Principles and Practice
of
Earth Electrode Measurements

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Principles and Practice of Earth Electrode Measurements

1. Introduction

This application note describes principles and methods for measuring the resistance to remote earth of grounding systems (earth electrode systems) used in telecommunications facilities. This note does not describe all earth electrode measurement techniques but only those found through field experience to be most useful and consistent. While test equipment is in the field for resistance measurements, it is convenient to also measure soil resistivity; therefore, this application note also describes soil resistivity measurements.

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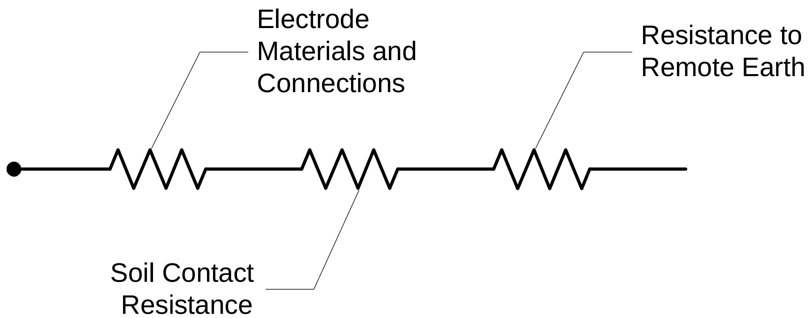
2. Ground Measurement Principles

The object of an earth electrode system is to provide a low resistance to foreign currents that may cause injury or damage or disrupt equipment. The currents will dissipate safely when properly conducted to earth via the electrode. There are three components to the resistance (Fig. 1):

- Resistance of the electrode materials and connections to them
- Contact resistance between the electrode and the soil surrounding it
- Resistance of the surrounding earth.

Fig. 1 – Equivalent Resistance Circuit of an Earth electrode System



The resistance of the electrode materials is purposely made small so their contribution to the total resistance is negligible. Generally, copper materials are used throughout. Ground rods usually are copper-coated steel for strength, although galvanized steel ground rods are found in applications where corrosion is a problem.

The contact resistance between the electrode and soil is negligible if the electrode materials are clean and unpainted when installed and the earth is packed firmly. Even rusted steel ground rods have little contact resistance because the iron oxide readily soaks up water and has less resistance than most soils (however, rusted ground rods may eventually rust apart in which case their effectiveness is greatly reduced).

Generally, the resistance of the surrounding earth will be the largest of the three components. An earth electrode system buried in the earth radiates current in all directions and eventually dissipates some distance away depending on the soil's resistance to current flow, as indicated by its *resistivity*.

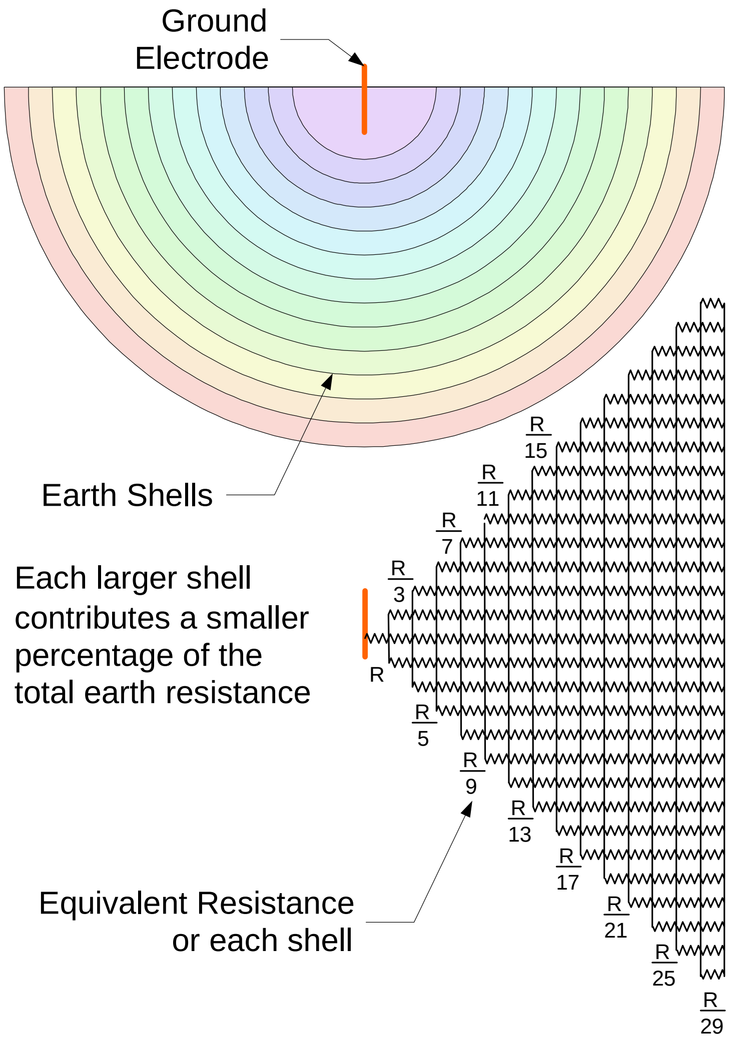
An earth electrode system consists of all interconnected buried metallic components including ground rods, ground grids, buried metal plates, radial ground systems and buried horizontal wires, water well casings and buried metallic water lines, concrete encased electrodes (Ufer grounds), and building structural steel.

The earth electrode can be thought of as being surrounding by shells of earth, each of the same thickness (Fig. 2). The shell closest to the electrode has the smallest surface area and offers the greatest resistance. The next shell has larger area and lower resistance, and so on. A distance eventually will be reached where the additional earth shells do not add significantly to the resistance. Earth electrode resistance is measured to remote earth, which is the earth outside the electrode's influence. A larger electrode system requires greater distance before its influence decreases to a negligible level.

Another way of thinking about the earth shells is as parallel resistances. The closest shell has some unit resistance. The next larger shell has more surface area so it is equivalent to several unit resistances in parallel. Each larger shell has smaller equivalent resistance due to more parallel resistances.

The resistance of the surrounding earth depends on the soil resistivity. Soil resistivity is measured in ohm-meters (ohm-m) or ohm-centimeters (ohm-cm) and is the resistance between two opposite faces of a 1 meter or 1 centimeter cube of the soil material. The soil resistivity depends on the type of soil, salt concentration and its moisture content and temperature. Frozen and very dry soils are a good insulators (have high resistivity) and are ineffective with earth electrodes. The resistivity of many soil types is provided in Section 8.

Fig. 2 – Concentric Earth Shells Around an Earth electrode



3. Test Equipment

Three typical test sets are shown in Fig. 3. A typical test set has four terminals – two current terminals marked C1 and C2 and two potential terminals marked P1 and P2. Other markings are used on test sets originally designed outside the United States. Cheap test sets may have only three terminals; these should be avoided because of their limited usefulness and questionable durability. Also, it has been found in the field that some expensive digital test sets are worthless, particularly some of the DETx/x models that have been sold by Biddle over the years.

Fig. 3 – Typical Test Sets (l-r: Biddle “Megger” 240241, AEMC 4630, Biddle DET5/2)

One current terminal (C1) is connected to the earth electrode under test and the other (C2) to a probe driven in the earth some distance away. The test set injects a current into the earth between the two current terminals. One potential terminal (P1) also is connected to the earth electrode but the other potential terminal (P2) is connected to a separate probe driven in the earth between the electrode and the current probe (C2). The potential probes detect the voltage due to the current injected in the earth by the current terminals. The test set measures both the current and the voltage and internally calculates and then displays the resistance

$$R = \frac{V}{I} \text{ ohms}$$

Some test sets use a resistive bridge circuit that requires manual adjustment of the resistance to balance the bridge as indicated by a null meter. When the meter has a null reading, the value is taken from the resistance controls. Most modern test sets require no manual adjustment.

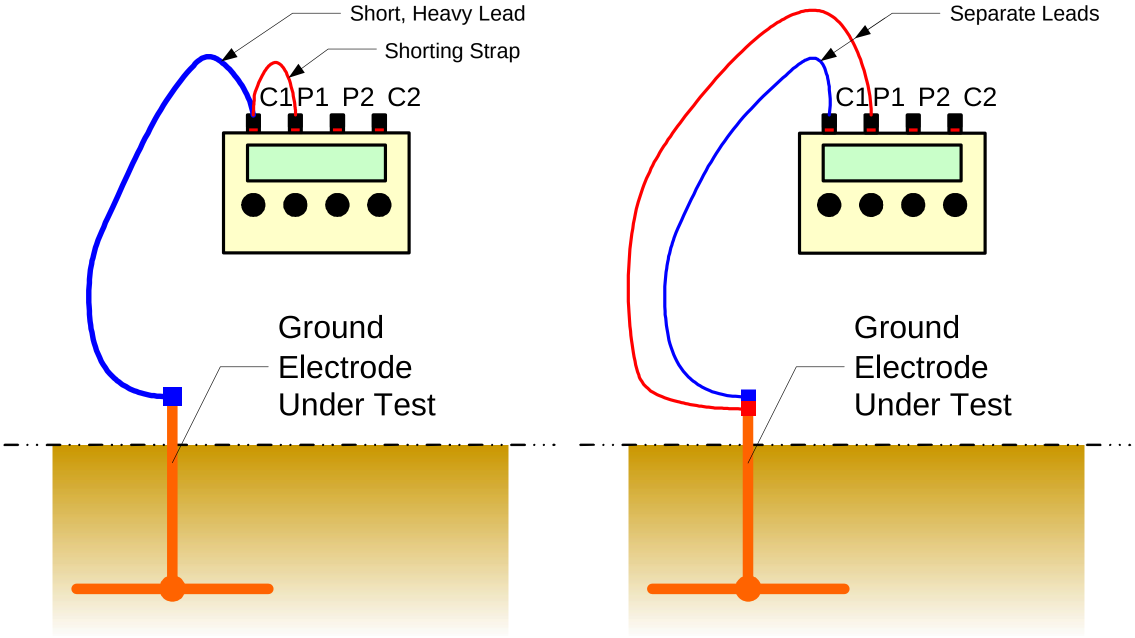
The resistance indicated by the test set is the resistance between the earth electrode and the potential probe. If the current and potential probes both are far enough away from the electrode, that is, outside the influence of the electrode, the reading corresponds to the resistance of the electrode to remote earth.

When measuring the resistance of earth electrode systems, C1 and P1 are connected together either at the test set or at the electrode. If connected at the test set, say with a jumper, the resistance of the wire from the test set to the earth electrode adds to the reading. The value of this resistance can be measured easily with the test set:

(1) Short C1 and P1 together with a short jumper;
(2) Short P2 and C2 together with a short jumper;
(3) Connect the test lead between P1 and P2 and measure the resistance;
(4) Subtract the reading from all electrode resistance measurements subsequently taken.

To avoid having to make these additional measurements and calculations, always use a short, low-resistance conductor between the test set and the electrode when C1 and P1 are shorted at the test set (Fig. 4 – left), or always connect C1 and P1 to the electrode with separate leads (Fig. 4 – right). If the two terminals are connected together at the electrode, the length and size of the conductor does not affect the measurement. The size of the wires connected to the other two terminals, P2 and C2, are not important from an electrical standpoint but should be large enough to provide the needed physical strength. Additional details concerning the probes, leads and test equipment are provided in Section 7.

Fig. 4 – Test Equipment to Earth electrode Connections



Test sets with four terminals also may be used to measure soil resistivity (test sets with three terminals cannot be used to measure soil resistivity). Each terminal is connected to an independent probe resulting in two potential and two current probes. Soil resistivity measurements are covered in Sect. 8.

4. Fall-of-Potential Method

The Fall-of-Potential method (sometimes called the Three-Terminal method) is the most common way to measure earth electrode system resistance, but it requires special procedures when used to measure large electrode systems (see Measuring Large Electrodes below). For small electrodes, such as one or a few ground rods or a small loop, the Fall-of-Potential method requires only simple procedures (see Measuring Small Electrodes below).

4.1 Basic Procedure

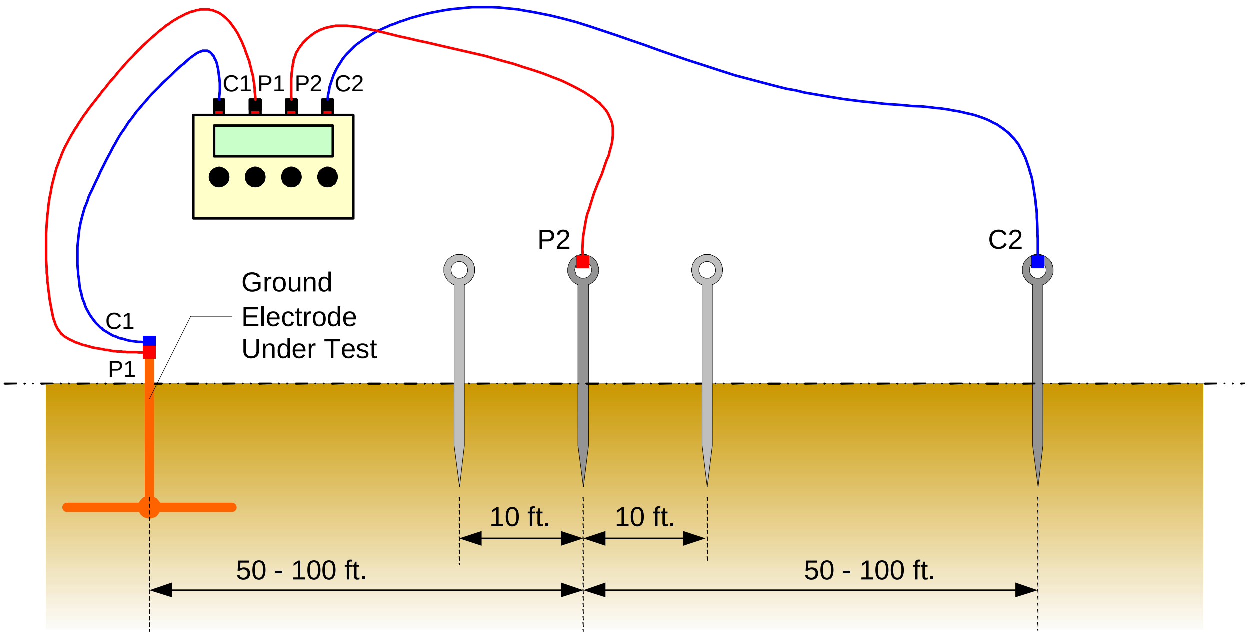
The basic procedure for the Fall-of-Potential method is to first connect the test set terminals C1 and P1 to the earth electrode under test, connect the test set C2 terminal to a current probe located some distance from the earth electrode and finally connect the test set P2 terminal to a potential probe located a variable distance between. The two probes normally are located in a straight line. At each potential probe location, the resistance is recorded (a form is provided in

Appendix I for this purpose). The results of these measurements are then plotted to graphically determine the electrode resistance.

4.2 Measuring Small Electrodes

1. Connect C1 and P1 terminals on the test set to the earth electrode (Fig. 5).
2. Drive a probe into the earth 100 to 200 feet from the center of the electrode and connect to terminal C2. This probe should be driven to a depth of 6 – 12 inches.
3. Drive another probe into the earth midway between the electrode and probe C2 and connect to terminal P2. This probe should be driven to a depth 6 – 12 inches.
4. Record the resistance measurement.
5. Move the potential probe 10 feet farther away from the electrode and make a second measurement.
6. Move the potential probe 10 feet closer to the electrode and make a third measurement.
7. If the three measurements agree with each other within a few percent of their average, then the average of the three measurements may be used as the electrode resistance.
8. If the three measurements disagree by more than a few percent from their average, then additional measurement procedures are required (see Measuring Large Electrodes).

Fig. 5 – Small Electrode Measurements

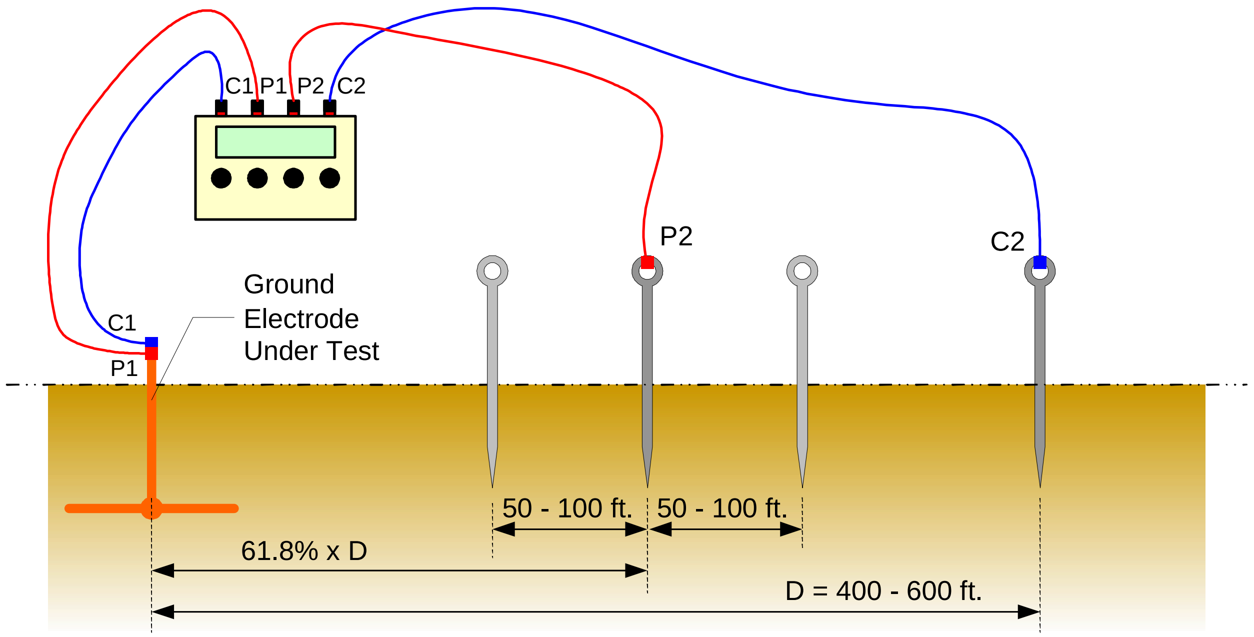


4.3 Measuring Large Electrodes

A quick set of measurements can be made as follows (Fig. 6). This method eliminates many tedious measurements but may not yield good accuracy unless the current and potential probes are outside the electrical influence of the electrode system:

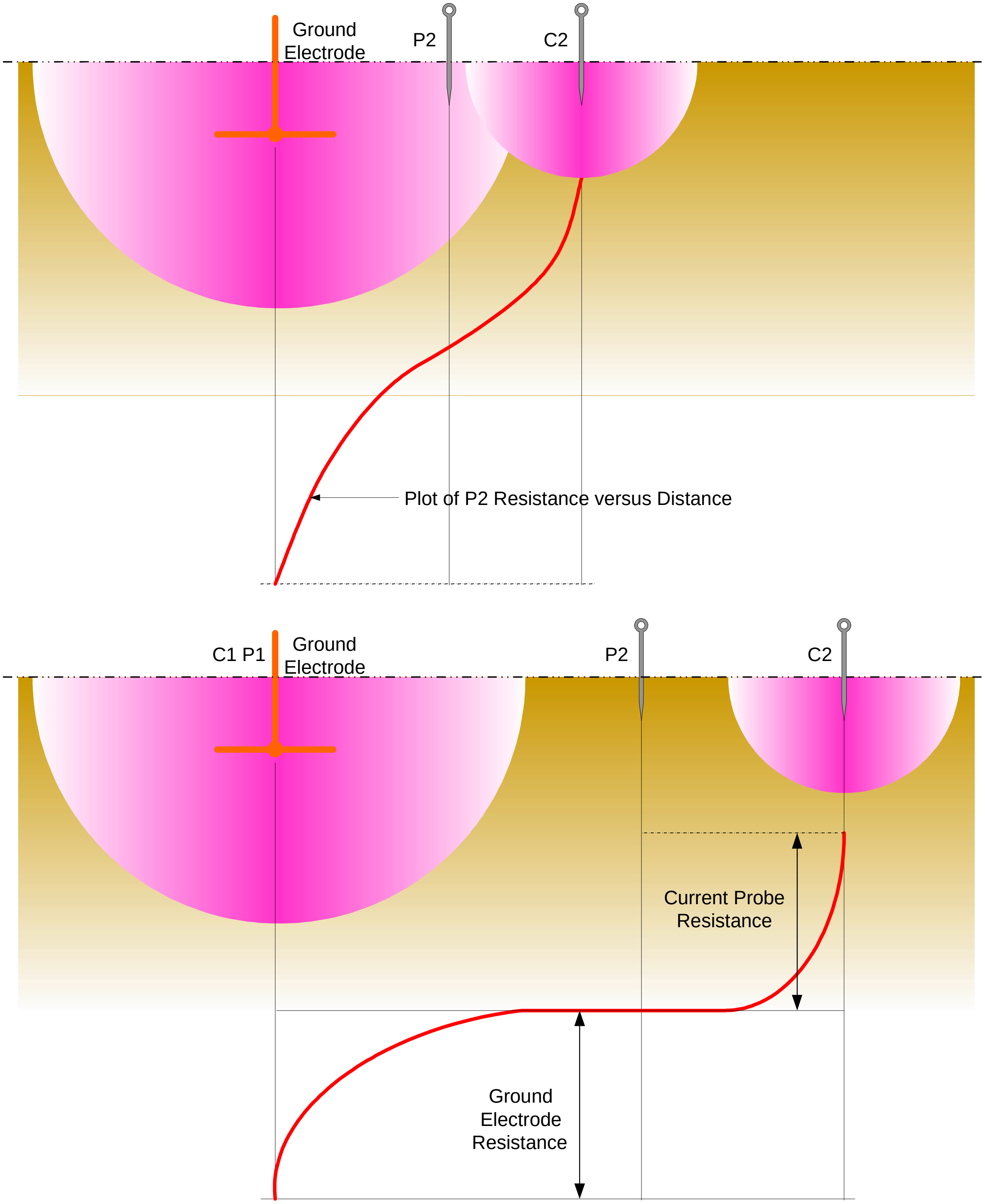
1. Place the current probe 400 – 600 feet from the electrode
2. Place the potential probe 61.8% of the distance from the electrode to the current probe
3. Measure the resistance
4. Move the current probe farther away from its present position by, say, 50 – 100 feet
5. Repeat steps 2 and 3
6. Move the current probe closer by, say, 50 – 100 feet
7. Repeat steps 2 and 3
8. Average the three readings

Fig. 6 – Quick Measurements of Large Electrode Systems



As discussed in Sect. 1, the earth electrode can be thought of being surrounded by concentric shells of earth. The current probe also is surrounded by earth shells but with a commensurately smaller influence. It is necessary to locate the current probe far enough away so the influential shells do not overlap (Fig. 7).

Fig. 7 – Overlapping and Non-Overlapping Shells of Earth



Fall-of-Potential measurements are based on the distance of the current and potential probes from the center of the electrode under test. However, the location of the center of the electrode seldom is known, especially if it consists of numerous types of bonded electrodes such as ground rods, grids, concrete-encased electrodes (Ufer grounds), water well casings and buried radial wires. In these cases, special procedures, such as the *Intersecting Curves* or *Slope* methods, are required. These are described in later sections.

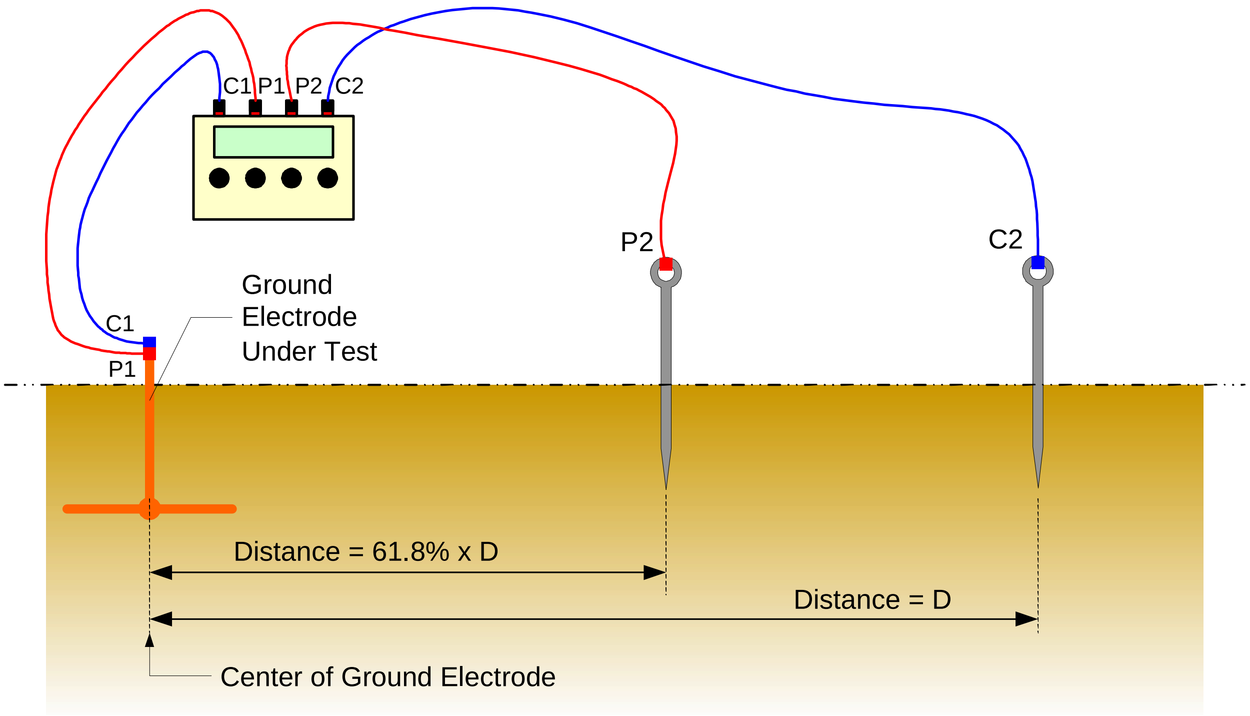
The farther a probe is placed from the electrode, the smaller the influence. The best distance for the current probe is at least 10 to 20 times the largest dimension of the electrode (Table 1). However, terrain or obstructions, such as buildings and paved roads, can greatly limit the space available for measuring larger systems. Nevertheless, acceptable accuracy can be obtained by using smaller distances in most situations.

Table 1 – Current Probe Distance from Electrode

Maximum Electrode Dimension (Feet)	Distance to Current Probe from Electrode Center (Feet)
15	300
30	450
60	600

It can be shown (Appendix II) that the actual electrode resistance is measured when the potential probe is located 61.8% of the distance between the center of the electrode and the current probe (Fig 8). For example, if the current probe is located 400 feet from the electrode center, then the resistance can be measured with the potential probe located 61.8% x 400 = 247 feet from the electrode center. The 61.8% measurement point assumes the current and potential probes are located in a straight line and the soil is homogeneous (same type of soil surrounding the electrode area and to a depth equal to 10 times the largest electrode dimension). While the latter condition is almost never known with certainty, the 61.8% measurement point still provides suitable accuracy for most measurements if other cautionary measures are taken as described below.

Fig. 8 – 61.8% Distance for Resistance Measurement



As mentioned above, the electrode center location seldom is known. In this case, at least three sets of measurements are made, each with the current probe a different distance from the electrode, preferably in different directions. However, when space is not available or obstructions prevent measurements in different directions, suitable measurements usually can be made by moving the current probe in a line away from or closer to the electrode. For example, the measurement may be made with the current probe located 200, 300 and 400 feet along a line from the electrode.

Each set of measurements involves placing the current probe and then moving the potential probe in 10 feet increments toward or away from the electrode, depending on the starting point. The starting point is not critical but should be 20 to 30 feet from the electrode connection point, in which case the potential probe is moved in 10 feet increments toward the current probe, or 20 to 30 feet from the current probe, in which case the potential probe is moved in 10 feet increments back toward the electrode.

The spacing between successive potential probe locations is not particularly critical, and does not have to be 10 feet, as long as the measurements are taken at equal intervals along a line between the electrode connection and the current probe. Larger spacing means quicker measurements at the expense of fewer data points; smaller spacing means more data points at the expense of slower measurements.

Based on the above, the basic steps for accurately measuring earth electrodes of the type found at telecommunications facilities are as follows. If obstructions do not permit using the probe spacings specified, make as many measurements as possible with the current probe as far and in different directions from the electrode under test as possible:

1. Place the current probe (C2) 200 feet from the electrode under test
2. Place the potential probe (P2) 20 feet from the point at which the test set is connected to the earth electrode
3. Measure and record the resistance
4. Move the potential probe (P2) farther away by 10 feet
5. Repeat steps 3 and 4 until the potential probe (P2) is within 20 or 30 feet of the current probe (C2)
6. Move the current probe (C2) 300 feet from the electrode under test
7. Repeat steps 2 through 5
8 Move the current probe (C2) 400 feet from the electrode under test
9. Repeat steps 2 through 5

Once all measurements have been made, the data is plotted with the distance from the electrode on the horizontal scale and the measured resistance on the vertical scale. The curves for each data set should be smooth with no significant peaks or valleys. If there are departures from a smooth curve, these data points can be re-measured, ignored or replaced artificially by interpolating between two good data points. If the current probe is outside the electrode's influence, the curves will rise as the potential probe is moved away from the electrode, increase with a slight positive (increasing) slope and then level off just beyond the mid-point between the electrode and current probe. As the potential probe approaches the current probe, the slope will increase sharply.

If the curves do not level off in the middle but have a small slope, the probes were only partially influenced by the electrode, and the resistance can be read from the curve at a point that is 61.8% of the distance to the current probe.

If the curves have a steep slope, the electrode influenced the measurements and reading the resistance at the 61.8% point usually gives a resistance that is higher than actual. In this case, the *Intersecting Curves* and *Slope* procedures may be used to manipulate the data to yield a more accurate resistance value.

Example: The resistance data in Table 2 were measured at a site near Seward, AK. The earth electrode consists of #2 AWG bare copper grid with overall dimensions of 40 feet by 60 feet. Grid spacing is 10 feet, and total conductor length is 580 feet. Burial depth is approximately 4 feet below grade (underneath the building foundation).

Measurements in Columns (2), (3) and (4) were taken with the C2 probe at 200, 300 and 400 feet from the connection to the earth electrode. Columns (5) through (11) are for separate intersecting curve calculations that will be used in the next section.

The Fall-of-Potential curve corresponding to the measurements with C2 at 200 feet is fairly steep, which indicates influence by the earth electrode (Fig. 9). The influence with C2 at 300 and 400 feet is considerably less as indicated by the comparatively flat slope and overlap of the two curves.

The earth electrode resistance can be estimated by examining the curves or field data at the 61.8% point, or a P2 distance of 124, 185 and 247 feet on the three curves, respectively. For P2 = 124 feet and C2 = 200 feet, the estimated resistance is approximately 16 ohms. The other two curves yield approximately 15.4 and 15.6 ohms, respectively. An average of the three is 15.7 ohms. Since the second and third data sets (C2 = 300 and 400 feet) yield resistances that are closer together than the first and second data sets, they probably are more accurate. The average of these two is 15.5 ohms.

Fig. 9 – Example Fall-of-Potential Curves

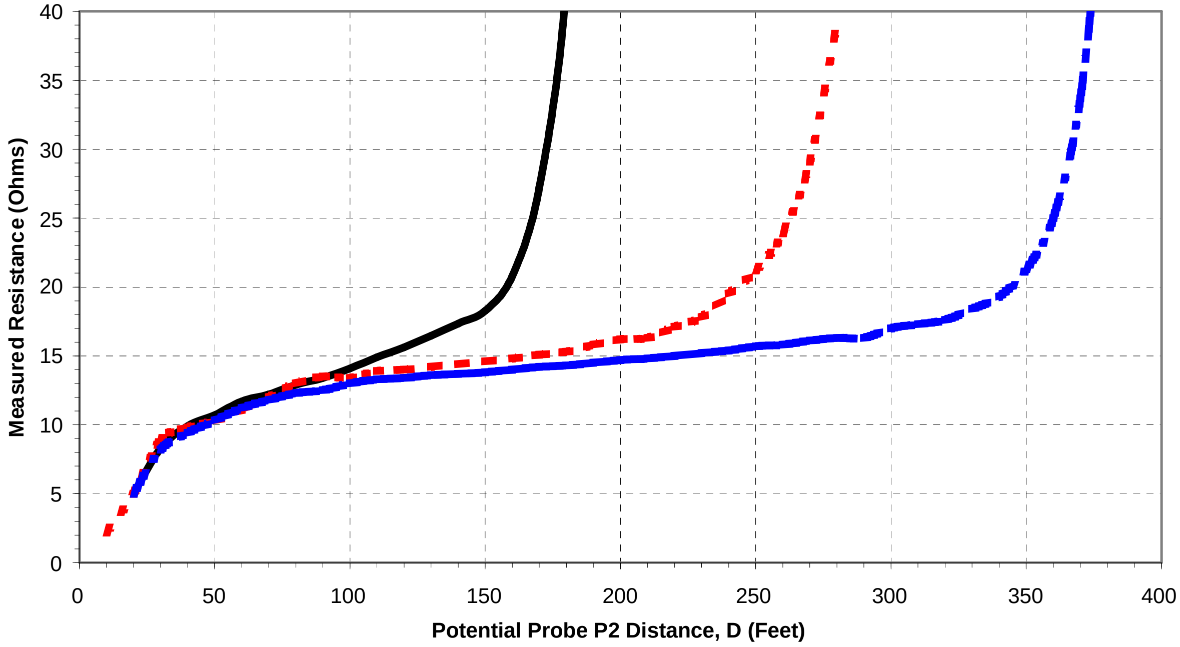


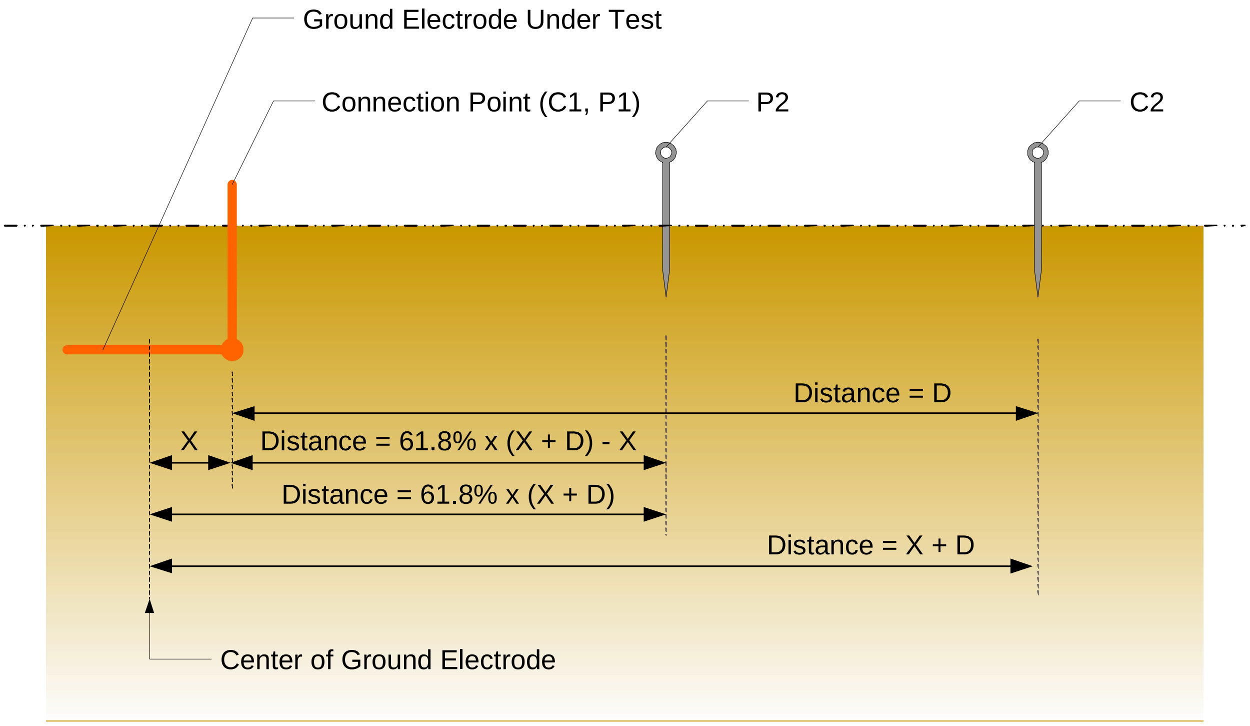
Table 2 – Example Data Sets

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
					C2 = 200 ft.		**C2 = 300 ft.**		**C2 = 400 ft.**	
P2 (ft)	**C2=200 ft**	**C2=300 ft**	**C2=400 ft**	**X (ft)**	**P' (ft)**	**R' (ohms)**	**P' (ft)**	**R' (ohms)**	**P' (ft)**	**R' (ohms)**
	R (ohms)	**R (ohms)**	**R (ohms)**	0	124	15.96	185	15.55	247	15.61
10				10	120	15.63	182	15.40	243	15.49
20	5.00	5.00	5.00	20	116	15.34	178	15.26	240	15.40
30	8.30	8.90	8.20	30	112	15.05	174	15.18	236	15.32
40	9.90	9.80	9.40	40	108	14.74	170	15.10	232	15.24
50	10.70	10.30	10.30	50	105	14.50	166	14.98	228	15.16
60	11.70	11.10	11.20	60	101	14.18	162	14.86	224	15.08
70	12.20	12.00	11.80	70	97	13.89	159	14.78	220	15.00
80	12.90	13.00	12.30	80	93	13.61	155	14.70	217	14.94
90	13.40	13.50	12.50	90	89	13.35	151	14.62	213	14.80
100	14.10	13.40	13.00	100	85	13.15	147	14.54	209	14.79
110	14.90	13.90	13.30	110	82	13.00	143	14.26	205	14.75
120	15.63	14.00	13.40	120	78	12.28	140	14.40	201	14.71
130	16.47	14.20	13.60	130	74	12.24	136	14.32	198	14.66
140	17.35	14.40	13.70	140	70	12.20	132	14.24	194	14.58
150	18.28	14.60	13.80	150	66	12.00	128	14.16	190	14.50
160	20.80	14.80	14.00	160	62	11.80	124	14.08	186	14.42
170	27.20	15.10	14.20	170	59	11.60	120	14.00	182	14.34
180	41.80	15.30	14.30	180	55	11.20	117	13.97	178	14.28
190	76.90	15.80	14.50	190	51	10.80	113	13.93	175	14.25
200		16.20	14.70	200	47	10.46	109	13.85	171	14.21
210		16.30	14.80	210	43	10.14	105	13.65	167	14.14
220		17.10	15.00	220	40	9.90	101	13.45	163	14.06
230		17.80	15.20	230	36	9.26	98	13.42	159	13.98
240		19.50	15.40	240	32	8.62	94	13.46	156	13.92
250		21.20	15.70	250	28	7.64	90	13.50	152	13.84
260		23.90	15.80	260	24	6.32	86	13.30	148	13.78
270		29.10	16.10	270	20	5.00	82	13.10	144	13.74
280		39.00	16.30							
290			16.30							
300			17.00							
310			17.30							
320			17.60							
330			18.40							
340			19.30							
350			21.30							
360			25.00							
370			33.70							
380			52.10							

5. Intersecting Curves Procedures

The intersecting curves calculations assume the center of the grounding system is at some distance X from the actual grounding system connection point. When using the Fall-of-Potential method, the actual grounding system resistance is theoretically measured at a point that is 61.8% of the distance to the C2 probe from the *center* of the grounding system. If the C2 probe is placed at distance D from the connection point, then the actual resistance R' is measured at a point P' = 61.8%(X + D) – X from the connection point (Fig. 10).

Fig. 10 – Dimensions for Intersecting Curves Method



The value of X is varied over a positive (or negative) range. To find the value of X that gives the actual resistance, it is necessary to calculate P' for various values of X and then interpolate the value of R' corresponding to each value of P' from the data set. This process is repeated for each data set. The results are plotted in the “Intersecting Curves” graph. The point at which the curves intersect is the actual earth electrode system resistance.

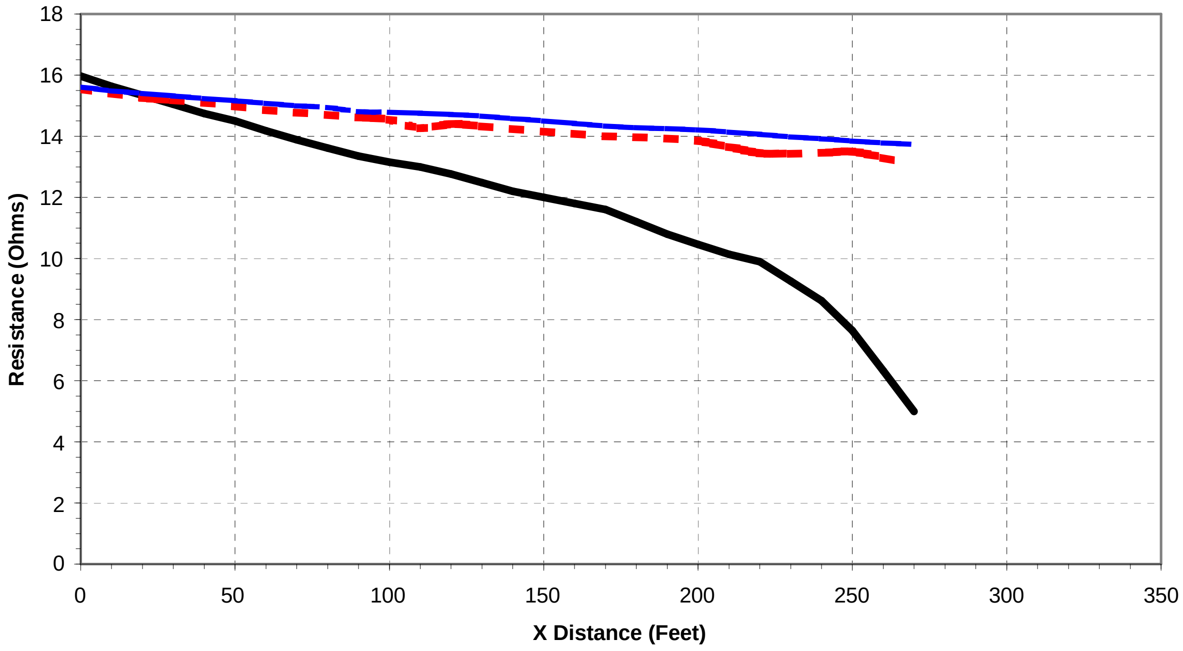
For example, assume the C2 current probe is located D = 300 feet from the connection point, then the probe is X + 300 feet from the electrode center. The resistance would be measured at 61.8% of this distance, that is, 61.8% (X + 300 feet). Next, assume that X is varied from 0 to 100 feet in 10 feet increments. When X is 0, the 61.8% point is 61.8% x (0 + 300) = 185 feet from the electrode center. The measured resistance corresponding to (185 – 0) = 185 feet distance from the connection point to the current probe is the first data point for the Intersecting Curves plot. The next point would be 61.8% x (10 + 300) = 192 feet from the electrode center. The measured resistance corresponding to (192 – 10) = 182 feet distance from the connection point to the current probe is the next data point for the plot. This sequence is repeated until the last point where the distance is 61.8% x (100 + 300) = 247 feet from the electrode center to the current probe, and the measured resistance corresponding to (247 – 100) = 147 feet distance from the connection point to the current probe is used as the last data point to be plotted.

The above procedures are repeated for each measurement set. At least three measurement sets are required for a reliable intersection. When the curves are plotted, they will intersect at the actual electrode resistance. In many cases, the curves do not intersect at exactly the same point but form a small irregular box. The size of the box indicates the uncertainty, and the smaller the box, the smaller the uncertainty.

It is possible the curves do not all intersect or only two intersect. If so, the measurements probably are unreliable because of a faulty test set, reading errors, poor connections or inadvertent shorts to ground or because of transcription errors in the data or in data reduction. Sometimes, buried conductive objects, such as buried power or telecommunications cables, engine blocks, or other large pieces of metallic junk can corrupt the measurements. If one or more curves are horizontal or almost horizontal, the current probe probably was located outside the earth electrode influence.

Example: The data used in this example are the same as in Section 4. The calculations of P’ for various values of X [Column (5)] and C2 =200 feet are in Columns (6), and the resistances corresponding to the P’ distances, as taken from the original data for C2 = 200 feet, are in Column (7). Similar calculations for C2 = 300 feet are in Columns (8) and (9) and for C2 = 400 feet are in Columns (10) and (11). The calculated data in Columns (7), (9) and (11). A plot of the resistance as a function of X is shown in Fig. 11.

Fig. 11 – Example Intersecting Curves



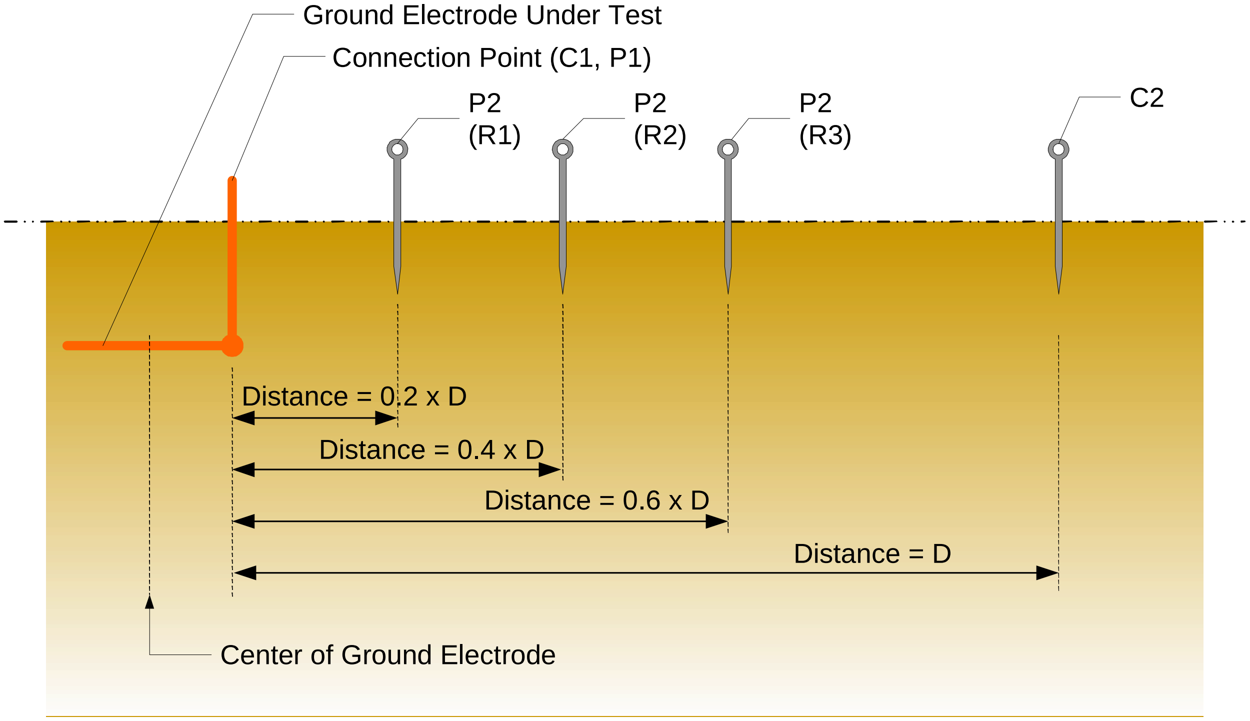
Examination of the Intersecting Curves shows that the three curves cross at a resistance of around 15.5 ohms, which very closely agrees with the estimation made in Section 4. The distance X at the curve crossing is about 20 feet, indicating that the center of the earth electrode was about 20 feet from the connection point as was actually the case.

6. Slope Procedures

If the time available to make resistance measurements is limited, the Slope method is much faster than the Fall of Potential method because fewer measurements are needed. The Slope method may use the same data sets as discussed above, which provides a crosscheck of the two methods. With the Slope method the data is manipulated in a different way. If the distance from the earth electrode to the current probe is D, the resistance is read from the data sets at potential probe locations corresponding to 0.2 x D, 0.4 x D and 0.6 x D. Call these resistance readings R1, R2 and R3, respectively (Fig. 12). The change in slope of the resistance curve, Δ, is calculated from

$$\Delta = \frac{(R3 - R2)}{(R2 - R1)}$$

Fig. 12 – Potential Probe P2 Locations for Slope Method



The table of values in Appendix III is then used to find the value of $\frac{P_D}{D}$ corresponding to the calculated value of Δ. If the calculated value of Δ is not covered in the table, then the current probe is too close to the electrode system and additional measurements are required with a greater distance.

P_D is the distance from the connection point to the potential probe where the true resistance would be measured. P_D is calculated by multiplying the quantity $\frac{P_D}{D}$ (taken from the Slope table) by the value D actually used. The resistance may then be found from the data set at the calculated distance P_D. If the data set does not include a measurement at the exact value of P_D, the data may be interpolated, or a separate measurement can be made at the calculated value of P_D. A field data form is provided in Appendix IV for the Slope Method.

For example, assume that D = 300 feet and the calculated value of Δ = 0.635. From the table in Appendix II, $\frac{P_D}{D} = 0.6079$. Multiplying by D gives 0.6079 x 300 feet = 182 feet. This value would be used to find the measured resistance from the original data with interpolation if necessary, or a resistance measurement would be made with the P_2 probe at 182 feet.

Similar calculations should be made for each data set and the resulting resistances should agree within a few percent. The resistances so calculated can be plotted on a new graph with the distance D on the horizontal scale (Fig. 11). Where the resistance significantly decreases as the distance D increases (Data Set 1 and Data Set 2 in the example), the resistance values are higher than actual. Where the resistances are reasonably close (Data Set 2 and Data Set 3 in the example), the values can be used with confidence.

<u>Example</u>: The data for this example is the same data that was used in Section 4. For C2 = 200 feet, the 0.2 xD = 40 feet, 0.4 x D = 80 feet and 0.6 x D = 120 feet. The corresponding resistances from the original data at these distances are R1 = 9.90 ohms, R2 = 12.30 ohms, and R3 = 15.63 ohms.

Calculating Δ for this data set gives $\Delta = \frac{(R3 - R2)}{(R2 - R1)}$ = 1.388.

From Appendix II, P_D/D = 0.4350. Since D = 200 feet, P_D = 0.4350 x 200 feet = 87 feet. The measured resistance corresponding to P2 distance of 87 feet, as interpolated from the original measurements for C2 = 200 feet, is approximately 15.1 ohms.

A similar set of calculations is made for C2 = 300 feet and C2 = 400 feet. These are summarized along with C2 = 200 feet in Table 3. The average of the three is 15.4 ohms, which closely agrees with the resistance estimated in the previous example.

Table 3 – Example Slope Calculations

0.2 x D	**R1**	**0.4 x D**	**R2**	**0.6 x D**	**R3**	**Δ**	**P_D/D**	**P_D**	**R**
C2 = 200 feet									
40 feet	9.90	80 feet	12.90	120 feet	15.63	0.910	0.5598	112 feet	15.1
C2 = 300 feet									
60 feet	11.10	120 feet	14.00	180 feet	15.30	0.448	0.6363	191 feet	15.8
C2 = 400 feet									
80 feet	12.30	160 feet	14.00	240 feet	15.40	0.824	0.5759	230 feet	15.2

7. Field Measurements and Data Reduction

7.1 Cautions:

- The electric utility multi-grounded neutral usually (but not always, depending on how well the electric utility grounds their system) contributes the most to a low system resistance.
- The resistances of parallel electrodes, such as several interconnected ground rods, do not combine like parallel resistors because of the mutual resistance between them. The resistance of interconnected parallel electrodes always will be higher than the parallel combination of the equivalent individual resistances.
- In permafrost areas, the central office grounding system usually is better (lower resistance) than other service grounding systems. Currents from electric utility faults in the neighborhood will flow through the central office ground.
- Never disconnect operating telecommunications equipment from the earth electrode system.

- Never disconnect live ac service equipment from the earth electrode system – this is for your safety.
- In a new central office, with no live equipment and no live ac service, it will be possible to test individual grounding system components (well casing, grid, ground rods, building structural steel, etc.) if they can be isolated from each other. Otherwise, leave everything interconnected and measure the overall system.
- Usually, telecommunications facility earth electrode systems consist of several components and the facility operates normally with all the components interconnected. Therefore, if your goal is to measure only the telecommunications facility earth electrode system, you would not measure them individually. Instead, you would make sure all components, except the electric utility MGN, are bonded as they would be in the final operating configuration and measure them as a complete system.
- If you leave all earth electrode components interconnected for safety, you are measuring the composite resistance of all earth electrode components together, including the electric utility multi-grounded neutral (MGN). Usually, the electric utility MGN will contribute the most to a low resistance reading. Remember: This kind of test (with everything interconnected, including the electric utility MGN) will not yield valid results if your goal is to measure only the building or enclosure earth electrode system.
- If you can safely disconnect an individual electrode component from the grounding electrode system, then you can correctly measure that component.
- Frozen ground is an insulator. Readings taken during the summer when the active soil layer is thawed are meaningless for winter. Where the winter frost depth exceeds the depth of earth electrodes, the electrodes are insulated from remote earth and the resistance of the electrode system will be very high. To reduce potential differences for safety and operation, all metallic components of the telecommunications facility must be bonded together.

7.2 Test Instruments:

- Battery operated test sets with an analog null meter are the best, provide the most consistent measurements and are the most reliable.
- The hand-crank test set by Biddle and other manufacturers works fine but are relatively difficult and awkward to use.
- Some digital test sets most often do not yield usable data. This is particularly the case if the earth electrode system being measured is near a power plant or substation.
- Always test your test set before taking it into the field. The manual tells you how to do this.
- Take an extra set of batteries. If the test set uses rechargeable batteries, make sure they are not worn out and have enough charge for the measurements to be made.
- Occasionally check calibration especially if the test set has not been taken care of in the field or in storage or if it has been in storage for a long time. The manual tells you how to do this (you will need some resistors).
- For earth electrode measurements, always short the P1 and C1 terminals together or use separate test leads, one from P1 to the earth electrode and one from C1 to the earth electrode. The latter provides the best accuracy.

7.3 Test Leads – General Information:

- Use a heavy-gauge (14 - 16 AWG) test lead wire and lots of it.
- The lead connected to the current probe (C2) should have a total overall length of 300-400 ft or more
- The lead connected to the potential probe (P2) should have a total overall length of 300-400 ft or more (it should have the same overall length as the C2 lead)
- The lead connected from C1/P1 to the grounding electrode system should be as short as possible, preferably less than 10 ft long. If this lead is too long, the readings will not be reliable. The resistance of this lead directly affects the measured resistance. One way to eliminate this measurement error is to use a separate lead from the C1 terminal to the grounding electrode system and a separate lead from the P1 terminal to the grounding electrode.

7.4 Test Lead Kit:

- You will need approximately 600 ft – 800 ft of test lead wire (300 ft – 400 ft for P2 and 300 ft – 400 ft for C2).
- Make up two test leads, each 100 ft long, with a large (2 in. or 3 in.) alligator clip at one end and 1/4 in. fork terminal lug at the other. One will connect to the C2 terminal and the other to the P2 terminal on the test set. Use rubber insulating boots over the alligator clips
- Use the remaining test lead wire to make 100 ft sections with large insulated alligator clips at each end.
- Make up one test lead, 10 ft long, with large alligator clip at one end and 1/4 in. fork terminal lug at the other. This will be used to connect P1/C1 terminal on the test set to the grounding electrode system. Also make up extra test leads if it is necessary to locate the test set some distance from the connection point at the earth electrode (one test lead for C1 and one for P1).
- Put test leads on 12 in. or 14 in. “Cordwheels.” These are available from hardware stores (Home Depot, Lowes) and are designed for coiling extension cords but work well with test leads.
- Put spare terminal lugs and alligator clips in the kit along with a crimping tool, screwdriver and any other tools you may need to repair the test leads in the field. Be sure to include a set of good gloves.
- The test lead kit also should include safety glasses, gloves, and a short-handle, 4 lb., double-head hammer, and test probes (see below).

7.5 Test Leads – Connections:

- When stringing out the test leads, make sure the insulation is not damaged. Use gloves to handle the wire, especially if the leads are strung below or above power lines.
- Where test lead sections are connected together to make a longer lead, be sure to insulate the alligator clips from the earth and foliage. Use 8 in. lengths of 1-1/2 in. or 2 in. flexible non-metallic conduit or other insulating material as insulator sleeves (these are slipped over the alligator clips to keep them from touching the ground).
- Be sure to clean the point of connection to the grounding electrode system. Use ScotchBrite or wire brush.

- The farther the current probe (C2) is from the grounding electrode system, the better. The object is to get the P2 probe out of the influence of the grounding electrode system when P2 is 61.8% of the distance to C2. If the largest dimension of the electrode system is x ft, the C2 probe should be 10x ft to 20x ft from the electrode system. For example, if the grounding electrode is 20 ft x 20 ft, C2 should be at least 200 ft to 400 ft away. Unfortunately, the extent of the grounding system usually is unknown, so you will try to place the C2 probe as far away as possible. To calculate resistance, you almost always will have to use the “Intersecting Curves” or the “Slope” method..
- Never disconnect the ac service equipment from the earth electrode system. Never disconnect working telecommunications equipment from ground. In a new central office, with no live equipment and no live ac service, it will be possible to test individual grounding system components (well casing, grid, ground rods, building structural steel, etc.) if they can be isolated from each other. Otherwise, leave everything interconnected and measure the overall system – this is for your safety.

7.6 Test Probes:

- Test probes should be 18 – 20 in. long and made from strong galvanized steel. They should have a loop at one end and sharpened to a point at the other. Purchase ready-made probes from Biddle (Fig. 15) or make your own but carry extras.
- It is a good idea to carry a couple longer probes made from a cut ground rod, 3 ft – 4 ft long, for use where the shorter probes do not make good enough contact with the earth. Weld a T-bar near the top of these longer rods so you can twist and pull them out of the ground.
- The probes normally only have to be driven to a depth of 6 in. – 12. in. The deeper the probe the harder it is to pull out. Wear safety glasses when driving the probes.
- Remove probes by twisting and pulling on the loop at the top of the probe; do not hit the side of the probe with a hammer or kick it to loosen it because all you will do is bend the probe and ruin it.
- If you have to place the probes in a parking area or roadway with very hard ground, concrete or pavement, use metal plates in place of the pointed probes. Lay the plates on the ground and wet them and the area around them thoroughly. An alternative is to drill through the pavement or concrete with a hammer drill.
- Be sure the alligator clip makes a good connection where it is connected to the probe. Use 3M ScotchBrite or wire brush to clean the probes where you connect the alligator clips.
- P2 should be placed in a straight line between the connection point and C2. Sometimes it will be necessary to place C2 in one direction but move in another direction with P2, although some test set manufacturers recommend against this procedure. If you do this, move P2 in a straight line away from the connection point and away from the electrode system.
- Avoid placing the probes in line with underground facilities (electric, telephone, metallic water and sewer pipes, etc.) but sometimes you have no choice.
- Be aware of shallow underground facilities, such as telephone cables, when you drive the probes.

7.7 Readings:

- Start your readings with the P2 probe 10 ft – 20 ft from the point of connection.
- Take a reading every 10 ft to within 20 ft – 30 ft of C2. You will notice the readings are low when you are close to the point of connection and slowly climb. If C2 is far enough away, the readings will level off in the middle. As you approach C2, the readings climb rapidly.
- If C2 is far from the influence of the electrode system, the readings will level off near the 61.8% point. When P2 is closer to the connection point, the readings will be lower and when closer to C2, the readings will be higher. Readings that decrease as you move away from the connection point indicate underground metallic facilities that are interfering with the measurements or that the P2 probe is over the grounding electrode. An occasional dip in the readings is not unusual, but if several readings follow this pattern, you have to move C2 and start over.
- Always take at least three separate sets of readings. Usually, you can take two sets of readings with the C2 probe at two different distances along the same direction, say 300 ft and 250 ft, although 400 ft and 300 ft are preferable. Take the third set of readings in another direction if possible. Depending on the topography and obstructions, you may have to take all three readings in the same direction (say, 400 ft, 300 ft and 200 ft or 300 ft, 250 ft and 200 ft).
- If you are able to move the test set analog meter needle to either side of null (with the resistance knobs), the probes are deep enough. If the needle moves only to one side (usually the " – " side), one or both probes are not deep enough, you have a bad connection, or the alligator clips used to splice lead sections are in contact with the earth. Check all connections and try driving the probes a little deeper or use the longer probes. You also can try pouring water around the probe. In any case, you must be able to move the needle to both sides of null with the resistance knobs; otherwise, the reading is not reliable.
- With analog instruments, the null sometimes will be lazy (move slowly as you adjust the resistance knobs), which indicates underground metallic facilities or inadequate probe contact. For the latter situation, drive the probes deeper or use longer probes.
- With analog instruments, the meter sometimes will oscillate around null. You will have to adjust the resistance knobs so the meter moves an equal distance left and right of null (center) and then take a reading; this takes practice and a little practice.
- Digital instruments include fault indicators that indicate excessively high probe resistance or bad connections. If you see this indication, check all connections and, if necessary, drive the probes deeper.

7.8 Data Reduction:

- The actual electrode system resistance is measured when P2 is 61.8% of the distance C2 is from the center of the electrode system. However, the actual center of the electrode system seldom is known except in small systems, so the location of this 61.8% point is never known accurately. A small system would be a few ground rods that are not connected to anything else other than each other.
- If measuring a small system, you can put C2 outside the influence (10X – 20X as mentioned above) and then put P2 at a point 61.8% of this distance. The reading you take at this point will be close to the actual electrode system resistance. Additional

readings are not necessary, but they should be taken anyway to ensure that the data is valid.
- If measuring larger systems, you should use the "Intersecting Curves" or "Slope" method.

Fig. 15 - T-Handle, Factory-Made Test Probes in a kit of four

8. Soil Resistivity Measurements

Soil resistivity is a measure of how well the soil passes electrical current. Soil with high resistivity does not pass current well. Resistivity is defined in terms of the electrical resistance of a cube of soil. The resistance of this cube, as measured across its faces, is proportional to the resistivity and inversely proportional to the length of one side of the cube.

The resistivity of the soil in which the earth electrode is buried is the limiting factor in attaining low electrode resistance. Soil with low resistivity is better for building low resistance earth electrodes than soil with high resistivity. Soil resistivity depends on soil type, salt concentration, moisture content and temperature.

Formulas for specific electrode configurations are available in reference handbooks. Therefore, if the soil resistivity is known, the resistance of many common earth electrode configurations can be readily calculated. These formulas are beyond the scope of the present article.[1] From an operational standpoint, soil resistivity measurements allow for initial earth electrode design based on these formulas and in prediction of the effects of changes to an existing electrode.

The resistivities of various soil types are given in Table 4. A wide range of soil types may be found in any given area or the soil types may vary widely with depth, or both. The season and weather conditions will greatly affect the soil resistivity. For example, high resistivity rock can be overlain by clays that have low resistivity in the summer but have high resistivities in the winter when frozen.

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[1] See, for example, MIL-HDBK-419a, Grounding, Bonding, and Shielding for Electronic Equipments and Facilities and Rural Utilities Service Bulletin 1751F-802, Electrical Protection Grounding Fundamentals.

Resistivity measurements provide an average reading. The method almost always used and described here assumes the soil is homogeneous (all the same or similar kind). Soil resistivity is measured by injecting a current into the earth, measuring the voltage drop, and then calculating the resistance. Four-terminal test sets do the resistance calculations automatically. If the four probes are placed equidistance from each other and in a straight line as shown in Fig. 13, the resistivity can be calculated from (for separation measured in ft)

$$\rho = 1.915 \cdot a_{ft} \cdot R \text{ ohm-m}$$

where
ρ = Soil resistivity, ohm-m
a = Distance between the four equally spaced probes, ft
R = Measured resistance, ohms

or (for separation measured in m)

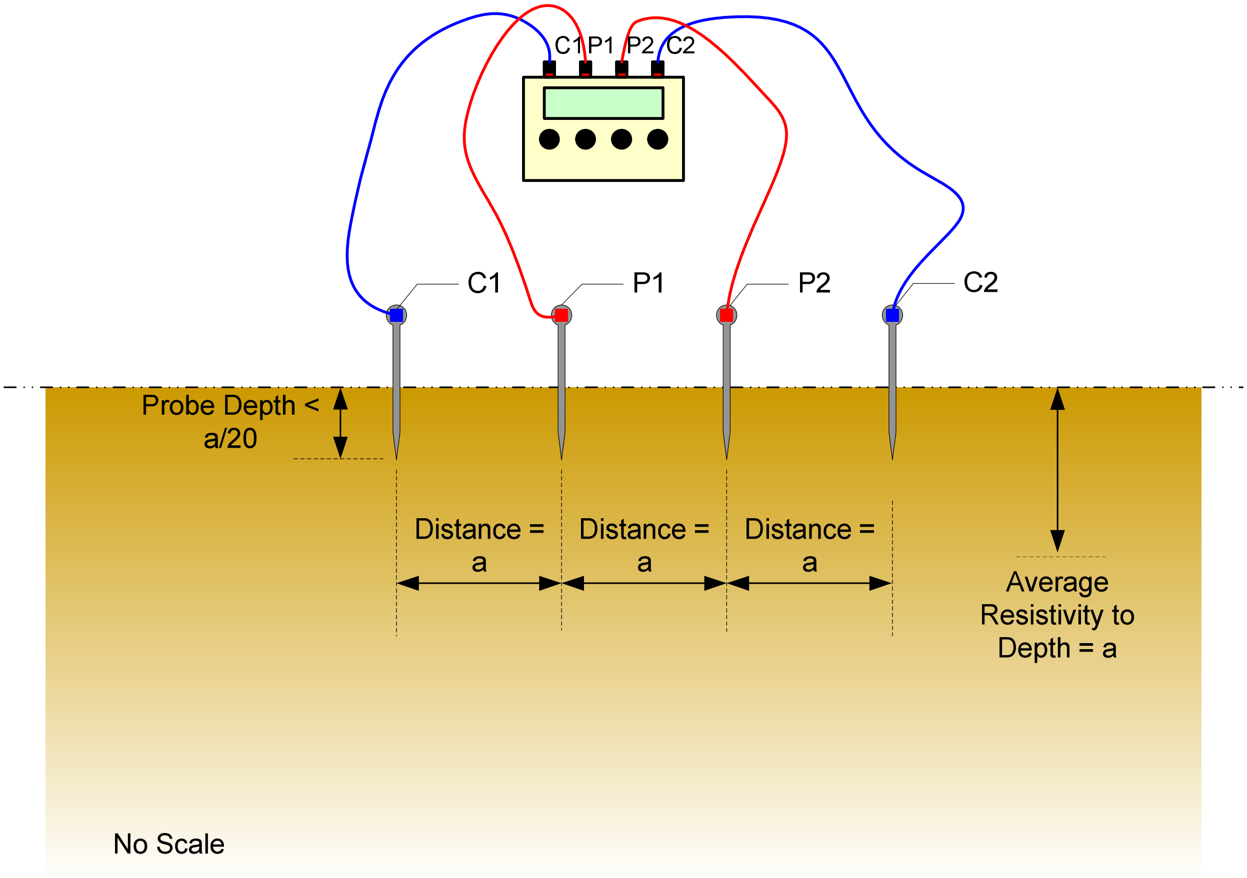
$$\rho = 6.283 \cdot a_m \cdot R \text{ ohm-m}$$

where
ρ = Soil resistivity, ohm-m
a = Distance between each of the four equally spaced probes, m
R = Measured resistance, ohms

Be careful with units of measurement and be sure to use the correct formula. Most soil resistivity tables are in units of ohm-m or ohm-cm but most distance or length measurements in the United States are (unfortunately) in ft.

The above formulas are valid only if the probes are buried no more than 1/20 of the separation distance, a. For example, if the probes are spaced 5 ft (1.5 m), they cannot be driven more than about 3 in. (0.075 m). Every effort should be made to drive all four probes to the same depth.

Fig. 13 - Soil Resistivity Measurement Setup



This type of measurement provides the average resistivity to a depth equal to the probe separation distance. For example, if the probes are spaced 10 ft (3.05 m), the measurement provides the average resistivity to a depth of about 10 ft.

Generally, soil resistivity measurements are taken at several probe spacings starting at 5 or 10 ft spacing and then increasing in 5 or 10 ft increments. The measurements may indicate that soil resistivity decreases dramatically as the depth increases. If so, the earth electrodes should be buried or driven deep to take advantage of the low resistivity. Fig. 14 shows the basic setup with 30 ft probe spacing. Fig. 15 shows measurements taken at a site in Anchorage, AK near Elmendorf Air Force Base.

A field data form for recording soil resistivity measurements is provided in Appendix V.

Fig. 14 - Basic Soil Resistivity Measurement Setup with 30 ft probe spacing

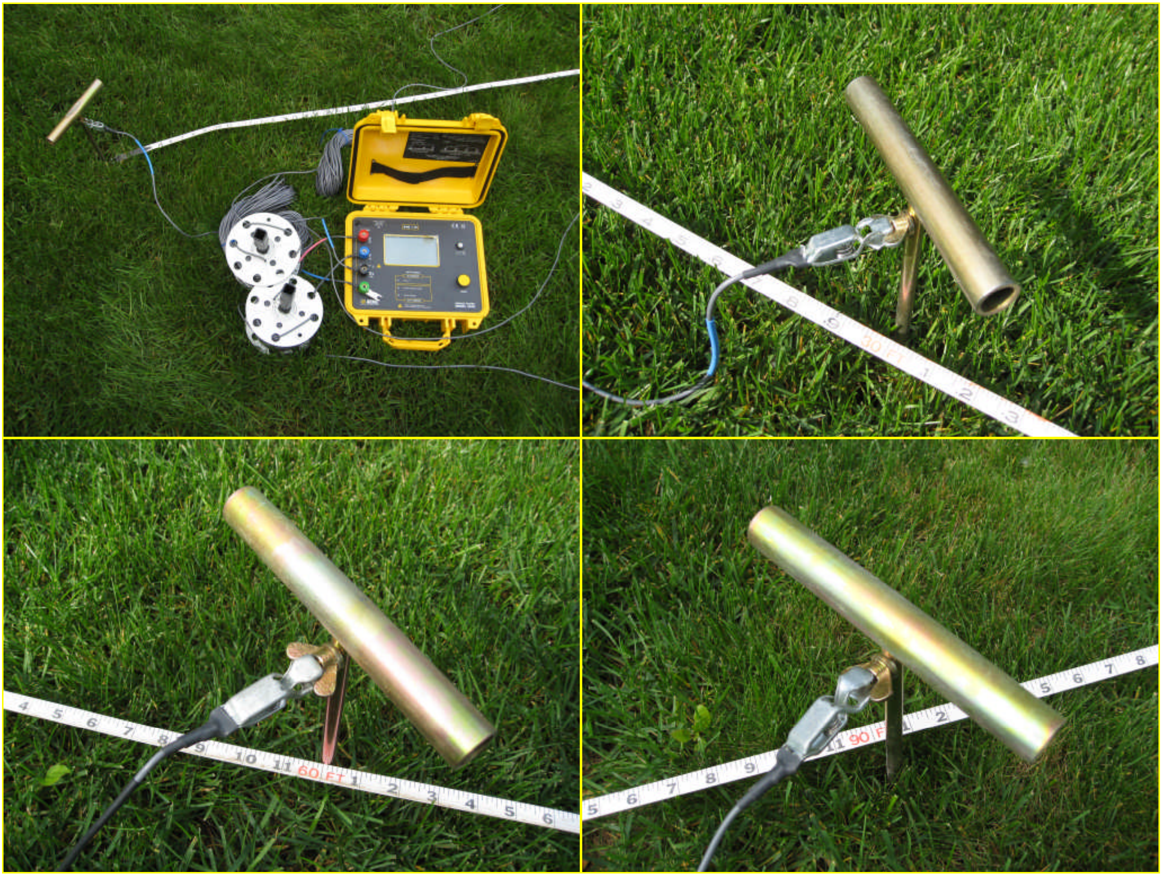


Fig. 15 - Soil Resistivity Measurements at a site near Elmendorf AFB (curve has been smoothed by Excel charting function)

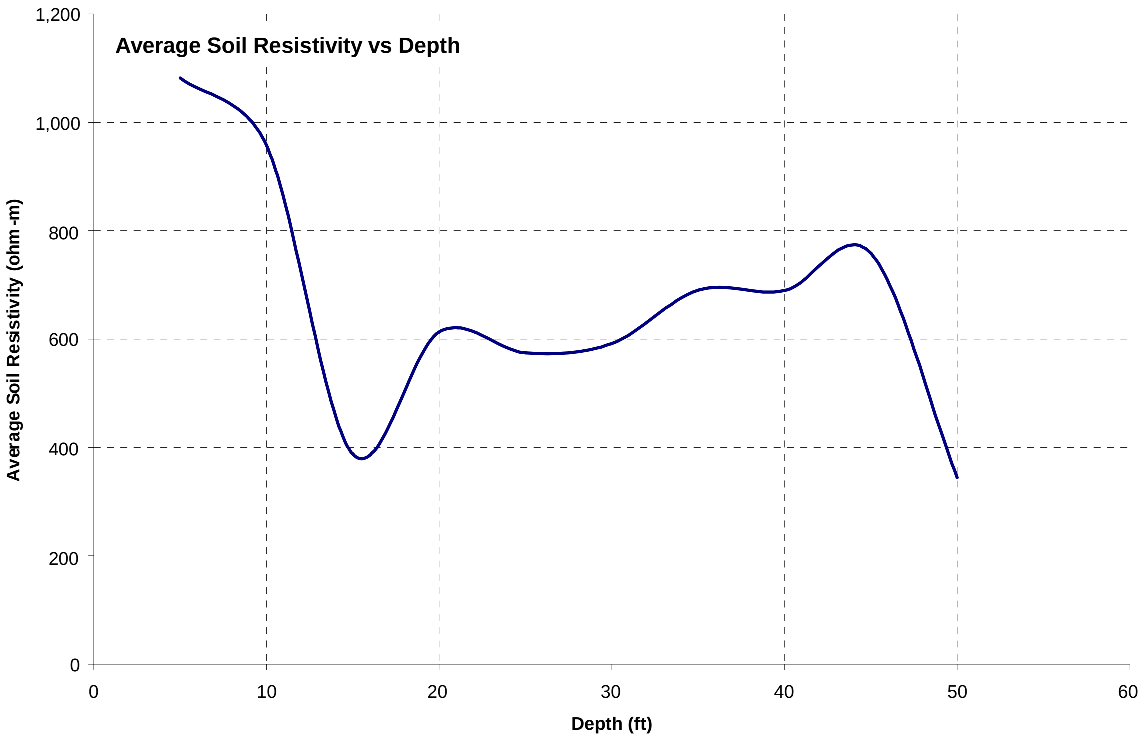


Table 4 - Soil Characteristics

Approximate Soil Resistivity
Source: Table 2-2, MIL-HDBK-419A

Soil Type	Resistivity (ohm-m)
Wet organic soil	10
Moist soil	100
Dry soil	1,000
Bed rock	10,000

Detailed Soil Resistivity
Source: Table 2-3, MIL-HDBK-419A

	Resistivity (ohm-m)		
Soil Type	**Minimum**	**Average**	**Maximum**
Surface soils, loam	1		500
Clay	2		100
Sand and gravel	50		1,000
Surface limestone	100		10,000
Limestones	5		400
Shales	5		100
Sandstone	20		2,000
Granites, basalts		10,000	
Decomposed gneiss	50		500
Slates	10		100
Fresh water lakes		200	
Tap water	10		50
Sea water	0.2	1	2
Pastoral, low hills, rich soil (typical of Dallas, TX and Lincoln, NE areas)		30	
Flat country, marshy, densely wooded (typical of LA near Mississippi River)	2	100	
Pastoral, medium hills and forestation (typical of MD, PA, NY, exclusive of mountainous territory and seacoasts)		200	
Rocky soil, steep hills (typical of New England)	10	500	1,000
Sandy, dry, flat (typical of coastal country)	300	500	5,000
City, industrial areas		1,000	10,000
Fills, ashes, cinders, brine, waste	6	25	70
Clay, shale, gumbo, loam	3	40	200
Same – with varying proportion of sand and gravel	10	150	1,000
Gravel, sandstones with little clay or loam, granite	500	1,000	10,000

Note: To convert to ohm-cm, multiply by 100 (for example, 100 ohm-m x 100 = 10,000 ohm-cm)

Appendix I – Fall-of-Potential Method Field Data Form

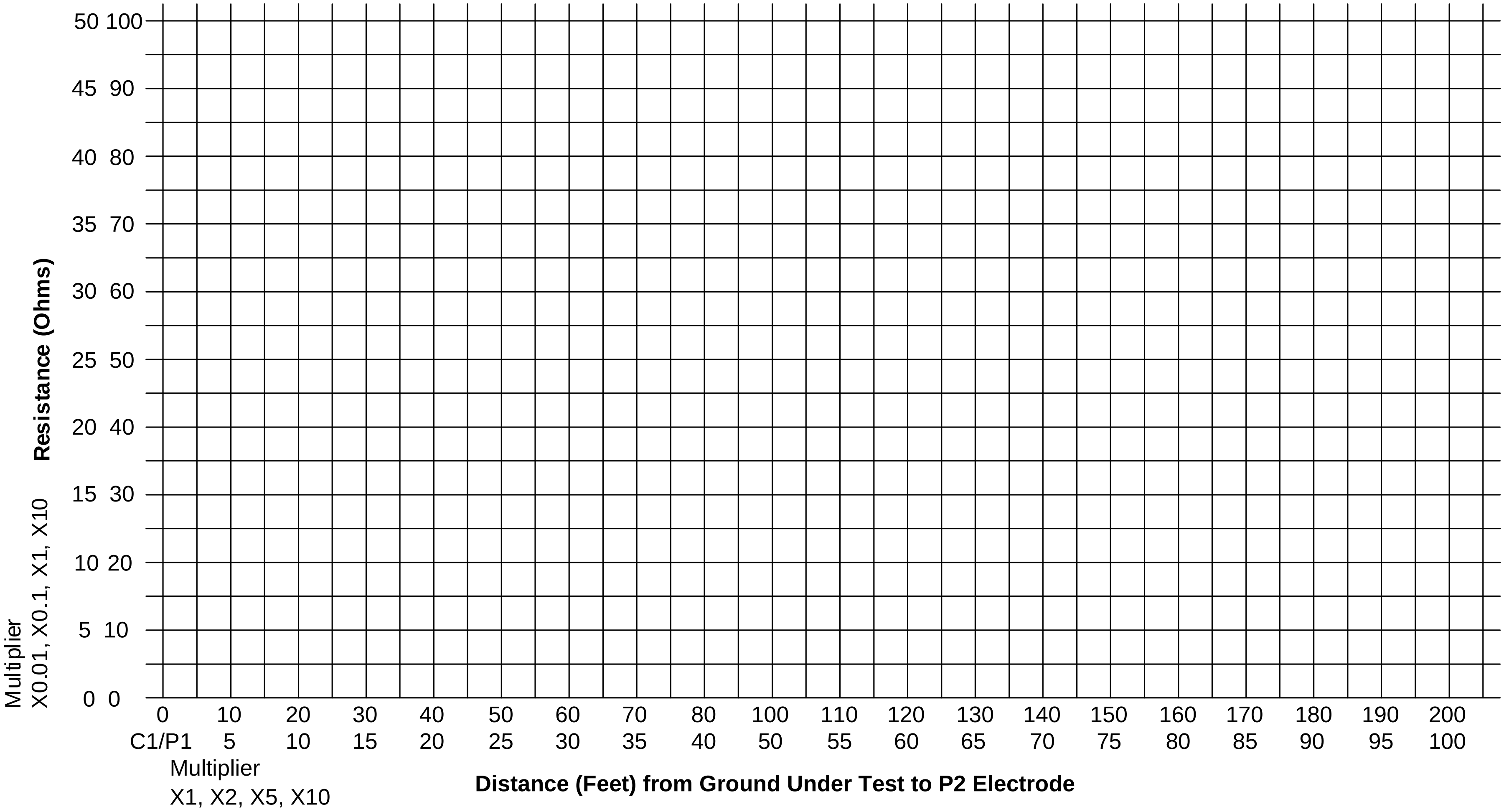
Place the C2 probe as far as possible from the ground under test (typically 200, 300 and 400 ft.). Place the P2 probe at 10 or 20 ft. intervals in a straight line with C2. Measure and record the resistance reading on the test set.

P2 (ft)	**R (ohms)**	**R (ohms)**	**R (ohms)**	**Site Info**	
0	**C2 =**	**C2 =**	**C2 =**	Test Set Model:	
10				Test Set S/N:	
20				Ground System Type:	
30				Temperature:	
40				Weather:	
50				Soil Moist or Dry:	
60				Soil Type (Circle):	
70					Loam
80					Sand & gravel
90					Shale
100					Clay
110					Limestone
120					Sandstone
130					Granite
140					Slate
150					Other
160					
170					
180					
190				Notes:	
200					
210					
220					
230					
240					
250					
260					
270					
280					
290					
300					
310					
320					
330					
340					
350					
360					
370					
380					
390					

Location: ____
Conditions: ____
Date: ____
By: ____

Appendix I – Fall-of-Potential Method Field Data Form

Fall of Potential Plot



Location: ____________________________________ Conditions: ____________________________________

Date: ____________________________________ By: ____________________________________

Appendix II – Derivation of Measurement Points

Derivation of 61.8% Measurement Point

Consider three grounds, ground 1, which has self-resistance R_{11} and is the ground to be measured, and two auxiliary grounds, 2 and 3, which have unknown self-resistances R_{22} and R_{33} and are temporary for measurement of ground 1. Auxiliary ground 2 corresponds to probe P2 and ground 3 corresponds to the probe C2 on the test set. The resistances between each pair of grounds are related to the self- and mutual-resistances of the grounds as follows

$$\begin{aligned} R_{1-2} &= R_{11} + R_{22} - 2R_{12} \\ R_{1-3} &= R_{11} + R_{33} - 2R_{13} \\ R_{2-3} &= R_{22} + R_{33} - 2R_{23} \end{aligned}$$

Eq. (1)

These equations can be rearranged to give the self-resistances of the grounds

$$\begin{aligned} R_{11} &= \frac{1}{2}\left[\left(R_{1-2} + 2R_{12}\right) + \left(R_{1-3} + 2R_{13}\right) - \left(R_{2-3} + 2R_{23}\right)\right] \\ R_{22} &= \frac{1}{2}\left[\left(R_{1-2} + 2R_{12}\right) - \left(R_{1-3} + 2R_{13}\right) + \left(R_{2-3} + 2R_{23}\right)\right] \\ R_{33} &= \frac{1}{2}\left[-\left(R_{1-2} + 2R_{12}\right) + \left(R_{1-3} + 2R_{13}\right) + \left(R_{2-3} + 2R_{23}\right)\right] \end{aligned}$$

Eq. (2)

If the spacing between the grounds is large enough, the mutual resistances (R_{12}, R_{23}, R_{13}) can be neglected and self-resistances of the grounds may be solved from the equations. However, in reasonably uniform soil, the mutual resistances can be cancelled by proper spacing of the auxiliary grounds 2 and 3. If the auxiliary grounds 2 and 3 are spaced such that

$$R_{23} = R_{12} + R_{13}$$

Eq. (3)

then the mutual resistances will cancel, which can be verified by substituting **Eq. (3)** in the equation for R_{11} in **Eq. (2)**.

In uniform soil, the mutual resistances between grounds are inversely proportional to the distances between them. The relationship of **Eq. (3)** can be written in terms of the distances as

$$\frac{1}{d_{23}} = \frac{1}{d_{12}} + \frac{1}{d_{13}}$$

Eq. (4)

where

d_{23}	Distance between ground 2 and 3
d_{12}	Distance between ground 1 and 2 (P2 on test set)
d_{13}	Distance between ground 1 and 3 (C2 on test set)

When the grounds are placed in a straight line

Appendix II – Derivation of Measurement Points

$$d_{13} = d_{12} + d_{23}$$ **Eq. (5)**

Substituting **Eq. (5)** in **Eq. (4)** and manipulating

$$\begin{aligned}
\frac{1}{d_{23}} &= \frac{1}{d_{12}} + \frac{1}{(d_{12} + d_{23})} \\
\frac{(d_{12} + d_{23})}{d_{23}} &= \frac{(d_{12} + d_{23})}{d_{12}} + 1 \\
\frac{d_{12}(d_{12} + d_{23})}{d_{23}} &= (d_{12} + d_{23}) + d_{12} \\
d_{12}^2 + d_{12}d_{23} &= d_{23}(d_{12} + d_{23}) + d_{12}d_{23} \\
d_{12}^2 + d_{12}d_{23} &= d_{12}d_{23} + d_{23}^2 + d_{12}d_{23} \\
d_{12}^2 - d_{12}d_{23} - d_{23}^2 &= 0
\end{aligned}$$ **Eq. (6)**

The last part of **Eq. (6)** is of the form $ax^2 + bx + c = 0$ and can be solved using the quadratic formula $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$ where

$x = d_{12}$
$a = 1$
$b = -d_{23}$
$c = -d_{23}^2$

giving

$$d_{12} = \frac{d_{23} \pm \sqrt{d_{23}^2 + 4d_{23}^2}}{2} = \frac{d_{23} \pm \sqrt{5d_{23}^2}}{2} = d_{23}\left(\frac{1 \pm \sqrt{5}}{2}\right)$$ **Eq. (7)**

Taking the ratio of d_{12} to d_{23} gives

$$\frac{d_{12}}{d_{23}} = \frac{1 \pm \sqrt{5}}{2} = +1.618 \text{ or } -0.618$$

The only practical value is positive, so when $d_{12} = 1.618d_{23}$ or $d_{23} = 0.618d_{12}$ the mutual resistances will cancel.

By substituting this result in **Eq. (5)**

Appendix II – Derivation of Measurement Points

$$d_{13} = d_{12} + 0.618d_{12} = d_{12}(1 + 0.618)$$ **Eq. (8)**

and

$$d_{12} = \frac{d_{13}}{1.618} = 0.618d_{13}$$ **Eq. (9)**

Appendix III – Slope Method Tables

For the calculated value of Δ in column 1 and row 1, read the corresponding value of P_D/D from the table

Δ	0	1	2	3	4	5	6	7	8	9
0.40	0.6432	0.6431	0.6429	0.6428	0.6426	0.6425	0.6423	0.6422	0.6420	0.6419
0.41	0.6418	0.6416	0.6415	0.6413	0.6412	0.6410	0.6409	0.6408	0.6406	0.6405
0.42	0.6503	0.6402	0.6400	0.6399	0.6397	0.6396	0.6395	0.6393	0.6392	0.6390
0.43	0.6389	0.6387	0.6386	0.6384	0.6383	0.6382	0.6380	0.6379	0.6377	0.6376
0.44	0.6374	0.6373	0.6372	0.6370	0.6369	0.6367	0.6366	0.6364	0.6363	0.6361
0.45	0.6360	0.6359	0.6357	0.6356	0.6354	0.6353	0.6351	0.6350	0.6348	0.6347
0.46	0.6346	0.6344	0.6343	0.6341	0.6340	0.6338	0.6337	0.6336	0.6334	0.6333
0.47	0.6331	0.6330	0.6328	0.6327	0.6325	0.6324	0.6323	0.6321	0.6320	0.6318
0.48	0.6317	0.6315	0.6314	0.6312	0.6311	0.6310	0.6308	0.6307	0.6305	0.6304
0.49	0.6302	0.6301	0.6300	0.6298	0.6297	0.6295	0.6294	0.6292	0.6291	0.6289
0.50	0.6288	0.6286	0.6285	0.6283	0.6282	0.6280	0.6279	0.6277	0.6276	0.6274
0.51	0.6273	0.6271	0.6270	0.6268	0.6267	0.6265	0.6264	0.6262	0.6261	0.6259
0.52	0.6258	0.6256	0.6255	0.6253	0.6252	0.6252	0.6248	0.6247	0.6245	0.6244
0.53	0.6242	0.6241	0.6239	0.6238	0.6236	0.6235	0.6233	0.6232	0.6230	0.6229
0.54	0.6227	0.6226	0.6224	0.6223	0.6221	0.6220	0.6218	0.6217	0.6215	0.6214
0.55	0.6212	0.6210	0.6209	0.6207	0.6206	0.6204	0.6203	0.6201	0.6200	0.6198
0.56	0.6197	0.6195	0.6194	0.6192	0.6191	0.6189	0.6188	0.6186	0.6185	0.6183
0.57	0.6182	0.6180	0.6179	0.6177	0.6176	0.6174	0.6172	0.6171	0.6169	0.6168
0.58	0.6166	0.6165	0.6163	0.6162	0.6160	0.6159	0.6157	0.6156	0.6154	0.6153
0.59	0.6151	0.6150	0.6148	0.6147	0.6145	0.6144	0.6142	0.6141	0.6139	0.6138
0.60	0.6136	0.6134	0.6133	0.6131	0.6130	0.6128	0.6126	0.6125	0.6123	0.6121
0.61	0.6120	0.6118	0.6117	0.6115	0.6113	0.6112	0.6110	0.6108	0.6107	0.6105
0.62	0.6104	0.6102	0.6100	0.6099	0.6097	0.6096	0.6094	0.6092	0.6091	0.6089
0.63	0.6087	0.6086	0.6084	0.6083	0.6081	0.6079	0.6076	0.6076	0.6074	0.6073
0.64	0.6071	0.6070	0.6068	0.6066	0.6065	0.6063	0.6061	0.6060	0.6058	0.6057
0.65	0.6055	0.6053	0.6052	0.6050	0.6049	0.6047	0.6045	0.6044	0.6042	0.6040
0.66	0.6039	0.6037	0.6036	0.6034	0.6032	0.6031	0.6029	0.6027	0.6026	0.6024
0.67	0.6023	0.6021	0.6019	0.6018	0.6016	0.6015	0.6013	0.6011	0.6010	0.6008
0.68	0.6006	0.6005	0.6003	0.6002	0.6000	0.5998	0.5997	0.5995	0.5993	0.5992
0.69	0.5990	0.5989	0.5987	0.5985	0.5984	0.5982	0.5980	0.5979	0.5977	0.5976
0.70	0.5974	0.5973	0.5971	0.5969	0.5967	0.5965	0.5964	0.5962	0.5960	0.5959
0.71	0.5957	0.5955	0.5953	0.5952	0.5950	0.5948	0.5947	0.5945	0.5943	0.5942
0.72	0.5940	0.5938	0.5936	0.5935	0.5933	0.5931	0.5930	0.5928	0.5926	0.5924
0.73	0.5923	0.5921	0.5920	0.5918	0.5916	0.5914	0.5912	0.5911	0.5909	0.5907
0.74	0.5906	0.5904	0.5902	0.5900	0.5899	0.5897	0.5895	0.5894	0.5892	0.5890
0.75	0.5889	0.5887	0.5885	0.5883	0.5882	0.5880	0.5878	0.5877	0.5875	0.5873
0.76	0.5871	0.5870	0.5868	0.5866	0.5865	0.5863	0.5861	0.5859	0.5858	0.5856
0.77	0.5854	0.5853	0.5851	0.5849	0.5847	0.5846	0.5844	0.5842	0.5841	0.5839
0.78	0.5837	0.5835	0.5834	0.5832	0.5830	0.5829	0.5827	0.5825	0.5824	0.5822
0.79	0.5820	0.5818	0.5817	0.5815	0.5813	0.5812	0.5810	0.5808	0.5806	0.5805
0.80	0.5803	0.5801	0.5799	0.5797	0.5796	0.5794	0.5792	0.5790	0.5788	0.5786
0.81	0.5785	0.5783	0.5781	0.5779	0.5777	0.5775	0.5773	0.5772	0.5770	0.5768
0.82	0.5766	0.5764	0.5762	0.5760	0.5759	0.5757	0.5755	0.5753	0.5751	0.5749
0.83	0.5748	0.5746	0.5744	0.5742	0.5740	0.5738	0.5736	0.5735	0.5733	0.5731
0.84	0.5729	0.5727	0.5725	0.5723	0.5722	0.5720	0.5718	0.5716	0.5714	0.5712

Appendix III – Slope Method Tables

For the calculated value of Δ in column 1 and row 1, read the corresponding value of P_D/D from the table

Δ	0	1	2	3	4	5	6	7	8	9
0.85	0.5711	0.5709	0.5707	0.5705	0.5703	0.5701	0.5699	0.5698	0.5696	0.5694
0.86	0.5692	0.5690	0.5688	0.5686	0.5685	0.5683	0.5681	0.5679	0.5677	0.5675
0.87	0.5674	0.5672	0.5670	0.5668	0.5666	0.5664	0.5662	0.5661	0.5659	0.5657
0.88	0.5655	0.5653	0.5651	0.5650	0.5648	0.5646	0.5644	0.5642	0.5640	0.5638
0.89	0.5637	0.5635	0.5633	0.5631	0.5629	0.5627	0.5625	0.5624	0.5622	0.5620
0.90	0.5618	0.5616	0.5614	0.5612	0.5610	0.5608	0.5606	0.5604	0.5602	0.5600
0.91	0.5598	0.5596	0.5594	0.5592	0.5590	0.5588	0.5586	0.5584	0.5582	0.5580
0.92	0.5578	0.5576	0.5574	0.5572	0.5570	0.5568	0.5565	0.5563	0.5561	0.5559
0.93	0.5557	0.5555	0.5553	0.5551	0.5549	0.5547	0.5545	0.5543	0.5541	0.5539
0.94	0.5537	0.5535	0.5533	0.5531	0.5529	0.5527	0.5525	0.5523	0.5521	0.5519
0.95	0.5517	0.5515	0.5513	0.5511	0.5509	0.5507	0.5505	0.5503	0.5501	0.5499
0.96	0.5497	0.5495	0.5493	0.5491	0.5489	0.5487	0.5485	0.5483	0.5481	0.5479
0.97	0.5477	0.5475	0.5473	0.5471	0.5469	0.5467	0.5464	0.5462	0.5460	0.5458
0.98	0.5456	0.5454	0.5452	0.5450	0.5448	0.5446	0.5444	0.5442	0.5440	0.5438
0.99	0.5436	0.5434	0.5432	0.5430	0.5428	0.5426	0.5424	0.5422	0.5420	0.5418
1.00	0.5416	0.5414	0.5412	0.5409	0.5407	0.5405	0.5403	0.5400	0.5398	0.5396
1.01	0.5394	0.5391	0.5389	0.5387	0.5385	0.5383	0.5380	0.5378	0.5376	0.5374
1.02	0.5371	0.5369	0.5367	0.5365	0.5362	0.5360	0.5358	0.5356	0.5354	0.5351
1.03	0.5349	0.5347	0.5345	0.5344	0.5340	0.5338	0.5336	0.5333	0.5331	0.5329
1.04	0.5327	0.5325	0.5322	0.5320	0.5318	0.5316	0.5313	0.5311	0.5309	0.5307
1.05	0.5305	0.5302	0.5300	0.5298	0.5296	0.5293	0.5291	0.5289	0.5287	0.5284
1.06	0.5282	0.5280	0.5278	0.5276	0.5273	0.5271	0.5269	0.5267	0.5264	0.5262
1.07	0.5260	0.5258	0.5255	0.5253	0.5251	0.5249	0.5247	0.5244	0.5242	0.5240
1.08	0.5238	0.5235	0.5233	0.5231	0.5229	0.5229	0.5224	0.5222	0.5219	0.5217
1.09	0.5215	0.5213	0.5211	0.5209	0.5206	0.5204	0.5202	0.5200	0.5197	0.5195
1.10	0.5193	0.5190	0.5188	0.5185	0.5183	0.5180	0.5178	0.5175	0.5173	0.5170
1.11	0.5168	0.5165	0.5163	0.5160	0.5158	0.5155	0.5153	0.5150	0.5148	0.5145
1.12	0.5143	0.5140	0.5137	0.5135	0.5132	0.5130	0.5129	0.5125	0.5122	0.5120
1.13	0.5118	0.5115	0.5113	0.5110	0.5108	0.5105	0.5103	0.5100	0.5098	0.5095
1.14	0.5093	0.5090	0.5088	0.5085	0.5083	0.5080	0.5078	0.5075	0.5073	0.5070
1.15	0.5068	0.5065	0.5062	0.5060	0.5057	0.5055	0.5052	0.5050	0.5047	0.5045
1.16	0.5042	0.5040	0.5037	0.5035	0.5032	0.5030	0.5027	0.5025	0.5022	0.5020
1.17	0.5017	0.5015	0.5012	0.5010	0.5007	0.5005	0.5002	0.5000	0.4997	0.4995
1.18	0.4992	0.4990	0.4987	0.4985	0.4982	0.4980	0.4977	0.4975	0.4972	0.4970
1.19	0.4967	0.4965	0.4962	0.4960	0.4957	0.4955	0.4952	0.4950	0.4947	0.4945
1.20	0.4942	0.4939	0.4936	0.4933	0.4930	0.4928	0.4925	0.4922	0.4919	0.4916
1.21	0.4913	0.4910	0.4907	0.4904	0.4901	0.4899	0.4896	0.4893	0.4890	0.4887
1.22	0.4884	0.4881	0.4878	0.4875	0.4872	0.4870	0.4867	0.4864	0.4861	0.4858
1.23	0.4855	0.4852	0.4849	0.4846	0.4843	0.4841	0.4838	0.4835	0.4832	0.4829
1.24	0.4826	0.4823	0.4820	0.4817	0.4814	0.4812	0.4809	0.4806	0.4803	0.4800
1.25	0.4797	0.4794	0.4791	0.4788	0.4785	0.4783	0.4780	0.4777	0.4774	0.4771
1.26	0.4768	0.4765	0.4762	0.4759	0.4756	0.4754	0.4751	0.4748	0.4745	0.4742
1.27	0.4739	0.4736	0.4733	0.4730	0.4727	0.4725	0.4722	0.4719	0.4715	0.4713
1.28	0.4710	0.4707	0.4704	0.4701	0.4698	0.4696	0.4693	0.4690	0.4687	0.4684
1.29	0.4681	0.4678	0.4675	0.4672	0.4669	0.4667	0.4664	0.4661	0.4658	0.4655

Appendix III – Slope Method Tables

For the calculated value of Δ in column 1 and row 1, read the corresponding value of P_D/D from the table

Δ	0	1	2	3	4	5	6	7	8	9
1.30	0.4652	0.4649	0.4645	0.4642	0.4638	0.4635	0.4631	0.4628	0.4625	0.4621
1.31	0.4618	0.4614	0.4611	0.4607	0.4604	0.4601	0.4597	0.4594	0.4590	0.4586
1.32	0.4583	0.4580	0.4577	0.4573	0.4570	0.4566	0.4563	0.4559	0.4556	0.4553
1.33	0.4549	0.4546	0.4542	0.4539	0.4535	0.4532	0.4529	0.4525	0.4520	0.4518
1.34	0.4515	0.4511	0.4508	0.4505	0.4501	0.4498	0.4494	0.4491	0.4487	0.4484
1.35	0.4481	0.4477	0.4474	0.4470	0.4467	0.4463	0.4460	0.4457	0.4453	0.4450
1.36	0.4446	0.4443	0.4439	0.4436	0.4432	0.4429	0.4426	0.4422	0.4419	0.4415
1.37	0.4412	0.4408	0.4405	0.4402	0.4398	0.4395	0.4391	0.4388	0.4384	0.4381
1.38	0.4378	0.4374	0.4371	0.4367	0.4364	0.4360	0.4357	0.4354	0.4350	0.4347
1.39	0.4343	0.4340	0.4336	0.4333	0.4330	0.4326	0.4323	0.4319	0.4316	0.4312
1.40	0.4309	0.4305	0.4301	0.4296	0.4292	0.4288	0.4284	0.4280	0.4275	0.4271
1.41	0.4267	0.4263	0.4258	0.4254	0.4250	0.4246	0.4242	0.4237	0.4233	0.4229
1.42	0.4225	0.4221	0.4216	0.4212	0.4208	0.4204	0.4200	0.4195	0.4191	0.4187
1.43	0.4183	0.4178	0.4174	0.4170	0.4166	0.4162	0.4157	0.4153	0.4149	0.4145
1.44	0.4141	0.4136	0.4132	0.4128	0.4124	0.4120	0.4115	0.4111	0.4107	0.4103
1.45	0.4099	0.4094	0.4090	0.4086	0.4082	0.4077	0.4073	0.4069	0.4065	0.4061
1.46	0.4056	0.4052	0.4048	0.4044	0.4040	0.4035	0.4031	0.4027	0.4023	0.4018
1.47	0.4014	0.4010	0.4005	0.4001	0.3997	0.3993	0.3989	0.3985	0.3980	0.3976
1.48	0.3972	0.3976	0.3964	0.3959	0.3955	0.3951	0.3947	0.3943	0.3938	0.3934
1.49	0.3930	0.3926	0.3921	0.3917	0.3913	0.3909	0.3905	0.3900	0.3896	0.3892
1.50	0.3888	0.3883	0.3878	0.3874	0.3869	0.3864	0.3859	0.3854	0.3850	0.3845
1.51	0.3840	0.3835	0.3830	0.3825	0.3820	0.3816	0.3811	0.3806	0.3801	0.3796
1.52	0.3971	0.3786	0.3781	0.3776	0.3771	0.3766	0.3760	0.3755	0.3750	0.3745
1.53	0.3740	0.3735	0.3730	0.3724	0.3719	0.3714	0.3709	0.3704	0.3698	0.3693
1.54	0.3688	0.3683	0.3677	0.3672	0.3667	0.3662	0.3656	0.3651	0.3646	0.3640
1.55	0.3635	0.3630	0.3624	0.3619	0.3613	0.3608	0.3602	0.3597	0.3591	0.3586
1.56	0.3580	0.3574	0.3569	0.3563	0.3557	0.3552	0.3546	0.3540	0.3534	0.3528
1.57	0.3523	0.3517	0.3511	0.3506	0.3500	0.3494	0.3488	0.3482	0.3477	0.3471
1.58	0.3465	0.3459	0.3453	0.3447	0.3441	0.3435	0.3429	0.3423	0.3417	0.3411
1.59	0.3405	0.3339	0.3393	0.3386	0.3380	0.3374	0.3368	0.3362	0.3355	0.3349

Data Source:

Measurement of the Resistance of Physically Large Earth-Electrode Systems, G.F. Tagg, Proceedings of the IEE, Vol. 117, No. 11, November 1970.

Appendix IV – Slope Method Field Data Form

D = Distance of C2 probe from electrode.
R1 = Resistance measured with P2 probe at 0.2 x D
R2 = Resistance measured with P2 probe at 0.4 x D
R3 = Resistance measured with P2 probe at 0.6 x D
R = Resistance measured with P2 probe at P_D

$\Delta = \frac{(R3 - R2)}{(R2 - R1)}$ P_D/D corresponds to Δ from Table $P_D = D \times (P_D/D)$

0.2 x D	**R1**	**0.4 x D**	**R2**	**0.6 x D**	**R3**	**Δ**	**P_D/D**	**P_D**	**R**
C2 (D) =									
C2 (D) =									
C2 (D) =									
C2 (D) =									
C2 (D) =									
C2 (D) =									

Location: ______________________________ Conditions: ______________________________
Date: ______________________________ By: ______________________________

Appendix V – Soil Resistivity Field Data Form

Spacing (ft)	Measured R (ohms)	Calculated ρ (ohms-m)	Site Info	
5			Test Set Model:	
10			Test Set S/N:	
15			Ground System Type:	
20			Temperature:	
25			Weather:	
30			Soil Moist or Dry:	
35			Soil Type (Circle):	
40				Loam
45				Sand & gravel
50				Shale
55				Clay
60				Limestone
65				Sandstone
70				Granite
75				Slate
80				Other

Location: ____

Conditions: ____

Date: ____

By: ____

For spacing (a) measured in ft:

$$\rho = 1.915 \cdot a_{ft} \cdot R \text{ ohm-m}$$

For spacing (a) measured in m:

$$\rho = 6.283 \cdot a_{m} \cdot R \text{ ohm-m}$$