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Resistivity and IP arrays, optimised for data collection and inversion

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ABSTRACT

The advent of 3D inversion packages for Resistivity and Induced Polarization has meant that geophysicists are no longer constrained by survey arrays designed to produce data to be plotted manually and interpreted by eye. 3D inversion processing means that there is no longer a need to place receiver and transmitter electrodes in a co-linear array. Electrode arrays can now be designed to optimise target definition and data collection efficiency.

The double offset pole–dipole array offers a way to collect large amounts of data efficiently and has superior inversion sensitivity and depth of investigation to standard arrays.

INTRODUCTION

Historically, mineral exploration and environmental geophysicists have used a small number of arrays for the collection of resistivity and Induced Polarization (IP) data. Arrays for DC resistivity surveying were developed in the 1920s, and were used for both depth sounding and traversing. The design criteria for these arrays were based around field operations, interpretability, and usage, either traversing or depth sounding. Most of the interpretation was performed by comparing hand-calculated curves with field data, or by simple rules of thumb.

Although the Overvoltage effect or Induced Polarization was known in the 1920s, it was not until the 1950s that IP surveying for economic mineralization was used routinely.

The use of time-varying voltages in the IP method can cause inductive coupling problems with conventional arrays such as Schlumberger and Wenner. Inductive coupling was minimised with the dipole–dipole array. The data from these surveys were generally plotted as pseudosections and interpreted by comparing the pseudosection with analogue, and later computer-generated, models.

The availability of 2D and, later, 3D inversion programs for resistivity and IP data (Loke and Barker, 1996a,b; Loke and Dahlin, 2002) has led to more rapid and accurate interpretation of survey data.

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Inversion of resistivity and IP data has also meant that the geophysicist is no longer constrained to using survey geometries that are based on the requirements of manual interpretability.

SURVEY DESIGN

Most conventional arrays have been designed to collect 1D and 2D data and, despite the fact that geology is mostly three-dimensional in form, the interpretation of the data sets generally assumes a layered or strike-continuous Earth. Most IP arrays are as sensitive to offline sources as they are to sources at an equivalent depth. In a 3D environment, this may lead to the drilling of anomalies interpreted to be at depth, but whose sources were shallow and off the line of data collection. With the advent of 3D inversion software, it is now possible to design arrays that are more suitable for the collection of 3D data.

The pole–dipole array geometry is more efficient than the dipole–dipole array because it only requires the movement of one transmitter electrode, and produces considerably higher receiver voltages. However, it has had limited use in IP surveys until now, because it is difficult to interpret manually and can give rise to problems with EM coupling.

A new IP survey design, based on a modified pole–dipole electrode array, was devised with the aim of achieving greater depth of investigation, efficient field operation, and a high rate of data collection. This survey technique was described by White et al. (2001). The method involved the use of standard survey equipment with sixteen fixed dipole receiver electrodes per set-up and a rapidly movable pole current electrode (Figure 1).

A single remote transmitter electrode was placed approximately 3 km from the survey grid. The moving transmitter electrode was positioned within the spread of receiver dipoles and off the ends of the survey lines. Transmitter electrodes were placed between, rather than at the location of receiver electrodes because all receiver dipoles were recording for all transmitter locations. To minimise the relatively high EM coupling of the pole–dipole geometry, the transmitter wire connecting the pole electrode was run 100 m perpendicular to the receiver line before connecting to the transmitter and remote electrode.

Although this technique was faster than the dipole–dipole array, considerable time was spent moving the transmitter electrodes, as

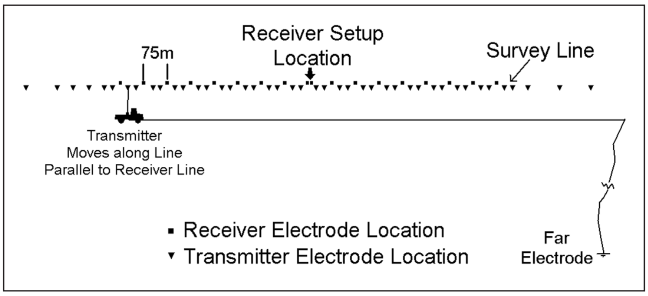

Fig. 1. Inline Pole–Dipole Set-up.

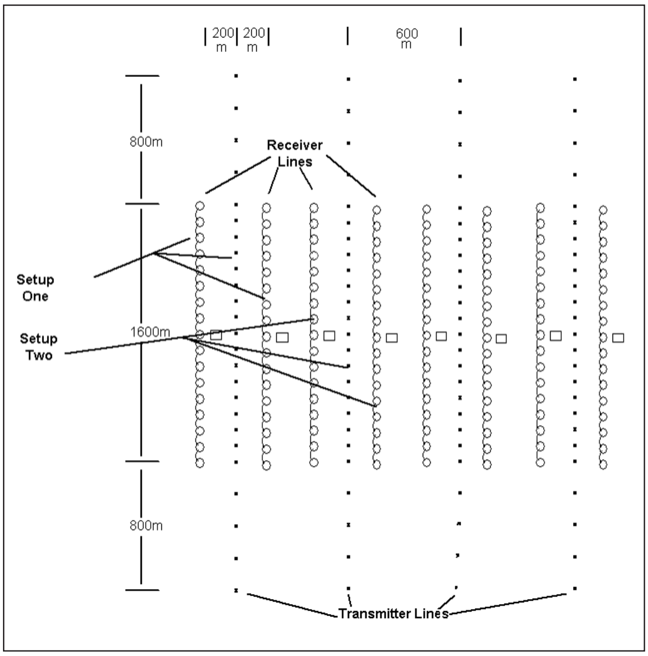

Fig. 2. Offset Pole–Dipole Set-up.

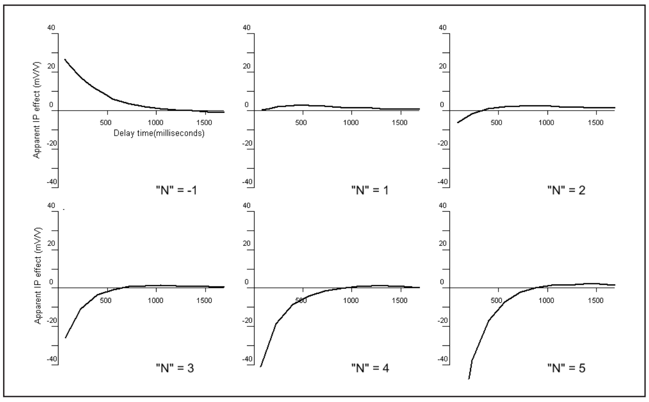

Fig. 3. IP decays showing apparent negative EM coupling as TX moves past Rx.

it was necessary to continually connect wire across the 100 m gap between the survey line and the remote electrode connection.

Since the interpretation is to be done in 3D by computer, there is no necessity to locate the transmitter and receiver electrodes on the same line. Instead, the transmitter electrodes can be located on parallel lines, provided that readings from the receiver dipoles directly opposite the current transmitter electrode, that fall on or close to lines of equipotential, are ignored. This removes the need to connect wires across the gap between the remote electrode wire and the receiver line, greatly increasing the speed of surveying. This survey geometry has been called the offset pole–dipole array.

The offset pole–dipole survey method speeds data collection and reduces the effects of EM coupling. In addition, it was found that the use of 32 receiver dipoles, 16 on either side of the transmitter line, is more cost effective (Figure 2.) This double offset pole–dipole array has now been used in a number of surveys (Collins and White, 2003).

A further modification of the offset pole–dipole array has also been tested, combining this array with the inline pole–dipole array, i.e., with the current electrode placed both off and on the receiver lines. This results in an appreciably higher number of readings, and a higher density of independent electrode locations that increases the shallow resolution but also increases the survey time.

One aspect of using the (offset) pole–dipole array for IP surveys is that care must be exercised to minimise EM coupling. EM coupling can become a problem for the early decay times in areas where the surface resistivities are below 10 Ω.m. Coupling is often ignored, or not recognized, in dipole–dipole surveys because it is positive with respect to the measured IP effect (Fullagar et al., 2000). For the offset pole–dipole array the coupling appears to reverse sign when the transmitter electrode crosses past the receiver dipole (Figure 3). The actual EM induced voltage does not change sign; it is the reference (primary) and secondary (IP) voltages that change. The apparent sign change and the steady increase in EM coupling effect as the transmitter pole passes the receiver dipole can be used to estimate and partially remove the EM coupling effect (Figure 4).

Studies have shown that the EM coupling voltage does not increase by an excessive amount in moderately conductive ground. Rather, it is the relatively low primary voltage, and hence IP signal, which causes EM coupling to be a problem in conducting environments.

Most of the field trials of the offset pole–dipole array conducted to date have been run in areas with background resistivities above 10 Ω.m. IP measurements were taken at delay times later than one second, where EM coupling can be ignored in these conditions.

ARRAY COMPARISONS

The dipole–dipole and offset pole–dipole array have been compared in terms of both model sensitivity and resolution.

The model sensitivity parameter indicates the degree to which a change in the resistivity of a part of the subsurface will influence the potential measured by the array (Loke, 2002). The higher the value of the sensitivity, the greater is the influence of this subsurface region on the measurements.

Figure 5a shows a long section (perpendicular to the survey lines) of computed model sensitivities across twelve parallel 100-m dipole–dipole lines. Figure 5b shows the same model sensitivity section for an equivalent double-offset pole–dipole survey. The sensitivity of the dipole–dipole arrays varies rapidly in the lateral direction, and the area of significant sensitivity extends about 200 m from the edge of the survey area and about 300 m vertically. In comparison, the high sensitivity values for the offset pole–dipole arrays are more uniform between the survey lines, and extend between 400 and 600 metres laterally away from the first and last survey line and 600 m vertically. This indicates that the pole–dipole array is more sensitive at depth and to near-surface responses up to 400 metres outside the survey area.

To determine the resolution of the two arrays, synthetic models were constructed that consist of two prisms 100 m apart. The survey geometries are the same as used for the sensitivity analysis. In these models, the prisms have a width of 200 m, a length of 600 m and a depth extent of 300 m. The background medium has a resistivity of 500 Ω.m and chargeability of 3 mV/V, while the prisms have resistivity of 50 Ω.m and chargeability of 30 mV/V. The long axis of the prisms is in the direction perpendicular to the survey lines.

Two models were created, one where the depth to the top of the prisms is 100 m, which is the same as the electrode dipole spacing, and the second using prisms with a depth to top of 200 m. Random Gaussian noise of 2% was added to the resistivity and IP data.

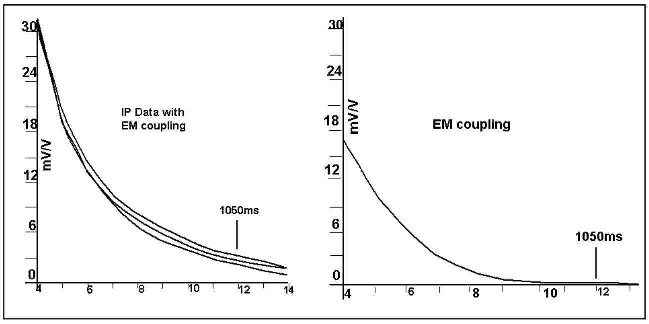

Fig. 4. IP decay with EM Coupling and the Estimated Coupling component in 2-5 Ω.m ground.

The results for the resistivity and IP data are similar. For simplicity, only IP chargeability results are presented here.

IP results for 100 m deep prisms are presented in Figure 6. In the dipole–dipole model, the prisms start to merge at a depth of 200 m and merge more closely at 250 m and below. In the offset pole–dipole model, the two prisms are still clearly resolved at 250 m and remain reasonably resolved to the base of the model

IP model results for prisms at a depth of 200 m are presented in Figure 7. The dipole–dipole model shows a very weak single anomaly with maximum amplitude of about 6.3 mV/V, compared to the true value of 30 mV/V. The anomaly lies in the 100–350 m depth range, well above the true depth.

The model for the pole–dipole array has slightly higher maximum amplitude of 8.2 mV/V, and the two prisms are better resolved compared to the dipole–dipole array model. While there is some merging of the high chargeability values, there are two distinct maxima at the location of the prisms. There are notable changeability values in the depth range 150–450 m (in comparison, the dipole–dipole array does not show any anomaly below 300–350 m depth).

ADVANTAGES AND PROBLEMS

The offset pole–dipole array offers many advantages over the traditional dipole–dipole array. The most obvious advantages are the speed of data collection, volume of data, and the superior depth of investigation. The offset pole–dipole array can be surveyed using standard IP equipment. One set-up of the offset pole–dipole, using 100-m electrodes and 200-m line spacing, can be read in one day if the survey conditions are reasonable. Field experience during a large survey of 40 set-ups, in bad conditions (small paddocks, access problems, and many livestock), averaged about one set-up per 1.5 production days. A single set-up covers about one square kilometre.

Pole–dipole arrays result in greater signal at the receiver electrodes than the dipole–dipole array (Madden and Cantwell, 1967). The offset pole–dipole array results in similar signal levels at the receiver as the pole–dipole array. Figure 8 shows the relative voltages at the receiver electrodes, for a transmitter current of 1 A and a 100-m receiver dipole, for the dipole–dipole array and the offset pole–dipole array on 100 Ω.m and 1000 Ω.m half spaces. The dipole–dipole array is limited to about n=8 in normal operating conditions because of signal strength, while the increased voltages from the offset pole–dipole array means that it is possible to collect meaningful data to the equivalent of n=20.

The offset pole–dipole array not only has a superior depth of investigation, but it also has more uniform lateral sensitivity than the dipole–dipole array. This higher lateral sensitivity means the

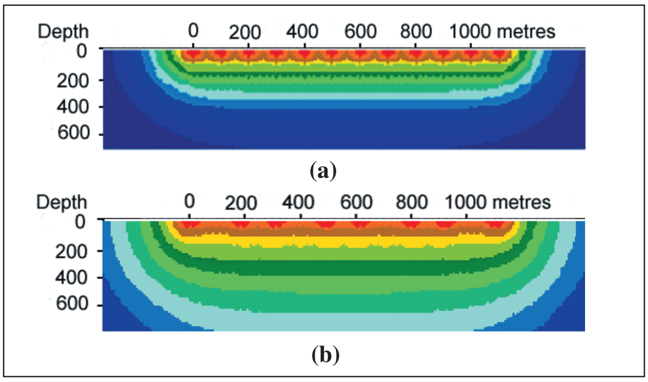

Fig. 5. (a) Dipole–Dipole model sensitivity long section. Section perpendicular to survey lines. (b) Offset Pole–Dipole sensitivity long section.

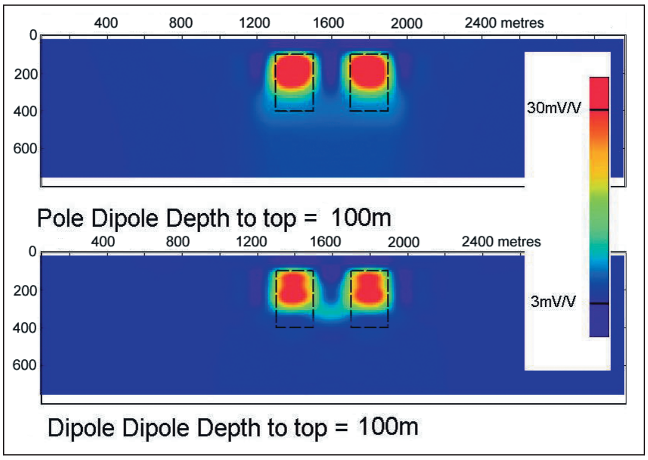

Fig. 6. Cross section of chargeability models buried at 100 m for offset Pole–dipole and Dipole–Dipole.

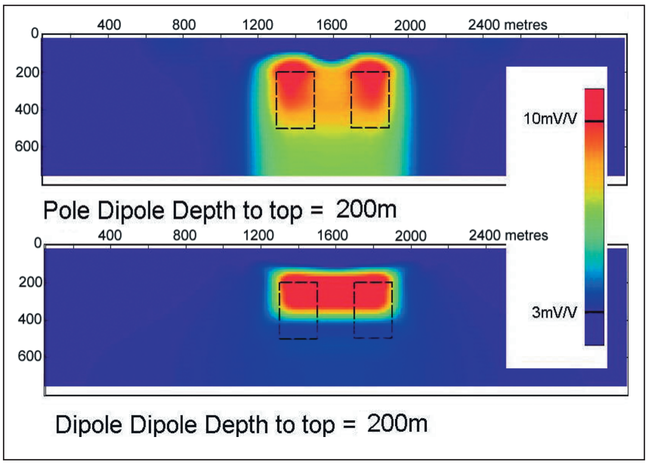

Fig. 7. Chargeability models buried at 200 m for offset Pole-dipole and Dipole–Dipole.

resolution between lines is improved, but at the edges of the survey, the increased volume of higher sensitivity can cause problems. Shallow near-surface anomalies located off the edges of the survey will appear as deep anomalies within the survey boundary. This phenomenon also occurs with the dipole–dipole array, but to a lesser extent because of the lower lateral sensitivity. This is partially a function of the greater effective penetration of the offset pole–dipole array. These "off line" anomalies are usually easy to recognise with experience, but care must be taken to ensure that anomalies near the edge of the model are closed off.

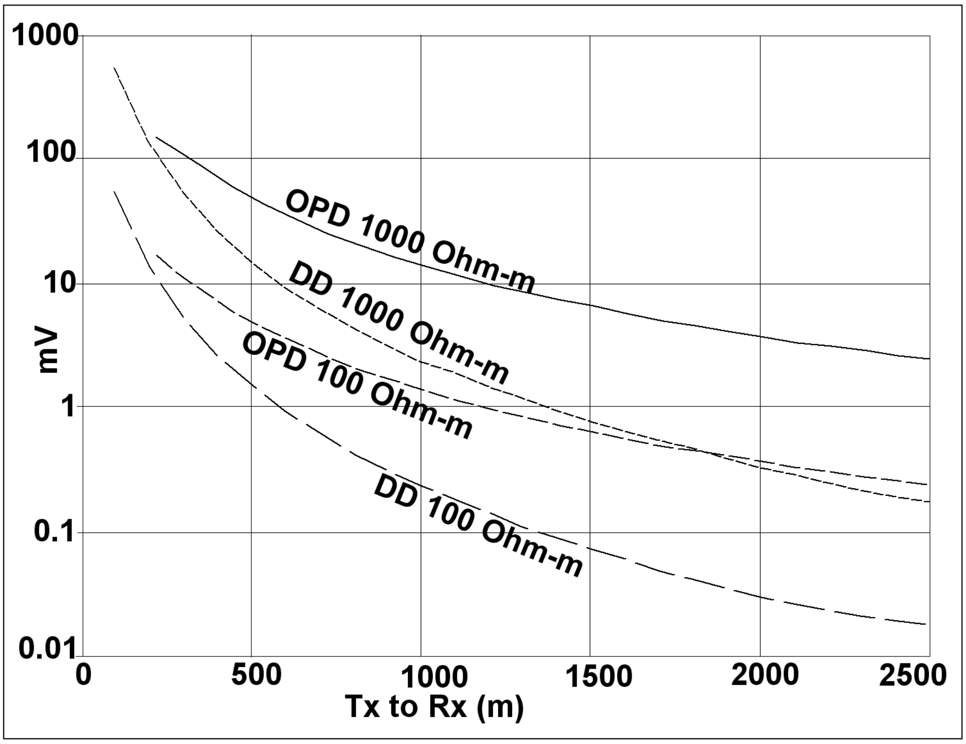

Fig. 8. Voltages at the receiver dipole for dipole–dipole (DD) and offset pole–dipole (OPD) arrays.

One of the disadvantages of the offset pole–dipole array is that it is difficult to plot and view the data as it is collected. Individual readings can be monitored for noise and signal decay, but plotting traditional pseudo-sections by the survey crew is difficult. However, data for each individual set-up can be easily processed with 3D inversion modelling independently of the surrounding results and used to monitor the progress of the survey on a daily basis.

The offset pole–dipole array produces many data. Typically, about 3000 individual readings are taken per set-up (before averaging). These readings may need to be analysed and edited. It is generally not practical to edit all the data by hand, so the data may need to be pre-processed before inversion. Programs are available for quality control, but care needs to be taken in selecting settings such as minimum acceptable receiver voltage, as these vary widely from survey to survey. The data are difficult to use without computer processing.

COST-BENEFIT COMPARISON

The double offset pole–dipole array offers a number of benefits that are summarised in Table 1. As well as offering better technical specifications for inversion, it is considerably cheaper than an equivalent dipole–dipole survey at approximately half the cost per square kilometre. If the appreciably greater depth of investigation is also considered, the method offers great advantages in terms of cost per cubic kilometre of ground explored.

CONCLUSIONS

The advent of 3D inversion software has led to the lifting of constraints on IP survey array design. Electrode arrays can be designed to optimise target definition and data collection efficiency.

Modelling and field use of arrays has shown that the offset pole–dipole array offers superior resolution and depth of investigation to the dipole–dipole array, for approximately half the cost.

As with all IP arrays, care needs to be exercised when analysing data along the survey edges because both the dipole–dipole and offset pole–dipole arrays sample the ground as well laterally as they do vertically. The offset pole–dipole has at least twice the depth of investigation of the dipole–dipole array and consequently will pick up lateral sources outside the survey area at a greater distance than the dipole–dipole array.

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Array	Cost/Square km.	Cost/Reading	Readings/Square km.	Depth
100m Dipole–Dipole	$7500	$25	300	200m
Offset Pole–Dipole	$4000	$5	800	>600m

Table 1. Approximate cost comparison of arrays (Aust. $).