Induced polarization chargeability calibration standards

John E. E. Kingman
Terrigena
Denver, Colorado, USA
john.kingman@terrigena.com

Terry J. Ritchie
Geophysical Resources & Services
Brisbane, QLD, Australia
tjritchie@consultgrs.com.au

Peter Rowston*
Geophysical Resources & Services
Brisbane, QLD, Australia
parowston@consultgrs.com.au

SUMMARY

Standard practices in scaling time-domain induced polarization (IP) chargeability estimates are frequently inconsistent or poorly supported. Antiquated M_{331} units (milliseconds) and scaling standards in particular, represent: a) ill-informed assumptions, b) conflicting scaling standards and c) a lack of adequate flexibility in time-gate start-time choices for mitigating inductive (EM) coupling.

Improvements are recommended that would ensure practitioners and the exploration geophysics industry in general, employ sound and consistent chargeability scaling or calibration practices.

Key words: induced polarization, IP, chargeability, M331

INTRODUCTION

Frequency-domain chargeability scaling standards in terms of phase are consistent and understandable[1]. This is not the case in the time-domain where multiple conflicting practices exist. In order to extrapolate a secondary signal level for a specific time gate used in practice, to a different time gate used as a theoretical standard, it becomes axiomatic that a standard response spectral character be employed. Without such, one cannot extrapolate what one time gate result implies as to the expected result for a different time gate with different start and stop times.

As an example, consider the often employed and referenced Newmont M_{331} standard. That standard reflects a half-duty square-wave response with 3-second pulse lengths and a one second off-time/decay integration time. It is seldom, if ever, mentioned what the start time associated with that 1s time gate is nor what the assumed spectral character is. In fact, as indicated in the decay plots and electrical network model shown in Dolan (Dolan 1967), the M_{331} standard reflects a very early start time (≤ 0.01 seconds) and a spectral character that suggests a spectrally atypical Cole-Cole frequency dependence (Pelton, 1978) that is less than 0.05. The Cole-Cole equation is:

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

[1] The tangent of phase carries a more direct relationship with time-domain chargeability standards.

… where c is the frequency dependence, m is the theoretical chargeability ($V \cdot V^{-1}$) and τ is the time constant in seconds.

The often-employed 1.87 scaling factor to convert a 0.125Hz (T = 8s) half-duty, 0.45s to 1.1s off-time averaged time gate voltage to the M_{331} standard is fairly accurate and only changes by roughly ±10 percent with varying but reasonable changes in assumed spectral character. However, the use of a short time-gate in the middle of the off-time decay is ill-advised. Even for relatively fast but otherwise reasonable IP decays, the level at the end of the 2s decay is not much smaller than at 1.1s.
Half-duty off-time time-gates should, in general, span from when inductive (EM) coupling can safely be ignored until very close to the end of the off time, depending on the width of any imposed smoothing or low-pass filtering. This allows considerably more robust filtering or random and periodic noise, given a carefully designed and tapered time-gate weighting scheme.

In summary:

- At this stage, some 60 years after the M_{331} standard was first established, M_{331} is a rather ad hoc and poorly supported standard. It should be abandoned for one or more better-considered standards.
- A carefully designed calibration methodology is needed that accommodates a wide range of inductive coupling persistence, time-gate specifications/designs, excitation base frequencies and waveforms, etc.

While an industry wide approved and accepted IP calibration standard might be a step forward, the more important concern is that standards reflecting differing preferences (between disciplines, companies or individuals) be adequately specified so that one standard can be accurately and confidently converted/scaled to another.

TIME-DOMAIN CHARGEABILITY CALIBRATION

To allow quantitative comparisons of measured and inverted chargeabilities across different surveys and processing specifications, we must be able to adjust or calibrate for differing time-gates, base frequencies and linear distortion (e.g. receiver and/or applied digital filtering). This cannot be done reasonably without:

a) specifying or establishing a preferred or well-supported *standard* response spectral character, …

b) considering both field-measured and spectral-standard responses in terms of their two fundamental components - primary and secondary signals and …

c) understanding and incorporating knowledge of the imposed system linear distortion.

In the context of this paper, IP primary and secondary signals connote substantially different meanings than in the context of induction (EM) geophysical methods. For galvanic physics the primary signal is that which is entirely in-phase and frequency independent; i.e. a scaled image of the current (amps) excitation signal. The secondary signal, that reflecting the IP phenomenon or behaviour, is then the difference of the measured response minus the primary signal component. This is illustrated in Figure 1 in terms of a theoretical Cole-Cole time-domain response to a half-duty square excitation waveform.
When calculating time-domain IP responses from a frequency-domain expression it is important to understand that IP responses to periodic waveforms are substantially different from the step-function responses (whether turn-on or turn-off) owing to the slowness of the spectrally reasonable relaxation phenomenon. It is also imperative that, if Gibbs-like ringing at the excitation switching edges are to be removed or mitigated, a degree of zero-phase (symmetric with an odd number of filter taps) smoothing be applied as a moving average or FIR digital filter. Filters with multiple gain zeros (notches) at the sampling Nyquist frequency serve best in this regard. For example: [1,4,6,4,1]/16.

As an entry example of a calibration standard and process, consider Figures 1 and 2. Figure 1 illustrates a theoretical response in terms of its primary and secondary signal components. Figure 2 portrays a hypothetical measured or real response curve. The on-time time-gate is typically fixed/locked with commercial non-time-series systems. The off-time usually carries greater time-gate flexibility and shown is a start-time of 0.75s after turn-off to just before the negative-polarity turn on. The “standard” decay time gate, as shown by the grey area in Figure 1, is the full average under the entire decay. The on-time “gate” is actually a single point since the primary signal is uniform throughout the 2s quarter period. Calibrating the measured results to those standards proceeds as follows:

1) Specify the start and stop times associated with the on-time and off-time time-gates employed with the field data (Figure 2). The associated measurement voltages are, respectively:

   M^{m1} and M^{m2} (V·A^{-1}).

2) Specify a “standard” theoretical IP response (generally spectrally typical) and associated “standard” off-time time gate window (e.g. from the beginning to the end of the off-time), breaking that response into the primary and secondary response components (Figure 1). Normalize to ensure the primary signal amplitude is 1.0 V·A^{-1}. For example, if using a spectrally typical Cole-Cole model set R_0 = 1.0. Calculate the associated time-gate averaged secondary signal voltages at the specified “standard” time-gates: V_s^{s1} (on-time) and V_s^{s2} (off-time). Note that the on-time primary signal is 1.0 and the off-time 0.0, of course. Also, the standard on-time time-gate may as well be a single-sample point, providing it is sufficiently displaced from the smoothing filter effects near the switching edge.

3) Calculate the averaged theoretical or standard-model secondary signals at the specified measurement on-time and off-time time-gates: -

   V_s^{m1} and V_s^{m2} respectively (V·A^{-1}).

4) Calculate the calibrated and normalized (V·A^{-1}) primary and secondary signals, respectively, as follows:

$$u_p = M^{m1} - \left(\frac{M^{m2}}{V_s^{m2}}\right)V_s^{s1}$$

$$u_s = \left(\frac{M^{m2}}{V_s^{m2}}\right)V_s^{s2}$$

In the specific circumstances suggested by Figure 2, the calibrated primary and secondary signals are 100.0 and 3.293 mV·A^{-1} respectively. The calibrated secondary signal is x2.0413 larger than the measured level. The calibrated chargeability is then 32.92 mV·V^{-1}.

Alternative theoretical models, such as Debye (Weigand, 2016), Drake (Van Voorhis, 1973), Halverson (Halverson, 1981), general effective-medium (Zhdanov, 2008) or Wong (Wong, 1979), certainly might be employed. As long as the model and related standards are specified, it will generally be unambiguous to scale from one standard to another.

The Cole-Cole model, a strictly empirical equation, is known to fit high-quality measured data in field surveys quite well. However, it carries an implication as to the IP phenomenon that is considered, by many, to be flawed. Consider an isolated chargeable particle such as a sulphide grain with a bounding electrolyte or complex-valued surface impedance film. When a uniform electric field is imposed encompassing the particle, charge begins to accumulate at the particle surface and to separate within the particle. According to many experiments, with sufficient time the charge build-up eventually renders the grain to effectively be a complete insulator and the net electric field and current flow warps around the charged particle. By most accounts, with a sufficiently long turn-on step or sufficiently low base frequency, sulphide grains change from being conductors at early times to resistors at late times rendering the effective bulk media resistivity to increase owing to the presence of disseminated sulphide grains. The net impact is illustrated in Figure 3.

The Cole-Cole model, to the contrary, implies a bulk resistivity change from being more conductive at early times (or higher frequencies) to being inert at late times (or lower frequencies). This leads to the Cole-Cole secondary signal showing a stronger on-time impact than in the Halverson model at high base frequencies, and vice versa at low base frequencies. It also explains the somewhat peculiar strong secondary signal negative offset during the on-time seen in Figure 1. The ultimate implication is that the calibration of primary versus secondary signal scales will differ when using the empirically-based Cole-Cole standard as opposed to formulae based on a physical model such as the Halverson model.

ALTERNATIVE WAVEFORMS

In the previous example, secondary signal estimation is based strictly on the off times of half-duty square waveforms. However, given full-waveform time-series data, one may wish to employ both the on and off times of the half-duty response in estimating and calibrating primary and secondary signal estimates. The rising curvature in on time responses is similar but not identical to the off-time decay curvature but still owing strictly to the presence of IP effects or secondary signal.

Improvements from employing both on-time and off-time portions of half-duty responses include better signal-to-noise and (potentially) EM-coupling rejection. Note the implication of stronger secondary signal amplitude during the on-time as compared with the off-time seen in Figure 1. This is a consistent character reflecting the slowness of spectrally typical IP step-function responses. While the on-time pulses in a half-duty waveform reflect the sum of adjacent turn-on step function responses, the off-times reflect the sum of opposing polarity adjacent step responses … thus in effect cancelling a portion of the secondary signal, again owing to how slow the step-function responses are.

Considering two matching on and off time-gates spaning from a specified start time (t0) after the preceding switch, to the end of the quarter period (a well advised practice), one can estimate the normalized amplitudes of the primary and secondary fields by posing the measured curves in the two time-gates as the weighted sum of those secondary and primary theoretical signals as suggested by Figure 1.

Using a virtually identical approach, one can also estimate primary and secondary signal levels for full-duty waveforms by fitting the measured data, for a specified time-gate window, to a weighted sum of spectrally typical theoretical primary and secondary signals. Note that a half-duty decay equates to one-half the difference of the second half of a full-duty half-period minus the first half of the full-duty half-period response. Linearity implies so. Hence, the half-duty response information is present in the full-duty response and its related rise-time curvature … it just may not be obvious to the eye. Bear in mind that, as a practical matter, current excitation waveforms are never as perfectly flat during the on-time as is needed for such full-duty based response estimations. Hence, it is required that one measures the excitation current in terms of high-fidelity time-series and subsequently transforms the directly measured responses to the implied ideal-excitation waveform responses.

When considering the options of employing both on and off times in half-duty waveforms, alternative waveforms and time-gates as well as base frequencies, what might be an amenable standard for estimating and calibrating primary and secondary signal estimates? Within the digital signal processing discipline is the concept of signal energy, which entails summing the squares of a series of samples. For a periodic function the square root of the signal energy spanning one period is directly proportional to the standard deviation of the signal spanning an integer number of periods, which is also proportional to the square root of the integral of the power spectra. Hence, from a discipline that the geophysical community relies heavily on, comes a concept that can serve as an elegant approach to calibrating primary and secondary signal response components for any waveform and base frequency. A generalized procedure is as follows, under the assumption of a nominally periodic and polarity-symmetric current excitation waveform:

1) Measure both the electric field (or dipole voltage) and excitation current signals as time-series with equal fidelity. Using tapered odd-harmonic stacking and other robust response estimation algorithms, transform the measured data to a half-period response estimate for an ideal excitation waveform of interest (e.g. full-duty whereby the excitation current was perfectly flat between switching).

2) Specify which segment(s) of the half-period response estimate will be employed in estimating the measured primary and secondary signal levels.

3) Choose a theoretical IP model and calculate the primary and secondary signal response components for the ideal excitation waveform of interest (employed in step 1). For a full-period of the theoretical model, calculate the standard deviations of the primary and secondary responses and well as that of the presumed ideal excitation current: σV_p, σV_s, σX

4) For the specified response segment(s), fit the measured data as a weighted sum of the theoretical primary and secondary response components. Assume those weights are aV_p and aV_s. The calibrated primary and secondary normalized signals ($V \cdot A^{-1}$) are, in order:

$$u_p = \frac{\left(aV_p\right)\left(\sigma V_p\right)}{\sigma X}, u_s = \frac{\left(aV_s\right)\left(\sigma V_s\right)}{\sigma X}$$

It is inevitable that secondary signal amplitude estimates (and to a lesser degree, primary signal estimates) can be misleading depending on the true response spectral character and the measurement base frequency. This is true for both standard decay amplitude, frequency domain and the proposed signal energy approaches. True Heaviside step-function IP responses are generally much slower than practitioners may realize and the impact on responses to periodic waveforms is not obvious. It is a topic and concern that carries a fair bit of complexity as to the interrelationship between response spectral character and measurement base frequency. It is a subject that merits careful study but is beyond the scope of this presentation.

CONCLUSIONS

Sound practices in calibrating induced polarization (IP)secondary signal and chargeability estimates are needed. The often sited and employed M_{331} standard is antiquated, poorly documented and should be abandoned in lieu of improved and properly documented approaches. The notion of signal energy in periodic waveforms forms an elegant standard and approach to consistently calibrating grounded-line responses regardless of waveform, base frequency and time-gate specifications. Carefully chosen theoretical IP response models and familiarity with spectrally typical response character are essential to the approach.

Inevitably, secondary signal and chargeability scaling is subject to errors or bias related to the interrelationship of the response spectral character and the measurement base frequency. This concern merits further study.

ACKNOWLEDGEMENTS

The authors are indebted to the insights and wisdom of Mark Halverson and E.O. (Mac) McAlister who, at a nascent stage in the development of induced polarization technology, recognized the importance of:

- measuring excitation current as time-series with equal fidelity to that in measuring dipole voltages
- establishing calibration standards allowing quantitative comparisons of chargeability amplitudes for varying base frequencies and levels of electromagnetic coupling.

REFERENCES

Dolan,W.M., 1967, Considerations Concerning Measurement Standards and Design of Pulsed I.P. Equipment, Symposium on Induced Electrical Polarization, U. California, Berkeley

Halverson, M.O., Zinn, W.G., et al., 1981, Assessment of Results of Broad-Band Spectral IP Field Tests, Advances in Induced Polarization and Complex Resistivity, U. of Arizona

Kingman, John, 1998, Geophysical Resources & Services Pty. Ltd. Short Note 129: M.I.M. Chargeability Standard

Pelton, W.H., Ward, S.H., et al., 1978, Mineral Discrimination and Removal of Inductive Coupling With Multifrequency IP, Geophysics, 48

Swift, C.M., 1973, The L/M Parameter of Time-Domain IP Measurements - A Computational Analysis, Geophysics, 38

Van Voorhis, G.D., 1973, Complex Resistivity Spectra of Porphyry Copper Mineralization, Geophysics, 38

Weigand, M.,Kemna,A., 2016, Debye decomposition of time-lapse spectral induced polarisation data, Computers & Geosciences, 86

Wong, J., 1979, An electrochemical model of the induced-polarization phenomeno in disseminated sulfide ores, Geophysics, 44

Zhdanov, M, 2008, Generalized effective-medium theory of induced polarization, Geophysics, 73

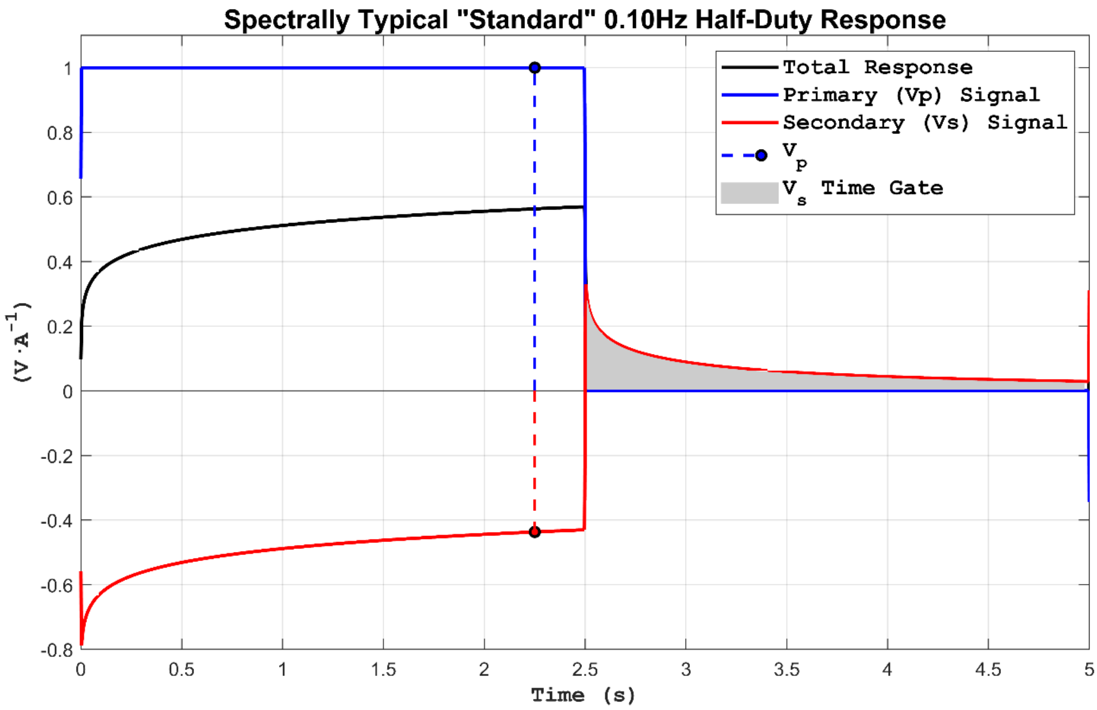

Figure 1. Primary and secondary signals comprising a total response are illustrated in terms of a spectrally typical Cole-Cole theoretical model (τ = 1.0, c = 0.225). The total response (black curve) during the off-time or decay is masked by the secondary response curve as, during the off-time, the two are identical.

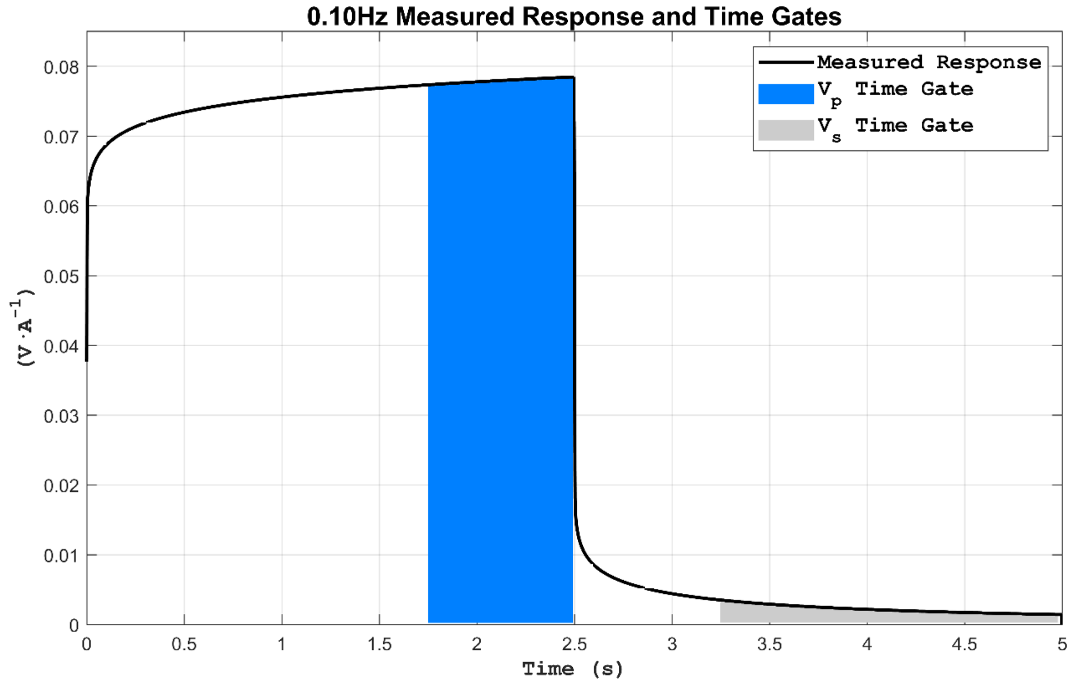

Figure 2. A hypothetical measured response is shown, along with hypothetical time gates employed to estimate, as a time-gate average, primary (V_p) and secondary (V_s) signals.

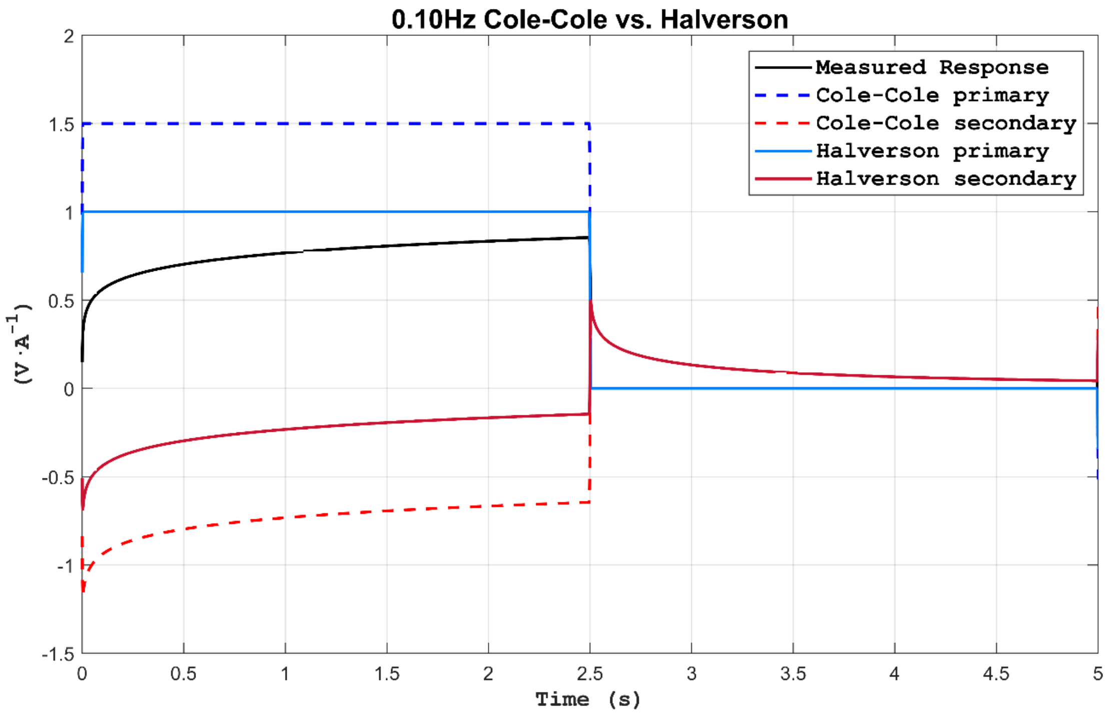

Figure 3. Cole-Cole and Halverson IP models sharing identical responses are compared in terms of their secondary and primary signal components. The impact of the assumed physics (or electrochemistry) of the chargeable particles in the Halverson model becoming resistive at sufficiently low frequencies leads to a real-valued scaling factor related to the volume loading (volume particles over total volume) of the chargeable particles. For the Cole-Cole equation to yield identical results to the Halverson model it must be multiplied by $3/(3\text{-}m_0)$, where m_0 is the Cole-Cole chargeability parameter.