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Technical Note TN-31

APPLICATION OF "DIPOLE-DIPOLE" ELECTROMAGNETIC SYSTEMS FOR GEOLOGICAL DEPTH SOUNDING

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Introduction

In Geonics Limited Technical Note TN-30 “Why Doesn’t Geonics Limited Build a Multi-Frequency EM 31 or EM 38?” we addressed the issue of why Geonics had never produced multi-frequency versions of their well known EM 31 or EM 38. Indeed in that note two apparently excellent reasons were given for building such instruments. These were (i) to allow the geoelectrical sounding of a multi-layered earth rather than measuring the depth-averaged bulk conductivity, and (ii) to supply additional interpretive data for improving target diagnostics in identifying the nature of buried metal.

However it was pointed out in the Technical Note that (i) unless the operating frequency range of a multi-frequency EM 31 or EM 38 extended up to the MHz frequency range it was impossible to resolve a multi-layered earth with such an instrument, and (ii) that the coil configuration of the EM 31 or EM 38 (or similar instruments) combined with the fact that they operated in the frequency domain meant that whilst they were indeed useful for indicating the presence of buried metal, they were extremely poor at accurately locating and identifying the nature of the buried metal. Indeed, it was for this reason that neither the EM 31 nor EM 38 were promoted by Geonics Limited for this latter application, although both instruments have seen a good deal of activity in the identification of buried metal.

There is still controversy on both of these matters, and a competing commercial multi-frequency instrument claims to be superior to both the EM 31 and EM 38 for both layered earth geoelectric sounding and the detection, location, and identification of buried metallic targets. It is one of the purposes of this technical note to explain in greater detail why these claims are unfounded. A second purpose is to describe the application of conventional (low induction number) electromagnetic systems for measuring variations in both electrical conductivity and magnetic susceptibility with depth. The last purpose is to show that certain instrument responses that arise from operation at low values of induction number allow a rapid and relatively accurate technique for ensuring that the instruments are indeed working correctly as they were designed; conversely, the technique allows quick detection of instrument operating faults or design defects.

Layered Earth Geoelectric Sounding
The Low Induction Number Approximation

Our discussion for this Technical Note extends (after some review) the treatment given in Geonics Limited Technical Note TN-6 “Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers”. We will restrict much of our attention to the situation where both transmitter and receiver dipoles are vertically oriented on a horizontally layered earth (which we initially assume to have an electrical conductivity which is invariant with depth, i.e. we assume that the earth is a "homogeneous half-space") as shown in Figure 1. We have chosen a vertical dipole transmitter since it is obvious from symmetry that if the ground is either homogeneous or horizontally layered the currents induced in the ground by this transmitter must consist of horizontal concentric circles centered on the transmitter axis, as shown schematically in Figure 1. It is less obvious but it can be shown that, under the same conditions, all other transmitter coil orientations will also generate only horizontal current flow (although no longer circular), and as we shall see, much of the basic physics described below will apply to other transmitter coil orientations as well.

We assume that the transmitter coil of magnetic dipole moment M is energized with a primary alternating current at frequency f, producing an alternating transmitter dipole moment $M\ e^{i\omega t}$, where $\omega = 2\pi f$. The electrical conductivity of the ground has the value σ. The various geological and hydrological factors which influence the value of σ are briefly discussed in Geonics Limited Technical Note TN-5 "Electrical Conductivity of Soils and Rocks" and McNeill (1990).

Now as indicated in Figure 1 the alternating primary current flow in the dipole transmitter generates a proportional (alternating) primary magnetic field H_P which is electrically "in-phase" with the transmitter current. Faraday's Law states that this (time-varying) primary magnetic field induces a primary electromotive force (EMF) e_P in the conductive ground, which in turn causes the loop current i_1 to flow. Since the primary magnetic field H_P is always "in-phase" with the transmitter current, and Faraday's Law dictates that the primary EMF e_P is proportional to the time rate-of-change of the primary magnetic field, the EMF e_P ($\propto \partial H_P / \partial t = i\omega H_P$) will be in "quadrature phase" with the primary magnetic field, i.e. it will lead the primary magnetic field by 90 degrees.

We wish to emphasize three important points. If (i) the value of R_1 (the electrical resistance of loop 1 is large; if (ii) the transmitter frequency is very small; and finally if (iii) we focus our attention only on those current loops that flow <u>in the immediate vicinity of the transmitter loop</u>, then simple circuit theory (described in Technical Note TN-6) shows that we can ignore the loop impedances caused by the self inductance L_1 and the mutual inductance M (which arises from magnetic coupling with other current loops generated by the primary magnetic field). In this case the ground current i_1 that flows in loop 1 is given (through Ohm's law) by $i_1 = e_P / R_1$. This ground current will be "in-phase" with e_P and thus in "quadrature" phase with the primary transmitter current and the primary magnetic field.

Of course this ground current i_1 will (like the primary current in the transmitter coil), generate a proportional (secondary) magnetic field which we can measure, along with the primary magnetic field arising directly from the transmitter current, using a receiver coil located on the surface of the earth at a distance s from the transmitter coil.

The major differences between the primary and the total secondary magnetic fields will be that the primary field caused by the large transmitter current will be much larger than the secondary field generated by the vastly smaller current flow in the ground, and furthermore that the secondary field will, for the reasons given above, be in quadrature phase with the primary field.

Since the secondary magnetic field is proportional to i_1, which in turn is inversely proportional to the loop resistance R_1, the measured secondary magnetic field will be directly proportional to the electrical loop conductance G_1 (where $G_1 = 1/R_1$) which is obviously directly related to the electrical conductivity of the ground. Thus, measurement of the ratio of the quadrature secondary magnetic field to the in-phase primary magnetic field will yield (after proper calibration of the system) the conductivity of the underlying terrain.

These, then, are the physical principles (including approximations) which describe operation of many of the Geonics Limited instruments (EM 31, EM 34-3, EM 38, and EM 39), all of which, for reasons outlined below, are said to be "operating at low values of induction number".

We now return to the more general case and no longer ignore the effects of the loop self inductance L_1 of loop 1 and the mutual inductance M between loop 1 and other current loops.

We know that in the immediate vicinity of the transmitter, it is the time-varying (in this case, alternating) primary magnetic field which induces an EMF and thus current flow in the nearby earth. This current flow in turn generates a new alternating magnetic field, which induces an additional EMF which causes additional current flow, but now at slightly larger depth (for example loop 2 in Figure 1) and at slightly larger radial distance from the transmitter. Now the alternating magnetic field arising directly from the nearby transmitter induced a quadrature phase EMF in the ground near the transmitter. The (until-now-ignored) effects of L_1 and M cause an additional phase shift between the EMF in any loop and the resultant current flow in that loop. Furthermore the phase shifts arising from the self and mutual inductances will be larger for currents flowing further from the transmitter, so that although these phase shifts may be safely ignored for current flow near the transmitter (i.e. at short radial distances and at shallow depths) current flow at larger distances and greater depths will definitely exhibit a significant additional phase shift (in addition to the 90 degrees discussed above) with respect to the primary magnetic field.

The alternating primary magnetic field from the transmitter causes a secondary magnetic field to diffuse radially away from the transmitter in all directions, and this secondary magnetic field is progressively more phase shifted with greater distance from the transmitter. Although we like to divide electromagnetic systems into "frequency domain" and "time domain", they are all, in reality, time domain, since by Faraday's Law every distant current loop has been induced by the time-rate-of-change of a current loop nearer the transmitter.

We are all familiar with the concept of skin depth, which is defined as the distance into a homogeneous half-space to which an incident plane wave will penetrate before its amplitude is reduced to $1/e$ of the amplitude of the wave at the surface of the half-space. The skin depth is defined by

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \sigma}} \ , \tag{1}$$

and we see that it, too, is determined by the values of the terrain conductivity and the operating frequency, decreasing as the conductivity and frequency increase. What is perhaps less well appreciated is that, as the incident wave propagates (or, more accurately diffuses) into the homogeneous half-space the phase of electric and magnetic components of the wave (relative to the value at the surface) also vary linearly with distance into the half-space, and the rate of phase change with distance into the half-space increases with decreasing skin depth, i.e. with increasing conductivity and frequency.

Exactly the same behaviour occurs with the dipole transmitter of Figure 1. If the ground conductivity and the operating frequency are both small (i.e. the skin depth in the ground is large) a receiver coil can be placed at a relatively large horizontal distance from the transmitter before the secondary magnetic field arising from the ground currents is other than quadrature phase with respect to the primary magnetic field. If on the other hand the skin depth in the ground is small, we will find an additional phase shift when the receiver coil is placed at a short distance from the transmitter.

From the above it will be apparent that the parameter which determines whether or not the measured secondary field is in quadrature phase with the primary field (and, more importantly for our purposes, whether measurement of the quadrature phase component of the secondary magnetic field will directly yield the ground conductivity), is the ratio between the distance s of the receiving coil from the transmitter, and δ, the skin depth in the ground. This important ratio, denoted by B,

$$B = s / \delta , \tag{2}$$

is known as the induction number of the survey system.

Now in the most general case of arbitrary values of transmitter frequency, ground conductivity, and intercoil spacing (for it is obviously the intercoil spacing which determines the distance from the transmitter at which the receiver coil is sensing the magnitude and phasing of the ground current flow by measuring the resultant magnetic field), it is shown by Keller and Frischknecht (1966) that the ratio of the magnetic field measured by the (vertical dipole) receiver coil with reference to the primary magnetic field arising directly from the (vertical dipole) transmitter coil is given by

$$\left(\frac{H_S + H_P}{H_P}\right) = \frac{2}{(\gamma s)^2}\left\{9 - \left[9 + 9\gamma s + 4(\gamma s)^2 + (\gamma s)^3\right]e^{-\gamma s}\right\}, \tag{3}$$

where
$$\gamma = \sqrt{i\omega\mu_0\sigma} \tag{4}$$

$$i = \sqrt{-1} \ . \tag{5}$$

The equation for the field ratio is a complicated function of the variable γs, which is, in turn, a reasonably complicated (complex) function of the frequency and ground conductivity.

However under certain conditions the expression simplifies considerably. The quantity γs is easily shown to be given by

$$\gamma s = \sqrt{2i}\,\frac{s}{\delta} = \sqrt{2i}B \,, \tag{6}$$

and under the condition that B « 1, i.e. that | γs |« 1, Kaufman and Keller (1983) show that the field ratio becomes (some care must be taken to include higher order terms in the expansion of the exponential term)

$$\left(\frac{H_S}{H_P}\right)_Q \simeq \frac{iB^2}{2} = \frac{i\omega\mu_0\sigma s^2}{4} \,. \tag{7}$$

The magnitude of the secondary magnetic field is now directly proportional to the ground conductivity, and the phase of the secondary magnetic field is shifted from the primary magnetic field by 90 degrees, i.e. is in phase quadrate. The condition B « 1 is technically known as "operation at low values of induction number". It is obvious from our discussion that operation under this condition implies that the transmitter frequency is sufficiently low that we can ignore the influence of self and mutual inductance in any ground current flow, the magnetic field of which is sensed by the (relatively nearby) receiver coil.

Under the same conditions of low induction number, Kaufman and Keller (1983) show that there is also a small inphase component to the secondary magnetic field, given by

$$\left(\frac{H_S}{H_P}\right)_I \simeq \frac{8B^3}{15} = \frac{2\sqrt{2}}{15} s^3 (\omega\mu_0\sigma)^{\frac{3}{2}} \,. \tag{8}$$

We note that, as a result of the dependence on B^3 rather than B^2, for small values of B the inphase component of the secondary magnetic field will be much smaller than the quadrature phase component.

Another coil configuration that will interest us is the horizontal dipole configuration which, as shown in Technical Note TN-6, consists of horizontal coplanar transmitter and receiver dipoles. It is shown by Keller and Frischknecht (1966) that for this configuration the ratio of measured to primary magnetic fields is given by

$$\left(\frac{H_S + H_P}{H_P}\right) = 2\left\{1 - \frac{3}{(\gamma s)^2} + \left[3 + 3\gamma s + (\gamma s)^2\right]\frac{e^{-\gamma s}}{(\gamma s)^2}\right\}. \tag{9}$$

Once again, under the condition that, $|\gamma s| \ll 1$, this expression simplifies to

$$\left(\frac{H_S}{H_P}\right)_Q \simeq \frac{iB^2}{2} = \frac{i\omega\mu_0\sigma s^2}{4} \tag{10}$$

and for this coil configuration as well, under the low induction number approximation, the system correctly indicates the true conductivity of the earth, and, furthermore, under this condition it can be shown that the inphase component of the secondary field is again much less than the quadrature component.

Geoelectric Sounding Using a Dipole-Dipole Configuration
Effect of Increasing Frequency

In ground-based electromagnetic exploration systems we will assume that the "dipole-dipole" configuration refers to coil configurations in which s, the intercoil spacing is a small fraction of a skin depth (unlike the case for airborne applications, where the term describes configurations in which the intercoil spacing is a small fraction of the bird height above the ground).

Let us examine typical values of induction number for short spacing, dipole-dipole electromagnetic systems.

For example let f=20 kHz, s=2 m, and let the ground conductivity be 20 mS/m, a typical value for near-surface conductivity. In this case the skin depth is 25 m, and the induction number B is less than 0.1, which qualifies as a low value. Even if the operating frequency is 50 kHz, and the ground conductivity is 33 mS/m, the skin depth is 12 m, and the induction number is still a small quantity. We see that at these (typical) frequencies, with typical values of near-surface terrain conductivity, and the short intercoil spacings employed in order to achieve instrument portability, such instruments will always be working at or near the low induction number range.

Now in our discussion above we pointed out that a salient fact accompanying operation at low induction number was that the magnetic coupling between all ground current loops was negligible, and thus that any two current loops were essentially unaware of each other. The magnitude of current flow in any loop is determined by the strength of the inducing EMF at the location of that loop, the local ground conductivity, and the frequency of the transmitter, which is of course the same for all loops. As long as we remain in the low induction number regime, increasing the transmitter frequency linearly increases the secondary magnetic field from all of the loops, but does not affect the relative contribution from any one loop. The resultant secondary magnetic field at the receiver coil is the sum of the independent magnetic fields from each of the individual current loops.

An extremely important ramification of this fact is that we can construct a mathematical function of depth which describes the relative contribution to the secondary magnetic field, measured at the surface, arising from the material within a thin horizontal layer at any given depth z. The relatively complex details of the derivation of this function will not be given here, but, for example, for the case of the vertical-dipole transmitter/receiver coil system, the extremely simple result is given by (Kaufman and Keller, 1983)

$$S(Z) = \frac{4Z}{\left(4Z^2+1\right)^{3/2}}, \quad (11)$$

where it is important to note that $Z = z/s$ is the actual depth z divided by the intercoil spacing s. (It should be noted that this expression is defined as $\Phi(Z)$ in Technical Note TN-6, but $S(Z)$ would appear to be more appropriate and is used in the remainder of this Technical Note). It is easy to show that the function $S(Z)$ obeys

$$\int_0^\infty S(Z)dZ = 1, \quad (12)$$

i.e. is normalized to the value unity, and thus, for a given conductivity distribution that varies with depth as $\sigma(Z)$, the apparent conductivity read by the instrument is given by

$$\sigma_a = \int_0^\infty \sigma(Z)S(Z)dZ, \quad (13)$$

Conversely, if the conductivity is uniform with depth, $\sigma(Z) = \sigma$ and $\sigma_a = \sigma$; the instrument correctly reads the true conductivity of the ground.

A plot of the function $S(Z)$ is shown in Figure 2. It illustrates, for example, that maximum sensitivity of the vertical dipole configuration as a function of normalized depth occurs at a depth of about 0.4 intercoil spacings, regardless of the actual intercoil spacing as long as this spacing, the operating frequency, and the ground conductivity are of values such that the low induction number approximation is still fulfilled.

An extremely important feature of this function is that it describes only how the instrument sensitivity varies with depth; it gives absolutely no information as to how the conductivity itself actually varies with depth. For example, examination of Figure 2 shows that a layer of conductivity 10 mS/m, with (normalized) thickness 0.10 situated at a (normalized) depth of 1.0 (where $S(Z)$=0.35), would give exactly the same contribution to the measured apparent conductivity as a second layer of conductivity (0.35/0.20)×10 mS/m, again with normalized thickness 0.10, but now located at (normalized) depth of 1.5 (where $S(Z)$=0.20).

Given that this curve offers no information about the variation of conductivity with depth, we must either alter the actual depth of this curve, or we must alter the shape of the curve as a function of depth, in order to study the variation of conductivity with depth. By successively varying either the depth or the shape of the curve, and by recording the resultant change in measured apparent conductivity, we can, at least in theory, mathematically invert the measured apparent conductivity to obtain the profile of true conductivity with depth.

To return briefly to the horizontal dipole intercoil orientation, it is possible to compute a similar function $S(Z)$. Once again, whilst the derivation is relatively complex, the resulting expression is extremely simple, and is now given by (Kaufman, 1993)

$$S(Z) = 2 - \frac{4Z}{\left(4Z^2+1\right)^{\frac{1}{2}}} \tag{14}$$

All of the comments made about the function $S(Z)$ above for vertical dipoles also apply to the same function for horizontal dipoles. In the latter case the shape of the new function $S(Z)$ is also shown in Figure 2, where it is seen that the system sensitivity with depth for horizontal dipoles is quite different from that for vertical dipoles, and is now a maximum for material immediately at the surface, decaying monotonically thereafter with depth.

Geoelectric Sounding

There are two main ways in which the geoelectric section of the ground can be obtained with electromagnetic systems of the type described here. In the first, called geometric sounding, the effective depth of exploration is varied by changing some aspect of the geometry of the system. For example this might be achieved by successively increasing the intercoil spacing, or by successively increasing the height of the system above the ground, or by altering the geometry of the transmitter coil/receiver coil configuration.

In the second method of geoelectric sounding, called multi-frequency sounding, the geometry of the system is fixed, and the frequency is varied to vary the depth of exploration.

Geometric Sounding

Suppose we decide to examine the geoelectric layering of the terrain conductivity using geometrical sounding. One way would be by increasing s, the intercoil spacing (whilst, if necessary, simultaneously lowering the transmitter frequency so as to always maintain the low induction number approximation). Referring to Figure 2 we would effectively, since $Z = z/s$, be dropping the function $S(Z)$ down through the layered earth structure (with ever increasing thickness of the region of maximum response) thus sampling the layered earth structure at greater and greater depths. This procedure, which is used with the Geonics Limited EM 34-3, is entirely analogous to conventional DC resistivity sounding, where we perform the sounding by making measurements of the apparent resistivity of the ground at successively increasing inter-electrode spacing.

A problem with such a sounding is that technical limitations make it difficult to employ a wide variety of intercoil spacings, and, for example, the EM 34-3 allows use of only three intercoil spacings, each a factor of two greater than the previous spacing. The resultant sparse data set can lead to relatively poor resolution of layered earth equivalences, so that when this sounding procedure is employed, measurements are usually taken in both vertical and horizontal dipole coil configurations to achieve more independent data points for the sounding. Inversion of such survey data is routinely achieved using commercial inversion programs such as those produced by Interpex Limited.

Another method of geometric sounding consists of lifting the instrument above the ground, taking measurements of apparent conductivity at increasing heights. In this case we are performing the geometrical sounding by lifting the function $S(Z)$ up through the layered earth conductivity structure as we lift the instrument itself. Such soundings are easily carried out with either the Geonics Limited EM 38 or EM 31. Examination of the two curves of $S(Z)$ shown in Figure 2 clearly indicate that use of the vertical dipole configuration will offer better survey data, since in this case the response maximum will successively be drawn up through the various layers of the geoelectric section as the instrument is raised to successively greater heights.

This procedure, which is appropriate for shallow sounding to depth of the order of $Z/2$ makes excellent use of the instrumental qualities of the EM 38 or EM 31, vis that both instruments are extremely well electrostatically shielded (see discussion below) and have, in addition, good (EM 38) to very good (EM 31) zero stability. Once again inversion of the survey data is carried out with commercial computer programs such as those offered by Interpex Limited.

It is interesting to consider the results of the last type of sounding for two specific conductivity distributions.

Consider first the special case where the geoelectric layering of the earth consists of a thin (with respect to the intercoil spacing) conductive layer of conductivity σ_0 and thickness ΔH located just beneath the surface, and overlying an infinitely resistive (zero conductivity) substrate of infinite vertical extent. For this case, since the function $S(Z)$ is defined as the sensitivity of the instrument with depth, it is clear that as we lift this function up through the thin conductive layer by lifting the instrument to various values of the (normalized) height H, equation (13) for the apparent conductivity becomes

$$\sigma_a(H) \simeq \sigma_0 \times \Delta H \times S(H) \tag{15}$$

and the curve of $\sigma_a(H)$ replicates the curve for $S(H)$, multiplied by the conductivity-thickness product of the conductive layer.

The second special case of interest is that in which the earth consists of a homogeneous half space of conductivity σ_0. It was shown in Geonics Limited Technical Note TN-6 that the function

$$R(Z)=\int_{Z}^{\infty} S(Z)\,dZ \tag{16}$$

(shown in Figure 3 for the two functions, i.e. the two coil configurations, of Figure 2) was of special interest since the apparent conductivity of an arbitrarily layered earth could be simply expressed in terms of $R(H)$.

For the case of vertical dipoles the function is given by

$$R(Z)=\frac{1}{\left(4Z^2+1\right)^{1/2}} \tag{17}$$

and for horizontal dipoles

$$R(Z)=\left(4Z^2+1\right)^{1/2}-2Z\,. \tag{18}$$

It was shown in Technical Note TN-6 that in the general case of an n-layered earth, where each layer of is of conductivity σ_i and the depth to the top of the nth layer is given by Z_{n-1}, where $Z_0=0$, the apparent conductivity on the surface of the earth is given by

$$\sigma_a=\sigma_1\left[1-R(Z_1)\right]...+\sigma_i\left[R(Z_2-Z_1)\right]...+\sigma_n R(Z_{n-1})\,. \tag{19}$$

For the special case of a layer of zero conductivity and thickness H overlying a layer of conductivity σ_0, the behaviour of $\sigma_a(H)$ (the apparent conductivity as a function of H, the (normalized) instrument height), is therefore given by

$$\sigma_a(H)=\sigma_0\times R(H), \tag{20}$$

and in this case the curve of $\sigma_a(H)$ replicates the curve $R(H)$, multiplied by the ground conductivity.

Now it is usually taken as a weakness of electromagnetic sounding techniques that they are relatively poor at resolving small variations in conductivity with depth, or conversely that small changes in conductivity will produce small changes in the shape of these response curves. However in our case this can be somewhat of an advantage. The significance of the two special earth geometries discussed above is that approximations to one or other of the two are often to be found in nature (more likely the second in most environmental applications). Therefore, in an area about which we know nothing, lifting the instrument above the earth and obtaining a data set which looks approximately like one of those shown in Figures 2 or 3 (depending on the subsurface geology) can be very reassuring in that it strongly suggests that the instrument is indeed working correctly. It is highly recommended that this procedure be periodically performed to ensure that all is well, particularly where a new instrument is being evaluated. Indeed, in any case it is highly recommended that a proper sounding and inversion be performed at some test site that can be periodically revisited to check out the instrument. Of course before carrying out such a sounding, the site should be thoroughly surveyed to identify buried metal or other localized conductivity inhomogeneities.

Finally, a third method of geometrical sounding, discussed in detail in the Geonics Limited EM 31 Operating Manual, relies on the fact that the function $S(Z)$ described above is quite different for the vertical and horizontal dipole coil configurations. Thus rotating the instrument from one configuration to the other immediately gives information as to whether the conductivity is increasing or decreasing with depth.

Furthermore in the case where the conductivity of the layered earth can be approximated by only two layers, one much more conductive that the other, the EM 31 Manual shows how to obtain the conductivity of the more conductive medium and either its thickness or depth (depending on whether the upper or lower layer is the more conductive).

In summary, to this point we have restricted our attention to the use of geometrical sounding where it was the vertical position or shape of the system response curve $S(Z)$ that was altered to perform the sounding (although in the first example we also altered the frequency but this was to ensure that we remained in the low induction number region). It was essentially the geometric properties of the dipole configuration that were employed to achieve the sounding, and we often say in this case that we are "source limited", meaning that it is the characteristics of the source/receiver field geometry that are used to achieve the sounding.

Magnetic Susceptibility Sounding

It is not generally realized, that in addition to measuring the electrical conductivity of the ground, dipole-dipole electromagnetic systems operating at low values of induction number are also effective in measuring and sounding the magnetic susceptibility of the ground. It was shown in equation (8) that, in the low induction number approximation, the inphase response of conductive ground was generally much less than the quadrature phase response. Moreover, and more importantly, the inphase response is also much less than the inphase response arising from typical values of terrain magnetic susceptibility. This is particularly true for very short intercoil spacing instruments such as the EM 38.

An excellent summary of the parameters affecting soil susceptibility is given in Dalan and Bannerjee (1998).

For our purposes it is sufficient to know that, as quoted in the EM 38 Operating Manual, the value of the magnetic susceptibility, κ, in RMKS units, of a homogeneous half space is given by

$$\kappa = 58\times10^{-6}\Delta\sigma_a \tag{21}$$

where $\Delta\sigma_a$ is the difference in apparent conductivity (in mS/m, with the instrument switch in the inphase position) measured first with the instrument located on the ground in the vertical dipole mode, and then elevated to a height of about 1.5 m above the ground.

It is furthermore not generally realized that, when measuring terrain magnetic susceptibility at low frequencies such as those of the EM 38, we can ignore the magnetic interaction between all secondary induced magnetic dipoles in the ground and can thus formulate functions analogous to $S(Z)$ and $R(Z)$ given above, but now for magnetically layered earth geometries. Details of the calculations, which are based on image theory, follow the procedures outlined in Keller and Frischknecht (1966). The results are as follows for vertical dipoles

$$S_v(Z) = \frac{-12Z\left(8Z^2 - 3\right)}{\left(4Z^2 + 1\right)^{7/2}} \tag{22}$$

$$R_v(Z) = \frac{-\left(8Z^2 - 1\right)}{\left(4Z^2 + 1\right)^{5/2}} \tag{23}$$

and for horizontal dipoles

$$S_h(Z) = \frac{-12Z}{\left(4Z^2 + 1\right)^{5/2}} \tag{24}$$

$$R_h(Z) = \frac{-1}{\left(4Z^2 + 1\right)^{3/2}} \;. \tag{25}$$

These simple functions are shown in Figures 4 and 5.

In exactly the same manner described above for conductivity sounding, i.e. by elevating the instrument above the ground, the inphase data obtained, as a function of (normalized) instrument height, can be inverted to give a profile of true susceptibility with (normalized) depth. And also of great importance, the act of raising the instrument over the ground will usually give an inphase response which approximates the expressions for $S(Z)$ or $R(Z)$ above. Over most soils, for example, our experience is that the response will resemble $R(Z)$, whereas over resistive bedrock, which contains thin layers of near-surface magnetite in any low-lying areas, the response will more nearly resemble $S(Z)$.

It must be emphasized that for either conductivity (i.e. quadrature phase) or susceptibility (i.e. inphase) the test of raising the instrument carefully over the ground and recording the data as a function of height has proven to be an extremely useful indicator of correct instrument performance. However, it must also be kept in mind that the curves of Figures 2-3 were calculated for the low induction number approximation, and will therefore become progressively less accurate as the quantities $\sigma\omega$ and s^2 or z^2 increase. Similar comments apply for Figures 4-5, but now related to the magnitude of κ and s^2 or z^2.

It should also be noted that while there are undoubtedly both advantages and disadvantages to geometrical sounding, one principal advantage is that the depth of exploration (which we wish to vary over a wide range to perform the sounding) is linearly proportional to the system dimensions, which in turn makes it relatively easy to achieve a reasonably large range of depth variation.

Multi-frequency Sounding

At least, in theory, as important as geometrical sounding is frequency sounding, in which the physical geometry of the survey system is fixed and the effective depth of exploration is altered by varying the transmitter frequency, and thus the skin depth. In this case we say that we are "skin depth" rather than "source" limited, and we now rely on the fact that, all other variables being equal, the effective depth of exploration decreases with decreasing skin depth and thus with increasing frequency. This method of geoelectric sounding is often used with slingram systems such as the Apex Max-Min.

In a multi-frequency sounding the required variation of system response with depth is achieved by varying the transmitter frequency. It is obvious that to achieve the best possible resolution of the geoelectric layering, we must select both the intercoil spacing of the instrument and the frequency range of operation so as to optimize the <u>variation of instrument response with depth</u> as we vary the frequency. Clearly we select the lowest frequency to give a skin depth that extends the instrumental response to the depth that includes the lowest layer of interest, and equally clearly we select the highest frequency that reaches the shallowest layers of interest. If we vary the frequency over a wide range, but other parameters of the instrument and ground are such that <u>variation of the response depth</u> is either very small, or does not extend over the region of interest, we will not achieve a useful geoelectric sounding.

In this respect a significant problem arises when we employ short values of intercoil spacing, for as we have seen above, under these conditions, for typical frequencies and values of ground conductivity, we are generally operating under conditions approximately those of low induction number, where, as discussed above, the effective depth extent of the curve of $S(Z)$ is essentially independent of the operating frequency. As we increase the frequency over the usual range for these instruments (typically from a few hundred Hz to the order of 50 kHz), while it is true that the shape and depth extent of the response curve do alter somewhat, the variation in the response with depth usually remains trivial, and a geoelectric sounding is therefore impossible to achieve.

That the depth of exploration is indeed virtually invariant with frequency in short spacing (dipole-dipole) multi-spectral instruments is almost always seen in actual survey practice. What one observes in such a multi-spectral survey profile (assuming that the survey objective is geoelectric sounding and <u>not</u> the detection of metallic targets), is that, except perhaps at the highest frequency, the survey profile at any frequency is virtually the same as that at any other frequency. There is absolutely no additional information gained from the fact that many frequencies are employed.

A further significant problem in multi-frequency sounding is that, as we have shown above, at low frequencies the inphase response arises not from the terrain electrical conductivity, but from the completely unrelated magnetic susceptibility. Thus any data inversion program must deal with these dual responses. An added complication is caused by the fact that the magnetic susceptibility can, depending on the mineral source, show either very little, or significant, frequency dependence over a given frequency range.

There are other significant disadvantages involved with the use of many frequencies. One such is that the "zero levels" of all inductive dipole-dipole instruments (single or multi-frequency alike) are extremely difficult to adjust and are even more difficult to maintain at stable levels over the life of the instrument (or, more seriously, just over the duration of the survey). It is obvious that the system with the most stable zero level will allow the most accurate measurement of the least conductive or least susceptible ground, and more importantly, allows contouring of the survey data to the smallest conductivity or susceptibility increments so as to achieve detection of the smallest anomalies. It turns out, however, that a major contributor to variations in the zero level is electric field rather than magnetic field effects. Such electric field effects are usually frequency dependent, and are virtually impossible to control with dipole-dipole multi-spectral instruments to the required accuracy. Indeed, even in using much larger spacing instruments of the slingram type, many surveyors have become altogether too familiar with the well known "swamp effects" where the survey readings depend, for example, on whether (or which) operator is wearing his rubber boots.

It is much better in the vast majority of cases to use a well-designed, extremely well shielded, single frequency instrument with highly stable zero and gain, than to use a multi-frequency instrument in which these parameters are poorly controlled.

To return again to the application of multi-spectral dipole-dipole systems to geoelectric sounding, the unfortunate fact is that, in order to obtain useful depth information, today's instruments, working at currently achievable levels of accuracy, will have to operate at values of induction number of the order of B ~ 1 rather than the current values of B ~ 0.1 in order to usefully resolve geoelectric equivalences, i.e. to produce useful geoelectric models.

Indeed a simple argument indicates the order of magnitude of B (call it B_{opt}) that will give the best geoelectric sounding. Consider the curve of Figure 2 which shows that the maximum response for the vertical dipole mode occurs at a value of $Z = z/s \simeq 0.4$ for the low induction approximation, i.e. where the response depth is not a function of frequency. As we increase the frequency we can imagine that this curve, when multiplied by a curve of the form $e^{-z/\delta}$, gives, very approximately, the new response with depth, now a function of frequency. It is not difficult to imagine that maximum sensitivity for inversion to yield the maximum resolution of equivalence would occur at a value of $z/\delta \simeq 1$ (certainly it will not be for values of $z/\delta \ll 1$ or $z/\delta \gg 1$ when, simultaneously, $Z \simeq$ 0.4. Solving these equations yields $B_{opt} \simeq$ 2.5.

But $B \propto \sqrt{f}$; therefore to achieve the necessary increase in B, say a factor of 5-10 to get us into the correct operating range, requires a substantial increase in f. For example a value of B ~ 1 implies, assuming that the intercoil spacing is 2 m and that the ground conductivity is of the order of 50 mS/m, that the operating frequency must be of the order of 1 MHz, much higher than the highest frequency of today's dipole-dipole systems (with the exception of the U.S.G.S. VETEM system).

Yet another very significant problem arises because at these high frequencies the influence of displacement currents (i.e. of dielectric phenomena in the ground) become significant, greatly complicating interpretation of survey data.

The main argument for using short spacing dipole-dipole instruments to perform geoelectrical soundings at high audio frequencies seems to be a carry-over from the use of such systems for airborne surveys where, other difficulties not withstanding, it is possible to measure signal levels of the order of parts per million (ppm). On the other hand, for ground dipole-dipole systems (i.e. those which are deployed either lying on the ground or at a height of a meter or so above it), the problems of measuring signal levels to accuracy of the order of a fraction of a percent over the wide range of high frequencies necessary to achieve the required range of B remain formidable.

Conclusions

As we have shown in this and earlier Geonics Limited Technical Notes, a great deal of extremely useful geological information can be derived from surveying with a well designed, single frequency, dipole-dipole electromagnetic system that has been appropriately chosen for the particular survey task.

On the other hand, the current state-of-the-art in the manufacture of multi-spectral dipole-dipole electromagnetic systems has not advanced to the stage where they provide acceptable geoelectrical soundings. To date, their only advantage lies in the fact that they allow rough characterization of various types of metallic targets, a role for which the constraints on equipment performance are much less demanding. In the very near future it is our opinion that the demands that will be made on instruments designed for accurate characterization of metallic targets will also have reached the stage where multi-spectral dipole-dipole instruments will still be of very limited use.

Acknowledgement

It is now over twenty years since Alex Kaufman started his immensely valuable association with Geonics Limited, and we would like to again extend our gratitude to him for his enormous contributions to our understanding of the physics of electromagnetic mapping and prospecting.

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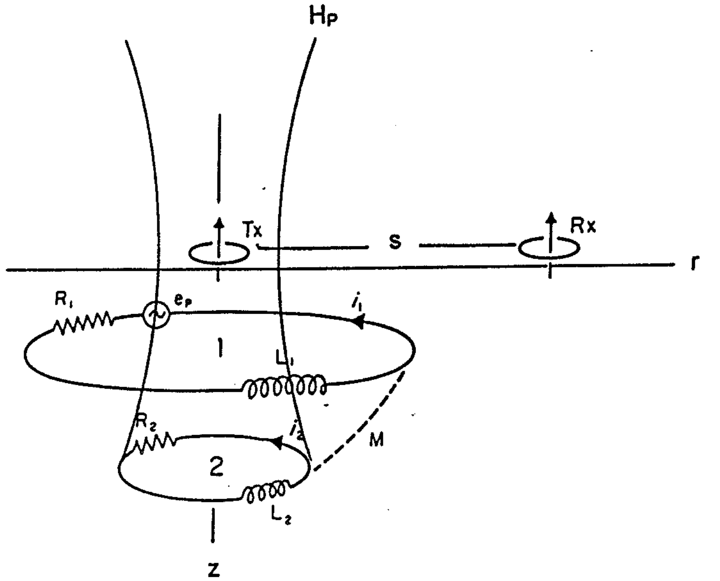

Figure 1. Electrical Model for Vertical Dipoles.

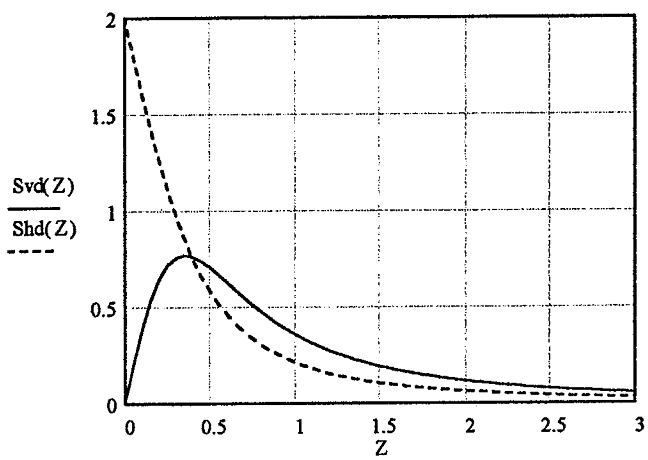

Figure 2

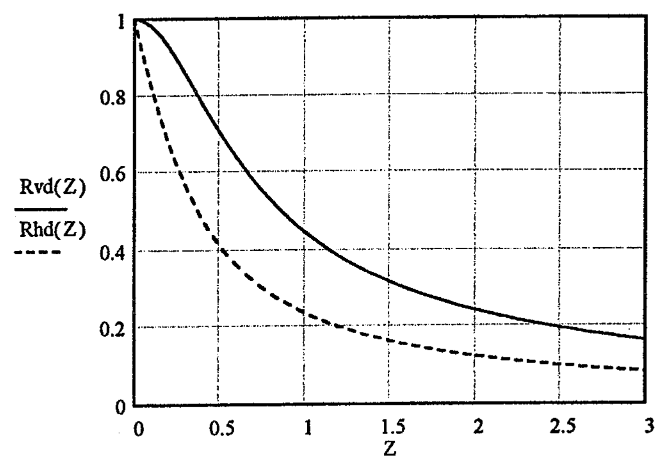

Figure 3

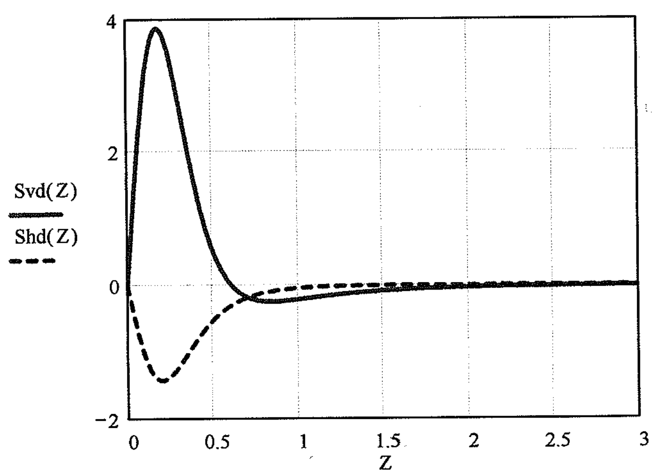

Figure 4

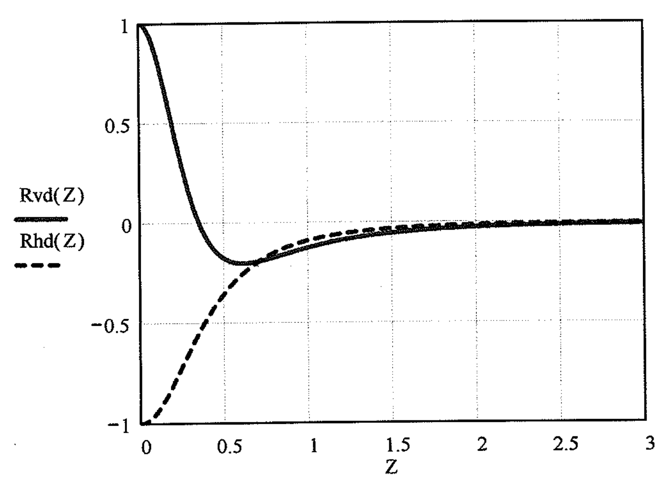

Figure 5

NOTE: Figures 2,3—Conductive Earth. Figures 4,5—Susceptive Earth.
Vertical magnetic dipoles=vd. Horizontal magnetic dipoles=hd.