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Environmental geophysics

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Low induction number approximation

Welcome readers to this issue's column on geophysics applied to the environment. As many of you who have worked with me in the field will know, I love to hate data collected using a Geonics EM31, or any of the various similar but different incarnations of terrain conductivity meters (TCM) that have been developed over the years (think DualEM and GF Instruments and probably others). It's not the instruments that drive me crazy, it's the low induction number (LIN) approximation that is used to calculate the apparent conductivity that these instruments record.

Over time I have come to realise that the LIN approximation is (was) a very clever idea – one that I have always credited to Duncan McNeill in his Technical Note 6 (TN-6) (McNeill, 1980), but may actually be based on a much earlier paper by Jim Wait (will have to look into that). Anyway to me it is a clever way to make use of the limited portable computing power that was available in the 70s and 80s to provide a pretty good estimate of apparent ground conductivity. The LIN approximation takes a non-linear, complex and complicated expression that equates the ratio of the secondary (received) magnetic field and the primary (transmitted) magnetic field (H_s/H_p) to many other parameters, including a number of deeply buried conductivity terms; in this equation it is impossible to explicitly solve for conductivity. The complete solution for conductivity is done numerically, with Hankel transforms, etc. Back then there was (overall) limited computing power (what will they say about the computing power that we have now in 35 years?), and even less computing power that a person could carry in a long straight tube with a transmitter coil at one end and a receiver coil at the other. So the LIN approximation allows this difficult equation to be solved analytically for conductivity, once the transmitter-to-receiver separation was set to be much less than the skin depth, by judiciously setting the length of the instrument and the operating frequency. The standard shorthand for the skin depth equation is given by:

$$\delta = 505 * \sqrt{\frac{\rho}{f}}$$

where δ is skin depth (in meters), ρ is resistivity (in ohm-m), and f is frequency in hertz. And it might be worth reminding readers that resistivity (ρ) and conductivity (σ) are reciprocals of each other, and that conductivity is given in units of S/m (and I have used mS/m in my figures). Skin depth is often used as the approximate depth of investigation (DOI) for instruments that operate in the frequency domain.

From the EM skin depth equation one can see that the skin depth (approximate DOI) is large when the ground is resistive, i.e. ρ is large (or σ is small), so the LIN approximation works, and that the skin depth is smaller when the ground is conductive, so the LIN approximation eventually fails. McNeill understood this and showed it graphically in TN-6, reproduced here (including its original caption), as Figure 1. As noted in TN-6, the indicated conductivity is about 20% too low (and getting worse with increased conductivity) once the conductivity of the ground is >100 mS/m (shown as 100 mmho/m – the conductivity unit of the day) or <10 ohm-m. This means that when the instrument is used to collect data in many normal Australian settings, e.g. to measure extent of shallow saline groundwater incursion in a wetland (a conductive setting), the output conductivities are incorrect. I do have to admit that as a relatively simple mapping tool the map of conductivity distribution that is produced using LIN approximated conductivities can still be useful (even when used to map saline ground water incursion).

In 2001 Reid and Howlett published a nice article in *Exploration Geophysics* that directly discussed these limitations (the only article that I have ever seen on the subject besides McNeill's 1980 statement of the limitations – there must be others) and how the response of the EM31 changes over ground where the LIN assumptions are not valid. In the process they wrote up some code that allows the input of a set of LIN-approximated data that outputs true conductivity values based on the more difficult numerical solution. It is worth noting that the program may be used on any TCM data, so long as the transmitting frequency, instrument height and the dipole spacing are known. I have used James' program to produce Figure 2, which compares the difference between the correct response (labelled as True Conductivity on the y-axis) and the LIN response (labelled as Indicated Conductivity on the x-axis) for a number of TCM instruments. The EM31 comparison is shown - looking a great deal like McNeill's 1980 results (Figure 1). Three other instruments, with three different dipole lengths, labelled here short, medium and long, are shown as well, to show how the response varies with dipole length. The executable is available from me if anyone wants to use it. Note that James does not guarantee the results, nor does he support it anymore, but does not mind seeing it being used.

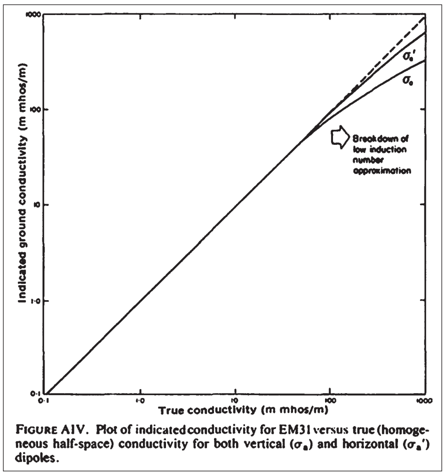

Figure 1. *Original figure from McNeill's TN6 showing how the indicated conductivity veers away from the true conductivity from conductivities <100 mmhos/meter (100 mS/m or 10 ohm-m).*

One of the conclusions from the Reid and Howlett paper is that the depth sensitivity of the instrument is generally much reduced under non-LIN (conductive) conditions than what is normally assumed; therefore not only are the conductivities inaccurate, but the assumed depth-sensitivity distribution is wrong as well; any inversion of data collected in conductive ground will be incorrect, both for depth and conductivity. I have been experimenting with an inversion routine that uses the raw data and makes no assumptions about LIN conditions – and the results are very interesting. In fact I am actually starting to like what can be done using TCM instruments, especially the newer instruments that collect data using a number of transmitter-receiver spacings, i.e. at a number of depths. The data density is excellent so lateral resolution is very good (limited to about 7 m depth though) and the inverted sections come out very reasonably; but that may be a subject for another column.

Ultimately my point is that it seems wrong to me to use an approximation when we have so much more portable computing grunt available these days than we did when the EM31 was developed back in the 70s. Instrument manufacturers are producing TCMs that provide conductivity information that is needlessly approximate. At the very minimum the instruments should be providing the user with the LIN approximated data, the 'true' apparent conductivity, and the quadrature ratio data in ppt so that the data may be properly inverted without having to back out the raw ratio data.

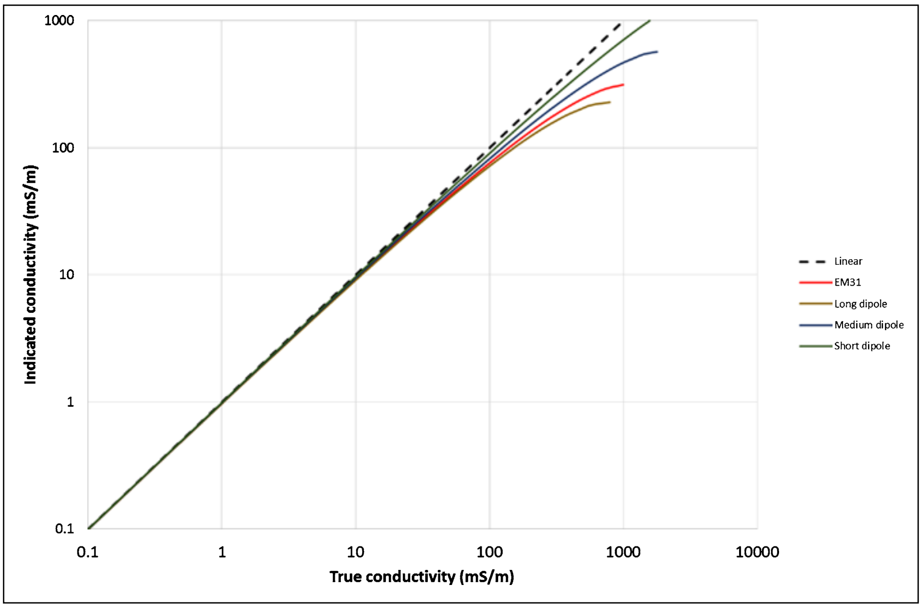

Figure 2. *Results of testing with James Reid's code that recalculates TCM data that is LIN approximated to 'true' apparent conductivity. The dashed line shows where the data would lie if the relationship between the Indicated conductivity and the True conductivity were one-to-one. EM31 results are shown, along with results from other similar devices – one with a long dipole length, etc. as indicated. As expected, long dipoles are more affected by the LIN approximation than short dipoles.*

References

McNeill, J. D., 1980, Technical note TN-6, electromagnetic terrain conductivity measurement at low induction numbers. Geonics Limited: Mississauga, Ontario, Canada.

Reid, J. E., and Howlett, A., 2001, Application of the EM-31 terrain conductivity meter in highly-conductive regimes: *Exploration Geophysics*, **32**, 219–224.