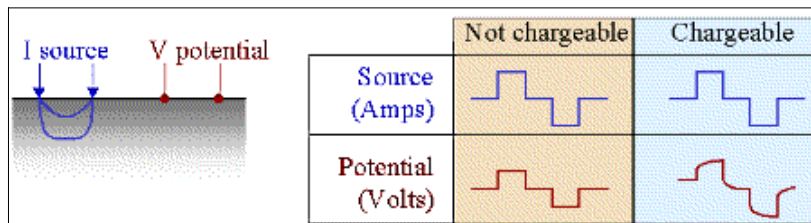


Introduction to induced polarization surveying

Descriptive outline

This module provides background about chargeability, and induced polarization surveying. There are no details about interpretation, inversion, or case histories - these will be added in a subsequent version of the module.

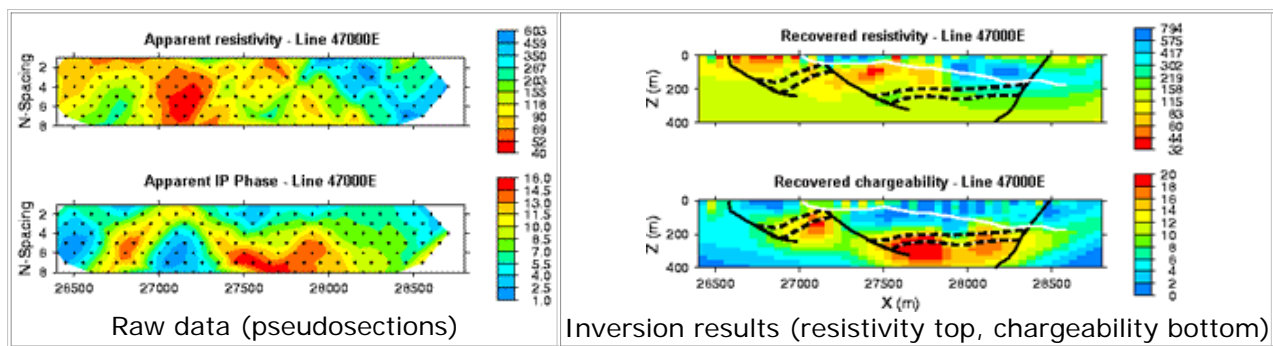
Chargeability is a physical property that is related to resistivity. The module about DC resistivity shows that potentials measured in a DC resistivity survey can be related to charges that accumulate when current is made to flow. However, when the transmitter current is switched off, the measured voltage may take up to several seconds to reach zero. Similarly, when the current is switched on, there may be a finite time taken for the voltage to reach a steady state value. In other words, current injected into the ground causes some materials to become polarized. The phenomenon is called induced polarization, and the physical property that is measured is usually called chargeability, which quantifies the material's capacity to retain charges after a forcing current is removed. The following figure illustrates the measurable effect.



Induced polarization can also be measured using low frequency sinusoidal signals, as discussed in the "Measurements and data" section of this chapter. The signals or data that are measured depend upon which of the various types of source signals are used. Note that IP surveys always include resistivity measurements because the potentials used to obtain apparent resistivity are required to calculate chargeability.

Examples

The data sets shown (below-left) were gathered simultaneously at the Century Deposit in Australia. Clearly they are exhibiting responses to different materials within the ground. However, this presentation of the raw data (plots called pseudosections) is deceptive, and does not represent true distribution of material properties in the ground. After inverting these data, the resulting resistivity model reveals information about rocks overlying the deposit, while the resulting chargeability model shows the deposit itself and underlying shale units.



The physical property - chargeability

The materials that are most chargeable include sulfide minerals (both massive and disseminated), clay-rich materials, and graphite. However, many chargeable materials have physical property values that range from nil to large even within the same region. This is because chargeability depends upon many factors, including mineral type, grain size, the ratio of internal surface area to volume, the properties of electrolytes in pore space, and the physics of interaction between surfaces and fluids.

Interpretation of chargeability models is further complicated by the fact that there is no standard set of units for this physical property. There are at least three ways of measuring the phenomenon and models recovered by inversion generally take on the same units as the measurement. This could be milli-seconds if measurements are made of the ground's response to impulsive sources. The units could also be percent if the response at two or more source signal frequencies is compared, or units of milliradians may be used if the phase difference between source and received signals is recorded.

Typical problems where chargeability is useful

IP surveys are useful primarily when there is little resistivity contrast between target and host, or when several equally valid resistivity models cannot be resolved. Mineral exploration for sulfides (disseminated and massive) is unquestionably the most common application of IP because those types of ore minerals are often chargeable.

There are also applications in hydrogeology. For example, mapping salt water intrusions in aquifers that include clayey layers may be difficult using resistivity alone. However, the increased chargeability associated with clay may help differentiate between zones with more saline water and clay, both of which have low resistivity.

In addition, there is a growing interest in the possibility of using chargeability to aid in the detection and delineation of contaminants in the ground. There has also been some effort to apply IP to oil and gas exploration.

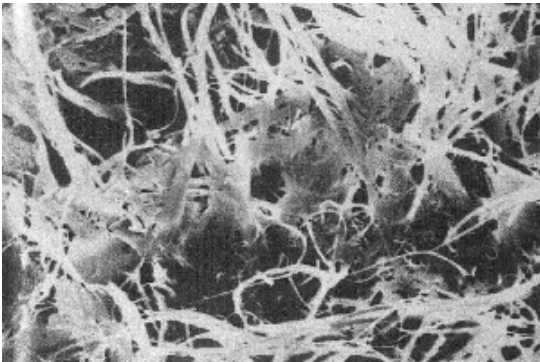
Introduction

Note: before gaining an appreciation for what makes ground chargeable, it is useful to understand why the DC electrical resistivity of ground varies. There is an AGLO module devoted to a discussion about electrical resistivity of geological materials.

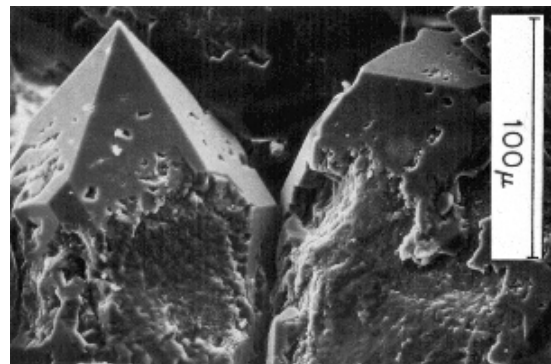
The chargeability of earth materials is essentially an electrochemical effect caused by many factors, not all of which are completely understood. If ground is chargeable, it responds as if resistivity was a complex quantity - it behaves somewhat like a leaky capacitor. Therefore the chargeability can be measured in a number of ways using time domain or frequency domain techniques (detailed in the section on [measurements and data](#)). Aspects affecting the chargeability of a sample include:

- the grain size of particles in the sample;
- the types of minerals involved;
- the type and mobility of ions within the pore fluids;
- the details of microscopic interactions between solid surfaces and fluids;
- the amount of surface area within a specific volume.

The surface area-to-volume ratio is an important factor. Clays tend to be chargeable while sandstones are not, and the images here illustrate one reason why this is true. In addition, the surface interactions between clay minerals and fluids enhance the ability of these materials to hold charges.



Illite (a clay mineral) with surface area-to-volume ratio of $100\text{m}^2/\text{g}$ (1000 times greater than sandstone)



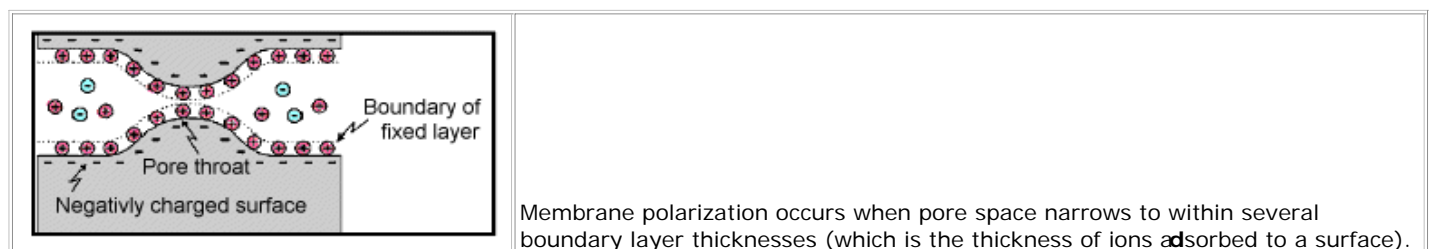
Quartz overgrowths in sandstone with surface area-to-volume ratio of $0.1\text{m}^2/\text{g}$

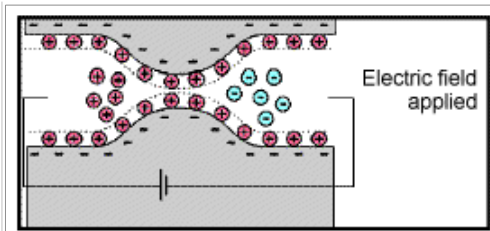
On the remainder of this page, some details about causes of chargeability are introduced.

Two microscopic effects cause macroscopic chargeability

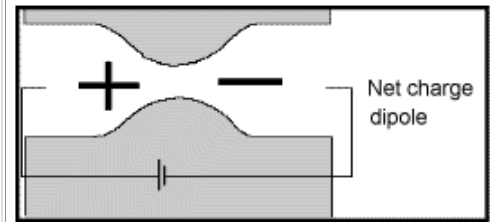
There are two primary causes of chargeability. In both cases the re-distribution of charges takes some time to occur when an external DC electric field is applied. Equivalently, it takes the same time to revert to a balanced charge distribution once the electric field is removed. "Charging" is hard to measure in practice. "Discharging" is measured using time domain IP survey techniques. The effect of finite charging time on sinusoidal signals at different frequencies also can be measured using frequency domain or phase IP surveys. The two types of polarization are called "membrane polarization" and "electrode polarization."

Membrane polarization





Charges cannot flow easily, so they accumulate when an electric field is applied.

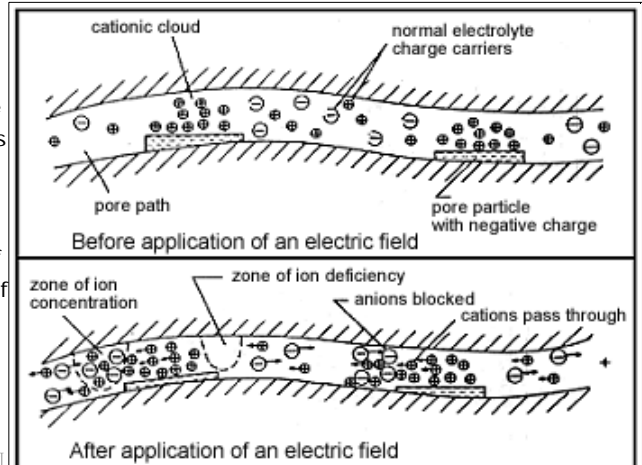


The result is a net charge dipole which adds to any other voltages measured at the surface.

A second form of membrane polarization is similar to the first:

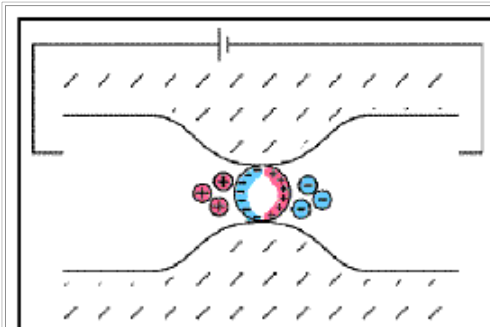
This occurs where clay particles partially block ionic solution paths, as in the adjacent figure. Upon application of an electric potential, positive charge carriers pass easily, while negative carriers accumulate. There is an "ion-selective membrane."

A surplus of both cations and anions occurs at one end of the membrane, while a deficiency occurs at the other end. The reduction of mobility is most obvious at frequencies slower than the diffusion time of ions between adjacent membrane zones; i.e. slower than around 0.1 Hz. Conductivity increases at higher frequencies.

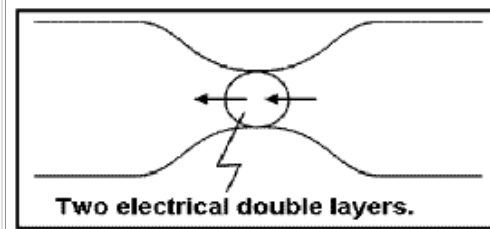


Membrane polarization in rock containing clay particles from S. Ward, 1990

Electrode polarization



Electrode polarization occurs when pore space is blocked by metallic particles. Again, charges accumulate when an electric field is applied.

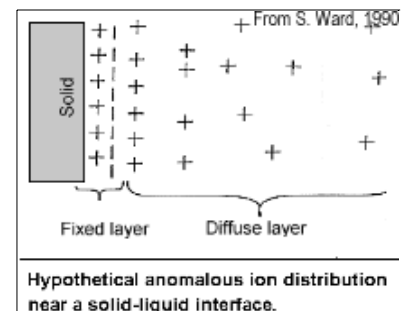


The result is two electrical double layers which add to voltages measured at the surface.

Comments on electrode polarization

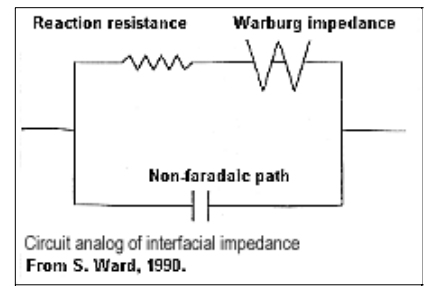
Some remarks are appropriate here in order to provide some sense of the complexity of the chargeability phenomenon.

At an interface between ionic and metallic conduction (for example, an ore grain in pore water), there is an impedance involved in getting current to flow across the barrier. These interfaces look like the top figure and have the simplified circuit analogue shown in the bottom figure. Current can flow via charge transfer (or ion diffusion), which involves electrochemical processes, or via a capacitive effect (no charge transfer), involving diffusion currents.



Hypothetical anomalous ion distribution near a solid-liquid interface.

Ion diffusion is not easy to model with circuit elements. The process is called the Warburg impedance. Its magnitude varies as approximately $1/\text{frequency}$.



Note that, while it is useful to understand simplified models of the relevant electrical behaviour of surface-electrolyte interactions, all rocks are, in fact, "dirty" in the sense that they are not simply pure "electrodes" (semiconducting mineral grains) and electrolytes (pore solutions). There are other materials and particles affecting ionic behaviour within and outside the diffuse layer, and some of the sample's constituents will affect the behaviour of the fixed layer near and on the liquid-solid interfaces.

Summary of what affects the chargeability of material

- Induced polarization is greater when there are larger regions of adsorbed anomalous charge (adjacent to an interface); i.e. when there is a large surface area-to-volume ratio.
- Non-ionic fluids (such as contaminants) can markedly change the behaviour of surface-electrolyte interactions.
- Changes in ion concentration (such as increased salinity) will also affect both types of polarization.
- Both effects (membrane and electrode polarization) are related to grain size as much as material type. Therefore, discrimination of mineral type on the basis of chargeability alone is not recommended.

Typical chargeabilities for materials

The following tables (from Telford et al, 1976) provides a very general guide to possible chargeabilities of materials. One reason that *in-situ* chargeabilities tend to appear lower than laboratory values is that large volumes of mixed materials are involved in field measurements.

These examples show that a wide range of variability can be expected, implying that it is difficult to use values of intrinsic chargeability (in models obtained by inversion of IP data) to determine exactly what type of rock or material is in the ground. However, this is an ongoing topic of research.

Table 1: Charging and integration times were about 1 minute each, which is much longer than field survey systems; therefore, values are larger than field measurements.

Material type	Chargeability (msec.)
20% sulfides	2000 - 3000
8-20% sulfides	1000 - 2000
2-8% sulfides	500 - 1000
volcanic tuffs	300 - 800
sandstone, siltstone	100 - 500
dense volcanic rocks	100 - 500
shale	50 - 100
granite, granodiorite	10 - 50
limestone, dolomite	10 - 20

Table 2: The values below involved more realistic charging and integration times of 3 seconds and 0.02-1.0 seconds respectively.

Material type	Chargeability (msec.)
ground water	0
alluvium	1 - 4
gravels	3 - 9
precambrian volcanics	8 - 20
precambrian gneisses	6 - 30
schists	5 - 20
sandstones	3 - 12

argilites	3 - 10
quartzites	5 - 12

Table 3: Chargeability of minerals at 1% concentration in the samples (charging and integration times as per Table 2 above).

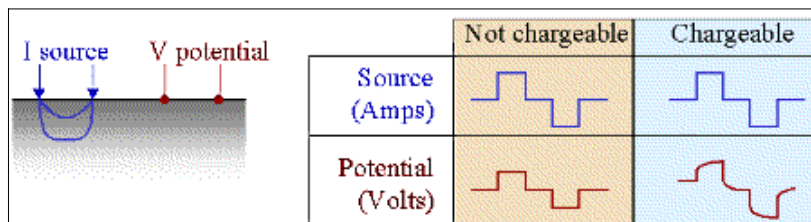
Material type	Chargeability (msec.)
pyrite	13.4
chalcocite	13.2
copper	12.3
graphite	11.2
chalcopyrite	9.4
bornite	6.3
galena	3.7
magnetite	2.2
malachite	0.2
hematite	0.0

Introduction

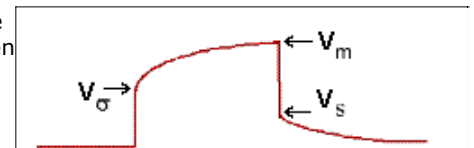
There are four techniques for observing chargeability: two using a charging current that is turned abruptly off so that discharging can be observed in the time domain, and two in which the dispersive nature (or effect as a function of frequency) of the phenomenon is observed in the frequency domain.

Two types of time domain data

Consider the experiment illustrated in the following figure. Current is injected into the ground at the I source electrodes and voltage is measured at the V potential electrodes. The source is DC (direct current) in the sense that when it is on, there is no variation. However, in this case it is turned on and off with a duty cycle as shown in the figure. Two methods of measuring chargeability in the time domain are described below.



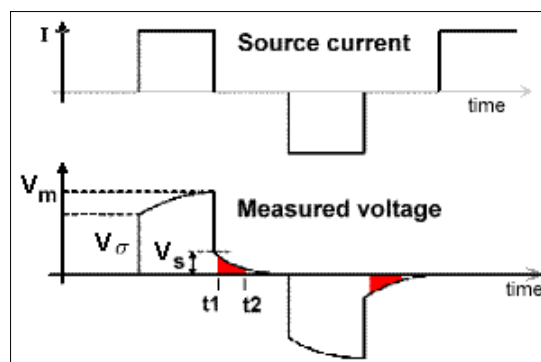
- The following simple definition of chargeability is less commonly employed, since it is impractical to measure. The figure to the right shows voltage measured when the transmitter is first turned on and then turned off some time later. Using parameters from this figure, one definition of chargeability is $M = V_s / V_m$, where V_s and V_m are the maximum and "secondary" potentials, respectively.



- The leading edge potential, V_σ , is what would be measured in the absence of chargeability. This potential would yield the ground's resistivity.
 - The maximum potential is the combined effect of current flowing in the ground and charges built up under the influence of the imposed electric field.
 - The so-called secondary potential is entirely due to the charge imbalance resulting from the build-up of charge.
 - Using this form, chargeability M will be $0 \leq M < 1$. If $M = 0$ the measured potential will follow the input current waveform exactly with no charging or discharging involved, as shown in the first column of the figure above.
- The most commonly measured form of time domain IP is the normalized area under the decay curve. It can be represented by the following equation, using parameters specified in the adjacent figure. The decaying potential that follows V_s is written as $V_s(t)$.

Chargeability M is essentially the red area under the decay curve, normalized by the source voltage.

$$M = \frac{1}{V_m} \int_{t1}^{t2} V_s(t) dt$$

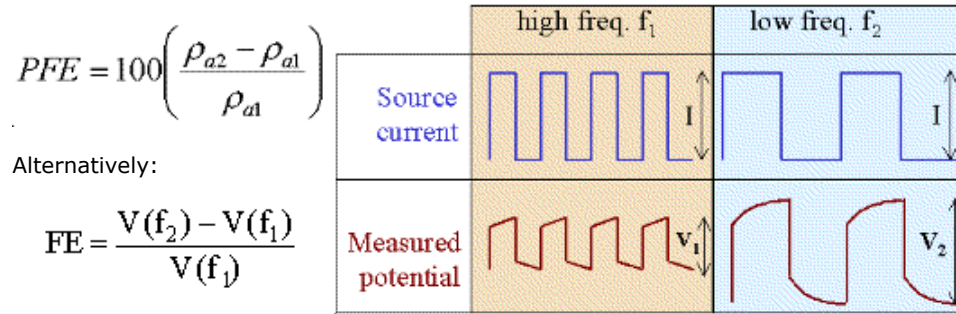


Two types of frequency domain data

An oscillating source current can be employed to observe chargeability. The measurements are often still referred to as "DC resistivity" because the frequencies are relatively low. The resulting data will include (i) a "DC resistivity" based upon the voltages measured with the lowest source frequency, and (ii) a chargeability based upon the measurements explained next. Two methods of measuring chargeability in the frequency domain are described below.

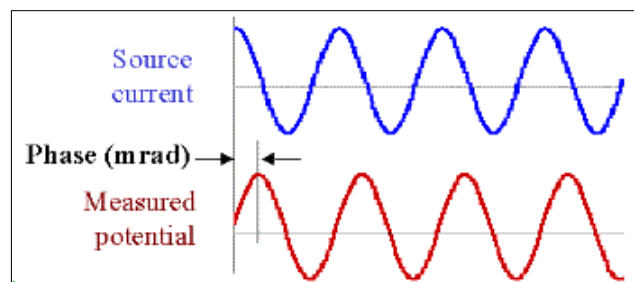
- If potential-signal amplitude is measured at two frequencies, a measure of chargeability is acquired, and be expressed as units of "percent frequency effect" or PFE. Since the ground has less time to respond at higher frequencies, the signal is expected to be smaller. Expressions for PFE are shown in the equations below. The data used in this calculation are

illustrated in the figure below. Recall that $\rho_a = K |V| / I$, where K is the geometric factor based upon electrode geometry (see the Geophysical surveys chapter, "DC resistivity" section), V is the measured potential, and I is the source current.



If the voltage version is used, the *Frequency Effect (FE)* can easily be converted to a *percent frequency effect* by multiplying by 100.

- Data with units of phase are gathered by transmitting a sinusoidal source current. Then the phase difference between this source and measured potentials is recorded as a measure of chargeability. Units are usually milliradians. The following figure illustrates:



Relating the four types of data

The different IP responses all result from the build up of polarizing charges, but they do not produce the same numbers. In fact, the units of the various measurements are different. Nevertheless, the following approximate rule of thumb allows conversion between the different data sets:

A chargeability of $M = 0.1$ is approximately equal to $10PFE$, or $70mrad$, or $70msec$.

Data acquisition

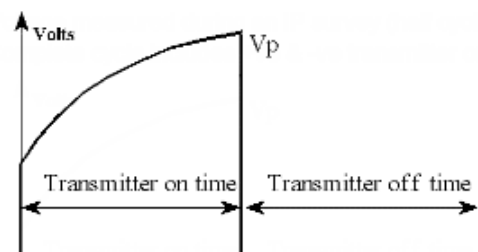
Time domain IP

As noted above, when time domain IP is recorded, chargeability M is measured as the area under the decay curve normalized by "primary" voltage V_p , using $M = \frac{1}{V_p} \int_{t_1}^{t_2} V(t) dt$. The t_1 and t_2 times may be any limits within the off-time, and there are

not really any standards, so comparison of different surveys can be difficult.

Source (input) current is a square wave with 50% duty cycle (equal on and off times) as per resistivity (repeated cycles of +on, off, -on, off). The use of positive and negative cycles in transmitter current is very important for time-domain IP work. The correct area under the decay curve will be measured only if the potential decays exactly to zero. This will not occur when there is a superimposed *spontaneous potential (SP)*, which is usually the case. If only one polarity was used, the inevitable SP could not be detected and removed. Recording both positive and negative cycles allows the "off-time" potential (i.e. voltages recorded when the transmitter is off) to be estimated, and any non-zero component removed.

Many instruments record measured voltage, V_p , just before the transmitter is turned off, and then again 10 times while voltages decay during the off times. The results can then provide a calculated chargeability and an estimated spontaneous potential. The adjacent figure illustrates each measured parameter. Note that if the transmitter is not on for a long enough time, V_p will be measured before the charging time is finished, resulting in a voltage that is smaller than the actual V_p .



Other instruments use alternative time windows, and some newer instruments digitize the whole waveform, but the fundamental concepts are the same for all time domain systems.

Frequency domain IP

The percent frequency effect was defined above as either

$$PFE = 100 \left(\frac{\rho_{a2} - \rho_{a1}}{\rho_{a1}} \right) \text{ or } FE = \frac{V(f_2) - V(f_1)}{V(f_1)}$$

The low frequency can be measured using DC or very low frequency, and the second type of resistivities can be measured at frequencies on the order of a few tens to hundreds of Hertz. In practice, measurements are often made at two or more frequencies, and a PFE is calculated from the results.

Phase IP

When the phase of voltage with respect to input current is measured directly, the impedance of the ground can be determined based on the material. However, this requires careful synchronization between the receiver and the transmitter, and may be difficult on large surveys in rough country.

Metal factor

Metal factor is a parameter given by **PFE** or chargeability, **M**, divided by the corresponding apparent (i.e. measured) resistivity. Plots of this parameter emphasize where both low resistivity and high chargeability exist, or where there are significant occurrences of metallic mineralization (or graphite). However, metallic minerals (such as sulfides) are often disseminated, in which case the ore will more likely have **high** resistivity correlated with high **M**. For this and other reasons, the use of metal factor has declined and it is now rarely used.

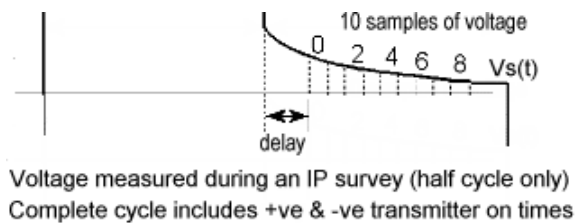
Choice of time, frequency or phase measurements

Here are a few factors affecting whether to choose time domain or frequency domain survey types:

- Time domain methods may provide more information, and will be less susceptible to induction effects (see the appendix on [noise](#)). However, decay curves are often shown in small units, such as millivolts or microvolts, so signal-to-noise ratio can be a problem. Stacking many repeat measurements can help, but this practice is expensive because it requires a longer investment in field time.
- Frequency domain methods require significantly smaller source currents and are less sensitive to most sources of noise. However the effects of EM coupling can be severe, and unless these are removed, frequency domain and phase measurements may contain no usable chargeability information at all. ("EM coupling" is an un-wanted signal which arises from inductive interactions (like a transformer) between conductive near-surface ground and the wires carrying transmitter current. It can completely hide IP effects when it is severe).
- See [Smith, 1980](#), for a comparison of time domain and frequency domain results recorded using three different instruments over the same ore body. Such studies are rare because of the cost, so this is an interesting examination of the pros and cons of various ways of measuring IP.

References

1. Smith, M.J., 1980, *Comparison of induced polarization measurements over the Elura orebody*, The Geophysics of the Elura Orebody, Cobar NSW, ASEG, 1980, 77-80.



Introduction

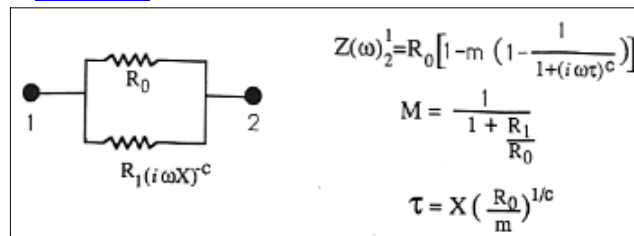
As for other sections of this module on IP surveying, the physical principles of DC resistivity surveying should be understood prior to learning about induced polarization.

Modeling the chargeability phenomenon

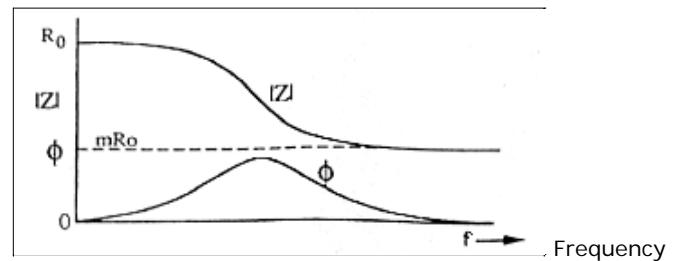
The behaviour of charging and decay curves versus time is logarithmic, not exponential as for a simple parallel resistor-capacitor circuit. Therefore, a more complicated model is required for explaining the induced polarization phenomenon. One model is the circuit shown below (from Ward, 1990). The impedance between points 1 and 2 is complex and is modeled empirically as $Z(\omega)$.

This is known as the Cole-Cole model, and the three parameters in the complex part (m or M , c , & τ) are known as Cole-Cole parameters. M (or m) is chargeability, τ is a time constant (of the decay curve), and c is a parameter controlling the frequency dependence. From several studies, τ appears to depend on rock type, and c tends to be poorly dependent on rock type.

For more discussion, see the page on [spectral IP](#).

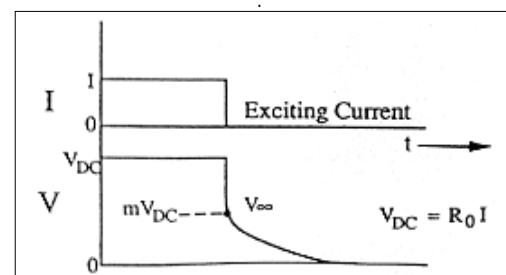


The adjacent figure (top) shows the frequency and phase behaviour of this circuit with its complex impedance. Phase is maximum at the amplitude curve's inflection point.



response, sine-wave excitation

In the time domain, response of this circuit to a transient shut-off is an instantaneous drop from V_{DC} to mV_{DC} , followed by a decay, with time constant determined by the reactive component (bottom panel).



Transient response square-wave excitation.

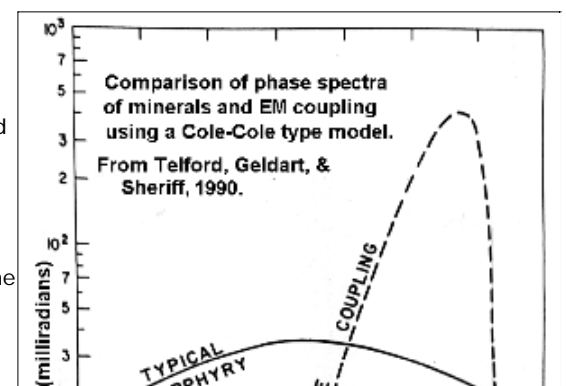
Note that m (different from M in the discussion of [data acquisition](#)) has units of mV per V, i.e. it is unitless. Its value is $0 > m > 1$, and it is one "definition" of chargeability, due to Seigle, 1959.

Inductive coupling

The fact that data are gathered using very high powered time-varying signals that are imposed on wires lying on the ground means there will be electromagnetic effects in the data. Think of it as the receiver seeing two impedances in parallel; one is due to the physical properties in the ground, and the other is due to the coupled system of wires and ground. This effect is most significant over conductive ground.

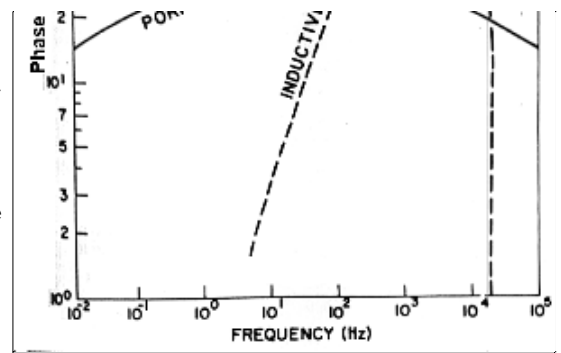
Time domain measurements can try to avoid the effect by recording at later times after the effects of the wiring have decayed, but then signals also become very small.

EM coupling cannot be easily removed from phase and frequency



measurements because the measured effect (PFE or phase) is the sum of the ground's complex resistivity and the EM coupling effect. But these methods are often preferred in conductive ground because they are less susceptible to other types of noise.

There has been plenty of work aimed at separating EM effects (inductive coupling) from true chargeability effects. Much of the work is based on how the Cole-Cole parameters differ for natural and coupling effects; the inductive coupling component of the signal, τ tends to be *small* compared to the geologic response, while the component, c , tends to be large compared to the geologic response. In fact, most researchers model the complete situation as consisting of two Cole-Cole impedances instead of only the one from the ground. For details see the appendix on [spectral IP](#). The system response is written as $Z(\omega) = Z_1(\omega) + Z_2(\omega)$, so there are two versions each of m , τ , and c ; one set for the ground's response, and one set for the inductive response. The figure above from Telford, Geldart and Sheriff, 1990, (figure 9.10) shows an example of the situation.



The effect can be forward modeled if the conductivity structure is known, but this is rarely the case since estimating resistivity structure is one of the goals of the survey. However, if a model of intrinsic resistivities in the earth can be obtained (for example, by rigorous inversion of primary voltage data), that resistivity model can be used to calculate the EM response. Then that response can be subtracted from the chargeability data and the residual inverted for the ground's true IP response. See Routh and Oldenburg, 2001, (referenced below) for details of this approach.

Negative apparent chargeabilities

Occasionally, negative **apparent** chargeability values will be recorded. Note that *intrinsic* chargeability can never be negative, but *apparent* chargeability can be negative. In particular, negative IP measurements will occur on time domain data when the off-time voltage drops below zero before decaying. This effect can be caused by EM coupling on flanks of 3-D targets, and over layered Earth structures of types K ($\rho_1 < \rho_2 > \rho_3$) and Q ($\rho_1 > \rho_2 > \rho_3$).

To understand how negative apparent chargeabilities can occur, think of what a time domain survey records. Secondary voltages (off-time voltages) are usually the same sign as primary (on-time) voltages because current flow during dis-charging (as charges revert to equilibrium) is in the same direction as during charging. If net current flow seen by the potential electrodes is in the opposite direction, the off-time decay curve will look upside down. The result is a negative apparent chargeability. Negative apparent chargeability is also possible in phase data.

2D and 3D chargeable bodies can cause negative effects on account of the combined geometry of discharge currents and electrode arrays.

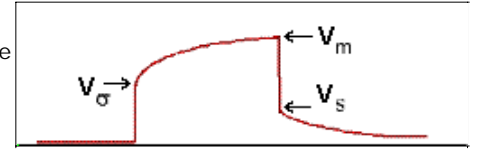
To understand the mechanism with layered media, it is best to refer to Nabighian and Elliot, 1976 (see below). They also list numerous earlier papers that show field examples of negative IP response in the presence of 2D and 3D targets.

References

1. Ward S.H., 1990, "Resistivity and induced polarization methods, in *Geotechnical and Environmental Geophysics*", Published by the Society of Exploration Geophysicists, 1991.
2. Siegel. H.O., 1959, "Mathematical formulation and type curves for induced polarization", *Geophysics*, 38, 49-60.
3. Routh, P.S., and Oldenburg, D.W., 2001, "Electromagnetic coupling in frequency-domain induced polarization: a method for removal", *Geophysical Journal International*, Vol 145, pp 59 - 76.
4. M.N. Nabighian and C.L. Elliot, "Negative induced-polarization effects from layered media", 1976, *Geophysics*, 41, 6A, pg 1236-1255.

Essential equations

We start by considering a theoretical form of time-domain IP data. Recall that if a square current signal is injected into the ground, the potential recorded over chargeable ground will exhibit a delayed response caused by the charging and discharging of the ground. There are three potentials that can be defined on this measured voltage waveform, as shown on the adjacent figure. The theoretical IP datum is defined as the ratio of the secondary voltage measured immediately upon shutting off the current source to the primary voltage measured after the signal has stabilized while the current is still on.



$$d = \frac{\phi_s}{\phi_\eta} = \frac{\phi_\eta - \phi_\sigma}{\phi_\eta} = \frac{F_{DC}[\sigma(1-\eta)] - F_{DC}[\sigma]}{F_{DC}[\sigma(1-\eta)]}$$

The right hand side of this equation is showing that each potential can be found using *aresistivity* forward modeling calculation using the conductivity of the region involved, and that conductivity is modified by chargeability, η . This is based upon the original definition of chargeability suggested by Seigel, 1959.

This equation turns out to be non-linear. It can, however, be approximated as linear for small values of η , which is usually true since in practice $\eta < 0.2$. Therefore, forward modeling of chargeability data can be done using the following formulation:

$$d_i = \sum_{j=1}^M J_{ij} \eta_j ; \quad J_{ij} = -\frac{\partial \ln \phi^i}{\partial \ln \sigma_j}$$

The matrix form for this equation is $\mathbf{J}\boldsymbol{\eta} = \mathbf{d}$, where \mathbf{J} is an $N \times M$ sensitivity matrix (N is the number of data points and M is the number of cells in a rectangular discretization grid), and the J_{ij} are sensitivities for the DC resistivity problem.

Finally, if "small" chargeabilities are assumed, the linear relationship means measured data and chargeabilities recovered by inversion have the same units. Therefore, all four types of IP data can be approximated by $\mathbf{J}\boldsymbol{\eta} = \mathbf{d}$. This means that the common types of IP data (time domain, phase, or PFE) can be employed as input to inversion routines without change.

These points are made in Oldenburg and Li, 1994.

References

1. Siegel. H.O., 1959, "Mathematical formulation and type curves for induced polarization" Geophysics, 38, 49-60.
2. Oldenburg, D.W. and Y. Li, 1994, "Inversion of induced polarization data", Geophysics, 59, pp1327-1341.

Introduction

This page is meant to provide an awareness of spectral IP. It should become evident that chargeability is not a simple phenomenon. Using it for enhancing the ability to discriminate between mineral types is an attractive proposition, but this is far from easy to do.

Definitions

Spectral IP has been a topic of much research because there is a need both to discriminate between different types of rocks, and to remove the EM coupling effect.

There have been several studies suggesting that rock types have distinctive spectral characteristics. They are most often described in terms of how phase response depends on frequency.

The figure to the right shows the phase response as a function of frequency (phase spectra) for typical target rocks (porphyry) and for inductive coupling.

The so called Cole-Cole model for complex impedance is the most often used relation for modeling the ground's impedance. The Cole-Cole model is written as:

$$Z(\omega) = R_0 \left[1 - M \left(1 - \frac{1}{1 + (j\omega\tau)^c} \right) \right]$$

This relation describes a complex impedance as a function of frequency, ω with three parameters. M is chargeability, τ is a time constant (of the decay curve), and c is a parameter controlling the frequency dependence.

- There have been studies showing that $10^{-3} > \tau > 10^4$ and that it does depend on rock type.
- The parameter c tends to range between $0.1 > c > 0.5$ and is poorly dependent on rock type.
- As a comparison, for inductive coupling, τ tends to be $< 10^{-4}$ and c tends to be $0.9 > c > 1.0$.

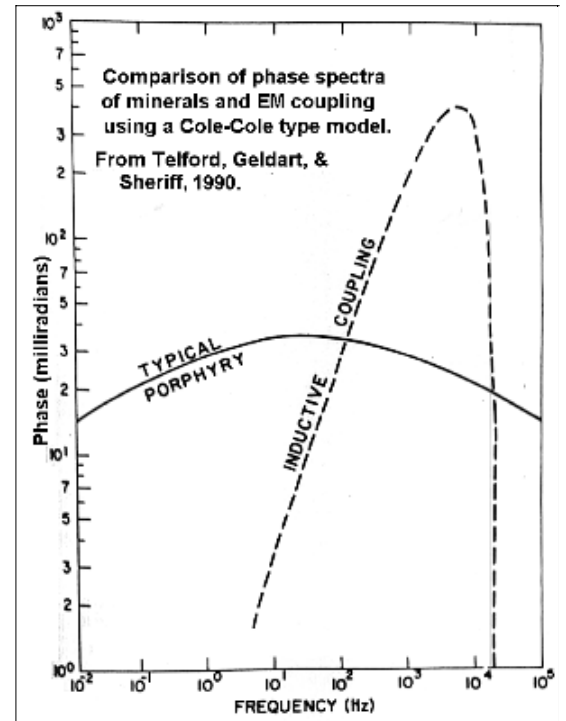
If EM coupling is included, then the impedance relation will look like a combination of two Cole-Cole models:

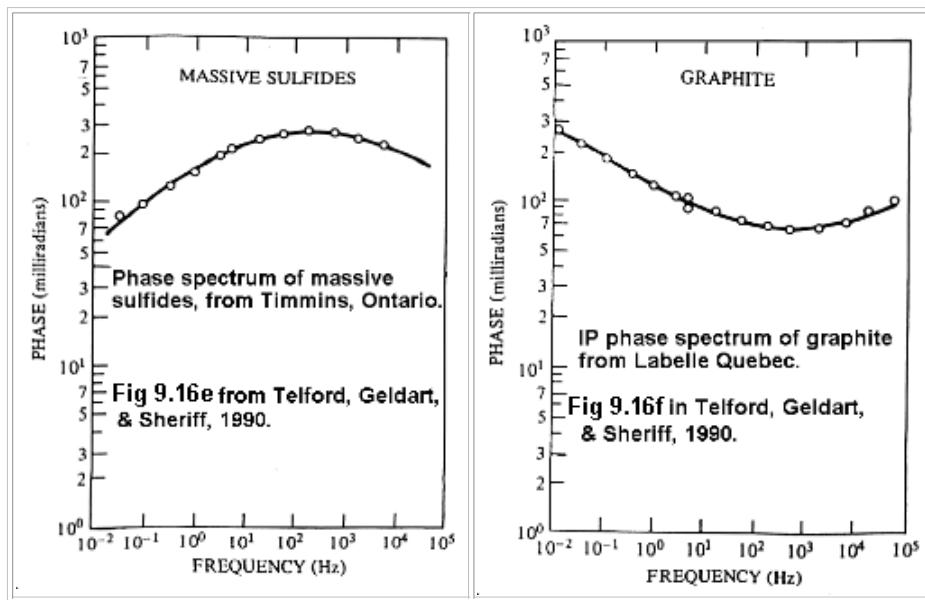
$$Z(\omega) = R_0 \left[1 - M_1 \left(1 - \frac{1}{1 + (j\omega\tau_1)^{c_1}} \right) \right] \times \left[1 - M_2 \left(1 - \frac{1}{1 + (j\omega\tau_2)^{c_2}} \right) \right]$$

as discussed further in [Appendix II: Noise](#).

Attempts to use spectral IP

Below are some examples of phase spectra for two different rock types (from Telford, Geldart and Sherriff, 1990). Data such as these clearly provide some optimism that differentiation between minerals should be possible.



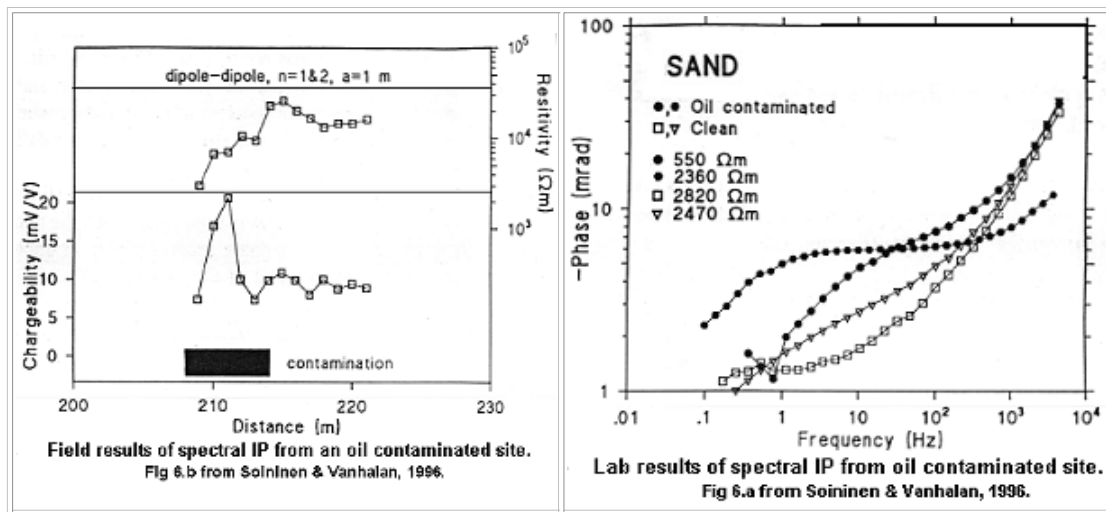


However, there has been rather mixed success at actually differentiating rock types in real field situations. This is perhaps because the causes for variations in phase spectra are not yet well understood. For example, grain size probably has at least as much influence on phase spectra as mineral type. Electrolyte type may also be very influential. Small amounts of clay are likely to have significant effects. None of these aspects is necessarily consistent amongst ore deposits.

The use of phase spectra to remove EM coupling effects has been more successful because there is a significant difference between the spectra of all rocks, and inductive coupling. However, the most successful method of removing EM effects so far appears to be the method of Routh and Oldenburg, which does not depend upon quantifying Cole-Cole parameters for the various contributions to signals.

Yuval and Oldenburg (1997) describe an inversion approach for extracting maps of τ and c from time domain IP data. Their method appears to work but they caution that the problem has not yet been solved. Also, relating these parameters to geology is still a poorly constrained problem.

There have been some studies on use of spectral IP to help detect contamination in various soils, but it is not yet a main-stream technique. The example below is a good lab study from Soininen, H. and Vanhalan, H. (1996). It shows field data over a contaminated site on the left, and results of testing contaminated soil samples in the lab on the right. These data do provide some reason to believe that the technique may be useful, but there have not been many examples of routine use in field situations.



References

1. Routh, P.S., and Oldenburg, D.W., 2001, "Electromagnetic coupling in frequency-domain induced polarization: a method for removal", *Geophysical Journal International*, Vol 145, pp 59 - 7
2. Soininen, H. and Vanhalan, H. (1996), "Mapping oil contamination in glacial sediments by the spectral induced polarization method", Sageep96 1007-10016
3. Yuval and D.W. Oldenburg, 1997, *Computation of Cole-Cole parameters from IP data*, *Geophysics*, 62, 2, 436-448.
4. See also Telford, Geldart, and Sheriff, 1990 "Applied Geophysics, 2nd ed", Cambridge University Press, section 9.5.3.c, pages 598 - 601.

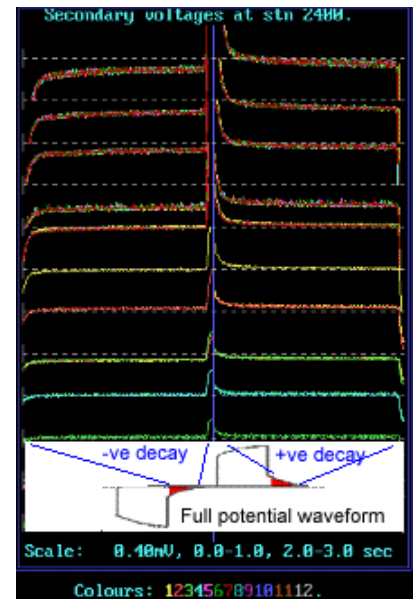
Introduction

IP signals are often noisy because there are many signal sources in the ground that cause potentials that are of similar magnitude and/or frequency as the chargeability effect. Telford, Gledart and Sherriff, 1990 have a good discussion of noise on pages 589 - 591. The discussion below employs figures generated in the field using a full-waveform DC resistivity/IP system. Figures show voltages during transmitter off times only.

Clean data

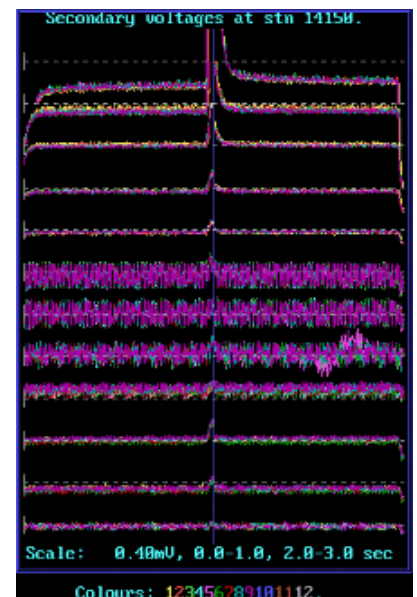
The figure to the right shows "clean" time domain IP signals on 12 potential measurements taken for one current station. Even on "clean" data, some electrical noise or chatter is visible. It is worth gathering multiple measurements and averaging (stacking) in order to reduce this type of random noise.

For this and subsequent figures, the survey involved a pole-dipole configuration with $n = 1$ through 12. Each figure shows 12 decay or discharge signals from both positive and negative transmitter cycles. Signals were gathered using a full waveform digitizing receiver.



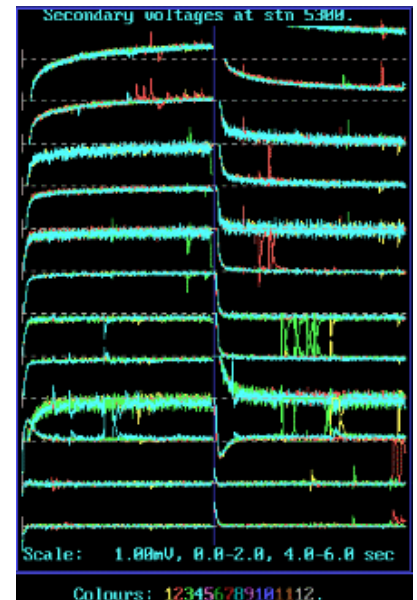
"Cultural" noise

Sometimes power lines are nearby, or there are fences or other sources of current channeling. We refer to signals caused by these and other man-made features as cultural noise. Here is an example using the same format as the first figure. 60Hz is clearly evident at location $n=6$, $n=7$, $n=8$, and $n=9$, which are the 6th, 7th, 8th, and 9th decay signal pairs down from the top.



Spherics

Spherics are spikes caused by nearby and distant lightning strikes. They can usually be filtered out, but this is harder to do in time domain data sets where significant energy can be added to individual decay curves. It is hard to remove from stacked data unless individual stacks with spikes can be identified and removed. This is not a commonly available solution since data are usually stacked in real time and only the results are saved. When viewing the image, note that each **colour** represent different "stacks" or repeat measurement.



Geological "noise"

Small scale effects near the electrodes that overwhelm the more important deeper targets are the most common problem. Other aspects to remember include conductive overburden masking underlying structure, topographic effects, 2D interpretation of 3D geology, current channeling due to cultural features (fences, etc.) and geological lineations (stream beds, buried dykes, etc.), and anisotropy. Some of these effects can be minimized by proper use of inversion techniques, but there will always be limitations with these methods, including limitations on cell size, and use of 2D methods when 3D structures are significant.

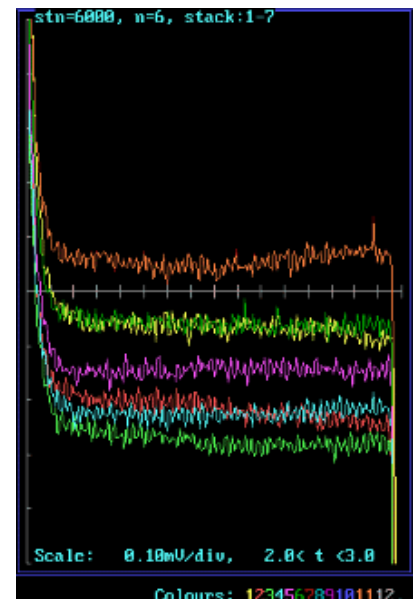
Tellurics

Telluric signals are currents in the ground that are caused by variations in Earth's magnetic field, which in turn are caused by interactions of the solar wind (charged particles) with the ionosphere. Telluric currents tend to vary at frequencies of around 0.1 to 10 Hz, which is exactly the range for time domain IP measurements. These signals can be very large in conductive ground - up to several volts compared to the few millivolts often used to record the apparent induced polarization.

One approach to minimizing the effect is to measure the phenomenon at a distant location (unaffected by transmitter currents) and subtract this reference from data. This assumes that telluric currents are the same over great distances, which may be more or less true at different field sites.

The example here shows seven decay signals (following the positive transmitter pulse) collected within 30 seconds. They should all be identical, but there is serious drift making it look like there is a variable SP (spontaneous potential). In fact, some of the signals are clearly on a drifting trend. Minor 60 Hz noise can also be seen. See the [sidebar](#) for an animated version of this figure.

Frequency and phase measurements are less susceptible to this type of noise, but they suffer from EM coupling.



EM coupling

Inductive or EM coupling is a serious form of noise that is discussed in the section on [measurements and data](#).