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Technical Note TN-30

WHY DOESN'T GEONICS LIMITED BUILD A MULTI-FREQUENCY EM31 OR EM38?

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Introduction

In this technical note we address the question of, "Why doesn't Geonics Limited build a Multi-frequency EM31 or EM38?"

There are, in principle, two reasons for building such instruments. These are (a) to allow the resolution of a multi-layered earth (geoelectrical sounding) rather than just measuring the bulk conductivity, and (b) supplying additional interpretive data for improving target diagnostics in identifying the nature of buried metal.

In this technical note we point out that (a) unless the operating frequency range of a multi-frequency EM31 or EM38 extends up to the MHz range it is impossible to resolve a multi-layered earth with such an instrument, and (b) the coil configuration of the EM31 or EM38, and the fact that they operate in the frequency domain, means that whilst useful for indicating the presence of buried metal, they are poor at accurately locating and identifying the nature of the buried metal.

(a) Multi-frequency ground conductivity meters. How useful?

Geonics Limited, the original designer of ground conductivity meters, has been building these devices for many years. Indeed, these instruments are now the principal tool for groundwater contamination mapping and are also widely used for detecting buried metal. The well-known EM31, with its 12 ft (3.67 m) intercoil spacing provides a maximum useful depth of exploration of about 18 ft (5.5 m).

The EM31 operates at a single frequency of 10 kHz. The question is often asked as to why Geonics does not make an EM31 with many frequencies so that the operator can detect and interpret multi-layered earth geometry.

Unfortunately, the physics which describes the operation of these devices gives good reasons for staying with a single frequency. The EM31, with a frequency of 10 kHz and intercoil spacing of 12 ft, has an intercoil spacing that is much less than a skin depth for all but the most conductive ground. This means that the response is directly proportional to the ground conductivity, and allows us to calibrate the units directly in mS/m. The penalty of operating at only 10 kHz (i.e. within the low induction number approximation) is that we cannot give information about layering within the earth.

Now it turns out that in order to give good information about layering we must operate a multi-frequency ground conductivity meter over a wide range of frequencies, the highest of which must be chosen so that the skin depth in the ground is significantly less than the intercoil spacing.

A typical earth conductivity is 25 mS/m. The skin depth (in meters) is given by

$$d = 500/\sqrt{s*f}$$

where s = ground conductivity (mS/m)
and f = frequency (kHz)

so that, if s = 25 mS/m (a typical value) and f = 1,000 kHz (i.e. 1 MHz), d = 3.16 m, and even at this high frequency the skin depth is only marginally less than the intercoil spacing. In order to give useful geoelectric information about a layered earth, a 12 ft ground conductivity meter must operate at frequencies up to at least 1 MHz. This situation becomes progressively worse as we shorten the intercoil spacing - i.e. we must go to even higher frequencies to resolve layered earths.

What happens if the frequency range does not extend to sufficiently high frequencies? In this case equivalence becomes a major problem. Equivalence is defined as the fact that many different layered earth models will give the same measured response with frequency. Thus the interpreter might, at most, be able to tell that, "Yes, the earth appears to be layered", but he will not be able to give any further useful information as to the nature of the layering. We have recently seen an example where a manufacturer of a multi-frequency EM instrument shows how the response would vary with different layering. What is ignored is that, except in extraordinarily conductive earth, it is not possible to uniquely define the layering. Anyone contemplating the use of a multi-frequency EM should investigate the problem of equivalence very thoroughly.

It has been stated by Won et al (1996) that their GEM-2, with intercoil spacing of 1.67 m and highest operating frequency of 22 kHz (or the more recent GEM-300), can be used for geoelectric sounding. For the reasons outlined above detailed examination of the theory will show that this is simply not possible.

Similar arguments can be brought to bear against their claim that the multi-frequency approach will serve to give the depth to metallic targets. Once again, the theory shows that this is simply not possible.

There is a further problem in the design of a multi-frequency instrument. It is not a simple matter to accurately set and maintain the instrumental zero for a "simple" single frequency instrument such as the EM31. The problem becomes much more severe for a multi-frequency instrument. For example, the manufacturers of the MaxMin multi-frequency EM system suggest that the zeroes should be set over "neutral" ground, i.e. ground that is of very low conductivity. But who is to tell that the ground is indeed "neutral" until the zeroes have been accurately set. This "chicken and egg" problem becomes more difficult as the zeroes have to be set (and accurately maintained) for an increasing number of frequencies. Particularly at the lower frequencies, drift becomes a virtually insolvable problem, rendering such instruments as the GEM-2 or the GEM-300 inappropriate for anything other than metal detection.

It should be noted that the original design concept for the EM31 was indeed to make a multi-frequency instrument that would accurately measure earth layering. Detailed examination of the theoretical and practical problems showed then that this was not possible (and still is not) and that a much more useful device would result if it operated at only a single frequency, chosen to be low enough so that the instrument read directly in units of ground conductivity, and high enough so that the instrument enjoyed a zero level that was sufficiently stable that the survey data could be accurately contoured at contour intervals of less than 1 mS/m. None of these factors have changed! While the concept of a multi-frequency instrument appears to be very attractive, the practical problems in manufacturing and maintaining an instrument that provides accurate data up to at least 1 MHz are formidable, and an instrument with smaller frequency range will simply not do the job.

We categorically state that the multi-frequency capability of the GEM-2 or GEM-300 provides no useful benefit in either geoelectric sounding or metallic target depth determination and, furthermore, that this instrument will not provide better data than the EM38 when used for conventional conductivity mapping.

(b) Multi-frequency EM devices for metal detection. How useful?

In the first part of this technical note we explained why a multi-frequency EM31 (or equivalent instrument) was completely inadequate for geoelectrical sounding unless the frequency range of the instrument extend to at least 1 MHz. But another useful application for such instruments appears to be the detection of buried metal. Surely a multi-frequency capability would assist in this application.

Unfortunately the answer is, "No, not significantly," and there are several reasons for this. It is not widely realized that, when a ferrous (for example, steel) plate is electromagnetically energized with the primary magnetic field parallel to the plane of the plate a large magnetic dipole moment is induced in the plate. More surprisingly, this magnetic dipole has both inphase and quadrature components, the ratio of which is a function of frequency, since it takes the induced magnetic dipoles a finite length of time to respond to the primary magnetic field. We will call this response the "permeability" response (noting that it is not a simple function of the plate electrical conductivity) to distinguish it from the normal "eddy current" response, which exhibits well-known behaviour as a function of plate conductivity. The frequency dependence of the inphase/quadrature phase ratio of the secondary magnetic field from the permeability response is, in general, quite different from that for eddy current flow. Furthermore the permeability response is, of course, induced by that component of the primary magnetic field which is parallel to the plane of the plate, whereas the eddy current response is induced by the component of the primary magnetic field that is perpendicular to the plate. Thus, in the general case as we traverse with an EM31 or EM38 over a ferrous plate-like target, (and all targets, other

than spheres or long pipes, exhibit this dual response) the fact that the response is being caused by two sets of induced magnetic dipoles, at right angles to each other, and with different I/Q ratios, makes interpretation of the target response extremely difficult. For this reason, although the EM31 and EM38 are widely used for metal detection, Geonics Limited did not pursue the metal detection application for these instruments since we knew that target interpretation (including even simple accurate location) would be very difficult.

There is, furthermore, a second difficulty with use of an EM31 or EM38 for metal detection. Both of these instruments have a finite intercoil spacing, but to achieve the ultimate in spatial resolution we really want to have an intercoil spacing of "zero" meters, which is not possible with a frequency domain instrument.

Is there a solution to these problems? The answer is, "Yes," and the solution is to operate in the time domain, which offers two important advantages over the frequency domain for the metal detection application. The first is that operation in the time domain indeed allows us to reduce the intercoil spacing to zero, as is done with the Geonics EM61 time domain metal detector, in which the transmitter and receiver coils are coincident. Thus the TDEM EM61 will resolve the lateral location of targets of moderate depth to within about 10 cm. This obviously makes a tremendous difference in the amount of earth that has to be removed in order to retrieve such targets. Furthermore, an important market for metal detecting instruments lies in the detection of unexploded ordnance (UXO). This application requires the ultimate in spatial resolution since the chance is always present that there are two targets rather than one, and nobody wants to inadvertently detonate the second (unresolved and thus undetected target) while attempting to retrieve the first.

But what about the complexity caused by the fact that two orthogonal dipole moments, each with different frequency dependence of the I/Q ratio, are induced in all but the simplest targets. Here again, operation in the time domain presents a very useful advantage, since in the time domain the difference in I/Q ratios simply means that the two responses exhibit different time decay characteristics, which are easily resolved with a TDEM. This is clearly shown by survey profiles of the response from a horizontal ferrous metallic plate to our fully time domain version of the EM61 (the EM61-3D has many time gates). As the EM61 approaches the target, but is still some distance from it, the primary magnetic field is essentially parallel to the plate, and the time decay of the response is that of the induced permeability. As the EM61 moves to a central position over the plate, the response shifts entirely to eddy current flow, which has a completely different and immediately recognizable decay characteristic. Thus separation of the dual response is relatively simple, much more so than for operation in the frequency domain.

A recent paper (McNeill and Bosnar, 1996) is available for those who wish to learn more about the time-domain response of various metallic and UXO-type targets.

Finally, as if the advantages of operation in the time domain described above were not enough (i.e. better target location, and better interpretation of target type) yet another advantage occurs. The compact nature of the coil configuration of the EM61 allows us to easily add a second receiver coil, which, using a technique for which a patent has been applied, allows us to measure the depths of the target to within the order of 20 cm, again greatly facilitating target retrieval.

For these reasons we state categorically that use of the fully TDEM EM61-3D will yield far better data quality and interpretability than use of the GEM-2 or the GEM-300.

Geonics Limited did not pursue a multi-frequency metal detection version of the EM31 or EM38 for excellent reasons. They realized many years ago, as a result of their understanding of the basic physics of the target response, that the advantages of operation in the time domain for metal detection were overwhelming, and subsequently developed their very successful and now widely used EM61.

References

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