Introduction to Geophysical Survey Techniques

This portion of the manual presents a guide to two of the most commonly applied geophysical survey techniques: magnetic or magnetometry surveys, and resistivity surveying. Like all remote sensing methods, those described are nondestructive and useful for describing subsurface conditions without requiring test excavations.

Magnetic surveying responds to contrasts in the magnetic properties of soils, but cannot easily be carried out easily be carried out near interfering magnetic sources such as buildings and power lines. Resistivity surveying responds to differences in the electrical conductivity of soils and is, thus, strongly dependent on contrasts in soil moisture and porosity. It is slower and more difficult to interpret but is free of interference of nearby buildings and power lines.

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GEOPHYSICAL SURVEYS

The various geophysical techniques for gathering information about subsurface features all depend, in one way or another, on differences in electric, magnetic, or elastic (seismic) properties of rocks and sediments. The techniques may be classified as passive or active. In the first category, existing force fields are measured directly without instrumentally generated signals, and the results are interpreted in terms of subsurface features perturbing the field. Magnetic, thermal, and gravity measurements fall in this category. In the second, or active category, instrumentally generated signals pass through the subsurface and are then detected and recorded. Seismic techniques, electromagnetic techniques (including the use of the simple metal detector, the pulsed-induction metal detector, and the soil conductivity meter), earth resistivity measurements, and ground-penetrating radar are all active devices.

Most types of geophysical surveys require a grid be marked out, related to permanent features on the ground. In the preliminary planning, and on site, a baseline must be established as close as possible to the longest edge of the survey area. This baseline should be marked with ranging poles. A secondary baseline should be established at right angles to the first, again where achieving the longest straight run is possible. The procedures for a normal 1 m detailed surveys are shown in Figure 1. The method applies to squares of any size, but a 10 m square is shown for clarity. The area is divided into 1 m squares, each containing a reading. A and B are measuring tapes or strings with the measuring points marked.

![Diagram](image)

**Figure 1.** Standard survey procedure.
MAGNETIC SURVEYING

Magnetic surveying consists of measuring the magnitude of the earth's magnetic field at each point on a grid established over a site. Variations in the magnetic properties of the subsurface material can produce an observable variation (anomaly) in the measured magnetic field. At any site successful application of the method depends on the magnetic properties of the local subsurface, the extent and nature of human activity, and, finally, the care taken in field measurement and analysis.

Theory

The magnetic field at any point on the earth can be defined, for our purposes, as the direction taken by a compass needle freely suspended there (Figure 2). The direction can be specified in terms of declination, the angle between the true north and the horizontal component of the earth's field, and inclination (or dip), the angle between horizontal and the direction of the total field. The field strength or magnitude is proportional to the maximum torque exerted on the compass needle by the field.

The geomagnetic field to which the compass needle is reacting seems to be caused by complex interactions between the Earth's hot, liquid, metal outer core as it rotates and convection within it, generating circular currents at the core-mantle boundary. These currents act as a solenoid to create the field, of which a distinctive characteristic is the varying angle of dip between the Poles and the Equator (Figure 2).

Figure 2. The Earth's magnetic field, generated by an east-west flowing current regime at the core-mantle boundary.
In this manual the unit of magnetic field strength used is the \textit{gamma}, which is numerically identical with the SI sub-unit \textit{nanotesla} (1 gamma = 1 nanotesla). While the latter is the preferred scientific term, gamma is still often used informally because saying it is easier.

Another aspect of the magnetic field with which we must be concerned is its variation with time. In a regular diurnal variation the magnitude decreases during the middle of the day by approximately 20 or 30 gamma from higher morning and evening values (Figure 3). During magnetic storms larger variations occur over time periods from a few hours to days.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Typical diurnal variation recorded by a stationary proton magnetometer.}
\end{figure}

**Magnetic Properties of Soils**

In the presence of a magnetic field, material such as soil, rocks and ferrous objects can become magnetized. Such a magnetization is said to be \textit{induced}. In addition to induced magnetization, which vanishes when the applied field is removed, some materials exhibit \textit{remanent} magnetization, magnetization that persists in the absence of an applied field. Baked clays and some rocks retain a thermo-permanent magnetization after being heated to several hundred degrees centigrade and then cooled in a magnetic field. Remanent magnetization can also arise from chemical change or from the settling of small particles in a magnetic field.
A range of time responses exists between the extremes of permanent magnetization and the very rapid component of induced magnetization. Because the time response depends on particle sizes in the soil, parts of soils can become magnetized very rapidly while other parts change their magnetization very slowly. The magnetization of the smallest and largest of the unstable magnetized particles will be free to follow the direction of the geomagnetic field, but particles in the middle size range will have magnetization that only gradually follow changes of the field.

The compounds in soils that are important in causing magnetization are hematite (α-Fe₂O₃), magnetite (Fe₃O₄) and maghemite (γ-Fe₂O₃). The latter two compounds are much more strongly magnetic than the first, their saturation magnetization being approximately 200 times that of hematite. Since soils contain a few to several percent iron oxides, these compounds and their conversion from one to another are the significant factors of soil magnetization. Two measures of response of a material to magnetization are its magnetic susceptibility, which is the ration of magnetization (dipole strength per unit volume) to magnetic field strength, and its specific susceptibility.

Typical values for susceptibility are as follows:

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Susceptibility</th>
</tr>
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<tbody>
<tr>
<td>Limestone</td>
<td>10</td>
</tr>
<tr>
<td>Subsoils</td>
<td>50-100</td>
</tr>
<tr>
<td>Topsoils</td>
<td>100-1,200</td>
</tr>
<tr>
<td>Heated soils</td>
<td>1,000-2,500</td>
</tr>
</tbody>
</table>

Units of 10⁻⁶ emu/g

**Measurement of the Magnetic Field**

The three instruments primarily used for near-surface surveys are the proton free-precession magnetometer, the fluxgate magnetometer, and the cesium or rubidium magnetometer. The proton magnetometer is the least expensive and by far the most widely used.

*Portable Proton Magnetometer*

This type of instrument has several advantages: readings are absolute, requiring no calibration; it measures total field without any direction sensitivity; and it requires no setting up procedure, or rigid support (see Appendix A, geoMetrics Model G-826 Portable Proton Magnetometer).
Protons are the nuclei of hydrogen atoms, of which there are two in every molecule of water. Because they are spinning, the protons are magnetized, and behave as very small magnets or magnetic dipoles. The principle of the proton free precession detector is illustrated by the example in Figure 4. It consists of a 250 ml polythene bottle containing a proton-rich liquid. Water is highly effective, but if there is any danger of freezing alcohol is preferable. The bottle is surrounded by a coil of copper wire and the whole is encapsulated in an epoxy resin to protect it. A polarization current through the coil creates in the liquid a magnetic field many time more intense than the earth's. This field partially polarizes the hydrogen's nuclear protons, which are spinning magnetic dipoles. The polarization current is then quenched and the protons precess (gyrate) in the field of the earth. For the few seconds that the protons precess coherently, a voltage is induced in the coil. This voltage can be amplified, the frequency measured, and the results displayed in gammas. (Note: In older units the total cycle time may be 7 seconds, but this can be shortened to 3 or 4 seconds with no loss of sensitivity; the normal sensitivity is 1 gamma, which can be increased to 0.25 gammas in portable models).

**Anomalies Produced by Local Features**

An isolated Magnetic feature (termed a source) whose dimensions are small compared with the sensor distance produces the simplest, so-called dipole anomaly. A normal dipole anomaly results from induced magnetization (such as in small pit), where polarization will be in the same direction as the earth's field. However, if the magnetization is permanent (such as in a piece of iron or a burned rock), the polarization will be in a different direction than that of the earth's field and the resulting anomaly is termed a nonnormal dipole anomaly. The total magnetic field in the neighbourhood of a normal dipole is the combination (vector sum) of the uniform, downward-pointing field of the earth and a weak, dipole field from the source feature. The profile of magnetic values measured along a south-north line is represented in Figure 5. Three characteristics of this anomaly type may be noted:

1. The maximum intensity of the magnetic profile is displaced to the south of the source by one-third the source-sensor distance.
2. The full width of the profile at half maximum is equal to the source-sensor distance.
3. The negative region, due to the source dipole field opposing the earth's field is about 10 percent of the maximum intensity.
Figure 4. Design of a portable proton magnetometer detector. The protons are shown as small bar magnets. The diagram shows the detector at the polarization stage, in which a DC current of about 1 amp is passed through the coil, so that it acts as a solenoid or electromagnet that tends to align the protons parallel with its axis. The current is then switched off and the coil becomes a detector connected to a sensitive amplifier. The protons turn to align with the ambient magnetic field, which is that of the Earth plus any magnetic anomalies. Because they are spinning, the protons precess like falling tops as they realign, generating a small alternating (AC) voltage in the coil. The frequency of this, which is measured, is exactly proportional to the strength of the field. The bottle is aligned roughly east-west to maximize the angle through which the protons reorientate, and therefore the amplitude of the signal.
Deviations of a magnetic anomaly from these characteristics imply a non-normal dipole - that is, a source with permanent magnetization. Long, narrow pieces of iron or burned stones in particular produce anomaly profiles with large deviations from those of normal dipole anomalies. Thus, if the minimum is not north of the maximum, or if the minimum deviates appreciably in size from 10 percent of the maximum, one can conclude that the source is not a feature resulting from induced magnetization.

The size of the anomaly depends strongly on the source-sensor distance, decreasing proportionally with the inverse of the cube of distance. The size also depends on source volume (V), and magnetic susceptibility contrast (K).

![Diagram of magnetic anomaly](image)

**Figure 5.** Combination of a dipole magnetic field produced by a local source and the magnetic field of the earth. The plot is that of the magnitude of the sum of the two fields as measured by magnetometer passing over the source.
Application of the Method

The method to be used in surveying a site depends on the information sought. If one wants information on possible linear features, then one or a few magnetometer traverses may suffice. If the surveying is done over short period of time, it is not necessary to use a second or reference magnetometer; plotting profiles of such traverses may be sufficient to reveal the information wanted.

If simple traverses do not suffice, then the problem is to seek patterns of anomalies in a two-dimensional mapping of the magnetic field over the site. Mapping is accomplished by measuring the field on a grid of points over the site. When more than a few minutes are needed to survey the area, some method must be used to correct for the temporal variations of the earth's field. Without such corrections, the resulting magnetic map will be distorted and spurious anomalies will appear, particularly along traverse rows. The basic idea behind all corrections is the assumption that the earth's field changes in time simultaneously everywhere over a region considerably larger than the site being sampled.

If only a single magnetometer is available, it alone can be used to correct for temporal variations. The operator simply intersperses repeated readings at a single reference station between groups of grid readings - for instance, after each row of points. The reference readings are then plotted against time and a curve drawn through them. In this way reference values corresponding in time to each grid value are estimated and subtracted from the grid values. This procedure, however, can still result in incomplete corrections and spurious anomalies, particularly linear anomalies along transverse lines.

Before starting the field survey, all visible geological and manufactured artifacts must be examined. Some evaluation of the survey's possible success may be obtained by measuring the magnetic susceptibility of a typical soil sample from the site. These samples should be taken at representative stratigraphic levels. By measuring the susceptibility of the samples before and after heating in a reducing atmosphere, it is possible to evaluate expected anomaly sizes.

The size of the survey grid unit is determined by the size of the features expected. Since the number of magnetic field measurements will be proportional to the square of the grid spacing, this choice is a compromise between detail sought and time available. Generally, speaking, the grid spacing should be comparable with, or somewhat smaller than, the linear dimensions of expected anomalies. Features of a
metre or two in size near the ground surface can be surveyed with a 1 m grid. If the features are deeper, then the spatial extent of the anomalies will be larger (as well as weaker) and a larger grid spacing can be used.

In choosing sensor height above the surface, two considerations must be noted:

1. First, since the width of an anomaly increases from the source-sensor distance, a greater sensor height will result in less resolution between anomalies from neighbouring sources. An approximate rule is to have the source-sensor distance no greater than the intersource distances that one wished to resolve. This suggests a source-sensor distance equivalent to or less than the grid spacing.

2. Second, the sensor height must be selected to reduce the relative contributions from surface noise arising from variations in surface-soil magnetization. The noise contribution compared with the signal will decrease with increasing sensor height. Probably the best compromise is to set the sensor height at between 40–60 cm for a 1-m grid.

Operational Details

Before taking measurements, evaluating the local magnetic environment is important. Vehicles can produce a shift of roughly 1 gamma at 30 m. Such disturbances are acceptable only if they remain stationary throughout the survey. Larger and closer amounts of iron, if stationary and not too large, can be treated by mathematical filtering techniques applied to the data. Power lines, moving trains, and other nonstationary sources must be avoided.

The person holding the moving sensor must be carefully checked before starting. Steel shoe tips, belt buckles, bank cards with magnetic strips, and even eyelets in hats can cause trouble. Repeated readings should be taken with the person assuming several positions relative to the sensor. Variations in readings should be random and not greater than one or twice the “least count” of the instrument (the smallest possible change in value displayed).

Even if the magnetic field is absolutely stationary in time, a random scatter or noise in reading values of about ±0.5 times the least count will be observed. In actual practice, the reproducibility of different values (taken by repeated readings at the same grid point, repositioning the
sensor each time and calculating the standard deviation) is more like three to five times the last count. This variation in the difference values is a measure of the least amount of noise to be expected. Anomalies smaller than this variation may be lost in this noise unless they are observed on several grid points.

**Interpretation**

The first requirement in the analysis of magnetic data is to produce a matrix of magnetic field values corrected for diurnal variations to be used in all subsequent mapping and profiling. The simplest treatment is then to plot profiles along transect rows. For more complicated situations it is necessary to examine the areal (two-dimensional) patterns of anomalies. Various forms of magnetic contour maps are generated in which the magnetic field strength is treated as a "height" on a map of the site (Figure 6).

![Figure 6. Grid-point map, where each increment in darkness represents an increase in two gamma.](image-url)
RESISTIVITY SURVEYING

The electrical resistance of the ground is almost entirely dependent upon the amount and distribution of moisture within it. Resistivity surveying indicates spatial differences in sediment moisture. Location of these anomalies or contrasts involves careful measurement of the sediment resistivity at discrete points on the surface along transverses or on a grid of points. The collected data are usually displayed as profiles or as electrical-resistivity contour maps, and can be used to distinguish types of subsurface materials, determine the composition of an overburden, determine depth to and thickness of sand, gravel, or metal deposits or aquifers, detect fault zones, and to find steeply dipping contacts between different earth materials.

Theory

The electrical resistivity technique of subsurface investigation is based on the variable resistance, in subsurface materials, to the conductance of electrical current depending on variations in moisture content, density, and chemical composition. In electrical resistivity investigation, an electrical current is introduced to the ground at a predetermined depth, through two current electrodes, and the potential difference between two or more potential electrodes are measured to detect the resistivity of the material at depth. Values for the distance between the electrodes and the measured potential difference are the data used to make interpretations of subsurface conditions.

To conduct successfully and interpret a resistivity survey, a grasp of basic electrical theory is necessary, beginning with the nomenclature. Electric current is the rate of flow of charge passing through a cross section of a conducting medium for a specific length of time. To cause current to flow, a voltage (also known as potential difference, a measure of the energy used to move the charges) must be applied. When a voltage is applied and a current flows, a resistance is encountered to the movement of the charge, which is dependent on the characteristics of the medium in which the charges are moving. These three physical quantities are related by Ohm's law:

\[ \text{resistance} = \frac{\text{voltage}}{\text{current}}, \text{ or } R = \frac{V}{I} \]  

(1)

Resistance is measured on Ohms (\(\Omega\)), voltage in Volts (V), and current in amperes (A).
In a conductor of length \( L \) and cross section \( A \) (Figure 7), the voltage difference per unit length can be thought of as the moving force, the current as the quantity moved, and the resistance as the opposition encountered by moving the current. If \( R \) is the resistance of a block of conductive material having a length \( L \) in a cross sectional area \( A \), then the resistivity is expressed as \( \Omega = RA/L \). Thus, resistivity, being a fundamental property of the material, is independent of the volume whereas resistance depends upon the shape and size of the specimen.

![Diagram](image)

**Figure 7.** Illustration of the relationship between resistivity and resistance.

From Ohm's law we can develop the concept of resistivity by incorporating into equation (1) the geometry of the medium. Resistivity \( (\rho) \) is defined as:

\[
\rho = \frac{V/L}{J}
\]

where \( V/L \) is the change in voltage with distance in the direction of current flow and \( J \) is the current density in the medium in which charge is flowing. The basic unit of resistivity is the ohm-metre or ohm-centimetre (1 \( \Omega \cdot m = 100 \Omega \cdot m \)). If a specified current is flowing in a known geometrical shape, we can deduce the resistivity of the material, providing the voltage difference is known. The inverse of resistivity \((1/\rho)\) is known as the conductivity.

**Resistivity Measurements**

The concept of subsurface resistivity measurements can be illustrated in an actual field situation. Current is induced into the ground by inserting in the ground two metal probes connected to a battery. In this idealized case, distribution of voltage and current in uniform earth is well understood (a model is shown in Figure 8). Also, shown are current- and voltage-measuring devices to indicate both the amount of charge flowing between the current probes and the voltage in the area of interest between the two potential or voltage probes.
**Figure 8.** Distribution of current and voltage in a homogeneous earth.

By calculating the volume affected by the flow of current, we can derive an expression for the average resistivity within the measuring probes:

\[
\rho = 2naV/I \quad (3)
\]

which is easily calculated because the distance between the probes (a) is known and the current (I) and voltage (V) are measured quantities. The resistivity is correct only for this probe configuration (or probe array), as other probe geometries change the volume of earth affected by the current flow.

We can alter this simple model to illustrate how the current and voltage are affected by some inhomogeneity in the uniform earth. The voltage and the current deviate from the normal pattern and the resistivity measurement of the earth between the two probes changes (Figure 9).
Figure 9. Distribution of current and voltage in the presence of a feature with a lower resistivity than that of the surrounding medium.

If these measurements are continued by moving all four probes from grid point to grid point, we can generate a series of readings indicating the lateral variations in electrical resistivity to a depth approximately equal to the separation of the voltage-measuring probes. By increasing the spacing between the probes for any given survey, one can examine a greater volume (and therefore depth) of material.

Electrical Properties of Sediments

Electricity is conducted through the ground through metallic soil and rock particles, and through mineralized water (electrolytes) present in pores, fissures and fractures. When the loosely held electrons of metallic soil and rock particles move from one atom to the other under the influence of an external current, this property is called electronic conductivity. When ions in electrolytes in pores, fissures and fractures carry the current, this property is called electrolytic conductivity. In electrical resistivity investigations, both types of conductivity are involved. The more mineralized the rock materials and the groundwater are, that is the higher their metal and ion content, the higher their conductivity. Because conductivity is the reciprocal of resistivity, the fewer free ions in a material and the dryer it is, the higher its electrical resistivity.
Soil Resistivity

The electrical resistivity of sediments shows wide spatial variation depending on climatic, geologic and edaphic conditions. Typical values of resistivity for different sediments are given in the following table.

<table>
<thead>
<tr>
<th>Types of Sediment</th>
<th>Resistivity (Ohms-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loams</td>
<td>500-5,000</td>
</tr>
<tr>
<td>Clays</td>
<td>800-5,000</td>
</tr>
<tr>
<td>Clay, sand and gravel mixture</td>
<td>4,000-25,000</td>
</tr>
<tr>
<td>Sand and gravel</td>
<td>6,000-10,000</td>
</tr>
<tr>
<td>Slates, shales, sandstones, etc.</td>
<td>1,000-50,000</td>
</tr>
<tr>
<td>Crystalline rocks</td>
<td>20,000-1,000,000</td>
</tr>
</tbody>
</table>

Instruments and Field Procedures

Probes

The probes used for the transfer of current or measurement of voltage usually consist of steel rods pointed on one end, with suitable hand holds on the other to ease insertion in the soil. Ideally, the probes should act as point sources, but since they must be inserted a finite distance into the ground this is not the case. The actual resistivity will change if the insertion depth is varied for one or all the probes, so steps must be taken to ensure uniformity. This can be accomplished by an adjustable ring on the probe that will arrest insertion at the desired depth. Field conditions usually dictates what is reasonable, although to maintain adequate precision in determining the resistivity the insertion depth should be less than 20% of the distance between the nearest adjacent probe. For a 1-m spacing insertion to 5-10 cm is usually provides adequate contact for all but the driest soils.

Care must also be taken in situating the probes relative to one another. For example, when using small spacings in the order of 30 cm, errors in the measured resistivity can be as large as 15% for the misplacement of a probe by 3 cm.
Probe Configurations

There are a variety of probe arrays to choose from, depending on the terrain, the size of the expected features and the experience of the operator. The original standard configuration is the Wenner array consisting of a four-in-line probe configuration (Figure 10, see Appendix B, ER-2 Electrical Resistivity Meter [ER-29-1], page 10).

![Diagram of the Wenner probe configuration](image)

**Figure 10.** Diagram of the Wenner probe configuration (array) and accompanying hemisphere of detection.

The Wenner array produces the largest percentage change over most lateral sediment variations. Most instruments are set up to accommodate this array. With the use of a fifth probe and a rotary switch, the last probe can be deactivated and "leapfrogged" to the front of the array while the instrument operator takes a reading using the other four probes (Figure 11). This allows each additional reading to be taken with the insertion of only one probe instead of moving the entire array. The main disadvantage of the Wenner array is that it tends to produce subsidiary peaking in the data, typified by large excursions in the readings before and after a resistivity contrast occurs. This gives M- and W- shaped anomalies as illustrated in Figure 10.

**Field Procedures**

Lateral variations in soil moisture are measured by using linear traverses or a regularly spaced grid, the choice depending primarily on required resolution and economy. Establishing the electrical properties of the site before systematic surveying aids in choosing the array and spacing.
Figure 11. Leapfrog survey.

A trial traverse can be run using the Wenner array and the later complete survey should be contrived to allow for current flow to encompass as much of the feature as possible.

The depth measured by the array is about equal to the distance between the voltage probes. In other words, a volume roughly equal to a hemisphere of diameter a is measured (see Figure 10). The test traverse should be extended 10 or 15 m on either side of a prospective feature to ascertain ground-noise conditions. When little is known about the geometry of the features on a site, a probe spacing of 1 m using the Wenner array is the best choice. Where the ground is level, easily penetrated, and clear of excessive vegetation, you should be able to take between five and seven readings per minute, or 150 to 190 readings per hour. Field notes should be maintained with observations on variations in soil type, ease or difficulty in probe insertion, change in density of vegetation, and noticeable topographic features. These factors affect the resistivity and can often be of valuable assistance during interpretation. A log of rainfall for the period of the fieldwork is also a valuable aid, since large amounts of rain can drastically affect the magnitude and even the polarity of resistivity anomalies.
Several simple field techniques can be used to distinguish more readily the resistivity anomalies due to background variation in areas where noise from surrounding soils is high. When the validity of a reading is suspect, the traverse should be rerun for verification. By running two or three traverses, sets of data are generated that encompass greater soil depths.

**Interpretation**

Once data are collected, they are processed and displayed in a way that will enhance the resistivity contrasts. Little alteration of the data is needed before preliminary display, since many instruments produce readings that are already converted to resistivity and compensate for the array being used. Because individual traverses are used more often in resistivity than magnetic surveying, profiling the data tends to be a more common display technique (Figure 12). Profiles can be plotted readily by hand and on occasion should be done in the field, to check for noise levels of the feasibility of a particular spacing.

![Graph](image)

**Figure 12.** Resistivity anomalies over an earth-filled pit.
Two-Layer Structures

1) Low-resistivity layer over high-resistivity layer

As a first example, consider a low-resistivity layer such as soil overlying a thick, high-resistivity layer such as dense rock. A completely uniform subsurface whose resistance equals that of the top (soil) layer would have line of current flow as shown by the dashed line in Figure 12. As the electrode spacing increases, the presence of the rock substratum starts to alter either the current density or the true resistivity ($\rho$) measured by the instrument along the surface line between the two potential electrodes.

![Diagram showing current flow in two-layer structure](image)

**Figure 12.** Two-layer model with low-resistivity layer over high-resistivity layer.

The true resistivity of the surface material is not changed by the presence of the rock, since the rock does not extend to the surface. Thus, $\rho_0$ will be completely unaffected by the rock substratum and cannot contribute to the change in apparent resistivity readings. The bedrock's effect upon the current density at the surface will depend upon the electrode spacing or, more precisely, upon the ratio of electrode spacing to the depth of bedrock. The left side of Figure 12 shows that when the electrode spacing is small compared with the depth, the current density will be largely unaffected by the rock. The corresponding apparent resistivity reading is shown at electrode spacing $A'$ on the resistivity curve in Figure 13. 

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The right side of Figure 13 shows the redistribution of current density for larger electrode spacings as the current starts to enter rock. The current is deflected away from the high-resistivity rock substratum as the current seeks to follow a path of lower resistance. The current density in the soil layer is increased everywhere and, in particular, the current density between the current electrodes is increased. A corresponding reading on the resistivity curve is shown at electrode spacing A' in Figure 14.

![Resistivity curve diagram](image)

**Figure 14.** Corresponding resistivity field curve.

Two conclusions should be apparent. First, the current density distribution will change gradually as the electrode spacing is increased (and the effect of the lower-lying, high-resistivity stratum increases). Therefore, the apparent resistivity curve will rise smoothly to approach the true resistivity of the bedrock layer gradually as the electrode spacing becomes very large compared with the depth of the rock. If sharp changes in a resistivity curve are observed, they can usually be accounted for only as lateral changes in the subsurface conditions, never by horizontal layering. Second, the true resistivity in the near-surface soil layer can be easily determined. It is simply the left-hand limit of the sounding curve. If the sounding curve is extrapolated back to the limit of zero electrode separation, this apparent resistivity will equal to the true resistivity of the surface layer. This may be seen in Figure 13.

2) *Effect of gravel deposit*

Figure 15 shows the effect on the lines of current flow produced by a high-resistivity gravel deposit. There will be relatively little effect for small electrode spacings (compared with depth to the top of the gravel). At larger electrode spacings the lines of current flow will be deflected upward, and this will increase the measured apparent resistivity.
Figure 15. Effect of a gravel deposit on the resistivity results.

From Figure 15, it may be surmised that too large an electrode spacing will reduce the probabilities of detection of a thin deposit. For a large electrode spacing, the redistribution of the lines of current flow will be relatively slight, because the non-uniformity represented by the gravel deposit occupies only a relatively small fraction of the total volume of current flow.

3) Miscellaneous

Because the signal-to-noise ratio is difficult to quantify in resistivity surveying, the data are often interpreted qualitatively. Essentially two types of noise are involved: correlated noise, caused by the contributions of natural soil variation, and uncorrelated noise, the sum of instrument variation, difference in probe spacing and depth, and the occasional poor contact of a probe with the ground.

Correlated noise from natural soil variations can be as large as or larger than the signal, and in these instances can be distinguished only when the noise signature has a different shape than that of the signal. If no specific correlated-noise anomalies are recognizable from natural soil variation, then the standard deviation of all the readings on the test traverse provides a reasonable background level. Uncorrected noise levels can be minimized by field procedures. If a measurement on a traverse is greater than the preceding one by a predetermined amount (usually standard deviation of test traverse), then the probe contacts should be checked and retaken.
Potential Field Geophysics Factsheet FS-076-95

The computer programs of the Potential-Field Software Package run under the DOS operating system on IBM-compatible personal computers. They are used for the processing, display, and interpretation of potential-field geophysical data (gravity- and magnetic-field measurements) and other data sets that can be represented as grids or profiles. These programs have been developed on a variety of computer systems over a period of 25 years by the U.S. Geological Survey.

Capabilities

The Potential-Field Software Package is designed to take geophysical (primarily gravity-field and magnetic-field) measurements in the form of point data, flight-line data, or gridded data; process them; display them; and aid in their interpretation. Among the basic elements of the package are a forward and inverse cartographic projection routine, a minimum-curvature gridding routine, various plotting and contouring routines, Fourier and spatial filtering routines, and a graphical editing routine for spatially registered point data. More advanced elements include image generation and display routines and forward and inverse modeling routines for interpreting map and profile data.

One of the strengths of the Potential-Field Software Package lies in the common data formats used for point, flight-line, and gridded data. These standard formats have allowed a variety of scientists to write and contribute computer programs that work smoothly together. The combined expertise of these scientists has produced a software package containing algorithms at the forefront of potential-field interpretation.

Additional advantages have accrued from adapting the package to run on a common and generally available platform, the IBM-compatible personal computer running under the DOS operating system. These personal computers are available in classrooms and scientific laboratories throughout the world. Their standard graphics screens, keyboards, and mouse pointers are used to great advantage for manipulating and displaying geophysical data.
A geophysical density model (bottom) having a calculated gravity anomaly (continuous curve, top) that fits observed gravity measurements (+ symbols, top).

A menu-driven user interface and extensive online help files are designed to aid the new user in becoming familiar with the more than 200 programs in the software package. The programs are broken into seven categories:
1. programs for displaying and generating contour maps and images,
2. programs for filtering grids,
3. utility programs for grids,
4. interpretation and modeling programs,
5. programs for gridding and manipulating point and flight-line data,
6. programs for extracting, manipulating, and interpreting profile data, and
7. miscellaneous programs.

Availability

The software package is available on diskettes (OFR 92-18[A-G] and OFR 93-560B) or on CD-ROM (DDS-9) from: USGS Information Services, Box 25286, Building 810, Denver Federal Center, Denver, Colorado 80225. (303) 202-4200

The package is also available by anonymous FTP in the pub/pf directory on musette.cr.usgs.gov [136.177.80.14].
APPENDIX A

OPERATING MANUAL

MODEL G-826
PORTABLE PROTON MAGNETOMETER

geoMetrics
395 Java Drive
Sunnyvale, California 94086 U.S.A.
(408) 734-4616

Cable: "GEOMETRICS" Sunnyvale
Telex No: 357-425

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<td>3.2</td>
<td>Battery Voltage Indicator</td>
<td>13</td>
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<td>Controls and Indicators</td>
<td>6</td>
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<tr>
<td>3-1</td>
<td>Battery Performance</td>
<td>12</td>
</tr>
</tbody>
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1.0 GENERAL INFORMATION

1.1 INTRODUCTION

The Model G-826 Portable Proton Magnetometer is a complete system designed for man-carry field applications requiring simple operation and stable measurements of the total intensity of the earth's magnetic field. The G-826 is accurate and has a sensitivity of ±1 gamma over a range from 20,000 to 90,000 gammas. Since the instrument measures total field intensity, the accuracy of each measurement is not affected by sensor orientation. The inherent simplicity of the G-826 proton magnetometer allows rapid, accurate measurements to be obtained from a rugged, compact field instrument. This is a precision instrument and reasonable attention must be given to handling, battery condition, and magnetic environment.

1.2 MAGNETIC ENVIRONMENT

It is important that the earth's magnetic field is not perturbed by allowing unwanted magnetic objects to come close to the sensor. Such objects include rings, keys, watches, belt buckles, pocket knives, metal pencils, zippers, etc. When the sensor is used on the staff, one gamma surveys are easily performed provided the sensor is kept at a distance of three feet from the operator. When the sensor is used in the backpack, certain articles of clothing and some types of batteries within the console will cause a five to ten gamma heading error in the readings. The G-826, however, still provides one gamma sensitivity and repeatability despite the presence of such a base line shift. The backpack feature is recommended for use in difficult terrain where "hands free" operation is required.

Prior to survey use, objects that are suspected to be magnetic may be checked in the following manner:

1. Attach sensor to staff and connect colled signal cable to console. Sensor should not be moved or turned during the test, and the suspected article should be far away initially.

2. Cycle the magnetometer a few times by depressing the READ button—releasing—and waiting for a reading each cycle.
3. Observe measurement readings. Each reading should repeat to ±1 gamma. (A slow shift may occur over several minutes due to a diurnal change in the earth's field.)

4. Place the suspected article at the distance from the sensor expected during actual survey operation.

5. Cycle magnetometer several times and note the readings.

6. Remove the article and repeat steps 2 and 3 to check for diurnal shifts in the earth's field. If a diurnal shift is present, repeat entire test.

7. If the readings obtained in step 5 differ by more than ±1 gamma (± one count) from those obtained in steps 3 and 6, then the article is magnetic.

IF THE ARTICLE IS HIGHLY MAGNETIC, OR IF THE SENSOR IS INSIDE OR NEAR A BUILDING OR VEHICLE, THE PROTON PRECESSION SIGNAL WILL BE LOST, GIVING COMPLETELY ERRATIC READINGS AND LOSS OF ±1 COUNT REPEATABILITY.

The magnetometer should not be operated in areas that are known sources of radio frequency energy, power line noise (transformers), in buildings or near highly magnetic objects. The sensor should always be placed on the staff above the ground, or in the "backpack." The sensor will NOT operate properly when placed directly on the ground.

1.3 SPECIFICATIONS

Sensitivity: ±1 gamma throughout range

Range: 20,000 to 90,000 gammas (worldwide)

Tuning: Multi-position switch with signal amplitude indicator light on display

Gradient Tolerance: Exceeds 800 gammas/feet
Operating Manual  
Model G-826  
Portable Proton Magnetometer

Sampling Rate: Manual push button, one reading each six seconds.

Output: Five digit numeric display with readout directly in gammas.

Power Requirements: Twelve 1.5 volt "D" cell universally available flashlight-type batteries. Charge state or replacement signified by flashing indicator light on display.

Temperature Range: Console and sensor: -40° to +85° C.

Battery pack: 0° to +50° C (limited use to -15° C; lower temperature battery belt operation optional).

Accuracy (Total Field): ±1 gamma through 0° to +50° C temperature range.

Sensor: High signal, noise cancelling, mounted on staff or attached to backpack.

Size:

<table>
<thead>
<tr>
<th></th>
<th>Console: 3.5 x 7 x 11 inches (9 x 18 x 28 cm)</th>
<th>Sensor: 3.5 x 5 inches (9 x 13 cm)</th>
<th>Staff: 1 inch diameter x 8 ft. length (3 cm x 2.5 m)</th>
</tr>
</thead>
</table>

Weight:

<table>
<thead>
<tr>
<th></th>
<th>Lbs</th>
<th>Kgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Console (w/batteries)</td>
<td>5.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Sensor and signal cable</td>
<td>4</td>
<td>1.8</td>
</tr>
<tr>
<td>Aluminum staff</td>
<td>2</td>
<td>0.9</td>
</tr>
</tbody>
</table>


1.4 INVENTORY INSPECTION

When received from the manufacturer, the G-826 magnetometer should include the following items:

1. G-826 magnetometer console 1 each
2. Sensor 1 each
3. Collapsible sensor staff 1 each
4. Signal cable-staff (long) 1 each
5. Signal cable-backpack (short) 1 each
6. Adjustable carrying harness 1 each
7. Batteries: Type D Premium Carbon Zinc with cardboard jacket (12 each within console) 24 each
8. Applications Manual for Portable Magnetometers 1 each
9. Operator's Manual 1 each
10. Storage/carrying case 1 each
2.0 FIELD OPERATION

2.1 INTRODUCTION

The G-826 comes complete and ready for field survey operation. A few simple procedures should be observed to obtain optimum results, and it is recommended that the operator follow each step as outlined to initially become familiar with the various controls and survey considerations.

2.2 TUKN ON PROCEDURE

PRELIMINARY CONSIDERATIONS: BEFORE OPERATING THE G-826, CHECK FOR:

a. Presence of sensor fluid:
   Shake sensor and listen for "sloshing" sound. If it is necessary to add or replace the sensor fluid, remove blue "cap plug" and fill with STRAINED unleaded gasoline to within 1/2 inch of top. (Fluid should be strained several times through paper filters, i.e., paper towels, coffee filters, etc.)

b. Batteries in place and fully charged:
   Remove cover, check battery polarity, and insure that batteries are held firmly in place by retaining straps. (See Figure 2-1) Check battery charge by pressing push button and counting the blinks of the BAT charge indicator light. (See Section 3.2)

THE FOLLOWING STEPS SHOULD BE PERFORMED TO CORRECTLY TUNE AND TURN ON THE MAGNETOMETER

1. Attach signal cable to sensor. There are two cables provided: a long coiled cable for staff use and a shorter cable for use with the "backpack."

2. Attach sensor to staff and assemble sections or place sensor in "backpack" pouch attached to carrying harness.

- 5 -
CONTROL AND INDICATORS

"Blinking" indicator of battery voltage

"Blinking" indicator of signal strength

5-digit readout of earth's magnetic field

Console cover latch

Broad tuning

Pushbutton operation

Battery remaining straps

Protective battery tubes

Test switch

Test (Factory test only)
THE INSTRUMENT IS NOW READY FOR FIELD SURVEY OPERATION.

Note that a true and repeatably correct reading is obtained in three or four tuning positions surrounding the estimated local magnetic fields, i.e., the tuning is quite broad and noncritical in most cases. Better operation is obtained in problem areas or high gradient areas if the instrument is properly tuned initially. Unless high field changes on the order of four or five thousand gammas occur during operation, it will not be necessary to retune.

2.3 SENSOR ORIENTATION

To insure optimum results, the sensor is marked with an arrow and the letter "N." The arrow should be roughly pointed north or south. This procedure will allow the sensor axis to be placed perpendicular to the earth's field and produce optimum signal. However, proper operation will be obtained in fields above 40,000 gammas with the sensor arrow pointed in any direction.

In low magnetic latitudes (where the field dips less than 40° and generally below 40,000 gammas), such as near the magnetic equator where the field is close to horizontal, the sensor should be mounted horizontally (saddlemount) on the staff. In this manner the sensor coils will be properly oriented for maximum signal in all directions.

2.4 SURVEY OPERATION

During survey operation and after the instrument is tuned to the local field intensity (Section 2.2), the operator need only depress the READ button and note the reading in a log. If the reading is in question, (i.e., a sudden shift of several hundred gammas) another reading should be taken.

THE ONE COUNT REPEATABILITY AND SENSITIVITY OF THE G-826 CAN ALWAYS BE VERIFIED BY REPEATING A MEASUREMENT WITH THE SENSOR IN THE EXACT SAME LOCATION.

The G-826 will operate accurately in areas where the magnetic gradient is as high as 800 gammas per foot. The only precaution is that the sensor be held very still. With the sensor mounted on the staff, surveys with ±1 gamma sensitivity and repeatability are easily achieved.
Operating Manual
Model G-826
Portable Proton Magnetometer

The sensor may also be mounted in the backpack for surveys requiring lower mapping accuracy and rapid operation through rugged terrain. Because of the magnetic properties of most "D" cell batteries, however, only the cardboard or plastic jacketed batteries should be used in the console for this application (See Section 3.1).

2.5 LOW TEMPERATURE OPERATION

At temperatures below 0°C, battery life decreases rapidly to only a hundred readings per set of batteries at -20°C. At these lower temperatures, an optional Battery Belt (P/N 16069) should be used, or the console may be held close to the operator's person - under warm clothing.

2.6 READOUT FILAMENT TEST

Occasionally, it is advisable to check the numeric readout display to guard against an erroneous reading due to a nonilluminating filament(s). Simply depress and hold down the READ button until all number 8's appear (88888) - check each segment. If any segments are missing, notify GeoMetrics for repairs.

2.7 INSTRUMENT STORAGE

After use, all of the components should be stored in the shipping container to prevent damage, loss of components, or possible contact with magnetic particles that could be imbedded in the sensor. The sensor signal cable must be DISCONNECTED from the console to prevent constant battery drainage. If long term storage is anticipated, the batteries should be removed from the console to prevent any damage from electrolytic leakage or corrosion of contacts. After long storage, always inspect the batteries.

2.8 POSSIBLE SURVEY DIFFICULTIES

The following is a list of possible survey difficulties, probable causes, and recommended corrective action.
Operating Manual
Model G-826
Portable Proton Magnetometer

<table>
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<tr>
<th>Survey Difficulty</th>
<th>Probable Cause</th>
<th>Corrective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>No reading on display</td>
<td>1. Poor battery contact</td>
<td>1. Check for loose batteries and retainer straps</td>
</tr>
<tr>
<td></td>
<td>2. Dead batteries</td>
<td>2. Replace batteries</td>
</tr>
<tr>
<td></td>
<td>3. Test switch in &quot;test&quot; position</td>
<td>3. Flip switch to &quot;run&quot; position as shown in Figure 2-1</td>
</tr>
<tr>
<td></td>
<td>4. Readout display board unplugged</td>
<td>4. Check readout display board for tight fit in socket</td>
</tr>
<tr>
<td>Console will not tune</td>
<td>1. Loose tuning knob</td>
<td>1. Tighten set screw</td>
</tr>
<tr>
<td></td>
<td>2. Broken wire between tuning switch and circuit board</td>
<td>2. Resolder wire</td>
</tr>
<tr>
<td></td>
<td>3. High noise area</td>
<td>3. Move to different location</td>
</tr>
<tr>
<td>Partial numeric blackout</td>
<td>Segments not illuminating</td>
<td>Depress READ button and hold down until all number 8's appear — check each segment, if any segments are missing, notify and return the readout board (P/N 16026) to geoMetrics immediately.</td>
</tr>
<tr>
<td>Slow blinking BAT light</td>
<td>Low battery voltage</td>
<td>Replace batteries</td>
</tr>
</tbody>
</table>
## Survey Difficulty

<table>
<thead>
<tr>
<th>Probable Cause</th>
<th>Corrective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erratic readout</td>
<td>1. Move sensor away from generators, power lines, buildings, highways, etc.</td>
</tr>
<tr>
<td>2. Highly magnetic environment</td>
<td>2. Check for magnetic articles (hats, knives, belts, eye glass straps, pencils, etc.) that are close to or imbedded in sensor (steel chips, magnetic dirt, etc.). Do not make readings inside buildings. (See Section 1.2)</td>
</tr>
<tr>
<td>3. No fluid in sensor</td>
<td>3. Shake sensor and listen for fluid. Fill as required. (See Section 2.2)</td>
</tr>
<tr>
<td>4. Sensor not connected or signal cable is broken</td>
<td>4. Check Bendix connector and sensor signal cable for damage. Use another signal cable to check console operation.</td>
</tr>
<tr>
<td>5. No polarize power</td>
<td>5. Weak or &quot;dead&quot; batteries - replace.</td>
</tr>
<tr>
<td>6. Intermittent battery contact</td>
<td>6. Check battery contacts for corrosion and tighten retaining straps.</td>
</tr>
<tr>
<td>7. Sensor not properly oriented</td>
<td>7. Point sensor arrow to north or south. (See Section 2.3)</td>
</tr>
<tr>
<td>8. Some segment(s) in display not lighting</td>
<td>8. Depress READ button, hold down, and check segment(s).</td>
</tr>
<tr>
<td>9. Diurnal shift or magnetic storm</td>
<td>9. Wait for several hours — repeat readings when field is stable.</td>
</tr>
</tbody>
</table>
### Survey Difficulty

<table>
<thead>
<tr>
<th>All 8's appear on readout</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Probable Cause</th>
<th>Corrective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Poor battery contact</td>
<td>1. Check that every battery is correctly positioned.</td>
</tr>
<tr>
<td>2. Bad battery</td>
<td>2. Check each battery for optimum charge.</td>
</tr>
</tbody>
</table>
APPENDIX A

HIGH SENSITIVITY FEATURE (0.25 gamma)

INTRODUCTION

When the magnetometer portion of the G-826 is optionally equipped with 0.25 gamma sensitivity, a special internal slide switch is utilized to allow operation in either the 1.0 gamma or 0.25 gamma mode. Refer to Figure 2-1, Page 6 in the Portable Proton Magnetometer manual immediately following this appendix for the location of this internal slide switch on the circuit board. A special access hole is provided on the aluminum circuitry shield for convenience. To change the position of this switch, unsnap and remove the outer green instrument cover, flip the "Test/Run" slide switch, to the desired position, and replace the cover. It is only necessary to change the internal "Test/Run" slide switch when the magnetometer's sensitivity is to be changed.

For 1.0 gamma sensitivity, the "Test/Run" slide switch should be set to the "2" position. For 0.25 gamma sensitivity, set the "Test/Run" slide switch to the "1" position. In some models, the sensitivity positions of the slide switch are marked on the aluminum circuitry shield.

NOTE: The cables (for portable operation) marked "18v. Pol." should be used only with the .25 gamma unit.

READOUT DISPLAY

In the 0.25 gamma mode, the magnetometer readout display does not include the Most Significant Digit* (extreme left-hand number), but does indicate the Least Significant Digit* (extreme right-hand number) to reflect 0.25 gamma changes within the earth's field. As such, the displayed 0.25 gamma measurement is four times higher than an equivalent 1.0 gamma display and must be divided by four (4) whenever the actual total field intensity is desired.

EXAMPLES:

Typical 1.0 gamma display

```
50314
```

Equivalent 0.25 gamma display

```
01256
```

M.S.D.  L.S.D.

* Most Significant Digit: Abbreviated M.S.D.
Least Significant Digit: Abbreviated L.S.D.
3.0 BATTERY REPLACEMENT

3.1 INTRODUCTION

When the magnetometer is used with the sensor mounted on the staff, readily available standard "D" cell batteries will work satisfactorily. The following chart compares the expected number of readings possible for different battery types. Because most standard batteries use a steel jacket, when the sensor is used in the "backpack" only cardboard or plastic jacket batteries should be used. If standard carbon zinc or alkaline batteries (steel jacketed) are used in the console during "backpack" operation, a directional dependent shift of several gammas will occur and will bias the measurement.

The G-826 will still provide one gamma sensitivity, but actual readings will be several gammas higher or lower than the "real" value.

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Brand Name</th>
<th>Readings at 25°C</th>
<th>Readings at 0°C</th>
<th>Jacket Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline</td>
<td>Burgess, Eveready Ray-O-Vac</td>
<td>10,000</td>
<td>8,000</td>
<td>Steel</td>
</tr>
<tr>
<td>Standard Carbon-Zinc (flashlight)</td>
<td>Burgess, Eveready Ray-O-Vac</td>
<td>1,700</td>
<td>1,999</td>
<td>Steel</td>
</tr>
<tr>
<td>Premium Carbon-Zinc</td>
<td>Eveready #1250 *</td>
<td>4,100</td>
<td>3,000</td>
<td>1. Cardboard</td>
</tr>
</tbody>
</table>

* Available from geoMetrics, Inc.
Figure 3-1 is based upon one reading every 30 seconds. Faster sampling rates will yield fewer readings, especially at lower temperatures. Photoflash and "Energizers" are not designed for this type of application, but may be used until proper batteries are available. It should be noted that battery capacity decreases rapidly below 0°C to only a few hundred readings at -20°C. These battery types will recover, however, when warmed above 0°C.

3.2 BATTERY VOLTAGE INDICATOR

Before starting, and occasionally during a survey, the battery voltage indicator lamp (BAT) should be observed with the sensor connected, and the number of blinks counted. Fully charged batteries will cause about ten rapid blinks. As battery voltage decreases, the number of blinks will also gradually decrease until the BAT lamp remains illuminated for approximately three seconds. At this time, the batteries MUST be replaced, as the voltage available is below that required for adequate operation.

When new batteries are installed, the number of (BAT) blinks should be noted. As the battery life decreases, the remaining battery life can easily be estimated.

3.3 BATTERY REPLACEMENT

The following steps should be followed for correct replacement of batteries:

1. Unsnap and remove instrument cover.
2. Loosen battery retaining straps.
3. Replace batteries, See Figure 2-1 for correct polarity. The positive contact has a Teflon tip.
4. Tighten battery retaining straps.
5. Replace instrument cover.
APPENDIX A (Continued)

Because the earth's field intensity can be estimated in the survey area (refer to the total field map on the aluminum circuitry shield or page II of this manual), the operator can easily pre-determine the constant Most Significant Digit by multiplying the estimated field by four (4).

EXAMPLE:

Estimated Earth's Field (1.0 gamma) M.S.D. (4 times higher)
50, --- 200, ---

Therefore, the displayed measurement will normally appear as:

1.0 gamma sensitivity 0.25 gamma sensitivity

As such, any changes in the Least Significant Digit (01256) represent a true 0.25 gamma change in the earth's field intensity.

EXAMPLE:

First Measurement Second Measurement
Divided by four (4) for actual field:

\[ \frac{50,314 \text{ gammas}}{4} = 12,586 \text{ gammas} \]

The following table indicates which Most Significant Digit is constant for a specific field intensity:

<table>
<thead>
<tr>
<th>TOTAL FIELD (gammas)</th>
<th>M.S.D.</th>
<th>DISPLAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000</td>
<td>0</td>
<td>8-------</td>
</tr>
<tr>
<td>30,000</td>
<td>1</td>
<td>2-------</td>
</tr>
<tr>
<td>40,000</td>
<td>1</td>
<td>6-------</td>
</tr>
<tr>
<td>50,000</td>
<td>2</td>
<td>0-------</td>
</tr>
<tr>
<td>60,000</td>
<td>2</td>
<td>4-------</td>
</tr>
<tr>
<td>70,000</td>
<td>2</td>
<td>8-------</td>
</tr>
<tr>
<td>80,000</td>
<td>3</td>
<td>2-------</td>
</tr>
<tr>
<td>90,000</td>
<td>3</td>
<td>6-------</td>
</tr>
<tr>
<td>100,000</td>
<td>4</td>
<td>0-------</td>
</tr>
</tbody>
</table>
### APPENDIX A (continued)

#### DISPLAY CONVERSION CHART

<table>
<thead>
<tr>
<th>0.25 gamma Measurement</th>
<th>Total Field Equivalent (gammas)</th>
<th>0.25 gamma Measurement</th>
<th>Total Field Equivalent (gammas)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M. S. D.</strong></td>
<td><strong>Display</strong></td>
<td><strong>M. S. D.</strong></td>
<td><strong>Display</strong></td>
</tr>
<tr>
<td>0</td>
<td>80000</td>
<td>20,000</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>80800</td>
<td>20,200</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>81600</td>
<td>20,400</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>82400</td>
<td>20,600</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>83200</td>
<td>20,800</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>20000</td>
<td>20,000</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>20800</td>
<td>30,200</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>21600</td>
<td>30,400</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>22400</td>
<td>30,600</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>23200</td>
<td>30,800</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>60000</td>
<td>40,000</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>60800</td>
<td>40,200</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>61600</td>
<td>40,400</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>62400</td>
<td>40,600</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>62200</td>
<td>40,800</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>00000</td>
<td>50,000</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>00800</td>
<td>50,200</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>01600</td>
<td>50,400</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>02400</td>
<td>50,600</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>03200</td>
<td>50,800</td>
<td>3</td>
</tr>
</tbody>
</table>

The above is provided for quick reference in converting the displayed 0.25 gamma measurement to the actual total field.

314
The Soiltest ER-2 Electrical Resistivity Meter is widely used by engineers, architects, testing organizations, government agencies, contractors, public utility companies, real estate developers and others concerned with the character, makeup, depth and thickness of the strata underlying the earth's surface. Water supply investigations, bedrock depth determinations, sand and aggregate deposit locations and mineral prospecting are just a few of the specific uses for this instrument.

Battery operated, this lightweight instrument is completely portable and is easy to use. Two men can easily cover a few hours an area that would take a drill rig and crew several days. The instrument and standard equipment may be used with any of the standard resistivity electrode spreads which are described in this manual.

OPERATION MANUAL FOR THE SOILTEST ER-2 ELECTRICAL RESISTIVITY METER

I. DESCRIPTION OF ER-2

A. Standard Equipment

Figure 2 shows the standard equipment supplied with the ER-2 Electrical Resistivity Meter:
1. ER-2 Electrical Resistivity Meter
2. Five copper-clad steel electrodes
3. Pre-assembled cable
4. Lee electrode cable
5. Barnes resistivity nomograph (not shown)

The pre-assembled cable has been especially prepared and measured for use with an electrode separation of 20 feet. The correct electrode spacing may be obtained from the points where the individual wires leave the main cable.

B. Optional Equipment

The following equipment is available at extra cost, and provides additional flexibility to the ER-2 system:
1. Pre-assembled cables are available for 50, 100, and 200 feet electrode separation. Cables can also be supplied for 10, 20, and 30 meters electrode separation.
2. Spare sets of batteries for the ER-2 are available from Soiltest, Inc. The ER-2 has been designed to use batteries readily available in most areas.
3. Hardwood cable reels are available from Soiltest, Inc. These are used to store the cables between usage.

C. Description of the ER-2

The ER-2 Electrical Resistivity Meter is designed to provide a direct measurement of the quantity, \( z = (V/I) \), where \( I \) is the current which flows between the two outer electrodes and \( V \) is the potential produced across the two inner electrodes. The measurement is accomplished with high precision.

The current which flows through the ground is reversed direct current, reversed at a rate of approximately 20 cycles per second. This relatively low rate of reversal greatly reduces problems of skin effect and electromagnetic coupling between wires which exist with instruments using vibrators and higher frequencies.
The ER-2 is completely transistorized. There are no moving parts such as commutators or vibrators or relays, and therefore the current waveform is almost completely free from switching transient, due to sparking or arcing or contact bounce.

The ER-2 includes an automatic current limiter to protect the batteries against accidental overload. The measured reading is obtained from a very precise potentiometer with a linearity of 0.1%.

D. Panel Controls

1. Read Switch
   Depress this switch to place the ER-2 immediately into full operating condition.

2. Test Switch
   Depress this switch and the Read Switch to test for proper internal operation of the ER-2. Further instructions are given in Section III.

3. Dial Multiplier Switch
   This switch provides a multiplying factor for the dial readings. For greater accuracy, all readings should be taken with the highest possible setting on the Dial Multiplier Switch, preferably 0.01.

4. Meter
   A correct reading is obtained by adjusting the pointer of this meter to the center mark (null position).

5. Indicator Light
   This light will usually flicker rapidly on and off during field operation of the ER-2. However, as the current drawn by the current electrodes approaches the upper limit of 20 milliamperes established by the automatic current limiter, the indicator light will go out. This does not indicate malfunction. Battery tests utilizing the neon indicator should be made in the test position only. Symptoms indicating the need for battery replacement are described in Section III.

6. Reading Dial
   To obtain a reading, the knob on the Reading Dial (and the Dial Multiplier switch, if necessary) must be adjusted to bring the meter pointer to zero. The reading appears directly on the Reading Dial. The reading is in units of ohms, and is equal to \(2\pi(V/I)\). When multiplied by the electrode separation in feet (or meters), the product is equal to apparent resistivity in ohm-feet (or ohm-meters).

7. Cable Input Socket
   The cable from the electrodes is plugged into this socket. Both socket and plug are polarized so that an incorrect connection is impossible. For reference, the connections are as follows:

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Socket Terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(_1)</td>
<td>A</td>
</tr>
<tr>
<td>P(_1)</td>
<td>B</td>
</tr>
<tr>
<td>P(_2)</td>
<td>C</td>
</tr>
<tr>
<td>C(_2)</td>
<td>D</td>
</tr>
</tbody>
</table>

8. Electrode Selector Switch
   This switch provides three positions labelled Lee Left, Normal and Lee Right. In the Normal position, the ER-2 can use any of the standard four-electrode systems.
   In the Lee Left position, the potential which is being measured is between \(P_6\) and \(P_1\) in Figure 3. In the Lee Right position the potential which is being measured is between \(P_6\) and \(P_2\) in Figure 3. The purpose of the Lee
electrode system is described in Section II-F, and in
greater detail in the Reference Manual which accom-
panies each unit.

9. Input Plug for Center Electrode
In using the Lee electrode system, a fifth electrode is
placed at the center of the normal four-electrode ar-
rangement. This is the electrode identified as P5 in
Figure 3. A special input plug is provided for connecting
this electrode to the ER-2. The other four electrodes
are connected in the normal fashion to input plug 7 in
Figure 1.

10. Add-To-Dial Switch
The Add-to-Dial Switch provides an increased upper
limit for the readings which can be obtained.
The largest value which can be measured on the ER-2
dial (6 in Figure 1) is 1000 units. By means of the
Add-to-Dial Switch, this upper limit is increased to
4000 units.

THE CORRECT READING ON THE ER-2 IS OB-
TAINED BY ADDITION. THE DIAL READING (6
in Figure 1) MUST BE ADDED TO THE SETTING
OF THE ADD-TO-DIAL SWITCH. For example, if
the dial reading is 999 and the Add-to-Dial Switch is
set at 2, the correct reading is 2999.

THE PRECEDING STATEMENTS ARE INDE-
PENDENT OF THE SETTING OF THE DIAL
MULTIPLIER. For example, if the Dial Multiplier (3
in Figure 1) reads 0.01, the above reading of 2999 must
be multiplied by 0.01 to yield 29.99. Do not multiply
only the dial reading of 999 by the Dial Multiplier
factor.

The Add-to-Dial Switch will be of value under two
types of conditions:

a. At Small Electrode Spacings.
For electrode spacings of 3, 5, or occasionally 10
feet or less (1 to 3 meters), very high readings are
to be expected on the ER-2 dial. These readings
may exceed the available 1,000 dial divisions. By
use of the Add-to-Dial Switch, readings up to
4,000 dial divisions can be measured.

b. For high resistivity soil conditions.
When the near-surface material is dry, or frozen,
the expected resistivity will be high. This will
cause the ER-2 readings to be high also. The
effect will be most severe for the smaller electrode
spacings.

II. FIELD PROCEDURES
A. Preliminary Layout
Figure 3 shows the arrangement* of the electrodes and how
they are connected through the cable to the ER-2 Electrical
Resistivity Meter. The cable may be laid along the ground
surface in any convenient way.
As shown in Figure 3, the electrodes are inserted into
the soil at equally spaced intervals along a straight line. The
distance between adjacent electrodes will be referred to as “A”.
A typical value is A = 20 feet. The total spread length equals
3A.
The electrode separation should be measured to an accu-

*The ER-2 Earth Resistivity Meter is recommended for use with the
Wenner arrangement for electrodes.
racy within 2%. This means that measurements for \( A = 20 \) feet must be accurate within one-half foot, and for \( A = 50 \) feet within one foot.

When the ER-2 is used for a horizontal resistivity profiling, (described in the Reference Manual), the distance measurements are simplified by use of the special cables supplied with the ER-2. The distance between take-off points along the cable has been accurately measured to yield the required separation. The standard cable supplied with the instrument is for \( A = 20 \) feet.

B. How to Take a Reading

1. Place the electrodes in position and connect them to the cable.
2. Connect the plug at the end of the cable to the Cable Input Socket on the ER-2. Attach the plug firmly, but do not tighten excessively or it may be difficult to remove.

It is absolutely essential that the cable plug and socket be kept dry. If moisture gets into either one, cease field work until corrected. See Section III.

3. Depress the Read Switch and hold it down.
4. Adjust the Reading Dial and the Dial Multiplier Switch to obtain a zero reading on the Meter.

If the Meter deflects to the left, rotate the Reading Dial knob clockwise (toward larger numbers). If the meter deflects to the right, rotate the Reading Dial knob counterclockwise (toward smaller numbers).

Use the 0.01 or 0.1 position if possible, preferably the 0.01 position.

If the reading is not completely steady, take an average reading over a few seconds. If the reading tends to drift with time, take an average reading over the first few seconds.

5. Record the dial reading and the Dial Multiplier Switch setting.
6. Convert the reading to apparent resistivity. To accomplish this, multiply the dial reading by the Dial Multiplied Switch setting and by the electrode separation in feet.

For example, a 246 dial reading on the 0.1 Dial Multiplier at a 20-foot electrode separation yields an apparent resistivity of \((246) (0.1) (20) = 492 \text{ ohm-feet} \).

Apparent resistivity is discussed further in the Reference Manual.

C. How to Insert Electrodes into the Earth

The best contact will be made by inserting each electrode at least several inches into firm moist soil. In many areas, this can be accomplished without difficulty. Deeper penetration to 12-18 inches is desirable but not always necessary.

If moist soil underlies turf, humus, frozen ground, or dry soil, each electrode should be pushed through into the underlying soil. In cases of extreme dryness, it may be necessary to pour water around each electrode in order to make good electrical contact. Sometimes it is sufficient to pour water around the two current (outer) electrodes, \( C_1 \) and \( C_2 \).

If the thickness of frozen ground is so great that the electrodes cannot be conveniently driven through into unfrozen soil, then it may be necessary to try to work along the surface of the ground.

If the ground is hard, a small hammer may be used to drive in the electrodes.

High electrode contact resistance can result from poor electrode placement and can cause incorrect readings. This is most likely to occur in very dry or frozen ground. An indication of poor electrode placement is low sensitivity in setting the null meter, or erratic drift of the null reading. The remedy is to drive the electrodes deeper into moist or unfrozen soil, using longer electrodes if necessary, or to pour water around each electrode until greater sensitivity is obtained.

A further discussion of electrode placement is given in the Reference Manual.

D. How to Select the Best Electrode Spacing

The choice of electrode spacing, \( A \), depends upon the desired depth of investigation. Larger depths of investigation require larger electrode spacings.
No exact relationship can be given between electrode spacing and depth of investigation. We suggest the following rough criteria: For profiling, choose the electrode separation, A, equal to twice the maximum depth to which reliable detection is required. For sounding, take readings out to a maximum electrode spacing equal to 3-5 times the maximum depth of interest.

Please consult the Reference Manual for further information on proper electrode spacing.

E. How to Handle the Cables during Field Work

Very rapid profiling surveys can be carried out if enough unskilled helpers are available to assign one person to each electrode. This is particularly true for the larger electrode separations. The instrument operator can easily handle one of the four electrodes, so that three helpers is an optimum number.

In this arrangement, the instrument may be operated at either the front or the rear of the spread as it progresses along the line of readings. If operated at the rear, the person handling the lead electrode can be given the responsibility of selecting the correct location for each reading.

If fewer persons are available, each person must handle more than one electrode. For an electrode separation of 20 feet, fairly rapid progress can be made with the instrument operator plus one helper.

F. Use of the Lee Electrode System

The use of the Lee electrode system is described in the Reference Manual. Its chief value is to distinguish resistivity changes with depth from resistivity variations in a horizontal direction. In the usual four-electrode system, it is sometimes difficult to decide whether the observed changes in the ER-2 readings are produced by the one or the other.

In addition to its primary value for resistivity depth sounding (as described in the Reference Manual), the Lee electrode system may also be used to advantage in resistivity profiling (described in the Reference Manual) where it provides more detailed information.

To use the Lee electrode system, the normal field procedure is modified as follows:

1. Insert a fifth electrode at the center of the electrode spread (shown as $P_0$ in Figure 3)
2. Connect this electrode to the red input plug (9 in Figure 1) by the wire supplied.
3. Take the normal reading with the Selector Switch (8 in Figure 1) in Normal position.
4. Take two additional readings without touching the electrodes, one with the Selector Switch in Lee Left position and one with the Selector Switch in Lee Right position.

The significance of these readings is as follows. The basic interpretation is carried out in terms of the Normal reading. The difference (if any) between the readings obtained in the Left and Right positions indicates whether there are no lateral variations in resistivity along the electrode spread. A large difference indicates a large lateral variation; depth determinations under these conditions may be unreliable. A small difference indicates little or no lateral variation; depth determinations under these conditions are more likely to be reliable. A further discussion is given in the Reference Manual.

G. Use of ER-2 with other Electrode Spreads

In addition to the symmetrical, four-electrode spread (Wenner), other arrangements are occasionally used as shown in Figure 4.

The ER-2 may be used equally well for any of these, with only the following changes:

*$The ER-2 Earth Resistivity Meter is recommended for use with the Wenner arrangement for electrodes.
1. The cables must be modified to yield the required electrode placement. Particular care must be taken to assure that the electrodes are connected to the ER-2 in the proper sequence.

2. A sensitivity limitation will be encountered at moderately large electrode separations for those spreads (like the Schlumberger) in which the potential electrodes are very close together.

3. The reading on the ER-2 dial must be multiplied by a different constant for each type of spread in order to obtain the correct value of apparent resistivity, as follows:

<table>
<thead>
<tr>
<th>Spread Type</th>
<th>Multiply ER-2 Reading by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wenner</td>
<td>A</td>
</tr>
<tr>
<td>Lee</td>
<td>2A</td>
</tr>
<tr>
<td>Schlumberger</td>
<td>((n + 1) \frac{nA}{2})</td>
</tr>
<tr>
<td>Three-electrode</td>
<td>((n + 1) nA)</td>
</tr>
<tr>
<td>Dipole</td>
<td>((n + 1) (n + 2) \frac{nA}{2})</td>
</tr>
</tbody>
</table>

III. MAINTENANCE

The ER-2 Electrical Resistivity Meter has been carefully designed and constructed to provide long trouble-free operation. In normal use, the only components which will ever require replacement are the batteries, and these should last for many months. Flashlight-size batteries have been selected to power the ER-2 because they are readily available in most areas throughout the world.

The battery complement consists of:

- 8 C-size flashlight cells
- 1 90-volt cell (Eveready 490, or Burgess V-60).

It is strongly recommended that replacement of the C cells be made with RM-3 mercury cells or alkaline manganese cells because of their superior electrical characteristics. Ordinary zinc-carbon flashlight cells may also be used as a temporary replacement.

To replace the C cells, snap off the retaining bracket. This bracket can be most easily replaced by using a screwdriver to pry it gently for the last \(1/4\)" until it snaps into position.

Most operational difficulties can be traced to poor electrode placement or to broken connections (usually at the clip on the electrode). Both of these should be checked visually when trouble is encountered.

A Test Switch is provided on the ER-2 panel by which to determine whether the difficulty is internal or external. Depressing this switch automatically disconnects the field cable and places an artificial load across the output of the ER-2. To perform this test, depress both the Test Switch and the Read Switch, and take a reading in the usual way. The reading should be within 10% of the following:

<table>
<thead>
<tr>
<th>Dial Multiplier Setting</th>
<th>Dial Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>0.1</td>
<td>95</td>
</tr>
<tr>
<td>0.01</td>
<td>960</td>
</tr>
</tbody>
</table>

If the reading is satisfactory, the difficulty must be in the cable or the electrodes.
This test may also be used to check the condition of the 90-volt battery. Hold the Test and the Read Switches down for 30 seconds. If the Indicator Light fails to remain lighted for the entire time, replace the 90-volt cell.

It is of great importance that no breaks in the cable insulation exist at any point where the wires might come into contact with any part of the earth. This will produce a partial short-circuit and cause erroneous and erratic readings. If the cable is ever damaged in such a way that undetected breaks in the insulation may exist, replace the entire cable.

The cable may be checked with an ohmmeter for broken or shorted conductors according to the following table.

<table>
<thead>
<tr>
<th>Connect One Clamp Lead to Electrode Clamp</th>
<th>Connect Other Clamp Lead to Cable Flag</th>
<th>Should Read Very Low Resistance</th>
<th>Should Read Infinite Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>E</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>P1</td>
<td>B</td>
<td>C</td>
<td>A,C.D</td>
</tr>
<tr>
<td>P2</td>
<td>C</td>
<td>D</td>
<td>A.B.D</td>
</tr>
<tr>
<td>C2</td>
<td>D</td>
<td>A</td>
<td>A.B,C</td>
</tr>
</tbody>
</table>

**TROUBLE-SHOOTING CHART**

**SYMPTOM**

1. Zero setting or meter seems insensitive.

   **CAUSE AND REMEDY**

   A. One or more of the electrodes is not making good electrical contact with the ground.

   The remedy is to push the electrodes deeper, into moist soil if possible. In dry areas, it may be necessary to pour water around the electrodes.

2. The meter cannot be zeroed, but deflects slightly to one side or shows zero for all final settings.

   A. One or more of the electrodes is not connected to the E.R.

   Usually the trouble will be found by visual inspection of the connections of the electrodes. In rare cases, the cable may have a broken conductor.

3. The indicator light does not function correctly.

   a) Comes on briefly and then goes out, or
   b) Flickers abnormally slowly.

   These symptoms indicate trouble only when using the test switch, not during normal field operation.

   **CAUSE AND REMEDY**

   A. All of these are indicative of weak batteries.

   It is usually necessary to replace all of the batteries at once. However, the symptom (a) can usually be traced to failure of the W-Shell cell and symptom (b) to failure of the C cell. Symptoms (a) may be due to either.

4. a) Readings drift badly, or
   b) Readings do not agree satisfactorily, or
   c) Readings differ substantially when cable is changed, or
   d) Inside of cable plug or cable socket is known to have been wet or moist.

   **CAUSE AND REMEDY**

   A. Moisture in the cable plug or cable socket.

   Dry thoroughly with gentle heat if necessary. If trouble is in cable plug only, use a different cable. It is essential that the cable plug and cable socket be kept clean and dry.

   **SPECIFICATION FOR SUBSURFACE TESTING BY ELECTRICAL RESISTIVITY MEASUREMENTS**

   **I. SCOPE**

   The electrical resistivity method constitutes a procedure for obtaining subsurface information from surface measurements. The goal is to determine the structure of the subsurface layers of soil and rock, or the location of water table, or the location of sand or gravel deposits, or the location of fault zones. This method works upon the known fact that electrical resistivity of earth materials will decrease with increasing values of (a) moisture content and/or (b) salinity or free ion content of the connate moisture. The method is capable of yielding the sequence or relative positions with depth of the various subsurface layers, plus an estimate of depths to the layers. An improved estimate of depth can be obtained if calibration readings can be taken at locations with known depth structure.

   **II. APPARATUS SPECIFICATIONS**

   **A. Equipment Required**

   The equipment consists of an electrical resistivity meter, connecting cables, and electrodes. Accessories which are usually needed include measuring tapes, data sheets, and graph paper.

   **B. Electrical Resistivity Meter Specifications**

   1. **General**

      The electrical resistivity meter must provide a measure of the mutual resistance obtained with four electrodes as described in Section III. This quantity will be obtained as the ratio of a voltage (V) to a current (I), V/I. Any of the following methods of measurement are acceptable:

      a. Measure V and I separately.
      b. Measure the ratio V/I directly.
      c. Measure the ratio V/I multiplied by some numerical factor, as for example 2 \pi V/I.
SPECIFICATION

2. Capability Categories
Various categories of decreasing capability will be established as follows:

<table>
<thead>
<tr>
<th>Categories</th>
<th>A.</th>
<th>B.</th>
<th>C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feet</td>
<td>300</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Meters</td>
<td>100</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>

a. The instrument will be certified for investigation to a maximum depth not to exceed

b. The instrument will use direct current; otherwise, it will use a square wave or sine wave with a frequency which does not exceed

Cycles per second

10 50 150

c. The instrument will give readings which are independent of electrode resistance within reasonable limits. Specifically, using the circuit shown in Figure 6, the instrument reading shall not deviate more than 5% from the reading obtained with the standard resistance values, under the following resistance changes:

(1) $R_1$, alone is varied between limits Kilohms

0 to 0.5 1 to 3

10 to 5 3

(2) $R_2$, alone is varied between the limits in (1)

(3) $R_{ad}$ alone is varied between the limits in (1)

(4) $R_{ac}$ alone is varied between the limits in (1)

(5) $R_1$ and $R_{ad}$ are kept equal and varied between the limits in (1)

(6) $R_{pf}$ and $R_{pg}$ are kept equal and varied between the limits in (1)

d. The instrument shall be capable of giving readings up to a maximum V/I value of at least

| Ohms | 1000 | 1000 | 1000 |

e. Using the Wenner electrode configuration, the instrument shall be capable of giving reliable, repeatable, and unambiguous readings, under field conditions and using field cables, of V/I values down to a minimum value no greater than

| Ohms | 0.027 | 0.08 | 0.27 |

f. For use with the Schlumberger electrode configuration, the same test conditions shall permit readings down to a minimum V/I value no greater than

| Ohms | 0.007 | 0.022 | 0.07 |

Figure 6: Circuit for tests of instrument stability under electrode resistance variations

Standard values for test: $R_1 = R_{ad} = R_{pg} = R_{ac} = 2K$ ohms

$R = a$ constant resistance between 0.2 and 1.0 ohms.
C. Cable Specifications
Cables may be selected on the basis of field convenience, subject to the following limitations:
1. Total resistance of the entire cable system shall not exceed a few ohms.
2. For Wenner electrode spacings greater than $A = 100$ feet or 30 meters, no multi-conductor cables shall be used which enclose both current and potential wires, unless shielding is provided for the potential wires.
3. Reels of wire for the current electrodes shall be physically separated, so far as possible, from reels of wire for the potential electrodes.

D. Electrode Specifications
Electrodes will normally be copper-coated steel or equivalent. If direct current is used with no provision for reversing the direction of current flow, however, then non-polarizing electrodes (copper sulfate or equivalent) will be used for the potential electrodes.

III. FIELD METHOD
The field survey should guard against proximity to disturbing metallic features such as metal fences, railroad lines, power lines, buried cables, etc. If possible, no electrode should be closer to such an object than the total distance between the current electrodes. If the survey must be made closer to the object than this, than the electrode spread should be kept perpendicular to the object so as possible.

Any of the standard recognized resistivity field procedures are acceptable including but not limited to:

A. Resistivity Profiling (Horizontal Resistivity Surveying)
In the Wenner electrode configuration (see Figure 7) using fixed electrode spacing, successive readings are taken as the fixed-spacing spread is moved to one location after another. This field procedure is normally used for the detection of lateral resistivity variations: sand or gravel deposits, highs or lows on a buried bedrock surface, fault zones, ore bodies, etc.

FOOTNOTE 1. These figures are based on an assumed minimum apparent resistivity of 100 ohm feet or 30 ohm meters at the maximum electrode spacing; and upon the assumption that depth of investigation $D$ is crudely related to electrode spacing by $A = 2D$ or $L = 3D$; and for the particular $L/MN$ value of 3. (See figure 7.)

Figure 7: Electrode configurations

Recommended electrode spacing would use an A-value (see Figure 7) between 1 and 2 times the expected depth of interest. Recommended intervals between readings would be from A (for detailed investigations) up to 3A (for reconnaissance).

B. Resistivity Sounding (Vertical Resistivity Surveying)
1. Wenner electrode configuration (see Figure 7)
Equal spacing, A, is maintained between adjacent electrodes at all times. The center of the spread is kept in a fixed location, and readings are taken with successively larger A-values. A recommended sequence of readings is: $2, 3, 5, 8, 10, 12, 16, 20, 24, 30, 40, 50, 60, 80, 100, 120, 160, 200, 240, 300, etc.$ The figures may be used for either feet or meters. Where less detailed information is required, the values in parentheses may be omitted.

For use with the Barnes Layer Method or the Moore Cumulative Resistivity method of interpretation, a recommended sequence of A-values would be: 4, 8, 12, 16, 20, 24, 28, etc. feet.

Other combinations of A-values may be acceptable.

For resistivity sounding, the Wenner configuration is particularly susceptible to errors due to undetected lateral variations. A recommended field procedure takes
two resistivity soundings at the same location, oriented at right angles to each other; divergence of one curve from the other reveals lateral variations rather than variations with depth. An alternative recommended field procedure uses the Lee modification of the Wenner configuration (see Figure 7), in which readings are taken at each electrode spacing using $P_1P_2$, $P_1P_6$, and $P_0P_2$.

2. Schlumberger electrode configuration (see Figure 7) The potential electrode spacing, MN, is fixed in position while successive readings are taken for increasing values of the current electrode spacing, L. When limitations on instrument sensitivity prevent further readings, MN is increased to a new fixed position and the sequence continued. Overlap or duplication of one or two L-values must be provided whenever MN is increased. L must be greater than 2.5 (MN) at all times. The same sequence of numbers for L-values is recommended as was suggested for A-values with the Wenner configuration. It is recommended that the first MN value be set at either 2 feet or 1 meter, that the next be 10 feet or 5 meters, etc.

IV. REQUIRED DATA

The following information should be obtained during the course of the field survey:

A. Background Information:
   1. Equipment description, including instrument serial number
   2. Location of survey
   3. Operator's name
   4. Type of electrode configuration (Wenner, Lee, Schlumberger, etc.)
   5. For profiling surveys:
      a. Orientation of the profile line
      b. Electrode spacing
   6. For sounding surveys:
      a. Orientation of the sounding line
      b. Location of center of symmetry of spread

B. Information for Each Station:
   1. Instrument dial reading
   2. Instrument multiplying factor
   3. Computed apparent resistivity
   4. For profiling surveys: location of the center of symmetry of the spread
   5. For sounding surveys: electrode spacing
      a. A-spacing for Wenner surveys
      b. L and MN-spacing for Schlumberger surveys
   6. Comments: stability or precision of the readings, nearby disturbing features such as fences or topographic irregularities, etc.

After completion of the survey, the following methods for presentation of the data are recommended as standard:

C. Resistivity Profiling

Use ordinary rectangular coordinate (Cartesian) graph paper. Graph apparent resistivity in ohm-feet or ohm-meters along the vertical axis. Graph position of the center of symmetry of the spread in feet or meters along the horizontal axis.

D. Resistivity Sounding: Normal Interpretation Procedures

Use double-logarithmic graph paper. Graph apparent resistivity in ohm-feet or ohm-meters along the vertical axis. Graph electrode spacing (A for Wenner, L for Schlumberger) in feet or meters along the horizontal axis.

E. Resistivity Sounding: Barnes Layer Method or Moore Cumulative Resistivity Method

Use ordinary rectangular coordinates (Cartesian) graph paper. Graph apparent resistivity in ohm-feet along the vertical axis. Graph electrode spacing, A, in feet along the horizontal axis.

FOOTNOTE 2. For interpretation by curve matching using the Orellana-Mooney or other standard master curves, a scale of 62.5 mm cycle is required. Certain European graph papers are manufactured to this scale, as for example #551T by Aerni-Leuch, Bern.