Step and impulse calculations from pulse-type electromagnetic data

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SUMMARY

It has been shown by others working in the field of time-domain electromagnetic induction, that the late-time step response of the ground can be very useful for the detection of large, slowly decaying secondary fields. (Lamontagne, 1975; West et. al., 1984). A simple method is outlined here to calculate the step response from pulse-type time-domain EM data. Pulse-type systems are often described as impulse systems, but a measured impulse response cannot be used to derive the step response. These systems would better be described as hybrid systems – lying somewhere between a pure impulse and pure step – because their current termination is of short duration, but not instantaneous. By taking at least one measurement during the current turn-off time, and by ensuring that the turn-off is a very linear, controlled ramp, a simple step response calculation can be made.

It can also be important to determine the impulse response of the ground since many interpretation schemes are based on this measurement (for example, Nabighian, 1979). It is shown that with a few additional calculations while the step response is being calculated, the impulse response can also be easily determined.

INTRODUCTION

Transient or time-domain electromagnetic (TDEM) systems can be classified by whether they attempt to measure the impulse response or the step response of the ground. A true measure of the impulse response, however, would require a unit step in the transmitted current, which is something that cannot be achieved in practice. In an attempt to approximate the impulse response, some pulse-type TDEM systems allow the transmitted current to shut off as quickly as possible and record the secondary field during the "off-time" of the current waveform. To measure the step response, on the other hand, requires a triangular waveform, which means that all measurements are during the "on-time" and the total field (primary plus secondary) is recorded (West et. al., 1984). See Figure 1.

In mathematical terms, the impulse response can be easily derived from the step response by differentiation, but the step response cannot be calculated from the measured impulse response due to our inability to sample and integrate during the instantaneous impulse at t=0. However, it has been shown that the step response can indeed be calculated from pulse-

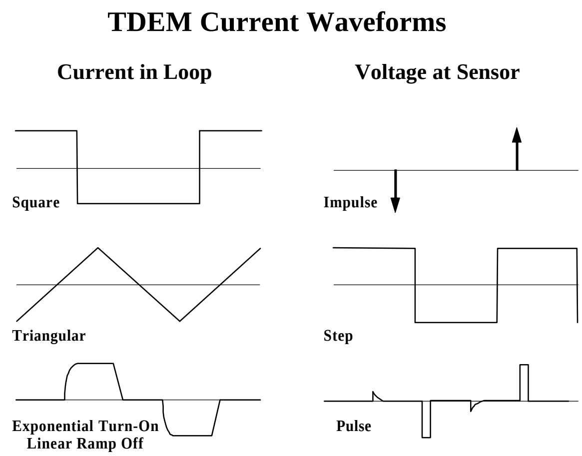

Figure 1.

type TDEM data, and this calculation takes on a very simple form provided that the system meets certain criteria (Hughes and Ravenhurst, 1996).

These criteria are:

- that the peak transmitted current before the shut-off is constant and does not drift;
- that the current shut-off is in the form of a very linear ramp
- that the ramp width (duration) is controlled and does not drift
- that at least one measurement of the total field (primary plus secondary) is made within the ramp;
- and that the off-time is well-sampled except for a small period of time (much less than the ramp width) following the end of the ramp.

This paper presents the specific formula for the late-time step response transformation on typical data with example, and also shows a new approach in the calculation of the early-time step channels. Finally, a technique is presented to calculate the impulse response from typical data.

MOTIVATION

For a given conductor geometry we see for the STEP response (see Figure 2) that:

- the initial value at t=0 is the same regardless of conductance

- the residual late-time response steadily increases with conductance
- the residual late-time response is determined by subtracting the measured response from the calculated theoretical free-space value. This means that the system geometry must be precisely known.
- perfect conductors produces the largest residual

For a PULSE system whose current ramps off over a short duration (R) followed by zero current we see that:

- the first part of the STEP response is seen during the current ramp. This means a perfect conductor would be seen during the current ramp of a pulse response.
- the STEP response of poor conductors is seen in the off-time
- as conductance increases the response begins to behave more like the impulse response
- perfect conductors cannot be seen in the off-time

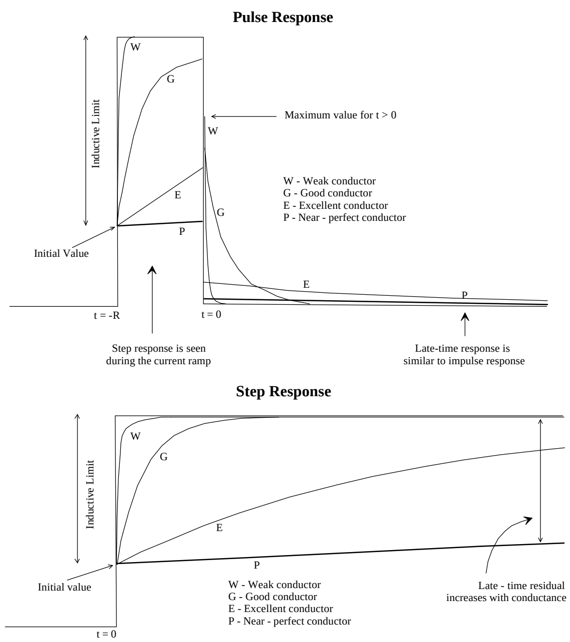

Figure 2. Pulse and step response for different conductance targets.

For the pulse system an in-hole conductor produces a positive off-time anomaly and negative distortion in the ramp and visa versa for an off-hole conductor. We can detect a good to excellent conductor by looking at the late off-time, and we will not miss a perfect conductor if we look at the distortion of the pulse.

However, in the instance of a combination of excellent in-hole conductor and near perfect off-hole conductor (Figure 3) the above no longer holds true. If we assume that to a first approximation we can just add individual responses to obtain the total response, the off-time sum is almost identical to the response from the excellent in-hole conductor alone. The response during the current ramp is also dominated by the in-hole conductor, and the sum is still negative suggesting an in-hole). Unless we notice that the response amplitude during the current ramp is too small to be caused by the in-hole conductor alone, the off-hole conductor will be missed. The late-time step response is much more definitive, as it clearly shows the presence of an off-hole conductor.

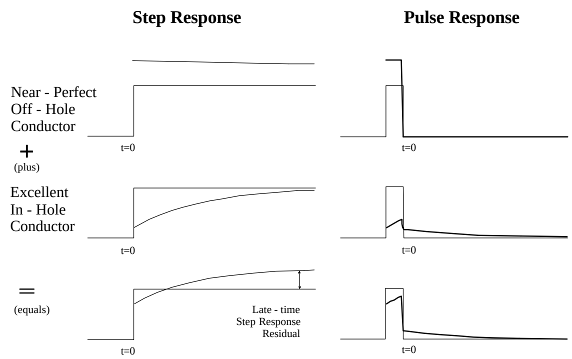

Figure 3. Step and pulse response due an excellent in-hole conductor and near perfect off-hole conductor.

METHOD

The method of conversion between pulse and step response is based on the realization that measurements made during the current ramp of pulse-type TDEM systems are step response measurements, and that measurements made during the off-time represent the difference between two identical step response functions offset in time by an amount equal to the ramp time (see Hughes and Ravenhurst, 1996).

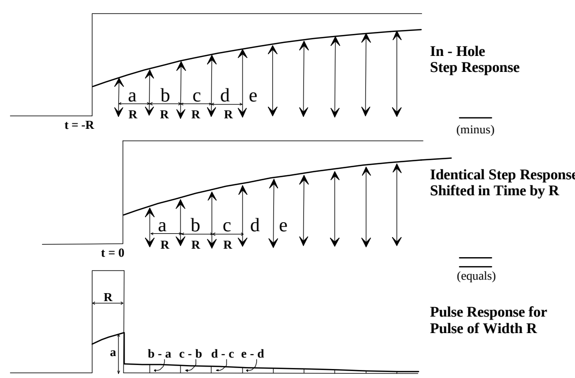

Figure 4. Pulse response is essentially the difference between two step responses separated by “R”.

Referring to Figure 4 step samples like “a” taken at offsets less than “R” will be the reading seen inside the pulse. By selecting “b” to be a distance “R” from “a”, the resulting response is “b-a”. Continuing to sample at an interval “R” results in the simple expressions for the pulse response.

Conversely, if we start with the pulse response, that includes a measurement within the ramp, we can calculate the step response by adding to the in-ramp measurement the off-time values at intervals of “R” from the ramp measurement position. Wherever the summation is terminated, the step response is known at that point in time.

The method is best described by using specific system parameters, and the system referred to will be the Crone Pulse EM (PEM) system (Crone, 1975). In the typical configuration of this system, the current ramp is 1.5 msec long, and this is followed by 15.16 msec of off-time. Time zero is defined to be at the end of the current ramp. One sampling window (the Primary Pulse, or PP channel) is positioned during the current ramp from –200 μsec to -100μsec, and 20 contiguous logarithmic windows are placed in the off-time starting at 76 μsec.

In the following formulas, S refers to the step response and its subscript is the offset in μsec from the start of the current ramp, O refers to off-time measurements and its subscript is its offset from the end of the ramp, and PP refers to the Primary Pulse reading in the ramp. This Primary Pulse reading is equivalent to the step response at an offset of 1350 μsec:

$$S_{1350} = PP \qquad (1)$$

With this system configuration, nine other samples of the step response can be calculated directly with the following recursive formula:

$$S_{(1350 + R)} = S_{(1350 + (n-1)R)} + O_{(1350 + (n-1)R)} \qquad (2)$$

where n = 1…9 and R is the ramp width in μsec (1500).

Thus, the final step response value that can be calculated with this system configuration is at an offset of 14,850 μsec. Using the symbol LS for "last step" value, it is given by:

$$LS = S_{14850} = PP + O_{1350} + O_{2850} + O_{4350} + O_{5850} + O_{7350} + O_{8850} + O_{10350} + O_{11850} + O_{13350} \qquad (3)$$

This value can be approximated by determining which off-time sampling window each of the off-time samples falls into, and using that window measurement directly in the formula:

$$LS \approx PP + ch.11 + ch.14 + ch.16 + ch.17 + ch.18 + 2(ch.19) + 2(ch.20) \qquad (4)$$

where ch. refers to the standard window or channel configuration in this TDEM system.

This is a very simple formula that can be applied to data collected with the system configuration detailed above, and in fact, this is done on a routine basis (Watts, 1997). Other similar formulas can be derived for various base frequencies, ramp times, and sampling configurations. Improved accuracy may be realized by fitting a curve to the off-time data and re-sampling this decay curve at the required points.

The step response that is calculated with this approach is based on the primary field strength produced by a ramp of width R (1.5 msec) and peak current I, even though the calculated sample points extend nearly to the end of the time base T (16.66 msec). Thus, to compare this response to one produced by a current ramp over the full time base, but with the same peak current, we should multiply our calculation by R/T.

This method produces a linearly sampled step response starting at an offset of 1350 μsec. Earlier step response values can be acquired by sampling in the current ramp before the PP sample, and this is an approach which has been used. Another way of accomplishing the same thing would be to work backward from the late step values were calculated and to make use of earlier off-time samples which are available. For the step samples with offsets between 0 and 1350, we can write:

$$S_t = S_{(13500 + t)} - \sum_{n=0}^{8} O_{(n(1500)+t)} \; ; \; 0 < t \leq 1350 \qquad (5)$$

From this we can see that the earliest step response value that can be calculated will have the same offset as the earliest off-time value that is measured. For the standard configuration this would be a sample centered at 90 μsec:

$$S_{90} = S_{13590} - (ch.1 + ch.12 + ch.15 + ch.16 + ch.17 + ch.18 + 2(ch.19) + (ch.20) \qquad (6)$$

The value at S_{13590} can be accurately interpolated between the last two step channels calculated above (S_{13350} and S_{14850}) because the interval is small and the transients decay slowly at that point in time. Therefore, the early step channels can be accurately calculated at the same offset values as the off-time samples.

Now that we have a method to calculate the step response, we can differentiate it to determine the impulse response. First, however, we would multiply the calculated step response by R/I, where R is the ramp width and I is the peak current, in order to get the unit step response. The easiest way to perform the differentiation is to do it in conjunction with the step response calculation. After calculating the late-time step response values, we can calculate the differential of each term on the right side of equation *(5)* and *(6)* through a curve-fitting procedure, and therefore we have the early-time differentials, including the one at the PP channel location. Then we can apply equations *(2)*, *(3)* and *(4)* in differential form to calculate the impulse response over the entire time base.

The impulse response is often important in the low conductivity case where there is no late-time response. Under these conditions, the slope of the decay in late time is zero, so the impulse response at any offset is just the summation, to the end of the time base, of the slope of the pulse-type TDEM data (multiplied by R/I) at sample points lying integer ramp widths away. Note that increasing the ramp decreases the number of terms in the summation, while decreasing the ramp width eventually results in the evaluation of the function itself (divided by I), instead of its slope. This again demonstrates that the response from pulse-type TDEM systems lies between that of an impulse and a step.

EXAMPLE

This is an example of DHEM from the Voisey's Bay nickel deposit in Labrador, Canada. The section in Figure 6 shows that the target is highly conductive nickel ore within a mineralised trocolite unit. The DHEM data is for drill-hole A which intersected 9m of weakly mineralised trocolite. Looking at the Z (A) DHEM data we see the late off-time response is a positive anomaly from the conductive intersected trocolite. Notice that the step response is also positive suggesting that the step response is detecting a more conductive off-hole target. Also shown is the X (U) and Y (V) data from drill-hole A. Again, the step response data is opposite to what is expected for an intersected conductor. From the X step component data, the off-hole conductor lies down-dip. The Y step component data is giving strike information.

Follow-up drill-hole B, drilled down-dip, intersected 20m of strongly mineralised trocolite, including 8m of massive sulphide.

CONCLUSIONS

Pulse-type TDEM systems are actually hybrid systems lying somewhere between a pure impulse system and a pure step system. The length of the current ramp and the time constant of the secondary field will determine whether the response looks more like the impulse response or the step response. Regardless of the time constant of the field, however, both the step response and the impulse response can be easily calculated over the entire time base of pulse-type TDEM systems provided that certain criteria are met. The key is to utilize a controlled linear current ramp, and to make at least one measurement inside that ramp. The formulas presented here can be refined by some form of interpolation of the off-time samples, but these simple formulas have already proven to be very useful in actual field applications.

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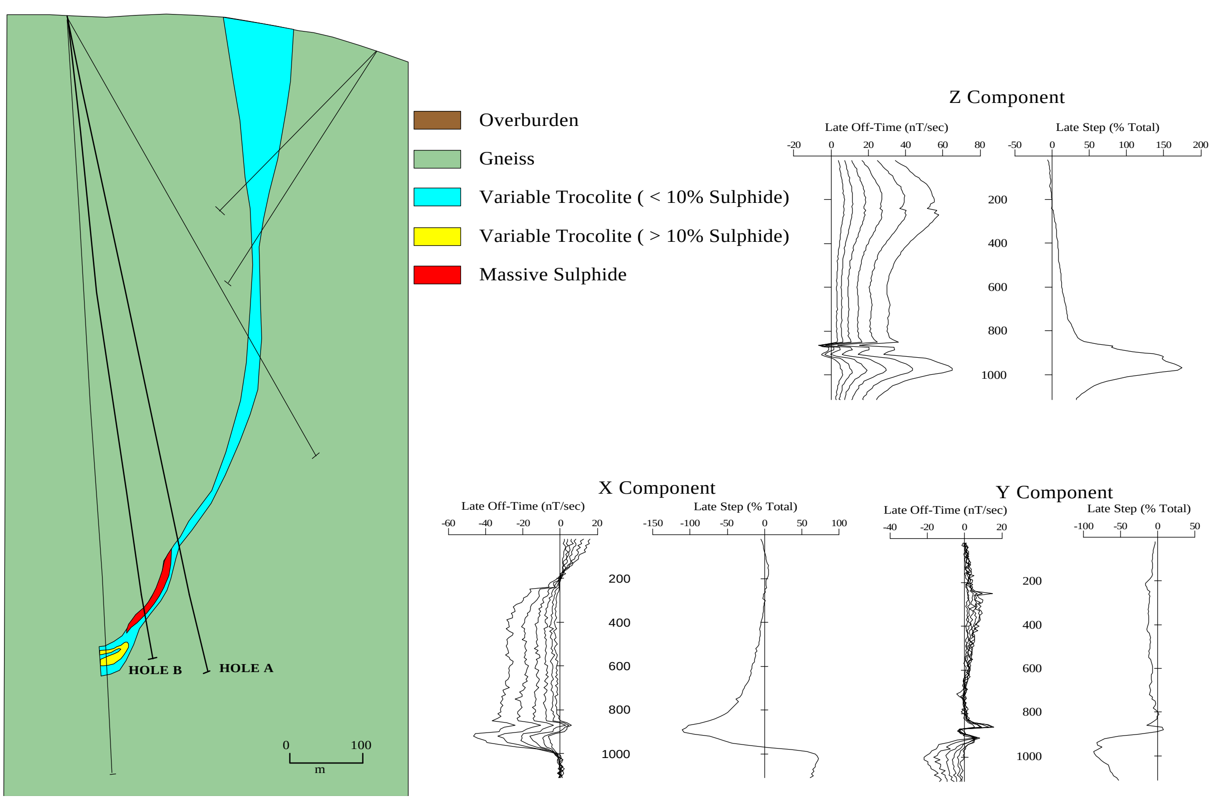

Figure 6. Voisey Bay nickel Section and DHEM profiles from drill-hole A.