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Technical Note TN-27

PRINCIPLES AND APPLICATION OF TIME DOMAIN ELECTROMAGNETIC TECHNIQUES FOR RESISTIVITY SOUNDING

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Principles and Application of Time Domain Electromagnetic Techniques for Resistivity Sounding

Section 1. General

Conventional DC resistivity techniques have been applied for many years to a variety of geotechnical applications. More recently electromagnetic techniques, with different advantages (and disadvantages) compared with conventional DC, have been used effectively to measure the resistivity (or its reciprocal, the conductivity) of the earth.

Electromagnetic techniques can be broadly divided into two groups. In frequency-domain instrumentation (FDEM) the transmitter current varies sinusoidally with time at a fixed frequency which is selected on the basis of the desired depth of exploration of the measurement (high frequencies result in shallower depths). In most time-domain (TDEM) instrumentation, on the other hand, the transmitter current, while still periodic, is a modified symmetrical square wave, as shown in Fig. 1. It is seen that after every second quarter-period the transmitter current is abruptly reduced to zero for one quarter period, whereupon it flows in the opposite direction.

A typical TDEM resistivity sounding survey configuration is shown in Fig. 2, where it is seen that the transmitter is connected to a square (usually single turn) loop of wire laid on the ground. The side length of the loop is approximately equal to the desired depth of exploration except that, for shallow depths (less than 40 m) the length can be as small as 5 to 10 m in relatively resistive ground. A multi-turn receiver coil, located at the centre of the transmitter loop, is connected to the receiver through a short length of cable.

The principles of TDEM resistivity sounding are relatively easily understood. The process of abruptly reducing the transmitter current to zero induces, in accord with Faraday's law, a short duration voltage pulse in the ground, which causes a loop of current to flow in the immediate vicinity of the transmitter wire, as shown in Fig. 3. In fact, immediately after transmitter current is turned off, the current loop can be thought of as an image in the ground of the transmitter loop. However, because of finite ground resistivity the amplitude of the current starts to decay immediately. This decaying current similarly induces a voltage pulse which causes more current to flow, but now at a larger distance from the transmitter loop, and also at greater depth, as shown in Fig. 3. This deeper current flow also decays due to finite resistivity of the ground, inducing even deeper current flow and so on. The amplitude of the current flow as a function of time is measured by measuring its decaying magnetic field using a small multi-turn receiver coil usually located at the center of the transmitter loop. From the above it is evident that, by making measurement of the voltage out of the receiver coil at successively later times, measurement is made of the current flow and thus also of the electrical resistivity of the earth at successively greater depths, which process forms the basis of central loop resistivity sounding in the time domain.

The output voltage of the receiver coil is shown schematically (along with the transmitter current) in Fig. 4. To accurately measure the decay characteristics of this voltage the receiver contains 20 narrow time gates (indicated in Fig. 5), each opening sequentially to measure (and record) the amplitude of the decaying voltage at 20 successive times. Note that, to minimize distortion in measurement of the transient voltage, the early time gates, which are located where the transient voltage is changing rapidly with time, are very narrow, whereas the later gates, situated where the transient is varying more slowly, are much broader. This technique is desirable since wider gates enhance the signal-to-noise ratio, which becomes smaller as the amplitude of the transient decays at later times. It will be noted from Fig. 4 that there are four receiver voltage transients generated during each complete period (one positive pulse plus one negative pulse) of transmitter current flow. However, measurement is made only of those two transients that occur when the transmitter current has just been shut off, since in this case accuracy of the measurement is not affected by small errors in location of the receiver coil. This feature offers a very significant advantage over FDEM measurements, which are generally very sensitive to variations in the transmitter coil/receiver coil spacing since the FDEM receiver measures while the transmitter current is flowing. Finally, particularly for shallower sounding, where it is not necessary to measure the transient characteristics out to very late times, the period is typically of the order of one millisecond or less, which means that in a total measurement time of a few seconds, measurement can be made and stacked on several thousand transient responses, which is important since the transient response from one pulse is exceedingly small and it is necessary to improve the signal-to-noise ratio by adding the responses from a large number of pulses.

Section 2. The Concept of Apparent Resistivity in TDEM Soundings

Fig. 5 shows, schematically, a linear plot of typical transient response from the earth. It is useful to examine this response when plotted logarithmically against the logarithm of time, particularly if the earth is homogeneous (i.e. the resistivity does not vary with either lateral distance or depth). Such a plot is shown in Fig. 6, which suggests that the response can be divided into an early stage (where the response is constant with time), an intermediate stage (response shape continually varying with time) and a late stage (response is now a straight line on our log-log plot). The response is generally a mathematically complex function of conductivity and time, however, during the late stage the mathematics simplifies considerably, and it can be shown that during this time the response varies quite simply with time and conductivity as

$$e(t) = \frac{k_1 M \sigma^{3/2}}{t^{5/2}} \qquad (1)$$

where k_1 = a constant
M = product of Tx current (amps) x area (m^2)
σ = terrain conductivity (Siemens/m)
t = time (seconds)
and e(t) = output voltage from a single turn receiver coil of area one m^2

We note that unlike the case for conventional resistivity measurement, where the measured voltage varies linearly with terrain resistivity, for TDEM the measured voltage, e(t) varies as $\sigma^{3/2}$, so is intrinsically more sensitive to small variations in the conductivity than conventional resistivity. We also note that, during the late stage, the measured voltage is decaying at the rate $t^{-5/2}$, which is very rapidly with time. Eventually the signal disappears into the system noise and further measurement is impossible. We have reached the maximum depth of exploration for our particular system.

Now with conventional DC resistivity methods, for example the commonly used Wenner array, the measured voltage over a uniform earth can be shown to be

$$v(a) = \frac{\rho I}{2\pi a} \tag{2}$$

where a = interelectrode spacing (m)
ρ = the terrain resistivity (ohm-m)
I = current into the outer electrodes
and v(a) = voltage measured across the inner electrodes for the specific value of a.

In order to obtain the resistivity of the ground equation (2) is rearranged (inverted) to give

$$\rho = 2\pi a \left(\frac{v(a)}{I} \right) \tag{3}$$

If the ground resistivity is uniform, as the inter-electrode spacing a is increased the measured voltage decreases directly with a so that the right hand side of equation (3) stays constant, and the equation gives the true resistivity. Suppose now that the ground is horizontally layered (i.e. that the resistivity varies with depth); for example it might consist of an upper layer of thickness h and resistivity ρ_1, overlying a more resistive basement of resistivity $\rho_2 > \rho_1$, (this is called a two-layered earth). At very short inter-electrode spacing ($a<<h$) virtually no current penetrates into the more resistive basement and resistivity calculation from equation (3) will give the value ρ_1. As we increase the inter-electrode spacing a, the current I is forced to flow to greater and greater depths, and we can suppose that, at large values of a ($a>>h$) the effect of the near surface material of resistivity ρ_1) will be negligible, and resistivity calculated from equation (3) will give the value ρ_2, which is indeed what happens. At intermediate values of a ($a \approx h$) the resistivity given by equation (3) will lie somewhere between ρ_1 and ρ_2.

Equation (3) is, in the general case, used to define an apparent resistivity $\rho_a(a)$ which is a function of a. The variation of a $\rho_a(a)$ with a

$$\rho_a(a) = 2\pi a \frac{v(a)}{I} \tag{4}$$

is descriptive of the variation of resistivity with depth. The behaviour of the apparent resistivity $\rho_a(a)$ for a Wenner array for the two layered earth above is shown schematically in Fig. 7. It is clear that, in conventional resistivity sounding, to increase the depth of exploration we must increase the inter-electrode spacing.

In the case of TDEM sounding, on the other hand, we observed earlier that as time increased, the depth to the current loops increased, and we can allow this phenomenon to carry out our sounding of resistivity with depth. Thus, in analogy with equation (4), we can invert equation (1) to read (since $\rho = 1/\sigma$)

$$\rho_a(t) = \frac{k_2 \quad M^{2/3}}{e(t)^{2/3} t^{5/3}} \tag{5}$$

Suppose once again that the terrain resistivity does not vary with depth (i.e. a uniform half-space) and is of resistivity ρ_1. For this case a plot of $\rho_a(t)$ against time would be as shown in Fig. 8. We see that, at late time the apparent resistivity $\rho_a(t)$ is equal to ρ_1, but at early time $\rho_a(t)$ is much larger than ρ_1. The reason for this is that our definition of apparent resistivity is based (as seen from Fig. 6) on the time behaviour of the receiver coil output voltage at late time when it decays as $t^{-5/2}$. At earlier and intermediate time Fig. 6 shows that the receiver voltage is too low (the dashed line indicates the voltage given by the "late stage approximation") and thus from equation (5) the apparent resistivity will be too high. For this reason, there will always be, as shown on Fig. 8, a "descending branch" at early time where the apparent resistivity is higher than the half-space resistivity (or, as will be seen later, is higher than the upper layer resistivity in a horizontally layered earth). This is not a problem, but it is an artifact of which we must be aware.

Supppose that once again, we let the earth be two-layered, of upper layer resistivity ρ_1, and thickness h, and basement resistivity ρ_2 ($>\rho_1$). At early time when the currents are entirely in the upper layer of resistivity ρ_1 the decay curve will look like that of Fig. 6, and the apparent resistivity curve will look like Fig. 8. However, later on the currents will lie in both layers, and at much later time they will be located entirely in the basement, of resistivity ρ_2. Since $\rho_2>\rho_1$, equation (5) shows that, as indicated in Fig. 9a, the measured voltage will now be less than it should have been for the homogeneous half-space of resistivity ρ_1. The effect on the apparent resistivity curve is shown in Fig. 10a and is (since at late times all the currents are in the basement) that the apparent resistivity $\rho_a(t)$ becomes equal to ρ_2, completely in analogy for Fig.7 for conventional resistivity measurements. In the event that $\rho_2<\rho_1$, the inverse behaviour is also as expected, i.e. at late times the measured voltage response, shown in Fig. 9, is greater than that from a homogeneous half-space of resistivity ρ_1, and the apparent resistivity curve correspondingly becomes that of Fig. 10b, becoming equal to the new value of ρ_2 at late time. Note that, for the case of a (relatively) conductive basement there is a region of intermediate time (shown as t*), where the voltage response temporarily falls before continuing on to adopt the value appropriate to ρ_2. This behaviour, which is a characteristic of TDEM, is again not a problem, as long as it is recognized. The resultant influence of the anomalous behaviour on the apparent resistivity is also shown on Fig. 10b at t*.

To summarize, we see that, except for the early-time descending branch, and the intermediate-time anomalous region described above, the sounding behaviour of TDEM is analogous to that of conventional DC resistivity if we let the passage of time achieve the increasing depth of exploration rather than increasing inter-electrode spacing.

Curves of apparent resistivity such as Fig. 10 tend to disguise the fact, that, at very late times, there is simply no signal, as is evident from Fig. 9. In fact in the TDEM central loop sounding method it is unusual to see, in practical data, the curve of apparent resistivity actually asymptote to the basement resistivity, due to loss of measurable signal. Fortunately, both theoretically and in practice, the information about the behaviour of the apparent resistivity curve at early time and in the transition region is generally sufficent to allow the interpretation to determine relatively accurately the resistivity of the basement without use of the full resistivity sounding curve.

Section 3. Measurement Procedures

As stated in Section 1 a common survey configuration consists of a square single turn loop with a horizontal receiver coil located at the center. The data from a resistivity sounding consists of a series of values of receiver output voltage at each of a succession of gate times. These gates are located in time typically from a few microseconds up to tens or even hundreds of milliseconds after the transmitter current has been turned off, depending on the desired depth of exploration. The receiver coil measures the time rate of change of the magnetic field e(t)=dB/dt, as a function of time during the transient. Properly calibrated, the units of e(t) are volts per m^2 of receiver coil area, however since the measured signals are extremely small it is common to use nanovolts per m^2, and measured decays typically range from many thousands of nV/m^2 at early times to less than 0.1 nV/m^2 at late times. Modern receivers are calibrated in nV/m^2 or V/m^2 and to check the calibration use is often made of a "Q-coil", which is a small short - circuited multi-turn coil laid on the ground at an accurate distance from the receiver coil, so as to provide a transient signal of known amplitude.

The two main questions in carrying out a resistivity sounding are (1) how large should the side lengths of the (usually single turn) transmitter be, and (2) how much current should the loop carry? Both questions are easily answered by using one of the commercially available forward layered-earth computer modelling programs. A reasonable guess as to the possible geoelectric section (i.e. the number of layers, and the resistivity and thickness of each) is made, this data is fed into the program, along with the proposed loop size and current, and the transient voltage is calculated as a function of time. For example, assume that it is suspected that a clay aquitard may exist at a depth of 20 m in an otherwise clay-free sand. The resistivity of the sand might be 100 Ωm, and that of the clay layer 15 Ωm. We want to know the minimum thickness of the clay layer that we could detect, and, if it is present, how accurately we can measure its thickness. The depth of exploration is of the order of the loop edge size, so we might try 10 x 10 m in our model calculation, and also a loop current of 3 amps, which is characteristic of a low power, shallow depth transmitter. Before doing the calculations we note one feature accompanying use of small (i.e less than 60 m x 60 m) transmitter loops for shallow sounding. In these small loops the inducing primary magnetic field at the centre of the loop is very high, and the presence of any metal, such as the receiver box, or indeed the shielding on the receiver coil itself, can cause sufficient transient response to seriously distant the measured signal from the ground. This effect is greatly reduced by placing the receiver coil (and receiver) a distance of about 10 m outside the nearest transmitter edge. As we shall show later, the consequence of this on the data is relatively small.

Our first task is to see whether we can resolve the difference between for example, a clay layer 0 m thick (no clay) and one meter thick. The results of the forward layered earth calculation, shown in Fig. 11, indicate that the apparent resistivity curves from these two cases are well separated (difference in calculated apparent resistivity about 10%) over the time range from about 8μsec to 100 μsec, as would be expected from the relatively shallow depths. Note that, to use this early time information, we require a receiver that has many narrow early time gates in order to resolve the curve, and also has a wide bandwidth so as not to distort the early portions of the transient decay. We note from the figure that resolving thicknesses from 1 to 4 m and greater will present no problem.

Having ascertained that the physics of TDEM sounding will allow us to detect this thin layer, our next test is to make sure that the 10 x 10 m transmitter running at 3 amps will provide sufficient signal to noise over the time range of interest (8 to 100 μsec). The same forward layered earth calculation also outputs the actual measured voltages that would be measured from the receiver coil, and these are listed (for the case of thickness of 0 m, which will produce the lowest voltage at late times) in Table 1, on which we focus our attention on the first column (which gives the time, in seconds) and the third column (which gives the receiver output as a function of time, in volts/m^2). Now the typical system noise level (almost invariably caused by external noise sources, see Section 4) for gates around 100 to 1,000 μsec is about 0.5 nV/m^2 or 5×10^{-10}V/m^2. From columns 1 and 3 we see that, for the model chosen, the signal falls to 5×10^{-10}V/m^2 at a time of about 630 μsec and is much greater than this for the early times when our apparent resistivity curves are well resolved, so we learn that our 10 x 10 m transmitter at 3 amps is entirely adequate. In fact if we were to use a 5 m x 5 m transmitter the dipole moment (product of transmitter current and area) would fall by 4, as would our measured signals, and the signal-to-noise ratio would still be excellent over the time range of interest. We are thus assured, assuming that our model realistically represents the actual conditions of resistivity, etc. we will be able to detect the thin clay layer. Before proceeding with the actual measurement it would be wise to vary some of the model parameters, such as the matrix and clay resistivities, to see under what other conditions the clay will be detectable. The importance of carrying out such calculations cannot be overstated. The theory of TDEM resistivity sounding is well understood, and the value of such modelling, which is inexpensive and fast, is very high.

It was stated above that offsetting the receiver coil from the centre of the transmitter loop would not greatly affect the shape of the apparent resistivity curves. The reason for this is that the vertical magnetic field arising from a large loop of current (such as that shown in the ground at late time in Fig. 3) changes very slowly as we move around the loop centre. Thus, at late time, when the current loop radius is significantly larger than the transmitter loop radius, we would expect that moving the receiver from the centre of the transmitter loop to outside the loop would not produce a large difference, whereas at earlier times when the current loop radius is approximately the same as the transmitter radius, such offset will have a larger effect. This behaviour is illustrated in Fig. 12, which shows the apparent resistivity curves for the receiver at the centre and offset by 15 m from the centre of the 10 x 10 m transmitter loop. At late time the curves are virtually identical.

How closely spaced should the soundings be? One of the big advantages of TDEM geoelectric sounding over conventional DC sounding is that for TDEM the overall width of the measuring array is usually much less than the depth of exploration, whereas for conventional DC sounding the array dimension is typically (Wenner array) of the order of 3 times the exploration depth. Thus, in the usual event that the terrain resistivity is varying laterally, TDEM sounding will generally indicate those variations much more accurately. If the variations are very closely spaced one might even take measurements at a station spacing of every transmitter loop length. It should be noted that most of the time spent doing a sounding (especially deeper ones where the transmitter loop is large) lies in laying out the transmitter loop, and in this case it can be much more efficient to have one or even two groups laying out loops in advance of the survey party, who then follow along with the actual transmitter, receiver and receiver coil to make the sounding in a matter of minutes, again very favourable compared with DC sounding. A further advantage of TDEM geoelectric sounding is that, if a geoelectric interface is not horizontal, but is dipping, the TDEM still gives a reasonably accurate average depth to the interface. Similarly TDEM sounding is much less sensitive (especially at later times) to varying surface topography.

It was explained above that, particularly at later times, the shape of the apparent resistivity curve is relatively insensitive to the location of the receiver coil. This feature is rather useful when the ground might be sufficiently inhomogeneous to invalidate a sounding (in the worst case, for example, due to a buried metallic pipe). In this case a useful and quick procedure is to take several measurements at different receiver locations as shown in Fig. 13. Curve 5 is obviously anomalous, and must be rejected. Curves 1-4 can all be used in the inversion process, which handles both central and offset receiver coils. Another useful way to ensure, especially for deep soundings, that the measurement is free from errors caused by lateral inhomogeneties (perhaps a nearby fault structure) is to use a three component receiver coil, which measures, in addition to the usual vertical component of the decaying magnetic field, both horizontal components. When the ground is uniform or horizontally layered, the two horizontal components are both essentially equal to zero, as long as the measurement is made near the transmitter loop centre (which is why the technique is particularly relative to deep sounding). Departures from zero are a sure indication of lateral inhomogeneties which might invalidate the sounding.

Finally most receivers, particularly those designed for shallower sounding, have an adjustable base frequency to permit changing the length of the measurement time. With reference to Figs.1 and 4 changing the base frequency f_b will change the period T ($T=1/f_b$) and thus the measurement duration T/4. For transients which decay quickly, such as shallow sounding, the measurement period, which should be of the order of duration of the transient, should be short, and thus the base frequency high. This has the advantage that, for a given total integration time of, say 5 seconds, more transient responses will be stacked, to improve the signal to noise ratio and allow the use of smaller, more mobile, transmitter loops, increasing survey speed. On the other hand for deep sounding, where the response must be measured out to very long time, it is clear that the measurement period must be greatly extended so that the transient response does not run-on to the next primary field cycle or indeed the next transient response, and thus the base frequency must be significantly reduced. The signal-to-noise will deteriorate due to fewer transients being stacked, and must be increased by either using a larger transmitter loop and transmitter current (to increase the transmitter dipole) and/or integrating the data for a longer stacking time, perhaps for 30 seconds or even a minute. It should be noted that should such run-on occur because too high a base frequency was employed, it can still be corrected for in modern data inversion programs, however, in extreme cases the accuracy and resolution of the inversion will start to deteriorate.

Finally, in Fig. 4 and our discussion to date it is assumed that the transmitter current is turned off instantaneously. To actually accomplish this with a large loop of transmitter wire is impossible, and modern transmitters shut the current down using a very fast linear ramp. The duration of this ramp is maintained as short as possible (it can be shown to have an effect similar to that of broadening the measurement gate widths) particularly for shallow sounding where the transient decays very rapidly at early times. The duration of the transmitter turn-off ramp (which can also be included in modern inversion programs) is usually controlled by transmitter loop size and/or loop current.

Section 4. Sources of Noise

Noise sources for TDEM soundings can be divided into four categories

(1) circuit noise (usually so low in modern receivers as to rarely cause a problem)
(2) radiated and induced noise
(3) the presence of nearby metallic structures
(4) soil electrochemical effects (induced polarization)

Radiated noise consists of signals generated by radio and radar transmitters and also from thunderstorm lightning activity. The first two are not usually a problem, however, on summer days when there is extensive local thunderstorm activity the electrical noise from lightning strikes (similar to the noise heard on AM car radios) can cause problems and it may be necessary to increase the integration (stacking) time or, in severe cases, to discontinue the survey until the storms have passed by or abated.

The most important source of induced noise consists of the intense magnetic fields from 50/60 Hz power lines. The large signals induced in the receiver from these fields (which fall off more or less linearly with distance from the powerline) can overload the receiver if the receiver gain is set to be too high, and thus cause serious errors. The remedy is to reduce the receiver gain so that overload does not occur, although in some cases this may result in less accurate measurement of the transient since the available dynamic range of the receiver is not being fully utilized. Another alternative is to move the measurement array further from the power line.

The response from metallic structures can be very large compared with the response from the ground. Interestingly, the power lines referred to above can often also be detected as metallic structures, as well as sources of induced noise. In this case they exhibit an oscillating response (the response from all other targets, including the earth, decays monotonically to zero). Since the frequency of oscillation is unrelated to the receiver base frequency, the effect of power line structural response is to render the transient "noisy" as shown in Fig. 14. Since these oscillations arise from response to eddy currents actually induced in the power line by the TDEM transmitter, repeating the measurement will produce an identical response, which is one way that these oscillators are identified. Another way is to take a measurement with the transmitter turned off. If the "noise" disappears it is a good indication that power-line response is the problem. The only remedy is to move the transmitter further from the power line.

Other metallic responses, such as those from buried metallic trash, or pipes, can also present a problem, a solution for which was discussed in the previous section (multiple receiver sites, as shown in Fig. 13). If the response is very large, another sounding site must be selected. Application of another instrument such as a metal detector or ground conductivity meter to quickly survey the site for pipes can often prove useful.

A rather rare effect, but one which can occur, particularly, in clayey soils, is that of induced polarization. Rapid termination of the transmitter current can charge up the minute electrical capacitors in the soil interfaces (induced polarization). These capacitors subsequently discharge, producing current flow similar to that shown in Fig. 3, but in the opposite direction. The net effect is to reduce the amplitude of the transient response (thus increasing the apparent resistivity) or even, where the effect is very severe, to cause the transient response to become negative over some range of the measurement time. Since these sources of reverse current are localized near the transmitter loop, using the offset configuration usually reduces the errors caused by them to small values.

In summary, it should be noted that in TDEM soundings the signal-to-noise ratio is usually very good over most of the time range. However, in general the transient response is decaying extremely rapidly (of the order of $t^{-5/2}$, or by a factor of about 300 for a factor of 10 increase in time). The result is that towards the end of the transient the signal to noise ratio suddenly deteriorates completely and the data becomes exceedingly noisy. The transient is over!

Section 5. <u>Data Reduction and Interpretation</u>

In the early days of TDEM sounding, particularly in Russia where the technique was developed (Kaufman and Keller, 1983) extensive use was made of numerically calculated apparent resistivity curves for a variety of layered earth geometrics. The field data would be compared with a selection of curves, from which the actual geoelectric section would be determined.

More recently the advent of relatively fast computer inversion progorams such as the Interpex TEMIX allow the field transient data to be automatically inverted to a layered earth geometry in a matter of minutes. A program such as TEMIX offers an additional significant advantage.

All electrical sounding techniques (conventional DC, magneto-telluric, TDEM) suffer to a greater or less extent from equivalence, which basically states that, to within a given signal-to-noise ratio in the measured data, more than one specific geoelectric model will fit the measured data. This problem, which is seldom addressed in conventional DC soundings, is one of which the interpreter must be aware, and the advantage of the TEMIX program is that, given an estimate of the signal-to-noise ratio in the measured data, the program will calculate a selection of equivalent geoelectric sections that will also fit the measured data, immediately allowing the interpreter to decide exactly how unique his solution really is. Equivalence is a fact of life, and must be included in any interpretation.

Section 6. Summary

The advantages of TDEM geoelectric sounding over conventional DC resistivity sounding are significant. They include

(1) improved speed of operation
(2) improved lateral resolution
(3) improved resolution of conductive electrical equivalence
(4) no problems injecting current into a resistive surface layer

The disadvantages are that TDEM techniques

(1) do not work well in very resistive material
(2) interpretational material for TDEM on, for example, 3D structures is still under development
(3) TDEM equipment tends to be somewhat more costly due to its greater complexity.

As mentioned above, the advantages are significant, and TDEM is becoming a widely used tool for geoelectrical sounding.

Section 7. References

Kaufman, A.A., and Keller, G.V., 1983, Frequency and Transient Soundings. Elsevier, N.Y.

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{RECTAN}:
 record :  1

 1.    Title                        :  TEST
 2.    Number of layers             :  1
 3&4.  Thickness & Resistivity      :     Thickness [m]  Resistivity [Ohmm]
                                          INFINITE        .100000E+03
 5.    Source - RECTANGULAR LOOP:      10.00 X  10.00
 6.    Point of receiver (X0,Y0):      .000E+00,    .150E+02
 7.    Current in transmitter    :     3.00 [A]
 8.    Induction numbers         :   DEFAULT SELECTION
 9.    Real time          [sec]  :   T0=     .1000E-05  NT=    5  TM=    .1000E-02
10.    Field component           :   BZ
11.    On output file            :   TIME DOMAIN
12.    Output file name          :   X.DAT          record  1
13.    Turn off time             :      1 [us]
14.    Runon correction          :   NO
15.    Low pass filter correct.  :   NO
16.    Asymptotic approximation  :   TAS=  .00000E+00
```

TIME DOMAIN RESPONSE

REAL TIME	TAU	dBz/dt	APP.RES	TAU/H1	APP./RO1
.10000E-05	.79267E+02	.85461E-03	.31459E+03	.79267E+02	.31459E+01
.15849E-05	.99791E+02	.47244E-03	.21679E+03	.99791E+02	.21679E+01
.25119E-05	.12563E+03	.22169E-03	.16663E+03	.12563E+03	.16663E+01
.39811E-05	.15816E+03	.87414E-04	.14384E+03	.15816E+03	.14384E+01
.63096E-05	.19911E+03	.34155E-04	.12492E+03	.19911E+03	.12492E+01
.10000E-04	.25066E+03	.11955E-04	.11674E+03	.25066E+03	.11674E+01
.15849E-04	.31557E+03	.41257E-05	.11014E+03	.31557E+03	.11014E+01
.25119E-04	.39727E+03	.13721E-05	.10650E+03	.39727E+03	.10650E+01
.39811E-04	.50014E+03	.44950E-06	.10402E+03	.50014E+03	.10402E+01
.63096E-04	.62964E+03	.14541E-06	.10246E+03	.62964E+03	.10246E+01
.10000E-03	.79267E+03	.46628E-07	.10151E+03	.79267E+03	.10151E+01
.15849E-03	.99791E+03	.15002E-07	.10035E+03	.99791E+03	.10035E+01
.25119E-03	.12563E+04	.45975E-08	.10247E+03	.12563E+04	.10247E+01
.39811E-03	.15816E+04	.14868E-08	.10094E+03	.15816E+04	.10094E+01
.63096E-03	.19911E+04	.48920E-09	.98312E+02	.19911E+04	.98312E+00
.10000E-02	.25066E+04	.15192E-09	.99507E+02	.25066E+04	.99507E+00

Table 1 Forward response calculation

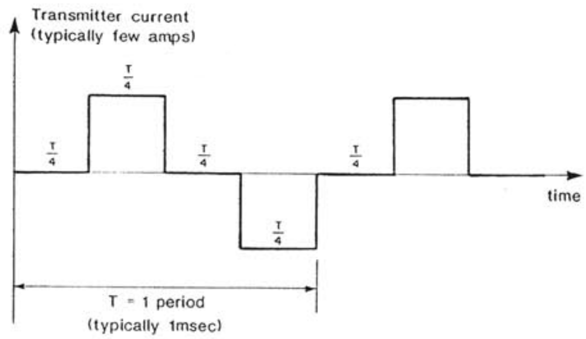

Fig. 1 Transmitter current waveform

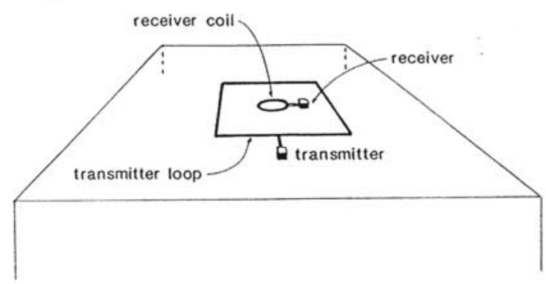

Fig. 2 Central loop sounding configuration

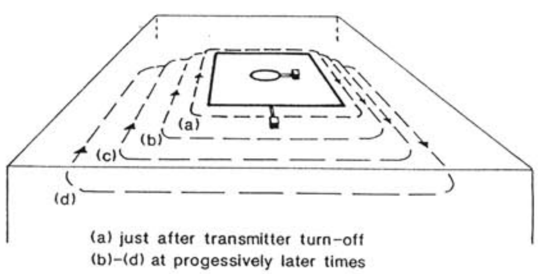

Fig. 3 Transient current flow in the ground

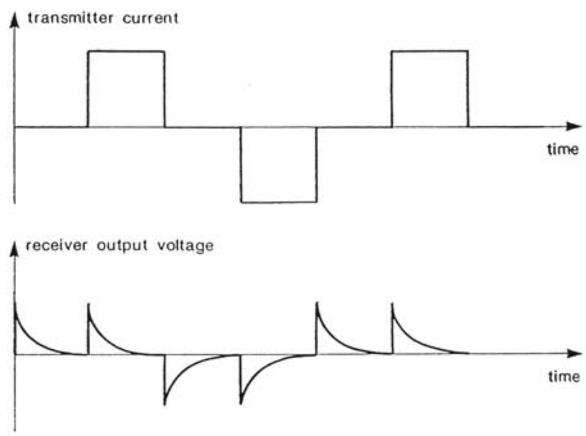

Fig. 4 Receiver output waveform

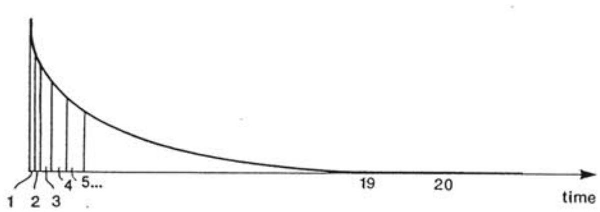

Fig. 5 Receiver gate locations

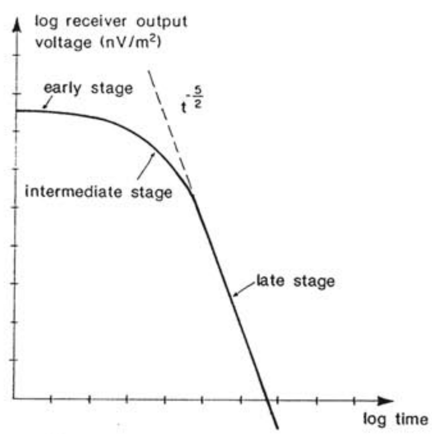

Fig. 6 Log plot – receiver output voltage vs time (one transient)

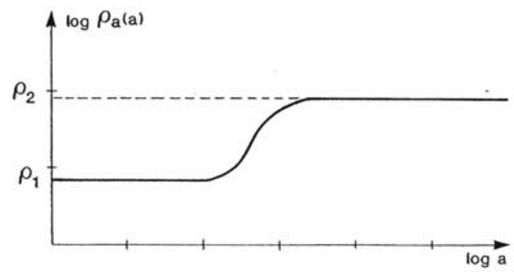

Fig. 7 Wenner array: apparent resistivity, two layer curve

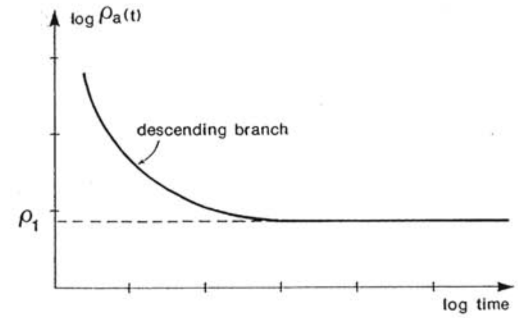

Fig. 8 TDEM: apparent resistivity, homogeneous half-space

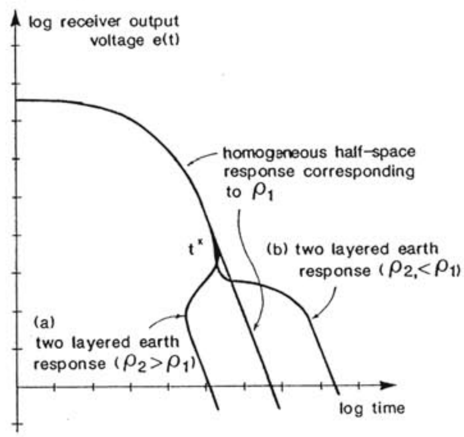

Fig. 9 TDEM: receiver output voltage, two layered earth

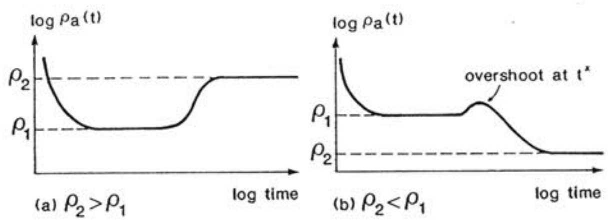

Fig. 10 TDEM: apparent resistivity, two layered earth

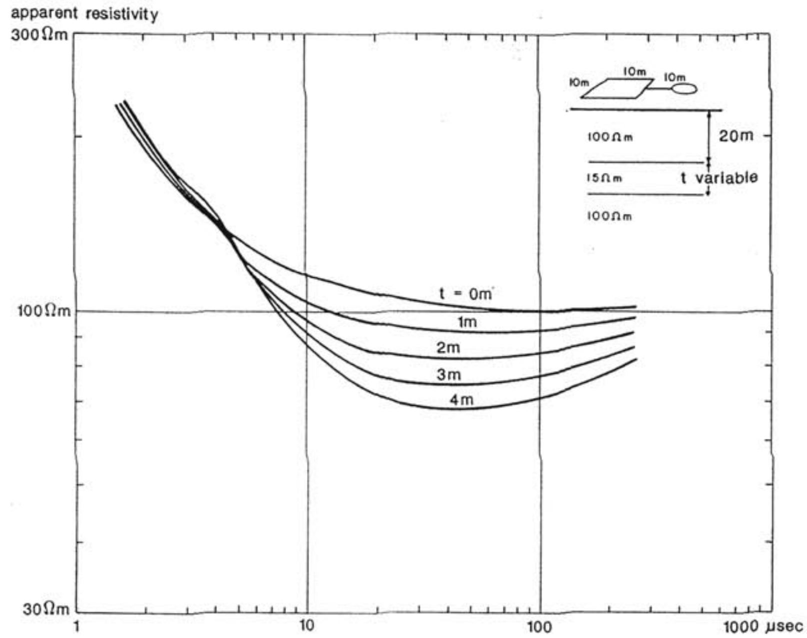

Fig. 11 Forward layered earth calculations

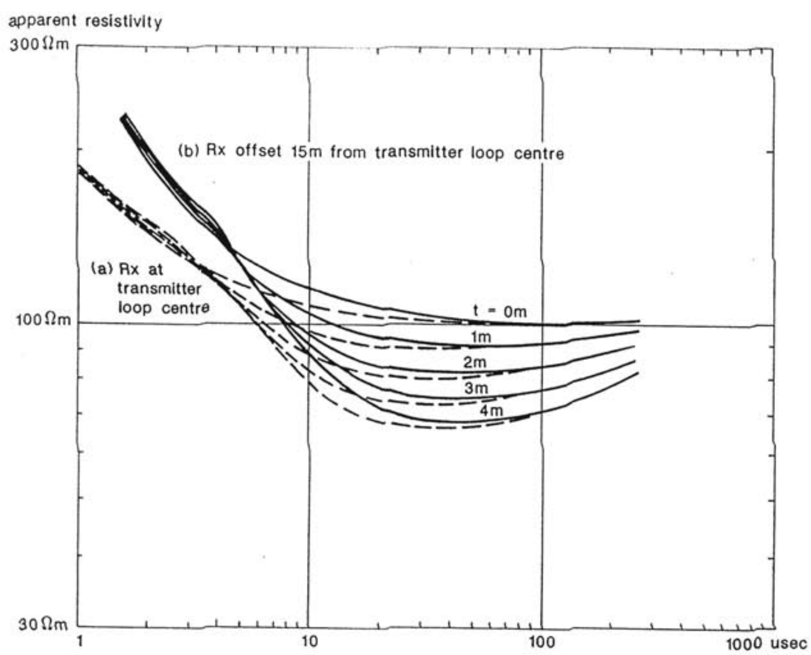

Fig 12 Forward layered earth calculations - (a) central loop sounding,
(b) offset sounding

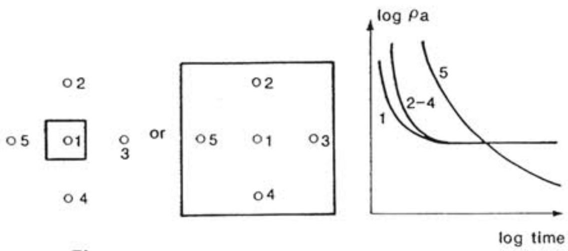

Fig. 13
Offset Rx locations to check lateral homogeneity, position 5 is near lateral inhomogeneity

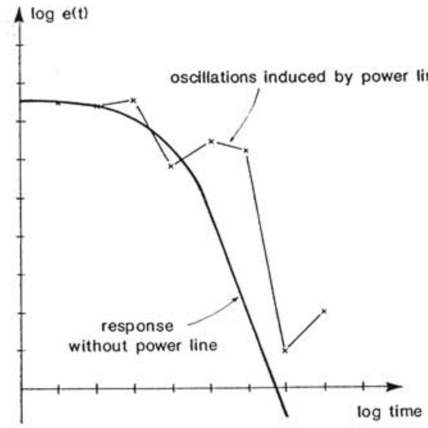

Fig. 14 Oscillations induced in receiver response by power line