THE COMPLEX RESISTIVITY METHOD

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1. INTRODUCTION

Induced Polarization methods have become increasingly important in geophysical exploration since their first major use in the 1950’s. A reasonable number of successes have been attributed at least indirectly to these methods, and gross domestic IP expenditures have increased at a rapid rate-some 40% per year through the 1960's and 70's.

As useful as IP has been, there are several significant problems that have limited its success in certain areas. First, data are often contaminated by electromagnetic coupling due to array geometry and geologic layering, making it difficult to determine the economic validity of a measured anomaly. Second, economic and non-economic sources of induced polarization (e.g., chalcopyrite-versus pyrite, graphite, clays, etc.) are not distinguishable in conventional IP data, regardless of the coupling situation. Additional problems involve limitations in depth penetration due to array geometry and problems obtaining repeatable data with standard IP instrumentation in high-noise environments. As a result, IP is often a capable reconnaissance technique, but it is not well adapted for detailed exploration, especially outside the realm of hard-rock mining interests.

In order to address the problems, a number of researchers began to investigate the possibilities of multi-frequency IP, know as “complex resistivity.” The mineral discriminating capabilities of multi-frequency measurements became apparent through the work of Zonge (1972a,b) Van Voorhis, Nelson and Drake (1973), Katsube and Collette (1973), and others, but wide-scale field applications were not possible until a practical, general solution of EM coupling was found by Zonge in 1973. The proprietary decoupling methods developed by Zonge Engineering & Research Organization permitted the resolution of problems associated with IP and the application of electromagnetic methods to a wider range of exploration problems.

1.1. <u>The Coupling Problem</u>

An electromagnetic measurement can entail the combination of three types of coupling represented schematically as:

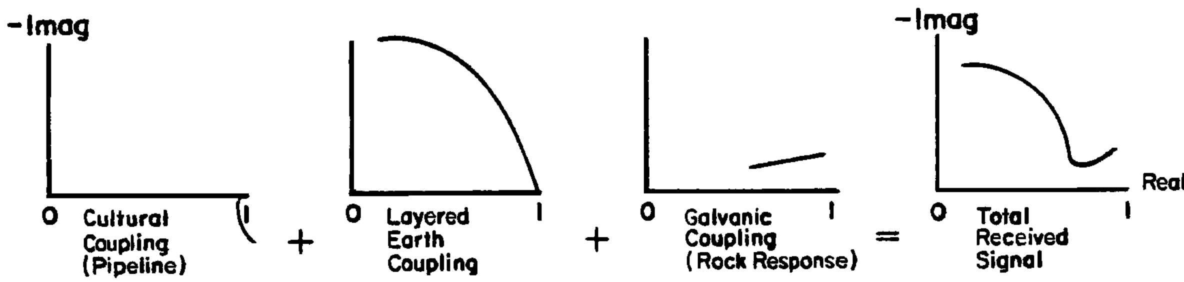
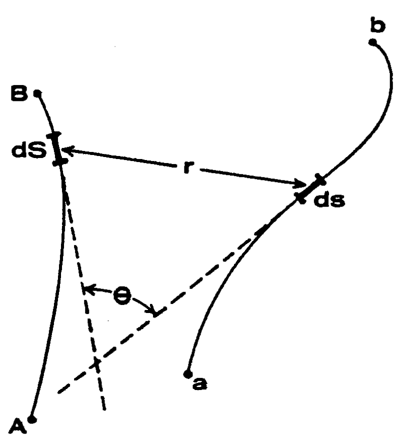


Figure 1. Schematic of coupling and IP response

Resistive or galvanic coupling results from the flow of current through a resistive polarizable ground mass. This represents the true ground response, which is usually the information desired in an electrical survey. Unfortunately, this information is often severely contaminated by inductive or electromagnetic (EM) coupling due to the measuring array and is enhanced by geological contacts or inhomogeneities in the ground. Cultural coupling can be the combination of both galvanic and inductive coupling responses due to transmission lines, powerlines, fences, pipelines, etc. that may cross or run parallel to the electric survey line. The problem then is to separate the induced polarization components from the cultural or inductive EM coupling components.

This turns out to be a very complex problem. As outlined in Sunde (1967) and in various other publications (See the REFERENCES section), the mutual inductance between two wires **S** and **s**, depends on two terms, **P** and **Q**, which are functions of the array geometry of the two wires (see Figure 2). Evaluation of these integrals becomes extremely difficult except in the simplest cases.



$$Z_{Ss} = \iint \left\{ P(r)\cos q + \frac{\partial^2 Q(r)}{\partial S \partial s} \right\} dSds$$

Figure 2. Mutual impedance between two wire elements lying on the surface of the earth.

The coupling integral, as noted, can be broken into the sum of two kernels, denoted **P** and **Q**. The **P** function is denoted the inductive term, as its value depends upon the angle between the two wires. It is also dependent upon resistivity layering in the ground to a lesser degree. The **Q** function is called the grounding function, since it is evaluated at the end points of the two wires. For a homogeneous earth, **Q** is a constant, real number is independent of frequency. For a layered earth, **Q** becomes complex and frequency dependent. It is much more sensitive to layering than is **P**, and exhibits spectacular changes in its behavior. These changes are the controlling factor in the shapes of field coupling curves.

The evaluation of EM coupling includes a series of calculations involving the geometry of the wires, the electrical properties of the subsurface layers, and the boundary conditions between the layers and the air-earth interface. Inductive coupling is a function a^2f/r, where a is the dipole size, f is the signal frequency and r is the resistivity. The means that coupling increases for larger arrays, lower resistivities, and higher frequencies. It also increases with complicated geologic layering and inhomogeneities. Due to the complexity of even moderately useful solutions to coupling, the problem is usually avoided or dealt with indirectly. Some groups use minimum coupling arrays, such as the perpendicular pole-dipole configuration. Another method is to work at low frequencies, where coupling is relatively small, or to use data at several frequencies to approximate dc values. However, since these approaches avoid dealing with coupling directly, multifrequency data are still contaminated by EM coupling. Hence, mineral discrimination on a spectral basis is often impossible because higher frequency data are required.

A reverse approach adopted by some is to model various coupling environments and to fit them to field data. This can be an expensive undertaking and it assumes a great deal of knowledge concerning the exact electrical nature of the subsurface; which is, after all, the information desired in the first place.

The Z.E.R.O. decoupling techniques do not make any assumptions as to the existing conditions of the ground. Instead, an iterative theoretically based solution is obtained. The details of the decoupling are proprietary. However, the success of the method has been clearly demonstrated in the correlation of field survey results with laboratory rock measurements, in-hole CR data, and EM computer modeling. Ultimately, client satisfaction with results of complex resistivity has been the most rewarding confirmation of the work over the last twenty-eight years.

1.2. <u>Zonge Complex Resistivity Systems</u>

Z.E.R.O. conducts complex resistivity surveys using one of two separate, but equivalent systems. The first system was used beginning in 1972, with a PDP-8 computer for data control and analysis, along with a Teletype, a two-channel receiver, and cassette units for recording the raw data. The PDP-8 system has been followed by four generations of portable geophysical data processors: the GDP-12 in 1978, GDP-16 in 1986, GDP-32 in 1993, and GDP-32^{II} in 2000. The PDP-8 and GDP-12 systems were two-channel receivers and are illustrated in Figures 3 and 4.

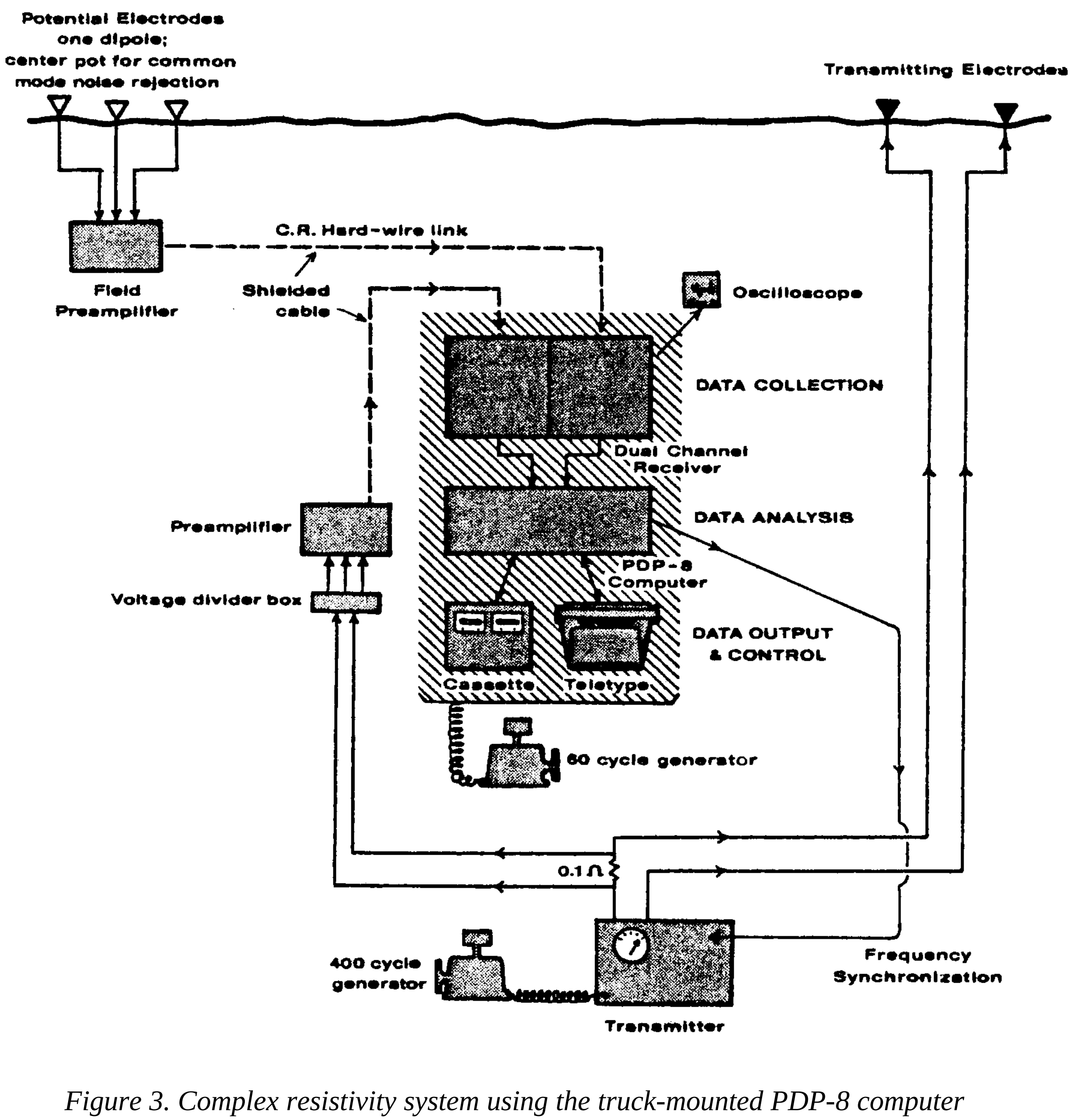


Figure 3. Complex resistivity system using the truck-mounted PDP-8 computer

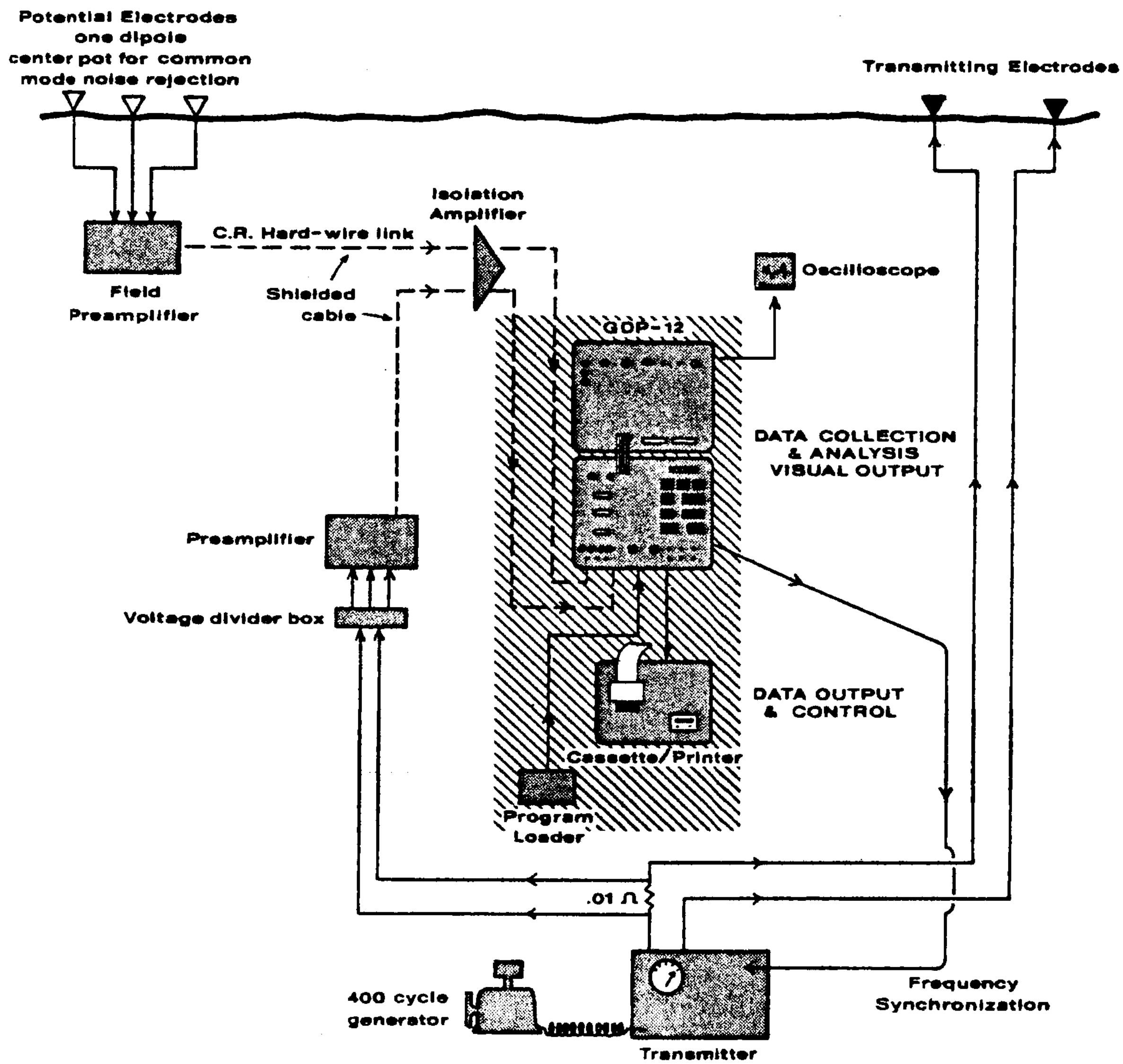


Figure 4. Complex resistivity system using the GDP-12 geophysical data processor.

2. DESCRIPTION OF COMPLEX RESISTIVITY DATA

We interpret complex resistivity field measurements to mean the gathering of multifrequency spectral data (magnitude and phase or real and imaginary) over the frequency range of interest. Complex resistivity data comprise a combination of spectral IP data, EM coupling data, and cultural coupling data. Using this description of CR, spectral IP is defined as decoupled CR data, consisting of coupling corrected apparent resistivity and phase data, which we usually plot in the complex plane and analyze for the intensity and source of polarization response. Usually it is not possible to separate normal EM coupling effects from cultural coupling effects, if the latter exists. Instead, the total EM coupling response is analyzed for both total and residual effects and these data are plotted in pseudosection form.

2.1. Apparent Resistivity (r_a,ohmmeters)

In an electrical circuit, the resistance R of a pure resistor is measured by impressing a fixed current **I** through it and measuring the potential drop **V** across it:

$$R = \frac{V}{I}(ohms) \qquad 2.1$$

This is the one-dimensional Ohm's Law. The three-dimensional equivalent of resistance is resistivity, r.

$$r = \frac{E}{J} \approx \frac{V}{I} K \quad (ohmmeters) \qquad 2.2$$

E = electric field in volts per meter
J = current density in amps per meter^2
K = "form factor" based on an assumed current distribution in a homogeneous half-space and the geometry of the measurement array

For a dipole-dipole array on the surface of the earth, the apparent resistivity r_a is given by:

$$r_a = \frac{V}{I} p \cdot a \cdot (n+1) \cdot (n+2) \qquad 2.3$$

where **I** is the transmitted current, **V** is the measured voltage, **a** is the dipole length and **n** is the number of a-spacings or dipole lengths between the transmitting and receiving dipoles. The term "apparent" resistivity is used to describe this parameter for two reasons. First, the current distribution in the vicinity of the transmitting dipole is not measured but is assumed; and second, the measurements average large volumes of heterogeneous rock with each setup. Therefore, the resultant resistivity is a bulk average rather than a specific value for any one rock type, and can be influenced to a great extent by geometric conditions. Apparent resistivity data are normally plotted in pseudosection form at either 0.1 Hz (PDP-8) or 0.125 Hz (GDP series), as a close approximation to the dc resistivity.

2.2. Raw Phase (f_r,milliradians)

Raw phase is a measurement of the combined effects of EM coupling and polarization, and as such is normally used as a rough polarization indicator in the field, and not often used by itself for final data interpretation. Recorded measurements are usually made at either 0.1 Hz (PDP-8) or 0.125 Hz (GDP).

2.3. Percent Frequency Effect (PFE, %)

Raw percent frequency effect is also a coupling plus polarization measurement. Calculations are made from the apparent resistivity data at 0.1 (PDP-8) and 1.0 Hz:

$$PFE = \frac{r_{0.1} - r_{1.0}}{r_{1.0}} \, x \; 100\% \qquad 2.4$$

Raw field calculations use the phase at 0.1 Hz and the geometric average at 0.9 and 1.1 Hz (PDP-8) or at 0.125 Hz and 1.0 Hz (GDP) to obtain this parameter.

2.4. Three-frequency Corrected Phase (f3pt, milliradians)

Assuming that EM coupling is smooth and the IP response is flat at low frequencies and that EM coupling is nonexistent at dc, one can fit phase data from three low frequency points to a generalized quadratic equation and extrapolate to dc to get a good approximation to coupling-free phase data. This technique is often referred to as a “three-point” phase angle and is often useful for a first look at CR raw field data. Calculations involve one of the following equations depending on the frequencies used.

For harmonically related frequencies;

$f_0, 3\,f_0, 5\,f_0$ *Hz:*

$$f_{3pt} = \frac{1}{8}\left(15 f_{f_0} - 10 f_{3f_0} + 3 f_{5f_0}\right) \qquad 2.5$$

$f_0, 3\,f_0, 10\,f_0$ *Hz:*

$$f_{3pt} = \frac{1}{21}\left(35 f_{f_0} - 15 f_{3f_0} + f_{10f_0}\right) \qquad 2.6$$

For any three sequential frequencies;

$f_0, 2\,f_0, 4\,f_0$ *Hz:*

$$f_{3pt} = \frac{1}{3}\left(8 f_{f_0} - 6 f_{2f_0} + f_{4f_0}\right) \qquad 2.7$$

In which $\mathbf{f_0}$ is the lowest frequency measured. Equation 2.5 and 2.6 are used for PDP-8 data acquisition. Equation 2.7 is used for GDP data acquisition.

Three-point calculations have several important drawbacks. First, this technique does not deal with coupling on a frequency by frequency basis, but rather avoids the problem by seeking data for a frequency at which coupling does not exist (dc). Hence, an examination of the coupling-free spectral response of the ground is not possible with this technique. A second drawback is that of noise: a half-milliradian error in the three frequencies used can result in one to two milliradians difference in the three-point calculations. A third problem is that the true IP phase response is assumed to be flat (constant) at low frequencies. This is not true over sulfides or alluvial clays, for example, but is often a good enough assumption to permit obtaining useable reconnaissance mode decoupled data. As a result, three-point is calculated in the field as an initial evaluation of coupling contamination or used for quick reconnaissance-mode data acquisition, but it is not used in the final interpretation of complex resistivity or spectral IP data. However, after theoretical spectral decoupling is performed on the data, a wealth of new information can be obtained as described in the following discussions.

2.5. Decoupled Phase and Spectral Plots (Spectral IP)

The corrected phase angles at the lowest frequency measured gives a good representation of the true ground polarization measured at that frequency. This can be compared to the raw phase values to get a good idea of how much coupling exists in an area, and to accurately delineate polarizing anomalies.

Data for a range of frequencies are obtained in terms of magnitudes and phase (polar coordinates) or in complex form (rectangular coordinates). For purposes of data handling and analysis, the rectangular coordinate system has proven to be the most convenient. The rectangular coordinate plot is done in the complex plane, with the in-phase or real component as the abscissa (horizontal axis) and the negative out-of-phase or negative imaginary component as the ordinate. Most CR data have negative imaginary values so you will notice that all Zonge Engineering spectra are inverted for viewing convenience: i.e., negative-imaginary is up rather than down. Figure 5 illustrates the coordinate conversion.

Spectra are characterized as types A, B, or C, depending upon how the out-of-phase or imaginary component behaves as a function or frequency: Figure 6. These types are furthered categorized according to slope:

Type	A	Slope greater than 20%
	a	20% to 10%
	B	10% to 0%
	b	0% to –10%
	c	-10% to -20%
	C	less than –20%
	X	noisy
	N	no response
	Y	severe contamination due to culture

Figure 7 depicts a typical spectral plot provided to the client, along with a key for its interpretation. For the pseudosections, a two-letter code is used. The first letter indicates the average spectral type on the 0.1 to 1.0 Hz decade, and the second indicates the type on the 1.0 to 10 Hz decade. Where a single letter appears both decades have the same letter code. When appropriate, a letter designation is also shown for the 10 to 100 Hz decade. Figure 8 illustrates a typical spectral pseudosection.

Spectral shape coding provides a quick qualitative indication of the host rock or mineralization response. Often, however, additional information may be obtained. When the response is fairly strong, the particular type of mineralization, its host environment, depth, and a real extent may be ascertained. As a initial indicator, type A spectra are frequently associated with strong alteration, clays, graphite, copper, and pyrite. Type C is often associated with certain types of alteration, such as chloritization, and usually does not host sulfides. Type B represents a transition from A to C, and depending upon other considerations, may be interpreted as an indication of sulfide mineralization.

A useful aspect of spectral analysis lies in the ability to distinguish sulfide minerals from polarizable responses due to clays and graphite. Copper sulfides can be detected directly in some cases; sulfides associated with pyrite can be detected indirectly by mapping the extent of the pyrite response and by the appropriate use of geologic information. Detection of other forms of mineralization is being continually investigated on a research basis in cooperation with several mining companies. The specific use of spectral information in oil field or uranium exploration is limited to delineation of alteration or pyritic halo phenomena. Residual electromagnetic data usually provide the best oil field information.

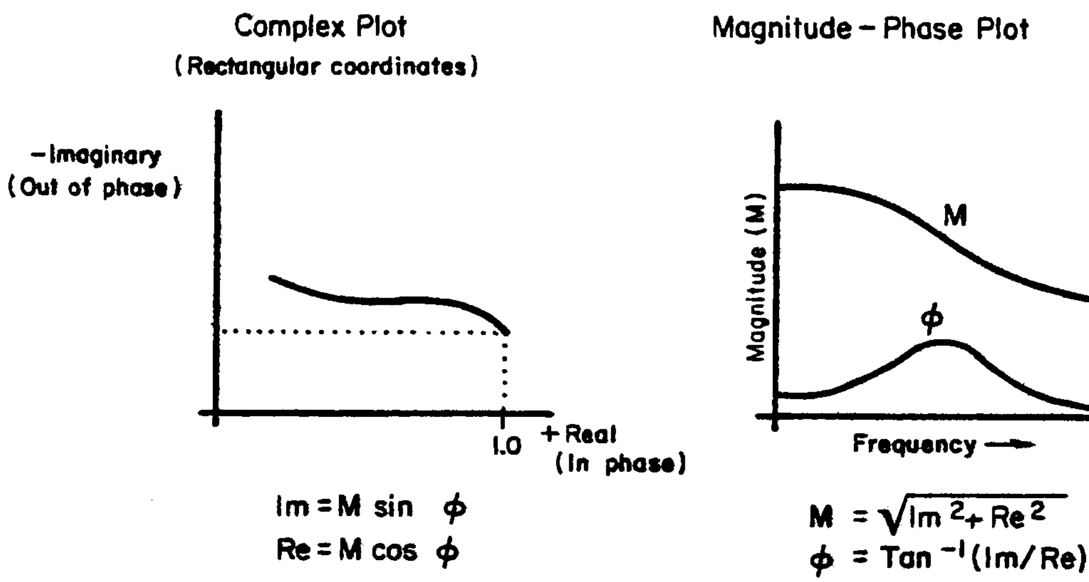


Figure 5. Relationship between the complex plot and the magnitude-phase plot. Magnitude and phase are the parameters measured in the field, but complex plots are much more convenient for data handling.

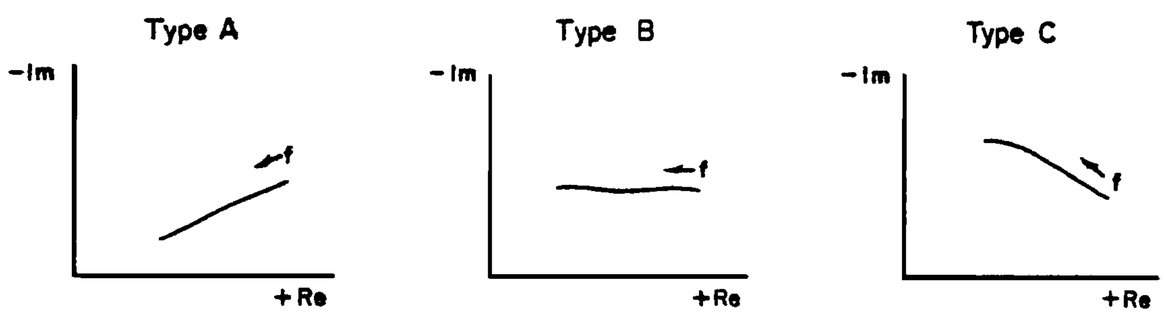


Figure 6. The Z.E.R.O. spectral classification scheme. Type A spectra have a decreasing out-of-phase component (as plotted) with increasing frequency; type C have a corresponding increasing out-of-phase response; type B spectra are defined as having a flat, or unchanging, out-of-phase response with frequency. These spectral types are further subdivided as described in the text.

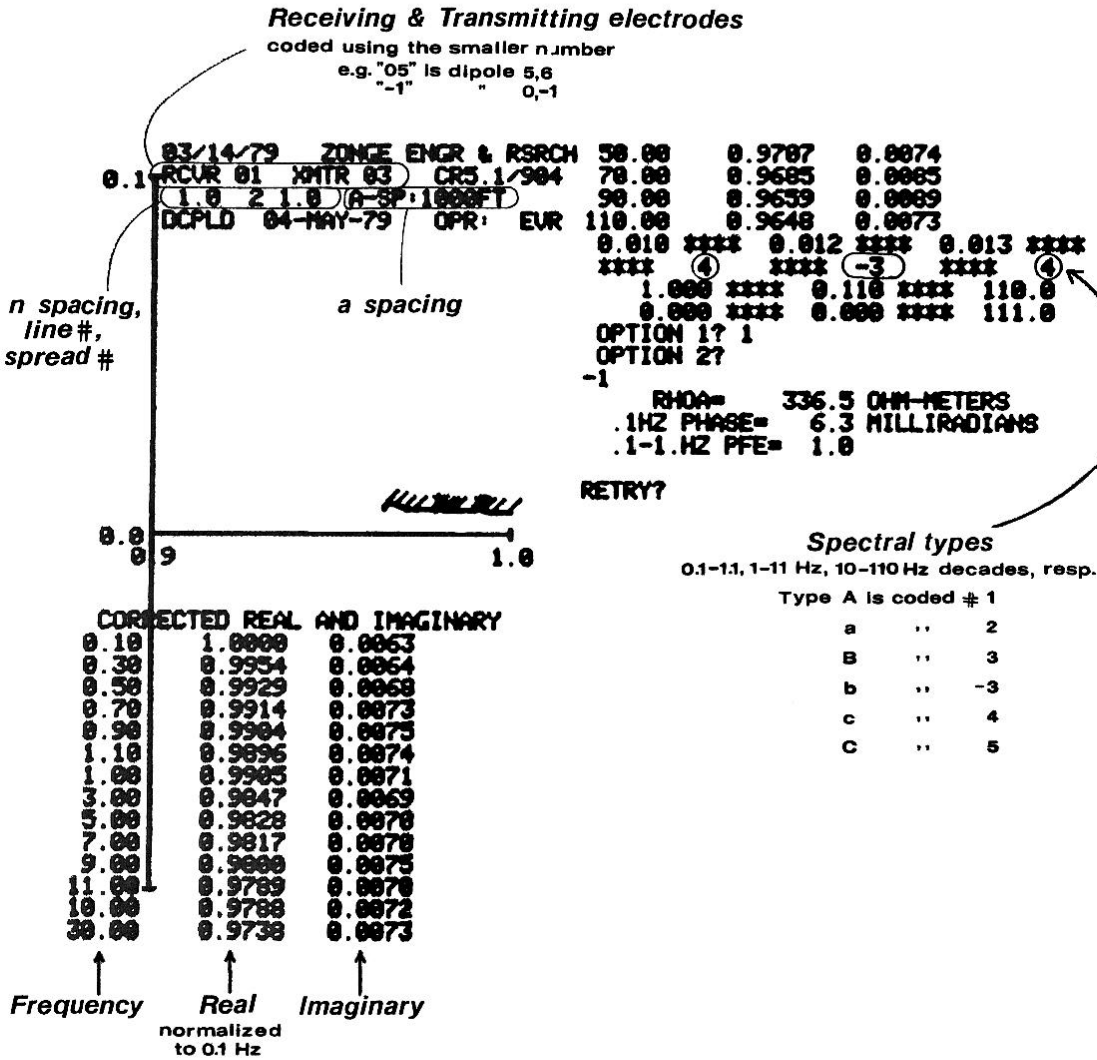


Figure 7. Explanation of coded information on spectral plots.

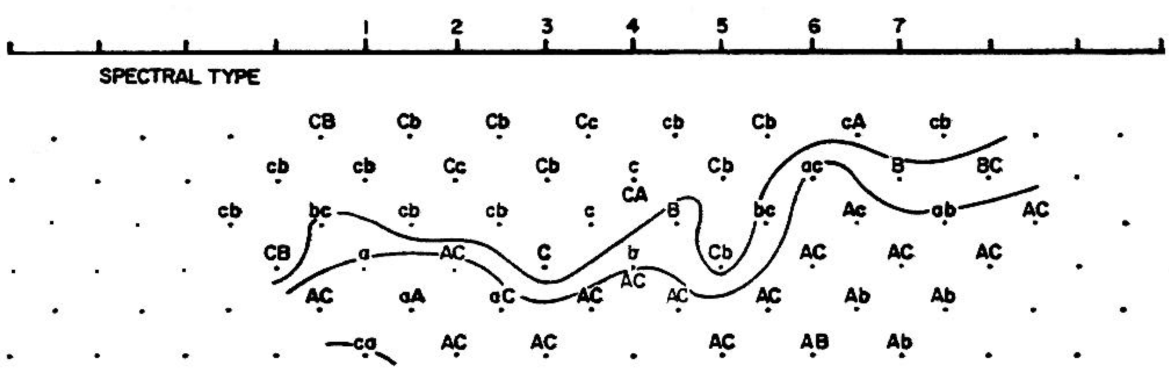


Figure 8. Example of a spectral type pseudosection from a survey conducted in Arizona.

2.6. Coupling Coefficient Data

Pseudosection parameters called coupling coefficients are provided on all complex resistivity survey data and provide a measure of the coupling environment due to resistivity layering in the ground. For a simple two layer case, the first order coupling coefficient (CC1) having a value of 1.0 indicates a homogeneous earth or a transition zone; a value greater than 1 indicates a low-over-high resistivity environment; and a value less than 1.0 indicates a high-over-low environment.

Coupling is an inductive or transient phenomenon as opposed to the galvanic or steady state nature of IP data. It has a greater penetration capability than IP. While the penetration of IP data is usually one to two a-spacings for a dipole-dipole array, coupling will penetrate four to six a-spacings. Hence, although it is plotted in pseudosection form, coupling information cannot be compared point-for-point with resistivity or polarization information.

Coupling coefficients are primarily useful in obtaining a clearer picture of resistivity layering than is usually possible using resistivity data. They are normally used in conjunction with Residual Electromagnetic Data (REM) for interpretation.

Second and third order coupling coefficients (CC2, CC3) are often plotted in pseudosection form to reflect the departure of the ground from a simple two layer coupling case. They are provided only when useful in overall interpretation.

2.7. Residual Electromagnetic Data (REM)

Residual electromagnetic data is one of the most useful byproducts of the decoupling process, yielding valuable information on deep electrical structure and alteration. It is calculated by removing both ground polarization and the theoretical homogeneous earth coupling (for a given resistivity and array geometry) from the total raw complex resistivity data collected in the field. Schematically, this can be represented in the complex plane as shown in Figure 9. Since complex resistivity is the total ground coupling plus polarization, REM can be thought of as the departure of the measured coupling of the ground from the homogeneous earth case. The data are similar to a very low frequency coplanar vertical loop EM system.

Since EM coupling is a function of $\boldsymbol{a^2 f/r}$ and also depends non-linerarly on the n-spacing, the data are normalized by an inverse frequency and by an experimentally derived n-spacing function. The frequency relationship we use is **110/*f*** so that the factor of the highest frequency obtained is unity, and the lower frequency components are amplified accordingly. Since most dipole-dipole surveys are run with n-spacing from 1 to 6 the measurements are all normalized to n=6 which is the maximum EM coupling configuration for our usual survey. Smaller n-spacings are scaled accordingly to approximate the coupling intensity at n=6. Field measurements and modeling have indicated that the maximum depth at which a ten to one resistivity contrast anomaly can be reliably discerned is approximately six spacings; for a two to one contrast, penetration is up to four a-spacings.

REM can be plotted either in spectral or pseudosection form. Pseudosection plots can take two forms: parametric or geometric, as illustrated in Figures 10 and 11. Parametric plots hold a particular n-spacing constant while varying frequency at each station, resulting in a depth sounding controlled by the resistivity and frequency used according to the skin depth equation:

$$d = 503\sqrt{\frac{r}{f}}\ \text{meters} \qquad 2.8$$

Geometric plots hold frequency constant and plot n-spacing versus station location as in the normal IP pseudosection plots. Plotting form for final analysis depends upon the exploration target and the amount of cultural contamination in the area. Cultural contamination usually affects the parametric plots the least and is therefore often used in culturally cluttered areas. The final decision is based on which plotting form displays the anomalous response in the most consistent manner.

An in-house plot, which we call a “thumbprint”, is used to display REM data in a compact manner for comparison of geometric and parametric responses. It is especially useful for models and may also be used to plot single stations of field data. The thumbprint is a frequency versus n-spacing plot, which is contoured in the same manner as a pseudosection.

REM currently has two very important roles. In the mining industry, it is often used to provide valuable information on both horizontal and lateral structural changes, especially in areas of limited access. In petroleum applications over more homogeneous structure, REM is a sensitive indicator of conductive anomalies, believed to be due to brine water and forms of alteration that are associated with oil deposits. Much of Zonge Engineering’s success in hydrocarbon detection is due to the development of REM processing and the continuing interpretation evolution that has accompanied the fieldwork. REM has also been an aide in detecting various forms of alteration, underground stream channels, and in the delineation of ground water and its pollutants. It has also been applied to the detection of uranium-hosting environments, and massive sulfides.

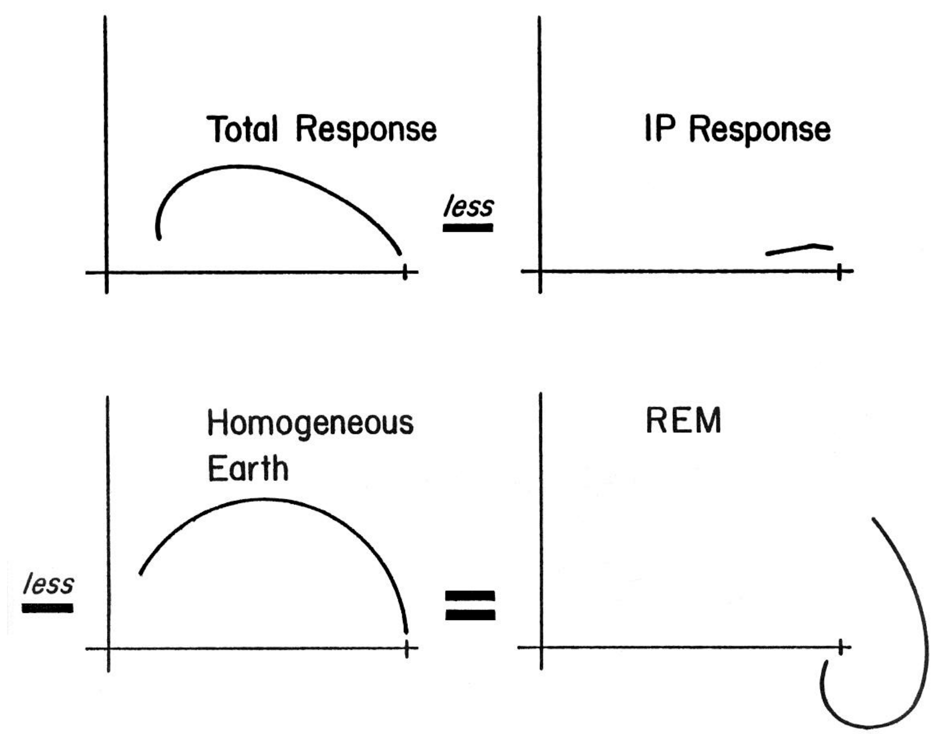


Figure 9. Schematic description of REM processing.

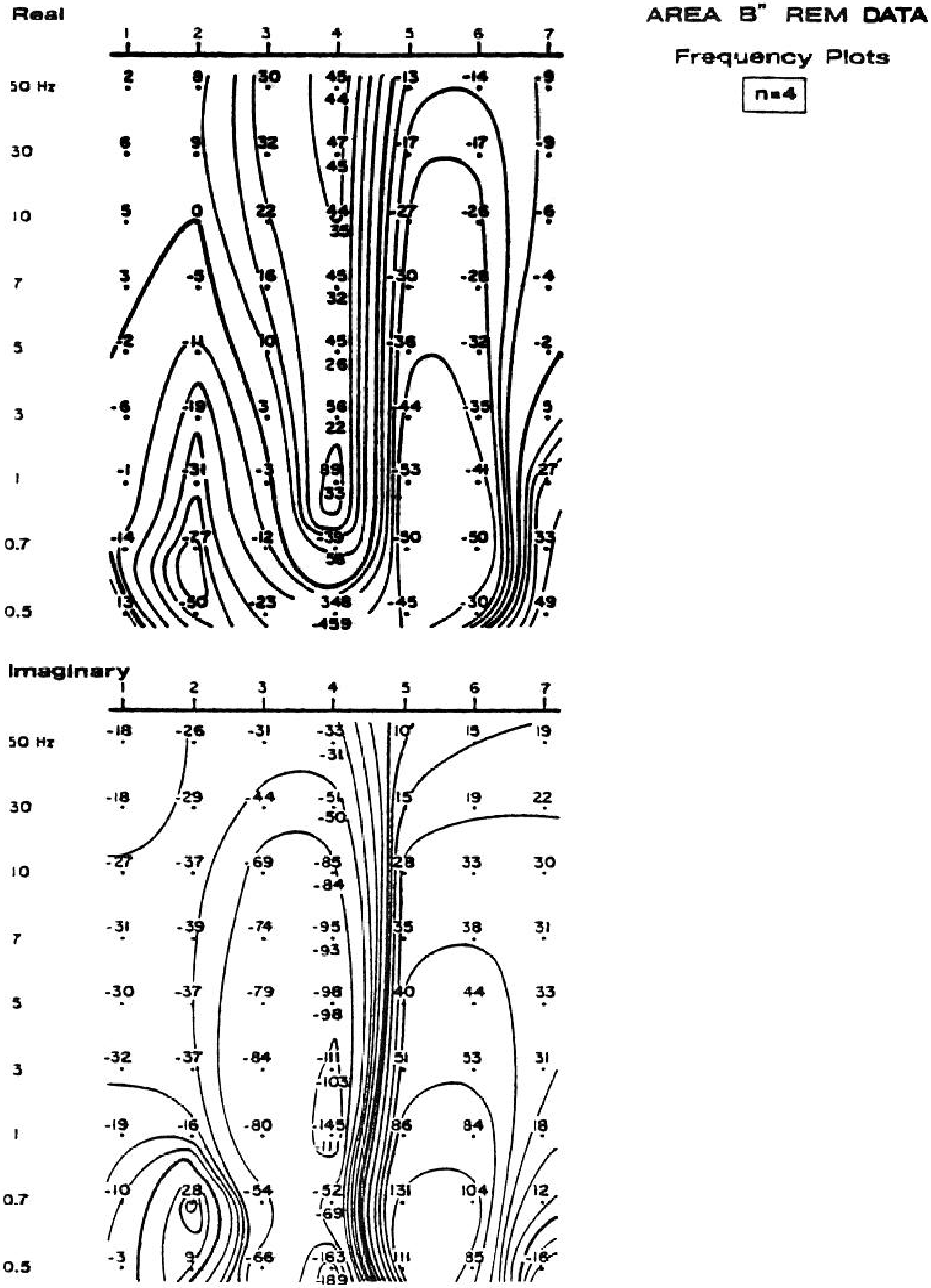


Figure 10. Parametric representation of REM data.

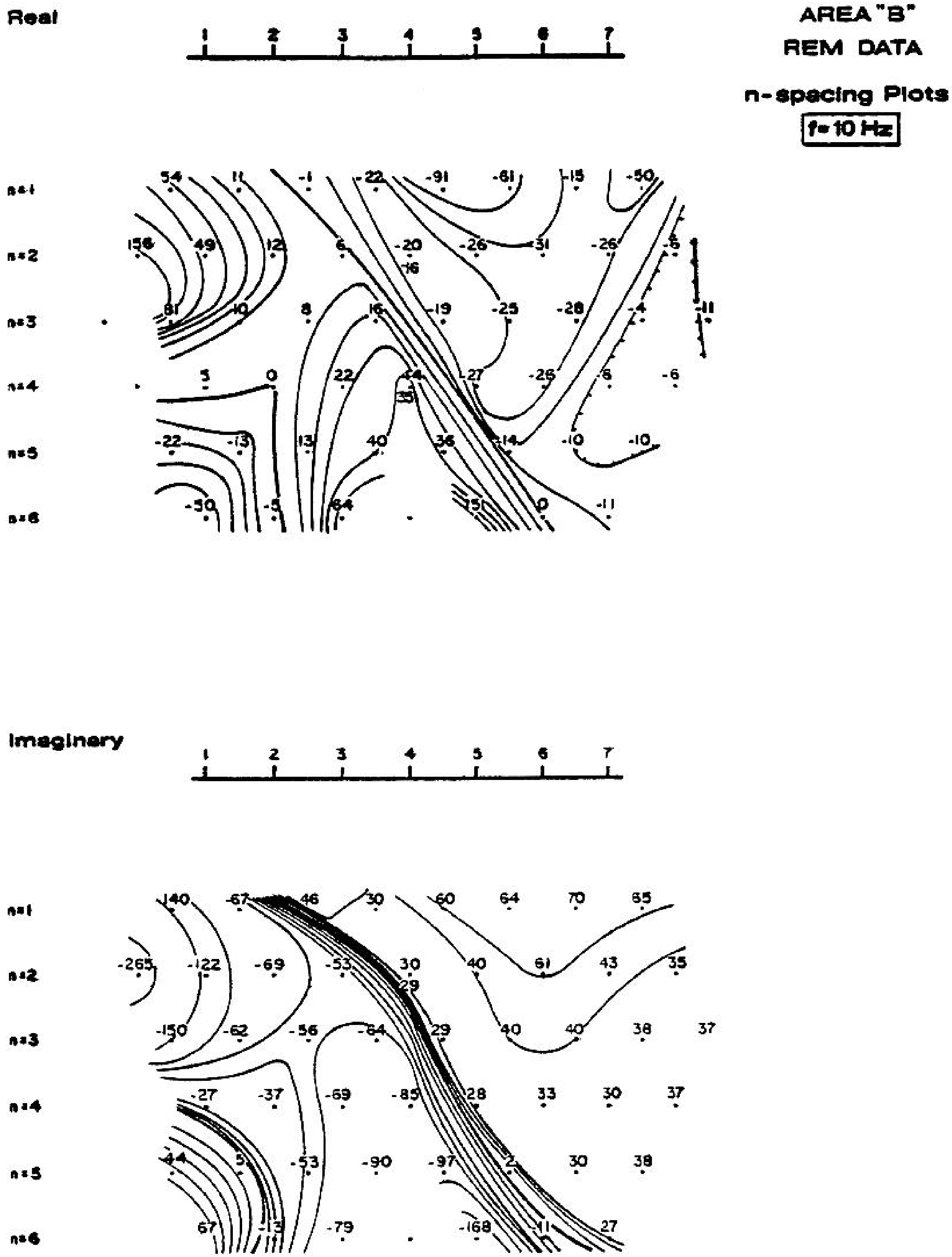


Figure 11. Geometric representation of REM data.

3. ADVANTAGES OF COMPLEX RESISTIVITY

As seen in Table 1, the decoupling process permits the evaluation of a wide range of data. These data are divided into two groups: IP data, consisting of apparent resistivity, polarization and spectral type, and deep sounding EM data, consisting of coupling and REM. The combination provides a more complete picture of mineralization, alteration, host rock type, and structure of a project area.

3.1. <u>Mineral Detection: IP versus CR</u>

Figure 12 compares spectra from three different environments. All three spectra have roughly the same polarization parameters at 0.1 Hz (31, 32 and 33 milliradians respectively), but they are type A, B, and C responses respectively. The area producing the type A spectra contains pyrite, calcocite, and chalcopyrite; the type B spectra was generated by 1% pyrite in a quartz monzonite host; and the type C spectra was produced over an area hosting barren chloritized rock near Casa Grande, Arizona. Induced polarization measuring phase at 0.1 Hz would not be capable of discriminating between the sources of the anomalous responses. However, complex resistivity spectral information definitely separates these three spectra into three distinct categories. Even if one cannot determine the economic viability of a complex resistivity spectral responses the host rock response alone will separate areas with a high probability of sulfide content from those where the response is due to barren rock or alluvial clay polarization effects.

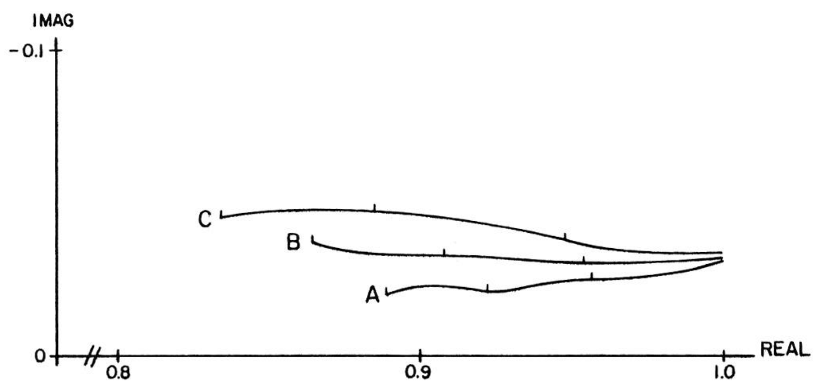


Figure 12. Comparison of spectra containing pyrite, chalcocite and chalcopyrite (A); pyrite only (B); chloritized biotite (C).

Figure 13 shows several spectra from pyrite-chalcopyrite bearing areas. These are spectra gathered in areas that have been tested and confirmed by drill holes, and are examples of “textbook” type pyrite/chalcopyrite responses which most often occur in highly disseminated environments. Although the exact cause or source of the two frequency dependent dispersions is not fully understood at this time, in every instance where “double-humped” spectra of this form have been obtained in the field, subsequent drilling has confirmed the presence of pyrite and chalcopyrite. Numerous in-house laboratory measurements have shown that for a given rock resistivity and grain size, pyrite bearing rocks peak about 1 to 2 decades below equivalent chalcopyrite bearing rocks. Hence, two distinct peaks are often visible in the spectra of rocks containing pyrite and chalcopyrite in the laboratory as well.

Naturally, use of these results in field interpretation are subject to a high degree of geologic control. However, results of drillcore laboratory measurements, in-hole CR logging and a large number of CR ground surveys have been found to be reasonably constant.

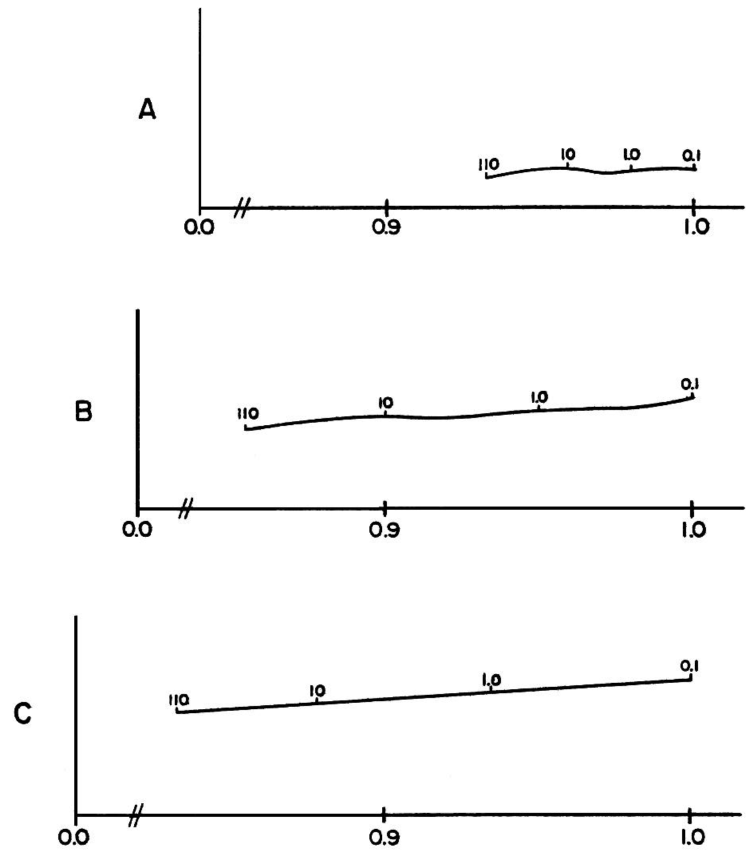


Figure 13. Spectra from different pyrite bearing area: (A) pyrite / chalcopyrite in a granodiorite porphyry; (B) pyrite / chalcopyrite in Duluth gabbro; (C) massive graphite containing up to 3% pyrite, Gibraltar, B.C., Canada.

TABLE 1

SUMMARY LIST OF CR DATA

Data	***Symbol***	***Units***	***Corrected for coupling?***	***Polarization source discrimination***	***Useful in oil work?***	***Useful for mapping structure?***	***Depth penetration (a=dipole size)***
Normal IP Data (before decoupling)							
• Apparent Resistivity*	ρa	Ohmmeter (Ωm)	No	No	Limited	Moderate	1-2a
• Polarization/coupling							
Raw Phase*	ϕ_r	Milliradian (mr)	No	No	Limited	Limited	1-2a
3-frequency Phase*	ϕ_{3pt}	Milliradian (mr) Percent (%)	Approx: at lowest freq.	Limited	Limited	Limited	1-2a
Percent Frequency Effect*	PFE		No	No	Limited	Limited	1-2a
Additional CR Data (after decoupling)							
• Coupling-free polarization			Yes	No	Limited	Limited	1-2a
Corrected Phase 0.1 or 0.125 Hz	$\phi_c, \phi_{.1}, \phi_{.125}$	Milliradian (mr)					
• Coupling			—	No	Limited	Yes	3-4a
Coupling Coefficient							
1st order	CC1	CC <1, high/low					
2nd order	CC2	CC = 1, homogeneous					
3rd order	CC3	CC > 1, low/high					
• Spectra[1]			Yes	Yes	Limited	Yes	1-2a
Complex plane plots	—	Real, imaginary					
Spectral type pseudosections	—	A, B, C types & subtypes					
• REM	REM	Real, imaginary	—	No	Yes	Yes	4-6a
Spectra							
Parametric plots							
Geometric plots							
Thumbprint plots							

[1] Raw, undecoupled spectra are also plotted prior to decoupling.

* Available in the field.

3.2. Coupling Removal

Figure 14 shows the apparent resistivity, raw phase, and decoupled phase pseudosections from a survey conducted in Nevada. The raw phase data shows high values at depth below station 9. However, once coupling is removed from the data the anomaly disappears, indicating that it was purely a result of EM coupling. The analysis with CR spectra obtained in this area indicated the response was coming from a combination of near-surface pyrite and alteration. There is no evidence of economic sulfide in any of the spectra. Subsequent drilling confirmed that the near surface anomaly was due to syngenetic pyrite.

Probably the most important advantage of complex resistivity measurements is the ability to remove EM coupling from induced polarization data. Whether or not one can distinguish between economic and noneconomic anomalous responses, the ability to distinguish between coupling anomalies and sulfide anomalies in itself is worth the extra investment in complex resistivity analysis.

3.3. Cultural Contamination

Cultural contamination results when powerlines, pipelines, fences, and other man-made conductors channel current in preferential paths through the ground. The result is often a confusing pseudosection in which there are high or low diagonals emanating from the disturbing culture.

IP data can be seriously contaminated by culture, even after steps have been taken to minimize its effects. In a similar manner, CR data is prone to contamination, but in many cases the data may be salvaged by being able to accurately delineate those stations that are seriously contaminated by cultural coupling.

Figure 15 presents data from a survey conducted by Zonge Engineering in Arizona. The survey line was oriented perpendicular to a pipeline that crossed the line beneath station 3. The apparent resistivity and polarization pseudosections are dominated by pantleg cultural effects, making it difficult to search for other polarization sources in these data. High frequency spectral contamination denoted by spectral (γ) signatures is also present, but several individual complex spectral plots indicate a low frequency peak, suggestive of pyrite. (See Figure 17). A second line was run by offsetting the line by one-half a-spacing, making the dipole stations symmetric about the pipeline (Figure 16). On this line the pipeline effect was minimized and a pyrite response was observed beneath the pipeline. This was subsequently confirmed by a drillhole that intercepted a narrow tabular body of five to eight percent pyrite in quartz sericite schist directly beneath the pipeline.

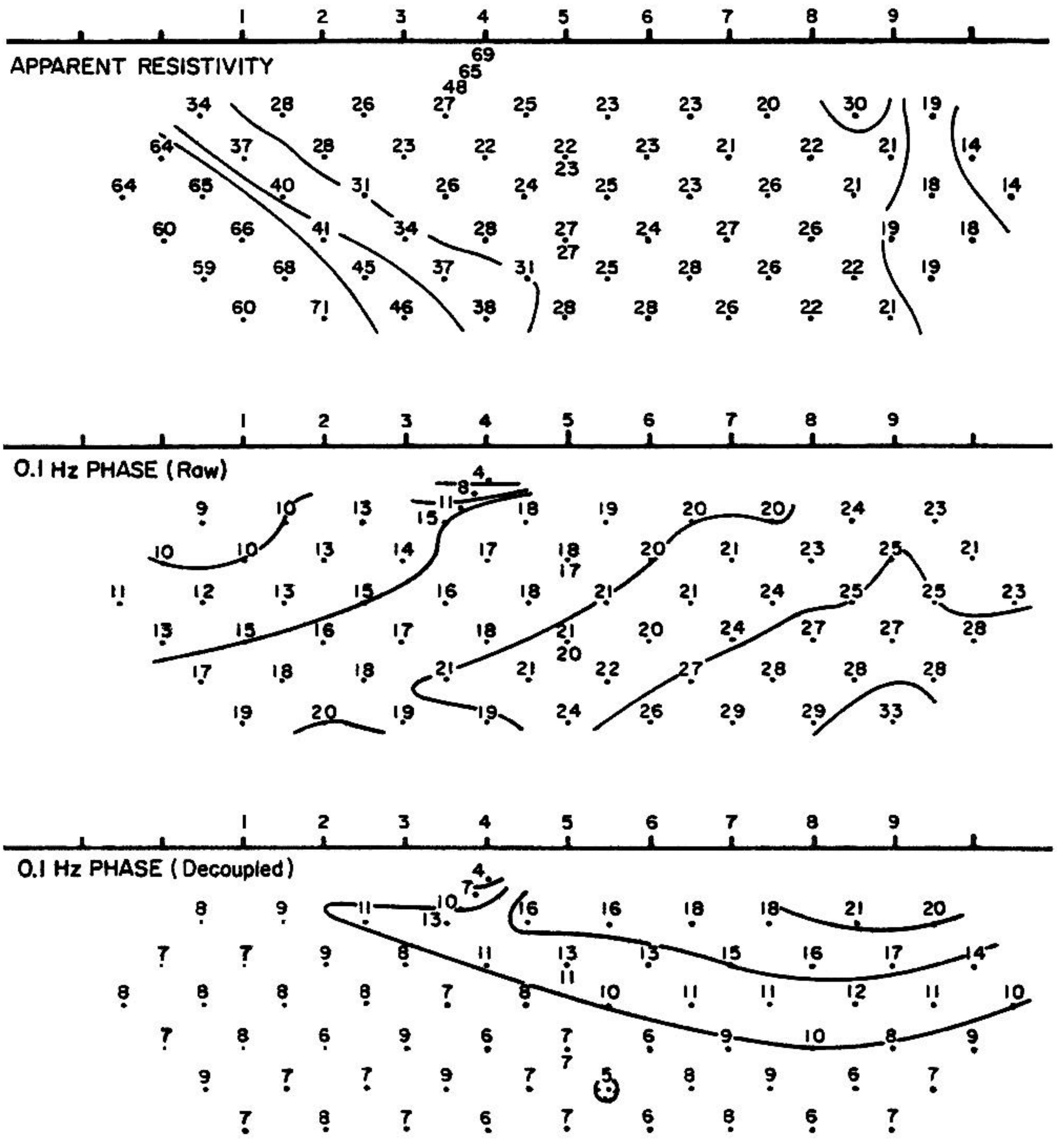


Figure 14. Pseudosections from a survey in Nevada comparing raw and decoupled data. Note that the high raw values below station 9 disappear once the data are decoupled. Examination of the CR spectra show that the remaining surface response is due to syngenetic pyrite. A-spacing = 1000 feet.

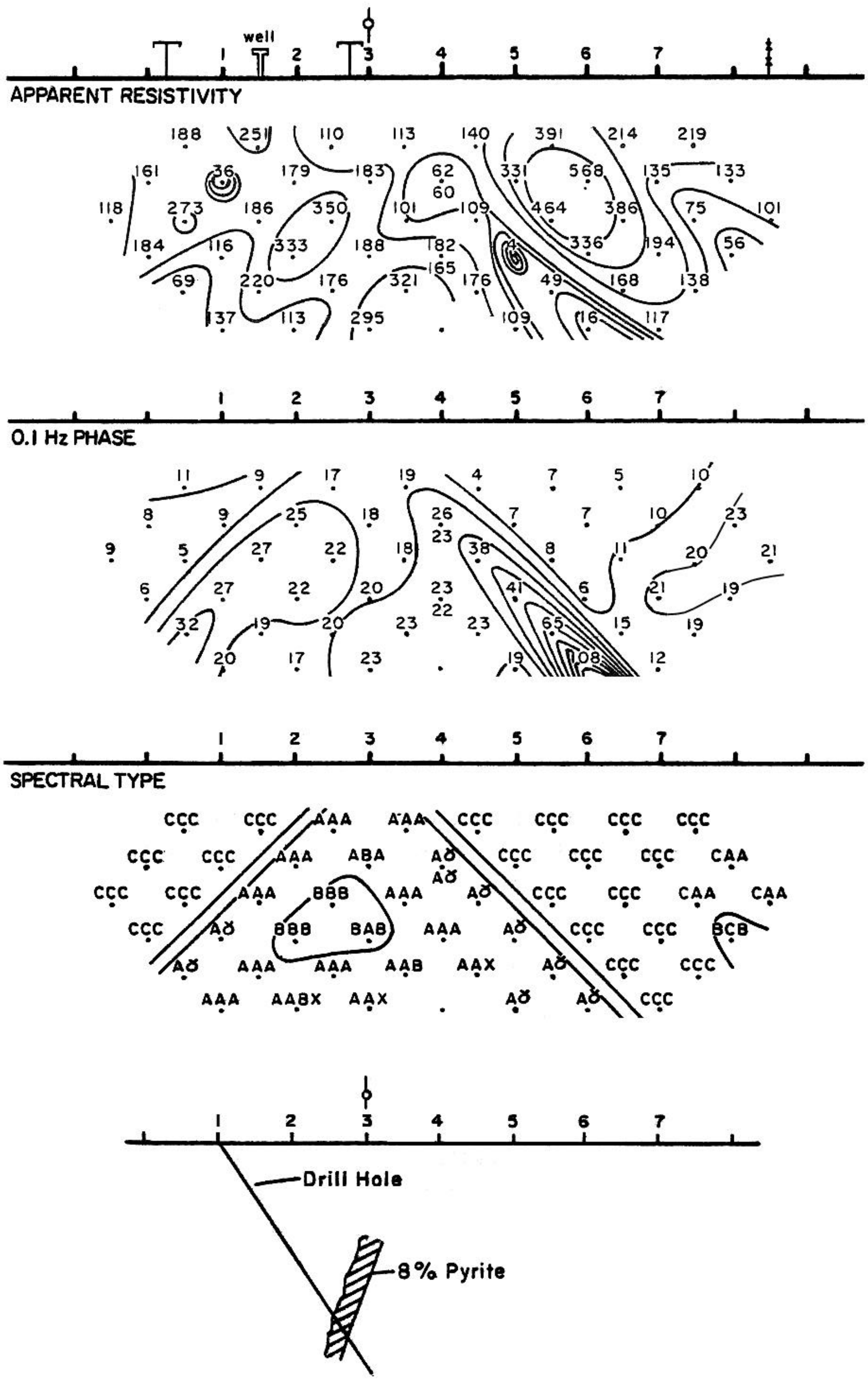


Figure 15. CR data for the case of a sulfide body occurring beneath a buried pipeline with one electrode directly over the pipeline.

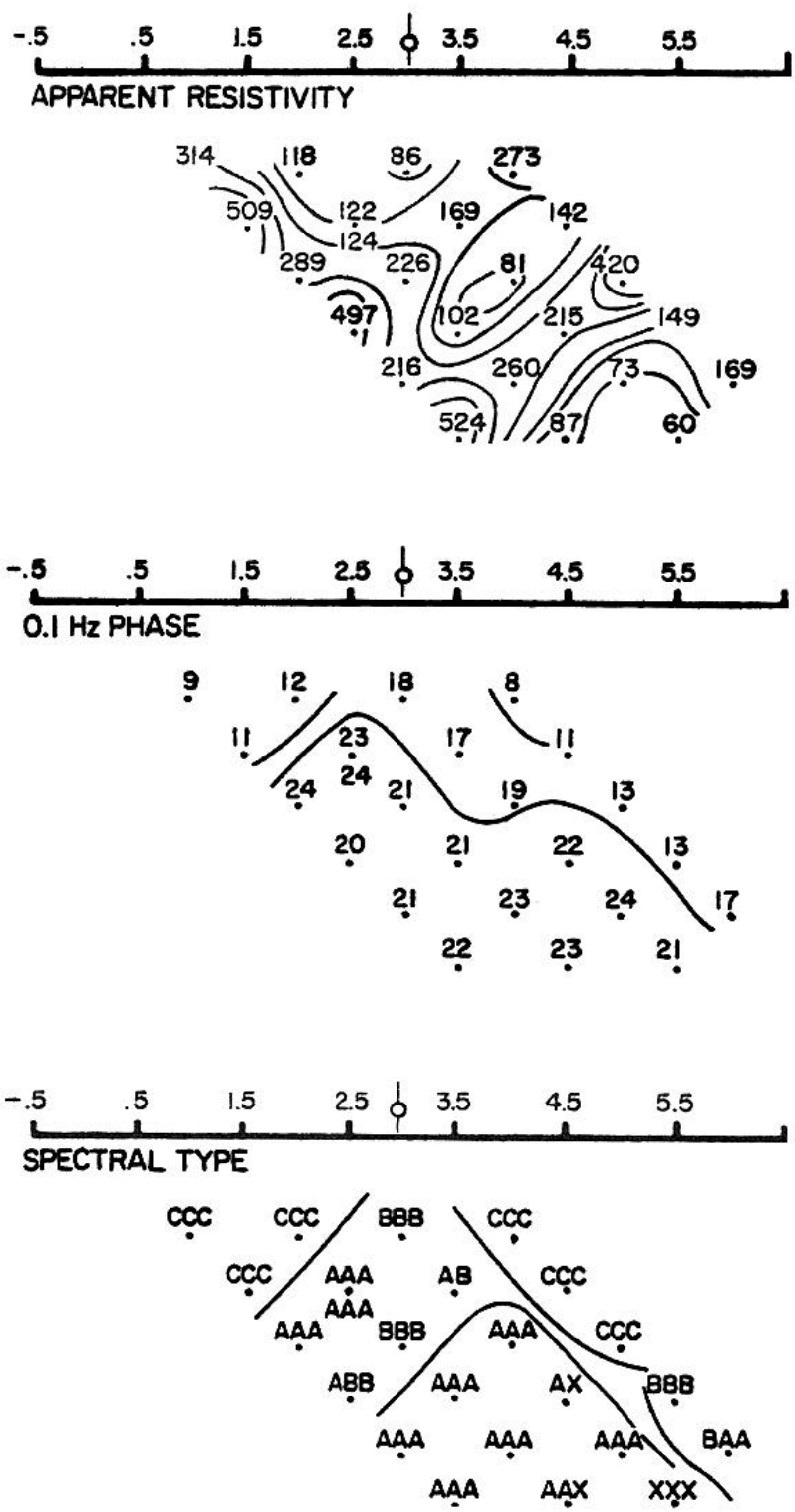


Figure 16. CR data for the case of a sulfide body occurring beneath a buried pipeline, with transmitting electrodes symmetric about the pipeline. Compare with Figure 15.

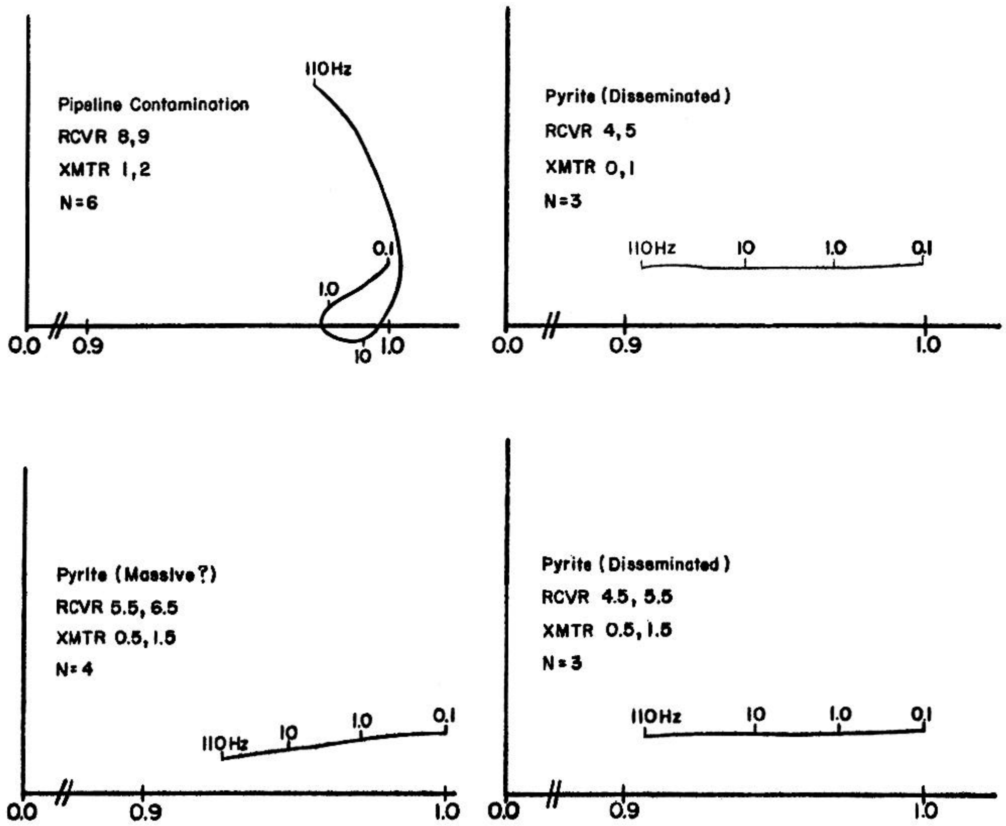


Figure 17. Samples of spectra from Figures 15 and 16.

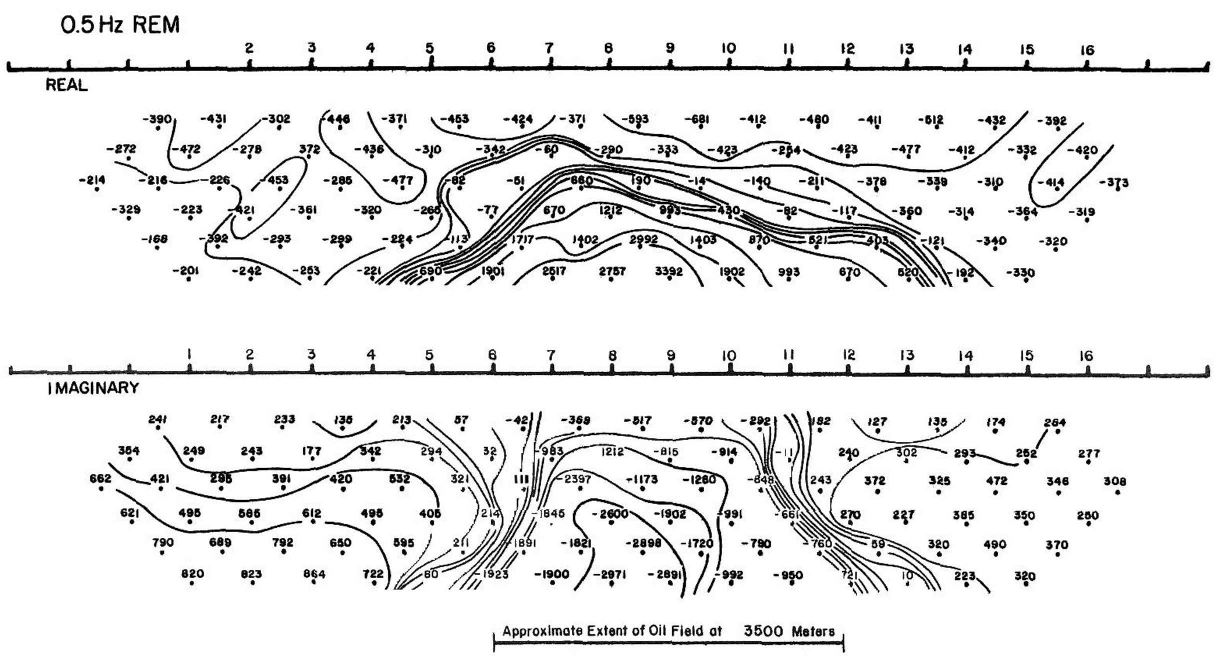


Figure 18. Geometric REM pseudosection of typical oilfield data.

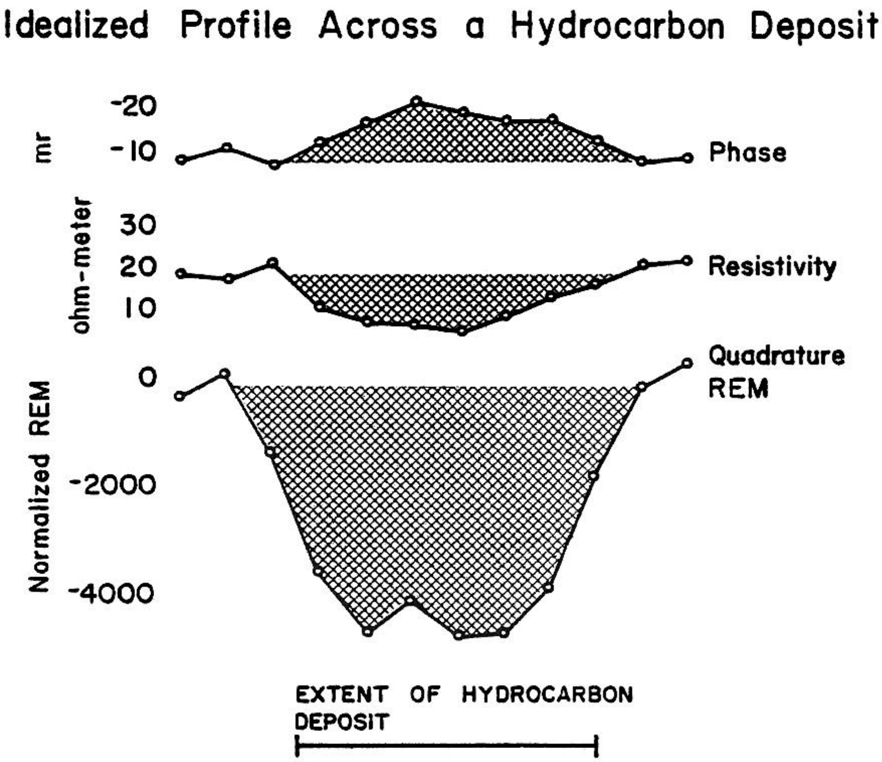


Figure 19. Typical phase, resistivity and REM responses over an oilfield.

3.4. Hydrocarbon Detection

Zonge Engineering began oil field work in 1976 and since then has conducted complex resistivity and multi-frequency resistivity-phase measurements over a wide variety of producing fields, seismic prospects, and wildcat prospects for several major oil companies. The work originally began on a research basis but the discovery of the utility of residual electromagnetic data in hydrocarbon detection and the rapid interpretational evolution that accompanied it allowed Z.E.R.O. to use its techniques on a production basis starting in 1979. An example of a typical REM anomaly over an oil field is presented in Figure 18. Often, an oil field will influence electrical parameters near the surface, providing both a polarization high and resistivity low, as shown in Figure 19, along with an REM profile. However, our experience has shown that while apparent resistivity and polarization anomalies occur over known oil fields approximately 50% of the time, REM anomalies occur 100% of the time.

4. DATA ACQUISITION

A typical complex resistivity survey involves a linear spread of seven to nine transmitting electrodes. Each electrode is connected by 14-gauge insulated wire leading to the transmitting/data processing truck. Ideally, the truck is parked at the center of the line during the data acquisition to reduce coupling effects.

When current is delivered to a pair of transmitting electrodes the resultant potential field is sensed at a pair of electrodes a fixed distance away. A center potential electrode is often used a ground reference for the receiving dipole for common mode noise rejection, effectively removing noise which is common between the rear half and the front half of the dipole. This technique is particularly useful in reducing certain types of radiated noise, and is electrically equivalent to the two-electrode dipole for data reception.

High-frequency harmonic analysis can be improved by dedicating one measurement channel to monitor the transmitted signal. A shielded communication cable carries the signal from transmitter to receiver. Precision clocks in the receiver and transmitter controller (and a stable transmitter) provide sufficient signal synchronization for middle and low frequency measurements.

The PDP and GDP systems amplify the signals, buck-out ground self-potential and filter out high frequency noise. Periodic 60, 180, 300, and 540 Hz powerline noise can be filtered out if needed. Filters are available for use in areas served by 50 Hz power. Other filters have been constructed as needed, including a 120 Hz notch for use near pipelines using cathodic protection.

During data acquisition, both waveforms are monitored in order to detect equipment problems, ground peculiarities, noise, etc. Monitoring noise allows the geophysicist in charge to select appropriate filters, to make logistical decisions and to determine the appropriate amount of data stacking necessary to meet the survey goals.

The transmitted frequency and synchronization between transmitted and received signals are controlled by the system, as well as digitizing and filtering the data and facilitating the removal of long period ground tellurics and wide band random noise.

A 16-bit analog to digital (A/D) converter in each receiver channel digitizes the transmitted and received waveforms, at a maximum sample rate of 1024 points per waveform. Successive cycles are stacked by synchronously adding each set of sample points to double precision storage buffers. When the desired number of cycles has been acquired, the stack is divided by the number of cycles to obtain an average waveform for each channel.

At this point, a Fast Fourier Transform (FFT) is performed on both waveforms. This is done according to standard Fourier analysis, which provides that any function can be represented by an infinite sum of sine waves, or harmonics. A square wave function of the type used in a CR survey can be represented by the sum

$$V = A\sum_{k=1}^{\infty}\frac{1}{k}\sin kwt \qquad \textit{(for odd k)} \qquad 4.1$$

$$V = 0 \qquad \textit{(for even k)}$$

$$V = A\sin wt + \frac{A}{3}\sin 3wt + \cdots + \frac{A}{n}\sin nwt + \cdots \qquad 4.2$$

in which **V** is the square wave amplitude and A=4/π. Figure 20 illustrates a square wave, the first six odd Fourier harmonics, and their summed approximation of the square wave. The summed approximation becomes better as more and more higher-order harmonics are considered.

Using the harmonic analysis approach, one can transmit a symmetrical square wave at some fundamental frequency f and obtain data for the odd harmonics 3f, 5f, 7f, …nf. For example, if a 1 Hz signal is transmitted, magnitude/phase data for 1,3, 5, 7…n Hz can be obtained. There is a limit as to how many of these harmonics are useful, since the power drops off with each successive harmonic by a factor of $1/n^2$ that produces a rapid deterioration in the signal-to-noise ratio.

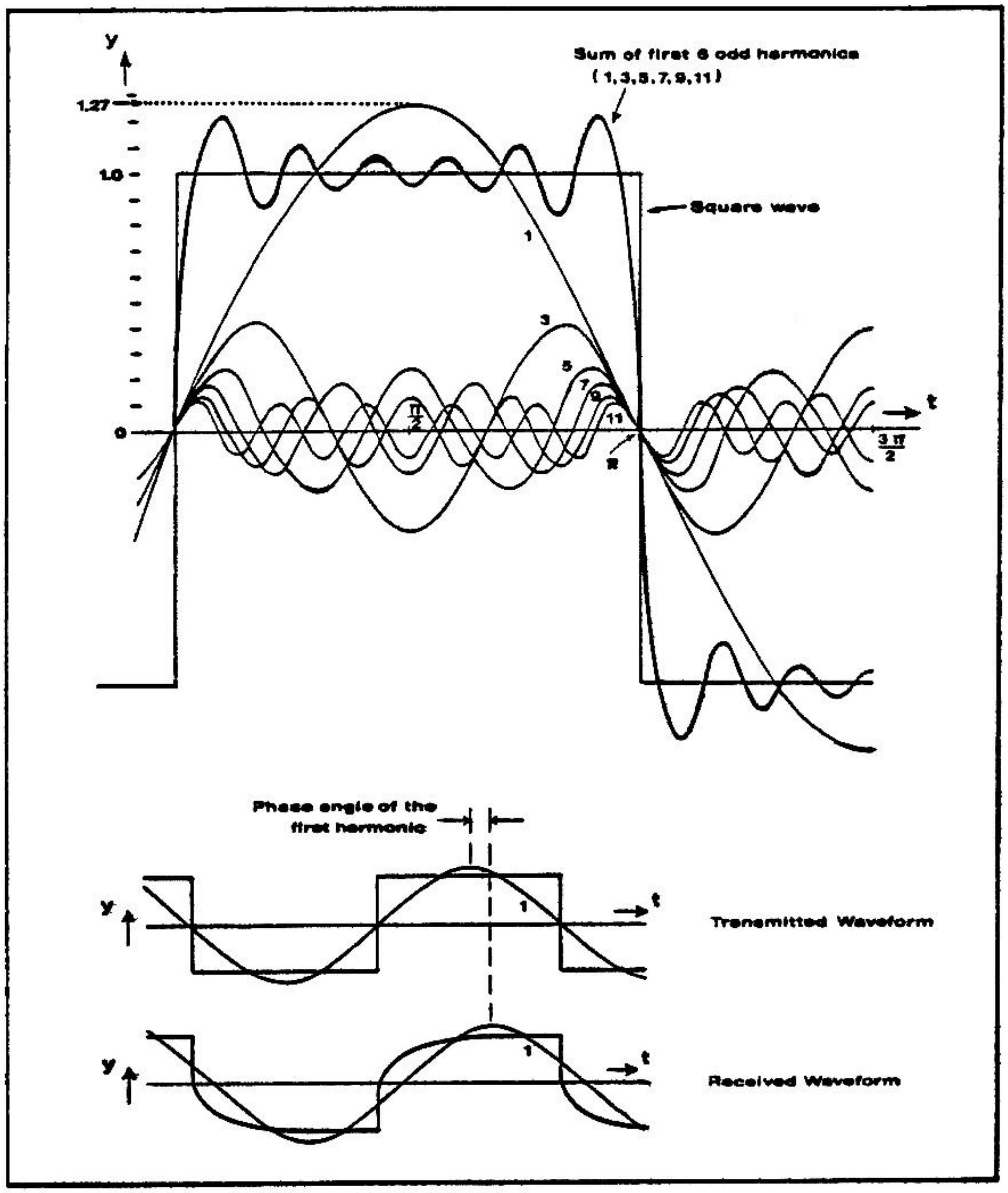


Figure 20. Schematic representation of Fourier synthesis of a square wave.

4.1. PDP-8 CR System

The PDP-8 CR system used fundamental frequencies of 0.01, 0.1, 1.0, and 10 Hz. The first six odd harmonics were output for each of these, providing a maximum coverage of four frequency decades:

Fundamental Frequency (transmitted)	0.01 Hz	0.1 Hz	1.0 Hz	10 Hz
3rd harmonic	0.03	0.3	3.0	30
5th harmonic	0.05	0.5	5.0	50
7th harmonic (calculated)	0.07	0.7	7.0	70
9th harmonic	0.09	0.9	9.0	90
11th harmonic	0.11	1.1	11.0	110

The overlap between the four frequency blocks provides a "bracket" test for continuity of the data, and thereby provided a further on-site evaluation of overall data quality.

Most PDP-8 surveys required only a frequency range of 0.1 to 110 Hz. Due to the increased stacking and averaging time necessary for low frequencies, however, the additional coverage from 0.01 to 0.11 Hz was provided when necessary; for example, to investigate the polarization effects of clays or other low frequency responders.

4.2. GDP CR System Harmonics

The GDP systems typically use fundamental frequencies of 0.125, 1.0, and 8.0 Hz, and provides the first five odd harmonics to form the following range of data:

Fundamental Frequency (transmitted)	0.125 Hz	1.0 Hz	8.0 Hz
3rd harmonic	0.375	3	24
5th harmonic (calculated)	0.625	5	40
7th harmonic	0.875	7	56
9th harmonic	1.125	9	72

Since the sample rate is dependent upon the fundamental frequency for GDP systems (from 1024 at lower fundamentals to xxx), the 11th harmonic can be more susceptable to noise and is not usually provided with the data although it is obtained in the field. Note that the frequencies for the GDP system are also selected in order to check data bracketing.

4.3. CR Data Processing

After the FFT is completed, the two sets of harmonics are deconvolved by dividing the received waveform by the transmitted waveform, on a harmonic-by-harmonic basis. This division or deconvolution provides raw resistivity / phase data for all calculated harmonics. Irregularities in amplitude and phase due to transmitter instability, electrode polarization and common mode drift are removed in this process.

Fourier transformation, deconvolution and IP parameter generator are performed real-time in the field to minimize the logistic problems associated with handling large amounts of data. As shown in figures 3 and 4 the transmitted and received waveform paths pass through a nearly identical array of amplifiers, filters and other electronic devices. However, small response differences in the two paths will occur due to slightly different electronic component characteristics. These differences are recorded prior to data acquisition in a system calibration, which is removed from the raw data before decoupling in the office.

Once the data has been processed it is displayed and stored internally. The raw data consists of magnitude and phase components for each frequency, apparent resistivity, and raw phase, three-point corrected phase and PFE. The geophysicist then determines the data quality from the continuity of the data and the bracketing, or overlap, of the three to four data blocks obtained. A second measurement is normally acquired to ensure data quality.

A rough pseudosection of resistivity and polarization may be kept updated by the geophysicist in order to monitor the IP information and to spot possible problems in the general trend of the data. This pseudosection is provided to the client immediately upon completion of the fieldwork.

When the suite of data received by the Tucson office are decoupled, the final results are normalized and plotted, and multi-dimensional modeling of the resistivity and IP can be performed. A full report is issued upon completion of the interpretation.

5. OTHER CR SERVICES

While the dipole-dipole array is the minimal coupling configuration for an in-line survey, Zonge Engineering occasionally conducts surveys using other arrays, depending upon specific needs of the client. Limitations of land access rights or needs for extra-ordinary penetration depths occasionally require the use of pole-dipole, Schlumberger and various in-hole radial arrays.

A downhole CR system with a draw works is available for general contracting purposes. The purpose of such a system is to correlate actual in-situ rock responses with those observed on a ground survey in the same environment. Hence, downhole CR operates as an interactive component of an exploration program, serving to more sharply define and explain previous CR results.

6. SURVEY PLANNING

Planning a complex resistivity survey should involve close cooperation between the client and the ZERO geophysical staff. Several factors need to be considered before the project is begun:

- Timing. Several weeks advance notice is usually needed in order to schedule a crew. Weather should be considered in planning, since particularly adverse conditions can slow fieldwork considerably. Also, since the workload during the first three months of the year is traditionally light, scheduling field projects is generally easier at this time.
- Land. All land permits upon which the survey is to be run should be obtained in advanced. Land damage due to complex resistivity work is normally negligible. Use of off-road vehicles helps survey logistics but is not absolutely necessary.

- Noise. Seasonal thunderstorm activity can slow data acquisition, due to the increased stacking and averaging time needed to maintain data quality. In particularly stormy areas, it is not possible to work in the afternoons due to the danger of lightning activity to both equipment and personnel. In these areas it is best to schedule work in the spring, winter or fall if possible.

- Culture. Powerlines, pipelines, fences, water pumps and other man-made devices which can conduct or transmit current into the ground can adversely affect data acquisition and quality. However, until data is actually being taken, it is difficult to accurately assess how badly culture will influence the survey. The main point to remember is that running a survey line parallel to culture is a maximum EM coupling situation, and running perpendicular is a minimum EM coupling situation but can generate galvanic or IP responses. If the line must be parallel, higher frequency contamination will occur if the culture is closer than one dipole spacing. Perpendicular lines should ideally be placed so that the dipoles symmetrically straddle the culture to minimize extraneous effects.

- Access. In order to minimize the amount of wire used on the survey, it is helpful to locate the transmitter at the center of the line. Offsetting the line involves more difficult logistics, but is occasionally necessary due to land restrictions or rugged terrain.

- Geology. Since geophysics in general provides basic but not necessarily unique images of the subsurface, any geologic knowledge or intuition that the client can supply is quite helpful in bringing a field project to a successful conclusion.

- Follow-up. As in most scientific endeavors, ZERO's interpretational capabilities are always in a state of evolution. Hence any information which the client can provide after the survey, such as drilling results, can be extremely valuable in assessing the original field interpretations and in augmenting future work.

7. REFERENCES

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