The Pole-Pole Resistivity Array
Compared to the Twin Electrode Array

6 February 2000

Geosight Technical Report No. 6

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Summary

The pole-pole array resistivity maps to be compared from one survey to the next. This is important for identifying seasonal changes in the soil; these changes might reveal features that are not visible with measurements made at single time. This seasonal comparison is difficult to do with maps that have been measured with the twin electrode array. With the pole-pole array, the resistivity of the soil is easily determined; this parameter, by itself, gives information that can assist with excavation and it adds to the general knowledge of the soil at the site.

The twin electrode array is excellent for creating resistance maps, but not resistivity maps. It is slightly easier to set up a twin electrode array than a pole-pole array. Resistance measurements with the twin electrode array can be converted into resistivity, and Figure 5 shows how this is done; extra measurements are needed for this conversion. It is probably better to modify the twin electrode array into a pole-pole array, as sketched in Figure 6. Then, each measurement is readily converted to resistivity.

Introduction

Measurements of electrical resistance are widely applied to archaeological surveys; they are probably suitable for a greater number of sites than any other technique. Resistance measurements are particularly successful at detecting pits that have been filled with cultural debris; they are also good for locating architectural stone if the surrounding soil contains little stone or sand.

The equipment that is needed for resistance surveys is simpler and less expensive than most other geophysical instruments. The central part of the resistance instrument is a box that displays the measurements. Four electrical wires connect this box to four metallic electrodes that are driven to a shallow depth into the earth.

The four electrodes may be arranged into different patterns, called arrays. With the Wenner array, the electrodes are equally-spaced along a straight line. Two other arrangements are illustrated in Figure 1; these are called the pole-pole array and the twin electrode array. With both arrays, two electrodes are close together and are moved around the area of survey, making measurements that create the resistance map. Two electrodes remain at fixed locations during these measurements; these can be called the reference or fixed electrodes.

The pole-pole array differs from the twin electrode array only in the locations of the two reference electrodes. With the twin electrode array, these two reference electrodes are set quite close to each other. With the pole-pole array, the two reference electrodes are distant from each other.

It is simpler to set the two reference electrodes close to each other, as is done with the twin electrode array. With this array, wire is spread in a smaller area than with the pole-pole array; this minimizes the hazard of tripping if there are pedestrians nearby.

The twin electrode array has a disadvantage that can be important: It is difficult to convert its measurements of electrical resistance to resistivity. If the goal of the survey is one of detecting features in the soil, a map of electrical resistance is just as good as a map of electrical resistivity. However, electrical resistance does not allow an identification of the type of soil that is underground; excavation plans may change if the soil is clay rather than sand, and the soil visible at the surface is not necessarily the same as that 10 cm underground. More importantly, measurements of electrical resistance cannot be compared from one site to another, or from one time to another at one site.

It will take longer to set the reference electrodes when the pole-pole array is used; this is just because they are farther apart. It is also possible that this array may detect more electrical interference than the twin electrode array; if the interference is large, the Wenner array can be better.

Several authors have given excellent introductions to the basis of resitivity surveys; these references are more complete than my discussion (Tagg 1964 p. 13; Hess 1990; Keller and Frischknecht 1966 p. 90).

Resistance and Resistivity

These four-electrode instruments measure the electrical resistance of the soil in the area of the electrodes. The unit of resistance is the ohm, and the capital Greek omega is a symbol for this unit.

Resistivity is different from resistance. Its unit in geophysics is the ohm-meter. Values of resistivity describe and distinguish different types of soil. For example, sandy soil can have a resistivity of 1000 ohm-m, while clayey soil can have a resistivity of 20 ohm-m. Tabulations of resistivity values for different soils are found in handbook, such as that of McNeill (1980).

If a measurement indicates a resistance of 50 ohm, this does not say anything about the type of soil. The measurement of resistance is affected by both the actual resistivity of the soil and by the locations of the four electrodes. Knowing the locations of the electrodes, it is possible to calculate a value of resistivity. This resistivity is correctly called an apparent resistivity, for it is an average of many lenses and strata of soil in the vicinity of the electrodes.

Voltages on the Earth’s Surface

Some of the fundamentals of resistivity measurements may clarify the methods of these surveys. If the soil is homogeneous, an electrical current will flow uniformly through the soil; it will spread radially from an electrode. This will generate a simple pattern for the voltage that is measured on the earth’s surface.

Figure 2 shows how this voltage diminishes with increasing distance from the electrode. The words “voltage” and “potential” are interchangeable, although “voltage” is used more in engineering, and “potential” is used more in physics. The voltages listed in Figure 2 are millivolts, abbreviated mV (100 mV = 0.1 V); the current of 40 mA equals 0.04 ampere. The resistivity of 100 ohm-m is typical of soils.

The equation that shows how the voltage changes with increasing distance (S) is given at the top of Figure 2. This implies that the voltage could be infinite right at the electrode (S = 0). Because the diameter of an electrode cannot be shrunk to a point, the voltage is high at the electrode, but not infinite (the length of the electrode driven into the soil also increases its apparent size).

Figure 2 shows an electrical current going into the earth at the middle of the figure; it must come out somewhere at a second electrode. This second electrode is assumed to be quite distant, and that is the basis for the voltage equation at the top of Figure 2. If the second electrode is moderately nearby, it is only slightly more difficult to calculate the voltages on the earth’s surface; Figure 3 is an example. Again, the soil is assumed to have a uniform resistivity. If the resistivity was not uniform and constant, there would be undulations on the simple, circular lines in Figure 3; these complex patterns would reveal the locations of underground features.

Note the high positive voltage that encircles the point E0 N0; this is where the current goes into the soil. Negative voltages surround the second electrode, at E200 N0; the current comes out of the soil there. In geophysics, it is conventional to define the voltage at a large (or infinite) distance from a current electrode as zero. Note that the contour line of zero voltage goes directly in between the two current electrodes.

If you wished to measure these voltages by an experiment on the earth’s surface, you could just connect a battery between the two electrodes, and this would create the current that would cause these patterns of voltage. You could measure the voltages with a normal voltmeter. Because of the convention above, you could connect the negative (reference) lead from the voltmeter to the ground at a very large distance from the electrodes using a long wire. However, you could save a lot of wire by just connecting that reference lead on the surface anywhere along the midline between the two electrodes. This idea also applies to the pole-pole array.

The Pole-Pole Array

Figure 3 is important for understanding the pole-pole array. Ideally, one would wish the second current electrode, there at E200, to be much more distant from the electrode that is moving during the survey; this electrode is at E0 in the illustration. Increasing this electrode distance requires additional wire and time, and a compromise between the quality of the survey and the time for equipment setup can be made. The goal is simply that of putting the reference current electrode far enough away that the contour lines of constant voltage, seen on the left side of Figure 3, are rather circular and concentric about the electrode at E0 N0. As the reference current electrode gets closer, these contour lines become more elliptical and skewed. See Figure C69 in my earlier report for an illustration (Bevan 1996).

The calculated pattern in Figure 3 suggests that if a square that is 100m on a side is to be surveyed, it is adequate to put the current reference electrode at a distance of 200 m from the moving electrode. The data would still be excellent if this electrode was moved closer, to 150 m from the middle of the survey area.

Figure 4 is a map of apparent resistivity that was calculated with the current reference electrode at E150. The actual resistivity of the earth was fixed at 100 ohm-m. However, the pole-pole array would measure slightly lower values of apparent resistivity, and the contours show the pattern. The lowest reading would be 97.2 ohm-m at the corner closest to the reference electrodes. An error of 3 percent is acceptable in a resistivity survey. Furthermore, part of this error can be removed from a measured resistivity map with the aid of calculations similar to that in Figure 4.

These illustrations have indicated a suitable distance for the reference current electrode: It is adequate that its distance from the edge of a square survey area be equal to the side of that square. If a 20 m square is to be surveyed, just put the reference current electrode at least 20 m outside the square. If it is necessary to put it closer, there will be a gradient in apparent resitivity across the map; this may cause little difficulty if its origin is remembered.

Where should the voltage reference electrode be placed? The goal is one of putting it as far from the current reference as possible, and also as far from the area of survey as possible. It should be in an area where the voltage is about zero, and stays near zero during the survey of a grid. As indicated in Figure 3, the closest point where the voltage is zero is midway between the moving electrode of the survey and the current reference electrode. Because the measurement location changes during the survey, there can be some advantage to placing this voltage reference along this midline, but north or south of the midpoint. This will keep the voltage at the reference point close to zero during the survey. I normally take the voltage reference electrode half-way to the current electrode, and then that same distance to the left and right; see Figure 1 and 4.

When a survey is continued between days, the two reference electrodes may be placed in different locations, for the resistance measurements will be the same as before. As a test of the reference electrodes, it is valuable to measure the resistance between them using a normal two-wire resistance meter, often a digital multimeter; the geophysical resistivity meter can also be converted to a two-wire resitance meter. I have found that this resistance, in ohms, will be about 10 times the electrical resistivity of the soil, in ohm-m, as seen by the following tests:

Site	**Resistance, ohm**	**Resistivity, ohm-m**
Petersburg NMP, VA	6300	1400-200
Wright-Patterson, OH	260	25- 50
	150	20
Cahokia Mounds, IL	130	15- 80
Pecos NHP, NM	690	60
Effigy Mounds NHP, IA	540	35

If this resistance is abnormally large, it may mean that the wire is broken or the one of the electrodes is disconnected; if the resistance is too low, perhaps the insulation of a wire to a reference electrode is bad and bare metal touches the ground. I typically place 3 –4 small metal stakes close together to form both the current and voltage electrodes; this lowers the resistance of the electrodes and also makes them more reliable (in case the connection to one goes bad during the day).

It is easy for one person to do a resistivity survey with a pole-pole array. The two wires going to the reference electrodes can be tied around one’s waist so that they can be pulled around the survey grid. The moving electrodes can usually be stepped so that only one of them changes location for each measurement. These moving electrodes can be stepped along a straight line, or they can be shifted to make both N-S and E-W measurements, as described in one of my earlier reports (Bevan 1996 p. B13, C22, Figure C80).

The resistance measurements form a pole-pole survey are converted to apparent resistivity by multiplying them by the spacing between the moving electrodes and then by twice pi; the equation is shown in Figure 6. Further information about the pole-pole array can be found in the geophysical literature (Das and Verma 1980; Kumar 1974).

The name, pole-pole array, is the most common and precise phrase that describes this electrode arrangement. The word “pole” comes from physics and other technical disciplines; it means that the associated point of a pair of points is quite distant, essentially an infinite distance. This describes the fact that the reference electrodes are quite distant from the moving, or measuring electrodes, while the pair of measurement electrodes are close to each other.

There are many different types of arrays that are applied to resistivity surveys. One is the dipole-dipole array. This is the opposite of the pole-pole array. With the dipole-dipole array, the two voltage electrodes are close to each other, as are the two current electrodes; however, the pair of current electrodes are quite distant from the pair of voltage electrodes. This array allows the exploration to be done to a great depth.

The Twin Electrode Array

The twin electrode array is used with the resistance-measuring instruments from Geoscan Research. This array has been described most completely by Clark (1996 p.44).

A schematic of the measuring circuitry is shown at the top of Figure 5. For this array, the two reference electrodes are set close to each other. The reason for this appears never to have been explained, although it is obviously more convenient this way.

The proximity of the reference electrodes causes no difficulty for the mapping of resistance. It does complicate the determination of the resistivity of the soil. This is because the resistance that is measured is determined by the resistivity of the soil below both the moving and the reference electrodes. Equation 1 in Figure 5 shows the relationship; this is derived from the equation in Figure 2. The net voltage that is measured is the sum of the voltage at the moving and the fixed electrodes.

While the two electrodes spacings (Sf and Sm) and the resistance (R) in equation 1 are known, there are still two unknown values (the two resistivities), and so it is not possible to determine the actual resistivity at either the moving or reference electrodes.

It must always be assumed that the earth below the reference electrodes is different from that in the area of survey. If the resistivities could be assumed to be the same, the resistivity must be uniform, and there would be no need for mapping its changes. While Figure 5 shows an impossibly simple change from one resistivity to another, the true pattern of the soil contrast is not important; it is only important that it is different under both electrode pairs.

As shown by Clark (1996 p. 44), an additional measurement of resistance will make it possible to determine the apparent resistivity at the moving electrodes. The second measurement of resistance is just made with a different spacing between the two moving electrodes. This same method allows the resistivity to be determined at the fixed or reference electrodes. The two resistances (R) and the two spacings (S) are entered into Equation 2, and the resistivity at the fixed electrodes is determined.

When the resistivity at the reference electrodes is found, then each measurement on the resistance map can be converted to resistivity with equation 3; this is just a rearrangement of equation 1. This equation shows that the resistance measured with the twin electrode array will always be fixed amount higher than the resistance measured with a pole-pole array when the moving electrodes are at the same location.

It is likely that the resistivity at the reference electrodes will change during a day's survey, although it may not be so large that it causes difficulties. Until its temporal change is known for certain to be small, it should be measured before the survey starts each day and after it is finished.

When a twin electrode resistance survey is finished, the reference electrodes are removed. If the measurements are redone at a later date, it is unlikely that the reference electrodes can be placed in the same locations as before, and so the resistance readings would not be the same. If a survey of a measurement grid takes several days, this same effect can happen on each of those days if the electrodes are removed at the end of every day.

The twin electrode array is easily modified to a pole-pole array, and Figure 6 shows all that is needed. The electrical wire that is added must be insulated, and the insulation must nowhere be cut so that bare metal is exposed. This wire is connected to one of the wires on the end of the cable coming from the resistance meter; that connection must also be insulated from the ground. If this insulation is not complete then additional, but unwanted, “electrodes” are created where bare metal touches the soil.

Perhaps the new reference electrode could be moved to another side of the survey grid. It may not be known which of the two reference wires is the voltage wire, and which is the current. Therefore, it may not be practical to move the voltage reference to an area where the voltage is closest to zero. Setting the reference electrodes so that they are distant from each other and distant from the area of survey is sufficient.

The twin electrode array appears to have been applied only to archaeological surveys, and this array name is not found in the general geophysical literature (Sheriff 1991). The pole-pole array has sometimes been called other names, such as the half-Wenner array or the two-electrode array. This latter term may confuse it with the twin electrode array, which perhaps has also been called the two-electrode array.

Conclusion

The pole-pole array allows easy determination of the resistivity of the ground. This enables the readings at one site to be compared to another site. It also allows the temporal change in the readings to be determined; this may aid the understanding of geophysical anomalies. During a few years of survey at the Petersburg National Battefield, in Virginia, I repeated many resistivity measurements to see how they changed with rainfall and season; see Figures C2 through C7 in my report on the survey (Bevan 1996). While these changes did not appear to be very interesting in the sandy soil at that site, seasonal changes in resistivity should always be examined for the additional archaeological information that they might supply.

These site-to-site and seasonal comparisons are not possible with the twin electrode array. This is because the unkown resistivity at the reference electrodes adds an unknown amount to each resistance reading.

If a twin electrode survey has already been completed, and the resistivity at the reference electrodes has not been measured, it will probably not be possible to convert the resistance readings to resistivity. One may assume that the average resistivity at the moving electrodes is the same as the constant resitivity at the reference electrodes, and then equation 3 in Figure 5 will allow a calculation of that resistivity; the assumption of equal resistivity is difficult to justify.

It is probably easiest to make the simple modification of a twin electrode array to a pole-pole array. For the survey of a 40 m square, one reference electrode can be set a distance of 40 m outside the grid and the other reference electrode can be placed so that it is distant from the other electrode and also the survey area.

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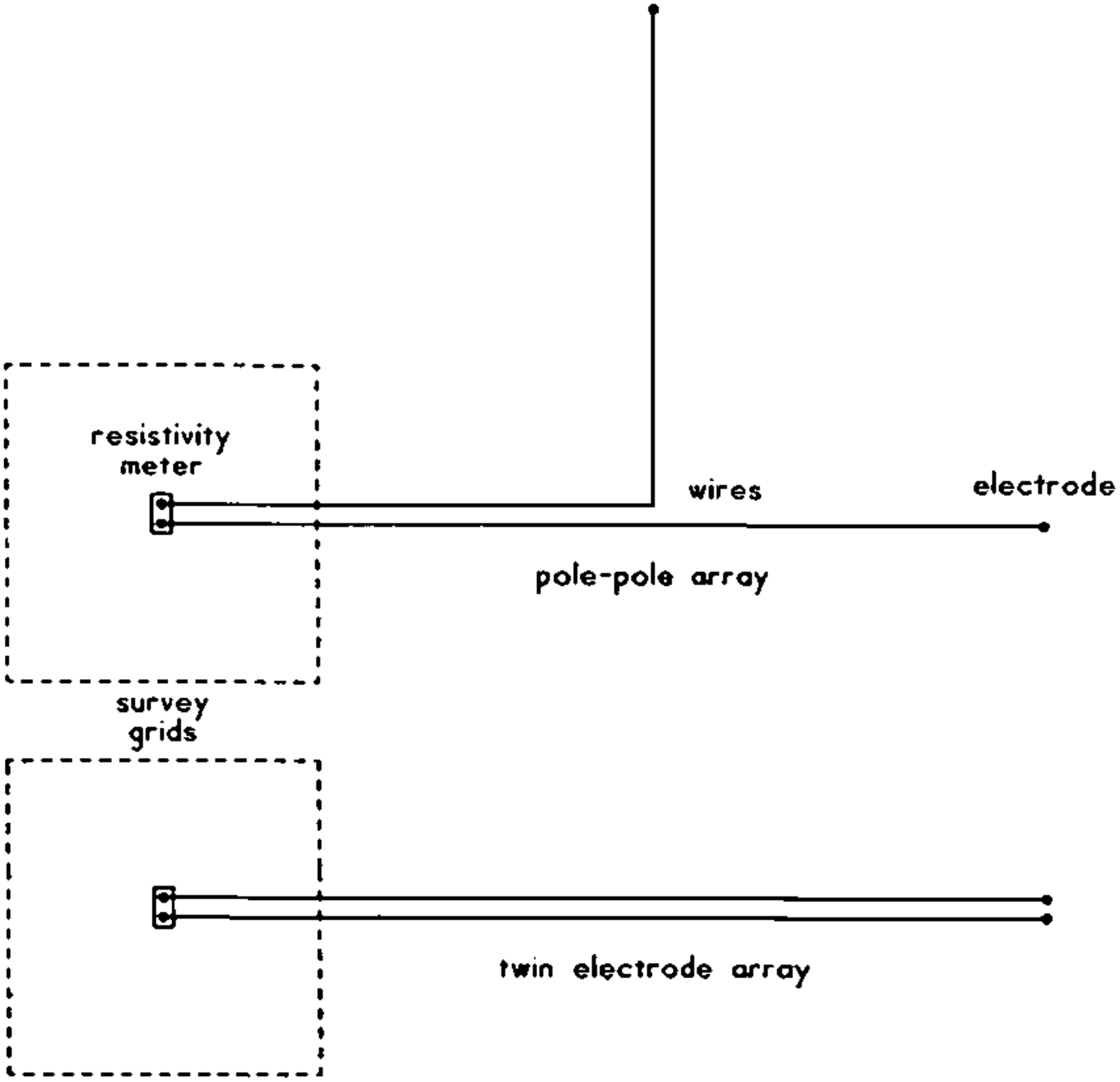


Figure 1. Two different ways of measuring the electrical resistance of the soil. The same equipment can be used for both arrays, and each has four electrodes that are grounded to the earth; two of these move within the survey grid, and two remain stationary as reference electrodes. With the twin electrode array, the two reference electrodes are near each other. With the pole-pole array, the two reference electrodes are distant from each other.

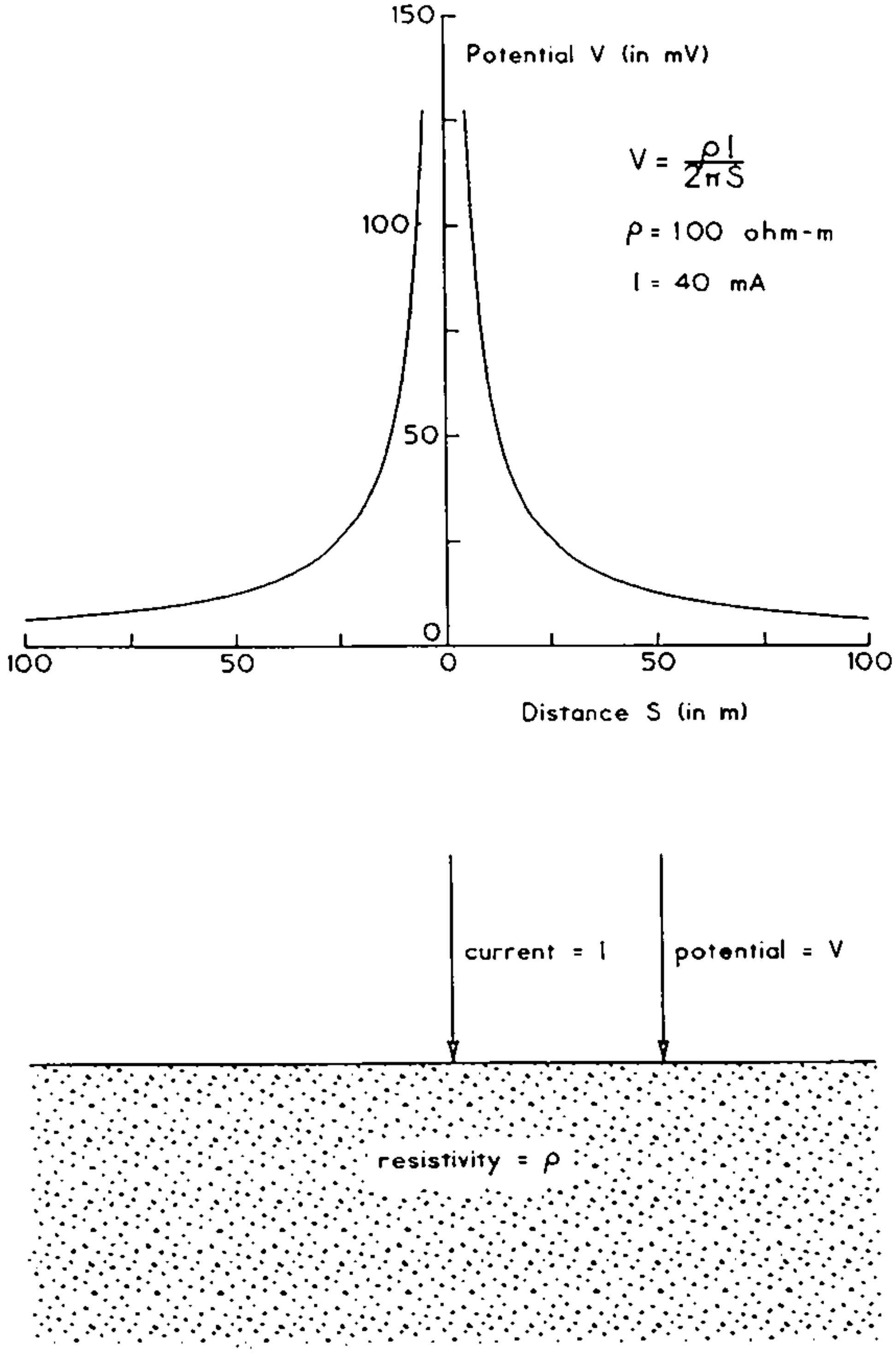


Figure 2. The voltage around a grounded electrode. While it is high close to the electrode, it decreases with the reciprocal of distance from the electrode. The equation shows how this voltage (or potential) is determined by electrical resistivity of the soil (rho), the current into the electrode (I), and the distance from the current electrode (S).

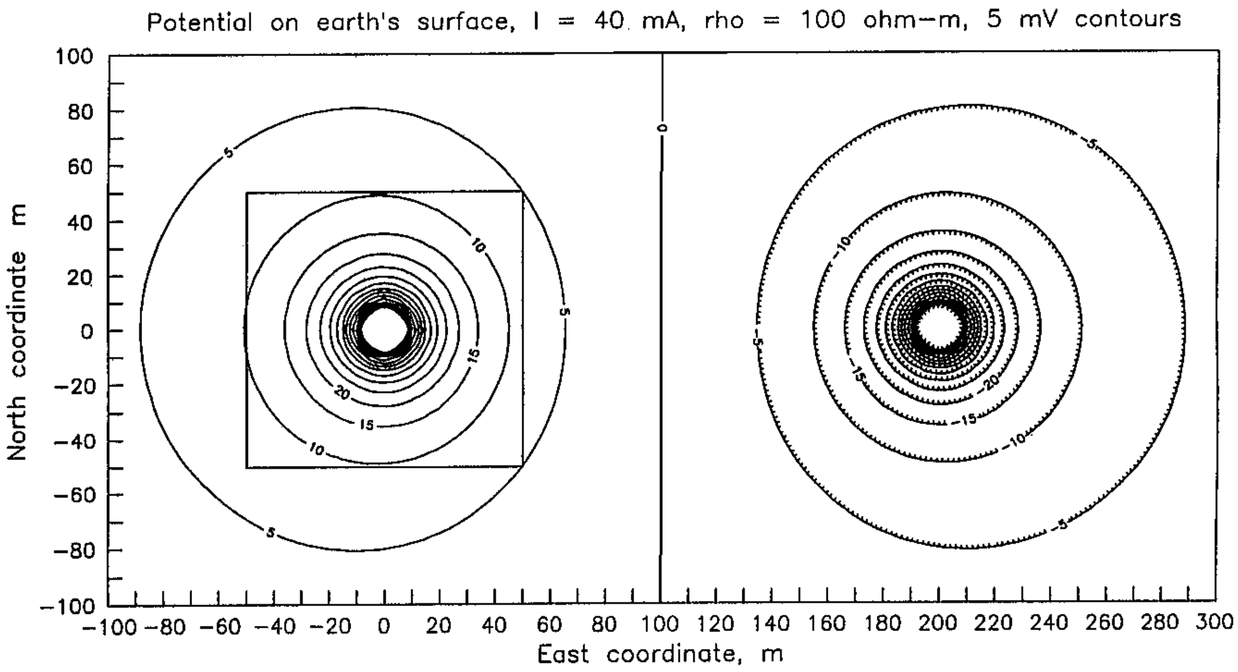


Figure 3. The voltage at the surface that results from the current between a pair of grounded electrodes. The current flows into the earth at the E0 N0 point and comes out of the earth at E200 N0. Note that the potential is zero along line E100, midway between the two electrodes.

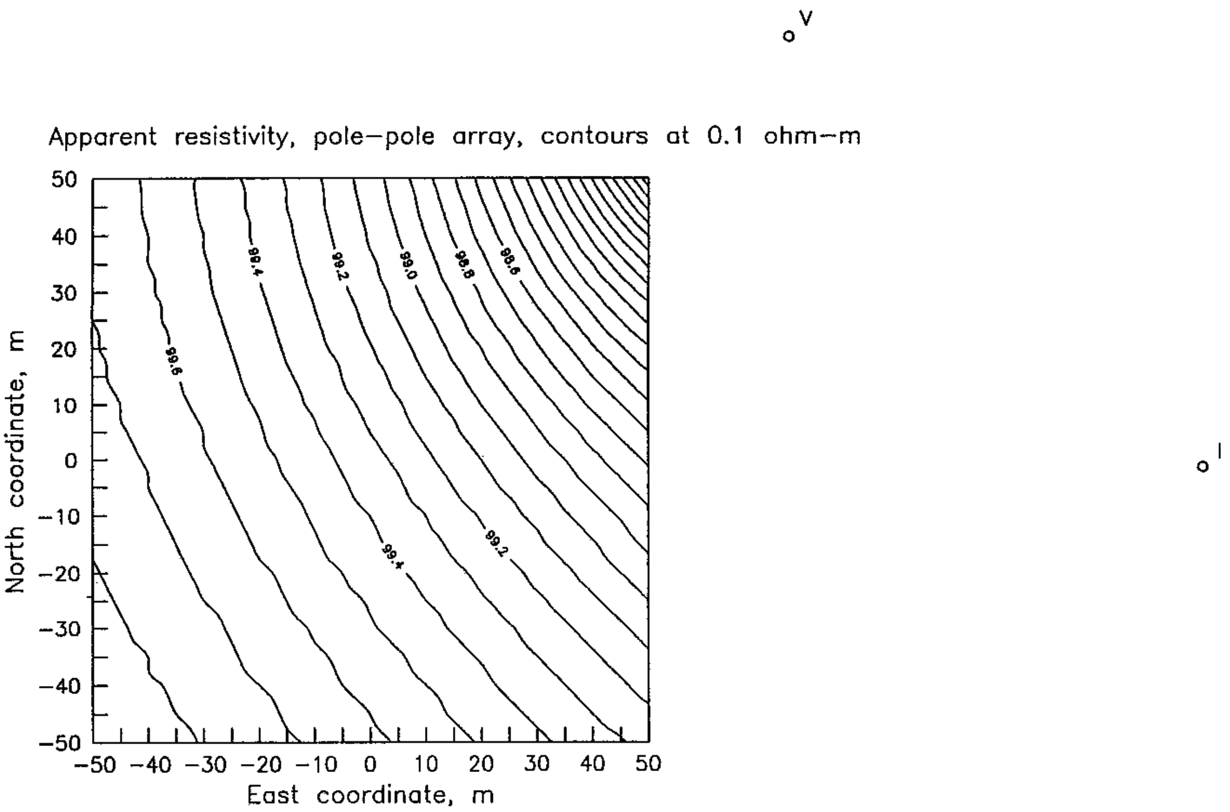
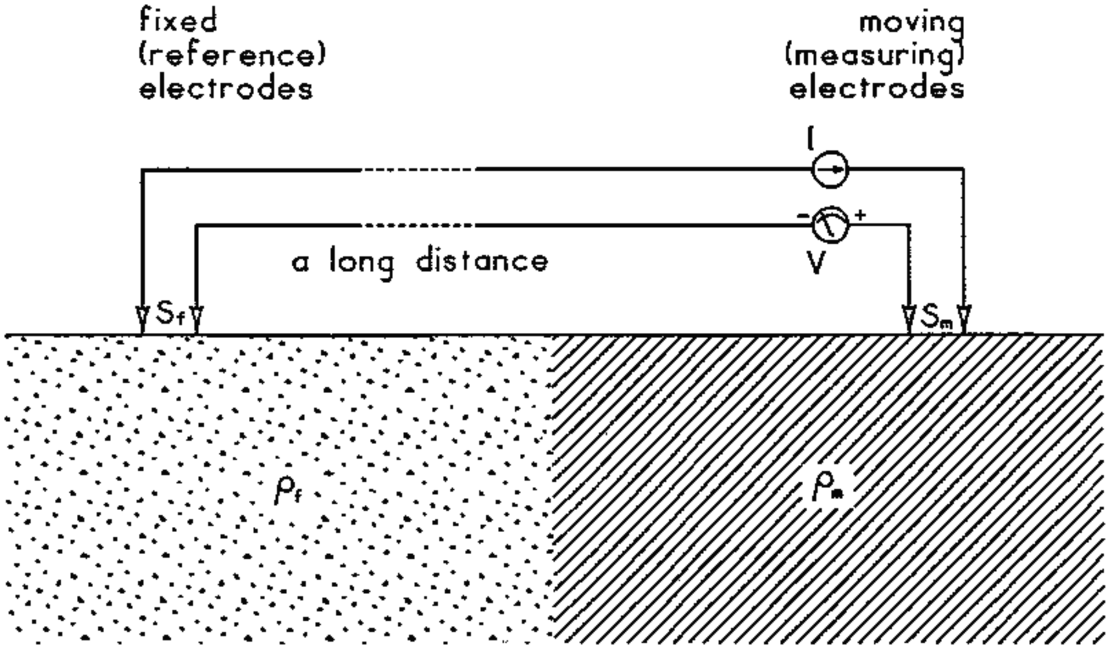


Figure 4. The error in resistivity that can be measured with a pole-pole array. The calculated resistivity values assume that the earth has a resistivity of 100 ohm-m, but the contours show that the measured values would be lower than the correct value close to the reference electrodes. The locations of the current (I) and voltage (V) reference electrodes are indicated with circles.



The resistance measured by the twin electrode array is determined by the resistivity below both pairs of electodes:

$$R = \frac{V}{I} = \frac{1}{2\pi}\left(\frac{\rho_f}{S_f} + \frac{\rho_m}{S_m}\right) \quad \text{(equation 1)}$$

The resistivity below the fixed electrodes can be determined by resistance measurements at two electrode spacings:

$$\rho_f = 2\pi \frac{R_1 - R_2}{\left(\frac{1}{S_{f1}} - \frac{1}{S_{f2}}\right)} \quad \text{(equation 2)}$$

The resistivity below the moving electrodes can then be determined with the following equation:

$$\rho_m = 2\pi S_m R - \rho_f\left(\frac{S_m}{S_f}\right) \quad \text{(equation 3)}$$

Figure 5. The resistance measurement of a twin electrode array. As indicated in equation 1, it depends on the resistivity found below both moving (m) and fixed (f) electrodes, and the spacing (S) between each pair of electrodes. Equation 2 shows how the actual resistivity below the fixed electrodes can be determined with a pair of resistance readings. Once this has been done, it is easy to convert the map of measured resistance to a map of electrical resistivity with equation 3.

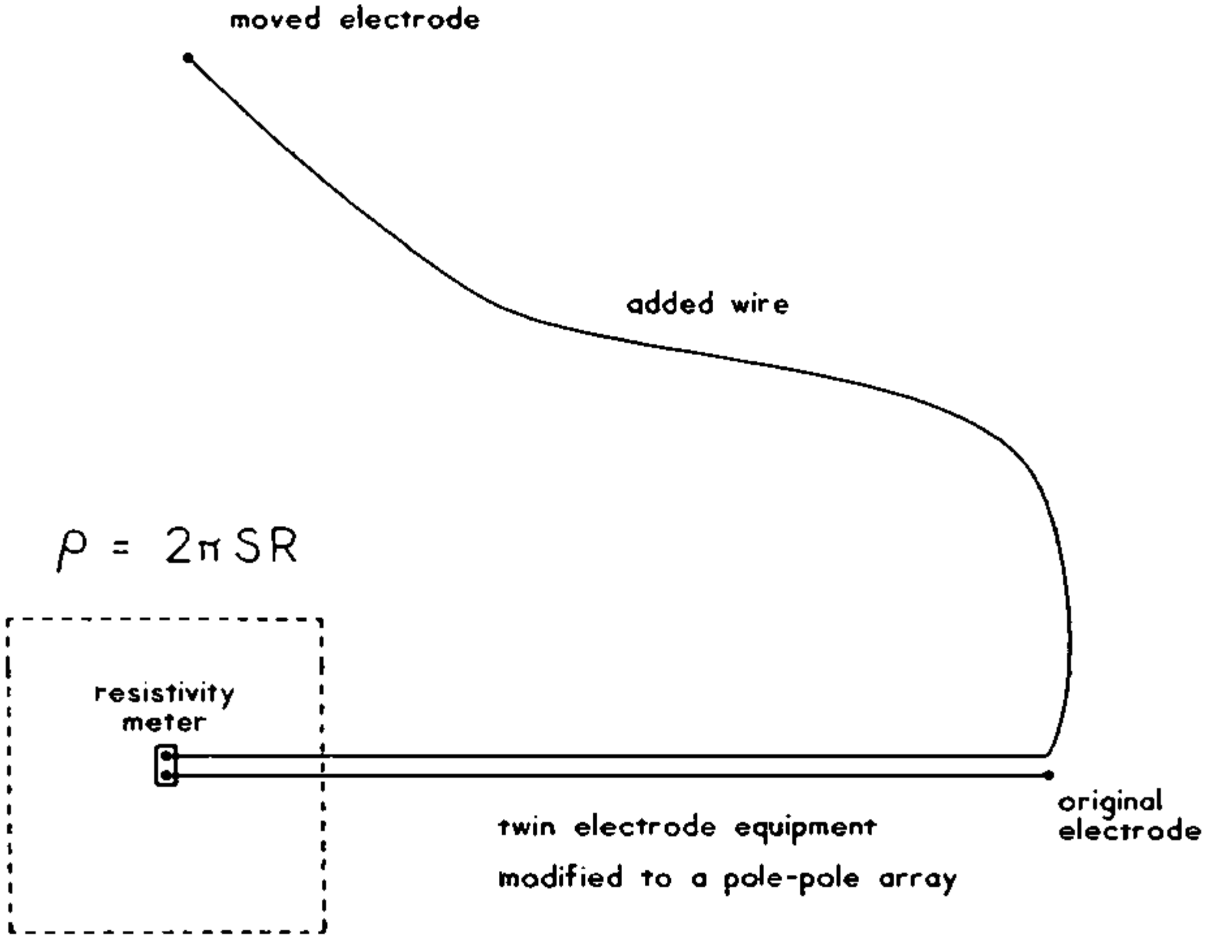


Figure 6. A simple modification of the twin electrode instrument. This converts it so its measurements of resistance can easily be converted to resistivity with the equation shown. The only additional equipment that is needed is a length of insulated wire.