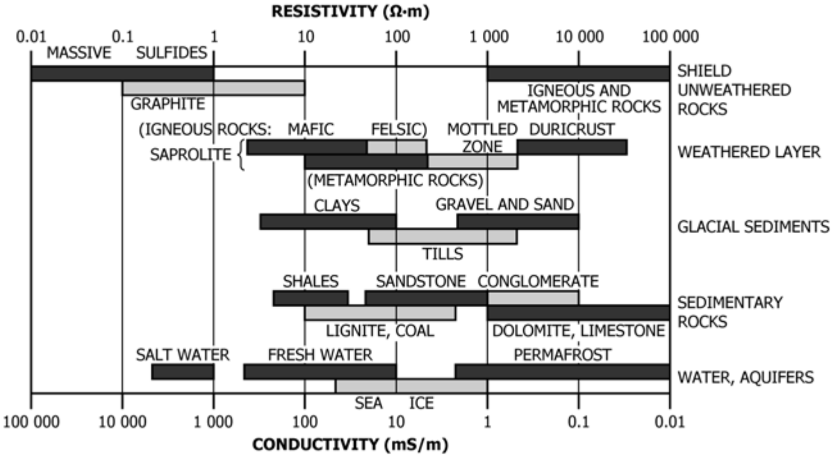


FIG. 6 Typical Ranges of Resistivities of Earth Materials (5)

$$\rho = a\rho_w\varphi^{-b} \quad (1)$$

where:

ρ_w = resistivity of the pore fluid,
φ = porosity,
a = a constant whose value depends on the material, but is approximately 1, and
b = a constant whose value depends on the material, but is approximately 2.

5.2.8 Variations in temperature above freezing will affect resistivity measurements as a result of the temperature dependence of the resistivity of the pore fluid, which is of the order of 2 % per degree Celsius. Thus, data from measurements made in winter can be quite different from those made in summer.

5.2.9 As the ground temperature decreases below freezing, the resistivity increases with decreasing temperature, slowly for fine materials (in which a significant portion of the water l remains unfrozen, even at quite low temperatures), and rapidly for coarse materials (in which the water freezes immediately).

5.2.10 Further information about factors that control the electrical resistivity or conductivity of different geological materials (**8**).

5.2.11 Because the TDEM/TEM technique measures subsurface resistivity, only geological or hydrological structures that cause spatial variations in resistivity are detected by this technique. If there is no resistivity contrast between the different geological materials or structures, if the resistivity contrast is too small to be detected by the instrument, or if the resistivity of the subsurface material is very high, the TDEM/TEM technique gives no useful information.

5.3 *Equipment*—Geophysical equipment used for the TDEM/TEM method includes a transmitter, a transmitter loop of wire, a transmitter power supply, a receiver and a receiver coil.

5.3.1 The transmitter may have power output ranging from a few watts to tens of kilowatts. Important parameters of the transmitter are that it transmits a clean square wave (Fig. 2), and that the "turn-off" characteristics are well known and extremely stable, because they influence the initial shape of the transient response.

5.3.2 The size of the transmitter power supply determines the depth of exploration, and can range from a few small batteries to a 10-kW, gasoline-driven generator.

5.3.3 The transmitter loop wire is usually insulated for safety. The size of the loop and the amount of current flowing through it (and thus the diameter of the wire) determines the desired depth of exploration. The weight of the loop, which is mounted on one or more reels, can be anywhere from a few kilograms to over 100 kg.

5.3.4 The receiver measures the time-varying characteristic of the receiver coil output voltage at a number of points along the decay curve and stores this data in memory. Because the voltage is small, and changes rapidly with time, the receiver must have excellent sensitivity, noise rejection, linearity, stability, and bandwidth. The transmitter/receiver combination must have some facility for synchronization so that the receiver accurately records the time of transmitter current termination. This synchronization is done either with an interconnecting timing cable or with high-stability quartz crystal oscillators mounted in each unit. The characteristics of a TDEM/TEM receiver are sufficiently specialized that use of a general-purpose receiver is not recommended.

5.3.5 The receiver coil must match the characteristics of the receiver itself. It contains a built-in preamplifier so that it can be located some distance from the receiver. The coil must be free from microphone noise, and it must be constructed so that the transient response from the metal of the coil and the coil shielding is negligible.

5.4 *Limitations and Interferences :*

5.4.1 *General Limitations Inherent to Geophysical Methods:*

5.4.1.1 A fundamental limitation of all geophysical methods is 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 additional information, such as borehole data, is required. Because of this inherent limitation in the geophysical methods, a TDEM/TEM survey alone is not considered a complete assessment of subsurface conditions. Properly integrated with other geologic information, TDEM/TEM surveying is a highly 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 TDEM/TEM Method:*

5.4.2.1 Subsurface layers are assumed horizontal within the area of measurement.

5.4.2.2 A sufficient resistivity contrast between the background conditions and the feature being mapped must exist for the feature to be detected. Some significant geologic or hydrogeologic boundaries may have no field-measurable resistivity contrast across them and consequently cannot be detected with this technique.

5.4.2.3 The TDEM/TEM method does not work well in highly resistive (very low conductivity) materials due to the difficulty in measuring low values of conductivity.

5.4.2.4 An interpretation of TDEM/TEM data alone does not yield a unique correlation between possible geologic models and a single set of field data. This ambiguity can be significantly reduced by doing an equivalence analysis as discussed in 6.11.3 and can be further resolved through the use of sufficient supporting geologic data and by an experienced interpreter.

5.4.3 *Interferences Caused by Natural and Cultural Conditions:*

5.4.3.1 The TDEM/TEM method is sensitive to noise from a variety of natural ambient and cultural sources. Spatial variations in resistivity caused by geologic factors may also produce noise.

5.4.3.2 *Ambient Sources of Noise*—Ambient sources of noise include radiated and induced responses from nearby metallic structures, and soil and rock electrochemical effects, including induced polarization. In TDEM/TEM soundings, the signal-to-noise ratio (SNR) is usually good over most of the measurement time range. However, at late times, the transient response from the ground decays extremely rapidly such that, towards the end of the transient, the signal deteriorates completely and the data become extremely noisy.

5.4.3.3 *Radiated and Induced Noise*—Radiated noise consists of signals generated by radio, radar transmitters, and lightning. The first two are not generally a problem. However, on summer days when there is extensive local thunderstorm activity, the electrical noise from lightning strikes can cause noise problems. It may be necessary to increase the integration (stacking) time or, in severe cases, to discontinue the survey until the storms have passed by or abated.

(1) The most important source of induced noise consists of intense magnetic fields arising from 50/60 Hz power lines. The large signals induced in the receiver from this source (the strength of which falls off more or less linearly with distance from the power line) can overload the receiver if the receiver gain is set too high, causing serious errors. The remedy is to reduce receiver gain to the point that overload does not occur. In some cases, this may result in less accurate measurement of the transient because the available dynamic range of the receiver is not fully utilized. Another alternative is to move the measurement array (particularly the receiver coil) further from the power line.

(2) It was mentioned above that one of the advantages of TDEM/TEM resistivity sounding was that measurement of the transient signal from the ground was made in the absence of the primary transmitter field, since measurement is made after transmitter current turnoff (Fig. 2). Modern transmitters use extremely effective electronic switches to terminate the large transmitter current. Nevertheless very sensitive receivers can still detect small currents that linger in the loop after turn-off. The magnitude of these currents and their time behavior are available from the equipment manufacturer, who can advise the user as to how closely the receiver coil can be placed to the actual transmitter loop wire.

(3) Another source of induced noise, common to ferrite or iron-cored receiver coils, is microphone noise arising from minute movements of the receiver coil in the earth's relatively strong magnetic field. Such movements are usually caused by the wind, and the coil must be shielded from the wind noise, or the measurements made at night when this source of noise is minimal. In extreme cases, it may be necessary to bury the coil.

5.4.3.4 *Presence of Nearby Metallic Structures*—TDEM/TEM systems are excellent metal detectors. Use of such systems for resistivity sounding demands that measurements are not made in the presence of metal. This requires removal of all metallic objects not part of the survey equipment (metallic chairs, toolboxes, etc.) from the area of the survey instruments. The recommendations of the manufacturer with regard to the location of the receiver case itself with respect to the receiver coil must be followed carefully.

(1) Power lines can often be detected as metallic targets as well as sources of induced noise. In this case, they exhibit an oscillatory response (the response from all other targets, including the earth, decays monotonically to zero without oscillation). Because the frequency of the oscillation is unrelated to the receiver base frequency, the effect of power line metallic response is to render the transient "noisy" (Fig. 7). Because these oscillations arise from response to eddy currents induced in the power line by the TDEM/TEM transmitter, repeating the measurement produces an identical response, which is one way that these oscillators are identified. Another way is to take a measurement with the transmitter turned off. If the noise disappears, it is a good indication that power line response is the problem. The only remedy is to move the transmitter loop further from the power line.

(2) Other metallic responses, such as those from buried metallic trash or pipes can present a problem. If the response is large, another sounding site must be selected. Use of a different geophysical instrument such as a metal detector or ground conductivity meter is helpful to quickly survey the sounding site for buried metal.

5.4.3.5 *Geologic Sources of Noise*—Geologic noise arises from the presence of unsuspected geological structures or materials, which cause variations in terrain resistivity. A rare effect that can occur in clayey soils, is induced polarization. Rapid termination of the transmitter current and thus primary magnetic field can charge up small electrical capacitors at soil particle interfaces. These capacitors subsequently discharge, producing current flow similar to that shown in Fig. 3, but reversed in direction. The net effect is to reduce the amplitude of the transient response (thus increasing the apparent resistivity) or, in severe situations, to cause the transient response to become negative over some portion of the measurement time range. Because these sources of reverse current are most significant in the vicinity of the transmitter loop, using the offset configuration (described in 6.6.1.1) usually reduces the induced polarization effect.

5.5 *Summary*—During the course of designing and carrying out a TDEM/TEM survey, the sources of ambient, geologic and cultural noise must be considered and the time of occurrence and location noted. The form of the interference is not always predictable, as it not only depends upon the type of noise and the magnitude of the noise but upon the distance from the source of noise and possibly the time of day.

5.6 *Alternate Methods*—In some cases, the factors discussed above may prevent the effective use of the TDEM/TEM method, and other surface geophysical methods such as conventional direct current (DC) resistivity sounding (Guide D6431), frequency domain electromagnetic surveying (Guide D6639)non-geophysical methods may be required to investigate subsurface conditions.

6. Procedure

6.1 This section includes a discussion of personnel qualification, considerations for planning and implementing the TDEM/TEM survey, and interpretation of the resistivity data.

6.1.1 *Qualification of Personnel*—Success of a TDEM/TEM survey, as with most geophysical techniques, is dependent upon many factors. One of the most important factors is the competence of the person(s) responsible for planning, carrying out the survey, and interpreting the data. An understanding of the theory, field procedures, and methods for interpretation of TDEM/TEM data along with an understanding of the site geology is necessary to successfully complete a resistivity survey. Personnel not having specialized training or experience should be cautious about using this technique and solicit assistance from qualified practitioners.

6.2 *Planning the Survey*—Successful use of the surface TDEM/TEM method depends to a great extent on careful and detailed planning as discussed in this section.

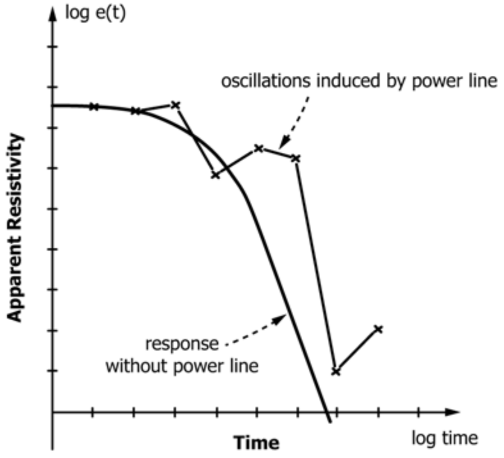


FIG. 7 Oscillations Induced in Receiver Response by Power Lines (7)

6.2.1 *Objectives of the TDEM/TEM Survey*—Planning and design of a TDEM/TEM survey should be done with due consideration to the objectives of the survey and the characteristics of the site. These factors determine the survey design, the equipment used, the level of effort, the interpretation method selected, and the budget necessary to achieve the desired results. Considerations include site geology, desired depth of investigation, topography, and access. The presence of noise-generating activities and operational constraints (which may restrict survey activities) must also be considered. It is good practice to obtain as much of the relevant information as possible about the site prior to designing a survey and mobilization to the field. Data from previous TDEM/TEM work, other surface geophysical methods, boreholes, geologic and geophysical logs in the study area, and topographic maps or aerial photos should be used to plan the survey.

6.2.2 A simple geologic/hydrologic model of the subsurface conditions at the site should be developed early in the design phase and include the thickness and type of soil cover, depth to and type of rock, depth to water table, stratigraphy and structure, and targets to be mapped with the TDEM/TEM method. This model will be used to evaluate the ability of the TDEM/TEM technique to provide useful data.

6.2.3 *Assess Resistivity Contrast:*

6.2.3.1 A critical element in planning a TDEM/TEM survey is the determination of whether there is an adequate resistivity contrast to produce a measurable TDEM/TEM anomaly. An inadequate resistivity contrast makes the survey useless.

6.2.3.2 If no previous resistivity surveys have been made in the area, information about the geology from published references containing the geologic character of earth materials and published reports of resistivity studies performed under similar conditions are required. From this information, the feasibility of using the TDEM/TEM resistivity sounding method at the site can be assessed.

6.2.3.3 Forward modeling using numerical modeling methods (**9**) should be used to calculate the TDEM/TEM resistivity sounding data for various sets of subsurface conditions. Given the depth and the shape of the subsurface feature and the difference in resistivity, such models can be used to assess the feasibility of conducting a TDEM/TEM survey and to determine the geometry of the field-survey equipment configuration (see 6.6.1).

6.3 *Survey Design:*

6.3.1 There must be a clear technical objective to the TDEM/TEM survey. Target size, depth, orientation, and resistivity should be estimated, as well as number and distribution of targets. It is extremely important that the length of a profile line or area of survey be larger than the area of interest so that sufficient measurements are taken in background conditions to establish that any detected anomaly is indeed anomalous.

6.3.2 The distance between station measurements should be close enough to define the expected anomaly. An anomaly must be defined by a minimum of 3 points and preferably by more points.

6.3.3 Preliminary location of survey lines is usually done with the aid of topographic maps and aerial photos if an on-site visit is not possible. Consideration should be given to:

6.3.3.1 The need for data at a given location,

6.3.3.2 The accessibility of the area with adequate space for the transmitter loop,

6.3.3.3 The proximity of wells or test holes for control data, and

6.3.3.4 The extent and location of any buried structures, power lines, fences, or other cultural features that may introduce noise into the data or noise that will prevent measurements from being made.

6.4 *Survey Geometry*—TDEM/TEM resistivity sounding data may be obtained along a single profile line, narrow or widely spaced profile lines, or over a uniform grid. The station spacing will be determined by the resolution required. Efforts should be made, if appropriate, to avoid biasing the data by taking many more measurements in one direction than in another.

6.5 *System Calibration*—The data from a resistivity sounding consists of a series of values of receiver output voltage $e(t)$, measured at each of a series of successive time gates. Properly calibrated, the units of $e(t)$ are volts per square meter of receiver coil area, however, since the received signals are very small, it is common to use nanovolts per square meter (nV/m^2). The amplitudes of measured decays typically range from many thousands of nV/m^2 at early times to 0.1 nV/m^2 at the last time gate where there is useful signal.

6.5.1 Modern TDEM/TEM systems are usually calibrated by placing a "Q-coil" (calibration coil) at a specified location with respect to both transmitter loop and receiver coil, and measuring the received signal in the normal way that would also be used for measuring the terrain signals. The "Q-coil" is a coil with known parameters, damped with one or more resistors so as to present a variety of known transient responses. This calibration technique calibrates the entire system so that satisfactory results arising from the calibration assure the operator that the entire system is operating correctly.

6.5.2 Since the response of the earth is added to the "Q-coil" response, two measurements must be made, the first with the "Q-coil" open circuited (so that only the earth response is measured) and the second with the "Q-coil" closed, to measure both. Response from the "Q-coil" alone is determined by subtracting the first data set from the second.

6.5.3 The "Q-coil" calibration should be performed before and after each project.

6.6 *Detailed Survey Design:*

6.6.1 *Transmitter Loop Size and Current*—A common survey configuration consists of a square, usually single-turn, transmitter loop, with a horizontal receiver coil located at the center. The two questions in carrying out a resistivity sounding are (*1*) how large should the side lengths of the transmitter loop be, and (*2*) how much current should the loop carry? Both questions are easily answered using one of the commercially available forward layered-earth modeling programs. An initial estimate is made about the possible geoelectric section (that is, the number of layers of different resistivities, and the resistivity and thickness of each layer), and these data are entered into the program, along with the proposed loop size and current. The resulting transient voltage is calculated as a function of time and the output data checked for signal-to-noise ratio (SNR) and also for geoelectric resolution of the model.

6.6.1.1 For example, a clay aquitard occurs at a depth of 20 m in otherwise clay-free sand. The resistivity of the sand might be 100 Ωm (ohm-meters), and the clay 15 Ωm. The survey objective is to determine the minimum detectable thickness of the clay layer and how accurately the thickness can be measured. In the TDEM/TEM method the depth of exploration is usually the length of the loop edge (assuming that the loop current is of the order of a few amperes). One might try using a 10×10-m loop carrying 3 amps (characteristic of a low power TDEM/TEM system) in the initial model calculation. Before doing the calculations for this shallow case, one feature accompanying the use of small (that is, less than 60×60-m) transmitter loops for shallow sounding should be noted. In small loops, the inducing primary magnetic field at the center of the loop is high, and the presence of metal such as the receiver case or the coil can cause sufficient transient response to distort the measured signal. This effect is reduced by placing the receiver coil and receiver about 10 m outside of the transmitter loop and away from the nearest transmitter wire. The effect of this offset on the data is relatively small.

6.6.1.2 The first task is to determine whether the difference between no clay layer and a clay layer 1-m thick can be resolved. Results of the forward layered-earth calculation are shown in Fig. 8. They indicate that the apparent resistivity curves for these two cases are well separated (maximum difference in apparent resistivity of about 10 %) over a time range from about 8 µs to 100 µs, as would be expected from the relatively shallow depth. Note that, to use this early time information would require a receiver that has many narrow, early time gates in order to accurately resolve the curve. The receiver and coil would also have to have a wide bandwidth so as not to distort the early portion of the rapidly varying transient signal. The figure shows that resolving clay layer thickness from 1 to 4 m and greater should be no problem.

6.6.1.3 Having ascertained that the physics of TDEM/TEM sounding will allow detection of this thin layer, the next test is to ensure that the 10×10-m transmitter operating at 3 amps will provide a sufficient SNR over the time range of interest (8 to 100 µs). The same forward layered-earth calculation also displays the actual measured voltages that would be generated from the receiver coil, and these are listed (for a thickness of 0 m, which will produce the lowest voltage at late times) in Fig. 9. The first column gives the time in seconds and the third column the receiver output voltage, in volts per square meter, as a function of time. The typical system noise level (almost invariably caused by external noise sources, see 5.4.3) for gates around 100 to 1000 µs is approximately 0.5 nV/m^2 or 5×10^{-1} V/m^2. From columns 1 and 3 it is seen that, for the model chosen, the signal falls to 5×10^{-1} nV/m^2 at a time of approximately 630 µs. It is much greater than this for the early times when the apparent resistivity curves are well resolved, so use of a 10×10-m transmitter loop operating at 3 amps will be entirely adequate. If a 5×5-m loop is used, the dipole moment (product of transmitter current and loop area) falls by 4, as does the amplitude of the measured signals, and the SNR would still be excellent over the time range of interest. The calculations show that, assuming that the model realistically represents the actual conditions of resistivity, depth, etc., the thin clay layer will be detected. The computer program, can be used to vary some of the other model parameters, such as the matrix and clay resistivity, to see under what different conditions the clay layer will still be detectable.

6.6.1.4 The importance of carrying out these calculations cannot be over estimated. The theory of TDEM/TEM resistivity sounding is well proven, and the value of pre-survey modeling, which is inexpensive and fast, is very high.

6.6.1.5 It was stated in Section 6.6.1.1 that offsetting the receiver coil from the center of the transmitter loop would not greatly affect the shape of the apparent resistivity curve at late time. The vertical magnetic field arising from a large horizontal loop of current (such as that shown in the ground at late time in Fig. 3) changes slowly with distance from the loop center. At early times, when the current loop radius is approximately the same as the transmitter loop radius, offsetting the receiver coil can have a significant effect. At late time, when the effective radius of the current loop is significantly larger than the transmitter loop radius, it would be expected that moving the receiver coil from the center of the transmitter loop to outside would produce a much smaller difference. Fig. 10 shows the apparent resistivity curves for the receiver both at the center, and offset by 15 m from the center, of the 10×10-m transmitter loop. At late time the curves are virtually identical. Inversion programs allow arbitrary location of the receiver coil.

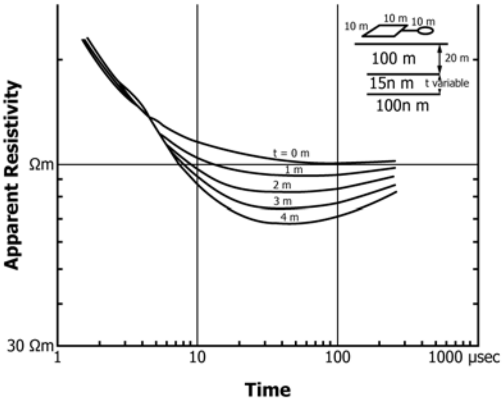
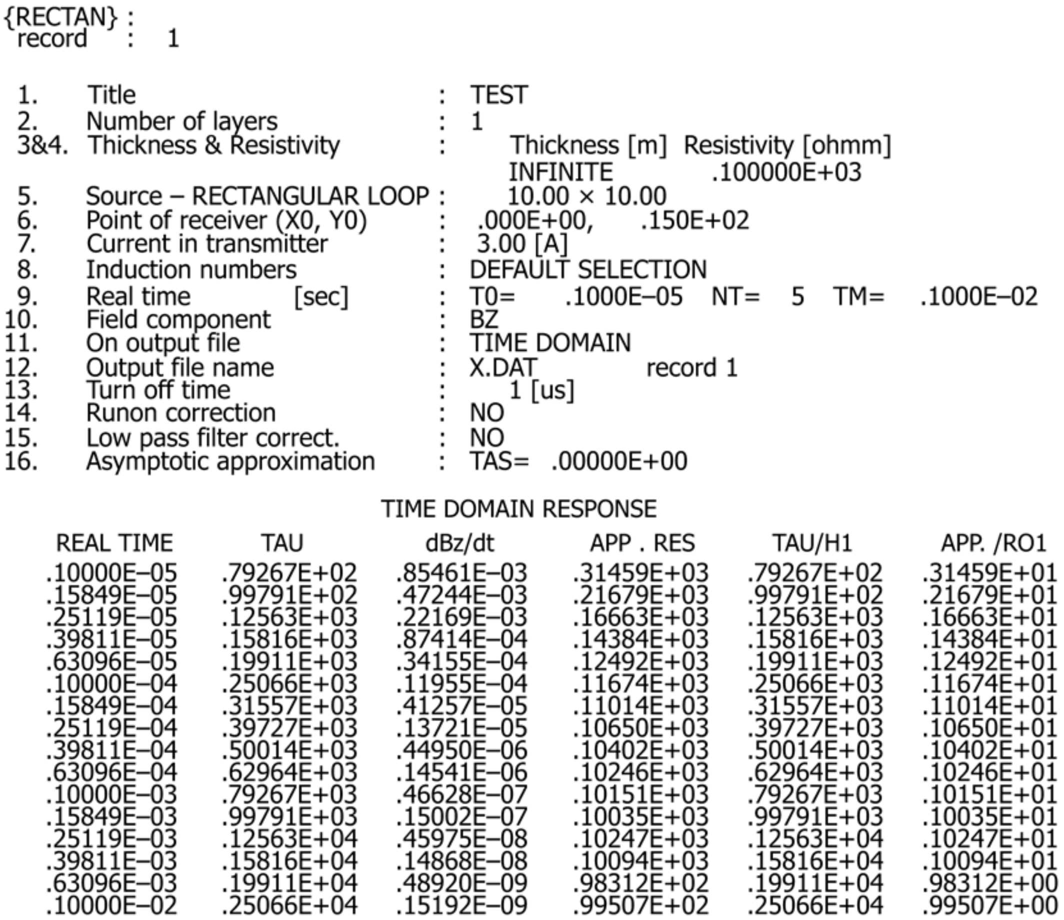


FIG. 8 Forward Layered Earth Calculation for a Clay Layer from 0 to 4 Metre Thickness (7)



```
{RECTAN} :
 record   :   1

 1.     Title                           :  TEST
 2.     Number of layers                :  1
 3&4.   Thickness & Resistivity         :     Thickness [m]  Resistivity [ohmm]
                                              INFINITE           .100000E+03
 5.     Source – RECTANGULAR LOOP       :     10.00 × 10.00
 6.     Point of receiver (X0, Y0)      :   .000E+00,     .150E+02
 7.     Current in transmitter          :   3.00 [A]
 8.     Induction numbers               :  DEFAULT SELECTION
 9.     Real time          [sec]        :  T0=     .1000E–05   NT=    5    TM=    .1000E–02
10.     Field component                 :  BZ
11.     On output file                  :  TIME DOMAIN
12.     Output file name                :  X.DAT            record 1
13.     Turn off time                   :     1 [us]
14.     Runon correction                :  NO
15.     Low pass filter correct.        :  NO
16.     Asymptotic approximation        :  TAS=  .00000E+00

                                TIME DOMAIN RESPONSE

   REAL TIME       TAU          dBz/dt        APP . RES       TAU/H1        APP. /RO1
  .10000E–05   .79267E+02   .85461E–03   .31459E+03   .79267E+02   .31459E+01
  .15849E–05   .99791E+02   .47244E–03   .21679E+03   .99791E+02   .21679E+01
  .25119E–05   .12563E+03   .22169E–03   .16663E+03   .12563E+03   .16663E+01
  .39811E–05   .15816E+03   .87414E–04   .14384E+03   .15816E+03   .14384E+01
  .63096E–05   .19911E+03   .34155E–04   .12492E+03   .19911E+03   .12492E+01
  .10000E–04   .25066E+03   .11955E–04   .11674E+03   .25066E+03   .11674E+01
  .15849E–04   .31557E+03   .41257E–05   .11014E+03   .31557E+03   .11014E+01
  .25119E–04   .39727E+03   .13721E–05   .10650E+03   .39727E+03   .10650E+01
  .39811E–04   .50014E+03   .44950E–06   .10402E+03   .50014E+03   .10402E+01
  .63096E–04   .62964E+03   .14541E–06   .10246E+03   .62964E+03   .10246E+01
  .10000E–03   .79267E+03   .46628E–07   .10151E+03   .79267E+03   .10151E+01
  .15849E–03   .99791E+03   .15002E–07   .10035E+03   .99791E+03   .10035E+01
  .25119E–03   .12563E+04   .45975E–08   .10247E+03   .12563E+04   .10247E+01
  .39811E–03   .15816E+04   .14868E–08   .10094E+03   .15816E+04   .10094E+01
  .63096E–03   .19911E+04   .48920E–09   .98312E+02   .19911E+04   .98312E+00
  .10000E–02   .25066E+04   .15192E–09   .99507E+02   .25066E+04   .99507E+00
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FIG. 9 Example of Forward Response Calculation (7)

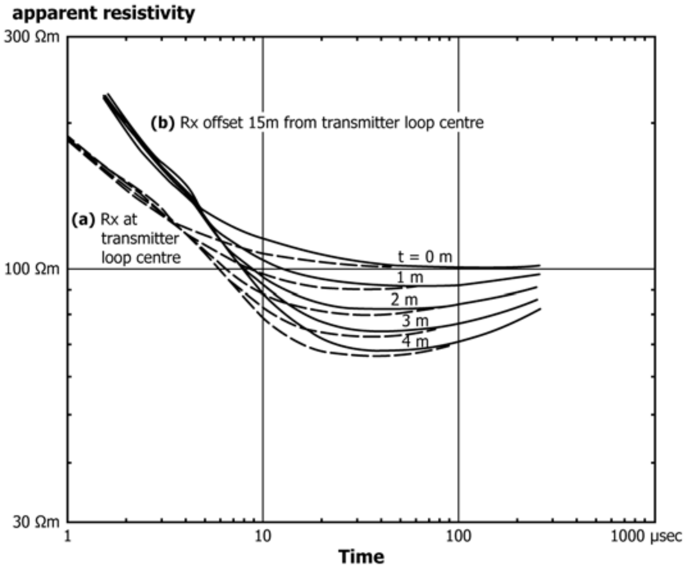

FIG. 10 Forward Layered Earth Calculations Comparing Central Loop Sounding with Offset Transmitter Sounding (7)

6.6.2 *Survey Station Spacing*—If survey stations are spaced too closely together, survey costs will be excessive. If too far apart, important detail in subsurface structures may be lost, making the data difficult to interpret, or at the worst, requiring that fill-in soundings be carried out later. An advantage of the TDEM/TEM technique over conventional DC resistivity soundings is that for the TDEM/TEM method, the length of a side of the transmitter coil is usually less than or equal to the depth of exploration. On the other hand, for conventional DC resistivity sounding, the Wenner array dimension is typically three to four times the exploration depth and the Schlumberger array dimension is typically three to five times the exploration depth. Thus, when terrain resistivity varies laterally, TDEM/TEM soundings will indicate the variations more accurately. If terrain resistivity variations are very closely spaced, it may be desirable or necessary to perform resistivity soundings at station intervals equal to the length of the side of the transmitter coil.

6.6.2.1 Ideally, a sounding technique measures conditions only directly under the array. For the central loop sounding technique described in this guide, the TDEM/TEM method measures a volume of the subsurface in a cone shape with the apex of the cone directly below the center of the loop.

6.7 *Survey Implementation:*

6.7.1 *On Site Check of Survey Plan*—A systematic visual inspection of the site should be made upon arrival to determine if the initial survey plan is reasonable. At this point, modifications to the survey plan may be required.

6.7.1.1 Initial measurements should be made to assess the noise conditions at the site. For this measurement, it is not necessary to lay out the transmitter loop. The receiver and receiver coil are set up, and a series of measurements made of the ambient noise level to characterize it. Results of the initial measurements may require changes to the original survey plan.

6.7.1.2 Note that most receiver coils have some form of integral leveling device. The sounding measurement is not sensitive to small errors in leveling.

6.7.1.3 When working on sloped ground, the transmitter loop is still laid flat on the ground. It is recommended that the receiver coil axis be perpendicular to the slope, in which case the geoelectric sounding is done into the slope, although it can also be vertical, in which case the sounding is essentially vertical, and depth to the various layers is the average depth.

6.7.2 *Lay Out Survey Lines:*

6.7.2.1 Locate the best position for the TDEM/TEM survey lines based on the survey design described in 6.6.1 and the on-site conditions.

6.7.2.2 The most time-consuming part of doing a sounding (especially deeper ones where the transmitter loop is large) is laying out the transmitter loop. It is more efficient to have one or even two crew teams laying out loops in advance of the survey party, who then follow with transmitter, receiver, and receiver coil to make the sounding.

6.8 *Survey Technique:*

6.8.1 Having ascertained that the noise conditions will not interfere with the survey, lay out the first transmitter loop. Usually the transmitter loop is mounted on one or more reels, depending on the loop and wire size. It is advisable to visibly mark the loop at the four points that will become the loop corners. It may also help to make small tape loops at the corners, through which stakes can be driven to secure the loop on the ground. A simple compass suffices to ensure that the various edges of the loop are parallel and point in the correct directions. Reasonable care should be taken to place the loop on the ground (especially for smaller loops less than 20 m). For larger loops, it is of little concern if the wire is up to one meter above the ground (if, for example, it is caught on bushes).

6.8.2 Make the first measurement of the ground response. The most important decision at this point is to decide on the correct value of receiver gain. If the gain is set too high, overload of the receiver may result, either from unexpectedly high signals from ground that is more conductive than expected, or from higher noise levels than were measured above. If the gain is set too low, the full advantage of the system dynamic range will not be properly utilized, with the result that the transient will be measured over a time range that is less than optimal, needlessly reducing depth of exploration. It is essential to constantly maximize the receiver dynamic range, adjusting the gain as necessary at each station to take into account the effect of varying terrain resistivity or varying ambient noise level.

6.8.3 It is also important to optimize the recording procedure for maximum SNR. Experience with TDEM/TEM instrumentation has shown that it is generally better to take several measurements with short integration time rather than one measurement with long integration time. The reason is that occasionally a large burst of short duration noise will occur, and such a burst is easily removed by deleting a short data sample. Modern TDEM/TEM receivers are often designed to automatically take a selectable number of short samples at each station. They also display the decay curve immediately after measurement, either as curve of transient voltage or of apparent resistivity as a function of time. Such a display allows the operator to ensure that good data has been obtained, as well as allowing him to observe changes in resistivity values as he moves from station to station.

6.8.4 The shape of the apparent resistivity curve is relatively insensitive to the location of the receiver with respect to the transmitter loop. This feature is useful when the ground is sufficiently heterogeneous to invalidate a sounding (in the worst case, for example, due to a buried metallic pipe). In this case, a useful and quick procedure is to take several measurements at different receiver locations (Fig. 11). Curve 5 is obviously anomalous, and must be rejected. Curves 1 through 4 can all be used in the inversion process, which handles both central and offset receiver coil locations. Another useful way to ensure, especially for deep soundings, that the measurement is free from errors caused by lateral inhomogeneities (perhaps a nearby fault structure) is to use a three-component receiver coil, which measures, in addition to the usual vertical component of the decaying magnetic field, both horizontal components. When the ground is uniform or horizontally layered, the two horizontal components are both much less than the vertical component, especially at late times, if measurement is made near the transmitter loop center. Departures of the horizontal components from a low value at late times indicate lateral resistivity inhomogeneities that may invalidate the sounding.

6.8.5 Most receivers designed for both shallow and deep sounding, have an adjustable base frequency to permit changing the duration of time $T = 1/f_b$ over which the transient is being measured. With reference to Fig. 2 and Fig. 4, changing the base frequency f_b changes the period T (where $T = 1/f_b$) and thus the measurement duration $T/4$. For transients that

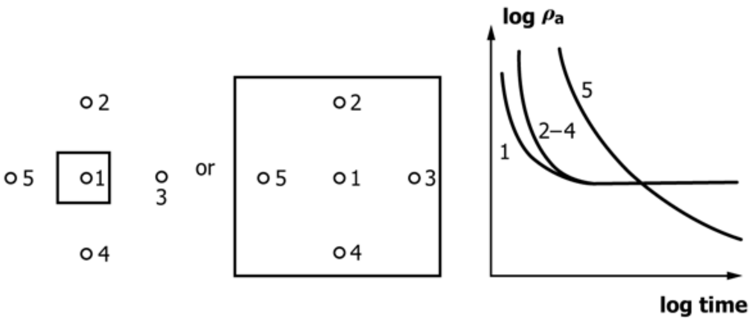

FIG. 11 Diagram Showing the Effect of Various Receiver-Coil Positions on Sounding Curves (7)

decay quickly, such as occur in shallow sounding, the measurement period, which should be of the order of duration of the measurable transient, is short, and thus the base frequency can be made high. This has the advantage that, for a given total integration time of, for example, five seconds, more transient responses will be stacked, which improves the SNR, in turn allowing use of smaller, more mobile transmitter loops, and thus increasing survey speed. On the other hand, for deep sounding, where the response must be measured out to very long times, the measurement period must be extended so that the transient response does not run into the next cycle of primary field, or the next transient response. Thus, the base frequency must be significantly reduced. As a result, the SNR will deteriorate due to fewer transients being stacked. The SNR must then be increased by using a larger transmitter loop or transmitter current (that is, increasing the transmitter dipole moment), or both, as well as integrating the data for a longer stacking time.

6.8.6 If such a run-on occurs because too high a base frequency is employed, the data can still be inverted. In extreme cases, the accuracy and resolution of the inversion will start to deteriorate.

6.9 *Quality Control (QC):*

6.9.1 *Calibration and Standardization*—The manufacturer's recommendations should be followed for calibration and standardization of equipment. If no recommendations are provided, a periodic check of equipment should be made, preferably using a "Q coil" as described in 6.5. A calibration and instrument check should also be made after each equipment problem and subsequent repair. An operational check of equipment should be carried out before each project and before starting fieldwork each day.

6.9.2 It is also useful to have a local measurement site where a sounding can be performed to check out the instrument. Note the comments in 5.2 regarding the dependence of terrain resistivity on soil moisture content and ground temperature.

6.10 *Data Processing:*

6.10.1 In a very few cases quantitative interpretation of the data may not be required and a simple qualitative interpretation may be sufficient. An example of qualitative interpretation is identifying the location of a buried channel. The level of effort involved in the interpretation depends upon the objectives of the survey and the detail desired.

6.10.2 A variety of computer programs are available to aid in processing of resistivity sounding data and modeling of the results. Use of such a program is recommended both in designing and planning the survey as well as for use in data reduction and inversion.

6.11 *Interpretation of TDEM/TEM Resistivity Data:*

6.11.1 Geologic conditions are generally such that the resistivity varies both vertically and laterally. Any geophysical technique measures a value of this resistivity that is averaged over some volume, the size of which depends upon the particular geophysical method used. The apparent resistivity is this average value of resistivity. If the true resistivity in the ground does not vary vertically or horizontally, the apparent resistivity is equal to the true resistivity. Because measurements are always carried out from the surface of the earth, the apparent resistivity is the average value of the subsurface materials as measured using a particular technique at the surface of the earth. The concept of apparent resistivity as it relates specifically to TDEM/TEM soundings is discussed in more detail in 5.4.1. It should be noted that the TDEM/TEM technique measures variation of terrain resistivity as a function of depth by measuring a decaying magnetic field as a function of time.

6.11.2 The interpreted resistivity is the resistivity of a particular horizontal layer at a given depth in the earth, and is determined by doing a data inversion procedure based on a horizontally layered earth model. Model interpretations are not unique and several different models will produce equivalent matches (to within the signal-to-noise ratio) of the survey data. Furthermore, the modeling and interpretation of TDEM/TEM resistivity data assumes (*1*) that the layers are all horizontal and (*2*) that each layer has uniform electrical properties.

6.11.3 All electrical sounding techniques (conventional DC resistivity, magneto-telluric, TDEM/TEM, etc.) suffer from equivalence, which is the condition that more than one layered geoelectric model fits the measured data. Data inversion programs calculate different geoelectric models that fit the data to within the known SNR. This allows the interpreter to decide how unique the interpretation really is. For example, after viewing the equivalent models it may turn out that what at first appeared to be an anomalous section of the surveyed area is not significantly different from the remainder of the surveyed area. Equivalence can be a major source of error in survey interpretation and must be addressed by using a data inversion program that produces a suite of "equivalent" geoelectric models.

6.11.4 The ambiguity caused by equivalence can be resolved or reduced through use of other geophysical, geological or hydrological data.

6.12 *Preliminary Interpretation*—Any preliminary interpretation should be treated with caution. Preliminary analysis done in the field is mostly a means of quality control.

7. Quality Assurance

7.1 It is generally good practice to have the entire survey results, including the report, reviewed by a person knowledgeable with the TDEM/TEM method and the site geology, but not directly involved with the project.

8. Report

8.1 *Components of the Report:*

8.1.1 The following is a list of the key items that should be contained in most reports. In some cases there may be no need for an extensive formal report.

8.1.2 The report should include a discussion of:

8.1.2.1 The purpose and scope of the TDEM/TEM survey,

8.1.2.2 The geologic setting,

8.1.2.3 Limitations of the TDEM/TEM survey (for example, sources of noise),

8.1.2.4 Assumptions that were made,

8.1.2.5 The field approach used, including a description of the equipment and the data acquisition parameters used,

8.1.2.6 The location of the TDEM/TEM survey line(s) or grid along with a site map,

8.1.2.7 Corrections applied to field data, and explanation for their use,

8.1.2.8 The results of field measurements,

8.1.2.9 Copies of typical raw data,

8.1.2.10 The format of recorded data,

8.1.2.11 Copies of the processed TDEM/TEM profiles and/or contours,

8.1.2.12 The method of interpretation used and specifically what analytical method(s) or software program(s) were used,

8.1.2.13 The interpreted results along with any qualifications and alternate interpretations,

8.1.2.14 If conditions occurred where a variance from this guide is necessary, the reason for the variance should be given,

8.1.2.15 Appropriate supporting data or references used in the interpretation, and

8.1.2.16 Persons responsible for the TDEM/TEM survey and data interpretation.

8.2 *Quality Assurance*—It is generally good practice to have the entire survey results, including the report, reviewed by a person knowledgeable with the TDEM/TEM method and the site geology, but not directly involved with the project.

9. Precision and Bias

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

9.1.1 *Some of the Factors that Affect Bias are:*

9.1.1.1 Errors in field procedures, record-keeping, corrections to data, processing and interpretation,

9.1.1.2 Instrument errors in measuring or recording,

9.1.1.3 Geometry limitations, relating to line location and topography,

9.1.1.4 Variation of the earth from simplifying assumptions used in the field and interpretation procedure,

9.1.1.5 Site-specific geologic limitations, such as ambient radiated or induced noise, or the presence of buried conductors, and

9.1.1.6 Ability and experience of the field crew, data processor and interpreter.

9.1.2 *Factors Specifically Affecting Bias of TDEM/TEM Resistivity Soundings:*

9.1.2.1 A detailed description of the various sources of error follows.

9.1.3 *Transmitter Dipole Moment*—This quantity is given by the product of the transmitter loop current and the loop area. The current is usually metered and the only caution is that, in those transmitters where the loop current is not regulated, the current will vary with loop temperature, and thus varies during the day.

9.1.3.1 The loop area is relatively forgiving to errors in loop layout. The most common error is that the loop is a parallelogram, of smaller angle θ, rather than a square (with $\theta = 90°$). In this case the actual loop area is smaller than the calculated loop area by a factor, sin θ, which is usually negligible.

9.1.3.2 The loop might conceivably be laid with all sides bowed outwards. In the worst case, for a given loop perimeter, the loop would be a circle rather than a square. In this case the actual loop area is larger than the calculated area by a factor of 1.27, resulting in an error of approximately 18 % in apparent resistivity, certainly significant.

9.1.4 *Measured Receiver Voltage*—The most serious source of error in this quantity is caused by the fact that the voltage decay curve is measured by sampling gates of finite time width. In a modern TDEM/TEM receiver, the width of the gates is sufficiently narrow as to cause negligible error. If this is not the case, the finite gate widths must be taken into account in the data inversion process.

9.1.4.1 The receiver coil axis must be vertical, otherwise an error given by the factor cosine of the angle of the departure from the vertical results.

9.1.4.2 Apart from these sources, assuming a relatively noise-free environment, and that the system has been properly calibrated and is in good working condition, the error in the receiver voltage will be of the order of a few percent except for the last few gates, where, because of the rapidly disappearing signal, the SNR quickly becomes zero.

9.1.5 *Timing of Receiver Gates*—In a well-designed receiver, errors from this source should be negligible. However it should be noted that any errors in timing produce large errors in apparent resistivity. In particular, it is important to ensure that the transmitter and receiver are always accurately synchronized, or large errors will result.

9.2 *Differences Between Depths Determined Using TDEM/TEM and Those Determined by Boreholes:*

9.2.1 The accuracy of a TDEM/TEM survey is commonly thought of as how well the resistivity results agree with borehole data or excavation data. In many cases, the depth to the feature obtained by resistivity data may agree with the borehole data. In other cases, there will be considerable disagreement between the TDEM/TEM results and borehole data. While a TDEM/TEM resistivity sounding measurement itself may be quite accurate, the interpreted results may disagree with a depth obtained from drilling for the following reasons.

9.2.1.1 The geoelectric properties of the subsurface materials may not be the same as those physical properties of the material itself.

9.2.1.2 The borehole data generally reflect the properties of the materials that are very near to the borehole, and thus delineate these properties in detail that is impossible to attain from a surface geophysical measurement.

9.2.1.3 Conversely, the surface geophysical measurement will be sensitive to material that lies at much greater distance from the borehole and to which the borehole techniques are insensitive. Moreover, the material at greater distance may have significant lateral variations that are averaged by the surface geophysical technique.

9.2.1.4 The physical act of drilling a borehole may have altered the geoelectric characteristics of the ground, for example the characteristics of the included moisture may have been seriously altered.

9.2.2 It is important that the user of TDEM/TEM results be aware of these concepts and understand that the results of a TDEM/TEM resistivity sounding survey will not always agree with drilling data.

9.3 *The Fundamental Differences between TDEM/TEM Resistivity Sounding and Drilling Measurements:*

9.3.1 A TDEM/TEM measurement integrates the resistivity over a large volume of the subsurface. In contrast, a borehole examines an extremely small volume of the subsurface. Therefore, it is unreasonable to expect a one-to-one correlation between these two measurements. The confirmatory borehole program must be carefully designed to yield appropriate data to support (or modify) the conceptual model of subsurface conditions.

9.3.2 *Lateral Geologic Variability*—Agreement between TDEM/TEM resistivity and borehole measurements may vary considerably along the survey line depending upon lateral geologic changes such as moisture or material changes. TDEM/TEM measurements do not account for small, lateral geologic changes. Therefore, it is not always possible to have exact agreement between TDEM/TEM and borehole data along a survey line.

9.3.3 *Positioning Differences*—The drilling location and the TDEM/TEM measurement may not be made at exactly the same point. It is common to find that the boreholes are located based on drill-rig access and may not be located along the survey line of the TDEM/TEM measurements. Differences in position can easily account for anywhere from a few meters to tens of meters of difference in depth where top of rock is highly variable, for example karst.

9.4 *Precision*—Precision is the repeatability between measurements. If a TDEM/TEM measurement is repeated under identical conditions with low noise levels, the measurements would be expected to be within 2 to 3 %. Different data quality objectives may be set depending on the purposes of the survey and on site conditions.

9.5 *Resolution:*

9.5.1 *Lateral Resolution*—Lateral resolution of a TDEM/TEM central loop resistivity survey is determined by the spacing between measurement stations. TDEM/TEM measurements are not able to resolve small individual features that are spaced less than the spacing between stations.

9.5.2 *Vertical Resolution*—Vertical resolution with the TDEM/TEM method is limited and is a complex function of the target(s), size(s), depth(s), relative position(s), and resistivities.

10. Keywords

10.1 conductivity; electrical method; geophysics; resistivity; subsurface investigation; surface geophysics; time domain electromagnetic method; transient electromagnetic method

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