A COMPARISON OF ELECTRODE ARRAYS IN IP SURVEYING

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This paper is to be presented at the AIME Annual Meeting –
San Francisco, California – February 20-24, 1972

INTRODUCTION

The induced polarization (IP) method of geophysical exploration is capable of detecting even small amounts of metallic luster minerals in a rock mass. Consequently, in the years since discovery, IP surveying has become the most popular ground geophysical survey method.

It is not too difficult to understand many applications of IP surveying as used in the search for mineral deposits. However, the basic theory of the IP phenomenon is not well developed or understood, and there has been some disagreement on fundamental concepts.

In order to most effectively apply the IP method in the field it is necessary to know the physical characteristics of the sought-for deposit including its size, shape, depth, and electrical properties. With this information an optimum IP search arrangement can be devised and one could use the best possible electrode interval, type of array, and line spacing. With uncertain target characteristics as encountered in the real world, geological guidance must be used to help direct an optimized IP survey.

SUMMARY AND CONCLUSIONS

Geometric arrangements of the grounded contacts, or electrodes, can be classified according to the shape of the electrical field that is being measured. In general there are three basic families of arrays. These can be described as approximately either a parallel electric field, the field about a point current electrode, or a dipolar electric field.

The ratio of the signal voltage to the external disturbing noise voltage is an important consideration in designing equipment, in making a survey layout, and in the interpretation of field data. Signal-to-noise ratio can be determined for each array in differing conditions and this ratio is helpful in selecting the best array for particular conditions of a given survey.

Electromagnetic (EM) coupling between the IP transmitter and receiver circuits is also an important matter in the choice of an electrode array. As a generalization the time-domain IP method has less difficulty with EM coupling and more problems with handling noise disturbances, while the converse is true with the frequency domain method.

Electrode arrays can be chosen to take advantage of the subsurface situation, surveying conditions, and the kind of equipment being used.

ARRAY FUNDAMENTALS

Ohm's law for three-dimensional materials can be applied to derive the electric field about a point current electrode. The field from a second current source can be superimposed on the first, which can be illustrated by curved current flow lines as shown on Figure 1.

Measurement of the resulting electric field is carried out by using two potential electrodes in contact with the ground, which give the voltage potential difference between the detecting points. This voltage difference V can be written

$$V = \frac{\rho I}{2\pi}\left(\frac{1}{r_A} - \frac{1}{r_B} - \frac{1}{R_A} + \frac{1}{R_B}\right) \tag{1}$$

where ρ is the resistivity of the medium, ***I*** is current in amperes, ***r*** is the distance from one potential point to current points ***A*** and ***B***, and ***R*** is the distance from the other potential point. Equation (1) is the general voltage relationship for any electrode array and it can be simplified for specific arrays, such as the Wenner ($r_A = a, r_B = 2a, R_A = 2a, R_B = a$), whereupon $\rho = 2\pi a \frac{V}{I}$

Figure 2 shows several of the common resistivity arrays. These can be classified according to the type of electric field being measured, whether parallel, hemispherical, or dipolar. Figure 3 illustrates these different types of electric fields from the standpoint of array geometry, that is, the location of the potential measuring electrode pair relative to the current electrode pair.

If all of the electrical contacts with the earth are <u>in</u> a drill hole then the varieties of geometric electrode arrangements are not much different than on the surface. However, if only one or two electrodes are <u>down</u> the drill hole and the other contacts are on the surface then the electric field of the array becomes more complex. Two of the common down hole arrays are illustrated in Figure 4.

The “mise a la masse” resistivity method whereby a conductive body is excited by a nearby current electrode, is very useful for enlarging the effective search radius of a drill hole. Similar drill hole IP methods give results that are more difficult to interpret.

Factors in Array Selection

There are a large number of variables in the choice of electrode arrays for IP surveying. In order of relative importance these factors are:

1. Signal-to-noise ratio
2. EM coupling rejection
3. Survey speed and economy
4. Resolution of subsurface bodies
5. Array symmetry
6. Other matters such as safety, topographic effect, communication and ease of interpretation

“Noise” is a term that applies to unwanted voltages whereas “signal” is the voltage that contains the desired information of the survey. The ratio of signal-to-noise is the best way of describing system characteristics in an electrical measurement. In measuring IP response, noise is primarily due to naturally fluctuating earth current, although several other noise sources are possible, if not more easily controlled.

Telluric Noise

Earth, or telluric, current fluctuations at the IP frequencies are primarily due to extraterrestrial sources. Figure 5 shows a burst of electromagnetic noise due to sunspot activity impinging on and penetrating the earth. These voltages can be rejected to some extent by the IP receiver, but they are bothersome in many circumstances.

The electromagnetic noise spectrum (Figure 6) can be generalized to some extent, but these voltages are random in both time and location. The IP band of interest is influenced by electromagnetic micropulsations which probably originate at the interface between the earth’s magnetic field and the impinging solar wind. Thunderstorm and man-made electrical noise can also be annoying.

The voltage-detecting wires in an IP survey system are similar to a grounded antenna, and noise voltages can be rejected to a large extent by the IP receiver. For any particular IP receiver it is possible to know the signal-to-noise ratio for given field conditions. Noise can then be compared to the voltage signal received by the grounded antenna. A derivation of this ratio can be obtained for the dipole-dipole array, where voltage signal V_S is

$$V_S = \frac{\rho I}{\pi a (n+1)(n+2) n}, \tag{2}$$

as can be derived from equation (1). Here "***a***" is the electrode spacing and "***n***" is the integral number of "***a***" spacings between the adjacent IP transmitter and receiver. Voltage signal V_S applies both directly and differentially to resistivity and IP measurements.

From Cagniard's (1953) formulation for a resistive earth, noise voltage V_N can be expressed in the form

$$V_N = Ka\sqrt{\rho} \tag{3}$$

where ***K*** is the filtering constant of a given IP receiver. Thus, for the dipole-dipole array, signal-to-noise ratio is

$$\frac{V_S}{V_N} = \frac{\rho^{1/2} I}{K \pi a^2 (n+1)(n+2) n} \tag{4}$$

This arbitrary threshold ratio is plotted for different electrode spacing values of ***a***, shown on Figure 7. Note that for larger values of "***a***," a larger current ***I*** is necessary to maintain a constant signal-to-noise ratio.

Figure 8 gives the signal-to-noise ratio for different resistivities with a fixed "***n***" interval. To maintain a constant $\frac{V_S}{V_N}$ ratio on a low resistivity earth, the current ***I*** must be increased.

A frequency IP transmitter usually uses a full square wave of current to stimulate polarization of the ground. This square wave is composed of a distribution of higher frequencies as shown on Figure 9. However, most of the square wave energy is contained in the fundamental frequency as shown in Figure 10. This larger concentration of power at the transmitted frequency is an advantage of the frequency IP method because random frequency noise can be more easily rejected in the field than with time domain equipment.

EM Coupling

In certain situations an IP transmitter and receiver circuit behave like the primary and secondary winding of an ordinary electrical transformer. The primary circuit of the transformer induces a current in the secondary circuit, the electrical induction effect being more pronounced at higher frequencies. Distance factors and low resistivities become important when interelectrode distance are an appreciable fraction of the wave-length of the transmitted electromagnetic radiation. This electromagnetic induction or "EM coupling" causes spurious IP-like effects that are not due to natural polarization causes. The EM coupling problem has been treated in some detail by Sunde (1949).

EM coupling becomes a severe problem when using higher frequencies or shorter times, in either the frequency or time domain IP methods. Figure 11 shows decay curves that have been affected by coupling. To avoid coupling in the frequency method, lower frequencies are used. In the time domain it is readily possible to merely ignore the shorter time interval portion of the decay curve, which effectively provides a low pass filter, as shown on Figure 12.

It must be stressed that EM coupling is not "noise" and must be avoided to give interpretable data. EM coupling effects cannot be eliminated from IP data by a simple correction factor, except for very small coupling effects. However, a type of electrode array can be selected to minimize the coupling problem.

Interpretation of IP Data

The dipolar field array has better resolution of subsurface bodies, as is illustrated on Figure 13. There usually is better resolution of subsurface bodies with IP than with resistivity, because an IP anomaly is measured against a relatively lower background level.

It is possible to tabulate the various electrode arrays, showing the advantages of each under different field survey conditions. This is given on Table 1 using the criteria outlined in this paper. It can be said that no particular array combines all of the desirable factors of IP surveying, but that some arrays are more effective for specific purposes than others.

REFERENCES

Cagniard, L., 1953, Basic theory of the magneto-telluric method of geophysical prospecting: Geophysics, vol. 18, no. 3.

Sunde, E. D., 1949 Earth conduction effects in transmission systems: New York, D. Van Nostrand Co.

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Table 1

COMPARISON OF IP SURVEY ELECTRODE ARRAYS

	Advantages	Disadvantages	Survey Speed	Signal-to-noise	EM Coupling Rejection
Potential Field Arrays Wenner	Anomalies symmetrical Synchronous detector possible. Many case histories available.	Requires more wire; larger field crew. Poor resolution. Unfavorable in capacitive coupling situations.	FAIR	GOOD	FAIR
Schlumberger	Symmetrical array. Synchronous detection possible. Fewer men required. Works well in layered earth. Type curves available.	Less horizontal resolution. Unsuitable for horizontal profiling. Capacitive coupling possible.	FAIR	FAIR	FAIR
Gradient	Map interpretation easier. Less masking by conductive over-burden. Penetration good; safer. Communications easier. Can use two or more receivers. Less topographic effect. Data easily contoured in plan. Useful where difficult to make good current contacts.	Poor resolution with depth. Poor in low resistivity areas except surface. Geometric factor varies complexly.	GOOD	FAIR	POOR
Potential-About-A-Point Three array	Good reconnaissance array. Fairly good resolution.	Asymmetrical. More wire needed.	FAIR	GOOD	GOOD
Pole-dipole, collinear	Good resolution. Good subsurface coverage.	Asymmetrical.	FAIR	FAIR	FAIR
Perpendicular three array pole-dipole pole-pole	Virtually eliminates EM coupling.	Asymmetrical. More wire needed.	FAIR to POOR	FAIR	VERY GOOD

	Advantages	Disadvantages	Survey Speed	Signal-to-noise	EM Coupling Rejection
Pole-pole (Two array)	Smaller crew needed. Less wire needed than for some arrays. Good penetration in non-conductive over-burden.	Susceptible to masking by conductive over-burden. Sometimes needs more wire.	GOOD	FAIR	POOR
PDR (Potential drop ratio)	Sensitive to lateral variations. "Common mode" noise rejection.	Complex interpretation. Edge effects.	FAIR	GOOD	FAIR
<u>Dipole Field Array</u> Pole-dipole collinear	Symmetrical, good resolution. Good penetration. Less survey wire needed.	Slow unless equipment is portable. Resistivity topographic effects. Interpretation somewhat involved.	FAIR	POOR	FAIR
Diople-dipole parallel	Special use for EM coupling interpretation.	Not used for routine surveying.	POOR	POOR	FAIR
<u>Down-Hole Arrays</u> Azimuthal array (one potential electrode down the hole)	Fair for exploration purposes. Useful in finding the best search direction.	Interpretation complex. Negative anomalies. Strong geometric effects. Mainly measures changes in resistivity.	FAIR	GOOD	GOOD
Radial Array (one current electrode down the hole, mise a la masse)	Good for exploration purposes. Useful in finding the best search direction. Hole need not stay open.	Interpretation complex. Negative anomalies. Not good for obtaining rock properties.	FAIR	GOOD	GOOD
<u>In-Hole Arrays</u> (more than one electrode in the hole)	Good for obtaining rock properties. Good for assaying. Interpretation simple.	Current densities may be too large. Possible capacitive coupling problems. Not designed for exploration. Special equipment, expensive.	GOOD	FAIR	GOOD

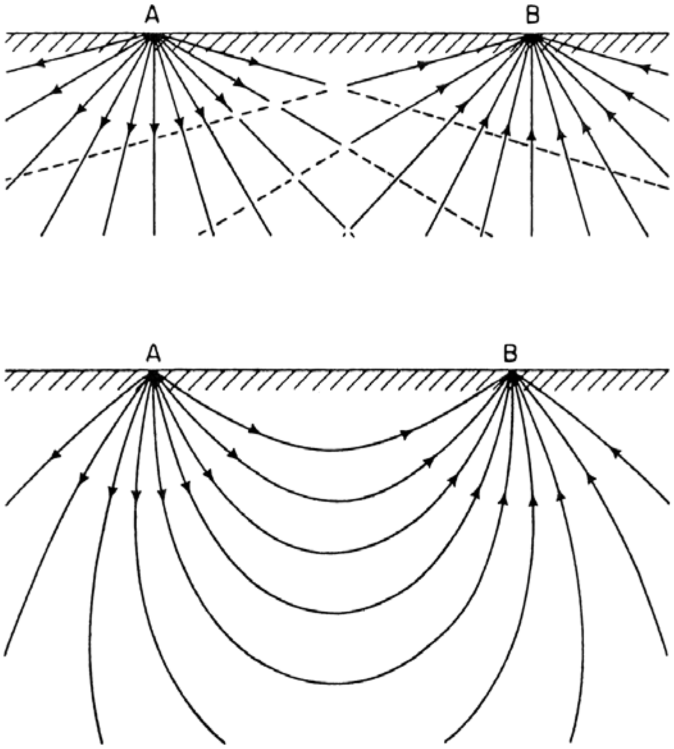

Figure 1. Cross-sectional view showing superposition of electric fields and the resulting field of a current electrode pair.

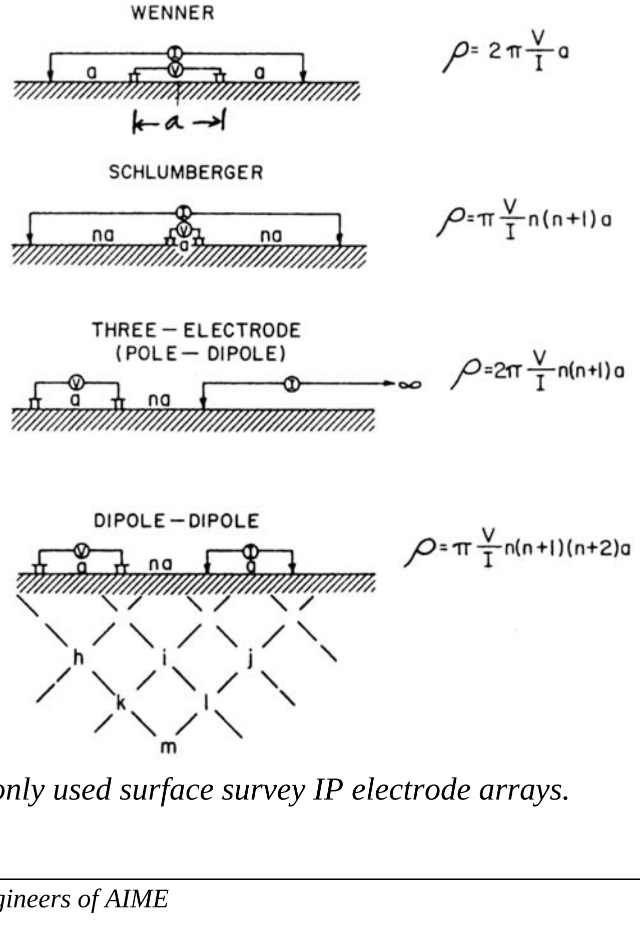

Figure 2. Commonly used surface survey IP electrode arrays.

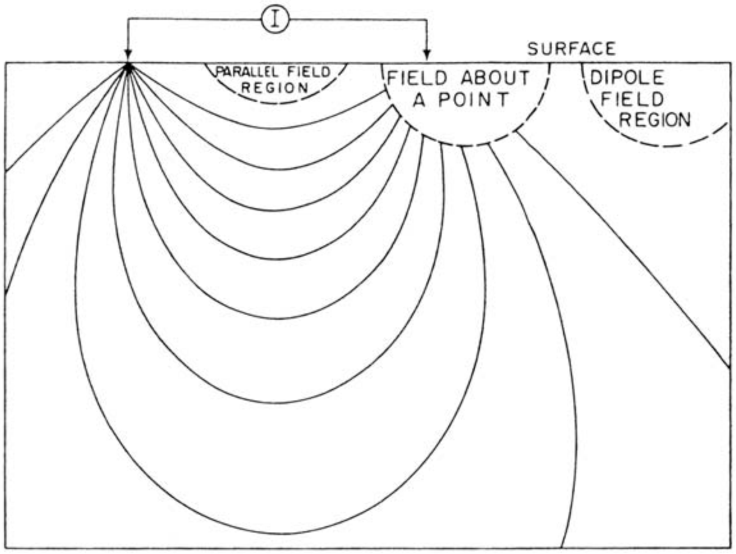

Figure 3. Electrode array classification, showing geometry of electric fields.

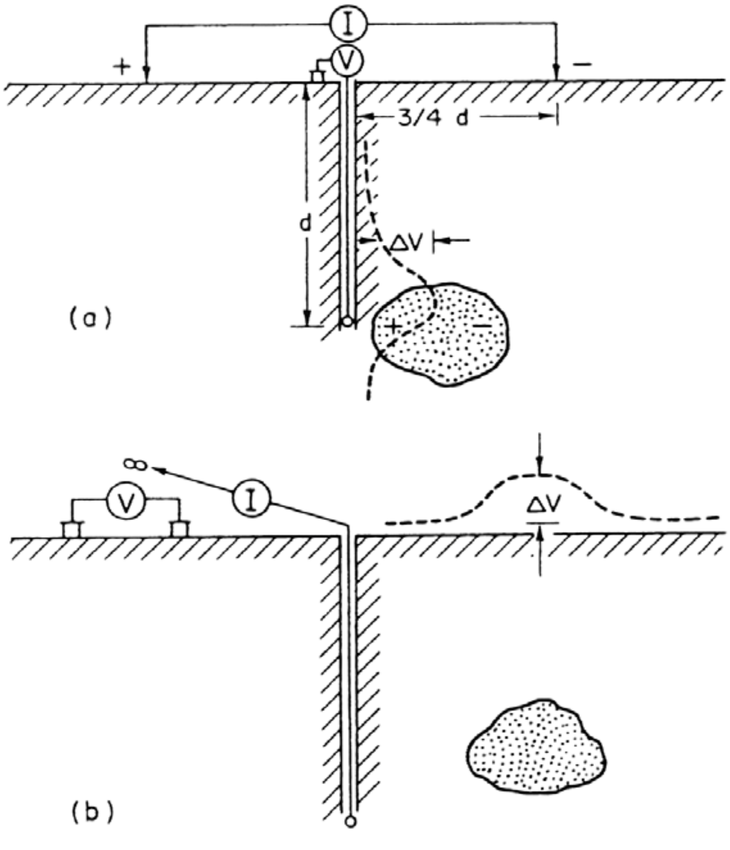

Figure 4. "Down hole" drill hole electrode arrays

a) Azimuthal array

b) Radial array

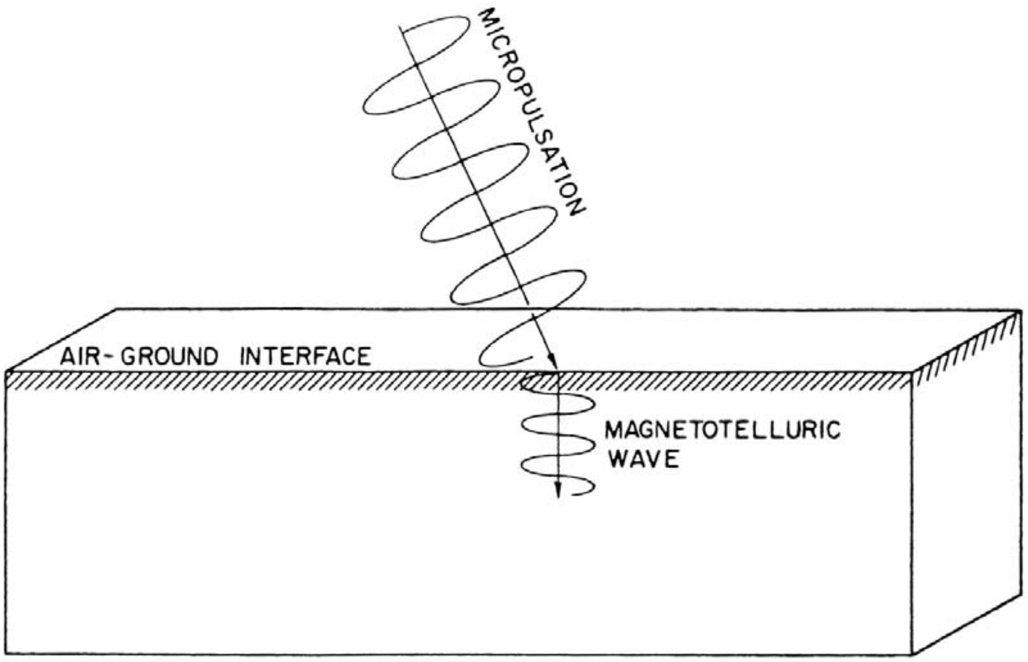

Figure 5. Magnetotelluric noise, showing a micropulsation burst penetrating the earth.

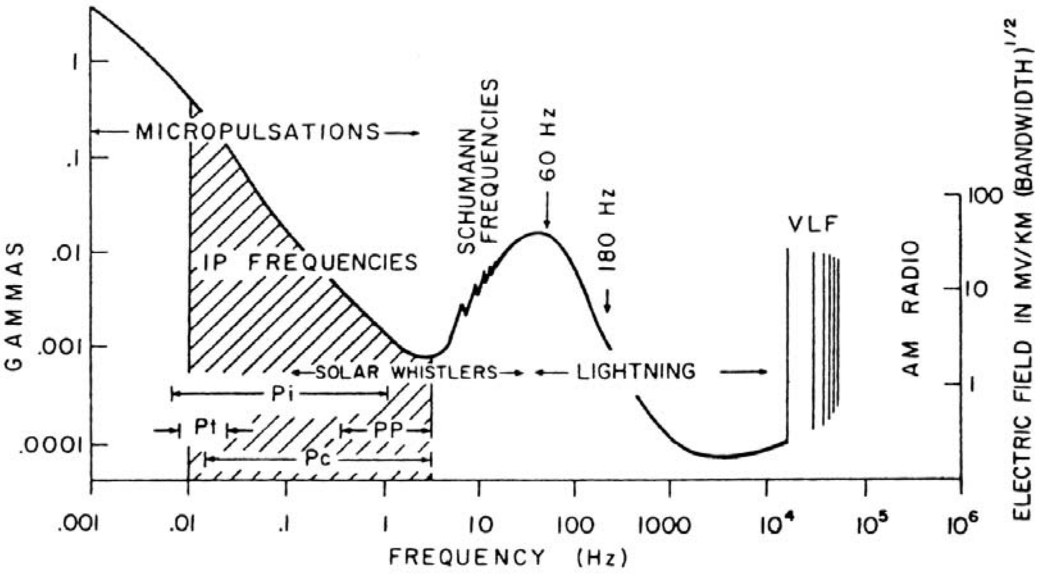

Figure 6. The electromagnetic noise spectrum.

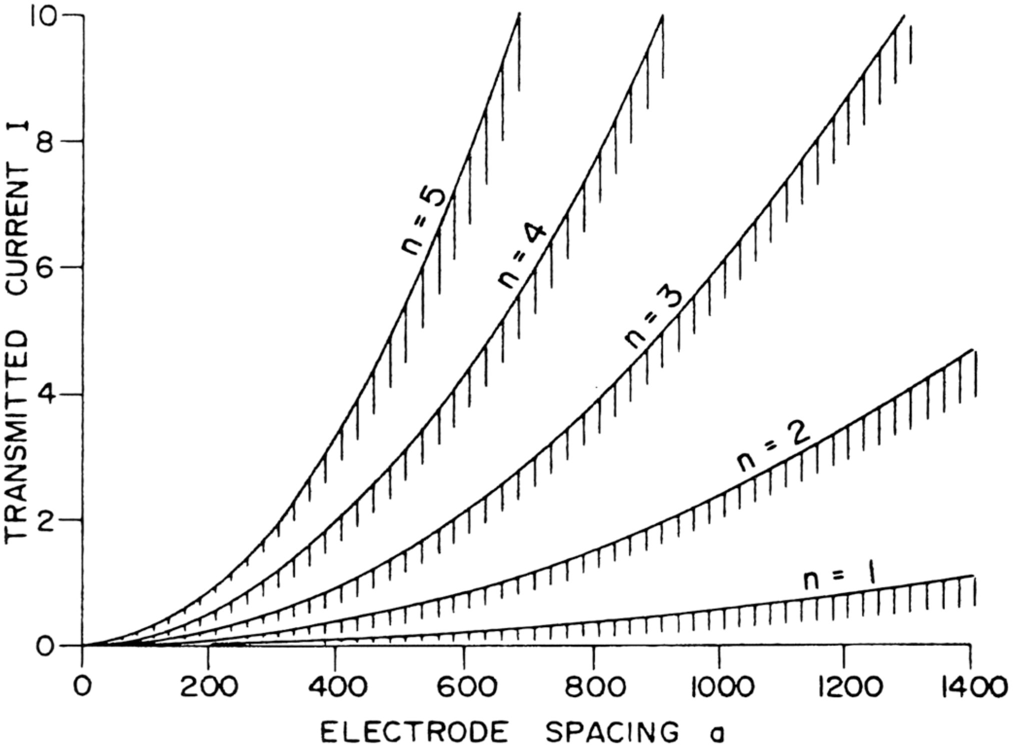

Figure 7. Dipole-dipole array curves for a constant signal-to-noise ratio. The electrode spacing "a" is varied and the ground resistivity is constant.

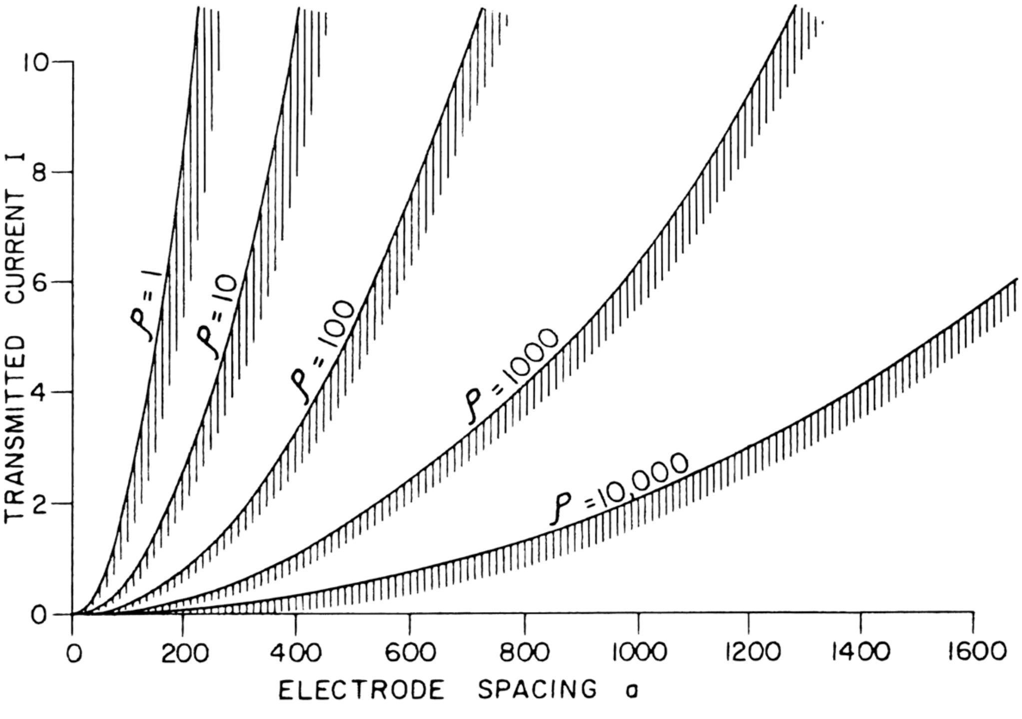

Figure 8. Dipole-dipole array for a constant signal-to-noise ratio. The homogeneous ground resistivity is varied, using a fixed "n" spacing.

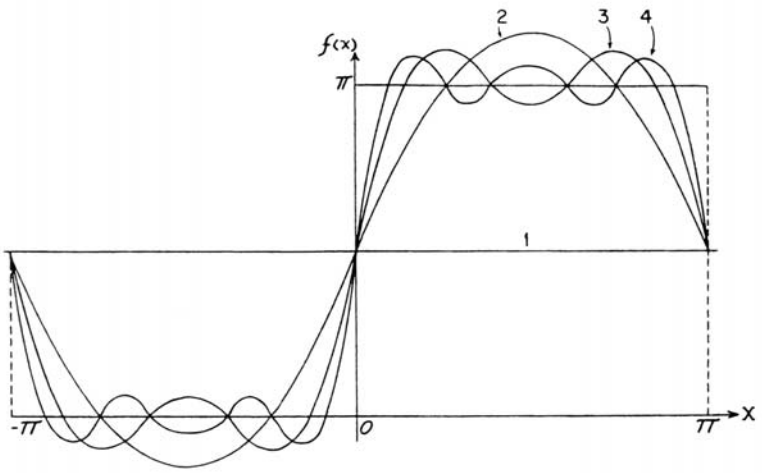

Figure 9. Fourier components of a full square wave. The numbers 1,2, 3, etc., refer to successive summation of terms of the Fourier expansion.

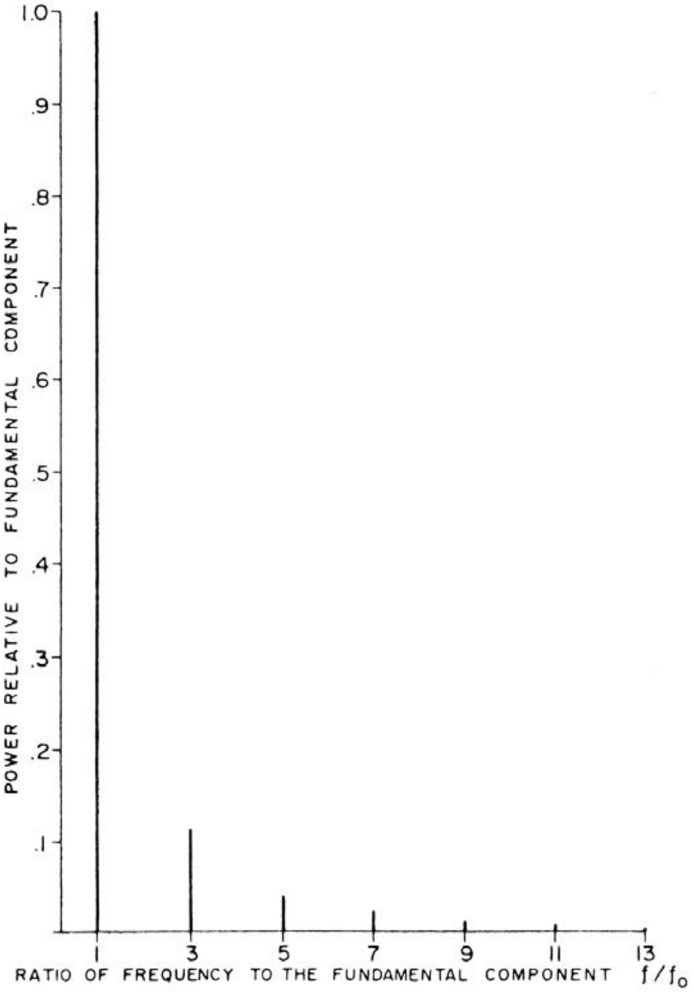

Figure 10. The power spectrum of a full square wave.

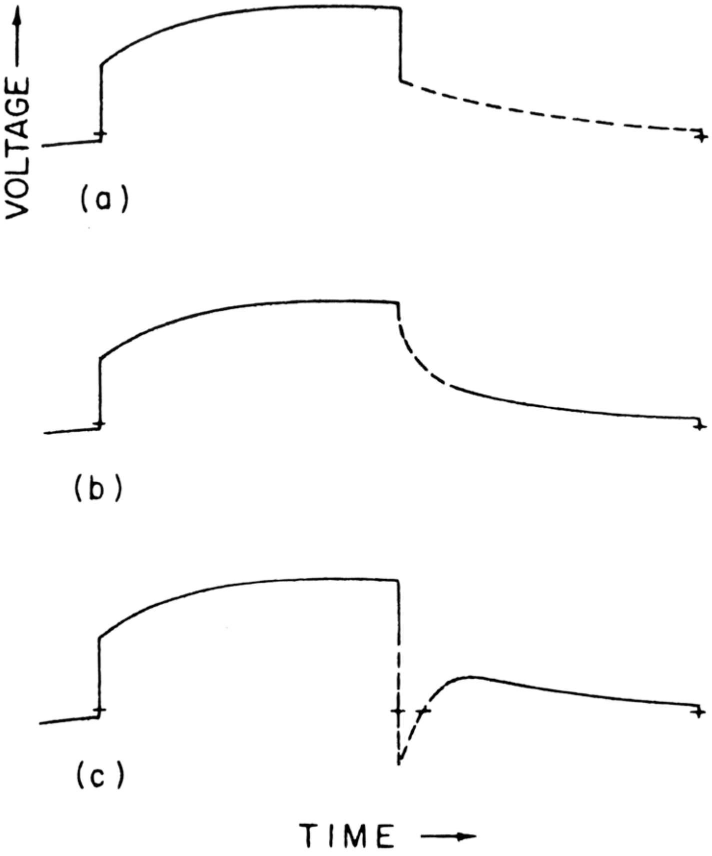

Figure 11. *EM coupling diagram*

a) A normal IP voltage decay curve
b) Positive EM coupling on a decay curve
c) Negative EM coupling on a decay curve

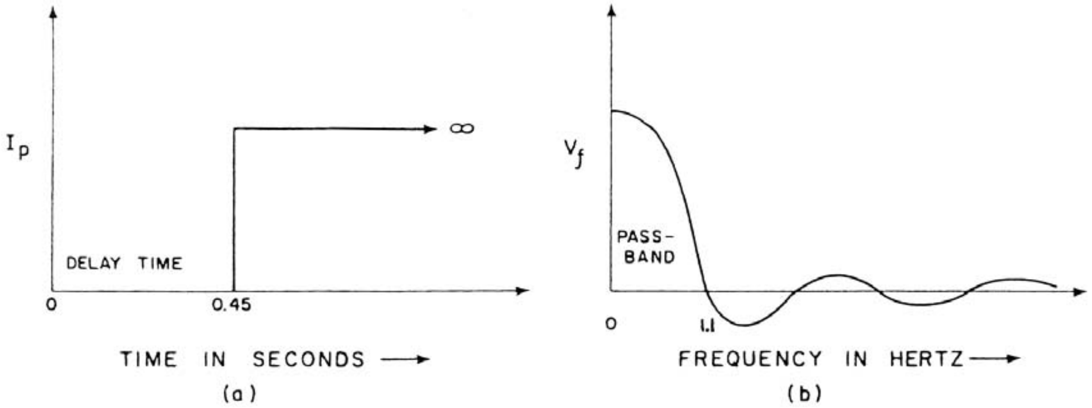

Figure 12. *Coupling rejection by filtering*

a) Time domain
b) Equivalent passband filter in the frequency domain

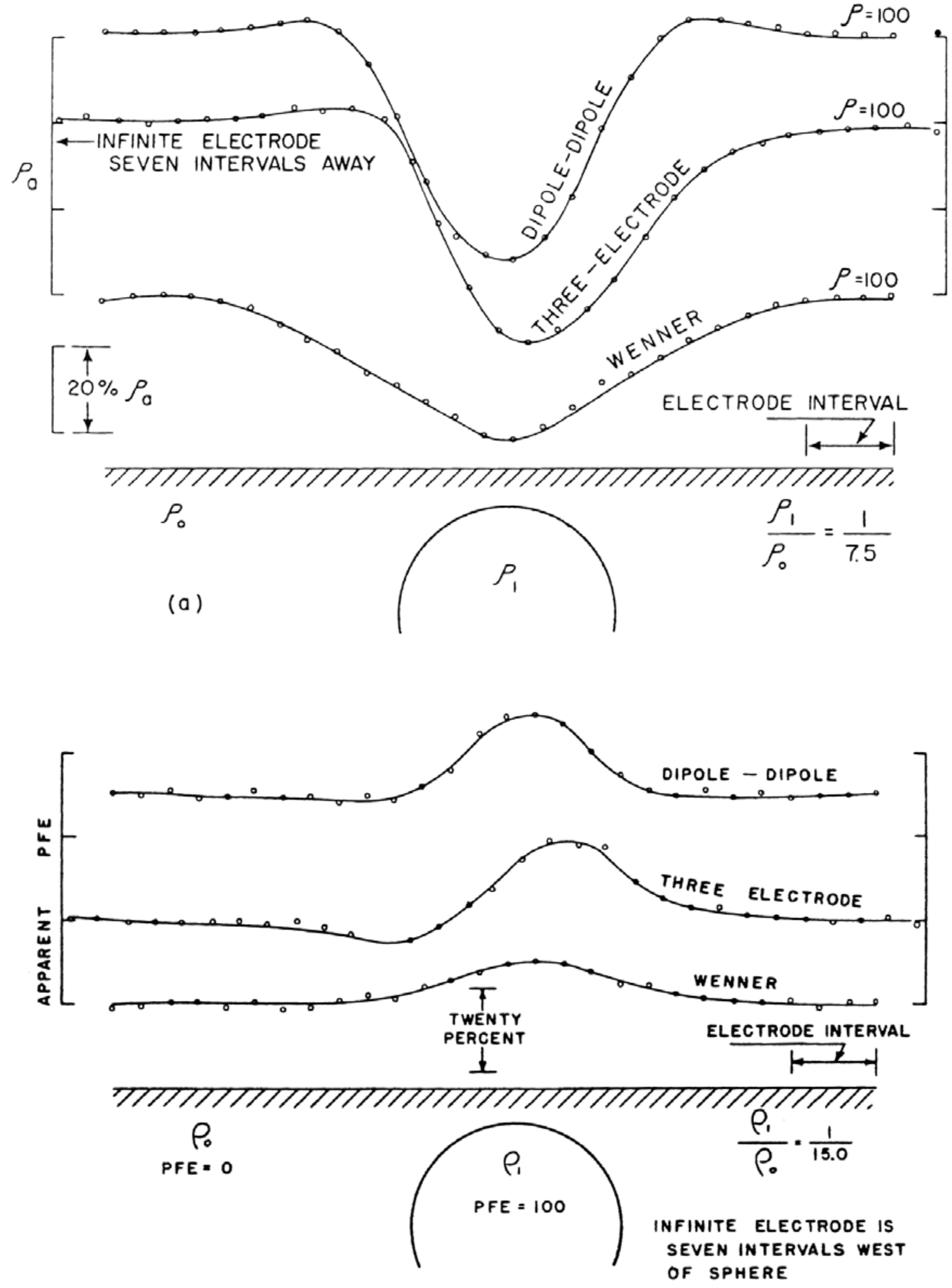

Figure 13. Array-resolution of a sphere

a) Resistivity

b) Induced polarization