L & R INSTRUMENTS

MiniRes Manual

Applies to all MiniRes Units

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Quick Start

Quick Start - Taking a Typical Field Reading

Four electrodes are used for field readings. They are placed along a straight line, usually at uniform intervals. The instrument is placed near the middle of the line. The far two electrodes are used to put electric current into the earth. The middle two electrodes are used to measure the voltage in the earth. The far electrodes are connected to the MiniRes with cables. The cables are connected to the C+ and the C- binding posts on the right side of the MiniRes. The middle two electrodes are connected to the P+ and the P- binding posts on the left side of the MiniRes. Be sure the C+ and P+ cables go to the electrodes on the same side of the MiniRes.

Field operations with cables can be hazardous. Please read the warnings in **Appendix A**

Selection of cables, placement of cables and care of cables is very important to obtaining good field data. Please read **Appendix E** for details about cables and electrodes.

To take a reading of earth resistivity, be sure that people are clear of the cables and electrodes then press the **RED** power button located in the middle of the faceplate. There is no "OFF" switch. The power will remain on for about a half-minute and then automatically turn off. The reading will appear on the digital meter. Record the meter reading, together with the spacing of the electrodes. If the electrodes were spaced at uniform intervals (**a**) along the line, then the apparent earth resistivity is calculated as follows:

$$\mathbf{R}(\text{apparent}) = \mathbf{R}_a = 2 \pi \mathbf{a} \mathbf{R} = 6.283 \mathbf{a} \mathbf{R}$$

where **R** is the resistance read on the MiniRes. If the units of **a** are feet, then the apparent resistivity is in Ohm-Feet. If the units of **a** are in meters, then the apparent reisistivity is in Ohm-Meters.

If the LINE OPEN LED is flashing the instrument does not have sufficient voltage to emit a constant current, the best solution is to reduce the transmitter electrode contact resistance by wetting the ground around them or inserting them deeper. If that fails, the RANGE switch can be moved to the HIGH position. On the *Super* MiniRes this reduces the output current from 10 milliamps to 1 milliamp but increases the available voltage from about 400 to about 730. On the *Standard* MiniRes it reduces the current from 5 to 0.5 milliamps

If the LINE OPEN LED is on steady, it indicates a very high resistance in the transmitter cables or electrodes. Check for a loose connection or broken cable.

THE INTELLIGENT RED "ON" BUTTON - All first generation (Standard) MiniRes units have a red ON button near the middle of the faceplate. When it is pressed the meter turns on for about 45 seconds. If more time is needed, the button can be pressed again and the meter will be on for another 45 seconds. Some users commented that 45 seconds was too long to wait if they were obtaining a solid reading in 25 or even 20 or 15 seconds.

On the second and subsequent generations (Super and ULTRA) MiniResunits the function of the ON button has been redesigned. If it is pressed the meter is on for about 45 seconds as before. However, if you are finished before 45 seconds, press the button again and the unit turns off. If you know you will need more than 45 seconds, press the button twice.

The CRI Circuit (**C**ontact **R**esistance **I**ndicator)

Starting partly through the third generation (ULTRA) MiniRes, the "CRI" circuit was added to the receiver of the MiniRes. It is somewhat analagous to the "LINE OPEN" circuit for the transmitter cables and electrodes. It consists of a two-colored LED located near the P+ and P- binding posts.

When one of the transmitter (current) cables is broken or one of the transmitter electrodes is not making contact with the earth, the "LINE OPEN" LED comes on. When one of the receiver (potential) electrodes or the receiver cables is not in contact with the earth, the red LED comes on. If a little contact is made then the LED turns green. Finally, if good contact is made with the earth the LED goes out.

In quantitative terms:

Red LED	50K Ohms	to	Infinite resistance
Green LED	5K Ohms	to	50K Ohms
LED out	no resistance	to	5K Ohms

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For details on the various field methods, read the next sections of the manual. For details on the care of the MiniRes, read that section of this manual. **Appendix C** has a detailed description of the MiniRes. Examples of resistivity surveys are presented in some of the appendices; for example **Appendix M**.

Uses, Advantages, Disadvantages

Uses, Advantages, Disadvantages

The electrical resistivity technique of geophysical exploration is one of the earliest methods. The Schlumberger brothers in France in the early part of the 20th Century did much of the early development.

The technique has been successfully employed for investigating:

- Groundwater depth
- Lithology favorable for groundwater
- Contamination of groundwater
- Depth to freshwater-saltwater interface
- Location of sinkholes and cavities
- Detection of fractures and dikes
- Thickness of overburden
- Geologic structure
- Archeological sites
- Electrical grounding of large electrical installation
- Electrical grounding of cell phone transmitting towers
- Electrical grounding of wind driven power generator towers

Advantages of the technique are:

- The equipment is light, portable and inexpensive
- Qualitative interpretation of the data is rapid and straightforward
- Field expenses are minimal
- It is flexible and can be used for various purposes and depths of investigation
- It can be used for both soundings and profiling
- Shallow investigations are rapid

Disadvantages of the technique are:

- Deep investigations require long cables and consume much field time
- Interpretation of complex geologic structures is difficult and ambiguous
- Presence of metal pipes, cables, fences and electrical grounds can complicate interpretation.
- Accuracy of depth determination is lower than with seismic techniques

The MiniRes and the GPR-Res also measure induced polarization. This additional information may be collected with only a few additional moments of field time at each observation setup. Since the same field setup is used, the only addition time required to make an IP observation is to press the blue IP switch and record the number. Newer units measure the IP reading at the same time as measuring resistance and there is no need to press an IP button.

Some of the advantages of having the IP data are:

- It can remove some of the ambiguity of interpretation. For example, the IP signal can allow you to distinguish between conductive clay and a conductive brackish saturated sand or gravel.

- It can detect corroding metals, such as an old pipeline or a valuable archeological artifact.
- It can be used to detect several types of mineral deposits.
- It can detect clays and the clays properties.
- See Appendix X note: "disturbed clays"

Field Work

Based on what is known about the site and the object of the resistivity survey, the type of survey and the electrode array are selected. Under most survey objectives, either Wenner profiling or Wenner soundings are used. For locating fractures or nearly vertical dikes, the azimuthal survey or square array survey technique might be considered. For details on types of surveys, see the following section of this manual, *Resistivity Methods*.

Some of the field factors to consider are:

- Read the safety warnings in **Appendix A**.

- Keep the instrument dry. Before working in moist weather, please read the ***Care of the MiniRes*** section of this manual.

- Keep the current (transmitter) cables away from the potential (receiver) cables. See **Appendix E** for more details on cable and electrodes.

- Try to avoid frozen ground. Frozen ground causes electrode installation to be difficult and introduces error into the data. Frozen ground is much more resistant than the same earth that is not frozen. Variations in the depth of the frozen layer and the degree of freezing cause scatter in the field data. **Appendix S** shows the variation of resistivity with the temperature of earth. If the depth of frozen ground is not too great, it is best to have the electrodes penetrate through the frozen zone into the unfrozen earth. A large heavy pry-bar could be helpful in making a hole through a thin frozen surface. Into this hole the electrode can be inserted into the unfrozen earth.

- Avoid severe terrain if possible. Ridges spread out the equipotential lines and make resistivity seem less than its true value. Gullies concentrate equipotential lines and make resistivity seen greater than its true value. **Appendix T** gives several references that deal with this problem.

- Try to avoid tight undergrowth that would be time consuming for working with cables. Keeping cables in good condition is important to obtaining reliable field data. See **Appendix E** for some suggestions on the selection and care of cable.

- Avoid paved areas where installation of electrodes would be very difficult and time consuming. Some surveys have been conducted where concrete pavement exists by drilling a hole through the concrete for each electrode position. Where there is asphalt pavement, surveys have been performed by punching a hole for each electrode position with a pointed heavy pry-bar.

- Try to avoid interfering cultural features such as metal fences, railroad tracts, and electrical grounds. If a tape measure is used to locate the electrode positions, a nonmetallic tape measure is safe. If a metallic tape measure must be used, be sure to real it up before taking resistivity measurements. Be sure to take careful field notes of nearby cultural features that are likely to introduce errors into the interpretation of the survey.

Resistivity Methods

Resistivity methods are numerous, almost too many to count. We will discuss the most common here and present example surveys of some of these methods in appendices of this manual. Most methods can be divided into either “soundings” or “profiles”. Soundings are sometimes referred to as VES; Vertical Electrical Sounding. Profile methods can be simple or more complex, such as the dipole-dipole technique, which can provide both profiling and sounding information.

Azimuthal surveys can be used to locate faults, fractures and dikes. Square Array surveys have been used for fracture studies and especially in archeological surveys. The MiniRes can be used for all of these methods.

Vertical Soundings

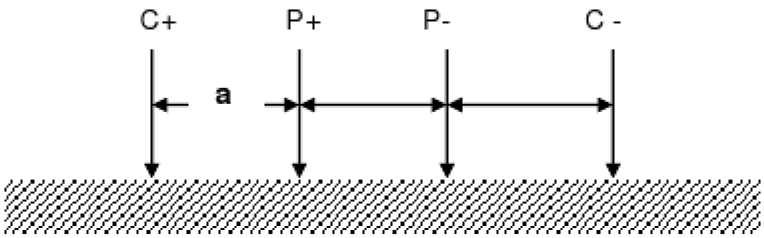
In vertical soundings, a series of field observations are taken, each successive observation has the electrodes at greater separation. The center of each observation remains the same. With the separation small, the apparent earth resistivity of the shallow earth is determined. With the separation greater, the apparent earth resistivity of the shallow and intermediate depth is determined. The resistivity of the intermediate earth can be determined by correcting for the already determined shallow earth resistivity. The electrode separation continues to be increased and the apparent earth resistivity of greater and greater depth is determined.

The two most common methods of electrical soundings are the Wenner method and the Schlumberger method. They will be discussed in the next few pages.

The qualitative interpretation of soundings may be made by examining a plot of apparent resistivity versus electrode separation. Traditionally LOG-LOG graphing is used. Quantitative interpretation has gone through an evolution culminating in computer forward and automated reverse modeling and interpretation. Several commercial programs are available. L and R Instruments has Windows and DOS versions of RESPAC, a computer program for forward modeling, automated reverse modeling and constrained reverse modeling.

Wenner Soundings

WENNER SOUNDINGS: This is the most common method of sounding in the United States and has the greatest signal to noise ratio and is least susceptible to near-surface homogeneities. The four electrodes are in a straight line and are at uniform separation. The separation between adjacent electrodes is designated **"a".**



Wenner Electrode Array

The are usually plotted on a log-log graph. To have a uniform spacing of data points, the following "**a**" spacings are suggested: 1.0, 1.4, 1.9, 2.7, 3.7, 5.0, 7.0, 10, 14, 19, etc.

If the maximum depth of investigation is to be **D**, then observations should be taken with "**a**" spacings from approximately one-fifth **D** to about five times **D**.

In Appendix I there is an example of a field form for collecting Wenner sounding data.

Apparent resistivity, **R**a, is given by the following formula where p is 3.14, **a** is the electrode spacing and **R** is the resistance read on the MiniRes.

$$Ra = 2\ p\ \mathbf{a}\ \mathbf{R} = 6.283\ \mathbf{a}\ \mathbf{R}$$

If the dimensions of **a** are in meters, the apparent resistivity is in Ohm-meters. If the **a** dimensions are in feet, the apparent resistivity is in Ohm-feet.

LEE ARRAY: There is a variation on the Wenner array called the Lee Array. Five electrodes are used with the fifth electrode located at the center of the array. The distance from the center electrode to each of the potential electrodes is **a/2**. Current is applied to the end electrodes as usual. First the potential is observed between one potential electrode and the center electrode and the resistance is measured. Then the resistance is observed between the center electrode and the remaining potential electrode. The resistivity of each half is calculated as:

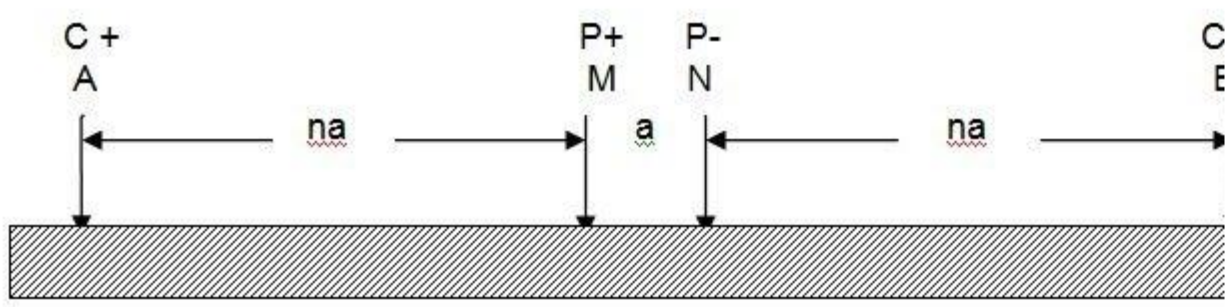
$$\mathbf{R}a = 4\ p\ \mathbf{a}\ \mathbf{R} = 12.57\ \mathbf{a}\ \mathbf{R}$$

The average of the two observations should be identical to the value that would be obtained by the standard Wenner observation. An advantage of the Lee technique is that it allows a check on lateral variability of earth resistance.

OFFSET OR BARKER METHOD This method uses five evenly spaced electrodes. Like the Lee array it yields a good check on lateral inhomogeneities. The method was devised to work with a multiconductor cable and a switching box. The details of the offset array are published by Barker in Geophysical Prospecting, 1981, vol. 29, pp.128-143.

Schlumberger Soundings

SCHLUMBERGER SOUNDINGS: This is the most common method of sounding in Europe and is common in the United States. It saves moving the potential electrodes every time the current electrodes are moved. The electrodes are in a straight line and like the Wenner array, the outer electrodes are the current electrodes and the inner electrodes are the potential electrodes. The potential electrodes, usually designated **M** and **N**, should never be separated by more that one-fifth the separation between the current electrodes. The current electrodes are usually designated **A** and **B**.

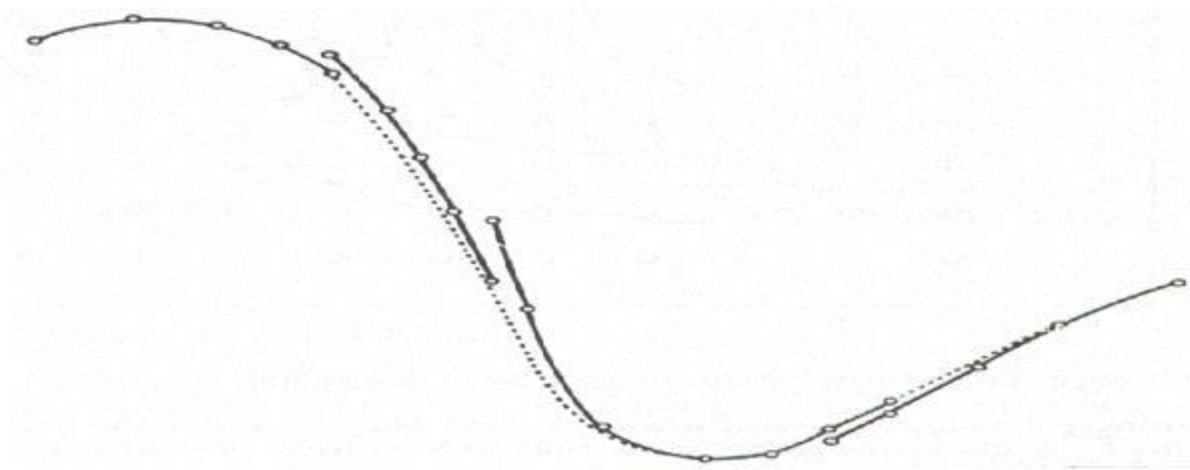


Schlumberger Array

Apparent resistivity is given by the following formula where π is 3.14, **AB** is the distance between the current electrodes, **MN** is the distance between the potential electrodes and **R** is the resistance read on the MiniRes. MN can also be designated **a** and the distance between a current electrode and the nearest potential electrode designated as **na**.

$$R_a = \pi R (AB)(AB)/4(MN) = \pi R a n (n+1)$$

As the current electrodes are expanded farther and farther, the potential difference between the fixed potential electrodes becomes smaller and smaller. Finally the signal to noise ratio becomes noticeably small. Then the potential electrodes are expanded and an observation is made with the current electrodes at the same spacing. Theoretically, the apparent resistivities should be the same. However, they will always differ by at least a small amount. This may be due to lateral inhomogeneities in the earth or to a localized irregularity near one of the potential electrodes. The survey is resumed with the several more observation made with the current electrodes being placed at greater and greater separation. For a single sounding there may be three, four or even five separations used for the potential electrodes. This, in turn, generates three, four or five segments of sounding curve, each with at least a small offset from the adjacent segments.



The field data are traditionally plotted on log-log graph paper. Because of the offset of the segments, some adjusting of the data is necessary. The adjusted data can then be entered into a resistivitiy inversion program.

The Schlumberger array has an advantage over the Wenner array. The potential electrodes are moved less often and therefore there is less fieldwork in collecting the data for a sounding. Despite this timesaving, there are great advantages to the Wenner sounding technique. First, the Wenner array gives the highest signal-to-noise ratio. Second, if there is an inhomogeneity in the vicinity of the inner (potential) electrodes, a whole segment of the apparent resistivitiy curve will have an erroneous offset. With the Wenner method, there would be only one data point having an erroneous offset. If there are numerous surficial inhomogeneities, the Wenner method would show the interpreter this important feature of the survey and the smoothed curve fitted through the Wenner data will reflect a truer value for the subsurface.

In Appendix I there are examples of work sheets for collecting Schlumberger sounding data.

PROFILES

Simple Profiles

SIMPLE PROFILING: The simplest and most common type of profiling is to do a simple Wenner array reading and then move the electrodes forward and take another reading, etc. The apparent resistivities are plotted at the midpoint of each array. The array can be aligned in the direction of profiling or normal to that direction. Surveying with the array aligned in the direction of profiling is faster. If the survey is to locate a soil or geological boundary normal to the profile, then a more distinct anomaly will be obtained if the array is also normal to the profile. This takes more field time but makes the interpretation far easier.

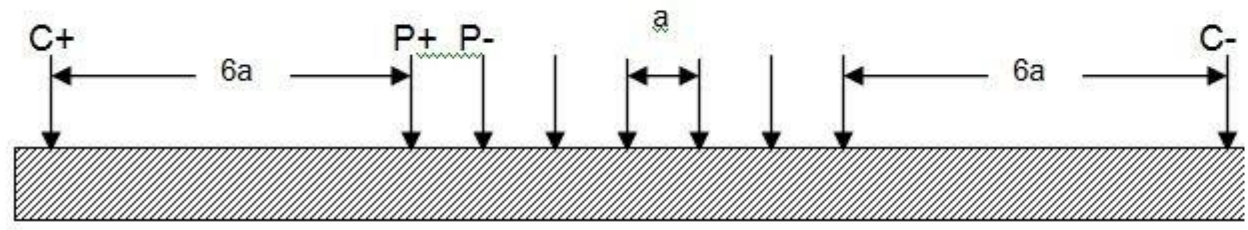
If the Wenner array is used, an "**a**" spacing of about one and one-half to two times the depth of interest should be used. A more precise selection of "**a**" spacing can be made by doing a depth sounding and selecting an "**a**" spacing where the curve indicates a rapid change in apparent resistivity with increasing "**a**" spacing.

If the Wenner spread is aligned in the direction of profiling, a convenient advancement of the spread is three times "**a**". The lead electrode of one observation becomes the trailing electrode of the next observation. For more detail, an advancement of only two times "**a**" or even one "**a**" can be used. For reconnaissance surveying an advancement of more than three times "**a**" can be used.

Appendix M presents a profile surveyed for both resistivity and IP using an "**a**" spacing of one foot.

Fixed Current Electrodes

FIXED CURRENT ELECTRODES: Another type of simple profiling that can be used for obtaining deeper information is with the current electrodes spaced far apart and left in the same position while the potential electrodes are moved in small increments across the middle third of the current electrode spread.



Fixed Current Electrodes

The fixed current electrode method can also be used for "mapping". Instead of a single line of potential observations located between the current electrodes, a grid of observations can be taken and the results contoured. This method of surveying is sometimes referred to as the gradient array.

In Appendix I there are examples of field forms for collecting fixed current electrodes profile data with six potential intervals (as in the above illustration) and also twelve potential intervals. There is also a form for collecting "map" data for a grid of six intervals by five lines.

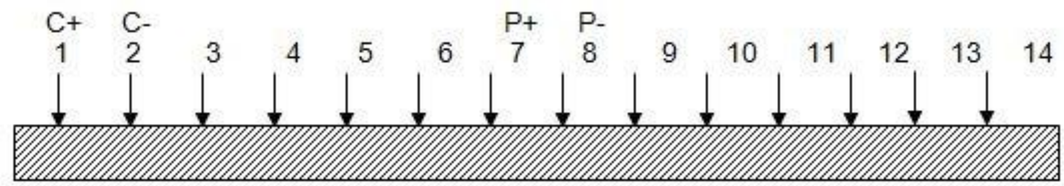
Remember that you can add the first and second interval resistances together to obtain a deeper sounding. And, adding the second and third interval resistances together gives you a deeper sounding, etc.

Adding all six intervals together you then have a Wenner array.

Dipole-Dipole

DIPOLE-DIPOLE PROFILING

This form of profiling does both profiling and sounding at the same time. With appropriate software, a two dimensional cross-section of the earth may be interpreted from the data. Therefore the dipole-dipole method is sometimes referred to as 2-D resistivitiy surveying. The current electrodes are placed at positions 1 and 2 and potential electrodes at positions 3 and 4. A resistivity observation is taken and then the potential electrodes moved to positions 4 and 5, etc. After finishing the profile with the current electrodes in positions 1 and 2, the current electrodes are moved to positions 2 and 3 and the process repeated.



Dipole – Dipole Array

Collection of the data, as well as inputting it to the computer is time consuming. Instrumentation is manufactured that includes cables with arrays of electrodes and a programmable resistivity meter with digital memory. Considerable time can be saved with such instrumentation. However, the cost of the automated instrumentation is about eight times greater than the MiniRes. Appendix I has examples of field forms for collecting dipole-dipole data. L and R Instruments can assist you in obtaining software for the inversion of dipole-dipole data

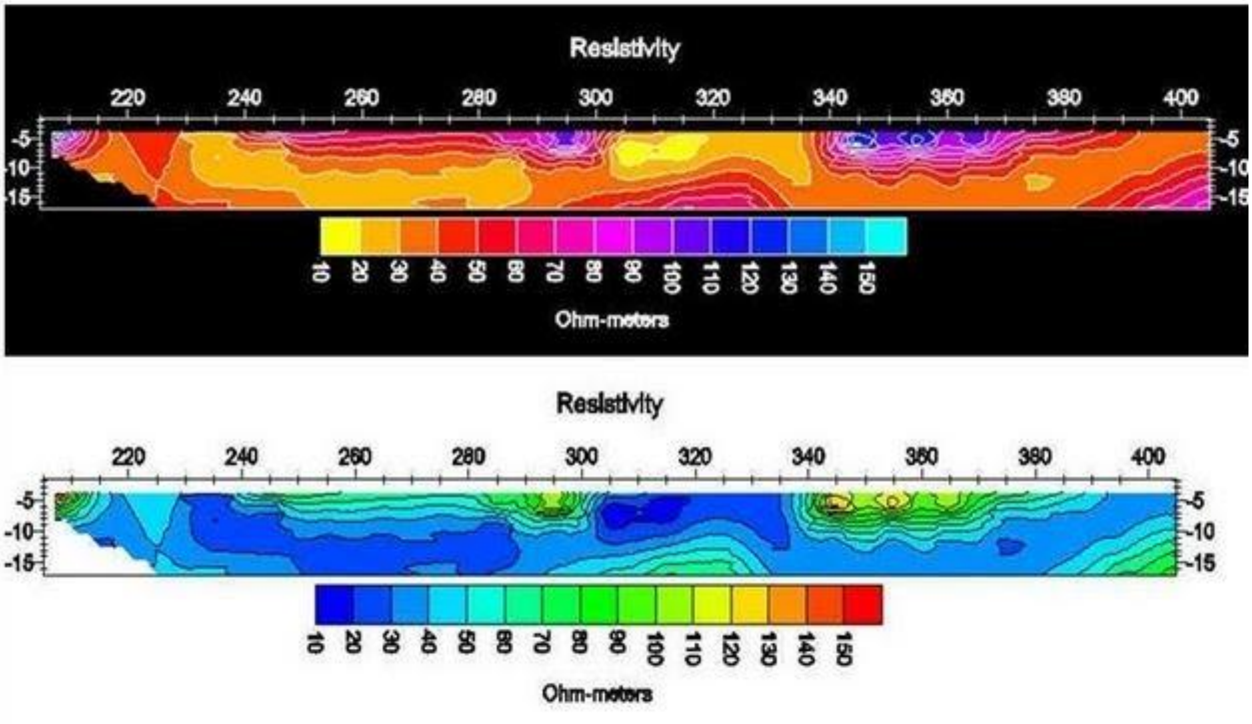
Apparent resistivity is

$$\mathbf{R}_a = \pi \mathbf{R}\, \mathbf{a}\, \mathbf{n} (\mathbf{n}+1)(\mathbf{n}+2)$$

Where **R** is the resistance measured by the MiniRes, **a** is the distance between adjacent electrode positions, and **n** is the number of internals between the nearest current electrode to its nearest potential electrode (**C-** and **P+** in the example above). In the above figure **C+** and **C-** are at electrode positions 1 and 2. The potential electrodes, **P+** and **P-** are at positions 7 and 8. There are 5 intervals between the nearest current and nearest potential electrodes. In this case, the apparent resistivity becomes:

$$\mathbf{R}_a = \pi \mathbf{R}\, \mathbf{a}\, 5\,(5+1)(5+2) = 210\ \pi \mathbf{R}\, \mathbf{a}$$

Following is a profile taken with MiniRes serial number 107:



Dipole-Dipole survey near San Antonio, Texas

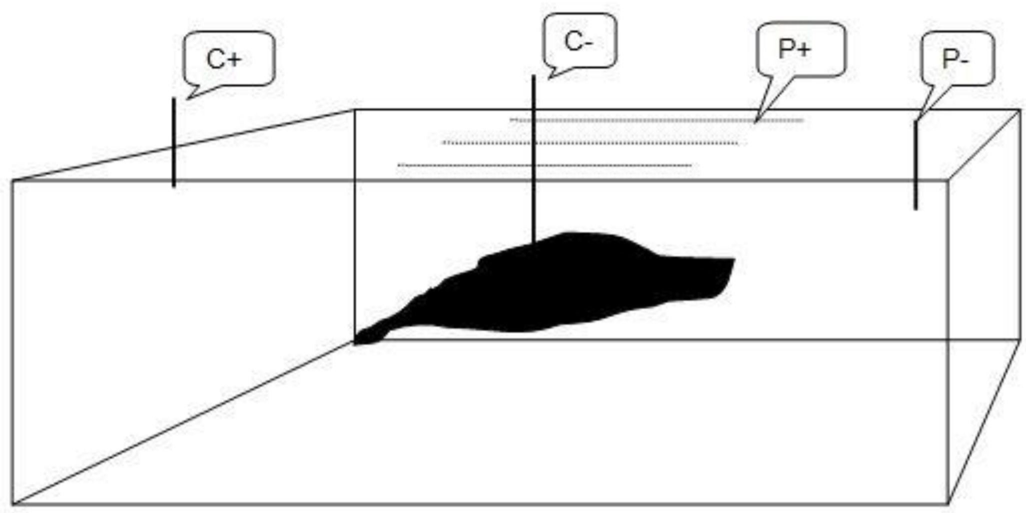
Super MiniRes serial number 107, 10 milliamps

Mise-a-la-Masse

The Mise-a-la-Masse method of surveying is used for examining highly conductive subsurface bodies and the area around them. The continuity, extent, dip and strike of the body can be determined with greater ease if the current is injected directly into the conductive body than by the other resistivity mapping methods. If the body does not extend to the surface, the connection could be made through a drill hole.

One current electrode (C-) is connected to the conductive body and the other current electrode (C+) is placed at a considerable distance. One potential electrode (P-) is located in line with the two current connections and at considerable distance on the opposite side of the conductive body. The survey is then conducted with only one potential electrode (P+) being moved over a square grid of measuring points. The readings from the instrument and the potential electrode (P+) coordinates are recorded. A contour map is then generated from these data.

The distance of the far current electrode (C+) from the potential electrode grid (P+) should be at least 2 or 3 times the maximum dimension of the grid. The same is true for the distance between the grid and the stationary potential electrode (P-).



Appendix P gives an example of a Mise-a-la-Masse survey over a steel pipe.

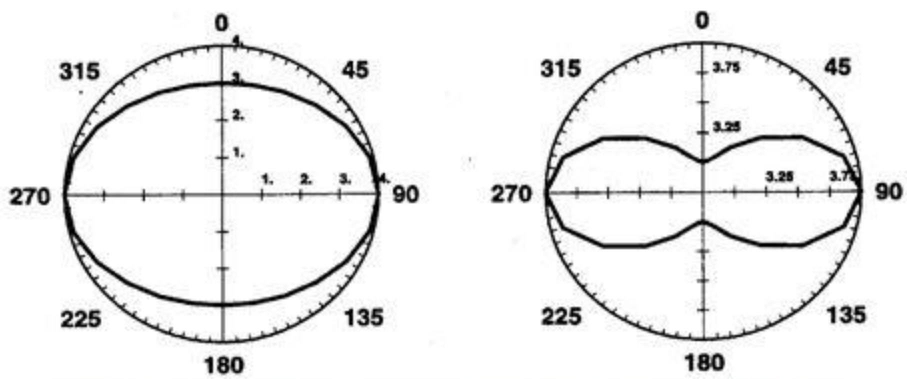
Beasley, CW and S.W. Ward, 1986, Three dimensional mise-a-la-masse modeling applied to mapping fracture zones, *Geophysics*, vol. 51, pp.98-111

Azimuthal Surveys

Azimuthal Surveys

Azimuthal resistivity surveys are performed to determine the direction of joints or fractures in rock or the direction of anisotropy in soils or rock. Often the Wenner array is used. These surveys are conducted using the same array spacing (“a” spacing) and with the center of the spread on the same position. Each successive spread is oriented in a different direction or azimuth until 170 degrees or 165 degrees are covered in increments of 10 or 15 degrees respectively. A full 360 degrees need not be surveyed at the setup for 0 degrees gives the same result as for 180 degrees and 10 degrees the same result as 190 degrees, etc.

The data are plotted in a polar diagram or “rosette”. If there is no anisotropy, the apparent resistivity will plot as a circle. If the apparent resistivity senses anisotropy, it will plot as an ellipse. The radial coordinate of the polar diagram need not start at zero. If it starts at a little less than the minimum apparent resistivity, the diagram will emphasize the irregularity with azimuth.



(From J. P. Busby, 2000, *Geophysical Prospecting*, Vol. 48, page 680; see Appendix Z)

Rock joints are often filled with decomposed rock, clay or conductive fluid. If the rock joints are more conductive than the unfractured rock, then the resistivity lines parallel to the joints should have less resistivity.

Before conducting an azimuthal survey, a resistivity sounding should be conducted to determine the optimum electrode spacing for the survey. If the spread is too short, it will not sense the fractures.

Appendix Z contains some references that might assist in interpretation of azimuthal surveys and also some containing examples of these surveys.

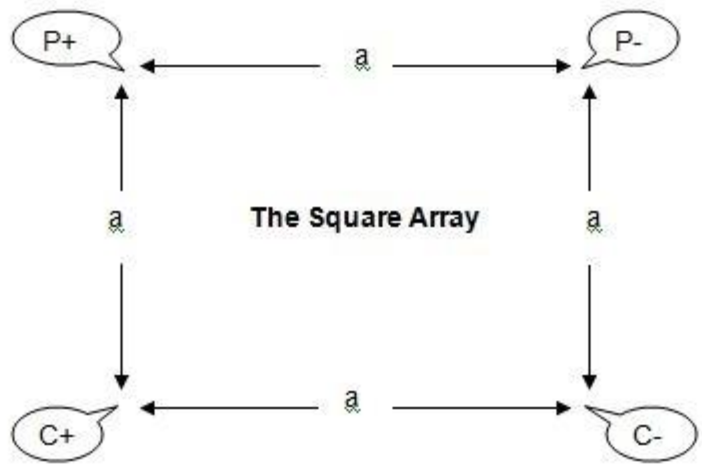
Square Array Surveys

The Square Array

Resistivity surveys have been performed using a square array of electrodes. The square array has been used for shallow environmental surveys, for assessment of joint orientation, and especially for archeological surveys. Appendix Y contains several references for the square array. A common "a" spacing is one meter for archeological surveys. The apparent resistivity is plotted at the center of the array.

Apparent resistivity is

$$R_a = \pi R a (2 + \sqrt{2}) = 10.73 R a$$



The square array is very sensitive to anisotropy. If the anisotropy of the site is to be evaluated, each observation can be repeated with the array rotated 90 degrees. The transverse anisotropy is the ratio of the two ororthogonal apparent resistivities at each site. Another method of plotting the anisotropy would be to plot:

$$\mathbf{A} = (\mathbf{R}_a 1 - \mathbf{R}_a 2)/(\mathbf{R}_a 1 + \mathbf{R}_a 2)$$

The square array can be used for determining the orientation of fractures and other linear features. See F. Boadu, Sept 2005 *Geophysics*.

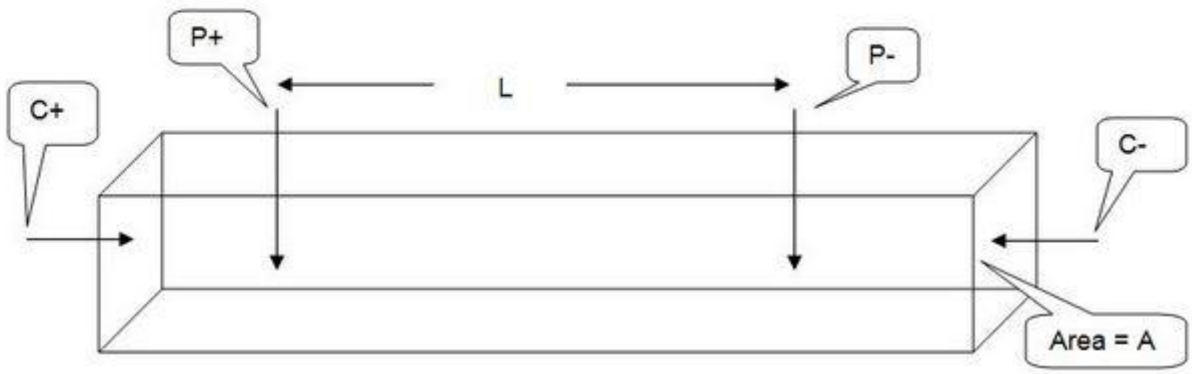
Lab Measurements

Lab Measurements

Resistivity of soil samples can be measured in the lab. The values determined will be only an approximation of the true in-situ values. The lab samples will be disturbed, will not be compacted to the exact same extent as in the field, will not have the same moisture content and will not be at the same temperature.

A sample box is used that contains contacts for the current and potential cables. The geometry of the box and positions of the electrodes will determine the factor that must be used to convert the meter reading to the resistivity value.

For a sample of uniform cross section A and distance between potential electrodes L the resistivity of the sample is given by $\rho = AR/L$ where R is the value read from the meter.



A box may be constructed with opposite ends of stainless steel and the long sides and bottom of non-conducting material such as Lucite or Nylon plastic. The stainless ends should have connectors to the current cables (C+ and C-). Small stainless pins can be used for the potential electrodes (P+ and P-). The sample should be compacted to approximately the same density as the soil in-situ. Moisture content should be as close to field moisture as possible. The easiest way is to preserve original moisture by transporting and storing the soil sample in a plastic bag.

Typical internal dimensions of the box may be 18 inches long, 4 inches wide and 4 inches high. L may be 12 inches. Resistivity in Ohm-feet would then be r = .333 x .333 R. This can be multiplied by 02.54 to convert the result to Ohm-centimeters, the unit most commonly used by engineers in the United States.

Typical internal dimensions of the box may be 18 inches long, 4 inches wide and 4 inches high. L may be 12 inches. Resistivity in Ohm-feet would then be ρ = .333 x .333 R. This can be multiplied by 30.48 to convert the result to Ohm-centimeters, the unit most commonly used by engineers in the United States

If the sample has very high resistivity and the MiniRes indicates an excess of voltage, the “L” dimension should be reduced to six inches or even 3 inches. The calculated resistivity would then be multiplied by 2 or 4, respectively.

If a box with stainless steel ends is not available, you might try several pins or nails at each of the two ends of the box. Connect the pins together at each end of the box for current “electrodes”

Following is a photo of a “soil box”.

Induced Polarization

Induced Polarization Methods

Types of IP Measurements

There are three basic methods of measuring induced polarization:

- The overvoltage method (Time Domain IP)
- The frequency domain method (Frequency Domain IP)
- The phase shift method (Phase Domain IP)

These methods are described in Appendix D. The MiniRes uses the phase shift method. This method requires the minimum of power and, by thoughtful design, the minimum of instrumentation. It is the newest of the three methods.

With the phase shift method, an alternating current is injected into the ground through the current electrodes. If there is no induced polarization, the signal received at the potential electrodes is in perfect phase with the injected signal. However, the more induced polarization in the earth, the more the received signal is out of phase with the injected signal.

The early MiniRes (serial numbers 1 through 32) inject a 30 Hertz current. More recent MiniRes (serial numbers above 100) inject a 5 Hertz current. As an option, the Ultra MiniRes is available with 2.5 Hertz injected signal.

IP Data Acquisition

Much more attention to detail is required for acquiring high accuracy IP data than is required for simple resistivity data. It is recommended that high quality cables be used. Leaky cables on moist ground will ruin the data. It is also recommended that spools of cable NOT be used. Cable segments should go straight from the MiniRes to the associated electrode. A spool of cable will have a tendency to introduce an unpredictable and varying phase response. If the "cable spread" is moved along a line then every effort should be made to keep the cable layout as identical as possible at each setup.

Whereas, the normal resistivity measurement is relatively immune to high electrode contact resistances, the IP method requires a good low-resistiviity electrode contact. Where the ground is very dry, it may help to wet down the area around each receiver electrode. As long as the "LINE OPEN" LED on the transmitter does not come on, it is not necessary to wet the transmitter electrodes.

The "real" component is simply the meter reading that is normally measured by pushing the red "POWER" pushbutton. This value should be written down in a field notebook.

The "imaginary" or "quadrature" component is measured by pushing and holding the "IP" blue pushbutton switch. This value should also be written down in the field notebook. The scale for the "imaginary" component is the same as the scale for the real component.

Calculating the IP Phase Value

The "PHASE" is simply obtained by taking the arctangent of the ratio of the imaginary to real components of the resistivity.

IP PHASE = arctan (imaginary / real)

For example, if the resistivity reading was 19.00 and the IP reading was 0.100 then:

IP PHASE = arctan (0.100/19.00) = arctan (.00526) = 5.26 milliradians

For small values of the arctan (x) the value in radians is approximately the same, (x).

Some people report the phase in degrees instead of milliradians. To calculate the phase in degrees:

IP PHASE (degrees) = 57.3 * IP / R = 57.3 * 0.100 /19.00 = 0.302 degrees

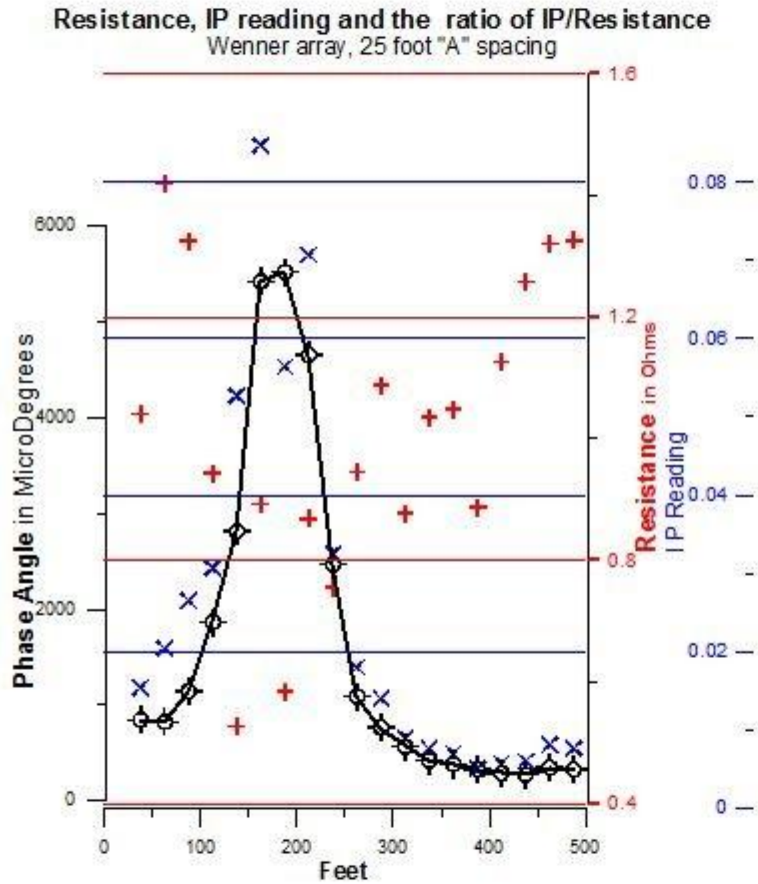
A simple calculator may be used to compute the phase in units of milliradians or degrees from the real and imaginary components stored in the field notebook. Typically, the phase response will be small, even for a strong IP area. A large copper porphyry deposit has been described having a maximum IP phase response of about 6 degrees (0.105 radian or 105 milliradians). Most non-sulfide, non-clay regions will exhibit an IP phase much smaller than 6 degrees.

Note that no geometry factors are associated with the phase formula. It makes no difference if the measurement array setup is Wenner or Schlumberger. The IP phase is always calculated the same way.

Plotting the Data

As mentioned above, instrument layout and ground conditions may exhibit a phase response that combines with the native IP response of the ground being measured. Therefore, it may be helpful to plot the difference in phase about the average of all the phases on a profile. A strong increase in phase should indicate an associated strong increase in IP effect.

It is the phase that should be plotted; NOT the IP. See the following illustration. Little sense can be made of the resistivity or IP reading, but the PHASE clearly shows a strong anomaly.



References

At the end of Appendix D are some general references on the IP method.

Care of the MiniRes

Care of the MiniRes

The MiniRes should not be used in direct rain or wet snow. Much effort has been expended to make the instrument water-resistant. The switches were carefully selected to be water resistant as well as the type and installation of the LED's. There is a rubber O-ring between the faceplate and the case. However, the instrument should never be considered waterproof. If it has been exposed to moisture, it should be opened and allowed to dry. Moisture or dirt between the binding posts will degrade the accuracy of the reading.

If the case is closed, the instrument is waterproof. If the instrument is moved to a much lower elevation or colder temperature, it might be difficult to open the case because of the lower air pressure inside the case. There is a small air port near the handle of the case. Loosen the black knurled knob and allow the internal air to equalize with the external air. Remember to retighten the knob so the case will again be watertight.

If the MiniRes is placed in storage for many months, the four "D" cell batteries should be removed in case they start to leak.

The instrument is available in a yellow case or a black case. Direct exposure to the sun on a hot day for a prolonged time can cause the internal temperature to become excessive, especially if the instrument is in the black case.

The LCD is specified by its manufacturer to operate accurately between 0º C and +50º C (+32º F and +122º F). In actual tests the LCD meters have operated at -15º C (5º F). The LCD should not be stored at temperatures below -20º C (-4º F) nor at temperatures above +75º C (+167ºF).

Troubleshooting

TROUBLE SHOOTING +++++++++++ PRELIMINARY

First go over Appendix F, ***Periodic Tests***

Moisture or dirt between terminals will degrade the accuracy of the reading.

If there is a **rattle** inside the case: remove the instrument from the case and determine what is rattling. Any metal object that is loose within the case poses a potential for electrical damage to the instrument.

If there is **moisture** inside the case: water left inside the case will corrode and destroy the instrument. Remove the instrument from the case and dry thoroughly.

There is a **fuse** inside the instrument. To date, one has never blown. If the instrument is “dead”, remove the fuse and examine for a broken or missing filament.

If there is poor contact between the potential electrodes and the earth, the potential cables tend to act as antennas and the readings can be noisy. Appendix Q gives an insight into problems with electrodes in dry ground.

If **reels** are used for the transmitter cables, see Appendix E if:

- There are wandering readings
- There are unusually low readings
- Readings that seem stable for a time then change erratically
- Readings that change drastically depending on battery voltage
- Readings that change drastically when cable on the transmitter spool is retracted or extended

NEGATIVE READING

Anytime that negative resistance readings appear every bell and whistle should go off. Although negative resistance readings are theoretically possible in geology of extreme resistivity contrasts and extremely irregular geological geometry, they are very RARE.

More than likely there is an error in measurement due to:

1) Incorrect polarity of transmitter or receiver cables. This is the most likely cause.

2) Using cables which allow excessive cross-talk or cross-leakage between the transmitter and receiver cables.

3) A malfunction in the instrument. In the strange case of negative resistance this should be examined by:

a) Assuring that the measured value of the calibration resistor is proper. The standard LRI calibration resistor harness that comes with each new MiniRes has a value of 19.00 ohms. It is marked on the resistor cover.

b) Assuring a good zero value with shorted receiver inputs. The shorted inputs test is described in Appendix F, Periodic Tests. Clamping a simple paper clip between the receiver terminals and pressing the red reading button should give a resistivity of zero.

c) Exchanging receiver and transmitter cable/electrodes (using the reciprocity theorem) to see that the same value of resistance is obtained.

4) An incomplete or open circuit (may be intermittently open) in one or both of the receiver wires or receiver wire-to-electrode connections. This error will clearly show up when doing the reciprocity check (in 3c above) since the receiver open circuit will be put into the transmitter side and then the LINE OPEN LED will illuminate brightly. The LINE OPEN LED should always be OFF during normal or reciprocal array arrangements.

5) Using transmitter cable spools with many turns of wire on them can also cause negative resistance readings. See the last section of Appendix E in the manual for a description and
solutions to this problem.

If any negative resistance readings show up again OR if the operator does not see a monotonic decrease in resistance readings with increasing "a" spacing THEN the operator should go through all of the checks listed above in order to locate and define the problem(s).

Accuracy of Calibration

Accuracy of Calibration

With the sale of each MiniRes there is a resistor calibration harness. For quality control, the MiniRes calibration can be checked with this resistor harness before and after each critical project.

The calibration harness for the ultra MiniRes and GPS-Res has two leads from the transmitter and four leads out the receiver side. Those four leads are color coded. Black is common, Red is 19.00 Ohms, Yellow is 1.90 Ohms and blue is19 milliOhms. Those values can be traced back to National Bureau of Standards references. and R Instruments purchased a 19.00 ohm reference resistor with a certified accuracy of 0.01%. That resistor has been measured in a Racal Dana model 6001 digital multimeter. That meter is periodically checked against a set of standards. That set of standards is periodically checked by Vishay Intertechnology Inc. whose primary standard has been certified by NIST Test No. 811/262153-99. The above certified resistor is then used by L and R Instruments to verify the accuracy of its digital multimeter. That multimeter is then used to trim the value of the main resistor in the calibration harness.

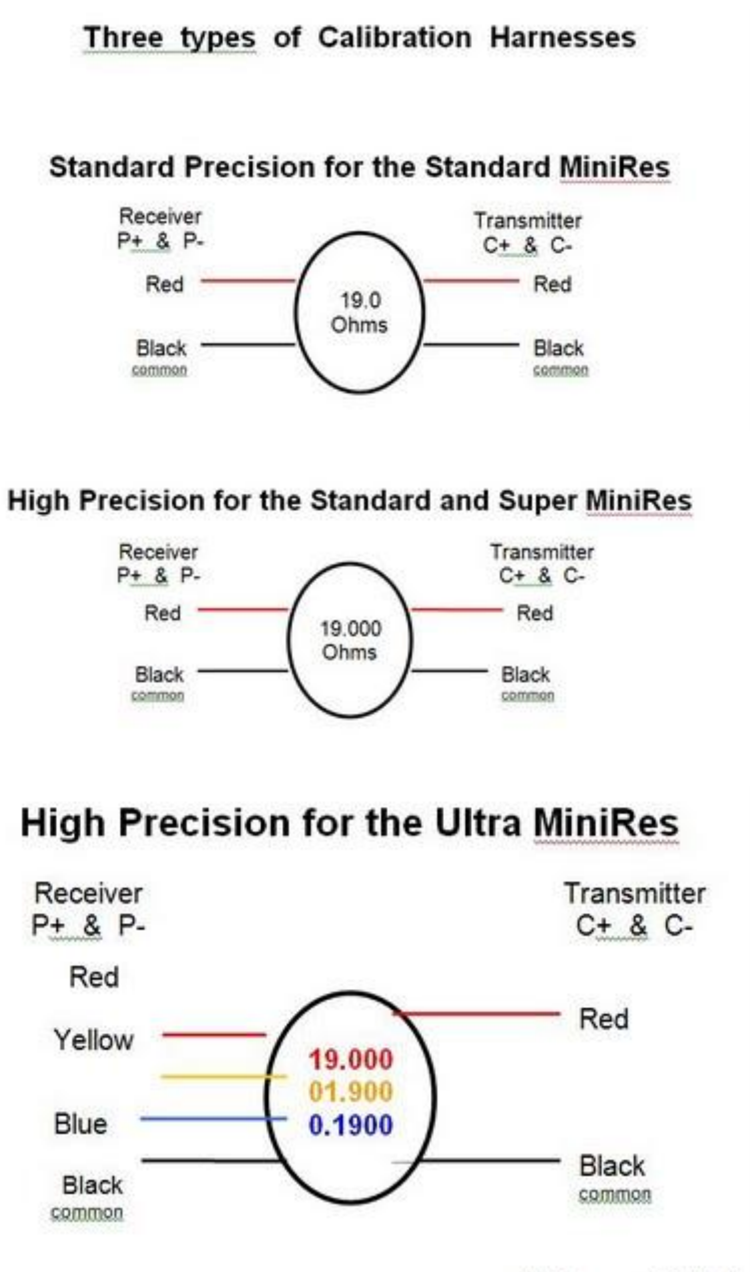
The type of main resistor used in the calibration harness has been selected for temperature stability and is specified at 15 PPM or less per degree Celsius. They have a resistance of 19.1 ohms. The trim resistors typically have a resistance of about 3.65 Kohms and therefore temperature changes have little effect on the overall accuracy of the calibration harness. The trim resistors are military specification metal foil with a temperature coefficient of 50 or 100 PPM per degree C. After the calibration harnesses are completed, they are allowed to age and then again checked for accuracy.

The ULTRA MiniRes calibration harness has two leads on the current (transmitter) side and four leads on the potential (receiver) side. It contains three resistance values; 1.900, 19.000 and 0.19000. All three ranges of the ULTRA MiniRes can be tested. On the potential side, the black is common and goes to the black binding post. The red plugs into the red binding post for use of the 19.000 ohm resistance. The yellow plugs into the red potential binding post for use of the 1.9000 ohm resistance and the blue plugs into the red potential binding post to use the 0.19000 calibration resistor. This calibration harness "loads" the transmitter and must not be connected in reverse.

In the MiniRes receiver, accuracy with ambient temperature changes has been optimized by the careful selection of quality components and temperature compensating circuits.

Moisture can have an adverse effect on the accuracy of the MiniRes. Considerable effort has been invested in making the MiniRes as water-resistant as practical. However, if the operator suspects that moisture has entered the instrument, he should use the calibration harness to check the accuracy of the instrument.

A full and complete check of the calibration should performed before beginning a survey. The results of that check should be documented in detail and timed and dated.



Factory Service

Factory Service

Before returning a MiniRes for service, whether in or out of warranty, please obtain an RMA (Return Material Authorization) number and current shipping address. Service will be prompt.

Warranty

Factory Service

Before returning a MiniRes for service, whether in or out of warranty, please obtain an RMA (Return Material Authorization) number and current shipping address. Service will be prompt.

Warranty

The MiniRes is guaranteed for **TWO** years after delivery. At the purchaser's request L and R Instruments, Inc. will make all necessary adjustments, repairs and parts replacements. All parts will become the property of LRI on an exchange basis. The guarantee will not apply if such adjustments, repairs or parts replacement are required by accident, neglect, misuse or causes other then ordinary use. All necessary adjustments, repair or parts replacement will be made at no charge to the purchaser provided that the purchaser pays all transportation costs to and from LRI. The period of the guarantee will be extended by the time the instrument is in transit and under repair. The foregoing guarantee is in lieu of all other guarantees expressed or implied, and all obligations or liabilities on the part of LRI for damages, including but not limited to consequential damages arising out of or in connection with the use of performance of the meter.

Appendix A

Appendix A: Warnings

SAFETY WARNING #1

This instrument can give a life threatening electrical shock of over 400 volts. Use this instrument with extreme caution. Only experienced and trained personnel should be allowed to operate this instrument. That chosen operator should also realize that the high voltage risk extends all the way to any of the electrodes. The operator of the instrument is responsible for assuring the safety of the entire array. No humans or animals should be allowed access to the electrodes, the electrode cables or the instrument during the survey.

SAFETY WARNING #2

Never operate this instrument during thunderstorms or any lightning activity. Even lightning that is very distant can generate thousands of volts over large electrode arrays. These lightning induced voltage transients can easily damage the instrument and kill or maim humans or animals.

SAFETY WARNING #3

These last possibilities are not very likely, but should, nonetheless, be avoided. A power line falling on or near one of the resistivity cables can route high voltage back to the operator and main or kill (avoid running the electrode cables near power lines if possible). Secondly, a strong cable run across a vehicle crossing can be caught by a passing vehicle and the vehicle can pull the entire cable with enough force to kill any person entangled in the cable. (this can happen when the cable is being "shoulder rolled" or "neck rolled"). At least one person has been killed in this strange circumstance.

SAFETY WARNING #4

Never use non-polarizable electrodes with any version of the MiniRes. These chemical-solution devices are susceptible to breakage, leaks, and freezing. The architecture of the MiniRes is such that use of non-polarizable electrodes actually yield poorer quality data.

Appendix B1

Appendix B(1) Specifications for Serial Nos. 001 through 032

- Accuracy: 0.3 percent plus or minus 5 least significant digits
- Switching frequency: 30 Hertz plus or minus 0.01 percent (optional 25 Hertz)
- No mechanical relays
- No nonpolarizing electrodes required for either resistivity or IP modes
- Transmitter maximum compliance voltage: over 400 volts
- Transmitter waveform: square wave with exact 50% duty cycle
- Measurement range: selectable, 0 to 200 ohms or 0 to 20,000 ohms
- Transmitter constant current choices: 0.50 milliamps or 5.0 milliamps
- Input resistance: 200 Megohms (s/n 001-014: 20 Megohms)
- Operating temperature range: -10 to +50 degrees Celsius (limited by LCD)
- Storage temperature range: -20 to +75 degrees Celsius
- Housing: water tight, high-impact plastic
- Display device: 4.5 digit LCD Digital Panel Meter
- Dimensions: 36.3 x 27.4 x 15.8 cm (14.3 x 10.8 x 6.2 inches)
- Weight: 4.3 Kilos (9.5 pounds)
- Impact resistance: will sustain a drop of one meter to a concrete surface
- Power source: four “D” alkaline batteries
- Readings per set of batteries at room temperature: 20KΩ range – 2,500 readings
200Ω range – 1,250 readings
- Typical resistance mode capability: Provides accurate Wenner Array resistivities with “a” spacings up to 200 or more feet.

Appendix B2

Appendix B(2) Specifications for serial numbers between 101 and 140

- Power source: 4 standard “D” size alkaline batteries

- Accuracy: 0.3 percent plus or minus 5 least significant digits

- Switching frequency: 5.00 Hertz plus or minus 0.01 percent (This frequency provides nearly perfect attenuation of 50 and 60 Hertz powerline noise)

- No mechanical relays

- Designed to operate with stainless steel electrodes. No nonpolarizing electrodes required to operate in either the resistivity or the IP mode.

- Transmitter maximum compliance voltage: 730 peak-to-peak at 1 mA or 530 peak-to-peak at 10 mA (values for compliance voltage assume fresh batteries at room temperature)

- Resistance measurement range: selectable, 0 to 19.999 ohms or 0 to 1999.9 ohms

- IP (Quadrature Component) measurement range: 0 to 1.9999 or 0 to 199.99 ohms

- Transmitter constant current choices: 1.0 milliamps when on the 1999.9 ohm range or 10.0 milliamps when on the 19.999 ohm range

- Input resistance: 200 Megohms

- Operating Temperature Range: -10 to +50 degrees Celsius (limited by LCD)

- Storage Temperature Range: -20 to + 75 degrees Celsius

- Housing: water tight, high-impact plastic

- Display device: 4.5 digit LCD Digital Panel Meter

- Dimensions: 36.3 x 27.4 x 15.8 cm (14.3 x 10.8 x 6.2 inches)

- Weight: 4.3 Kilos (9.5 pounds)

- Impact resistance: will sustain a drop of one meter to a concrete surface (vibration isolated printed circuit board.

- Resistance mode resolution: 1 milliohm

- IP (quadrature component) mode resolution: 0.1milliohm

• Typical resistance mode capabilities: Provides accurate Wenner Array resistivities with “a” spacings of 1 foot to 600 feet (current electrode separation of 1800 feet or more)

• Typical induced polarization mode capabilities: Provides accurate Wenner Array IP phase readings with “a” spacings of 1 foot to over 100 feet

• Readings per set of batteries at room temperature: 1999.9 Ω range – 1400 readings
19.999 Ω range – 750 readings

Appendix B3

Appendix B(3) Specifications for serial numbers from 141 and up

and meters having a serial number followed by a U

- Three resistance measurement ranges:1.9999 Kohms, 19.999 Ohms and 1999.9 milliOhms.
- IP (Quadrature Component) measurement range:1.9999 and 199.99 ohms
- Transmitter constant current choices:2.0 milliamps when on the 1999.9 ohm range or 20.0 milliamps when on the 19.999 ohm range or the 1.9999 ohm range
- Input resistance: 200 Megohms
- Power source: 4 standard “D” size alkaline batteries
- Accuracy: Better than 0.1 percent plus or minus 3 least significant digits (LSD) over 0°C to 50°C ambient.
- Switching frequency: 5.00 Hertz plus or minus 0.01 percent. Optional: 2.50 Hertz
- No mechanical relays
- Designed to operate with stainless steel electrodes. No nonpolarizing electrodes required to operate in either the resistivity or the IP mode.
- Transmitter maximum compliance voltage: up to 640 peak-to-peak at 2 mA or 450 peak-to-peak at 20 mA (values for compliance voltage assume fresh batteries at room temperature)
- Operating Temperature Range: -10 to +50 degrees Celsius (limited by LCD)
- Storage Temperature Range: -20 to + 75 degrees Celsius
- Housing: water tight, high-impact ABS plastic
- Display device: 4.5 digit LCD Digital Panel Meter
- Analog to digital converter: laboratory grade +/- 20,000 dual slope integrated
- Method of demodulation and detection: Synchronous Demodulation
- Dimensions: 36.3 x 27.4 x 15.8 cm (14.3 x 10.8 x 6.2 inches)
- Weight: 4.3 Kilos (9.5 pounds)

- Impact resistance: will sustain a drop of one meter to a concrete surface (vibration isolated printed circuit board)

- Resistance (in phase or real) mode resolution: 0.1 milliohm

- IP (quadrature component) mode resolution: 0.01 milliohm

- Typical resistance mode capabilities: Provides accurate Wenner Array resistivities with “a” spacings of 1 foot to 600 feet (current electrode separation of 1,800 feet or more). The 2.50 Hz version is accurate for a "Wenner" spacings of 1000 feet or more.

- Typical induced polarization mode capabilities: Provides accurate Wenner Array IP phase readings with “a” spacings of 1 foot to over 100 feet (300 feet between current electrodes). The 2.50 Hz version is accurate for a "Wenner" spacings of 200 feet or more.

- Readings per set of batteries at room temperature: 1999.9 Ω range – 1,400 readings

  19.999 Ω range – 750 readings

Appendix C1

Apprendix C(1) General Description of the *standard* MINIRES (For serial nos. 001-032)

The MiniRes geophysical resistivity meter is a highly accurate and precise portable scientific instrument designed to provide years of rugged use while maintaining laboratory levels of stability and accuracy. The instrument is also very easy to use.

The MiniRes is not reliant on a digital microprocessor for operation. This has several advantages over typical microprocessor-based systems. A microprocessor-based system generally relies on a menu where the operator has to work his way up or down the menu system to get where he can control the function of interest. In the MiniRes, every function of the instrument corresponds to an individual switch or indicator on the front panel. Therefore, access to a particular function is instantaneous. Another disadvantage of microprocessor-based systems is that they generate electromagnetic noise. Also, they are susceptible to electromagnetic interference (EMI) and electrostatic discharge (ESD). The MiniRes has a slow (but accurate) system clock that generates very little noise. Since it is synchronous with all other functions of the instrument, it does not interfere with the operation of the instrument.

A key characteristic of the MiniRes is the receiver architecture. The receiver utilizes a technique called "synchronous detection". This is an extremely powerful theoretical concept that allows stable and accurate readings to be taken in noisy environments with a minimum of transmitter power. Thus, the MiniRes is able to acquire hundreds of measurements with 4 standard "D" cell alkaline batteries as its sole power source.

The "synchronous detection" method has the intrinsic ability to filter out vast amounts of noise, allowing stable readings to be taken in extremely noisy environments. Other electronic architectures use a "brute force" method of generating large amounts of transmitter power. This brute force approach is effective, but suffers two disadvantages. First, the brute force method requires large, heavy batteries that lose power with each measurement and, second, the large transmitter currents demand excellent, low resistivity transmitter electrode "plants". Operators of that equipment regularly carry extra water and salt to douse the transmitter electrodes and, thereby, reduce their resistances to the point that the heavy transmitter currents can pass. The MiniRes would require this only in the most extreme of circumstances.

The MiniRes utilizes some of the latest, most sophisticated solid state electronic components available. Many other resistivity meters use mechanical relays for switching the transmitter and receiver circuitry. The MiniRes has no mechanical relays. It utilizes rugged high voltage solid state components for all receiver and transmitter functions. These provide reliable and stable readings year after year.

The power supply for the MiniRes consists of four standard alkaline "D" cells hooked in series providing approximately 6 volts. A set of batteries provides hundreds of readings. There is no need for a battery charger. A "BATTERY LOW" indicator light comes on when the batteries get close to needing replacement. Typically, a few hours of data can be taken even after the "BATTERY LOW" LED illuminates. Also, the operation can be further extended if the "RANGE" switch is changed from the 200 Ohm position to the 20,000 Ohm position, since the 20,000 Ohm position requires less power.

The transmitter circuit can generate over 400 volts. This allows the instrument to work in very resistive environments with long transmitter electrode spacing.

Considerable effort was expended in the design of the MiniRes to provide continuous feedback to the operator of every critical function of the instrument. Hence, an "OVERRANGE" detection indicator light assures the operator that the instrument is working properly within its linear bounds. The "BATTERY LOW" indicator provides an early warning for battery replacement. The "LINE OPEN" indicator signals to the operator that the transmitter, transmitter cables or electrodes are not operating properly. All of these quality control indicators assure consistent and robust measurements.

Appendix C2

Apprendix C(2) General Description of the *super* MINIRES for serial numbers between 100 & 140

The MiniRes geophysical resistivity meter is a highly accurate and precise portable scientific instrument designed to provide years of rugged use while maintaining laboratory levels of stability and accuracy. The instrument is also very easy to use.

The MiniRes is not reliant on a digital microprocessor for operation. This has several advantages over typical microprocessor-based systems. A microprocessor-based system generally relies on a menu where the operator has to work his way up or down the menu system to get where he can control the function of interest. In the MiniRes, every function of the instrument corresponds to an individual switch or indicator on the front panel. Therefore, access to a particular function is instantaneous. Another disadvantage of microprocessor-based systems is that they generate electromagnetic noise. Also, they are susceptible to electromagnetic interference (EMI) and electrostatic discharge (ESD). The MiniRes has a slow (but accurate) system clock that generates very little noise. Since it is synchronous with all other functions of the instrument, it does not interfere with the operation of the instrument.

A key characteristic of the MiniRes is the receiver architecture. The receiver utilizes a technique called "synchronous detection". This is an extremely powerful theoretical concept that allows stable and accurate readings to be taken in noisy environments with a minimum of transmitter power. Thus, the MiniRes is able to acquire hundreds of measurements with 4 standard "D" cell alkaline batteries as its sole power source.

The "synchronous detection" method has the intrinsic ability to filter out vast amounts of noise, allowing stable readings to be taken in extremely noisy environments. Other electronic architectures use a "brute force" method of generating large amounts of transmitter power. This brute force approach is effective, but suffers two disadvantages. First, the brute force method requires large, heavy batteries that lose power with each measurement and, second, the large transmitter currents demand excellent, low resistivity transmitter electrode "plants". Operators of that equipment regularly carry extra water and salt to douse the transmitter electrodes and, thereby, reduce their resistances to the point that the heavy transmitter currents can pass. The MiniRes would require this only in the most extreme of circumstances.

The MiniRes utilizes some of the latest, most sophisticated solid state electronic components available. Many other resistivity meters use mechanical relays for switching the transmitter and receiver circuitry. The MiniRes has no mechanical relays. It utilizes rugged high voltage solid state components for all receiver and transmitter functions. These provide reliable and stable readings year after year.

The power supply for the MiniRes consists of four standard alkaline "D" cells hooked in series providing approximately 6 volts. A set of batteries provides hundreds of readings. There is no need for a battery charger. A "BATTERY LOW" indicator light comes on when the batteries get close to needing replacement. Typically, a few hours of data can be taken even after the "BATTERY LOW" LED illuminates. Also, the operation can be further extended if the "RANGE" switch is set to the HIGH (19.999) Ohm position, since the 19.999 Ohm position requires less current and less power.

The transmitter circuit of units with serial numbers less than 100 can generate over 400 volts. Those units with serial numbers greater than 100 can generate up to 720 volts, peak-to-peak. This allows the instrument to work in very resistive environments with long transmitter electrode spacing.

The frequency of the transmitted signal on units with serial number less than 100 is 30 Hertz and there is excellent rejection of 60 Hertz AC power line noise. On units with serial numbers greater than 100, the frequency is 5 Hertz and there is excellent rejection of both 50 and 60 Hertz AC power noise.

Considerable effort was expended in the design of the MiniRes to provide continuous feedback to the operator of every critical function of the instrument. Hence, an "OVERRANGE" detection indicator light assures the operator that the instrument is working properly within its linear bounds. The "BATTERY LOW" indicator provides an early warning for battery replacement. The "LINE OPEN" indicator signals to the operator that the transmitter, transmitter cables or electrodes are not operating properly. All of these quality control indicators assure consistent and robust measurements.

Appendix C3

General Description of the *ULTRA* MINIRES

The MiniRes geophysical resistivity meter is a highly accurate and precise portable scientific instrument designed to provide years of rugged use while maintaining laboratory levels of stability and accuracy. The instrument is also very easy to use.

The MiniRes is not reliant on a digital microprocessor for operation. This has several advantages over typical microprocessor-based systems. A microprocessor-based system generally relies on a menu where the operator has to work his way up or down the menu system to get where he can control the function of interest. In the MiniRes, every function of the instrument corresponds to an individual switch or indicator on the front panel. Therefore, access to a particular function is instantaneous. Another disadvantage of microprocessor-based systems is that they generate electromagnetic noise. Also, they are susceptible to electromagnetic interference (EMI) and electrostatic discharge (ESD). The MiniRes has a slow (but accurate) system clock that generates very little noise. Since it is synchronous with all other functions of the instrument, it does not interfere with the operation of the instrument.

A key characteristic of the MiniRes is the receiver architecture. The receiver utilizes a technique called "synchronous detection". This is an extremely powerful theoretical concept that allows stable and accurate readings to be taken in noisy environments with a minimum of transmitter power. Thus, the MiniRes is able to acquire hundreds of measurements with 4 standard "D" cell alkaline batteries as its sole power source.

The "synchronous detection" method has the intrinsic ability to filter out vast amounts of noise, allowing stable readings to be taken in extremely noisy environments. Other electronic architectures use a "brute force" method of generating large amounts of transmitter power. This brute force approach is effective, but suffers two disadvantages. First, the brute force method requires large, heavy batteries that lose power with each measurement and, second, the large transmitter currents demand excellent, low resistivity transmitter electrode "plants". Operators of that equipment regularly carry extra water and salt to douse the transmitter electrodes and, thereby, reduce their resistances to the point that the heavy transmitter currents can pass. The MiniRes would require this only in the most extreme of circumstances.

The MiniRes utilizes some of the latest, most sophisticated solid state electronic components available. Many other resistivity meters use mechanical relays for switching the transmitter and receiver circuitry. The MiniRes has no mechanical relays. It utilizes rugged high voltage solid state components for all receiver and transmitter functions. These provide reliable and stable readings year after year.

The power supply for the MiniRes consists of four standard alkaline "D" cells hooked in series providing approximately 6 volts. A set of batteries provides hundreds of readings. There is no need for a battery charger. A "BATTERY LOW" indicator light comes on when the batteries get close to needing replacement. Typically, a few hours of data can be taken even after the "BATTERY LOW" LED illuminates. Also, the operation can be further extended if the "RANGE" switch is set to the HIGH (1.9999 Kohms) Ohm position, since the 1.9999 Kohms position requires less current and less power.

The transmitter circuit can generate up to 720 volts, peak-to-peak. This allows the instrument to work in very resistive environments with long transmitter electrode spacing.

Units come standard with a frequency of 5.00 Hertz and there is excellent rejection of both 50 and 60 Hertz AC power noise. Optionally, units can be ordered with a frequency of 2.50 Hertz. A new 3 position range switch offers settings of 1.9999 Kohms, 19.999 Ohms, and 1999.9 milliOhms.

Considerable effort was expended in the design of the MiniRes to provide continuous feedback to the operator of every critical function of the instrument. Hence, an "OVERRANGE" detection indicator light assures the operator that the instrument is working properly within its linear bounds. The "BATTERY LOW" indicator provides an early warning for battery replacement. The "LINE OPEN" indicator signals to the operator that the transmitter, transmitter cables or electrodes are not operating properly. All of these quality control indicators assure consistent and robust measurements.

Appendix D

Appendix D Induced Polarization

General Description of Induced Polarization

Compared to basic resistivity measurements, IP is a relatively new method, first used in the late 1940s in exploring for disseminated sulfide ores. IP has also been used in water and clay exploration. Certain earth materials do not act as perfect ohmic conductors. A perfect ohmic conductor always has a current flowing exactly "in phase" with the applied voltage. A perfect ohmic conductor shows no "memory effect" and there will be no current flow when there is no voltage applied (referred to as zero in, zero out). However, certain earth materials have an IP response that may exhibit all of these phenomena; current may flow in the IP material with no voltage applied, the current due to an applied voltage will not be exactly "in phase" with the applied voltage and the IP materials will exhibit a "memory effect" in that the voltage at any point on the earth will depend of the history of the applied voltages. The IP effect is a useful and interesting earth characteristic. The MiniRes resistivity meter has an IP function that allows for precise and efficient measurement of the IP response.

There are four main instrument architectures used for measuring the IP response of the earth.

1) The first and the oldest architecture is sometimes called the "overvoltage" method. In this method, voltage is measured by a receiver dipole. The ratio of the voltages during the transmitter "ON" to the "OFF" interval is used to estimate the IP effect. This is a "time domain" technique in that voltage measurements are taken at precise times. A drawback of this technique is that large and heavy current generators are needed to overcome the noise associated with electric dipole measurements at low frequencies (< 10 Hertz).

2) The second method is referred to as the "variable-frequency method". This is a "frequency-domain" method and requires the measurement of apparent resistivity at two (or more) widely separated frequencies. A perfect ohmic conductor will show a constant apparent resistivity, independent of the frequency, assuming that skin effects are minimal. IP materials, however, will exhibit a small decrease in resistivity with increasing frequency. This technique has the advantage of being able to work at higher frequencies than the "overvoltage" method and, therefore, may not require large and heavy transmitters. The disadvantage is that data must be taken at two widely separated frequencies. This requirement demands a much more complicated instrument because the instrument must remain accurate and stable at two widely separated frequencies.

3) The third IP method is referred to the "IP phase method". Electrical engineers, many years ago, realized that, instead of measuring the frequency response difference at two widely separated frequencies, as in the "variable-frequency method", a simpler single measurement of the PHASE at one frequency may provide equivalent information. This method overcomes all of the disadvantages of the two earlier techniques. The PHASE can be measured at a relatively high frequency (5 or 30 Hertz in the case of the MiniRes) and, therefore, large and powerful transmitters are not needed as in the "overvoltage method". Also, only the phase response at a single frequency is required. This provides a smaller, lighter and simpler instrument than the "variable-frequency method" or the "overvoltage method" allow.

4) The fourth method is the “Spectral IP method”. Phase and magnitude are measured over a range of frequencies from 10^{-3} to 4×10^{3} Hertz.

The MiniRes utilizes the "IP phase method". The "IP phase method" is incorporated with the synchronous demodulation architecture of the MiniRes to allow low noise estimates of the IP phase. This is done by making separate measurements of the "real" or "in-phase" component of resistivity and also the "imaginary" or "quadrature" component of resistivity.

Induced Polarization Comparison

PHASE DOMAIN (PD) vs. conventional TIME DOMAIN (TD) IP systems

1. **Faster! Less Hassle!** TD systems require porous-pots (non-polarizable electrodes) for best performance. This type of electrode has many environmental concerns. The PD MiniRes prefers standard stainless steel electrodes (old rusted rebar may be used as well). This single difference makes the MiniRes much easier to deploy and more cost effective.

2. **Low Cost!** The PD MiniRes is a fraction of the purchase or rental cost of the TD IP systems.

3. **Safe!** The PD MiniRes provides high signal-to-noise ratio results with less power, battery weight and electrocution hazard. This survey was acquired with a transmitter current of 10 milliAmps RMS, which is, generally, insufficient to maim or kill animals or humans. TD IP systems, on the other hand, produce hundreds to thousands of milliAmps. These current levels are potentially lethal for both humans and animals. No potential chemical exposure from porous-pot style electrodes either.

4. **Easy to use!** The MiniRes has no software or confusing menus to choose -

just two buttons to operate - the Resistivity (in phase) and the IP (quadrature) mode buttons.

5. **Rugged and accurate with higher resolution!** The lighter weight components associated with the 5 Hertz PD architecture allow for a more rugged mechanical design. Accuracy is unsurpassed at better than 0.1 plus or minus 3 LSDs. IP Phase resolution is 300 microDegrees or 5.2 microRadians.

6. **Realistic field deployment!** PD IP systems inherently produce a unitless measure of phase angle which is virtually unaffected by errors in array geometry. Thus, a transmitter or receiver electrode may be displaced from its proper position without adversely affecting the PD measurement value. TD systems exhibit a sensitivity to electrode-position-error which is approximately proportional to the error. This allows easier field deployment of a PD system. The electrodes may be offset to avoid sidewalks, roads, rocks, etc. without impacting the resultant measurement. TD IP is much more adversely affected by near-surface inhomogeneities than the PD MiniRes.

7. **Better at mapping solvent contamination?** The 5 Hertz PD MiniRes may be more sensitive to clay-organic solvent polymerization IP effects than the lower-frequency TD systems. {Reference: Mapping Organic Contamination by Detection of Clay-Organic Processes - Gary R. Olhoeft)

8. **Better at sub-surface imaging!** The PD method is not nearly as susceptible to the adverse effects of near-surface inhomogeneities, which can often render the TD IP method useless.

Olhoeft, G. R., (1992) Geophysical detection of hydrocarbon and organic chemical contamination: Symposium on the Application of Geophysics to Engineering and Environmental Problems, Environmental and Engineering Geophysical Society, Proceedings, pp. 587-595

Reynolds, John M., (1997) *An Introduction to Applied and Environmental Geophysics*, Chapter 9, pp. 522-552, John Wiley & Sons

Sumner, J. S., (1976) *Principle of Induced Polarization for Geophysical Exploration*; Elsevier

Ward, S. H., (1990) Resistivity and Induced Polarization Methods in *Geotechnical and Environmental Geophysics*, Vol. 1, pp. 147-190; Society of Exploration

Geophysics

Zonge, Ken, Jeff Wynn and Scott Urquhart, (2005) Resistivity, Induced Polarization, and Complex Resistivity, Chapter 9, *Near-Surface Geophysics*, pp. 265-300, Society of Exploration Geophysics

Appendix E

Appendix E Cables, Electrodes and Reels

CABLES

The MiniRes provides laboratory levels of accuracy. However, to take advantage of this high level of accuracy, considerable attention must be paid to auxiliary field equipment and field procedures. For example, improper layout of cables or abused cables can degrade the acquired data to the point of worthlessness. Attention must be paid to detail!

Both the transmitter and receiver cables should be of high quality and as free from nicks and abrasions as possible. A cable will be severely degraded if a car or truck (or human) runs over it and, thereby, cuts small nicks into the insulation. That damaged cable may work sufficiently well on dry ground, but if there is the slightest moisture due to dew or precipitation, the resistivity readings may be worthless. A wise procedure to follow as you roll up or roll out the cable is to run the wire along your bare fingers and feel for any nick, abrasion or cut in the wire's insulation. Any nick should be carefully covered with electrical tape or other insulating material. A section of wire that has had a vehicle run over it may have to be cut out entirely. The remaining wire should be spliced together with a good quality solder joint and insulated with self insulating heat shrink tubing. Both the receiver and transmitter cables must have perfect insulating integrity.

Prime concern should be focused on the type and condition of the cables, both receiver and transmitter. A set of poor cables may work well in a situation of short electrode spacings, dry surface conditions, and low earth resistivities. But the same cables may be absolutely worthless if there is the slightest amount of moisture on the ground, the electrode spacings are large or the earth resistivity is large. It is wisest to always use high quality cables that are in excellent condition.

Neither the transmitter nor receiver cables need to be of heavy gauge. The gauge of the conductors can be as small as 24 AWG (American Wire Gauge). A larger gauge wire will tend to be more durable in the field but heavier to carry around. The conductor may be tinned or untinned. Stranded conductor wire is best since it provides the greatest flexibility, but unstranded (solid) wire may also be used. The exposed wire ends (where the connections to the electrodes and MiniRes binding posts are made) tend to accumulate coatings of oxides and carbonates after exposure to field conditions. The transmitter cables are more tolerant of this degradation, however, the receiver connections should always be clean, bright, tight and solid. An occasional stripping of the insulation at the ends of the receiver cables to expose fresh conductor surface is recommended. Pliers, wire cutters, wire strippers or a knife can be used to strip the insulation.

The ends of the cables may be fitted with “banana” plugs. The MiniRes cable terminals can accept either stripped wire or banana plug. The electrodes that are supplied with the MiniRes have a hole near the top designed to accept a banana plug.

All types of cable insulation leak electricity to a certain degree. Teflon leaks the least of all and PVC (PolyVinyl Chloride) is at the other extreme. However, there are other field considerations besides leakage. PVC insulation, despite its leakage characteristics, is strong in many other aspects and is generally sufficient for high quality surveys. Manufacturer representatives should be consulted about a type of cable and insulation that may be used in a particular situation. Cable characteristic to consider are cost, brittleness at low temperatures, deterioration from ultra violet sunlight, weight, flexibility, abrasion resistance, and ease of stripping.

More important than the type of insulation, is the condition of the insulation. A single small nick in the insulation of a Teflon cable can increase its leakage beyond the worst PVC cable. It is poor practice to leave cables on the ground overnight. Many animals find the cable insulation a delightful nighttime morsel!

ELECTRODES

Generally, any type of conductive metal may be used as an electrode. However, it is advisable to use the same type of electrode for both receiver electrodes. The transmitter electrodes may be made of different metals - steel, copper, stainless steel, brass, lead, etc., but both of the receiver electrodes should be of the same metal. Copper sulfate or cadmium containing non-polarizing electrodes are neither required nor recommended.

The electrodes supplied with the MiniRes are stainless steel. They have a hole just below the top designed to accept a “banana” plug. The electrodes are or two types. The small electrodes are about 25 cm (10 inches) long and 3/8-inch in diameter. They are NOT designed to be driven into the ground. They have a large plastic knob on their top end to allow a good hand grip and allow them to be pushed and wiggled into the ground. If the ground is too hard for this, the ground can be wetted before pushing into the ground.

If this is not practical, cheap metal rods can be used. Half-inch or five-eighths-inch reinforcing rod is often used for this purpose. LRI also manufactures 60cm (2 foot) long and 7/16-inch diameter stainless steel electrodes for driving into the ground. Eight cm (3 inches) below the top is a hole for accepting a “banana” plug. At the opposite end, the rod is pointed.

ELECTRODES IN DRY SOIL See Appendix Q for details.

RECEIVER ELECTRODE CONTACT

If the receiver (potential) cables are connected to the MiniRes or MiniGPS receiver at one end and not connected to the earth at their other ends, they form an antenna. Stray electrical signals such as distant lightning noise can be detected by the instrument. The better the electrode ends of the receiver cables are connected to ground the more the antenna property of the receiver cables are “shorted” and the less the tendency to pick up stray atmospheric noise. So, it is always good practice to minimize receiver electrode ground resistance.

A precarious situation arises when wire reels (spools) are used for deploying the transmitter cables. This condition can cause extreme instability, wandering readings, and unreasonably high or low value readings. Very little information exists in the literature describing this condition, but, if reels are used for the transmitter cable deployment, eventually this frustrating behavior will manifest itself.

Nature of Problem

This problem typically shows up as:

1) wandering readings or time varying readings

2) unusually high or unusually low readings (but constant in time)

3) readings that seems stable for a time - then change erratically

4) readings that seem to change quite drastically depending on battery voltage

5) readings that change quite drastically when the cable on the transmitter spool is retracted or extended

Cause of Problem

This problem is caused by the constant current generator trying to drive a precise constant current into the ground through the transmitter reeled cables. These transmitter reeled cables can be viewed in terms of their "equivalent circuit" which appears as a high "Q" resonant circuit. The cable, which is coiled around the spool, acts as an inductance and the capacitance between the adjacent windings on the reel act as distributed capacitance and that combination of inductance

and capacitance forms a resonant circuit. It is very difficult for the constant current generator to remain stable while feeding a resonant circuit. In fact, the constant current generator, in particular instances, will not be able to maintain the current constant or, if it maintains it constant, it may be completely inaccurate and quite different than the value of current that is expected.

The constant current generator, in such instances, will break into high frequency "parasitic" oscillation - typically in the hundreds of kilohertz or megahertz. This high frequency oscillation may be transparent to the operator unless he happens to be monitoring the transmitter current by means of a high frequency oscilloscope. The oscillation may be constant, in which case, the readings may be constant, or the oscillation may start and stop at a slow rate, in which case, the readings will fluctuate at the same rate that the oscillations start and stop. In either case the readings may be greatly in error.

This tendency to oscillate does not indicate a deficiency in the design of the constant-current-generator. This tendency is a physical phenomena which is inherent to the problem of trying to drive a constant current into a high "Q" resonant circuit. Every resistivity or IP instrument (independent of manufacture) faces this problem. Although each instrument will be selective in the number of turns or wire which will cause the oscillation. Even same model instruments from a single manufacturer will show differences in the sensitivity to oscillate. And, complicating matters further, that tendency to oscillate may arise or disappear with changing temperature or battery voltage. So clearly, this is not a well-behaved problem, difficult to replicate, nearly impossible to compensate for, and exhibits dependence on many different variables.

Receiver Cable Reels - NOT a Problem

Due to the nature of the problem, high "Q" cable reels can be used in the receiver portion of the circuit without any of the above mentioned abnormal behavior. The equivalent circuits of the transmitter and receiver portions of the instrument are very different. High "Q" resonant circuits can be added in series with the receiver circuit without any deleterious effects on the measurement. The same cannot be said about the transmitter circuit. This difference in behavior of the transmitter and receiver circuits may be used to advantage in attempting to diagnose an instability problem.

Possible Solutions to the Problem

There are a few methods that may minimize the tendency to oscillate:

1) Use NO reels for the transmitter cables. Even an unspooled length of wire has inductance and capacitance but those values are so small and the equivalent "Q" value is so low that the constant current generator can function properly. The constant current generator was designed and tested to drive these types of "well behaved" loads.

2) Have only small amounts of cable on reels. Likewise, if there are very few turns of wire on the reel and/or the diameter of those turns is small then there will be little tendency for the constant current generator to break into oscillation. There is a limit of turns of wire and spool diameter, beyond which, the constant current generator will break into oscillation. The problem is knowing where that limit is. That limit is sensitive to battery voltage and instrument temperature.

3) Add damping mechanism to the transmitter reels. A way to minimize the tendency for constant-current-generator oscillation is to lower the "Q" of the equivalent resonant circuit. This concept can be best understood by viewing the reel as a transformer rather than a simple coil. If a single shorted turn is added to that transformer than the transmitter coils of wire will couple their energy (inductively) into that shorted turn. The reel may still show some resonance phenomena but the "Q" of that resonance will be drastically reduced by the added shorted turn of wire. And the constant-current-generator will be able to operate properly when driving such a low "Q" device.

Adding Damping Mechanism to Reels

There is a simple method for adding "damping" (the same as lowering the "Q") to existing reels of cable:

a) Remove all wire from the cable so that the inner spool surface is exposed

b) Obtain some copper foil or thin sheet whose width is nearly as wide as the width of the inner spool surface

c) Cut the copper foil or sheet so that it fits over the inner spool surface and can overlap itself so that it becomes like a single shorted turn of wire. (A lot of overlap is not detrimental and may make the soldering operation easier.)

d) With a heavy-duty soldering iron, solder the exposed copper foil seam. Try to solder along the entire length of the seam.

e) Protect the transmitter cable from nicks by winding electrical tape around the soldered copper foil. Ideally, no exposed copper will show after winding with electrical tape.

f) Rewind the original cable back onto the reel. The revised cable now has had its effective "Q" lowered drastically.

Appendix F

Appendix F Periodic Tests

Power Up Test

The power up test consists of simply opening the plastic lid of the MiniRes and pushing the "POWER" switch. No wires should be attached to the binding posts for this test. The MiniRes should power up for 30 to 50 seconds after pushing the "POWER" switch, then the instrument will automatically turn off unless the switch is pushed again during the interval.

At the instant that the "POWER" switch is activated, the "BATTERY LOW" LED should also turn on for a fraction of a second. This confirms that the battery voltage sensing and indicator circuitry is operating properly. Failure of this LED to light suggests a problem with the battery voltage sensing and indicator circuitry. A continually lit LED suggests weak batteries.

The "LINE OPEN" LED should illuminate and stay lit until the MiniRes automatically shuts off. This LED is correctly indicating that the transmitter lines are not properly hooked up.

The DPM (4.5 digit Digital Panel Meter) should come on and settle to a reading close to zero within a few seconds. This specific reading of the DPM is called the "open circuit zero reading". The "open circuit" refers to the receiver circuit input being "open" (no wires attached to it). The actual reading of the instrument will significantly deviate from zero if any of the binding posts have even the slightest amount of moisture or dirt on (or in) them. Keep these posts clean and dry for the best measurements! A PERFECTLY clean and dry MiniRes will have an "open circuit zero reading" of between -0010 and +0010. A seriously dirty unit will have a reading less than -1000 or greater than +1000.
.

Shorted Input Test

This test is identical to the "POWER UP TEST" with the exception that the input (receiver) red and black binding posts (P+ and P-) are shorted together with a short wire (an unraveled paper clip is ideal for this test). The transmitter binding posts (C+ and C-) are left unconnected.

The purpose of the "shorted inputs" test is to assure that the instrument can generate an accurate zero measurement. A perfectly operating MiniRes should settle to display +1, 0 or -1 on the DPM (Digital Panel Meter) during this test, although from -3 to +3 is within specifications. Any reading that has settled to a value outside this range is reason for concern. The prime suspect is probably moisture or dirt on or between the binding posts. Note that this specification holds for both the LOW “RANGE” (199.99 Ohm) and the HIGH “RANGE” (19.999 Ohm).

Accuracy Or Calibration Test

This test is the most thorough test of the entire instrument. It checks the transmitter and receiver circuits. The test can be performed with the calibration harness supplied with the MiniRes or with an easily obtained resistor and some wire. If the LRI calibration harness is not available, a precision resistor of 1000.0 to 1900.0 ohms is required. The resistor should have an accuracy of, at least, 0.1% and, ideally, 0.01%. Also, two short wires that can reach between the transmitter and receiver binding posts are required for this test.

Connect the calibration harness according to the color-coding. If the LRI calibration harness is not available, connect the resistor between C+ and C-, then attach one of the wires between C+ and P+ and the other wire between C- and P-. Tighten the binding posts lightly with your fingers. No other wires should be connected to the binding posts.

Switch the "RANGE" switch to HIGH (19.999 Ohms). Now, power up the MiniRes. After a few seconds, the DPM reading should settle to the accuracy specifications for the MiniRes. For example, on the 19.999 Ohm range, a true 1500 ohm resistor should read a maximum of 1508 ohms and a minimum of 1492 ohms. Now switch the "RANGE" switch to LOW (199.99 Ohms). A true 150.0 ohm resistor should read a maximum of 150.35 and a minimum of 149.65 ohms.

Appendix G

Appendix G Accuracy of Resistivity Measurements

The following is a test performed on MiniRes Serial Number 11.

Various precision resistors were used to derive an estimate of the accuracy of the MINIRES measurements. Some of the resistors used were 0.01% accuracy and, therefore, are more accurate than the Fluke is able to measure.

The last resistor measured, a 16.5 Kohm 0.1%, read 16507 on the Fluke, but read 16468 on the MINIRES. The input impedance of the MINIRES has a magnitude at 30.0 Hertz of about 6.7 Megohms, even though the input resistance is 20 Megohms. The reason that the MINIRES is reading abnornally low on the higher values is because of the loading effect of the 6.7 Megohm input impedance. The calculation of the parallel combination of 16507 ohms and 6.7 Megohms is 16466 which clearly explains the reason for the small error on the higher resistance measurements. Every earth resistivity meter has this loading effect, most have an input resistance of 10 Megohms. Since the MINIRES has 20 Megohms of input resistance it is very likely that the MINIRES is less effected by this loading effect than other earth resistivity meters. (**Serial No. 15 and above have 200 Megohms input resistance.**)

Type of Resistor	MINIRES READING 200 Ohm Range	MINIRES READING 2 Kohm Range	IP READING	Fluke READING	"TRUE" VRS. MINIRES READING
200 Ohm .1%	199.92	200	-.03	199.9	0.06%
100 Ohm .1%	99.99	100	.00	99.98	0.01%
5 Ohm 1.0%	4.98	5	.01	4.95	0.6%
300 Ohm .01%	N/A	300	0 to +1	300.0	0%
1000 Ohm .01%	N/A	999	+2	1000.1	0.1%
2000 Ohm .01%	N/A	1998	+3 to +4	2000	0.1%
16.5 Kohm .1%	N/A	16468	+22	16507	0.2% see note above

All of these results fall within the accuracy specification of the MINIRES. The large error on the IP illustrates a problem that naturally arises when IP data is acquired in areas of high ground resistivity. Much more attention to field procedure details should accompany IP surveys with any IP instrument compared with basic resistivity measurements.

Appendix H

Appendix H Comparison of output voltage per unit weight of resistivity meters

a) "*Super*" MiniRes (s/n >99 & < 141) is 720 Vpp / 4.3 Kg = 167 Vpp per Kg

b) Lippman is 80 Vpp / .75 Kg = 107 Vpp per Kg

c) STING 800 Vpp / 6.6 Kg = 121 Vpp per Kg

d) IRIS (SYSCAL R1 PLUS) 800 Vpp / 9.5 Kg = 84.2 Vpp per Kg

e) Syscal Junior 800 Vpp / 7 Kg = 114.3 Vpp per Kg

f) Terrameter SAS 300C 320 Vpp / 5.6 Kg = 57.1 Vpp per Kg

The MiniRes is the clear winner in terms of output voltage per unit weight. This is NOT an accident, nor is it due to flimsy, lightweight construction. One of the main reasons for the MiniRes being so lightweight is because of its High Voltage architecture - it is an architecture designed by a person named Royer. The ideal thing about it is that it allows complete saturation of the B-H magnetic curve of the high voltage transformer on negative AND positive excursions. Thus, you can get a much larger voltage swing with a lot smaller mass of ferrite. The STING uses the conventional flyback technology. Conventional flyback technology allows only one half of the B-H magnetizing curve to be utilized. It typically requires twice the mass of ferrite that the Royer technology uses.

Modern electrical engineers choose the Royer technology for the high voltage supply for driving the cold fluorescent lamps on laptop computers. The flyback technology is too heavy for this high voltage application in laptops.

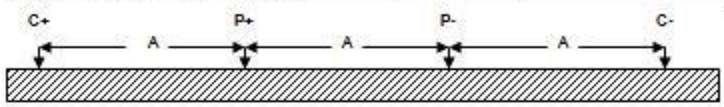
Appendix I

WENNER SOUNDING

Sounding No.	Date	Observers	Units: Meters or Feet?

Project / Location

Electrode Spacing A	A/2	3A/2	factor	Resistance	Apparent Resistivity	Notes
1	0.5	1.5	6.283			
1.4	0.7	2.0	8.796			
1.9	0.95	2.85	11.94			
2.7	1.35	4.05	16.96			
3.7	1.85	5.55	23.25			
5.0	2.5	7.5	31.42			
7.0	3.5	10.5	43.98			
10	5	15	62.83			
14	7	21	87.96			
19	9.5	28.5	119.4			
27	13.5	40.5	169.6			
37	18.5	55.5	232.5			
50	25	75	314.2			
70	35	105	439.8			
100	50	150	628.3			
140	70	210	879.6			
190	95	285	1194			
270	135	405	1696			
370	185	555	2325			
500	250	750	3142			
700	350	1050	4398			
1000	500	1500	6283			
1400	700	2100	8796			



Cultural Features____________________

Ground Cover______________________

Weather ________________________

Line Bearing ______________________

Line Location____

Appendix I-A [illegible] R Instruments, Inc.

Fixed Current Electrodes Profile with six divisions

Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

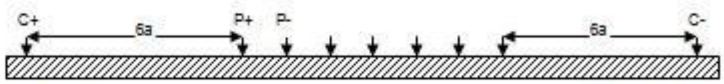
Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

Project____________Line____________Date____________Weather________________

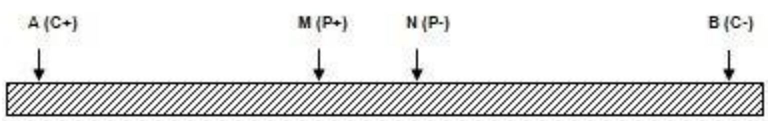
Ground Cover _______________________Crew________________Units: Meters / Feet_______



SCHLUMBERGER SOUNDING

Sounding No.	Date	Observers	Units: Meters or Feet
Location			

Electrode Spacing AB/2	MN/2	factor	Resistance	Apparent Resistivity	Notes
5	1	37.70			
7	1	75.40			
10	1	155.5			
12	1	224.6			
15	1	351.9			
20	1	626.8			
25	1	980.2			
30	1	1412			
40	1	2512			
40	5	494.8			
50	5	777.5			
60	5	1123			
80	5	2003			
100	5	3134			
130	5	5301			
160	5	8035			
160	20	1979			
200	20	3110			
250	20	4877			
300	20	7037			
350	20	9590			
400	20	12535			
500	20	19604			



Cultural Features____________________

Ground Cover____________________

Weather__________________________

Line Bearing______________________

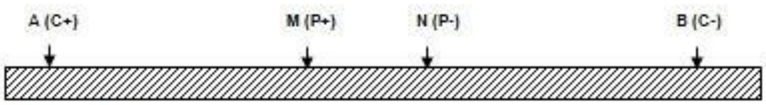
Line Location____

Appendix I-C L and R Instruments, Inc.

SCHLUMBERGER SOUNDING, electrode spacing in feet, apparent resistivity in Ohm-Meters

Sounding No.	Date	Observers	Electrode spacing in feet Ap. Resistivity in Ohm-meters
Location			

Electrode Spacing AB/2	MN/2	factor	Resistance	Apparent Resistivity	Notes
5	1	11.49			
7	1	22.98			
10	1	47.40			
12	1	68.47			
15	1	107.2			
20	1	191.0			
25	1	298.8			
30	1	430.4			
40	1	765.6			
40	5	150.8			
50	5	237.0			
60	5	342.3			
80	5	610.4			
100	5	955.2			
130	5	1616			
160	5	2449			
160	20	603.3			
200	20	948.0			
250	20	1487			
300	20	2145			
350	20	2923			
400	20	3821			
500	20	5975			



Cultural Features____________________

Ground Cover______________________

Weather___________________________

Line Bearing_______________________

Line Location____

Appendix I-D L and R Instruments, Inc

Fixed Current Electrodes Profile

with six divisions

Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

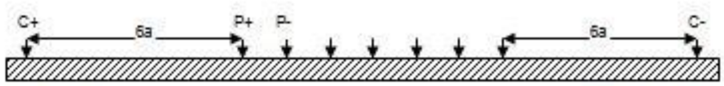
Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

Factor	200.2	233.2	251.3	251.3	233.2	200.2
a						
R						
R_a						

Project__________ Line__________ Date__________ Weather______________

Ground Cover ____________________ Crew______________ Units: Meters / Feet_______



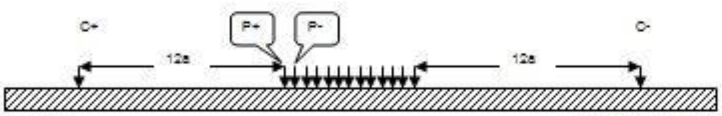
Fixed Current Electrodes Profile (Gradient Profile) with twelve divisions

	1	2	3	4	5	6
Factor	764.2	841.1	907.1	959.6	996.1	1015
a						
R						
R_a						

	7	8	9	10	11	12
Factor	1015	996.1	959.6	907.1	841.1	764.2
a						
R						
R_a						

	1	2	3	4	5	6
Factor	764.2	841.1	907.1	959.6	996.1	1015
a						
R						
R_a						

	7	8	9	10	11	12
Factor	1015	996.1	959.6	907.1	841.1	764.2
a						
R						
R_a						



Appendix I-F

R Instruments, Inc.

Dipole-Dipole Resistivity Field Data

Sheet _____

C-dipole	P-dipole	Factor	a	R	R_a	Notes
1 - 2	3 – 4	18.85				
	4 – 5	75.40				
	5 – 6	188.5				
	6 – 7	351.9				
	7 – 8	659.7				
	8 – 9	1056				
	9 – 10	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
2 - 3	4 – 5	18.85				
	5 – 6	75.40				
	6 – 7	188.5				
	7 – 8	351.9				
	8 – 9	659.7				
	9 – 10	1056				
	10 – 11	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
3 - 4	5 – 6	18.85				
	6 – 7	75.40				
	7 – 8	188.5				
	8 – 9	351.9				
	9 - 10	659.7				
	10 – 11	1056				
	11 – 12	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
4 - 5	6 – 7	18.85				
	7 – 8	75.40				
	8 – 9	188.5				
	9 – 10	351.0				
	10 – 11	659.7				
	11 – 12	1056				
	12 - 13	1584				

R_a = Factor x a x R   Project ______ Line ______ Crew ______

Units: Meters or Feet ______ Date ______ Line Bearing ______

Weather ______ Ground Cover ______

Appendix I-GA   L.app R. Instruments, Inc.

Dipole-Dipole Resistivity Field Data

Sheet _____

C-dipole	P-dipole	Factor	a	R	R_a	Notes
5 - 6	7 – 8	18.85				
	8 – 9	75.40				
	9 – 10	188.5				
	10 – 11	351.9				
	11 – 12	659.7				
	12 – 13	1056				
	13 – 14	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
6 - 7	8 – 9	18.85				
	9 – 10	75.40				
	10 – 11	188.5				
	11 – 12	351.9				
	12 – 13	659.7				
	13 – 14	1056				
	14 – 15	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
7 - 8	9 – 10	18.85				
	10 – 11	75.40				
	11 – 12	188.5				
	12 – 13	351.9				
	13 – 14	659.7				
	14 – 15	1056				
	15 – 16	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
8 - 9	10 – 11	18.85				
	11 – 12	75.40				
	12 – 13	188.5				
	14 – 15	351.9				
	15 – 16	659.7				
	16 – 17	1056				
	17 – 18	1583				

R_a = Factor x a x R Project Line Crew ____________

Units: Meters or Feet ________ Date Line Bearing ________________

Weather ________________________ Ground Cover ________________________

Appendix I-G8 L and R Instruments, Inc.

Dipole-Dipole Resistivity Field Data

Sheet _____

C-dipole	P-dipole	Factor	a	R	R_a	Notes
9 – 10	11 – 12	18.85				
	12 – 13	75.40				
	13 – 14	188.5				
	14 – 15	351.9				
	15 – 16	659.7				
	16 – 17	1056				
	17 – 18	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
10 – 11	12 – 13	18.85				
	13 – 14	75.40				
	14 – 15	188.5				
	15 – 16	351.9				
	16 – 17	659.7				
	17 – 18	1056				
	18 – 19	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
11 – 12	13 – 14	18.85				
	14 – 15	75.40				
	15 – 16	188.5				
	16 – 17	351.9				
	17 – 18	659.7				
	18 – 19	1056				
	19 – 20	1583				

C-dipole	P-dipole	Factor	a	R	R_a	Notes
12 - 13	14 – 15	18.85				
	15 – 16	75.40				
	16 – 17	188.5				
	17 – 18	351.9				
	18 – 19	659.7				
	19 – 20	1056				
	20 – 21	1583				

R_a = Factor x a x R Project Line Crew ____________
Units: Meters or Feet________ Date Line Bearing ____________
Weather______________________ Ground Cover ____________

Appendix I-GC L and R Instruments, Inc

Fixed Current Electrodes Map (Gradient) with six divisions in each of five lines

Plus 2a	Factor	224.4	254.3	270.7	270.7	254.3	224.4
	a						
	R						
	R_a						

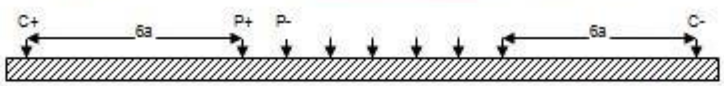
Plus 1a	Factor	206.2	238.4	256.1	256.1	238.4	206.2
	a						
	R						
	R_a						

Center	Factor	200.2	233.2	251.3	251.3	233.2	200.2
	a						
	R						
	R_a						

Minus 1a	Factor	206.2	238.4	256.1	256.1	238.4	206.2
	a						
	R						
	R_a						

Minus 2a	Factor	224.4	254.3	270.7	270.7	254.3	224.4
	a						
	R						
	R_a						

Project____________ Line____________ Date____________ Weather____________
Ground Cover ____________________ Crew____________ Units: Meters / Feet________



Appendix I-M

R Instruments, Inc.

Appendix J

Advantages of *Super* and *ULTRA* MiniRes over the *Standard* MiniRes

The high-power *Super* MiniRes (serial number between 100 and 140) uses several methods to improve the SNR compared to the original *Standard* MiniRes (serial numbers less than 32). Here is a list of those improvements:

1) The *Super* MiniRes has a maximum transmitter current output amplitude of 10.0 milliAmps and can easily be modified to 20.0 milliAmps. The ULTRA is standard with 20.0 milliAmps. Whereas the original MiniRes has a maximum of 5.0 milliAmps - giving a factor of 2 or 4 improvement in signal-to-noise-ratio (SNR).

2) The *Standard* MiniRes has a very simple (but extremely accurate) square wave transmitter waveform with some DC offset. The *Super* and *ULTRA* MiniRes use a different and very specific type of transmitter waveform that, by itself, provides a SNR improvement of a factor of about 3.6 compared to the conventional unit. But the improvement in random noise SNR is not the only thing the special waveform does. It also, inherently, provides extremely deep "notches" in the response at 50 and 60 Hertz.

3) Lastly, the *Super* and *ULTRA* MiniRes have a narrower (sharper) bandpass filter to reject any noise outside of its 5.00 Hertz band compared to the *Standard* MiniRes. Not only is the width of that filter narrower, but the "skirts" of the filter have a greater rejection slope. This narrower and higher-sloped-skirt filter improves the SNR by about a factor of 1.3 to 1.4 compared to the *Standard* MiniRes.

The total improvement in SNR is given by the product of all of those individual SNR improvements:

2 X 3.6 X 1.35 = 9.72 improvement in SNR of the *Super* unit over the *Standard* MiniRes

and twice that (19.44) for the *Super* units modified to 20 milliAmps and all the *ULTRA* MiniRes.

There is also an improvement due to the strong rejection of the 50 and 60 (and 10, 20, 30, 40, etc) Hertz noises. But, that is hard to calculate since it is dependent on the particular noise level of the area where one is working. Clearly, the *Super* MiniRes has about a ten fold greater SNR than the *Standard* MiniRes. The *ULTRA* has about a twenty fold greater SNR

There are other major improvements in the *Super* MiniRes compared to the *Standard* MiniRes:

a) the *Super* MiniRes frequency is 5.00 Hertz compared to 30.00 Hertz for the *Standard* MiniRes. So, there is much less need to worry about skin effects when using very long arrays in very conductive environments. There is a 2.5 Hertz option for the *ULTRA* so that Wenner arrays with "a" spacings of up to 300 meters can be used before skin effects become noticeable.

b) The *Super* MiniRes has a new high voltage automatic DOUBLER. This allows many more readings without exhausting the batteries. The DOUBLER only comes on when needed - thus saving batteries. The DOUBLER operation is completely transparent to the user. It switches on automatically in a fraction of a millisecond and remains ON until the unit powers down. The *ULTRA* uses the same technology

c) The *Super* and *ULTRA* MiniRes are nearly all surface mount technology on the printed circuit board (PCB). This reduces assembly costs, makes the meter lighter weight, and more rugged to vibration and abuse. The *ULTRA* has its PCB mounted on four rubber shock absorbers.

d) The *Super* and *ULTRA* MiniRes have special "cut-outs" on the PCB which help to minimize leakage currents on the PCB. Thus, humidity has less of an effect on the leakage current between the transmitter and receiver sections of the *Super* and *ULTRA* MiniRes. Much effort was spent on the *Standard* MiniRes to minimize PCB leakage currents - but it does not have the special "cut-outs" which are so effective. All resistivity meters suffer to some degree from this problem.

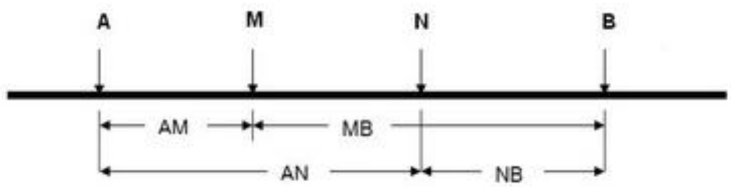
e) Because of these (and a few other) improvements, the *Super* MiniRes has ten times more resolution in the resistivity mode: 1 milliohm for the *Super* MiniRes versus 10 milliohms for the *Standard* MiniRes. The IP mode in the *Super* MiniRes has one hundred times more resolution than the conventional unit! The IP mode was "pushed" so that the last significant digit may appear a bit noisy and may drift over a day or so - but that increased resolution may allow laboratory measurements to be made with the unit. That IP resolution is better than one thousandth of one degree in phase! The *ULTRA* has an additional tenfold increase in resolution and a three position range switch.

The *Super* MiniRes is a major improvement over the *Standard* MiniRes - not simply an increase in transmitter power. However, the *Standard* MiniRes is more than adequate for electrical grounding surveys, archeological surveys, lab measurements, and shallow to moderate depth geotechnical and groundwater surveys. The *Super* MiniRes has been tested side by side with the *Sting* and *Terrameter* to “a” spacings of 200 meters (600 feet) and 600 meters (1800 feet) between current electrodes at resistive field sites. With the 2.5 Hertz option on the *ULTRA*, the “a” spacing can go 300 meters (1000 feet).

Appendix L

General Formula for Apparent Resistivity

If there are two current electrodes and two potential electrodes on the surface of a half-space, the configuration can be represented as follows:



It is not necessary that the four electrodes be in a straight line.

If apparent resistivity is R_a and V is the difference in voltage between M and N then

$$R_a = (2\pi V/I)\left(1/AM - 1/MB - 1/AN + 1/NB\right)^{-1}$$

Most modern earth resistivity instruments report V/I as resistivity, R. Therefore

$$R_a = (2\pi R)\left(1/AM - 1/MB - 1/AN + 1/NB\right)^{-1}$$

For a clear derivation of the above equation, see:

Reynolds, J.M., 1997, An Introduction to Applied and Environmental Geophysics: New York, John Wiley & Sons, Inc. pp. 424-426

Appendix M

Resistivity and I P Survey

A survey was conducted with closely spaced observation points using MiniRes serial number 14 (an early "standard" design MiniRes). It illustrates the value of induced polarization. The MiniRes allows the observer of resistivity to take an IP reading with a minimum investment in time; usually an additional 10 or 20 seconds. Many small targets that do not yield a significant resistivity anomaly do yield a noticeable IP anomaly. This advantage of IP is particularly helpful in shallow surveys of archeological or engineering sites. See Appendix X.

Figure A below is a graph of resistivity and IP conducted over a grass covered athletic field. The geology consisted of weathered limestone covered with about one foot of residual soil. The Wenner "A" spacing of the electrodes was 1.283 foot (0.391 meter). The orientation of the array is parallel to the direction of the survey line. Variations in the resistivity are believed to be due mostly to variation in the thickness of the residual soil.

On the field was a ten-foot by ten-foot (3-meter by 3-meter) reinforced concrete slab. The survey line passed along one side of that slab at a distance of one-half foot. The slab extended from Station 32.2 to 42.2. Note the minimal effect on the resistivitiy readings but the major effect of the slab and its steel on the IP observations.

There was also a vertical steel pole adjacent to the line at about station 28. Again, the IP signal is clear and there is little or no resistivity anomaly.

Resistivity in is Ohm-Meters and has been calculated by multiplying the resistance by $2 * \pi * A = 2.46$. The IP is in degrees of phase. It has been calculated by multiplying the IP reading by 180/Pi and dividing by the resistance.

Figure B below is a short survey line that shows the major IP anomaly caused by the slab. It also illustrates how the IP anomaly decreases rapidly as the line moves away from the slab. The electrode array was parallel to the side of the slab.

Figure C displays the resistivity along the same survey line as on Page 3. There is a small decrease in resistivity as the line approaches the slab and its reinforcing steel.

Clearly the IP signal is much greater for certain small targets and can be of great advantage in most archeological and engineering investigation, especially considering how little time is required to obtain the IP reading with the MiniRes.

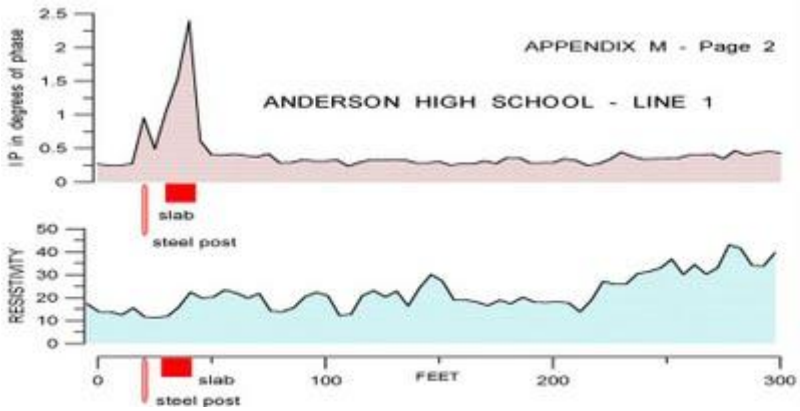


Figure A

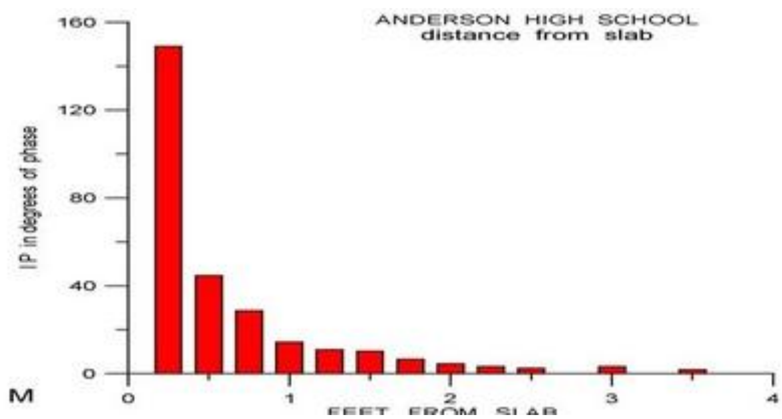


Figure B

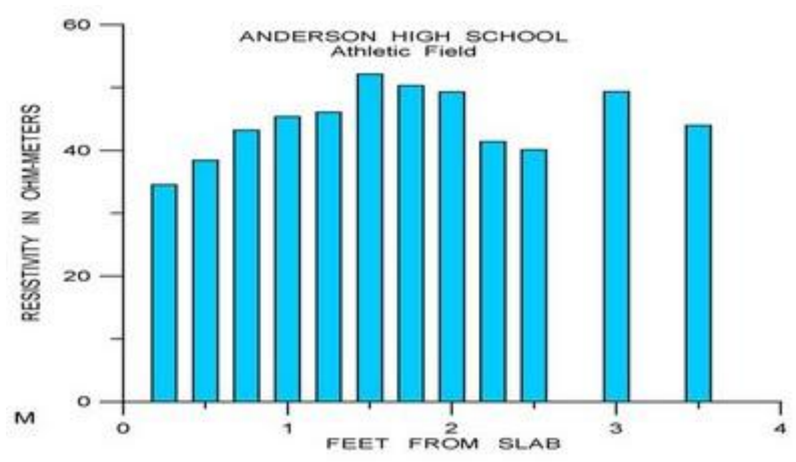

ANDERSON HIGH SCHOOL
Athletic Field
RESISTIVITY IN OHM-METERS
60
40
20
0
M
0
1
2
3
4
FEET FROM SLAB

Figure C

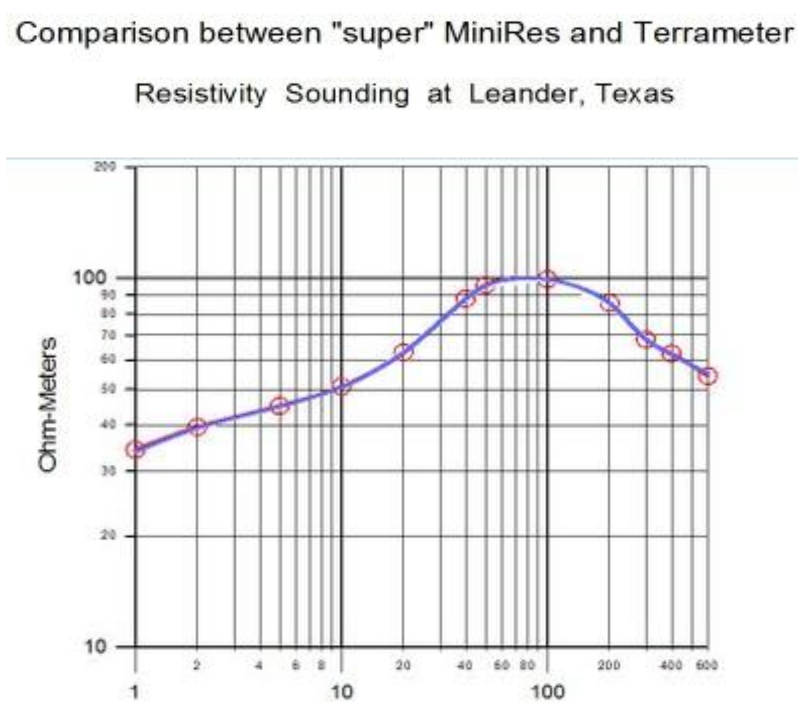
Appendix N

Comparison of Terrameter with MiniRes

Like the ABEM Terrameter, nearly all other competitive reistivity meters use the TIME DOMAIN mode of operating. We respect the choice of our honorable and competent Swedish competitors.

The MiniRes uses the FREQUENCY DOMAIN for resistivity and the PHASE DOMAIN FOR IP. The PHASE DOMAIN method of measuring IP, In our opinion, is MUCH better than the TIME DOMAIN method of measuring IP. The PHASE DOMAIN IP method records at the same time as it transmits. This gives the PHASE mode a tremendous energy efficiency advantage over the TIME DOMAIN IP method which records only after the transmitter is turned off/

The Terrameter displays the resistivity at the end of each reading and after a pre-specified number of readings it displays and holds that averaged reading. The MiniRes is constantly displaying the real-time values. If they are wandering, the observer can do a good job of averaging them. If there is an excursion due to local lightning, the observer of the MiniRes can disregard that observation. The Terrameter observer would probably be unaware of the noise level of the site.



"A" Spacing in Feet

- A is the “A” spacing in the Wenner electrode array
- B is the apparent resistivity in Ohm-Meters from the MiniRes
- C is the actual meter reading from the MiniRes
- D is the apparent resistivity in Ohm-Meters from the Terrameter
- E is the actual meter reading from the Terrameter

A	B	C	A	D	E
1	34.25795	17.784	1	33.82646	17.56
2	39.46677	10.244	2	39.25872	10.19
5	45.02810	4.675	5	44.88362	4.66
10	50.81674	2.638	10	50.66263	2.63
20	62.91413	1.633	20	62.79855	1.63
40	87.91797	1.141	40	87.68681	1.138
50	95.73889	0.994	50	95.35363	0.99
100	99.20630	0.515	100	99.20630	0.515
200	85.52931	0.222	200	85.52931	0.222
300	68.19229	0.118	300	68.30787	0.1182
400	62.41328	0.081	400	62.02801	0.0805
600	54.32267	0.047	600	55.24731	0.0478

The data points virtually fall on top of each other. The “Super” MiniRes obtains reliable data with 1,800 feet (600 meters) between current electrodes**.** MiniRes current is 10 milliamp

Appendix Q

Appendix Q Electrode Experiment In Dry Soil

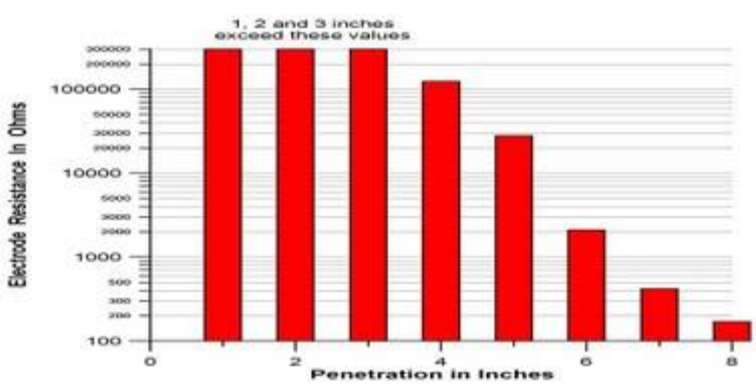
The following tests were performed in undisturbed dry soil in north central Nevada. The soil was dry silty sand with sagebrush growing nearby. Two holes were dug for reference electrodes. No indication of moisture was encountered at any depth in the holes. The bottom of each hole was light colored, dusty extremely dry soil.

The two holes were 1.5 meters (4.5 feet) apart. Half-inch reinforcing rod (rebar) electrodes were inserted 0.6 meter (2 feet) into the soil at the bottom on the holes and eight liters of water added to the bottom of each hole. After about ten minutes the resistance between the two electrodes settled to 11.5 ohms. The two electrodes were connected together to form a reference electrode. The resistance of the two connected electrodes was then somewhat LESS than 11.5 ohms; about 6 ohms.

Two different electrodes were tested: the first was a pointed stainless steel 3/8-inch diameter 10-inch long rod. The rod was inserted into the soil to greater and greater depth and the decrease in resistance recorded.

Electrode Depth	MiniRes Open Circuit Indicator	MiniRes Resistance Setting	MiniRes Voltage #	Electrode Resistance
1 inch	On	2 K	328 VAC	>300 Kohms
2 inch	On	2 K	328 VAC	>300 Kohms
3 inch	Flickers	2 K	291 ? VAC	?
4 inch	Off	2 K	124 VAC	124 Kohms
5 inch	Off	2 K	28 VAC	28 Kohms
6 inch	Off	20 Ohms	21 VAC	2.1 Kohms
7 inch	Off	20 Ohms	4.2 VAC	420 Ohms
8 inch	Off	20 Ohms	1.7 VAC	170 Ohms
8 inch	Off	20 Ohms	1.3 VAC	130 Ohms*

* change after pouring 2 liters of water down electrode hole
# as measured by a Fluke Model 87 multimeter



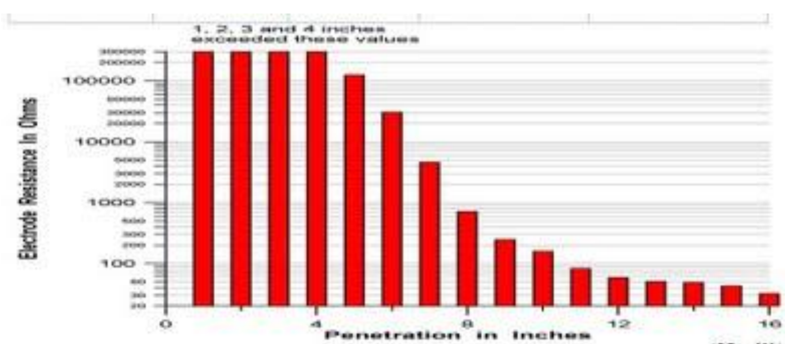
The second electrode tested was a cadmium plated 18-inch long steel rod with a blunt end. The results of those tests follow.

Electrode Depth	MiniRes Open Circuit Indicator	MiniRes Resistance Setting	MiniRes Voltage #	Electrode Resistance
1 inch	On	2 K	328 VAC	>300 Kohms
2 inch	On	2 K	328 VAC	>300 Kohms
3 inches	On	2 K	291 ? VAC	>300 Kohms
4 inches	Flickers	2 K	276 VAC	?
5 inches	Off	2 K	125 VAC	125 Kohms
6 inches	Off	2 K	30.5 VAC	30.5 Kohms
7 inches	Off	20 Ohms	46.0 VAC	4.60 Kohms
8 inches	Off	20 Ohms	7.15 VAC	715 Ohms
9 inches	Off	20 Ohms	2.48 VAC	248 Ohms
10 inches	Off	20 Ohms	1.58 VAC	158 Ohms
11 inches	Off	20 Ohms	835 mVAC	83.4 Ohms
12 inches	Off	20 Ohms	590 mVAC	59.0 Ohms
13 inches	Off	20 Ohms	510 mVAC	51.0 Ohms
14 inches	Off	20 Ohms	488 mVAC	48.8 Ohms
15 inches	Off	20 Ohms	433 mVAC	43.3 Ohms
16 inches	Off	20 Ohms	392 mVAC	39.2 Ohms

as measured by a Fluke Model 87 multimeter

These resistances are higher than those of the stainless electrodes. The difference is significant. It is possible that the pointed end compacts the soil near the point, thus enhancing the electrical contact. The blunt end of the steel rod "rattled" in the ground and pushed the dirt away from the metal. Electrodes with pointed ends seem to give better electrical contact for the same depth of penetration and are also easier to insert.

The effect of the two reference electrodes that were tied together probably adds about six ohms to the total resistance of the reference electrodes plus the test electrodes. Thus the test electrode values as given above are slightly higher than actual value.



Appendix R

Typical Resistivities of Soils and Rocks

Material	Ohm-Meters	Ohm-Cent.	Ohm-Feet
Wet to moist clayey soils	2 to 3	200 to 300	5 to 10
Wet to moist silty clay & silt soils	3 to 15	300 to 1,500	10 to 50
Well-fractured to slightly fractured bedrock with moist cracks	15 to 150	1,500 to 15,000	50 to 500
Sand and gravel with silt	150 to 800	15,000 to 80,000	500 to 3,000
Slightly fractured bedrock with dry soil filled cracks	300 to 2,500	30,000 to 250,000	1,000 to 8,000
Sand and gravel with layers of silt	300 to 2,500	30,000 to 250,000	1,000 to 8,000
Massive bedrock	2,500 plus	250,000 plus	8,000 plus
Coarse dry sand and gravel	2,500 plus	250,000 plus	8,000 plus

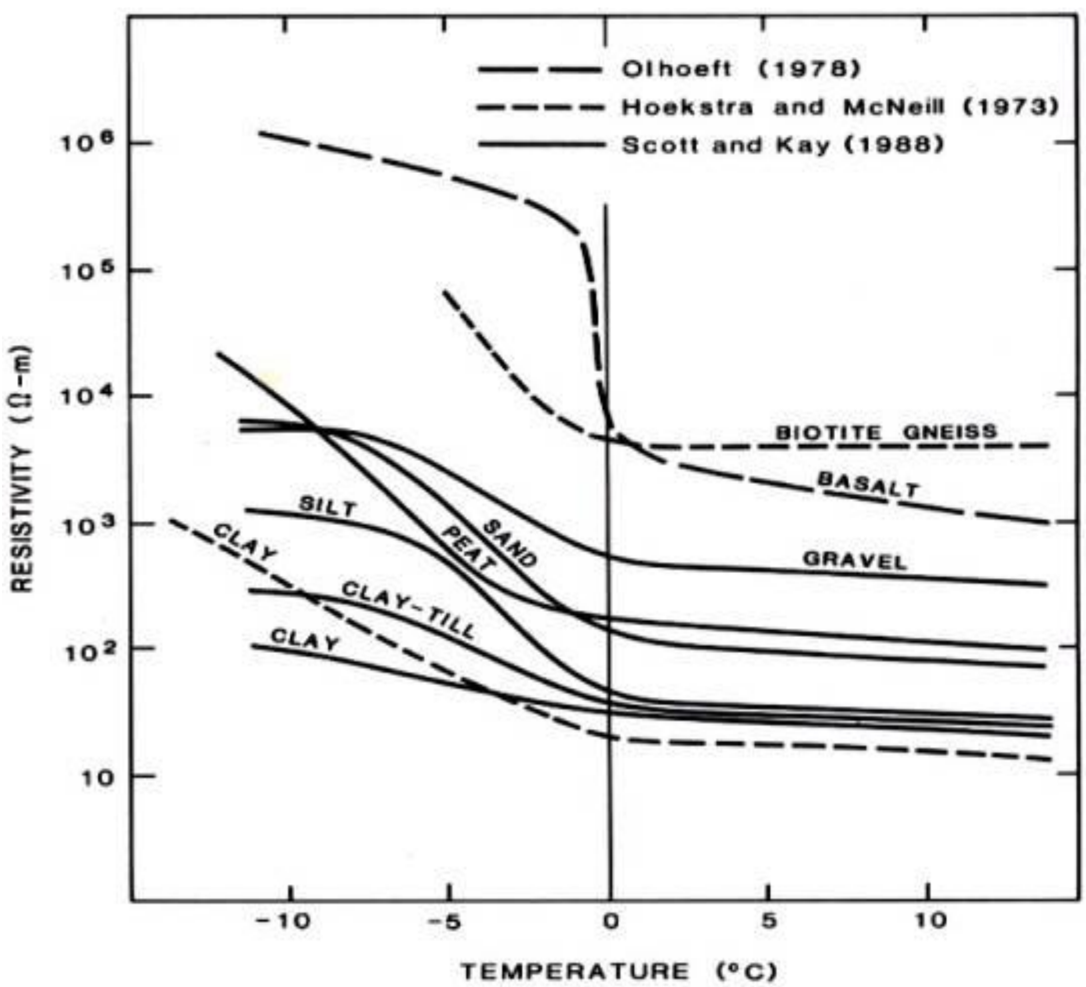
Appendix S

Appendix S Effects of Temperature and Freezing

Temperature effects the resistivity of soils. To adjust the resistivity observed at one Celsius temperature to the approximate resistivity that the same soil would have at another Celsius temperature the following approximation can be used:

$$R_{t2} = R_{t1} /(1 + .025(t_2 - t_1))$$

Freezing reduces the resistivity of soils and rocks. Following is a graph from *Geophysics in the Study of Permafrost* by Scott, Sellmann and Hunter pulished in Geotechnical and Environmental Geophysics, Volume 1, 1990, page 356



The graph is based on three papers:

Hoekstra, P., Sellman,P.V., and Delaney, A. J., 1975, Ground and airborne resistivity surveys

of permafronst near Fairbanks: *Geophysics*, Volume 40, pages 641-656.

Olhoeft, G.R., 1978, Electrical properties of permafrost: Proc. 3rd International Conf. on Permafrost, National Research Council of Canada, pages 127-131.

Scott, W.J. and Key, A.E., 1988, Earth resistivities of Canadian soils: Can. Elect. Assoc., Montreal. Vol. 1, Main Rep., Vol. 2, Site data.

Appendix T

References for terrain effects

The following is a short list of technical paper on the effect of terrain on resistivity surveys.

Fox, R., Hohmann, G., Killpack, T., and Rijo, L., 1980, Topographic effect in resistivitiy and induced polarization surveys: Geophysics, Vol. 45, 75-93.

Holcombe, J., and Jiracek, G., 1984, 3-D terrain corrections in resistivity surveys: Geophysics, Vol 49, 439-452.

Oppliger, G. L., 1984, Three-dimensional terrain corrections for mise-a-la-masse and magnetometric resistivity surveys: Geophysics, Vol. 49, 1718-1729.

Tong, L., and Yang, C., 1990, Incorporation of topography into 2-D resistivity inversion: Geophysics, Vol. 55, 354-361.

Tsourlos, P. I., Szymanski, J. E., and Tsokas, G. N., 1999, The effect of terrain topotraphy on commonly used resistivity arrays: Geophysics, Vol. 64, No. 5, 1357-1363.

Appendix U

Fall of Potential Method

The receiver portion of the MiniIRes is completely separated from the transmission portion of the MiniRes. You can not damage the MiniRes by connecting the wrong terminals together

There are at least three methods for measuring the electrical resistance of an **existing** grounding electrode. In the following it is assumed the existing electrode is a single 10-foot rod.

THREE ELECTRODE METHOD

The triangulation or "three electrode" method has the disadvantage that small errors in measuring or in positioning can generate large errors in the final answer. Two temporary electrodes are driven in the ground to form a triangle with the existing electrode as the third corner of the triangle. The temporary electrodes should be at least 15 feet (5 meters) and preferably 25 feet (8 meters) meters away from the electrode to be tested. Resistances are read between each of the pairs of electrodes. The resistances of the three electrodes (a, b, and x) are **Ra, Rb,** and **Rx**

$$Rx = \frac{(Rx + Ra) + (Rx + Rb) - (Ra + Rb)}{2}$$

DIRECT METHOD

The Direct method is some times referred to as the two-terminal method It is straight forward but subject to many sources of error. On the MiniRes the **P+** terminal is connected to the **C+** terminal and from there connected to the existing electrode The **P-** terminal is connected to the **C-** terminal and from there connected to the metallic water system or other metallic systems in good contact with the ground. Be careful of insulating couplings or systems isolated from ground by plastic moisture barriers or foam thermal insulating covers.

FALL OF POTENTIAL

The “Fall of Potential “ method is the most common method for measuring the electrical resistance of an **existing** grounding electrode. This method is some times referred to as the three terminal method. The various models of the MiniRes have been used extensively for the grounding of cell phone towers, electrical transmission line towers and, most recently, wind turbine towers.

First, be sure that the grounding electrode to be measured MUST be disconnected from the NEUTRAL connection during the grounding test. If the grounding electrode remains connected to NEUTRAL during your testing, the results will be erroneous

Connect the **P**- terminal of the MiniRes to the **C**- terminal and from there over to the grounding electrode that is being measured. That leaves the **C+** terminal to connect to the far electrode and the **P+** terminal to connect to the intermediate electrode. The distant electrode should be at a distance of at least ten times the length of the grounding electrode. All three electrodes should be in a straight line. Take readings with the intermediate electrode at **numerous measured** positions. Plot the readings. If the central quarter of the plot is relatively horizontal, you can use this value for the resistance of the ground electrode.

If the electrodes are too close together, there will not be a level “plateau” in the graph. You must expand the array until you do have a “plateau”. The value should be taken where the graph is about 62% of the distance from the electrode being tested and the far (C-) electrode.

If the ground electrode is not a single rod then the following would apply (the following is quoted from Brewer (1987)):

1. When the grounding system contains two or more electrodes along a straight line, the maximum dimension is the distance between the first and last electrode.
2. The maximum dimension for a grounding system containing electrodes in a circular ring configuration is the diameter of the circle.
3. The diagonal distance across a grounding system having a square or rectangular form is the maximum dimension.
4. The maximum dimension for a grounding system containing electrodes

in a star configuration is twice the length of a single branch.

NO EXISTING ELECTRODE

For sites where the grounding electrode system has not been installed as yet, the most common method of obtaining the necessary parameters for the designer is the Wenner technique. It is explained in another section of this manual. There are also some ASTM standards that can be obtained directly from ASTM over the internet.

CAUTION

All of the above methods assume lateral homogeneity and it is seldom the situation found. The designer of the system should make ample use of “the safety factor”.

REFERENCES

Brewer, Myron L., (1987), Measurement of resistance to ground, Chapter 12. Practical Grounding, Theory and Design (published by **abc** TeleTraining, Inc. Geneva, IL.

Tagg, G.F. *Earth Resistances* (1964), Pitman Publishing, London

Appendix W

Understanding the "Line Open" Light

If the LINE OPEN LED is flashing the instrument does not have sufficient voltage to emit a constant current, the best solution is to reduce the transmitter electrode contact resistance by wetting the ground around them or planting them deeper. If that fails, the RANGE switch can be moved to the HIGH position. On the *Super* MiniRes this reduces the output current from 10 milliamps to 1 milliamp but increases the available voltage from about 400 to about 730. On the *Standard* MiniRes it reduces the current from 5 to 0.5 milliamps

If the LINE OPEN LED is on steady, it indicates a very high resistance in the transmitter cables or electrodes. Check for a loose connection or broken cable.

Appendix X

Use of I P in Archaeology

If the induced polarization technique could be used with the same ease as the resistivity technique, it could be a great assistance in archaeological surveying. Now it can. The MiniRes is a reasonably priced instrument and does NOT require nonpolarizing electrodes. The MiniRes overcomes to the two long-standing objections to the use of I P in archaeological surveying.

The following is a quote from:

A Review of Geophysical Methods Used in Archaeology
by
Jeffrey C. Wynn

"The induced-polarization (IP) method has been used with moderate success since the 1960s (Aspinall and Lynam, 1968,1970). IP is useful because it can provide information on the presence of disturbed clay- or pyrite-rich horizons in an area where there has been human occupation. Limited field experience suggests that the IP method provides information of greater clarity than resistivity methods (Aitken, 1974: 191). The requirement of nonpolarizing electrodes slows down the field work considerably, however. The method is only rarely used now because of this time constraint and the cost of necessary sophisticated electronic equipment."

Aspinall, A., and Lynam, J.T. (1968). Induced polarization as a technique for archaeological surveying. *Prospezioni Archeologiche* 3, 91-93.

Aspinall, A., and Lynam, J.T. (1970), An induced polarization instrument for the detection of near-surface features. *Prospezioni Archeologiche,* vol. 5, pp. 67-75.

Aitken, M.J. (1974). *Physics and archaeology,* 2nd edition. Oxford: Clarendon Press, 286 pp.

In addition to disturbed soil, the IP survey can often detect buried metal objects of rather small size; objects difficult or impossible to detect by the resistivity method. See the survey presented in Appendix M

Appendix Y

References for the Square Array

For more details on the use of the square array see:

Habberjam, G.M. and G.E. Watkins, 1967, The use of a square configuration in resistivity prospecting, *Geophysical Prospecting*, Vol. 15, pp. 445-467

Habberjam, G.M., 19972, The effects of anisotropy on square array resistivity measurement, *Geophysical Prospecting*, Vol. 20, pp. 249-266.

Reynolds, J.M., 1997, *An Introduction to Applied and Environmental Geophysics*: New York, John Wiley & Sons, Inc. p. 796

An example of the use of the square array in an archeological survey is given in:

Mankowski, L., et al., A geophysical investigation of a sugar cane plantation, St. Croix, U.S. Virgin Islands: Using multiple techniques to assess a complex industrial site: SAGEEP 2000 Conference Proceedings, pp. 369-378

Examples of the use of the square array in fracture investigation are given in:

Lane, J.W., Jr., F.P. Haeni, and W.M. Watson, 1995, Use of a square-array direct-current resistivity method to detect fractures in crystalline bedrock in New Hampshire, *Ground Water*, Vol. 33, No. 3, pp. 476-485

Kenyon, R.M. and L.A. Brown, 1999, Use of square array resistivity to assess the style of jointing on the Palisades Cliffs, Northern new Jersey: SAGEEP 1999 Conference Proceedings, pp 21-29

Appendix Z

Appendix Z References for the Azimuthal Survey

For more details on the use of the azimuthal survey see:

Busby, J.P., 2000, The effectiveness of azimuthal apparent-resistivity measurements as a method for determining fracture strike orientations, *Geoophysical Prospecting*, Vol. 48, pp. 677-695

Carpenter, P.J., M.C. Keeley and R.S. Kaufmann, 1994, Azimuthal resistivity surveys over a fractured landfill cover, *Bulletin of the Association of Engineering Geologists,* Vol. 31, pp. 123-131

Cohn, M.E. and A.J. Rudman, 1995, Orientation of near-surface fractures from azimuthal measurements of apparent resistivity, 65th SSEG meeting, Houston, USA, Extended Abstracts, pp. 372-274

Matias, M.J.S. and G.M. Habberjam, 1986, The effect of structure and anisotropy on resistivity measurements, *Geophysics,* Vol. 51, pp. 964-971

Ritzi, R.W., Jr. and R.H. Andolsek, 1992, Relation between anisotropic transmissivity and azimuthal resistivity surveys in shallow, fractured, carbonate flow systems, G*round Water*, Vol. 30, pp. 774-780

Skjernaa, L. and N.O. Jorgensen, 1994, Evaluation of local fracture sustems bu azimuthal resistivitiy surveys; examples from south Norway, *Applied Hydrogeology,* Vol 2, pp. 19-25

Steinich, B. and L.E. Marin, 1997, Determination of flow characteristics in the aquifer of the northwestern peninsular of Yucatan, Mexico, *Journal of Hydrology,* Vol. 191, pp. 315-331

Taylor, R.W. and A.H. Fleming, 1988, Characterizing jointed systems by azimuthal resistivitiy surveys, *Ground Water*, Vol. 26, No. 4, pp. 464-474

Watson, K. and R.D. Barker, 1999, Differentiating anisotropy and lateral effect using azimuthal resistivity offset Wenner soundings, *Geophysics*, Vol. 64, pp. 739-745

Appendix ZZ

Negative Resistance Readings (Preliminary)

MiniRes manual, 30 July 2006

One of the most disconcerting events that occurs while taking resistivity measurements is to obtain negative resistance readings. Negative resistance readings should ALWAYS be examined with suspicion. A negative resistance reading should cause every bell and whistle to go off. It is possible, although extremely unlikely, that negative resistance readings can represent the true electrical response of a particular location. But that situation can ONLY arise under extreme conditions of 3 dimensionality and associated high contrast in subsurface resistivity distribution. It is unlikely that an operator will EVER measure a true negative resistance subsurface.

The vast majority of negative resistance measurements are associated with two causes, **instrumentation** problems or **field procedure** problems. **…….*It is wise to try and determine if the negative resistance readings are caused by instrumentation problems, field procedure problems or a combination of the two……*.** Simple and effective tests to determine whether the **instrument** is the cause of the negative resistance readings are:

1) **Zero reading with shorted receiver inputs test.** Shorted receiver inputs should always give a good zero measurement, typically to within a milliohm of so of true zero.

2) **Calibration resistor harness test.** The 19.00 ohm calibration resistor should give a reading typically within 0.1% of 19.000 ohms. It is also wise to swap the polarity of either the receiver or transmitter terminals of the calibration resistor and see that the absolute value of the negative reading is very close (to within 0.05%) to the value of the positive reading.

There are several tests and behaviors that determine whether the **field procedure** is proper:

a) **Proper electrode connection polarity test.** This is the prime cause of the majority of negative resistance readings. The first thing to do when seeing a negative resistance is to assure that the electrodes are hooked up in proper sequence, that none of the electrode wires is frayed and that the receiver and transmitter electrode wires separated.

b) **LINE OPEN LED test.** Hook up the transmitter output to the transmitter electrode pair and then the receiver electrode pair. The LINE OPEN LED should always be completely OFF in both configurations. If the LED comes ON or even flickers for an instant then there is too high of a resistance somewhere in the circuit. The LINE OPEN LED may come on due to bad electrical connections, an intermittently open wire, or, more commonly, high electrode contact resistances. High electrode contact resistances can be reduced by inserting each electrode deeper into the ground. See the section on Depth of Electrode Insertion Versus Contact Resistance. Sometimes the contact resistance can be lowered by wetting ***the soil around*** each electrode ***<u>with water</u>***. Good field procedure mandates that each electrode's contact resistance be minimized as much as practical.

c) **Reciprocity Theorem test.** This test is performed by simply swapping the transmitter electrodes with the receiver electrodes, maintaining the same polarity. According to the reciprocity theorem, the resistance measurement should be identical under either configuration. However, the noise may be much greater in one configuration than the other. But under low noise conditions the readings should be identical. If the two readings are not identical then try checking for high contact resistances or leakages from cables to ground or transmitter cables to receiver cables. The reciprocity test is one of the most basic and valuable tests of the validity of the field procedure. It is wise to perform the reciprocity test on EVERY array setup if integrity of the data is of utmost concern. The measurements in standard and reciprocal mode should both be logged. The reciprocity test is one of the best quality control checks available.

In general, the reciprocity theorem states that a perfect constant current generator applied to any two nodes (the transmitter ports) of any complicated linear circuit network (example: the earth and the electrodes and cable connections to it) may produce a voltage at any other two nodes (anywhere in the network - the receiver ports). The complex ratio of the receiver voltage to the transmitter current is the complex impedance of that network and those two ports. The reciprocity theorem states that if the positions of the constant current generator and the voltage receiver are swapped then the new complex ratio (impedance) of this new reciprocal configuration will be identical to the original. This theorem holds for the complex case, both RESISTIVITY and IP readings should be identical under normal or reciprocal configurations.

The reason that the reciprocity test is so effective is because it tests the validity of the assumption of the "perfect" constant current generator and the "perfect" receiver. When the transmitter electrodes are swapped for the receiver electrodes the transmitter and receiver are presented with, typically, different loading characteristics. If the transmitter is not capable of outputting an exactly equal amount of current with the new loading characteristics then the measured value in the reciprocal mode will be different. Likewise, if the receiver presents a different amount of "loading" in the reciprocal mode then the measured value will be different.

The reciprocity test senses several types of instrument and field procedure problems.

1) Instability of the transmitter's constant current generator under varying load conditions

2) Too low of an input impedance on the receiver's input

3) Too high (or low) of electrode contact resistance for the transmitter to maintain a constant current output

4) Too high of a receiver electrode resistance - causing the receiver's input impedance to load the reading - causing the measured reading to be lower than it should be

5) The infamous "cable reel" problem will exhibit its nature during the reciprocity test, especially if the configuration of the receiver reels is quite different from the configuration of the transmitter reels

6) The nested-bridge error condition (see below) may show up also, depending on the specific values in the individuals legs of each of the two nested bridges

d) Reversed Polarity Test. Reverse the polarity of the transmitter electrode pair and then the receiver electrode pair. The reading should first reverse polarity and then return to normal polarity. This is very similar to the "shorted receiver inputs test". But this test tests the linearity of the receiver under non-zero bipolar conditions. For example, an abnormally weak negative analog receiver supply voltage will cause the positive reading to be different than the negative of the reversed polarity reading, whereas the "shorted receiver inputs test" would not show an error.

e) Resistor in-series with Electrode test. This test involves inserting a resistor (typically 1 Kohm in value) in series with any one of the four electrodes. This is most conveniently done at the respective binding post. The change in the resistance reading caused by the insertion of the resistor into either receiver electrode line should be in the neighborhood of 1 part in 100000. This means that the change should be imperceptible (essentially constant reading) if the instrument is operating properly and the field procedure is proper. Also, if the transmitter constant current generator is operating properly, the transmitter voltage will increase to maintain the current exactly constant and the resistance reading will remain constant. So the resistance reading should remain completely constant when the 1 Kohm resistor is inserted into any one of the four legs of electrode circuit. However, if the resistance reading varies by a noticeable amount then an error condition exists. The possible error conditions that this tests locates are:

1) Inability of the transmitter current generator to maintain a proper constant current

2) Too low of an input impedance on the receiver

3) Electrical leakage internal to the instrument

4) Nested-Bridge error condition described below

f) Nested-Bridge leakage error. Lastly, many times an interaction between high (and unequal) contact resistances and surface leakage currents arise within the instrument which can cause mysteriously befuddling problems, including negative resistance readings. To grasp the nature of this interaction it is simplest to present a very simple (and unrealistic) model of the instrument, earth, contact resistances and leakages. Firstly, assume that the innate resistivity of the earth is zero. Secondly, assume that each of the four electrodes has its singular contact resistance. Thirdly, assume that each binding post has current leakage to the faceplate. Fourthly, define the faceplate as being at zero volts - it will be the voltage reference for this simple and unrealistic model. The MiniRes, is, of course, an alternating current device, but a simple DC model will be used to simplify this illustration while giving intuitive insight into the nature of the problem. See drawing "Electrical Model of Faceplate, Earth, Leakage and Contact Resistances"

Model assumptions:

1) faceplate is the voltage reference, by definition zero volts

2) the leakage resistance of each receiver and transmitter terminal to the faceplate is 1 Gigaohm (1000 Megohms). This 1 Gigaohm value is reasonable and realistic, however, it is NOT realistic that all four leakage resistances be equal, but we assume so for the benefit of analysis of this model. The leakage can realistically be much better or worse than this value depending on the temperature, humidity, cleanliness of the binding posts' insulators and the type of material used for the binding post insulator.

3a) the contact resistance between the transmitter's C+ electrode and ground is 100 ohms

3b) the contact resistance between the transmitter's C- electrode and ground is 20 Kohms

4) the contact resistance between the receiver's P+ electrode and ground is 100 ohms

4a) the contact resistance between the receiver's P- electrode and ground is 10 Kohms

5) the earth's resistivity for this model is zero - it is a perfect conductor

6) the transmitter's constant current generator is outputting exactly 10 milliamps = 0.01 amps

7) assume that the receiver's input impedance is infinite, not loading the receiver's signal

8) The transmitter's 0.01A constant current generator will develop about 200 volts across the transmitter's output terminals (20 Kohms/.01Amp = 200 volts)

9) The 100 ohm and 20 Kohm transmitter electrode contact resistances will act as a voltage divider resulting in about +100 volts (with respect to the faceplate) between the faceplate and ground

10) The receiver's P- electrode contact resistance of 10 Kohm and its leakage resistance to the faceplate of 1 Gigaohm acts as a voltage divider resulting in a voltage of +99.999 volts at the P- terminal with respect to the faceplate

11) The receiver's P+ electrode contact resistance of 100 ohms and its leakage resistance to the faceplate of 1 Gigaohm acts as a voltage divider resulting in a voltage of about +100 volts at the P+ terminal with respect to the faceplate

12) The differential voltage between the P+ and P- terminals is +100-99.999 volts = +1 millivolt.

13) This +1 millivolt error voltage will create a error resistance reading of +0.1 ohms (+0.001volt/0.01A = +0.1 ohms)

14) If the transmitter and receiver electrode contact resistances are swapped then the same exercise can be carried out and the results would show a NEGATIVE error of -0.1 ohms

So, it is clear that this simple model can produce a negative resistance component of -0.1 ohms. This error would, normally, add itself to the "true" resistance reading. So, for example, if the "true" resistance reading of a particular array configuration was +0.045 ohms then the actual reading with the error would be +0.045 - 0.1 = -0.055 ohms and the operator, likely, would be perplexed by this NEGATIVE reading.

It is instructive to redraw the above electrical model in the form of two electrical bridges, with one inside of the other. This can be referred to as a NESTED BRIDGE electrical model. This makes it more clear that this complex response of the resistivity meter to leakages and contact resistances is a "balancing act" with characteristics of the common "bridge" circuit, but complicated by being "nested". This simple model explains several befuddling and mysterious aspects of resisitivity measurements:

A) The +1 millivolt error voltage described above can be reduced by DECREASING the value of

either or both of the larger receiver or transmitter contact resistances

B) More, seemingly mysterious, is the fact that the + 1 millivolt error voltage can also be decreased by INCREASING either or both of the 100 ohm receiver or transmitter contact resistances, thus bringing the bridges more into balance

C) Also, it should be clear that the binding-post-to-faceplate leakage resistances can also be manipulated to increase or decrease the error voltage

D) It should be clear that this error voltage of +1 millivolt is of little consequence (a small percentage of the total "true" voltage) if the earth's resisitivity is very high and/or the Wenner Array "a" spacing is small. In other words, if the true earth resistance measurement is 15.000 ohms then this +1 millivolt error will only represent a 0.7% error.

E) That implies that this error becomes a greater problem as the earth's resistivity decreases and/or the Wenner Array "a" spacing increases. The problem may always be there, but it will become a greater percentage of the total as the "true" resistance measurement becomes smaller

F) Note that it is possible that varying ANY one of the leakage resistances or contact resistance may drastically change the error voltage. For example, if ONLY the transmitter contact resistances had been matched in the above model so that they were both 10 Kohms or both 100 ohms then the faceplate to ground voltage would be 0 volts and the imbalance of the receiver's contact resistances would be immaterial, there would be NO error voltage. Likewise, a balance of the receiver's electrode contact resistances would cause a high COMMON mode voltage but a zero DIFFERENTIAL voltage and there, again, would be NO error voltage.

G) On the other hand, it should be clear than an imbalance in any one of the legs of the nested bridge can be compensated by a counteracting imbalance in another leg of the nested bridge - another one of the befuddling mysteries explained with this simple model.

H) One of the key unusual characteristics of this "mysterious" situation is the fact that the error voltage is proportional to the VOLTAGE at the transmitter's binding post, and, typically, that voltage is very unstable and noisy. The reason for the noise and instability of the transmitter's output voltage is because, although the output current is precisely regulated, noise free and stable, the transmitter's two electrode contact resistances can change quite drastically with time, and as those contact resistances change, the transmitter's output voltage changes, and, therefore, the error voltage changes proportionately also. This is in distinct contrast to what is EXPECTED of a resistivity meter - that the response of the instrument is proportional to the CURRENT output of the transmitter - NOT the voltage output.

WIth this general understanding of this error phenomenon the question arises, how is it recognized and how is it ameliorated? The ideal situation is to have extremely LARGE leakage resistances from the binding posts to the faceplate - the higher the better. In the limiting condition of infinite leakage resistances from the binding posts to the faceplate this model indicates that the error voltage will disappear. Likewise, the ideal situation is to have extremely LOW electrode contact resistances. Again, in the limiting condition of zero resistance for each electrode contact resistance, the model indicates that the error voltage will disappear.

In practice these behaviors suggest that the binding posts' insulators should always be clean and free from moisture and that each electrode's contact resistance should be minimized. It also shows that a standard Wenner Array will have smaller percentage errors than a Schlumberger Array under identical conditions of contact resistances and leakage resistances - in this respect the Wenner Array is clearly superior.

A few ways to recognize this condition in the field is to reduce the electrode resistance (by pushing each electrode deeper into the ground) and look for a significant variation in the meter reading after adjusting each electrode. The NESTED BRIDGE model indicates that the meter reading may either increase or decrease by pushing any one electrode deeper in the ground - it depends on the particular imbalance that exists within the nested bridge.

Another way to test for the nested-bridge error condition is to add a resistance into one or more legs of the bridge and see if it unbalances or balances the bridge and, therefore, changes the resistance reading. This is NOT proof-positive of the nested-bridge error condition because other problems can create variations in readings when resistances are put in series with the electrodes.

Although this model is simplistic it is, nonetheless, true that EVERY resistivity meter and EVERY array setup will ALWAYS experience an error (however slight) from this situation. However, that error can be made negligible by:

1) Minimizing all electrode contact resistances

2) Maximizing all leakage resistances

3) Designing the resistivity array to measure a larger proportion of the voltage drop created by the transmitter current (hence, a Wenner Array will suffer less than a Schlumberger Array)

4) In the extremely unlikely event that it is too difficult to reduce all of the contact resistances sufficiently, then an attempt may be made to balance one or another of the legs of the bridges by INCREASING the contact resistances by pulling it out so that it is not so deeply in the ground.

The model presented above was simple, it only showed the zero resistance ground and the faceplate. In reality, every piece of conductor on the printed circuit board acts as a small "faceplate" and there is leakage between electronic components in the receiver and transmitter that make the model much more complicated. Significant design effort was expended on the MiniRes in order to minimize those leakage currents. The lowest leakage optical couplers were chosen for communication between the transmitter and receiver and the DC-DC converter was specifically chosen for its low leakage specifications. The printed circuit board itself has slots designed in to maximize the path length of leakage currents from the transmitter to the receiver greatly increasing the value of the leakage resistance between the transmitter and receiver