GEOPHYSICS, VOL. 49, NO. 7 (JULY 1984); P. 913–917, 5 FIGS., 1 TABLE.

Simplified prediction of transient electromagnetic response

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ABSTRACT

In general the target response to an electromagnetic system is a complex function of target geometry and of the geometrical and electrical parameters of the apparatus used to make the measurements. Thus, the prediction of system performance is usually done with respect to a particular target. Under some circumstances, however, one can predict the effect of changing one of the system parameters by assuming that the typical conductor in a given area is well represented by a shorted single-turn loop. This simple, classical concept is shown to be valid for evaluating the effect of primary pulse width on target response to the Input airborne electromagnetic system.

The justification of our basic technique for predicting this aspect of AEM system performance is provided by the analysis of Input surveys done in two areas of the Precambrian Shield in Canada. Repeat surveys were done in each area with a 1 ms and a 2 ms primary pulse width. The change in system performance that could be expected by doubling the pulse width was correctly predicted after an analysis of the 1 ms data.

INTRODUCTION

It is customary to evaluate the response of any given electromagnetic (EM) apparatus with respect to a particular target. Thus for example when Gupta Sarma et al. (1976) wished to demonstrate the advantages of measuring the magnetic field rather than its derivative as is normally done in most time-domain EM systems; they did so by computing the system response for a sphere. While this approach to predicting the performance of an EM system is most useful in considering an isolated case (i.e., a specific mineral deposit) it cannot be taken where one wishes to estimate the average system response in an area containing a variety of different conductors. In this situation one may take a simpler approach as was done by Gupta Sarma et al. (1976) and assume that each discrete conductor behaves as a single-turn closed loop circuit. Within limits, this simplistic assumption makes it possible to forecast the behavior of a proposed EM system in a given area on the basis of the response observed with another EM system. In this paper we examine the validity of the simple approach for predicting system performance.

We propose that the system response of any new apparatus in a given area may be readily estimated in the following manner.

(1) Obtain survey data for the area in question with some standard EM system similar in dimension to the system under evaluation.
(2) Interpret each anomaly in terms of a single-turn closed loop conductor assuming that each anomaly can be characterized by its amplitude and a single average time constant. Under these assumptions the anomaly for a time domain system can be defined by

$$A(x_0, t) = A_0(x_0, \tau)e^{-t/\tau}.$$

Here x_0 corresponds to the position of the anomaly center, τ is the time constant of the equivalent closed single-turn circuit, and A_0 is the anomaly amplitude at the instant of primary field extinction. It is usually normalized to the peak value of the primary field.
(3) Predict the response of any proposed system by using the values and statistics for A_0 and τ obtained above in step (2).

The above approach may appear to oversimplify the solution to a complex problem. In particular we know (Kaufman, 1978a) that, in general, the response of a bounded conductor can be defined by an infinite series of exponentials with different amplitudes and time constants. The form for the response of layered media is even more complicated. Nevertheless, as will be justified below by examining field test data, we contend that the simple approach proposed here is valid. In the case at hand, it will be used to predict the effects of doubling the width of the primary field pulse in the airborne Input® system from its customary 1 ms duration.

THE INPUT SYSTEM

Since its invention in 1958 and its first presentation to the public by the inventor four years later (Barringer, 1962), the Input (Induced Pulse Transient) airborne electromagnetic

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Table 1. MK VI detector gate settings.

Channel	Gate center position (μs)	Gate width (μs)
1	300	180
2	480	180
3	750	360
4	1110	360
5	1560	540
6	2100	650

(AEM) system has approximately maintained its original operating parameters. Although the equipment was periodically upgraded to take advantage of new technology (Lazenby, 1973), the principles of operation laid down by the inventor 25 years ago were carefully retained. The central idea in this system is the transmission of a strictly periodic waveform with equally spaced half-sine pulses of alternating polarity but identical shape. Since the beginning of commercial service, the transmitted pulse width was set at about 1 ms. In practice, the transmitter loop is placed about the aircraft in a horizontal plane to constitute a vertical dipole with a peak moment of about 2×10^5 Am^2. A horizontal-axis receiver coil is towed in a bird which is located some 100 m behind and 65 m below the aircraft. It responds to the time derivative of the primary and secondary magnetic fields. A six-channel coherent detector records the secondary field once the primary pulse is extinguished. Traditionally the six detector gates were set as shown in Table 1. The times indicated for the gate center positions are measured with respect to the instant of termination of the primary field pulse.

Because the duration of the primary half-sine current pulse, its repetition rate, and the detector gating can all be independently controlled, it is relatively easy to modify any one of these parameters for experimental purposes. In the experiments reported on here, the primary pulse width was doubled to 2 ms while the pulse repetition rate was decreased to 210 pps from its normal value of 300 pps. The changes in pulse repetition rate correspond to a lowering of the fundamental frequency from 150 to 105 Hz. The decrease in the pulse repetition rate was usually accompanied by an increase in transmitter dipole moment which varied from 30 percent for the Ontario test to 60 percent for the Northern Manitoba surveys. All the tests were carried out with the system installed in a Short Brothers Skyvan aircraft. Because the detector timing is an independent quantity, the channel gate widths and positions were maintained as near as possible to the values cited above in Table 1.

THEORETICAL RESPONSE

Neglecting the effects of pulse repetition, Mallick (1972) showed that the amplitude of the response of a single-turn closed-loop target to an Input half-sine pulse, at the instant of extinction of the primary field, is given by

$$I_C(\Delta) = S\left(\frac{1 + e^{-\Delta/\tau}}{1 + \pi^2\tau^2/\Delta^2}\right)\left(\frac{\pi\tau}{\Delta}\right). \tag{1}$$

Here, the transmitter current is given by

$$I_T(t) = I_0 \sin\frac{\pi t}{\Delta} \qquad 0 \le t \le \Delta,$$
$$= 0 \qquad t > 0. \tag{2}$$

The definition of the other symbols is given as follows:

$$S = \frac{M_{TC}}{L_C} I_0 \tag{3}$$

is the amplitude of the conductor step response corresponding to a change of magnitude I_0 in the primary current,

$I_C(\Delta) \equiv$ conductor current at the instant of primary field extinction,
$L_C \equiv$ target inductance,
$M_{TC} \equiv$ mutual inductance between the transmitter and the target conductor,
$\Delta \equiv$ duration of the primary pulse,

and

$\tau \equiv$ target time constant.

Figure 1 illustrates the variation of the normalized conductor current as a function of τ/Δ. The conductor current is a maxi-

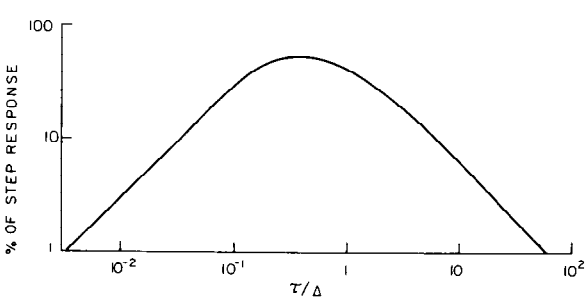


FIG. 1. Normalized response to half-sine pulse as a function of time constant to pulse-width ratio.

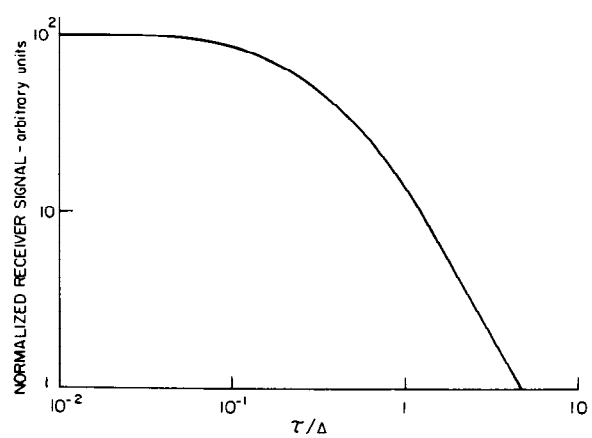
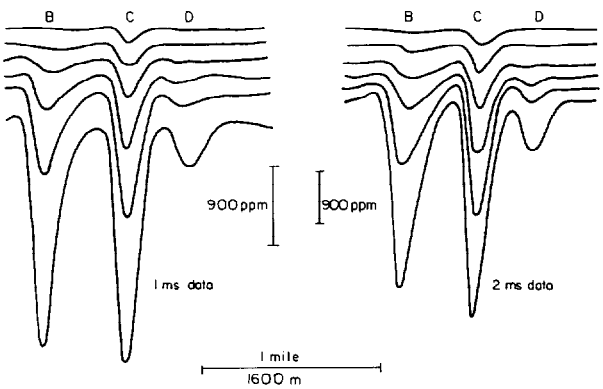


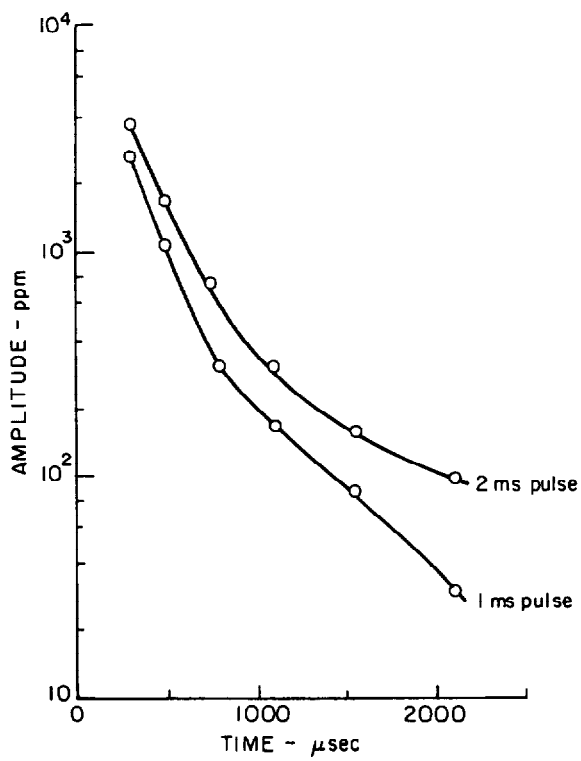
FIG. 2. Relative receiver voltage as a function of time constant to half-sine pulse-width ratio.

mum when the independent variable attains a value of $\sqrt{2}/\pi$ which corresponds to a ratio of about two between the primary pulse width and the conductor time constant. This ratio defines the optimum value for the pulse duration to be used in the search for a conductor of a given time constant. To put it simply, if we wish to find a target whose time constant is 500 μs using a half-sine pulse, then the pulse should be 1 ms wide. The voltage induced in the receiver at the instant termination of the primary field is related to the conductor current by

$$E_R(\Delta) = M_{CR} I_C(\Delta)/\tau. \tag{4}$$



(a)



(b)

FIG. 3. Sample of Central Ontario test data. (a) Profiles, (b) transient for anomaly B.

Here, $E_R(\Delta)$ is the receiver voltage and M_{CR} is the mutual inductance between the target and the receiver.

In order to compare the observed field data with the theoretical expressions, it is necessary to normalize the latter with respect to the amplitude of the voltage induced in the receiver directly by the primary field variation. In this way the system response only depends upon the geometrical parameters of the system and its pulse width. Its dependence on the amplitude of the transmitter current is removed. The voltage induced by the primary field pulse is given by

$$E_P(\Delta) = M_{TR} I_0 \pi/\Delta, \tag{5}$$

where M_{TR} is the mutual inductance between the receiver and the transmitter. The normalized target response is given by

$$E(\Delta) = \frac{E_R(\Delta)}{E_P(\Delta)} = \frac{M_{TC} M_{CR}}{M_{TR} L_C} \frac{(1 + e^{-\Delta/\tau})}{(1 + \pi^2\tau^2/\Delta^2)}. \tag{6}$$

The functional dependence of the normalized target response on the parameter τ/Δ is shown in Figure 2. We note that the normalized response is independent of the conductor time constant whenever this quantity is much less than the primary pulse width. On the other hand, once the conductor time constant is greater than the pulse width the normalized response falls rapidly as the inverse square of the time constant.

Using equation (6) one can readily predict the change in target response as a function of primary field pulse duration. In particular the ratio of the relative target response to a primary pulse lasting Δ_2 ms compared to the relative response of the same target to a Δ_1 ms pulse can be immediately written as

$$R(\Delta_1, \Delta_2, \tau) = \frac{(1 + e^{-\Delta_2/\tau})}{(1 + e^{-\Delta_1/\tau})} \frac{(1 + \pi^2\tau^2/\Delta_1^2)}{(1 + \pi^2\tau^2/\Delta_2^2)}. \tag{7}$$

For low values of the time constant τ (compared to Δ_1, Δ_2) this ratio equals unity. High values of τ yield a ratio of (Δ_2^2/Δ_1^2). In practical terms this means that doubling the pulse width in the Input system from its conventional value of 1 ms will result in a four-fold increase in normalized response for targets with time constants larger than 2 ms. Response for targets where the time constant is less than about 100 μs will remain unaffected by the change in pulse width.

It must be pointed out that the change in normalized response as a function of pulse width is not equivalent to the variation in signal-to-noise (S/N) ratio (for a given target) with the pulse duration. Because noise is not a function of this variable, the change in S/N ratio as a function of pulse width can only be obtained from equation (4) which defines the absolute value of the voltage induced in the receiver at the instant of primary field cessation. Changes in normalized response and S/N ratio as a function of pulse width, however, are related to each other via

$$\text{S/NR}\ (\Delta_1, \Delta_2, \tau) = R(\Delta_1, \Delta_2, \tau)\left(\frac{\Delta_1}{\Delta_2}\right)\left(\frac{P_2}{P_1}\right). \tag{8}$$

Here S/NR = change in signal-to-noise ratio (assuming constant noise),
P_2 = transmitter moment for Δ_2 pulse,
and
P_1 = transmitter moment for Δ_1 pulse.

Thus, for constant noise and for constant dipole moment, increasing the pulse width from 1 to 2 ms will improve the S/N

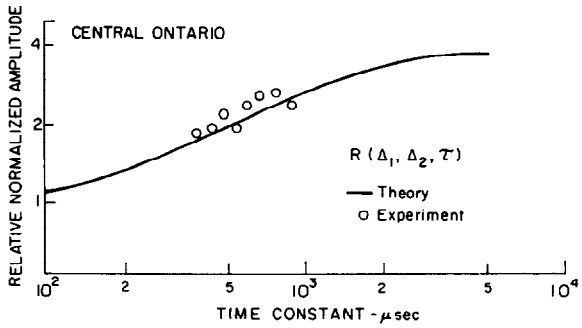


FIG. 4. Increase in relative anomaly amplitude with doubling of primary pulse width to 2 ms. Central Ontario test area.

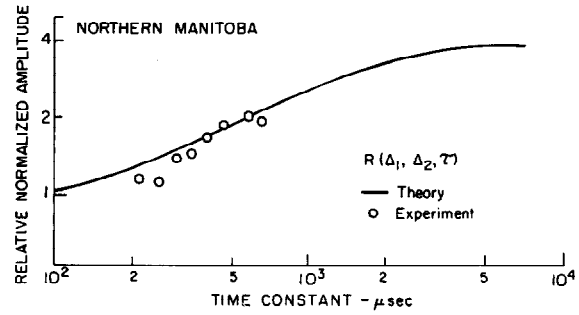


FIG. 5. Increase in relative anomaly amplitude with doubling of primary pulse width to 2 ms. Northern Manitoba test area.

ratio by a factor of two for good conductors. For poor conductors, however, those whose time constant is less than 100 μs, we should expect a 50 percent decrease in the S/N ratio.

FIELD RESULTS

The theoretical premises reviewed above were tested in two Canadian field surveys. In each case the same area was surveyed twice, once with the conventional 1 ms pulse width and again with a 2 ms primary pulse. The first survey took place near Lake Cordova in central Ontario (44°35′ N, 77°50′ W). This area was chosen because previous surveys had located a number of long linear conductors. Little other geologic information was available. Typical survey data for this area is shown in Figure 3a. Here, because the data are taken directly from the analog field records, we were unable to maintain equal horizontal and vertical data scales. The secondary field transients for anomaly B are shown in Figure 3b. Decay patterns observed with both the 1 and 2 ms primary pulses resemble each other but cannot be represented accurately by a single time constant. An average time constant of about 450 μs, however, can be assigned to this anomaly by noting that the early part of the transient here decays with a time constant of about 275 μs while in the later channels the decay shows a 750 μs time constant. The "average value" for the anomaly time constant here is then computed by taking the geometric mean of the early and late decay rates. The amplitude ratio for the two transients is determined by the relative average vertical displacement between the two curves when these are plotted (as shown) on semilogarithmic coordinates. Taking the two different calibration scales into account, we observe a 50 percent increase in relative anomaly size as the pulse width is increased to 2 ms from the conventional value of 1 ms. Each of the 139 conductor intersections (anomalies) in this area was similarly analyzed. Where necessary, that is when any given anomaly was not observed twice at the same altitude, an amplitude correction that assumed a fourth-power fall-off with height was applied to one of the two observed anomalies.

The results of the analysis for the Lake Cordova test surveys are presented in Figure 4. Each experimental point represents the average amplitude change for a number of anomalies whose average time constants fall within a 50 μs interval centered on the point's abscissa. In this area, the mean observed secondary field decay time constant amounted to about 500 μs. Seventy percent of the anomalies showed a time constant in the 450–700 μs range. The experimental data points are superimposed on the expected improvement derived from equation (7). If we consider the possible errors introduced by the approximate altitude corrections and the minor position errors associated with repeat surveys, the agreement between theory and experiment is quite good.

The second test survey was located in northern Manitoba. This area was known to enclose numerous conductive bodies containing pyrite, pyrrhotite, chalcopyrite, and an abundance of graphite. The conductors are mainly located within metagreywacke, meta-arkose, or amphibolite. They are totally contained within rocks of the Aphebian era of the Churchill Province. There is little or no conductive overburden. A total of 56 anomalies was evaluated here. The data were processed in a manner similar to that used in the Lake Cordova area. Figure 5 shows these results superimposed on the theoretical curve. Once again we note excellent agreement between experiment and theory.

CONCLUSION

On the basis of the experimental data presented we can conclude that the simple method we propose for determining changes in the system response of a time-domain airborne electromagnetic system is fairly reliable. Although only conductors that exhibit a secondary field decay time constant in the 200–1000 μs range were observed, there is no reason to think that our conclusion is not valid outside this range. Some caution, however, should be exercised in using this technique for predicting system response in the case where the geometrical scale of the system used on the test survey is much different from that of the projected system whose performance is to be defined. As pointed out by Palacky (1978), interpreted geophysical parameters for a given target vary considerably as the scale of the instrumentation changes.

In most cases the decay of the secondary field observed with the 2 ms pulse was 10 to 20 percent slower than that observed with the 1 ms pulse. This was to be expected because the secondary transient field can be considered to be composed of a number of exponentially decaying components. As the primary pulse width changes, the weighting of the various components is modified, resulting in a shift of the apparent anomaly time constant. The fact that the observed shifts were no larger than a

few percent demonstrates that in most cases the principal exponential components of the decaying eddy current series were being detected.

The consequences of being able to use the simple exponential representation for the conductor response reach farther than the estimation of system performance. In particular, the experimental results presented here lend credibility to the classical simple concept of representing an isolated buried conductor by a single shorted loop. If the time constant for this model conductor is chosen on the basis of actual field measurements, then the model becomes quite useful for the design of further field experiments or new apparatus. The fact that we have been able to obtain good agreement between simple theory and expensive experiment lends much weight to theoretical arguments such as those put forward by Kaufman (1978b) regarding the resolving power of different EM methods. However, one must guard against using our simple method of predicting system performance in geologically complex environments. The concepts outlined here will probably need modification in areas where strong EM coupling exists between the target conductor and a conducting host rock or conducting overburden. In these complex cases one can only consider the late-time features of the secondary field transient when we can assume that the eddy currents in the various components of the geologic model are decoupled from each other.

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