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

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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 ground water salinity, and for the direct exploration for ground water.

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 D 420, D 653, D 5088, D 5608, D 5730, D 5753, D 6235, D 6429 and D 6431.

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 transmitters, and also across the transmitter loop, which is

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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.

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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:*

D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes[3]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 3740 Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction[3]

D 5088 Practice for the Decontamination of Field Equipment Used at Nonradioactive Waste Sites[3]

D 5608 Practice for the Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites[3]

D 5730 Guide to Site Characterization for Environmental Purposes with Emphasis on Soil, Rock, the Vadose Zone and Ground Water[4]

D 5753 Guide for Planning and Conducting Borehole Geophysical Logging[3]

D 6235 Guide for Expedited Site Characterization of Hazardous Waste Sites[4]

D 6429 Guide for Selecting Surface Geophysical Methods[4]

D 6431 Guide for Using the Direct Current Resistivity Method for Subsurface Investigation[4]

D 6639 Guide for Using the Frequency Domain Electromagnetic Method for Subsurface Investigations[4]

3. Terminology

3.1 *Definitions*:

3.1.1 See Terminology D 653.The majority of the technical terms used in this document are defined in Sheriff (**5**) and Bates and Jackson (**6**).

[3] *Annual Book of ASTM Standards*, Vol 04.08.

[4] *Annual Book of ASTM Standards*, Vol 04.09.

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.

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

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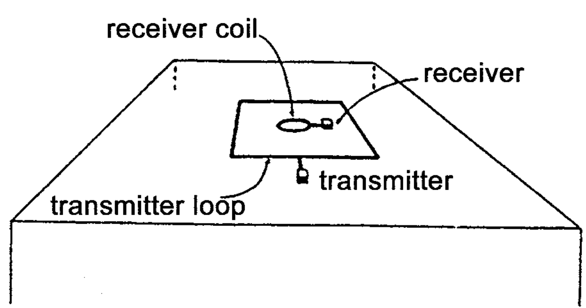

FIG. 1 Typical TDEM/TEM Survey Configuration (9)

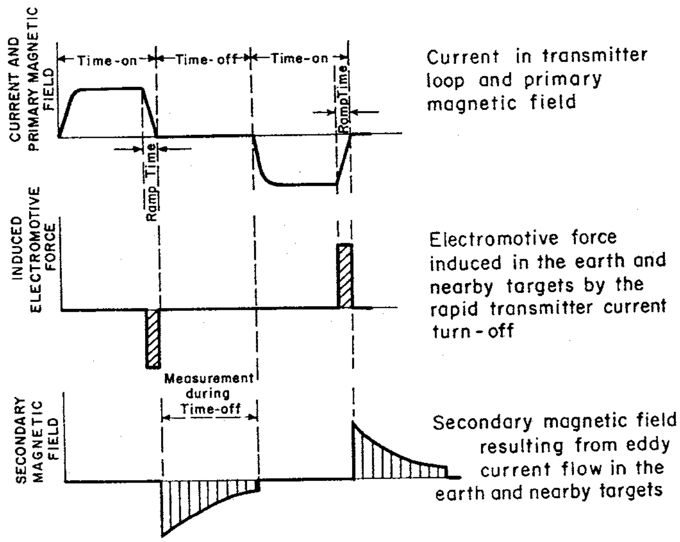

FIG. 2 Typical Time Domain Electromagnetic Waveforms (2)

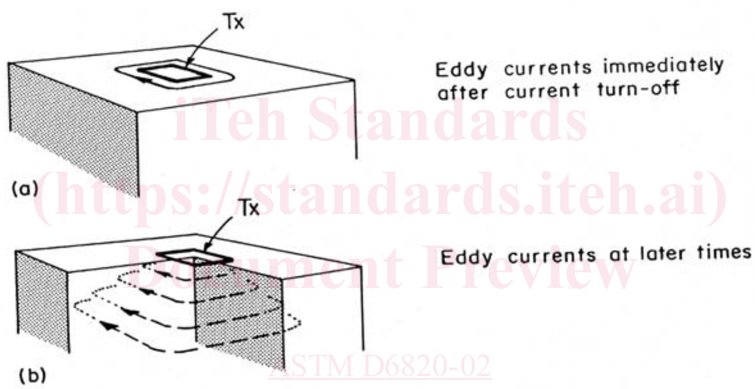

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FIG. 3 Time Domain Electromagnetic Eddy Current Flow at (a) Early Time and (b) Late Time (2)

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 D 6429) and borehole geophysical methods (Guide D 5753) 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 D 3740.

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:

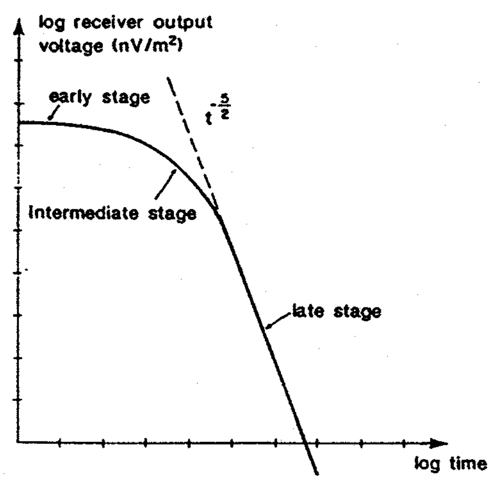

FIG. 4 Typical TEM Receiver Output Voltage Versus Time Plot (9)

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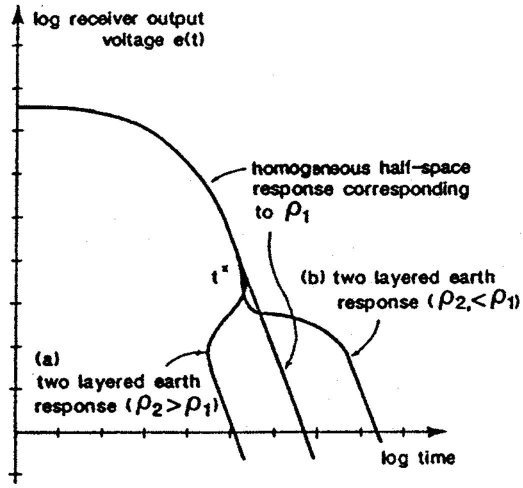

FIG. 5 TDEM Receiver Output Voltage for Various Earth Models (9)

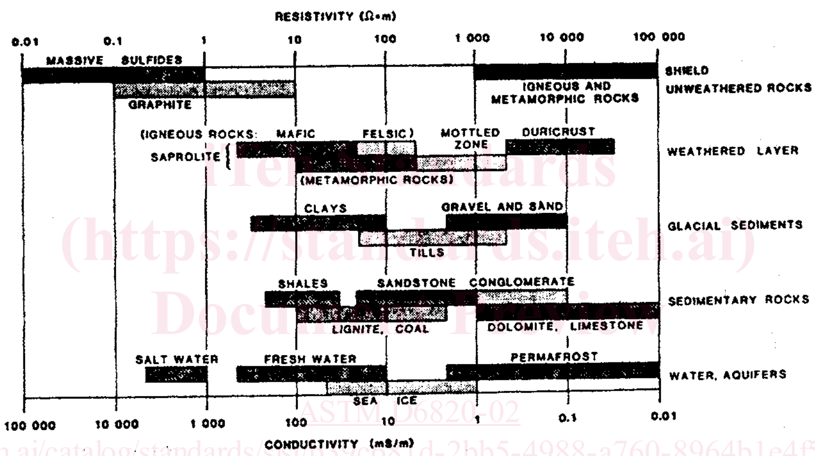

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FIG. 6 Typical Ranges of Resistivities of Earth Materials (5)

$$\rho = a\rho_w\phi^{-b} \qquad (1)$$

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 (7).

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.

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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.