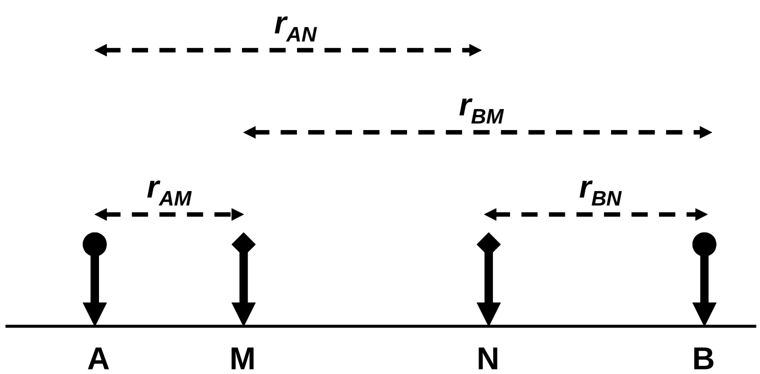
Earth 461/668 Classnotes (Set 2)

II.) ELECTRICAL RESISTIVITY METHODS

E.) Four Electrode Array

1.) Consider four electrode array (two current electrodes A & B; two potential electrodes M & N) located on the surface of a homogeneous Earth having a resistivity ρ.



2.) Using the result for the potential due to two current electrodes, the potential difference between the potential electrodes is

$$\Delta V_{MN} = V_M - V_N = \frac{\rho I}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}}\right) - \frac{\rho I}{2\pi}\left(\frac{1}{r_{AN}} - \frac{1}{r_{BN}}\right) \Rightarrow$$

$$\Delta V_{MN} = \frac{\rho I}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)$$

3.) The resistivity of the homogeneous Earth can be obtained from the ΔV_{MN} measurement using

$$\rho = \frac{\Delta V_{MN}}{I}\left\{2\pi\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)^{-1}\right\}$$

The term $K = 2\pi\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)^{-1}$ is referred to as the geometric factor.

F.) Concept of Apparent Resistivity

1.) In reality, the Earth is not homogeneous. However, it is customary to express ΔV_{MN} measurements in terms of a quantity called the "apparent resistivity" ρ_a where

$$\rho_a = \frac{\Delta V_{MN}}{I}\left\{2\pi\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)^{-1}\right\} = \frac{\Delta V_{MN}}{I} K$$

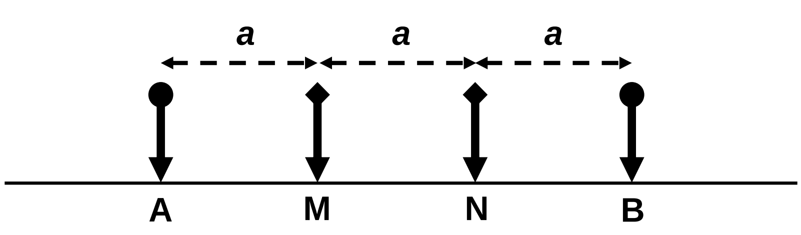
2.) The apparent resistivity ρ_a is the resistivity of equivalent homogeneous Earth that corresponds to the ΔV_{MN} measurement for a given applied current I.

3.) It needs to be remembered that ρ_a is not a physical property of the subsurface; it is a representation of the survey measurements that normalizes for the variation in the applied current I.

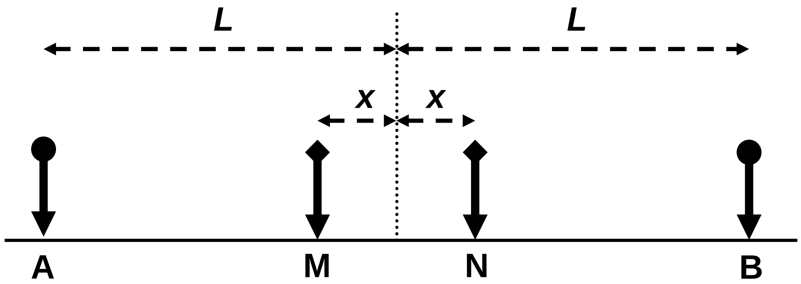
G.) Types of Four Electrode Arrays

1.) There are a number of different electrode arrays are used (A literature review by Szalai & Szarka (2008) identified 102 arrays). The geometric factor K is determined by the array. For a heterogeneous Earth, the value of ρ_a will depend on the array used.

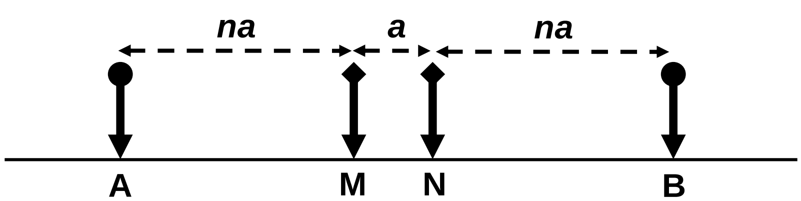
2.) Wenner array: $K = 2\pi a$



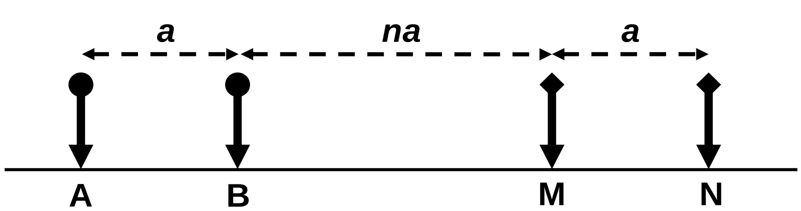
3.) Schlumberger array: $K = \frac{\pi}{2}\left(\frac{L^2 - x^2}{x}\right)$



4.) Wenner Schlumberger array: $K = \pi n\,(n+1)\,a$



5.) Dipole-dipole array: $K = \pi n\,(n+1)\,(n+2)\,a$



H.) Depth of Investigation

1.) In practical/qualitative terms, the depth of investigation of a given electrode array (type & dimensions) is the depth in subsurface that is best associated with the measured apparent resistivity (i.e., the “mean” depth of the effective sampling volume).

2.) Several studies have proposed quantitative definitions for the effective depth of investigation of electrode arrays based on the array sensitivity function for a one-dimensional resistivity depth profile.

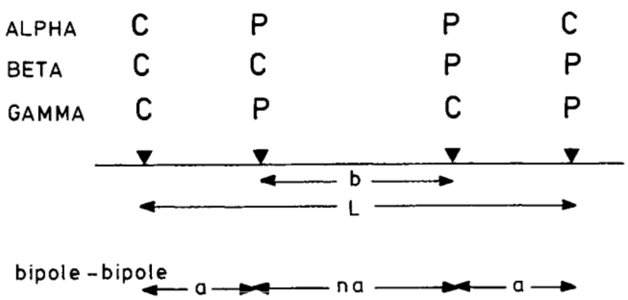


Fig. 1. Generalized symmetrical four-electrode array and tripotential arrangements. Current and potential electrode locations are designated by C and P, respectively. Conventional notation for the axial bipole-bipole array is also shown.

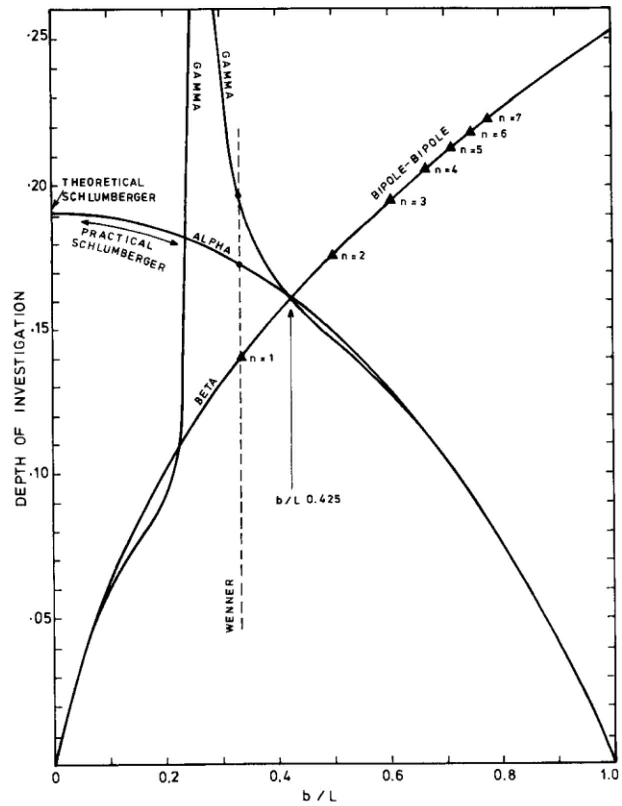


Fig. 7. Depth of investigation (Edwards definition) of the three tripotential arrangements of the generalized four-electrode array.

Example: Wenner array = 0.17 *AB* = 0.51 *a*

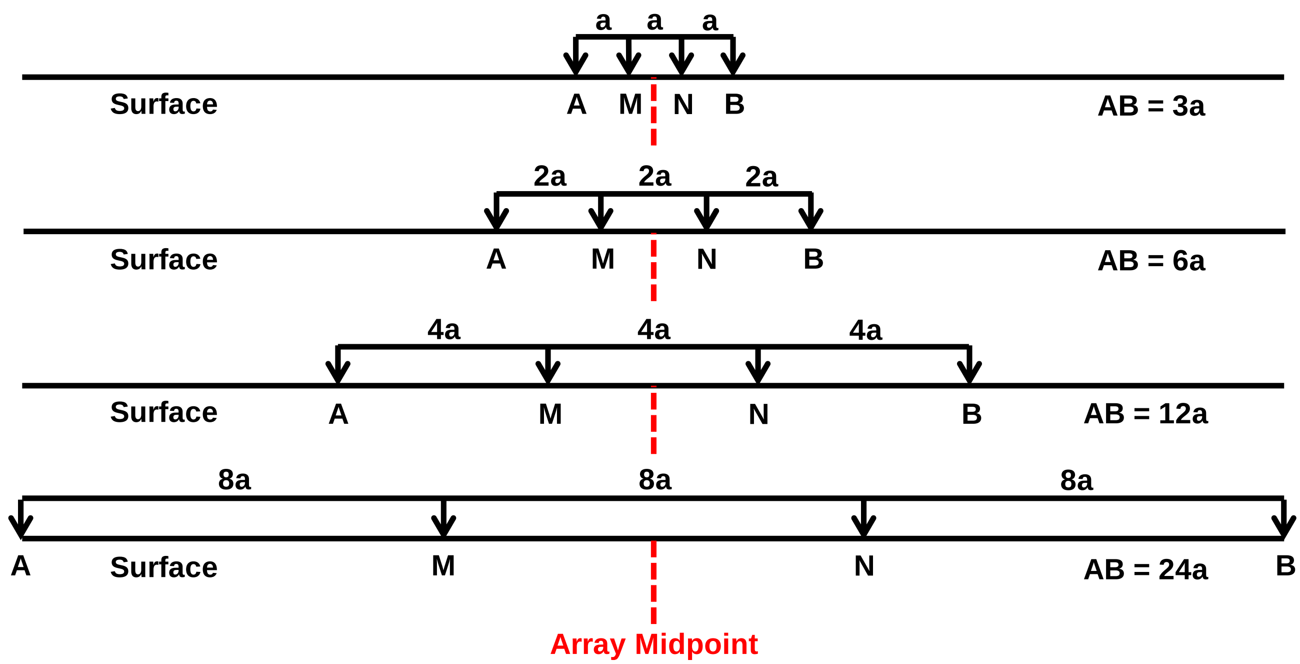
Figures from Barker (1889).

I.) Survey Modes for Resistivity Method

1.) Vertical Electric Sounding (VES)

a.) Used to detect vertical resistivity variations when bedding is horizontal or near horizontal.

b.) Sounding is performed by systematically expanding array dimensions while the array remains centered at a fixed midpoint.



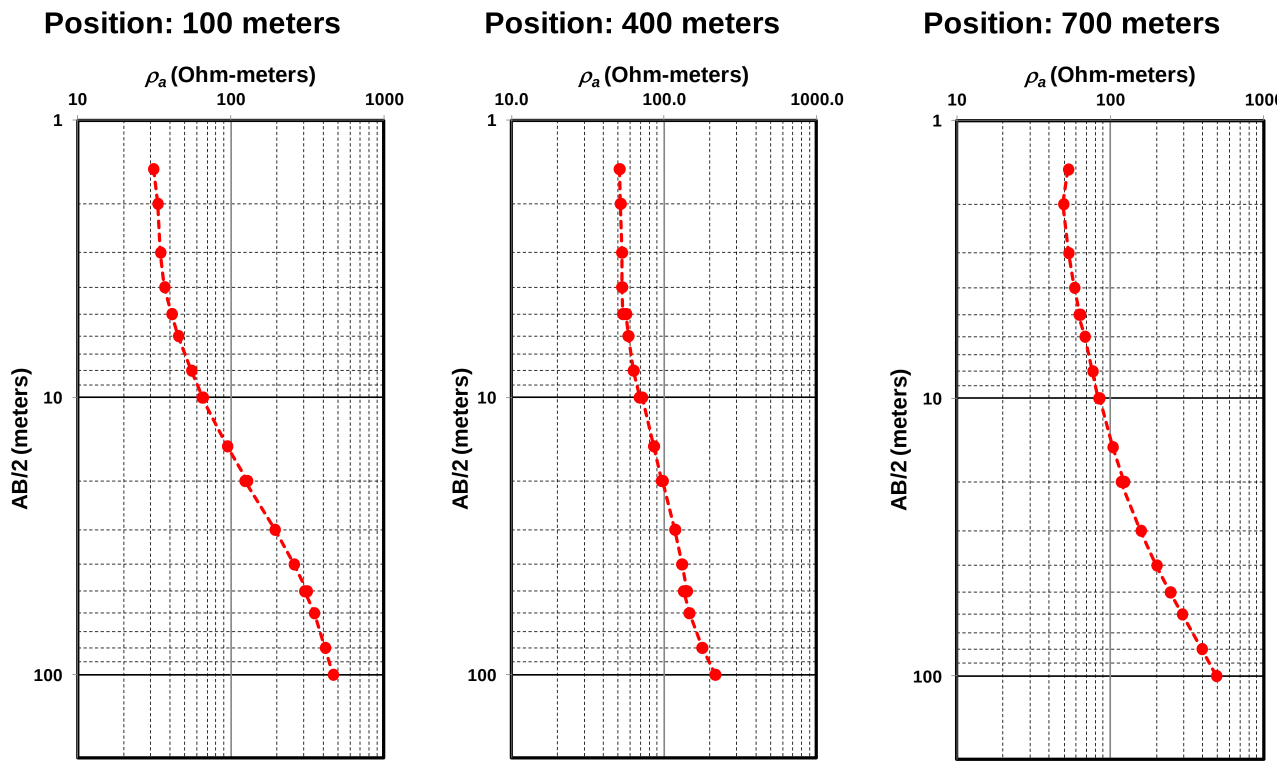
c.) As the array expands, current flow lines penetrate deeper into the Earth. Hence, the resulting ρ_a values contain information about progressively deeper resistivity structure.

d.) VES produces ρ_a data as a function of array dimension (e.g., current electrode spacing). These data give qualitative information about the resistivity variation with depth. (The current electrode space is measure of the depth of investigation; ρ_a is an "average" of the Earth's resistivity structure to that depth.)

e.) VES measurements can be adversely affected the effects of small scale, near surface heterogeneities located in the vicinity of the electrode (in particular, the potential electrodes).

Note, the Schlumberger array is less susceptible to these effects due to the limited movement of the potential electrodes.

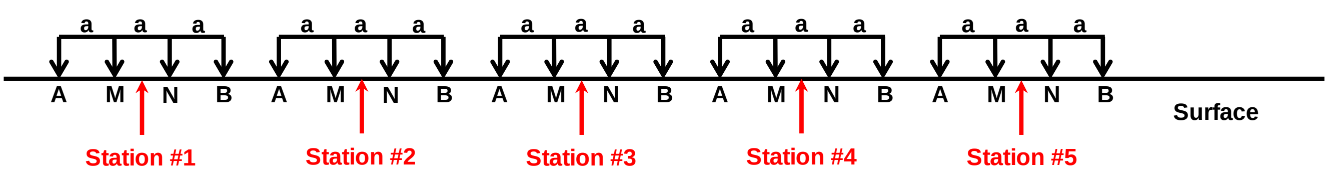
Example of vertical electrical sounding (VES): Elora buried valley site (Schlumberger array)



2.) Constant Separation Traversing (CST) / Electric Profiling

a.) Used to detect horizontal variations in subsurface resistivity structure.

b.) Profile is generated by systematically moving an array with fixed electrode separations along a profile line.



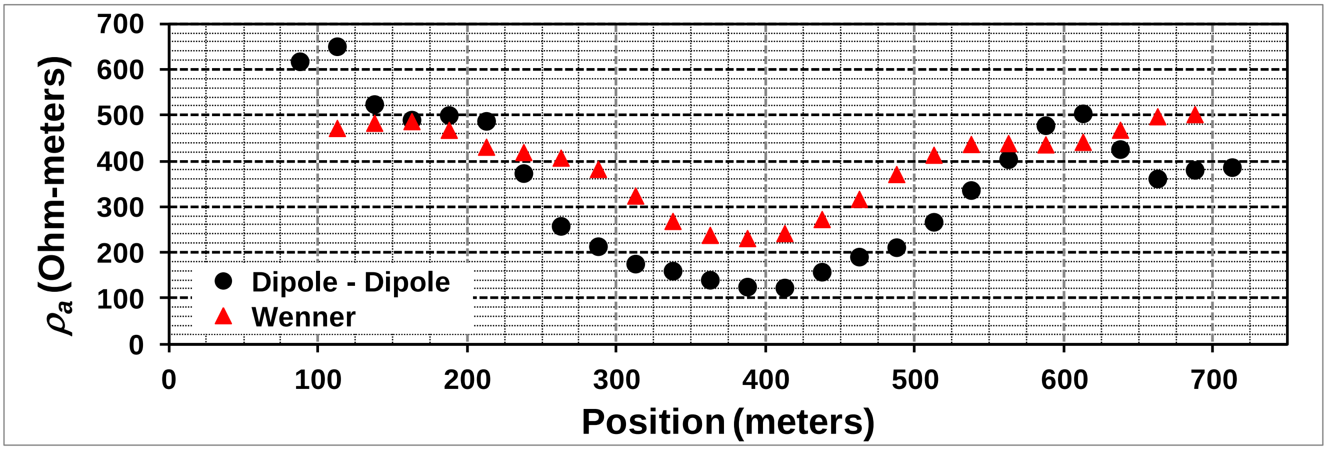
c.) This procedure produces a spatial distribution of ρ_a values at sampling points along a profile line (or grid of profile lines).

d.) Since the electrode array dimensions are fixed and that determines the effective depth of investigation, CST data provides no information about vertical variations of ρ.

Example of constant spacing traverse(CST) / electrical profiling: Elora buried valley site.

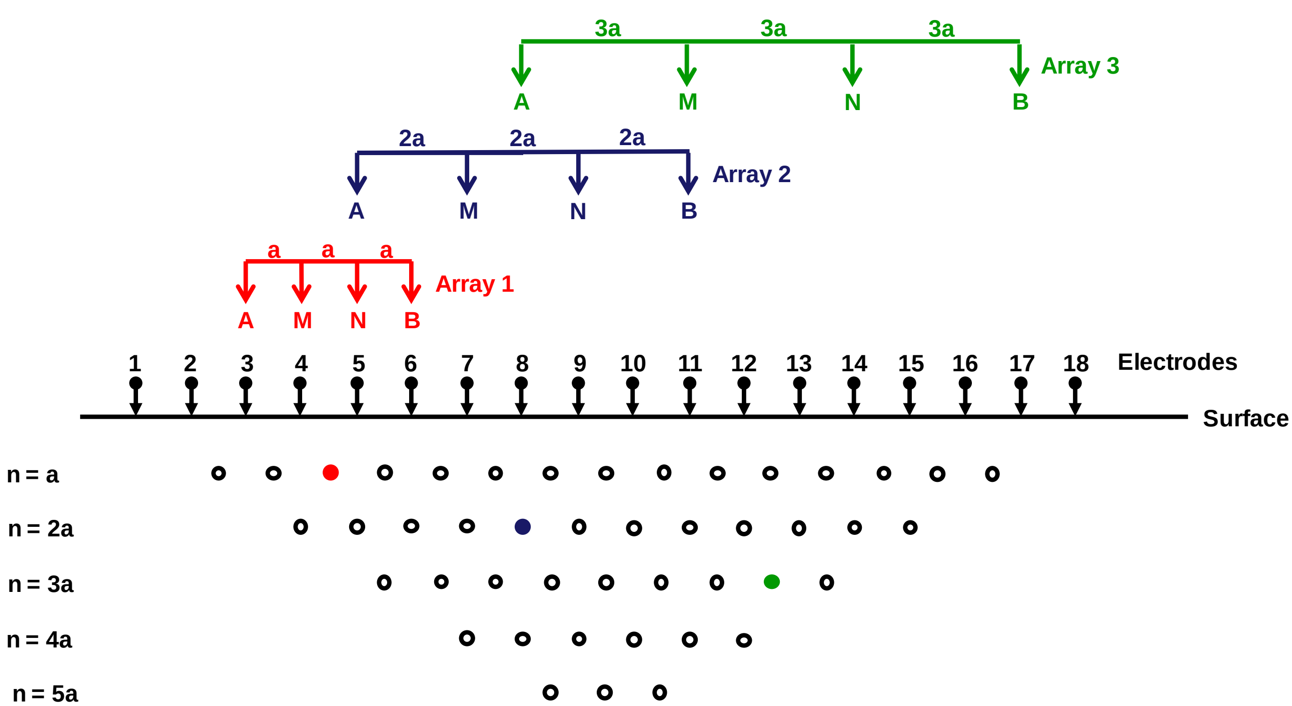
Wenner array: AB = 225 meters, est. DI = 39.2 meters

Dipole-Dipole: a = 25 meters, n = 5, est. DI = 37.3 meters



3.) Electrical Resistivity Tomography (ERT)

a.) Used to simultaneously detect horizontal and vertical variations in subsurface resistivity structure by combining elements of VES and CST methods.

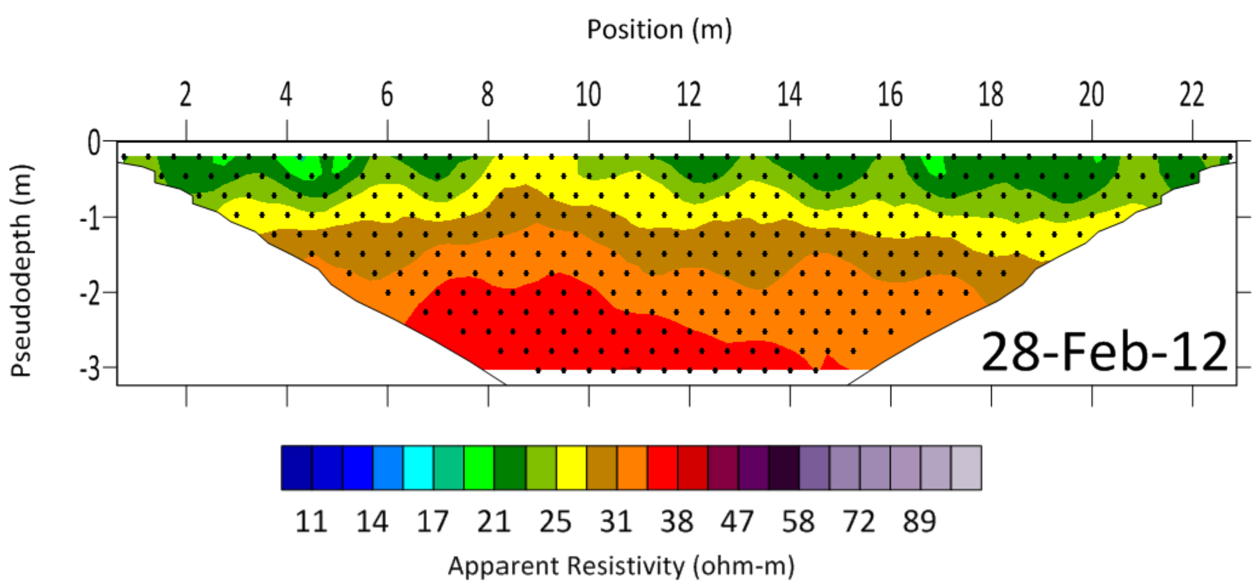


b.) Data is acquired using regularly spaced electrodes distributed on the Earth's surface. Electrode combinations are selected to obtain the desired range of electrode spacings and array locations.

c.) In general, the shallower heterogeneities are detected with the shorter electrode spacings; deeper features affect readings made with longer electrode arrays.

d.) The measurements are displayed as a "pseudosection" that shows ρ_a as a function of array location (i.e., its center point) and electrode spacing (or depth of investigation). While this is not an actual resistivity image/cross-section, it shows horizontal and vertical resistivity variations.

Example of a pseudosection (Vineland soil moisture monitoring experiment)



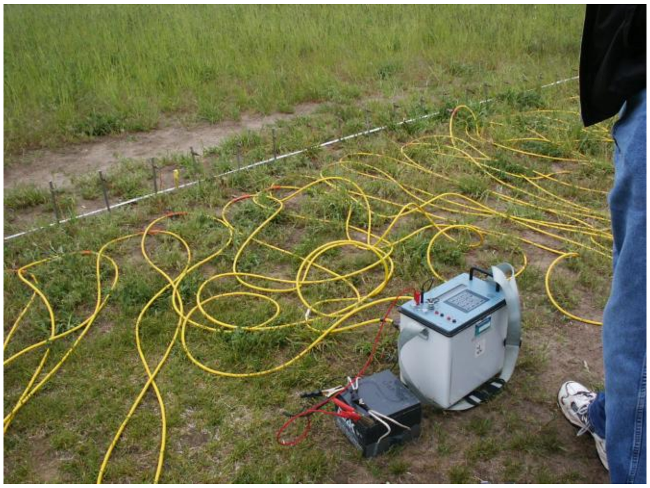
J.) Acquisition of Resistivity Data

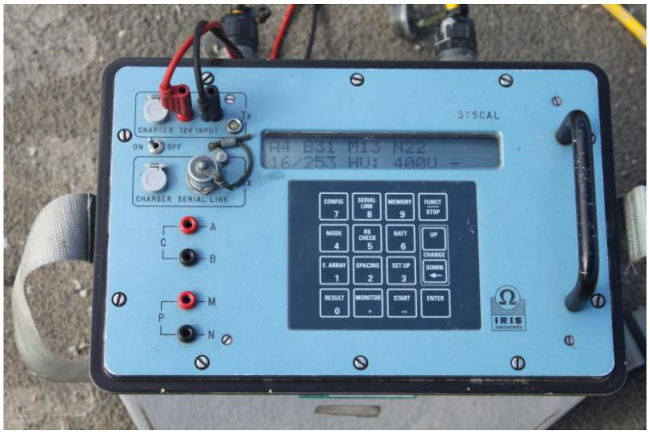
1.) Field Equipment

a.) Conceptually, the acquisition of resistivity data is relatively simple, requiring four electrodes (usually stainless steel spikes), a current source with an ammeter, a voltmeter for measuring potential differences and cables.

b.) ERT data acquisition is performed using automated systems with numerous electrodes systematically distributed on the Earth's surface. The equipment & controlling software select combinations of current and potential electrodes to obtain the desired array spacings and locations.

Example of a multi-electrode acquisition system (Iris Instruments Syscal unit)





2.) Input Current Signal / Waveform

a.) Ideally, a simple DC current can be used for resistivity measurement if there is no noise.

b.) To suppress the impact of DC and low frequency noise (e.g., SP signals), alternating polarity square waveform are commonly used as the current signal.

c.) The duration and peak amperage of the square wave can be selected to control data quality and acquisition effort.

d.) Measurements are repeated and averaged (i.e., stacked) to further improve the signal / noise ratio of the data.

3.) Choice of Electrode Array Type and Dimensions

The electrode array appropriate for a particular survey will depend on a number of factors, such as survey mode, resolution, sensitivity to horizontal or vertical features.

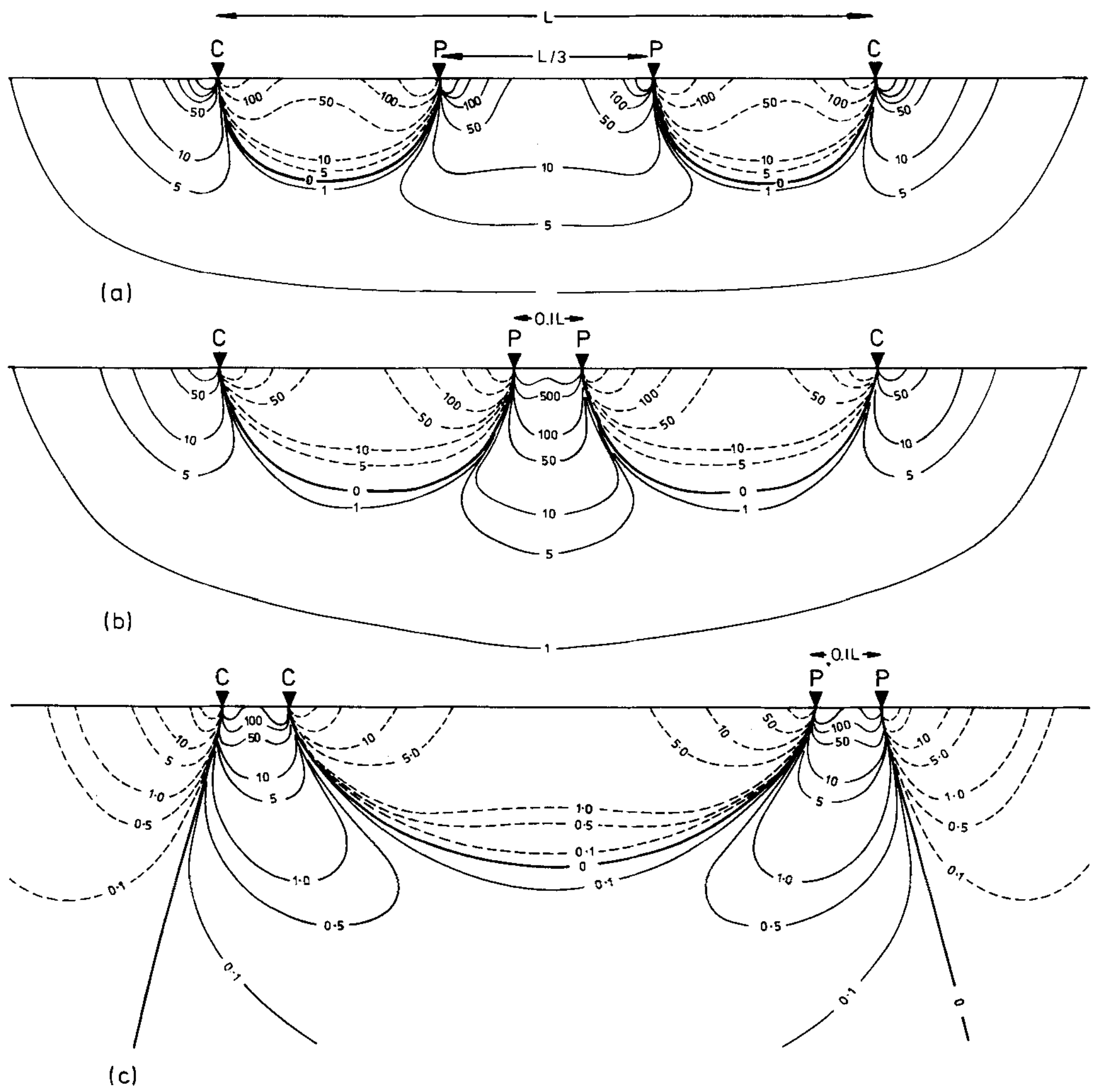


Figure 1. Signal contribution sections for: (a) Wenner, (b) Schlumberger and (c) dipole–dipole configurations. Contours show the relative contribution made by individual volume elements of earth to the total potential difference measured between the two potential electrodes; broken lines are negative contours.

(Figure from Barker, 1979)

2.) Electrode Contact Resistance

a.) The input current from the current electrodes is limited by their contact resistance.

b.) Contact resistance is a function of the surface material resistivity and the electrode surface area.

c.) Contact resistance can be a serious problem when the surface material is highly resistive (e.g., dry sand, frozen soil, laterites). In this case, the small input current will results in small values for the measured potential difference. This low signal energy means that the measurement is susceptible to noise contamination and measurement error, producing large uncertainties in ρ_a.

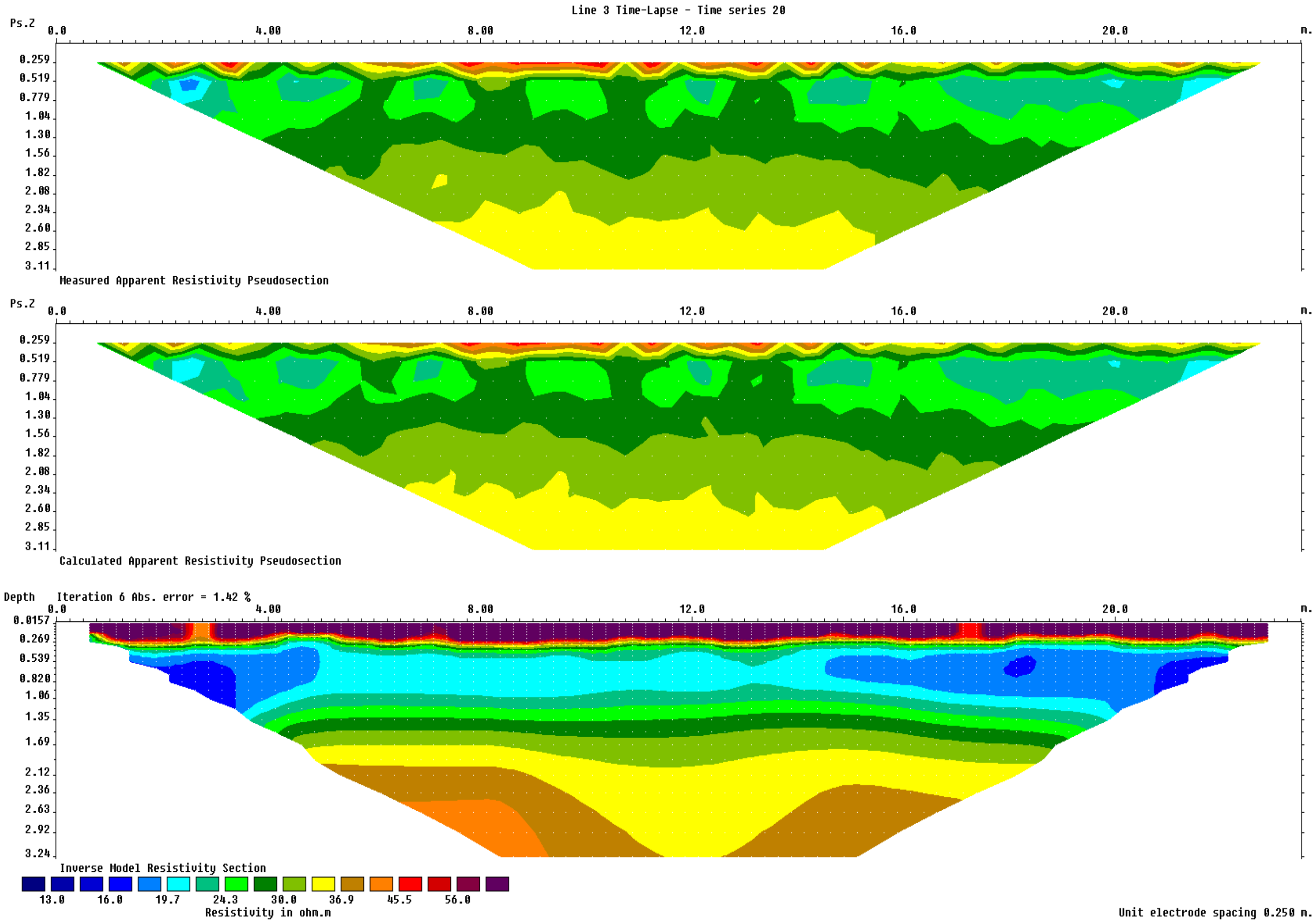
d.) This problem can be mitigated by lower the surface resistivity (by wetting the material at the electrode) and/or increasing the electrode surface area.

K.) Data Analysis for Resistivity Methods

1.) In the past, the analysis techniques for resistivity data were fairly rudimentary (i.e., qualitative categorization of sounding profiles or estimation of resistivity profiles using master curves for simple layered Earth models.

2.) Recently, sophisticated software has become available for the forward modeling and inversion of resistivity data (e.g., RES2DINV).

Example (Vineland soil moisture monitoring experiment)



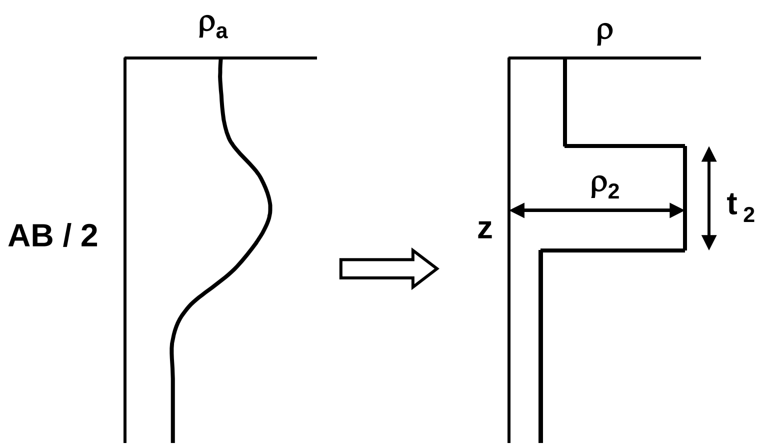
L.) Principles of Equivalence and Suppression

1.) There is an inherent ambiguity in the results obtained from the analysis of resistivity data: an unlimited number of models can be generated that can reproduce a particular data set. This property is called non-uniqueness.

2.) The non-uniqueness problem is illustrated by the equivalence and suppression principles involved in the analysis of 1-D soundings.

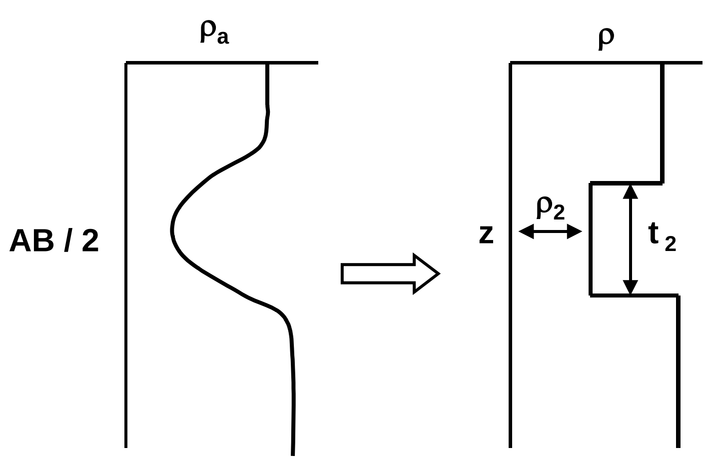
3.) Equivalence

a.) Case 1: a more resistive layer in a less resistive background.



Only the product $\rho_2 t_2$ can be determined for the more resistive layer.

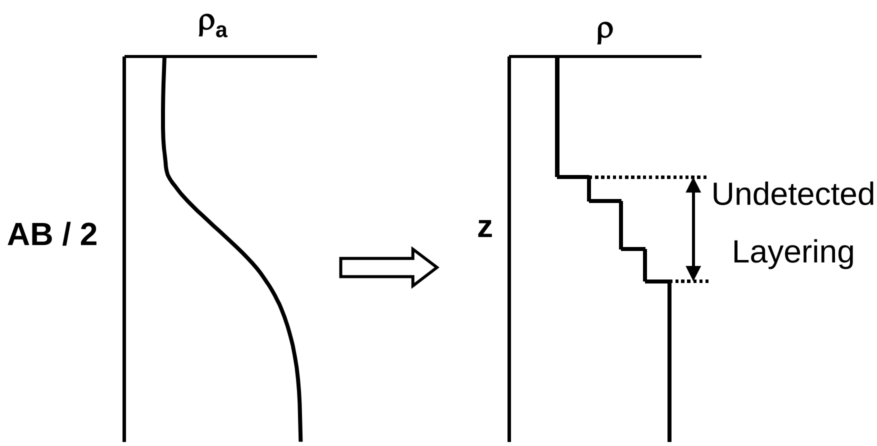
b.) Case 2: a conductive layer in a less conductive background.



Only the product $\sigma_2 t_2$ (where $\sigma_2 = 1/\rho_2$) can be determined for the more conductive layer.

4.) Suppression

The intermediate layers in a progressively increasing or decreasing resistivity profile cannot be detected.



5.) This inherent ambiguity can be limited (but not eliminated) by placing sensible geological & geophysical constraints on the interpretation/inversion.

References

R. D. Barker, 1979. Signal Contribution Sections and Their Use in Resistivity Studies, *Geophys. J. R. Astr. Soc.*, **59**, 123-129.

R.D. Barker 1989. Depth of Investigation of Collinear Symmetrical Four-Electrode Arrays, *Geophysics*, **54**(8), 1031-1037.

S. Szalai & L. Szarka, 2008. On the Classification of Surface Geoelectric Arrays, *Geophysical Prospecting*, **56**, 159-175.