The Transient Phase Method for Classifying Super Conductors in HTEM Profiles

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ABSTRACT

A method for identifying super conductor responses in helicopter time domain electromagnetic (HTEM) profiles has been developed in a manner analogous to the calculated phase in frequency domain electromagnetic (EM) systems. For a given transient of amplitude versus time, the transient phase treats the sum of the off-time profiles as the quadrature response and the sum of the on-time profiles as the in-phase response. High conductance sources exhibit little to no measurable decay during the transmitter off-time and these responses are better represented as a ratio of the quadrature to in-phase response. As conductance increases, the on-time response amplitude exceeds the off-time response. This ratio approaches "zero" as the quadrature response approaches zero and the in-phase response approaches its maximum. A series of examples from conductor responses ranging from 1.8 μs to 10,800 μs is shown, comparing the off-time and on-time profiles and the calculated transient phase for base frequencies of 150, 90 and 30 Hz. It is shown that for conductor responses having a time constant longer than the sampled off-time, on-time measurements and transient phase estimates are better indicators of high conductance than lower base frequency off-time alone.

INTRODUCTION

Helicopter time domain electromagnetic (HTEM) systems have emerged as the airborne system of choice in mineral exploration. The combination of high dipole moment for depth penetration and excellent lateral resolution for development of direct-drill targets makes these systems an excellent choice for grass-roots exploration where targets can be generated in a few months without the need for line cutting and follow up ground geophysical surveys.

An important aspect of HTEM systems is in estimating target conductance (conductivity times thickness) as such estimates offer insight into the composition of the source. For example, nickel and copper sulphide deposits are rich in pyrrhotite, a mineral that is highly conductive. Therefore, high conductance anomalies are more likely to contain pyrrhotite and could contain economic concentrations of nickel and copper (Balch et al, 2010). Kimberlite pipes containing diamonds, however, have lower conductance, can produce negative transients and may or may not have an associated magnetic response (Boyko et al, 2002).

HTEM systems cannot measure conductance directly as this property is dependent on the size of the conductor which is generally unknown. Instead, conductance is estimated indirectly by calculation of the time constant Tau defined as:

$$Tau_i = \frac{t_{i+k} - t_i}{ln\frac{A_i}{A_{i+k}}}$$

where t_i and t_{i+k} are the time channels and the i^{th} and k^{th} samples and A_i and A_{i+k} are the respective amplitudes of H_S (see for example, Huang and Rudd, 2006).

The Tau calculation can be performed independently from off-time profiles (dB/dt), on-time profiles, or B-field profiles. For low conductance targets, the off-time response is greater than the on-time response. As conductance increases, the on-time response increases relative to the off-time response. For high conductance targets, the on-time response will be much greater than the off-time response, even at low base frequencies.

This paper defines an alternative method for estimating the conductance of highly conductive sources, based on the ratio of the off-time to the on-time responses.

METHOD

Consider a typical HTEM consisting of a pulsed transmitter waveform and having an on-time duty cycle of 35% and an off-time lasting the remaining 65% of the half cycle. The HTEM system can record the full waveform (on-time and off-time) but the primary field during the on-time cannot be accurately measured do to small distortions of the HTEM airframe while in motion which changes the bucking voltage during the transmitter on-time and produces voltages that far exceed the on-time secondary field.

For a pulsed current waveform, integration of the on-time provides a method of estimating the secondary field (Smith and Balch, 2000), which can be summarized as:

$$\int_0^n H^P = 0$$

and

$$\frac{1}{n}\int_0^n H_{ON}^S = -avgH_{ON}^S$$

where n is the number of samples during the transmitter on-time, H^P is the primary field and H^S is the on-time secondary field.

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In a similar manner, the average off-time secondary field can be estimated as follows:

$$\frac{1}{N-n+1}\int_{n+1}^{N} H_{OFF}^{S} = +avgH_{OFF}^{S}$$

where N is the total number of sample points during the half cycle.

Plotting of the average value of the secondary field on-time and off-time response is a robust way of visually estimating the conductance of targets because the average is a better estimate of the secondary field than any one channel and comparison between the on-time and off-time amplitudes is a better way to identify high conductance targets compared to conductance estimates derived from dB/dt and B-field profiles.

For a more quantitative estimate of conductance the transient phase ($\emptyset_\tau$) can be calculated as follows:

$$\emptyset_\tau = tan^{-1}\left(\frac{H_{OFF}^{S}}{-H_{ON}^{S}}\right)$$

Based on the transient phase, estimates of conductance can be derived by forward modeling using the full waveform and reproducing the average off-time and on-time secondary field responses as outlined above.

EXAMPLES

A proto-type HTEM system was constructed to allow for ground calibration over conductors of known conductance (determined by coil diameter, wire diameter and number of turns) from 1.8 µs to 10,800 µs. The HTEM system was operated at the three base frequencies: 150, 90 and 30 Hz. The full waveform was recorded using a 24-bit A/D converter operating at a 9.48 µs sample rate for all base frequencies. Profiles of the average on-time and off-time were calculated in addition to the normal off-time and on-time profiles. Transmitter dipole moment was 15,000 Am^2 from a triangular waveform having a 35% duty cycle and 200 A peak current.

In the first example, five calibration coils representing resistive targets were placed on the ground at a separation of 10 m and were surveyed using a base frequency of 150 Hz. These coils have a time constant range from 1.8 - 84 µs. Figure 1 shows the unfiltered off-time profiles and Figure 2 shows the unfiltered on-time profiles. The amplitude is unscaled ppm. Note that the on-time profiles do not detect the calibration coils below a 20 µs time constant. Figure 3 shows the averaged on-time and off-time secondary field for the data presented in Figures 1 and 2.

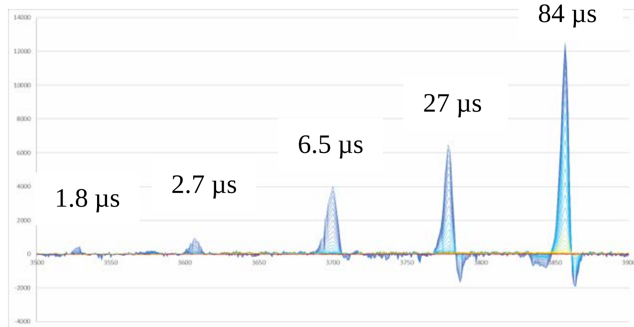

Figure 1: Off-time profiles over resistive calibration coils at 150 Hz.

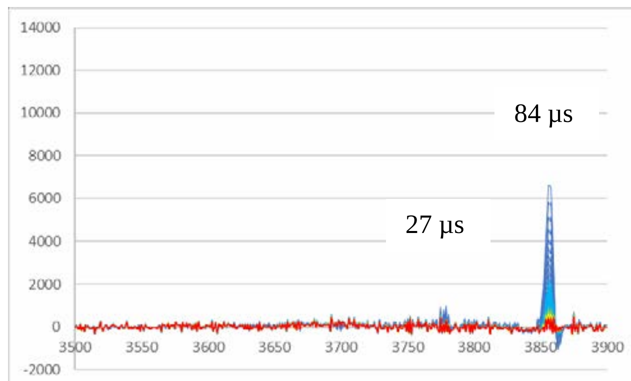

Figure 2: On-time profiles over resistive calibration coils at 150 Hz.

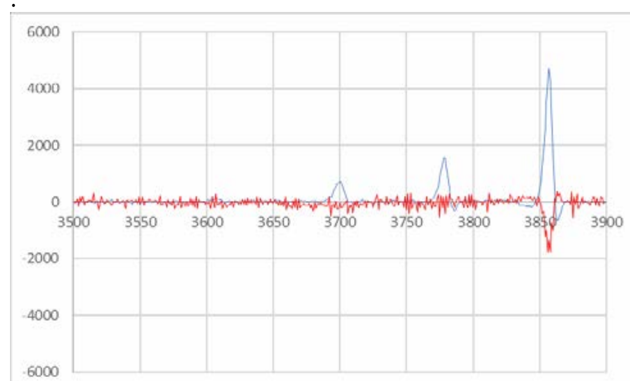

Figure 3: Secondary field averaged over the off-time (blue) and on-time (red) for the resistive calibration sources profiled in Figures 1 and 2.

From Figure 1 it is apparent that all resistive calibration coils are detected during the off-time. However, only the two most conductive coils (27 and 84 µs) are detected during the on-time. For the most conductive coil surveyed in example 1, the off-time response exceeds the on-time response therefore the transient phase is neither needed nor calculated.

In the second example, five calibration coils representing conductive targets were placed on the ground at a separation of 10 m and were surveyed using a base frequency of 150 Hz.

These coils have a time constant range from 195–10,800 µs. Figure 4 shows the off-time profiles and Figure 5 the on-time profiles for the conductive calibration coils. Figure 6 shows the average secondary field for both the off-time and the on-time.

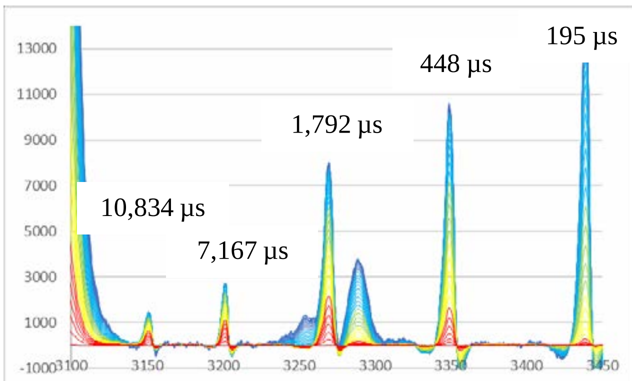

Figure 4: Off-time profiles over conductive calibration coils at 150 Hz.

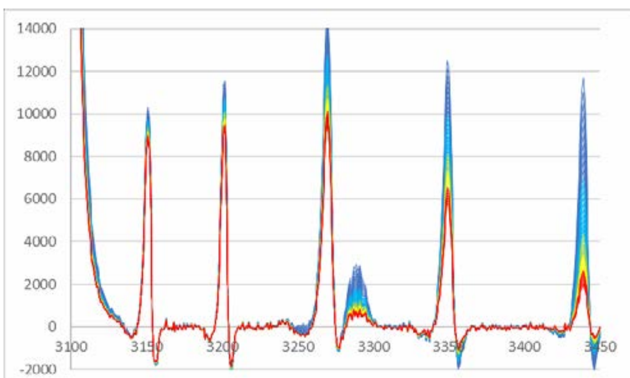

Figure 5: On-time profiles over conductive calibration coils at 150 Hz.

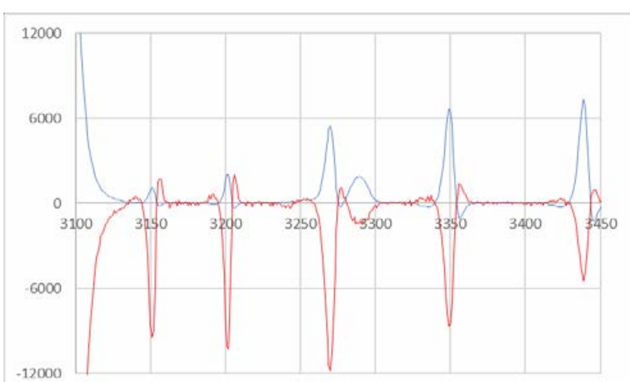

Figure 6: Secondary field averaged over the off-time (blue) and on-time (red) for the conductive calibration sources profiles in Figures 4 and 5.

In the third example, the five calibration coils representing conductive targets are re-surveyed at a 30 Hz base frequency. Figure 7 shows the off-time profiles, Figure 8 shows the on-time profiles, and Figure 9 shows the average off-time and on-time secondary field, all at a 30 Hz base frequency.

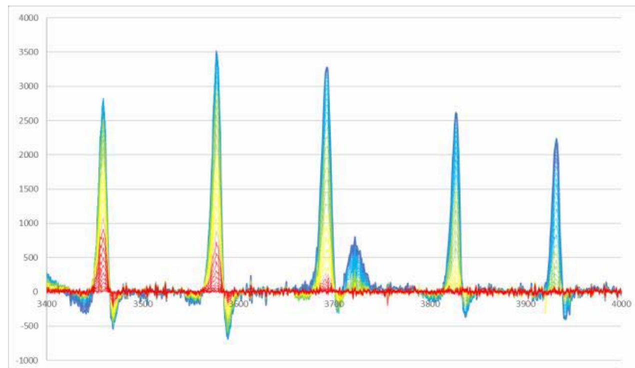

Figure 7: Off-time profiles over conductive calibration coils at 30 Hz.

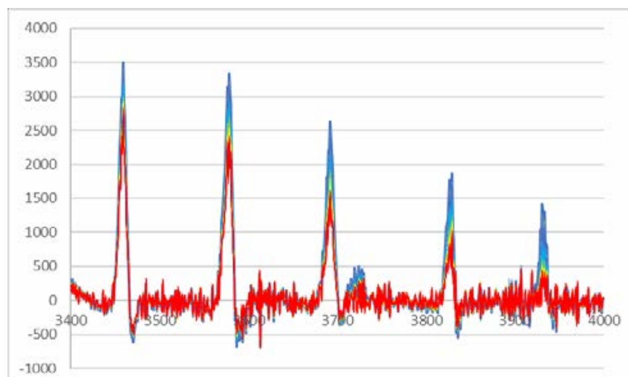

Figure 8: On-time profiles over conductive calibration coils at 30 Hz.

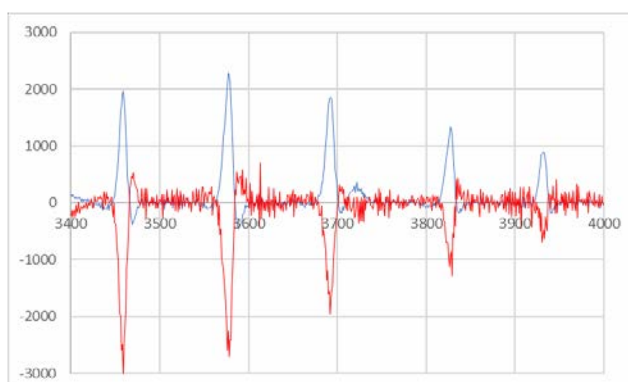

Figure 9: Secondary field averaged during the off-time (blue) and on-time (red) at 30 Hz.

DISCUSSION

For low conductance targets the off-time profiles provide greater detection than the on-time profiles as can be seen in Figure 3 where the average off-time response exceeds the average on-time response for all resistive calibration coils.

For high conductance targets the on-time profiles provide greater detection than the off-time profiles as can be seen in Figure 6 where the on-time response is higher for all conductive coils with a time constant greater than 448 µs.

Test surveys using the resistive and conductive coils were also conducted at a 90 Hz base frequency. This reduced base frequency (150 to 90 Hz) shifted the Tau value at which the on-time response exceeds the off-time response, but not dramatically. Shifting to a lower base frequency increased the Tau value at which the on-time response was greater.

For the 30 Hz base frequency tests, the on-time response exceeded the off-time response for Tau values of 1,792 µs and higher. The factor that the base frequency is shifted is approximately equal to the shift in Tau where the on-time response exceeds the off-time. While this shift represents an improvement by a factor of five toward a higher Tau (150 to 30 Hz), the more salient point is that the on-time response is greater than the off-time response for conductor Tau values of 2,000 µs and higher at 30 Hz (typically the lowest HTEM base frequency).

Table 1 summarizes the peak amplitudes of the off-time and on-time average secondary field for the 30 Hz base frequency. These amplitudes are used to calculate the transient phase. Poor conductors have a phase much greater than 45º while high conductance targets have a phase much less than 45º and super conductors have a phase approaching 0º.

From Table 1, the off-time response peaks for the 7,167 µs calibration coil while the on-time peak response peak is not reached even at the 10,834 µs time constant. In the search for super conductors, a lower base frequency off-time Tau estimate is not as robust as the off-time to on-time ratio (the transient phase) because the response will be far greater during the transmitter on-time and the response may not even be detectable in the off-time.

It is unlikely that B-field Tau estimates offer much improvement over the dB/dt as the response from poor conductors is integrated into the response from good conductors and the latter response has lower amplitude.

CONCLUSIONS

Measuring the conductance indirectly from the calculated time constant of the off-time secondary field is an effective way to measure conductance when the off-time response is greater than the on-time response (transient phase > 45º).

As conductance increases there is a rotation in the average response from the off-time to the on-time. At some point the on-time response will exceed the off-time response. By comparing the average secondary field measured during the off-time with that measured during the on-time, high conductance targets are better identified when compared to B-field estimates that integrate and combine the on-time and off-time or the off-time response only.

The use of off-time and on-time amplitudes is a more effective indicator of high conductance and the calculation of transient phase could be a superior quantitative estimate of high conductance than either off-time (dB/dt) or B-field estimates.

Off-time (ppm)	On-time (ppm)	T-Phase (deg)	Conductance (µs)
1961	3032	32.9	10,834
2242	2715	39.5	7,167
1845	-1949	43.4	1,792
1205	-1126	46.9	448
858	-629	53.7	195

Table 1: Determination of transient phase from off-time and on-time amplitudes for 30 Hz conductive coils.

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