ESTIMATION OF SOIL-PROFILE PROPERTIES FROM ELECTROMAGNETIC INDUCTION

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Abstract

Electromagnetic induction (EMI) has become widely used for measuring the apparent electrical conductivity of soils. Where apparent conductivity is measured to several depths of investigation, quantitative estimates can be made of the electrical properties of the soil profile. For example, where (i) there is significant contrast in conductivity between a surficial layer and underlying material, and (ii) the base of the surficial layer lies within the general depth of investigation, estimates of the conductivity of the surficial layer, the thickness of the layer, and the conductivity of the underlying material can show reasonable agreement with the independent measurements of these properties. Where there is low-to-modest contrast but thickness is known, reasonable estimates can be made of the conductivities of the surficial layer and sub-layer.

Introduction

A type of EM instrument that has seen increasing use since 1999 incorporates horizontal co-planar (HCP) and perpendicular (PRP) arrays that operate at very low frequency. The depth sensitivity of such arrays is a function of their length, *i.e.* the horizontal separation between their transmitter and receiver.

The annotations of Figure 1 show the configuration of an instrument with 1-m arrays. The transmitter-coil, shared by both arrays, has horizontal windings. The HCP receiver has windings that are horizontal and co-planar with those of the transmitter. The PRP receiver has windings that are vertical and perpendicular to the array axis.

Figure 1: EM Instrument with 1-m HCP- and PRP-Arrays. (Photo: Dr. B. Allred)

The HCP- and PRP-arrays have distinct depth sensitivities: The HCP array develops half its sensitivity to a depth equivalent to about 0.9 array lengths; the PRP array develops half its sensitivity to a depth equivalent to about 0.3 array lengths.

Figure 2 shows a DUALEM-42 instrument that houses two sets of HCP- and PRP-arrays. One set of arrays is 4-m in length; the other set is 2-m in length. The instrument provides four simultaneous measurements of apparent conductivity, each with distinct depth-sensitivity. Such measurements enable the identification of conductive layering in the earth and practical estimation of up to three earth-parameters, e.g. the conductivity of a surficial layer, the thickness of the surficial layer, and the conductivity of the underlying earth.

Figure 2: EM Instrument with 4-m and 2-m HCP- and PRP-Arrays. (Photo: D. Lalonde)

A similar instrument with sets of arrays at three lengths of 4-, 2- and 1-m provides six simultaneous measurements of apparent conductivity, increasing the robustness of estimates for a 3-parameter earth, or occasionally enabling the analysis of an earth with greater complexity. A shorter instrument of the same class, with array lengths of 2- and 1-m, is more convenient for mounting in a sled and yields measurements that are effective for the analysis of a 3-parameter earth within the range of depths frequently of interest in agriculture.

Site and Data Acquisition

Data from the instrument shown in Figure 2 were acquired at the surface of a freshwater lagoon. Figure 3 shows the location of the lagoon, about 30 km northeast of Toronto, Ontario. Figure 4 shows the survey path, overlaid on a chart that shows water depths in metres.

Figure 3: Location of Freshwater Lagoon Survey Site near Toronto, ON.

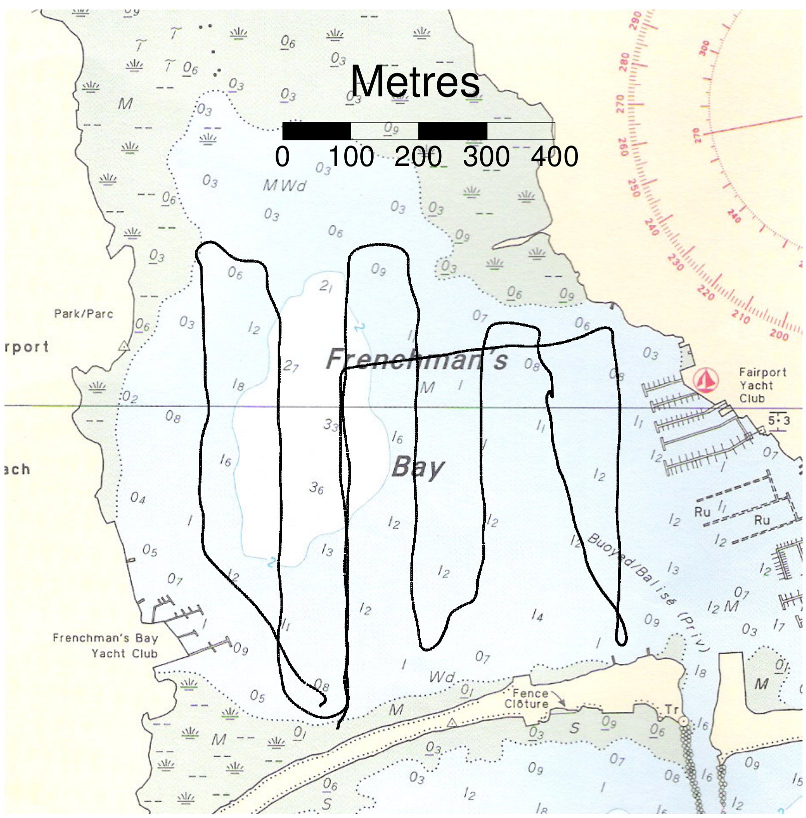

Figure 4: Survey Lines on Freshwater Lagoon.

The raft held the instrument arrays about 0.22 m above the water surface. A WAAS-enabled GPS receiver built into the instrument provided positioning. An acoustic depth-sounder fixed to the raft measured water depths. Data were recorded at 1-s intervals. Figure 5 shows the apparent conductivities of the four arrays, annotated with approximate half-sensitivity depths.

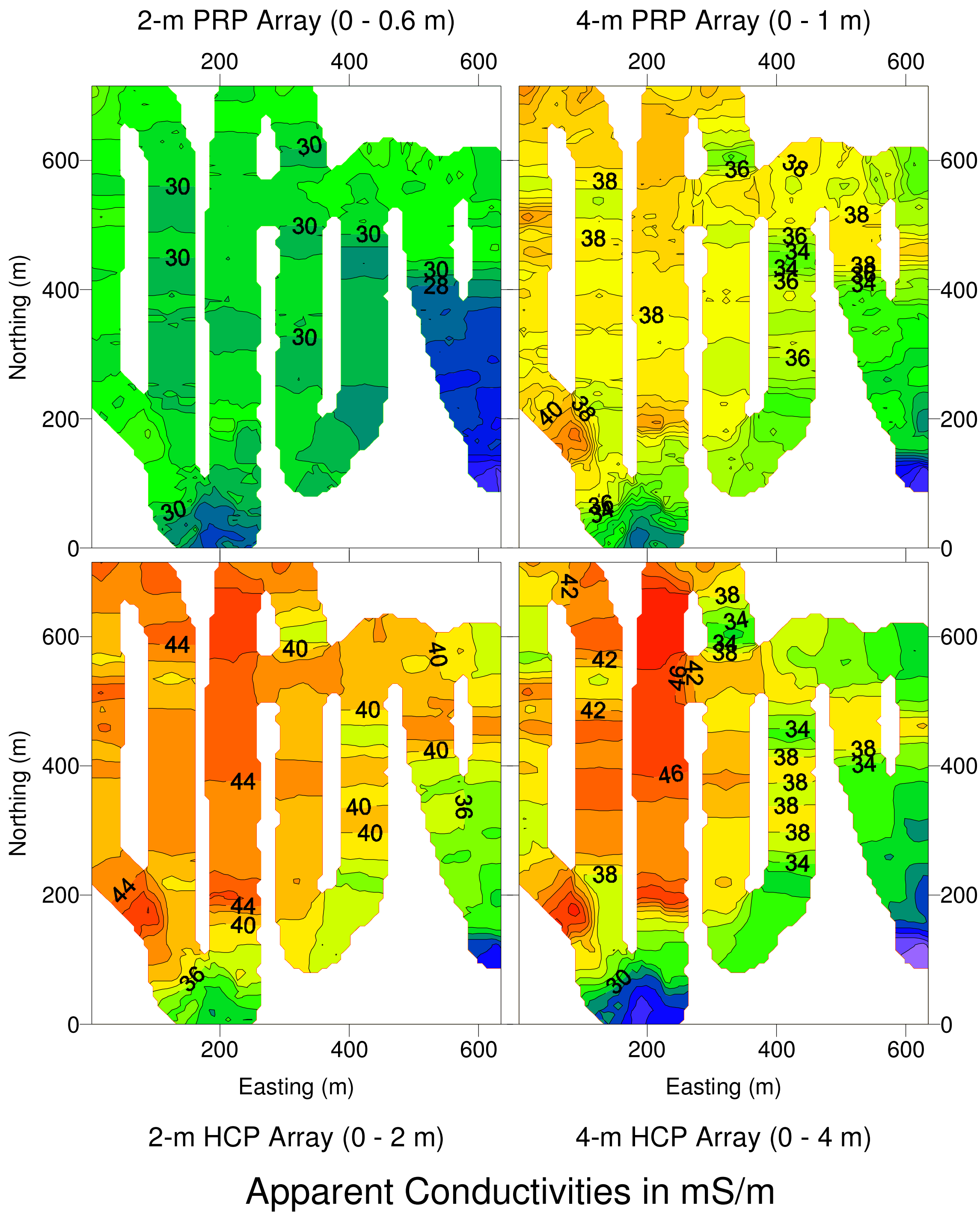

Figure 5: Apparent Conductivities on Freshwater Lagoon.

The sensing depth of the 2-m PRP array is generally within the water depth of the lagoon; data from the array show water conductivity is somewhat lower (i) in the south-eastern portion of the survey, near the channel that communicates with Lake Ontario and (ii) at the southernmost point, near the sand barrier between the lagoon and Lake Ontario. Measurements on nearby Lake Ontario (not shown) reveal the conductivity of the shallow lake is less than 20 mS/m, so infiltration of lake-water might cause the lower conductivities in the lagoon. Apparent conductivities show some increase with sensing depth, but the 4-m HCP array senses lower conductivities than the 2-m HCP array at the southern and other edges of the survey area.

Weeds in the shallower parts of the lagoon caused noise in acoustic depth-soundings. To obtain usable depths for an example profile, data acquired on along 200 E were grouped by northing in 6-m intervals, and then averaged. Figure 6 shows the example profile.

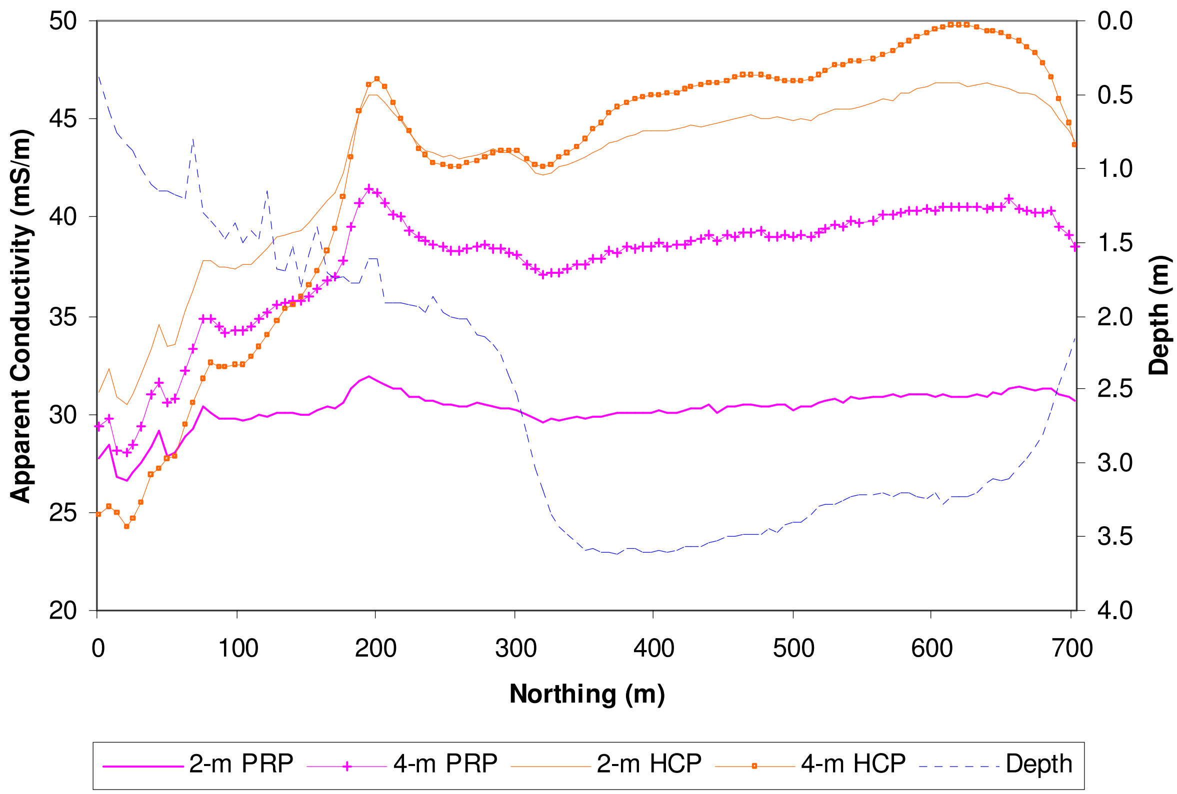

Figure 6: Apparent Conductivities and Water Depth along 200 E.

As noted previously, apparent conductivity tended to increase with increasing sensing depth. Much of the increase is attributable to the diminishing influence of the 0.22 m of air between the instrument and the water surface. A change in the conductivity of the sediment, relative to the conductivity of the water, can be inferred from a comparison of the 2-m HCP and 4-m HCP values: From 0 N to about 150 N, the 4-m HCP values are substantially lower, indicating that the sediment is relatively resistive; from about 400 N to about 650 N, 4-m HCP values are slightly higher, suggesting that the sediment is more conductive.

Conductivities for a surficial layer (beneath 0.22 m of air) and a sub-layer can be estimated by optimizing the fit of apparent conductivities predicted by such conductivities to the apparent conductivities that were recorded. Figure 7 shows these estimates, where depths measured with the depth sounder are used as *a priori* values of the thickness of the layer. The figure also shows the percent fitting error between the predicted and recorded apparent conductivities, as the square root of the sum of the squared differences.

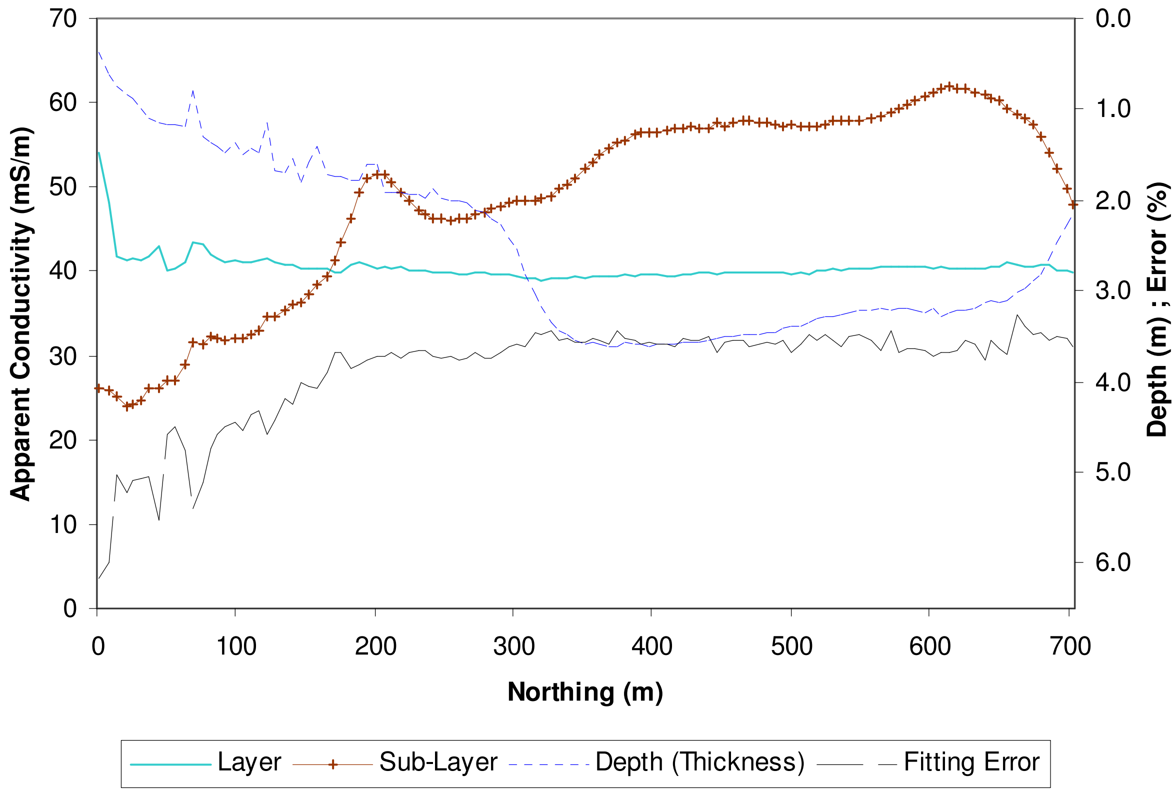

Figure 7: Estimated Conductivities, Water Depth and Estimation Error along 200 E.

Except for two somewhat higher estimates near the sand barrier, the estimated conductivity of the (water) layer is about 40 mS/m. The estimated conductivities for the (sediment) sub-layer increase from about 25 mS/m at the sand barrier to 57 mS/m at 400N; the trend is disturbed by a local rise to 52 mS/m around 200 N. Sub-layer conductivity reaches a maximum of 62 mS/m at 615 N, north of which conductivity declines to 48 mS/m as the sub-layer comes closer to the surface. At 6.2 %, estimation error is highest near the sand barrier. Error declines as water depth increases to 2 m. Where depths trace a smooth profile greater than this value, error is stable around 3.6 %.

In perhaps the first publication describing this technique, Saey, *et al*. (2009) report estimating layer thickness, along with layer conductivity and sub-layer conductivity, from sets of four apparent conductivities measured on layered soil. The thickness estimates compared well with depths measured by coring. The conductivity contrast between the layer and sub-layer was about 8-fold, based on average conductivity estimates.

For the present example of the freshwater lagoon using *a priori* thickness, 41 mS/m is the average estimate of conductivity for the layer and 49 mS/m is the corresponding estimate for the sub-layer. The low contrast in this case indicates that estimating layer thickness would be generally impractical; of course, any estimate of layering is invalid where there is no contrast, as Figure 7 suggests is the case around 170 N.

Nevertheless, estimates of layer thickness, layer conductivity and sub-layer conductivity were made for the 200 E profile. From 129 N to 704 N the layered model degenerated into simpler models (not shown) in which the earth has essentially uniform conductivity to the sensitivity depth of the instrument. Between 0 N and 110 N, however, estimates of layered conductivity and most depths vary within reasonable ranges, as shown in Figure 8.

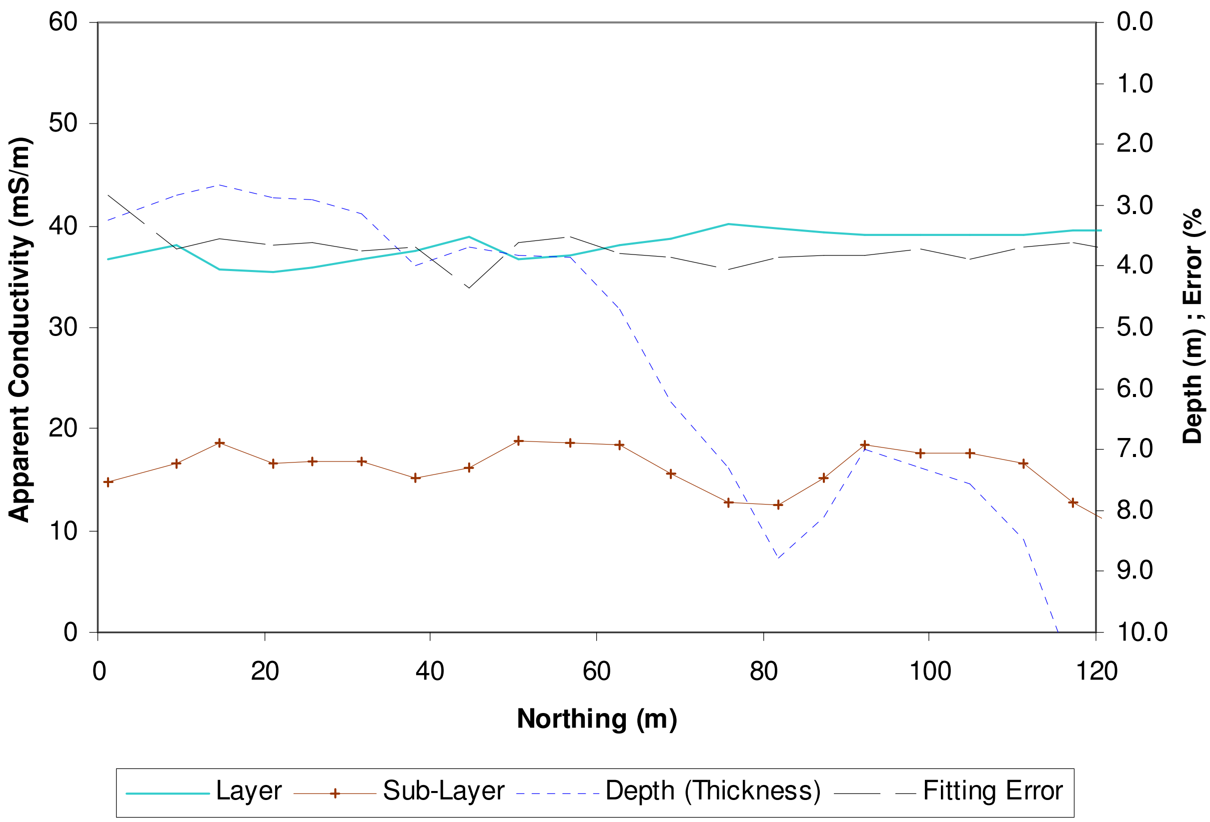

Figure 8: Estimated Conductivities and Depth, with Estimation Error for Portion of 200 E.

At about 3.5 %, fitting errors compare favourably with those of estimates that use *a priori* information from the depth sounder. The conductivities and depths estimated in this portion of the profile thus represent an alternate model of the earth that is as valid, relative to the data, as the model that incorporates the water-sediment interface. In this alternate model, an electrical interface lies at about 3-m depth at 0 N to 8-m depth at 100 N. Above the interface is lagoon water and relatively conductive sediment, with overall conductivity about 38 mS/m. Below the interface is sediment with typical conductivity around 17 mS/m, perhaps infiltrated by colder, denser lake-water.

Comparing the apparent conductivities measured with various arrays can indicate the suitability of data for layered-earth analysis. Within the portion of the example profile along 200 E where the analysis was unsuccessful, we might choose the apparent conductivities at 500 N as an example. For arrays in order of increasing depth-sensitivity, the apparent conductivities in mS/m were 30.2 for 2-m PRP, 39.0 for 4-m PRP, 44.9 for 2-m HCP and 47.0 for 4-m HCP.

The layered-earth analysis takes into account the effect of non-conductive air between the arrays and the surface. The effect decreases apparent conductivity, and it is more pronounced for shallower sensing arrays. If the measurements had been made at the surface of a uniform earth, the depth sensitivity functions suggest the apparent conductivities at 500 N would have been 38 mS/m for 2-m PRP, 44 mS/m for 4-m PRP, 46 mS/m for 2-m HCP and 47 mS/m for 4-m HCP. Evidently, this range is insufficient for the quantification of conductive layering. The quantitative analysis by Saey, *et al.* (*ibid.*) provides an example of a sufficient range, where the average apparent conductivities measured at the surface were 29 mS/m for 1-m PRP, 48 mS/m for 2-m PRP, 66 mS/m for 1-m HCP and 88 mS/m for 2-m HCP.

Despite the muted range of apparent conductivities through most of the survey area, the freshwater-lagoon example shows that meaningful conductivities can be estimated for a layer and sub-layer if accurate and independent information is available for layer thickness, even where the estimates indicate there is negligible conductivity contrast.

Conclusions

Apparent conductivities measured with a multiple transmitter-receiver configurations and separations can indicate the presence of conductive layering, and provide a sound basis for the estimation of layering parameters. Minimizing the effect of non-conductive air on apparent conductivity, for example by taking measurements on the surface, facilitates the identification of depth-influence on apparent conductivity.

Four apparent-conductivities represent the practical minimum for modeling a 3-parameter earth, *e.g.* estimating the conductivity and thickness of a surficial layer along with the conductivity of the sub-layer. Additional measurements can increase the robustness of estimates, and allow the estimation of additional parameters for a more complex earth.

The example presented here has gradational changes in conductivity such that there is a zone where there is no substantial contrast between the surficial layer and the sub-layer. Nevertheless, the example demonstrates that conductivities can be estimated for the layer and sub-layer if accurate and independent measurement of layer thickness is available.

The author thanks Geosensors Inc. for constructing the means for and assisting with the measurements on the freshwater lagoon.

Reference

Saey, T., Simpson, D., Vermeersch, H., Cockx, L. and Van Meirvenne, M., 2009, Comparing the EM38DD and the DUALEM-21S sensors for depth-to-clay mapping: Soil Science of America Journal, **73**, 7-12.