Comparison between time- and frequency-domain induced polarisation parameters

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ABSTRACT

Physical properties of rock samples from exploration or mining sites are often needed to assist in the planning of geophysical surveys or in the interpretation of geophysical results. For example, the output from a physical property study may be used in numerical model studies aimed at assessing the applicability or performance of a geophysical technique, or to constrain model parameters during processing and interpretation of field data. Electrical property data are often recorded in the time-domain, yielding resistivity and chargeability values; however, a frequency-domain, or even complex resistivity approach, may also be followed. The latter approach, for example, would produce resistivity magnitude and phase angle outputs. Intuitively, one might expect a one-to-one relationship between time-domain chargeability and frequency-domain phase angle, but despite the fact that this relationship is commonly acknowledged and observed, exceptions are known to occur. These exceptions relate to differences in the spectral IP behaviour of different rock types, and particularly in the case of mineralised rocks that exhibit significant frequency dispersion. In this paper, a comparison of time-domain and frequency-domain measurements on the same samples is presented. It is shown that both the standard time-domain and (single-frequency) frequency-domain approaches could underestimate the polarisable nature of mineralised samples.

It is shown that both the commonly used standard time-domain chargeability parameters and the (single-frequency) complex resistivity phase angle parameter could produce misleading estimates of the polarisable nature of mineralised rocks and of the contrast between different rock types. It is further shown that a multi-frequency (spectral) approach can be used to avoid this pitfall; alternatively, the time-domain parameters, which are

Key words: Physical properties, induced polarisation, spectral IP

INTRODUCTION

Knowledge of the physical properties of rocks from exploration or mining sites is often needed to assist in the planning and/or interpretation of geophysical surveys. For example, physical property information may be used in numerical model studies aimed at assessing the applicability or performance of a geophysical technique, to determine optimum acquisition parameters, or to constrain model parameters during data processing and interpretation.

In electrical and induced polarisation (IP) investigations the physical properties of interest are the direct-current (DC) or steady-state resistivity and some parameter that reflects the polarisation characteristics associated with the termination of the current field. Most modern-day DC/IP surveys are conducted with a low-frequency alternating current waveform, which allows data to be recorded in either the time- or frequency-domain. The latter can be achieved using a complex resistivity approach. In time-domain surveys the IP parameter is generally referred to as 'chargeability' and is derived from the transient voltage decay curve. In the complex resistivity approach the IP information is contained in the phase shift between the source current field and resulting voltage field.

Intuitively, one might expect the time- and frequency-domain IP parameters to be equivalent and that either approach should enable the discrimination between rocks that have different polarisation properties. However, this misconception is a classic pitfall in the application of IP. One of the primary underlying reasons for this pitfall is the spectral behaviour of different rocks – this is particularly true in the case of mineralised rocks where significant frequency dispersions are often observed. In this paper, a comparison of various time- and frequency-domain IP parameters is done through a numerical model study. Results of actual time- and frequency-domain laboratory measurements on mineralised samples are also compared.

SPECTRAL BEHAVIOUR AND THE COLE-COLE MODEL

The electrical properties of many rocks, especially those containing mineralisation, behave according to the well-known Cole-Cole impedance model. The Cole-Cole resistivity is complex, implying a phase shift between the source and recorded fields. The Cole-Cole model is described by four model parameters: the steady-state resistivity ρ, a dimensionless chargeability m, a time constant τ and a frequency dependence c. The dimensionless chargeability m is equivalent to the chargeability as defined by Seigel in 1959 (Kemna, 2000); that is, the ratio of the secondary voltage divided by the primary or steady-state voltage, derived from a voltage decay curve (Figure 1):

$$m = V_s/V_p \tag{1}$$

Higher values of chargeability m would result in a higher polarisability and also a higher phase angle response. The time constant τ relates to the time it takes for the voltage signal to decay; for higher values of τ, the phase angle peak is shifted to lower frequencies. Higher values of the frequency dependence c manifest as more distinct phase angle peaks.

In terms of the petrophysical meaning, the chargeability m is related to the concentration of conductive mineral particles. Differences in m are thus indicative of differences in mineral composition. The time constant τ is related to the spatial scale at which polarization takes place, and typically increases with increasing size of mineralised grains (Kemna, 2000). Differences in τ are thus indicative of differences in mineral texture. The frequency dependence exponent c is related to the distribution of relaxation times, or particle size distribution – larger values of c are associated with more uniform particle size distributions. Differences in c are thus indicative of differences in mineral structure.

'CHARGEABILITY' AND AMBIGUITY OF TIME-DOMAIN IP PARAMETERS

Apart from the dimensionless chargeability m defined in Equation 1, another commonly used time-domain IP parameter is the integral chargeability. Since V_s used to be difficult to measure in practice, the average or integral chargeability M has been used:

$$M = \frac{1}{(t_2 - t_1)V_p} \int_{t_1}^{t_2} V(t)dt \tag{2}$$

The time window t_2-t_1 is subjectively chosen along the voltage decay curve. For example, Newmont-type IP receivers typically use a time window of between 0.45 s and 1.1 s in the case of a 2 s switch-off time.

Duckworth and Calvert (1995) demonstrated the ambiguous nature of the time-domain chargeability parameters. They pointed out that rocks that have strong polarisation characteristics could exhibit misleadingly low integral chargeability (M) values, as the latter depends on the value of the Cole-Cole time constant. This effectively implies that two rocks may show a contrast in either m or M, but not necessarily in the other. This ambiguity is complicated by the fact that the time constant value for rocks can vary over a range of several orders of magnitude.

Note that there is also some degree of ambiguity when it comes to IP related terminology. The term 'chargeability' is often used to describe both the dimensionless (Seigel) chargeability m and the integral chargeability M. Furthermore, 'chargeability' is sometimes expressed in units of mV/V or as a percentage when using the Seigel definition; when using the integral definition, chargeability can be expressed as either a ratio or in milliseconds. In the latter case, Equation 2 is not normalised by the length of the integration time window.

MODEL STUDY: METHOD AND RESULTS

A synthetic modelling investigation aimed at highlighting some of the ambiguities and pitfalls associated with IP parameter analyses was conducted. Various Cole-Cole models, representing different rock types, were defined and the associated spectral response for each model was determined. The calculations were performed using the commercial software package, *EMIGMA* (Habashy et al., 1003; Groom & Alvarez, 2002). The spectral data was calculated for a total of 56 frequencies ranging from 3 mHz to 185 Hz. These spectral data sets were then transformed to time-domain responses. For the transformation, a generalised square current waveform was assumed, which is typically used by

equipment manufacturers such as Geonics and Zonge (Figure 2). A base frequency of 0.125 Hz and a short linear ramp of 1 millisecond were specified, resulting in a near-square wave duty cycle with a period of 8 seconds and a 2 second off-time per half cycle. The output time series was determined from time zero to 1950 milliseconds with at least three measurements in the very early time to define the rapid drop-off of the primary voltage and a 20 millisecond interval thereafter to accurately define the decaying portion of the curve. In order to simulate a realistic field scenario the survey geometry assumed for the time-domain transformation involved a fixed current dipole of 6 m length on the surface of the earth and a 6 m voltage dipole, with the dipole midpoints separated by 15 m. This equates to a dipole-dipole measurement associated with a dipole spacing of 1.5 dipole lengths. The respective spectral outputs were then be used to compare different IP parameters, using the definitions of chargeability as defined earlier.

Sample:	BLUE	GREEN	ORANGE
m	0.282	0.327	0.174
IP percent (IP%)	28.2	32.7	17.4
M (Newmont)	0.024	0.125	0.04
M (Newmont) in msec	15.3	81.1	25.7
Phase (mrad) @0.125 Hz	-30.7	-92.3	-28.3
Phase (mrad) @ 1 Hz	-90.5	-55.6	-27.5

Table 1: Comparison of IP parameters for the three Cole-Cole models.

DISCUSSION OF RESULTS

The spectral plot of the three samples (Figure 3) immediately reveals a potential pitfall: if the polarisation characteristics of the samples were to be evaluated at a single frequency, the result would depend on the selected frequency. For example, if the evaluation is done at 0.125 Hz, the contrast between the GREEN sample and the ORANGE sample is approximately 3:1, but the BLUE and ORANGE samples have almost identical phase responses. At a frequency, approximately 1 decade higher, the BLUE sample would have a 3:1 phase angle contrast with the ORANGE sample, while the GREEN and ORANGE samples would have nearly no contrast. Discrimination between the BLUE and GREEN samples is even more critically dependent on selecting the appropriate frequency as the relative contrast of 3:1 effectively changes polarity within approximately a single decade of frequencies.

The differences in the time-domain curves can also be seen in Figure 1 and is quantified by the various derived parameters given in Table 1. The dimensionless chargeability m (and IP percent) values suggest a low contrast of approximately 2:1 between both the BLUE and GREEN sample and the ORANGE sample; it also indicates that there is almost no contrast between the BLUE and GREEN samples. The integral chargeability M does, however, reveal a contrast of more than 5:1 between the GREEN and BLUE samples, and of approximately 3:1 between the GREEN and ORANGE samples. Note that, in contrast to the dimensionless chargeability results, the integral chargeability values indicate that the ORANGE sample is slightly more polarisable than the BLUE sample. When comparing with the spectral results it is clear that the integral chargeability underestimates the polarisable nature of the BLUE sample. It can also be seen from Table 1 that by using different integration limits (here later in time) the underestimation of the BLUE sample's polarisability is

Finally, a comparison of actual laboratory measurements is shown in Figure 4. The original data sets were in the form of a Seigel-type IP percent values and spectral complex resistivity data. For the purpose of comparison, data was extracted for approximately the same signal base frequency (~0.05 Hz) and also for similar source current levels of approximately 1-5 μA. Here, the time-domain (TD) and frequency-domain (FD) data has been normalised to enable plotting on the same graph. The correlation between the FD and TD results is generally good, but notable exceptions occur for three mineralised samples A4-A6. For these samples the FD normalised parameter is between five and seven times greater than the TD parameter, while for most other samples a near 1:1 relationship is evident. The samples that show this discrepancy are also the samples that showed the most prominent dispersive behaviour. Even though the time-

domain parameter does show the contrast between the three most polarisable samples and the other samples in the batch, the contrast that can be exploited is underestimated.

CONCLUSIONS

Comparison of the IP properties of rocks, or the exploitation of these properties for the purpose of geophysical discrimination should be conducted with caution. Reliance on a specific time-domain parameter or on a single frequency measurement may result in misleading comparisons or even the selection of sub-optimum field parameters when the objective is to discriminate between specific rock types.

A spectral analysis is recommended and if this is not possible it is recommended to derive different time-domain parameters for the purpose of better comparisons.

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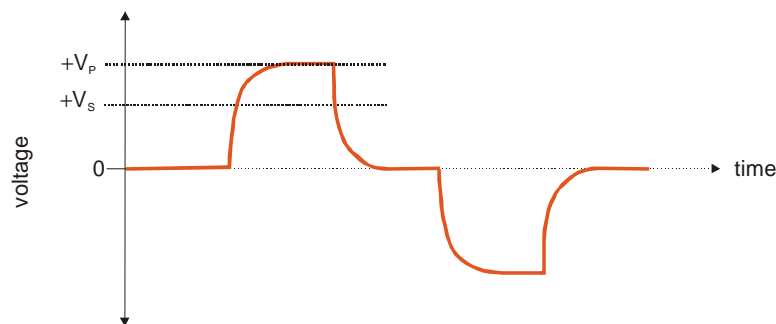
FIGURES

Figure 1: Typical DC current source and corresponding earth voltage response.
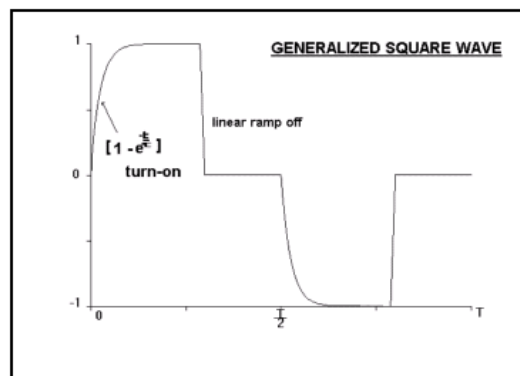
Figure 2: A generalised square current waveform was used in the frequency- to time-domain transformation. A short linear ramp of 1 ms and a base frequency of 0.125 Hz was used.
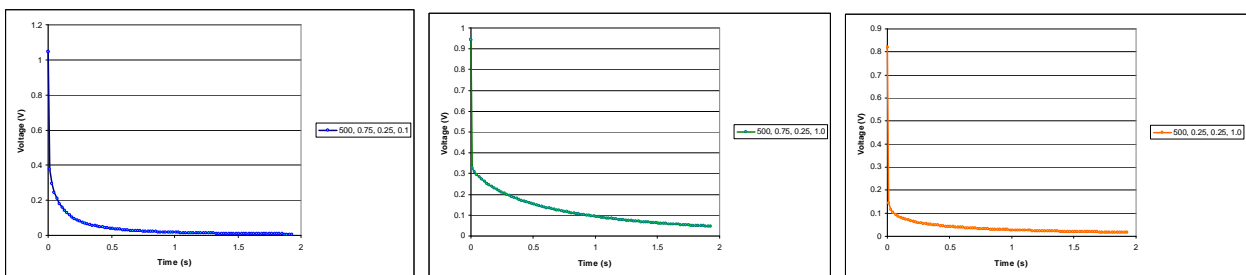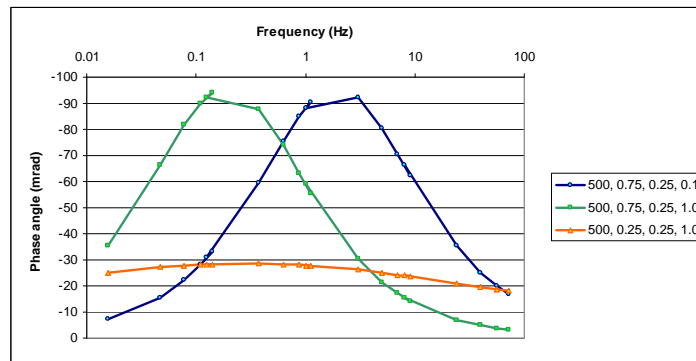

Figure 3: Spectral (top) and equivalent time-domain plots for three different Cole-Cole models. The values in the legend for each curve are for ρ, c, m and τ, respectively.
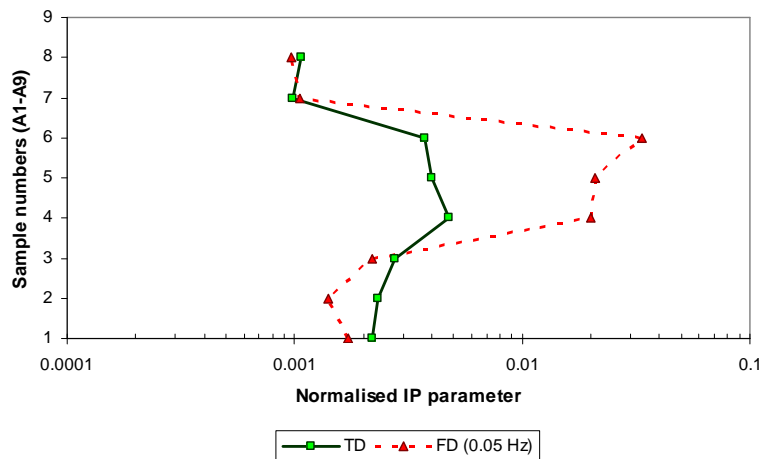

Figure 4: Comparison of time-domain (TD) and frequency-domain (FD) laboratory measurements on actual samples.