# Low induction number, ground conductivity meters: a correction procedure

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# Abstract

Ground conductivity meters, comprising a variety of coil-coil configurations, are intended to operate within the limits provided by a low induction number (LIN), electromagnetic condition. They are now routinely used across a wide range of application areas and the measured apparent conductivity data may be spatially assembled and examined/correlated alongside information obtained from many other earth science, environmental, soil and land use assessments. The theoretical behaviour of the common systems is examined in relation to both the prevailing level of subsurface conductivity and the instrument elevation. It is demonstrated that, given the inherent high level of accuracy of modern instruments, the prevailing LIN condition may require operation in environments restricted to very low (<12 mS/m) conductivities. Beyond this limit, non-linear departures from the apparent conductivity that would be associated with a LIN condition occur and are a function of the coil configuration, the instrument height and the prevailing conductivity. Using both theory and experimental data, it is demonstrated that this has the potential to provide biased and spatially distorted measurements. A simple correction procedure that can be applied to the measured data obtained from any of the LIN instruments is developed. The correction procedure would, in the limit of a uniform subsurface, return the same (correct) conductivity, irrespective of the ground conductivity meter used, the prevailing conductivity or the measurement height.

## 1. Introduction

Ground conductivity meters are specific electromagnetic (EM) devices that use a small coil transmitter (Tx) and one or more coil receivers (Rx) to provide a measure of the EM field coupling in the shallow subsurface. They typically operate at small Tx-Rx separations and at low frequency (e.g. < 15 kHz). The combined separation-frequency EM attribute is designed to provide a measure of the subsurface conductivity across a depth scale that is governed by the Tx-Rx separation and the coil orientations used. One of the main contributions to the practical understanding of such devices is the information provided by McNeil (1980). In order to provide direct measures of the ground conductivity the devices have to be operated under a Low Induction Number (LIN) EM condition that, for a given instrument, will depend on the prevailing conductivity. Here we use the phrase 'LIN apparent conductivity' to convey the apparent conductivity as the quantity measured by ground conductivity instruments. The guidance provided by McNeill (1980), still quoted by many users of the devices, relates to the operation of the instrument on the ground surface (zero elevation).

The LIN instruments discussed here represent a specific case of a more general EM formulation. The electromagnetic solution for an elevated magnetic dipole on or above a homogenous earth was developed by Wait (1954, 1955). The model was extended to the 2-layer case by Frischknecht (1967). Anderson (1979) discusses the subsequent generalisation to a layered half space. The frequency domain electromagnetic vector potentials can be used to obtain the quasi static electric and magnetic fields within the half-space. Accurate techniques for the numerical integration of the expressions have been established (Frischknecht, 1967; Anderson, 1979, Christensen, 1990). Here the calculations follow those described by Beamish (2003).

The general use of LIN instruments has increased considerably in recent years. A range of very practical survey instruments has been developed with coils mounted within rigid booms and with coil separations ranging from about 0.5 m to around 6 m. Other forms of related EM ground conductivity instruments exist and are typically multi-frequency Tx devices with either fixed or variable coil separations. These devices generally require a more complex (i.e. a non-LIN condition) modelling and inversion of the data acquired, and, as such, are not specifically addressed here. The ground conductivity meters considered here are usually understood to provide the user with a direct measure of subsurface conductivity and are now used, and the results discussed, alongside information obtained from many other earth science, environmental, agricultural and land-use site assessments.

The sensor measurements of ground conductivity are now routinely acquired at high spatial densities (e.g. on mobile platforms) and used in spatial correlation studies such as those described in relation to soil and crop management systems (e.g. precision agriculture) as described by Corwin and Lesch (2003). Many of these application areas are contained across a wide range of publication outlets such as those related to ground water (Scanlon et al., 1999), soil science (McNeil, 1992, Suddoth et al., 2010), precision agriculture (Sudduth, 2001), soil and water conservation (Doolittle et al., 1994; Kitchen et al., 1996), soil-crop dynamics and silage (Woodbury et al., 2009), environmental quality (Drommerhausen et al., 1995) and the application and movement of agrochemicals (Yoder et al., 2001). The use of such devices, for mapping site-specific attributes, is also incorporated into best-practice documents for land management within the European Community (Adhikari et al., 2009). There is also a standards guide published by the American Society for Testing and Materials (ASTM, 2008) relating to the use of ground conductivity meters for subsurface investigations.

There are broadly three ways in which use is made of the ground conductivity measurements:

(a) Spatial mapping using the individual or combined measurements of particular coil configurations/instruments to provide shallow and deep information (e.g. Triantafilis et al., 2005; Corwin et al., 2010).

(b) Use of the data to obtain an approximate vertical distribution of conductivity, where the approximation depends on operation within the LIN condition (e.g. Monteiro Santos, 2004; Saey et al., 2009).

(c) Full quasi-static numerical EM inversion of one or more measurements of apparent conductivity to provide an assessment of the vertical distribution of conductivity (e.g. Reid and Howlett, 2001; Monteiro Santos et al., 2010).

The first category in which direct use is made of the ground conductivity measurements in relation to other information and data sets is the subject considered here. It is also possible to examine the behaviour of the instruments in the context of non-1D situations such as those relating to small object detection such as the investigation of subsurface utilities. These situations are not considered here and a 1D framework is used throughout.

## 2. Ground conductivity measurements

The three coil-coil systems used in ground conductivity instruments are shown schematically in Figure 1. It is possible to describe coil systems in terms of either the direction of the magnetic dipole (the arrows in Figure 1) or by the orientation of the coils. Here a coil orientation system description is used. Figure 1a shows a pair of horizontal coils in a coplanar configuration referred to as an HCP system. Figure 1b shows a pair of perpendicular coils referred to as a PERP configuration. A vertical coplanar coil arrangement (VCP) is shown in Figure 1c. The VCP system may be obtained by rotating the HCP system though 90° about the centre-coil axis line. If an identical rotation is performed on the PERP system, the coil-coil configuration is described as null coupled (Wait, 1982) and no coupling takes place with conductive material (assuming the ground is horizontally planar in the schematic diagram).

A non-exhaustive list of some of the fixed boom ground conductivity meters that are available is given in Table 1. Since some of the devices have been available for over 30 years, there are a number of variants of the basic models. In most systems it is possible to obtain a VCP configuration by rotation of the HCP system through 90°, as noted previously. In recent years manufacturers have developed multi-separation and/or multi-receiver meters, as indicated in Table 1.

**Table 1**

Ground conductivity instruments, intended to operate within a LIN condition. S refers to coil separation. MC refers to a multiple-coil configuration and ROT indicates that the VCP component may be measured by rotation of the instrument.

| Name | Manufacturer | S (m) | Configuration |
|---|---|---|---|
| EM 38 | Geonics Ltd. | 1.0 or 1.5 | HCP, VCP (rot) |
| EM31 | Geonics Ltd. | 3.66 | HCP, VCP (rot) |
| EM31-3 (MC) | Geonics Ltd. | 1, 2, 3.66 | HCP, VCP (rot) |
| DUALEM-1 | DualEM Inc. | 1.0 | HCP, PERP, VCP |

| | | | |
|---|---|---|---|
| | | | (rot) |
| DUALEM-2 | DualEM Inc. | 2.0 | HCP, PERP, VCP (rot) |
| DUALEM-4, -42(MC) | DualEM Inc. | 4.0, 2.0 | HCP, PERP, VCP (rot) |
| DUALEM-421 (MC) | DualEM Inc. | 1.0, 2.0, 4.0 | HCP, PERP, VCP (rot) |
| CMD series | GF Instruments s.r.o. | 0.45 to 5.79 | HCP, VCP(rot) |
| CMD Explorer (MC) | GF Instruments s.r.o. | 1.48, 2.82, 4.49 | HCP, VCP (rot) |

The principle of a multi-separation instrument is to retain the same Tx (operating at a fixed single frequency) and then provide receivers (e.g. Figure 1) at one or more increasing separations. It should also be noted that multi-separation instruments, although intended to remain within the LIN condition, will *intrinsically* provide a progressive departure from the LIN condition with increasing coil separation and will potentially return different values of apparent conductivity. As described later, the differences are not necessarily connected with 'the variation of conductivity with depth' and could better be regarded as a 'geometrical' effect of the EM measurement system.

The use of the perpendicular coil (PERP) arrangement is intended to provide the user with an equivalent behaviour to that of the vertical coil arrangement in terms of shallow depth discrimination. The relative and cumulative behaviour of the system responses as a function of depth, when operating within the LIN condition, have been published on many occasions since they were described by McNeill (1980). The use of PERP configuration measurements has been described by Abdu et al. (2007) and Sudduth et al. (2010). In general, for a given coil-coil separation, the measurements associated with the VCP and PERP configurations are understood to provide shallower information than that obtained in the HCP configuration.

### *2.1 Ground conductivity data*

The instruments actually measure EM coupling ratios (a complex number) as described below. The complex number has in-phase (P) and in-quadrature (Q) components that are presented to the user as apparent conductivity (mS/m) and an in-phase (P) coupling ratio for each coil-coil configuration. The manufacturers of the instruments provide the limits of the measurement ranges and sometimes estimated accuracy figures for each instrument. Resolution (not accuracy) of apparent conductivity is invariably 0.1 mS/m while that of the in-phase component may be between 0.01 and 0.03 ppt (parts per thousand).

As with all EM instruments, the ground conductivity devices require an ‘absolute’ calibration and this may be attempted/achieved by a null or calibration adjustment procedure in the field or the instrument may be ‘factory-calibrated’. The absolute calibration of an EM device may ultimately require an ‘out-of-ground effect’ condition and this is particularly difficult at low frequency and particularly for the in-phase measurement. It is assumed here that the instruments are adequately calibrated and that thermal drift effects (e.g. Robinson et al., 2004) are absent or have been minimised. It is also worth noting that some of modern instruments assist with quality control by the provision of internal temperature and tri-axial tilt measurements (for precision coil orientation).

It is a normal part of geophysical survey procedure to provide one, or more, static tests of the instrument’s performance under site/survey conditions. This is simply a matter of recording and examination of the data over an interval of a few minutes (or longer as required) at a suitable, potentially repeatable, location. Figure 2 shows a 4 minute recording of a DUALEM-4 system providing apparent conductivities and P components in the HCP and PERP modes. The instrument is as close to ground surface as can be achieved (e.g. an estimated elevation of the inter-coil centre line of 0.05 m). The sampling interval is 4 Hz. Data accuracies may be improved in static mode measurements by increasing the integration/sampling interval; however 4 Hz is a typical interval for mobile operation and this is assessed here. In Figure 2 apparent conductivities are shown using a scale range of 1 mS/m and P components use 0.5 ppt. The data distributions obtained during static tests are typically close to normal and may be summarised using normal modes of the distributions. The means and standard deviations of the data shown in Figure 2 (N=960) are 45.05 ± 0.126 mS/m (HCP, apparent conductivity), 1.24 ± 0.040 ppt (HCP, in-phase), 48.45 ± 0.152 (PERP, apparent conductivity) and 0.60 ± 0.045 ppt (PERP, in-phase). As noted later, in a 1D context, only positive responses (in both P and Q components) are permitted and negative values, particularly in the in-phase measurements, indicate either equipment malfunction (including thermal effects) or a measurement below the resolution capabilities of the device.

The resolution of apparent conductivity is typically 0.1 mS/m and this registration limit can be seen in the data plots in Figure 2. Given the qualities of the apparent conductivity data it could be suggested that an increased measurement resolution of at least 0.05 mS/m might be worthwhile. The low levels of variance that can be achieved by modern instruments are significant in relation to subsurface assessments. This is particularly the case when considering detailed static modes of measurement and time-dependent behaviour of near-surface properties. In presenting the purely theoretical behaviour of the ground conductivity systems below it should be noted that the reference level of accuracy in apparent conductivity data may be less than 0.25 mS/m.

### *2.2. Measurement height*

An examination of the literature, such as the references cited previously, will reveal two main features relating to the general use of ground conductivity meters. The first is that data are obtained across a very wide range of prevailing ground conductivities, such that the LIN EM condition, discussed by McNeill (1980) may be compromised. The second feature is that the instruments are clearly operated at a wide-range of elevations above ground. The behaviour of the systems with elevation is highly significant in relation to understanding the data acquired and it is unfortunate that in many descriptions of survey parameters, the acquisition height goes unrecorded (i.e. it appears not to be regarded as significant).

The LIN operation described by McNeill (1980) assumes a zero elevation. Due to the finite size of coil construction, the height of a coil-coil instrument is probably best referred to the along-axis line joining the centres of each coil-coil pair (e.g. Figure 1). Again due to instrument construction the coils are then housed in a survey instrument that, when resting on the ground, typically provides a further offset. It is unlikely that any of the ground conductivity meters actually operate at zero elevation. As an example, the control housing used in the construction of the EM31 provides an estimated offset (to the assumed coil-coil centre-line) of 7 cm when the instrument (actually the central housing) is resting on flat ground in its lowest operational position. Other instruments and mobile platforms used to house them obviously vary in their elevation offsets. Many of the larger instruments are also supplied with harness straps that allow for hip-height operation (say 0.9 m). In the agricultural context, some instruments appear suspended on booms and heights may exceed 1

m. The analysis conducted here examines the behaviour of the systems with elevations extending to 2 m.

## 3. Coupling ratios

The ground conductivity instruments use a phase sensitive measurement between the Tx and Rx magnetic fields to obtain the secondary (Hs) to primary (Hp) field ratio. The ratio is complex and comprises a secondary field that is in-phase (P) and in-quadrature (Q) with the primary field. In the general case of EM induction, material properties may involve magnetic, conductivity and dielectric components. At the low frequencies (e.g. < 15 kHz) considered here, only magnetic and conductivity contributions are significant. Generally, when first considering the response from conductivity we assume a magnetic permeability of free space ($\mu_0 = 4\pi.10^{-7}$ H.m$^{-1}$, SI units) i.e. a survey conducted in a non-magnetic soil/geological environment. We also use a vertically-uniform depth profile (a half-space) to provide the simplest, reference behaviour of the systems.

The coupling ratios (Hs/Hp) that would be obtained from the three standard coil systems are shown in Figure 3 over a range of half-space conductivities extending to 200 mS/m. The coil separation used is 4 m, the operating frequency is 9 kHz and the height of the coil centre-line position is 0.05 m above ground. In general terms, the magnitudes of the in-quadrature responses (used to obtain apparent conductivity) exceed those of the in-phase responses by an order of magnitude until low values of conductivity are approached. Here, with increasing resistivity, it becomes difficult to induce sufficient current in the ground to obtain measureable responses (using the same Tx). In order to maintain precision of the in-quadrature (conductivity) response at low conductivities, the ground conductivity instruments invariably provide a highly accurate measurement of Q but only a limited registration of the in-phase P component. The P measurement returned by the instruments is provided in units of parts-per-thousand (ppt) which corresponds to 1000 ppm. At low conductivities (e.g. < 20 mS/m), all three coil systems will provide in-phase measurements below a value of 1 ppt. In this non-magnetic environment, with increasing conductivity, the instruments will register valid in-phase measurements typically in the range from 1 to 10 ppt arising from the conductivity component of the material. The in-phase response will increase with increasing conductivity as shown in Figure 3. A characteristic behaviour of the three coil configurations is $P_{HCP} > P_{PERP} > P_{VCP}$ although the same uniform material is assessed by all three measurements.

### *3.1 Magnetic susceptibility*

The magnitude of the in-phase components will increase with increasing magnetic susceptibility content. The HCP configuration provides the largest in-phase response in the non-magnetic (free space) condition considered (Figure 3). The in-phase response to increasing magnetic content can be modelled and typically becomes a linear function of half-space conductivity. The non-magnetic case considered in Figure 3 however provides in-phase values that theoretically exceed the resolution capability of modern instruments (i.e. 0.01 to 0.03 ppt) when half-space conductivity values exceed 10 to 20 mS/m. Under these circumstances, there should be no requirement to invoke ‘magnetic effects’ when unusual or negative values are obtained in either or both of the in-phase data components. Such values should be regarded as instrumental level malfunctions in the more challenging measurement of the in-phase coupling ratio. In low conductivity situations, when magnetic materials are present, in-quadrature magnetic effects may also interfere with the accurate measurement of apparent conductivity (Tabbagh, 1986). It is also worth noting that the P values shown in Figure 3 are theoretical values obtained at an elevation of 0.05 m and the values will decrease with increasing elevation. The remainder of the analyses conducted here use a magnetic permeability of free space in the calculations.

## 4. Apparent conductivity

As noted previously, the ground conductivity instruments use a phase sensitive measurement between the Tx and Rx magnetic fields to obtain the secondary ($H_s$) to primary ($H_p$) field ratio. The ratio is complex and comprises a secondary field that is in-phase (P) and in-quadrature (Q) with the primary field.  Thus we may write $P+iQ = H_s/H_p$. The instrument measurement involving the in-quadrature $H_s/H_p$ coupling ratio is converted to apparent conductivity (with $\sigma_a$ in mS/m) using the formula:

$$\sigma_a = \frac{4000}{\omega s^2 \mu_0}\left(\frac{H_s^Q}{H_p}\right) \qquad (1)$$

where ω is angular frequency, ω=2πf, f is the frequency in Hz, s is the Tx-Rx coil separation in m, $\mu_0$ is the magnetic permeability of free space (= $4\pi.10^{-7}$ $H.m^{-1}$, SI units) and the quantity in brackets is the measured in-quadrature (Q) component of the secondary to primary magnetic field coupling ratio, discussed previously.

As noted by many authors referencing McNeill (1980), equation (1) is an approximation based on the assumption of operating the instrument in a low induction number (LIN) mode. The two assumptions discussed in Appendix 1 of McNeill (1980) are that (a) the instrument is operated at zero elevation (i.e. the coil centres are on the ground surface) and (b) that the induction number (B) is much less than unity. The dimensionless induction number (B) is defined as the ratio of the coil separation (s) divided by the plane-wave EM skin depth δ. The skin-depth is defined as the distance within a half-space that a plane wave is attenuated by 1/e (37%) of the value at the surface (Spies, 1989). Thus B = s/δ with the skin depth defined in metres as:

$$\delta = \sqrt{\frac{2}{\sigma \omega \mu_0}} \qquad (2)$$

where σ is the conductivity of the half-space in S/m and the remaining parameters have been defined previously. When operated correctly in LIN mode, the instruments are intended to provide estimates of $\sigma_a$ that are equivalent to the true conductivity of the half-space, as discussed by McNeill (1980).

The scientific literature contains a number of discussions about what value of B constitutes a valid LIN approximation such that the instrument will return the correct conductivity of a uniform half-space. McNeill (1980) indicated that $B \ll 1$ (for a system at zero elevation) and the issue is further discussed by Callegory et al. (2007). In practice such discussions are not particularly useful unless the three factors of (i) the coil configuration under consideration, (ii) the elevation and (iii) the required accuracy are jointly considered.

To illustrate this point, Figure 4 shows the behaviour of measured apparent conductivity with true (half-space) conductivity for coil systems obtained at 3 separations. At each of the 3 separations (s = 1, 2 and 4 m), the apparent conductivity that would be obtained from the 3 standard coil configurations is shown. The results were obtained assuming the lowest practical elevation of 0.05 m and a frequency of 9000 Hz was used. The reference linear (LIN) relationship is shown by a dash line. Also for reference, the B-values, depending on separation, frequency and true half-space conductivity, are shown in Figure 4d.

The well-established progressive deviation to lower values of measured apparent conductivity with increasing true conductivity is observed. Although, in general, the deviation increases with coil separation, the behaviour of the 3 different configurations is not systematic between separations of 1 and 2 m (Figure 4a,b). At the scale shown, large deviations in apparent conductivity are evident at true conductivities in excess of ~40 mS/m. The various deviations from LIN behaviour shown in Figure 4 can be described as a non-linear bias that provides incorrect low values of the half-space conductivity. The bias effects can be seen to be a function of the coil configuration used and coil separation.

If we next consider a minimum required accuracy of 1 mS/m or better (i.e. the difference between apparent and true conductivity) in each of the 3 configurations considered then the true conductivities must be less than 12 mS/m for 1 m separation systems, 17 mS/m for 2 m separations and 18 mS/m for systems operating at a separation of 4 m. In a multi-separation instrument, the maximum value is obtained at the shortest separation. These maximum values relate to systems operated at a practical lowest ground level elevation of 0.05 m. It should also be noted that the stated values are effectively independent of the operating frequencies that are used in these instruments. The use of a frequency of 14500 Hz (e.g. the EM38) with a separation of 1 m would not change the stated value of 12 mS/m.

## 5. Height dependence

The issue of height dependence is next considered using 2 m coil separation systems located above 2 uniform half-spaces of 5 and 20 mS/m. The 5 mS/m half-space is within the LIN limits prescribed above for a system elevation of 0.05 m while the 20 mS/m half-space conductivity lies just above the limiting value. The behaviour of apparent conductivity across a range of elevations extending to 2 m is shown in Figure 5. In the case of the 5 mS/m half-space, all 3 coil configurations provide accurate estimates of the true conductivity at the lowest elevations (<0.05 m) but the deviation with increasing elevation is particularly significant for the PERP and VCP configurations. The sensitivity to elevation is far more significant at the enhanced conductivity of 20 mS/m and once again the PERP and VCP responses are particularly sensitive to elevation over the first meter. In broad terms, the elevation effect appears as a further bias (to lower values) in the apparent conductivity values returned by the instruments. It is suggested that instrumental elevation should be recorded to the nearest ~1 cm.

## 6. A LIN apparent conductivity correction procedure

The results of the previous section are intended to provide a summary of the behaviour of the 3 standard coil configuration systems to variations in half-space conductivity and the operating height of the instrument. It is evident that a large number of ground conductivity surveys have been, and will continue to be, acquired in a context that results in data being obtained beyond the LIN approximation. The basic premise of the ground conductivity instruments is that the devices provide a direct measure of subsurface conductivity (when operated at zero elevation). Many users may also understand that with increasing conductivity there is a deviation (to lower values) from the 'true' value so that the measurements may become 'less accurate'.

In order to maintain the principle of LIN operation it would be useful (to many users) if each particular instrument always provided a estimate of subsurface conductivity consistent with a LIN approximation whatever the operating height and whatever the prevailing conductivity. If we consider the uniform half-space as a reference, then the user might expect to use different LIN instruments (i.e. different coil configurations from the same or different manufacturers), and by providing a measure of the height of the coil-coil centre-line, obtain the same measurement of apparent conductivity. The measured apparent conductivity would then be uniform across all instruments and equal to that of the half-space. The existing, potentially confusing, situation is exemplified is Figure 5. Given a uniform conductivity of 20 mS/m, the user of an instrument (2 m coil separation) operating the device at hip-height (0.9 m) will potentially record 3 different values of apparent conductivity of between 6.6 and 13.8 mS/m. If the user then lowers the instrument to ground level, and achieves an elevation of 10 cm, the instrument will record 3 apparent conductivities of between 17.5 and 18.8 mS/m. The user will then have obtained 6 different measurements of ground conductivity all of which lie significantly outside (below) the true value of the conductivity.

Following the above discussion, it is possible to develop a simple correction procedure that, when applied to the existing measurements of apparent conductivity, provides a consistent estimate of LIN ground conductivity. The correction may best be described as a LIN-equivalent correction factor. The correction factor(s) must be separately determined for each instrument (i.e. each coil configuration and associated separation and frequency) to maintain accuracy. As there are only a limited number of such instruments, the procedure is not too onerous. It should also be noted that departures from the half-space value in the various measurements that may be undertaken would then indicate a non-uniform subsurface conductivity, an understanding that is already embodied in the principle of LIN operation.

Two approaches to the issue of elevation may be considered. The first approach assumes the survey height is known and is constant. This approach is demonstrated here. The second approach is a possible development of the first approach and is discussed later. As has already been noted, the concept of operation at zero elevation is not a practical proposition, and many users will typically operate an instrument on a static or towed platform at elevations of between 0.05 and 0.5 m. Other users may also routinely operate instruments with the supplied harnesses (for example) at greater elevations. The first correction procedure assumes the survey height is known to say 0.01 m accuracy and is always constant. The procedure is illustrated using a DUALEM-4 instrument that is routinely operated on a standard platform that provides an elevation of 0.40 m between the inter-coil centre line and the ground. The theoretical response of the apparent conductivity measurements for an elevation of 0.4 m are shown in Figure 6. Here, the true, half-space conductivity is used as the ordinate and only the behaviour to a maximum conductivity of 200 mS/m is shown (for clarity). In practice the theoretical response is calculated beyond the stated maximum range of the instrument (in this case 1000 mS/m). The correction principle is illustrated by the arrow indicating a true half-space conductivity of 120 mS/m. The correction procedure requires that the observed/measured apparent conductivities of 89.2 (HCP mode), 93.6 (PERP mode) and 83.4 (VCP mode) mS/m be converted to the correct half-space value of 120 mS/m with a defined precision (e.g. 0.5 mS/m).

The observed responses appear as low-order polynomials and can be readily estimated by a least-squares fitting of the data. A cubic expression may be considered in the first instance.

The cubic expressions ( $\sigma_t = a_0 + a_1\sigma_a + a_2\sigma_a^2 + a_3\sigma_a^3$) are obtained by fitting each of the three apparent conductivity responses ($\sigma_a$) curves shown in Figure 6. The coefficients obtained in this case are given in Table 2 alongside the standard error of the least-squares fit.

**Table 2**

Coefficients of the cubic expressions obtained by least-squares fitting of the 3 curves (HCP, PERP and VCP) shown in Figure 6. The standard error of the fit is shown in the final column.

| | $a_0$ | $a_1$ | $a_2$ | $a_3$ | Std. Error |
|---|---|---|---|---|---|
| HCP | -1.5839367 | 1.19965370 | 0.00180971 | 9.3192e-07 | 0.59008773 |
| PERP | -0.1544921 | 1.24416952 | 0.00036078 | 1.8373e-07 | 0.10581487 |
| VCP | -1.1349591 | 1.35473569 | 0.00125258 | -2.464e-07 | 0.39862707 |

The accuracy of the correction must also be evaluated over the full range of measurement values since the observed response behaviour is not strictly a cubic polynomial over the entire measurement range. In order to maintain an accuracy better than 0.5 mS/m using this simple approach, numerical tests indicate that it may be necessary to provide a low conductivity range correction (say for observed conductivities below 15 mS/m) and a high conductivity range correction (for all other conductivities).

## 7. A survey example

The correction procedure is briefly demonstrated on data from a small survey conducted on a beach in eastern England. The ground conductivity survey was part of a larger geophysical and geotechnical investigation of methods to characterise beach thickness. Beaches provide sediment stores and have an important role in the development of the coastline in response to climate change. Quantification of beach thickness and volume is required to assess coastal sediment transport budgets. Detailed descriptions of the location and experiments conducted are given by Gunn et al. (2006). Obviously the salt loading of materials typically encountered in a beach context provides very high conductivities well beyond the normal LIN limit.

The ground conductivity data were acquired with a DUALEM-4 instrument across a control area of 42.5 m (in x) by 24 m (in y) as described by Gunn et al. (2006). The control area is confined to the beach area between low cliffs and the sea. Profile data were acquired using a line sampling (in y) of 2 m and the inter-coil sensor height was fixed at 0.4 m (wheeled cart acquisition). The two apparent conductivities (HCP and PERP) were used in a numerical EM 1D inversion procedure to provide 'true' (or best-estimate) subsurface conductivities, which for this survey exceed 2,000 mS/m. It is generally observed that measured apparent half-space conductivities are generally much less than 'true' conductivity estimated by numerical modelling of the vertical distribution of conductivity.

The apparent conductivities obtained by the survey are shown in Figure 7a,b as colour-contoured images of grids obtained at a 1 x 1 m interval. All the images in Figure 7 use the same colour scale and we typically refer to the PERP data as a shallow or near-surface response and the HCP data as a deeper response. In Figure 7a,b low values extend towards 75 mS/m with central values in the PERP data extending beyond 400 mS/m. The apparent conductivities in the deeper (HCP) data are significantly reduced (by a factor of about 2) across the central conductive zone. The main conductivity gradients are observed parallel to the cliff and shore lines along x=-2.5 and x=40 m respectively. The apparent conductivity values corrected using the cubic expressions discussed previously are shown in Figures 7c,d. As expected the corrected values increase considerably and due to the large range of values across the area, the degree of correction is spatially non-linear (refer to the degrees of non-linearity displayed by the apparent conductivity curves in Figure 4). The near-surface (PERP) corrected data now extend towards a maximum value of 600 mS/m while the HCP corrected data extend to 400 mS/m. The corrected data are now apparent half-space conductivity values that are consistent with the LIN approximation, the two different coil configurations and the operational height. These therefore could potentially be used as conductivity data sets for spatial mapping and correlation with other spatial data sets. It is worth noting however that the corrected data still remain 'approximate' in the sense they are appropriate only to a vertically uniform half-space. If this condition was met at a particular location, the two corrected PERP and HCP apparent conductivity values would be identical. When the condition is not met, the two apparent conductivity values simply indicate some approximate behaviour with depth (e.g. over a near-surface and deeper depth interval).

## 8. Discussion and conclusions

The principal aim of this study has been to address the practical (user) understanding of apparent conductivity measurements obtained from ground conductivity instruments. There has been an increasing use made of such data in relation to spatial mapping and subsequent correlation with many other forms of site specific information. It is understood that the different coil configurations and separations provide a degree of control in relation to subsurface depth discrimination and this may be adequate in relation to the use made of such data. Much of the data acquired however do not conform to a LIN condition and it would be preferable to correct all such the data so that it conforms to behaviour consistent with the LIN condition. As has been demonstrated both theoretically and experimentally, both the magnitudes and form of the spatial measurements may be increasingly distorted in a non-linear fashion across data sets displaying variable conductivity.

Absolute calibration aside, it has been demonstrated that modern conductivity meters are capable of high precision and a LIN condition maximum conductivity of between 12 mS/m (at 1 m separation ) and 18 mS/m (2 and 4 m separation) appears to be a requirement to retain a LIN measurement accuracy of 1 mS/m. As already noted, measurement errors in static mode may be < 0.25 mS/m and this level of accuracy would be even more restrictive in terms the maximum conductivity required to maintain a LIN condition.

Taking a uniform half-space as a reference, then the user might expect to use different LIN instruments (i.e. different coil configurations from the same or different manufacturers), and by providing a measure of the height of the coil-coil centre-line, obtain the same measurement of apparent conductivity. The measured apparent conductivity would then be uniform across all instruments and equal to that of the half-space (when such a condition applies). When the half-space condition does not apply, the LIN-equivalent (corrected) apparent conductivity measurements would still retain variations that are consistent with the true vertical depth distribution and the vertical sensitivity of each measurement.

A simple correction procedure that would allow the measured data to be transformed into a LIN-equivalent apparent conductivity has been demonstrated. The correction procedure needs to be developed and applied for each instrument and for any specific operational height of a survey instrument. Such a method would require the user to have access to the appropriate quasi-static EM forward modelling software. Since the instruments now have a very wide, non-geophysical user base, the suggested correction procedure would have a limited use. A second, potentially less-involved, correction procedure is therefore suggested.

For each instrument, it is a straightforward matter to produce a digital look-up table (or nomogram) of the measured parameters (apparent conductivity and elevation) with true half-space conductivity. Values within the calculated table would span the range of required operational values. A 2m coil separation system, operating at a frequency of 9000 Hz in the HCP configuration is chosen as an example. Figure 8 shows a nomogram constructed by cycling true half-space conductivities across a range from 0.1 to 1001 mS/m employing 20 points per decade and by cycling elevation from 0 to 2 m using an interval of 0.02 m. The nomogram contains 8181 points. A similar nomogram cycling at 40 points per decade of apparent conductivity and at 0.01 m intervals in elevation would still comprise only 32,361 points. The user requirement is to supply measured apparent resistivity and elevation and obtain a corrected LIN half-space conductivity at accuracy consistent with the original measurement. The nomogram can achieve this by either using a high sampling density of parameters or by employing a simple interpolation algorithm across the tabulated values to achieve the desired accuracy. It is suggested that it would be useful if manufacturers of the instruments could supply a simple software tool, possibly employing something as simple as a digital look-up table, along with each specific device. This would allow general users to map LIN-equivalent apparent conductivities using the existing measurements at any specific measurement height chosen by the user. In the limit of a uniform conductive soil/ground, all the instruments, in any of the coil-coil configurations considered, would then return the same correct conductivity. The correction procedure would also remove potential non-linear spatial behaviour (distortions) in the measured apparent conductivities at locations in which conductivities are elevated (say > 12 mS/m) and highly variable. The correction procedure would also assist in inter-site and cross-experimental comparisons of apparent resistivity data sets acquired by the same or different ground conductivity instruments.

Finally it is worth pointing out a potential pitfall in understanding the nature of the corrected LIN-equivalent apparent conductivities. It is apparent that some user understanding of the vertical sensitivity and depths of investigation of LIN instruments remains rooted in the relative and cumulative instrument response curves that operate within the LIN condition (e.g. McNeill, 1980; Sudduth et al., 2010). These are perfectly valid and useful approximations however they become increasingly invalid as the bulk conductivity or near-surface layers become more conductive. As has been pointed out on a number of occasions (e.g. Reid and Howlett, 2001; Callegary et al., 2007), ultimately the depth sensitivity and depth of investigation is governed by the conductivity distribution itself and the presence and thickness of any significantly conductive zones. The LIN-equivalent corrected apparent conductivities discussed here do not modify/correct the intrinsic vertical sensitivities and depth of investigation of the measurements.

## Acknowledgements

Any use of product names is for descriptive purposes only and does not imply any endorsement. This report is published with the permission of the Executive Director, British Geological Survey (NERC).

## References

Abdu, H., Robinson, D.A., Jones, S.B., 2007. Comparing bulk soil electrical conductivity determination using the DUALEM-1S and EM38-DD electromagnetic induction instruments. Soil and Water Management and Conservation 71, 189–196.

Adhikari, K., Carre, F., Toth, G., Montanarella, L., 2009. Site specific land management: general concepts and applications. EUR 23978 EN – Joint Research Centre – Institute for Environment and Sustainability, Luxembourg, pp. 1-60.

Anderson, W.L., 1979. Numerical integration of related Hankel transforms of order 0 and 1 by adaptive digital filtering. Geophysics 44, 1287-1305.

ASTM, 2008. Standard Guide for Using the Frequency Domain Electromagnetic Method for Subsurface Investigations. ASTM D6639 - 01, ASTM International, West Conshohocken, PA. DOI: 10.1520/D6639-01R08.

Beamish, D., 2003. Airborne EM footprints. Geophysical Prospecting 51, 49-60.

Callegary, J.B., Ferré, T.P.A, Groom, R.W., 2007. Vertical spatial sensitivity and exploration depth of low-induction-number electromagnetic-induction instruments. Vadose Zone Journal 6, 158–167.

Christensen, N.B., 1990. Optimized fast Hankel transform filters. Geophysical Prospecting 38, 545-568.

Corwin, D.L., Lesch, S.M., 2003. Application of soil electrical conductivity to precision agriculture: theory, principle, and guidelines. Agronomy Journal 95, 455–471.

Corwin, D.L., Lesch, S.M., Segal, E., Skaggs, T.H., Bradford, S.A., 2010. Comparison of sampling strategies for characterizing spatial variability with apparent soil electrical conductivity directed soil sampling. Journal of Environmental and Engineering Geophysics 15, 147–162.

Doolittle, J.A, Sudduth, K.A., Kitchen, N.R., Indorante, S.J., 1994. Estimating depths to claypans using electromagnetic induction methods. Journal of Soil Water Conservation 49, 572–575

Drommerhausen, D.J., Radcliffe, D.E., Brune, D.E., Gunter, H.D., 1995 Electromagnetic conductivity surveys of dairies for groundwater nitrate. Journal of Environmental Quality 24, 1083-1091.

Frischknecht, F.C., 1967. Fields about an oscillating magnetic dipole over a two-layer earth and application to ground and airborne electromagnetic surveys. Colorado School of Mines Quarterly 62, pp 1-326.

Gunn, D.A., Pearson, S.G., Chambers, J.E., Nelder, L.M., Lee, J.R., Beamish, D., Busby, J.P., Tinsley, R.D., Tinsley, W.H. 2006. An evaluation of combined geophysical and geotechnical methods to characterize beach thickness. Quarterly Journal of Engineering Geology and Hydrogeology 39, 339-355.

Kitchen, N.R., Sudduth, K.A., Drummond, S., 1996. Mapping of sand deposition from 1993 midwest floods with electromagnetic induction measurements. Journal of Soil Water Conservation 51, 336–340.

McNeill, J.D., 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6. Geonics Ltd., Mississauga, ON, Canada.

McNeill, J.D., 1992. Rapid, accurate mapping of soil salinity by electromagnetic ground conductivity meters. Advances in Measurement of Soil Physical Properties: Bringing Theory Into Practice, Spec. Pub. 30, Soil Science Society of America, Madison, Wisconsin, 209–229.

Monteiro Santos, F.A., 2004. 1-D laterally constrained inversion of EM34 profiling data. Journal of Applied Geophysics 56**,** 123-134.

Monteiro Santos, F.A., Triantafilis, J., Taylor, R.S., Holladay, S., Bruzgulis, K.E., 2010. Inversion of conductivity profiles from EM using full solution and a 1-D laterally constrained algorithm. Journal of Environmental and Engineering Geophysics 15, 163-174.

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

Robinson, D.A., Lebron, I., Lesch, S.M., Shouse, P., 2004. Minimizing drift in electrical conductivity measurements in high temperature environments using the EM38. Soil Science Society of America Journal 68, 339–345.

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

Scanlon, B.R., Paine, J.G., Goldsmith, R.S., 1999. Evaluation of electromagnetic induction as a reconnaissance technique to characterize unsaturated flow in an arid setting. Ground Water 37, 296–304.

Spies, B.R., 1989. Effective depth of exploration in electromagnetic sounding methods. Geophysics 54, 872–888.

Sudduth, K.A., 2001. Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. Computers and Electronics in Agriculture 31, 239–264.

Sudduth, K.A., Newell R., Kitchen, N.R., Myers, D.B., Drummond, S.T., 2010. Mapping depth to argillic soil horizons using apparent electrical conductivity. Journal of Environmental and Engineering Geophysics 15, 135–146.

Tabbagh, A., 1986. What is the best coil orientation in the Slingram electromagnetic prospection methods? Archaeometry 28, 185-196.

Triantafilis, J., Lesch, S.M., 2005. Mapping clay content variation using electromagnetic induction techniques. Computers and Electronics in Agriculture 46, 203–237.

Wait, J.R., 1954. Mutual coupling of loops lying on the ground. Geophysics 19, 290-296.

Wait, J.R., 1955. Mutual electromagnetic coupling of loops over a homogenous ground. Geophysics 20, 630-637.

Wait, J.R., 1982. Geo-electromagnetism. Academic Press, New York.

Woodbury, B.L., Lesch, S.M., Eigenberg, R.A., Miller, D.N., Spiehs, M.J., 2009. Electromagnetic induction sensor data to identify areas of manure accumulation on a feedlot surface. Soil Science Society of America Journal 73, 2068–2077.

Yoder, R.E., Freeland, R.S., Ammons, J.T., Leonard, L.L., 2001. Mapping agricultural fields with GPR and EMI to identify offsite movement of agrochemicals. Journal of Applied Geophysics 47, 251–259.

## Figure Captions

**Figure 1**. Schematic coil-coil configurations used by ground conductivity meters operating at low induction number. (a) HCP, Horizontal coplanar coils. (b) PERP, Perpendicular coils. (c) VCP, Vertical coplanar coils. s refers to the separation between coil centres. Arrows denote orientations of magnetic dipoles in transmitters (Tx) and receivers (Rx).

**Figure 2**. Example of test data from a static recording lasting 4 minutes using a ground conductivity meter with an HCP separation of 4 m and a PERP separation of 4.1 m. The diagram shows the measured apparent conductivities in mS/m (range 1 mS/m) and in-phase (P) components in ppt (range 0.5 ppt).

**Figure 3**. Electromagnetic coupling ratios ($H_s/H_p$) in ppm over a range of half-space conductivities extending to 200 mS/m. The coil separation is 4 m, the frequency is 9000 Hz and the instrument elevation is 0.05 m above ground. In-phase (P) and in-quadrature (Q) components are shown for 3 configurations comprising horizontal coils (HCP), perpendicular coils (PERP) and vertical coils (VCP).

**Figure 4**. Apparent conductivities at 3 coil-coil separations (a) 1 m, (b) 2m and (c) 4m above a range of half-space (true) conductivities extending to 200 mS/m. The frequency is 9000 Hz and the instrument elevation is 0.05 m above ground. Results are shown for 3 configurations comprising horizontal coils (HCP), perpendicular coils (PERP) and vertical coils (VCP). Dash lines denote the expected true linear behaviour. (d) shows the induction number (B) for the 3 separations.

**Figure 5**. Apparent conductivities at a coil separation of 2 m using a frequency of 9000 Hz and an elevation of 0.05 m, above 2 uniform half-spaces of 5 and 20 mS/m. Results are shown for 3 configurations comprising horizontal coils (HCP), perpendicular coils (PERP) and vertical coils (VCP).

**Figure 6**. Example of apparent conductivities, shown now along the abscissa, at a coil-coil separation of 4m above a range of half-space (true) conductivities extending to 200 mS/m. The instrument elevation is 0.4 m and the frequency is 9000 Hz. Results are shown for 3 configurations comprising horizontal coils (HCP), perpendicular coils (PERP) and vertical coils (VCP). The arrow denotes the required correction of a set of 3 apparent conductivity measurements , ranging from 83 to 96 mS/m, to a correct half-space value of 120 mS/m.

**Figure 7**. Example of LIN-equivalent correction procedure applied to survey data from a highly conductive (beach) location. The approximate cliff and sea locations are noted in the first panel. The survey area is 42.5 x 24 m. Panels (a) and (b) show the measured apparent conductivities obtained using the PERP (shallow) and HCP (deeper) coil orientations. Panels (c) and (d) show the corrected PERP and HCP coil orientation data. The same colour-contour range is used in all 4 panels and a contour interval of 20 mS/m is used throughout.

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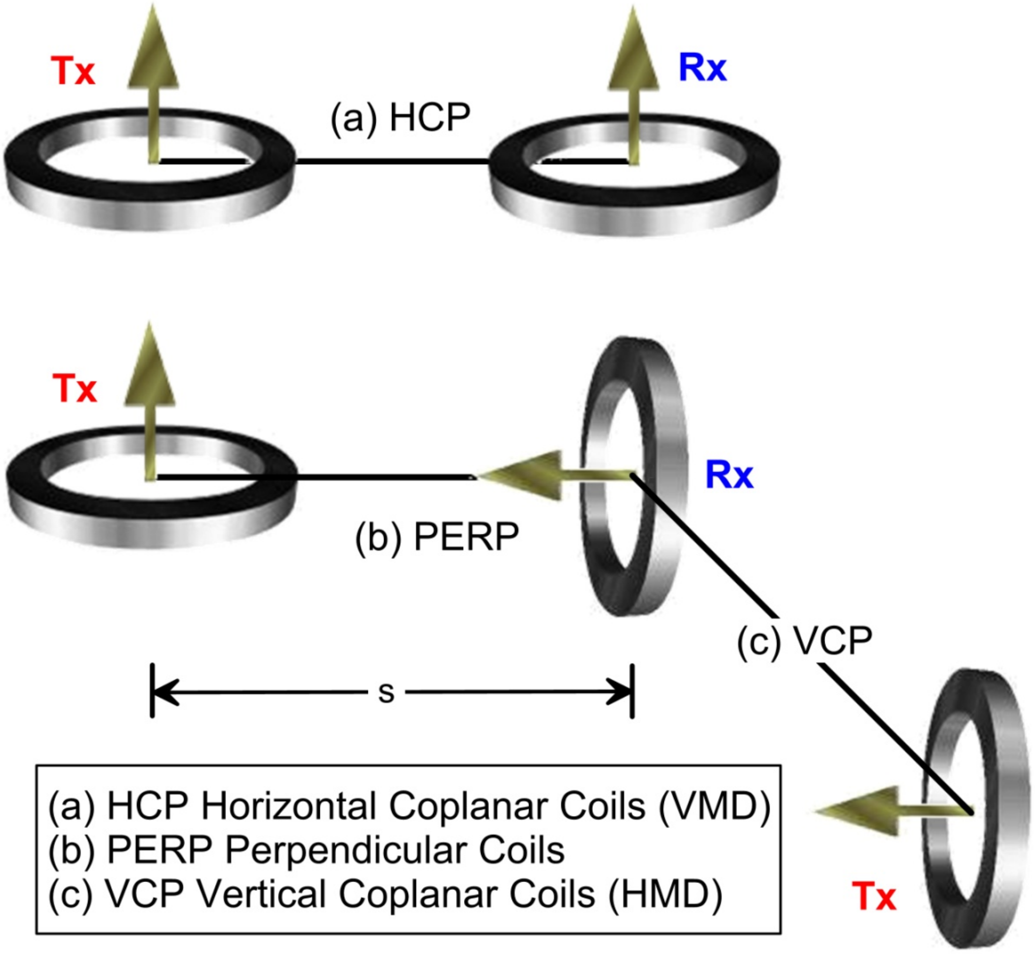

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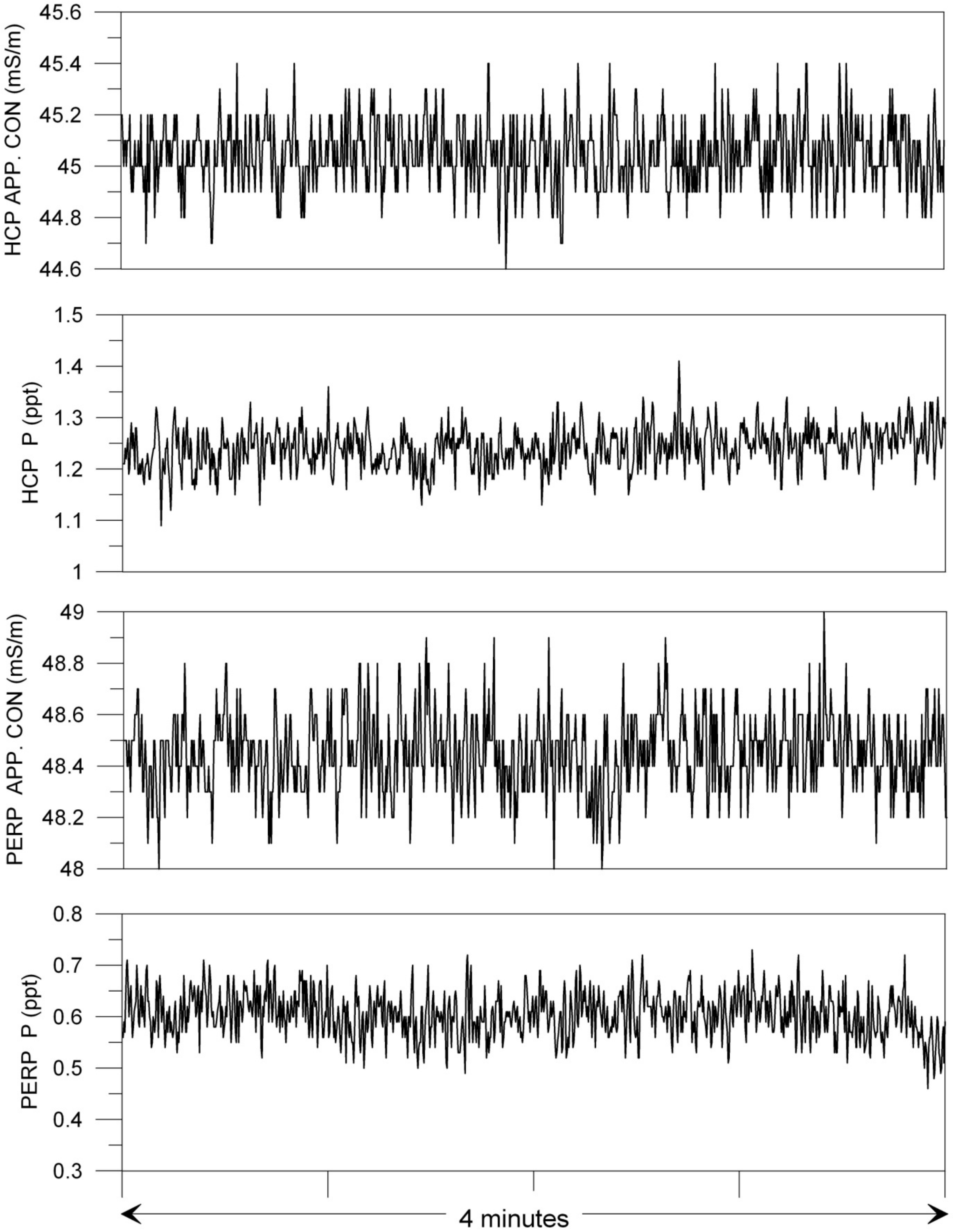

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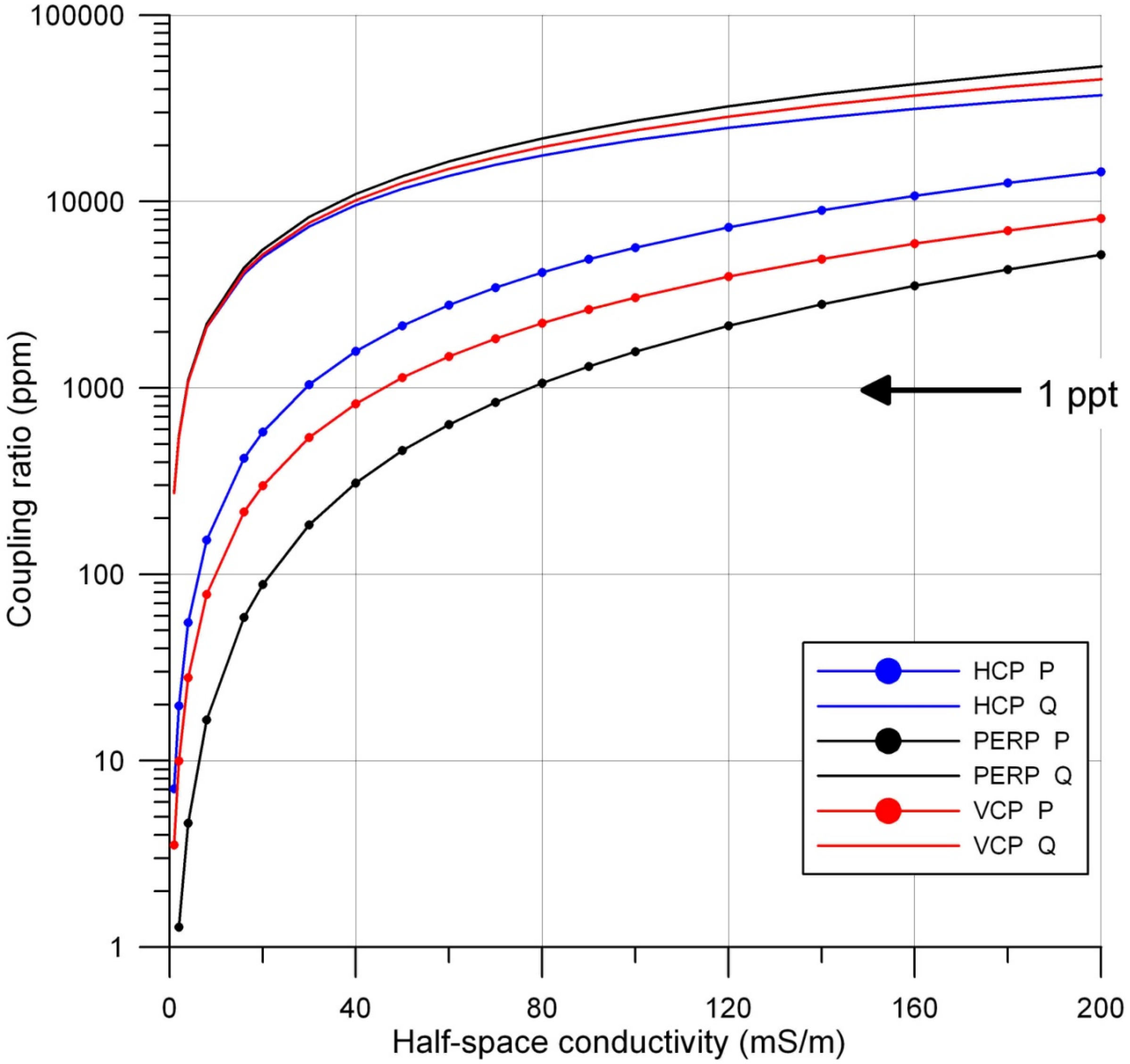

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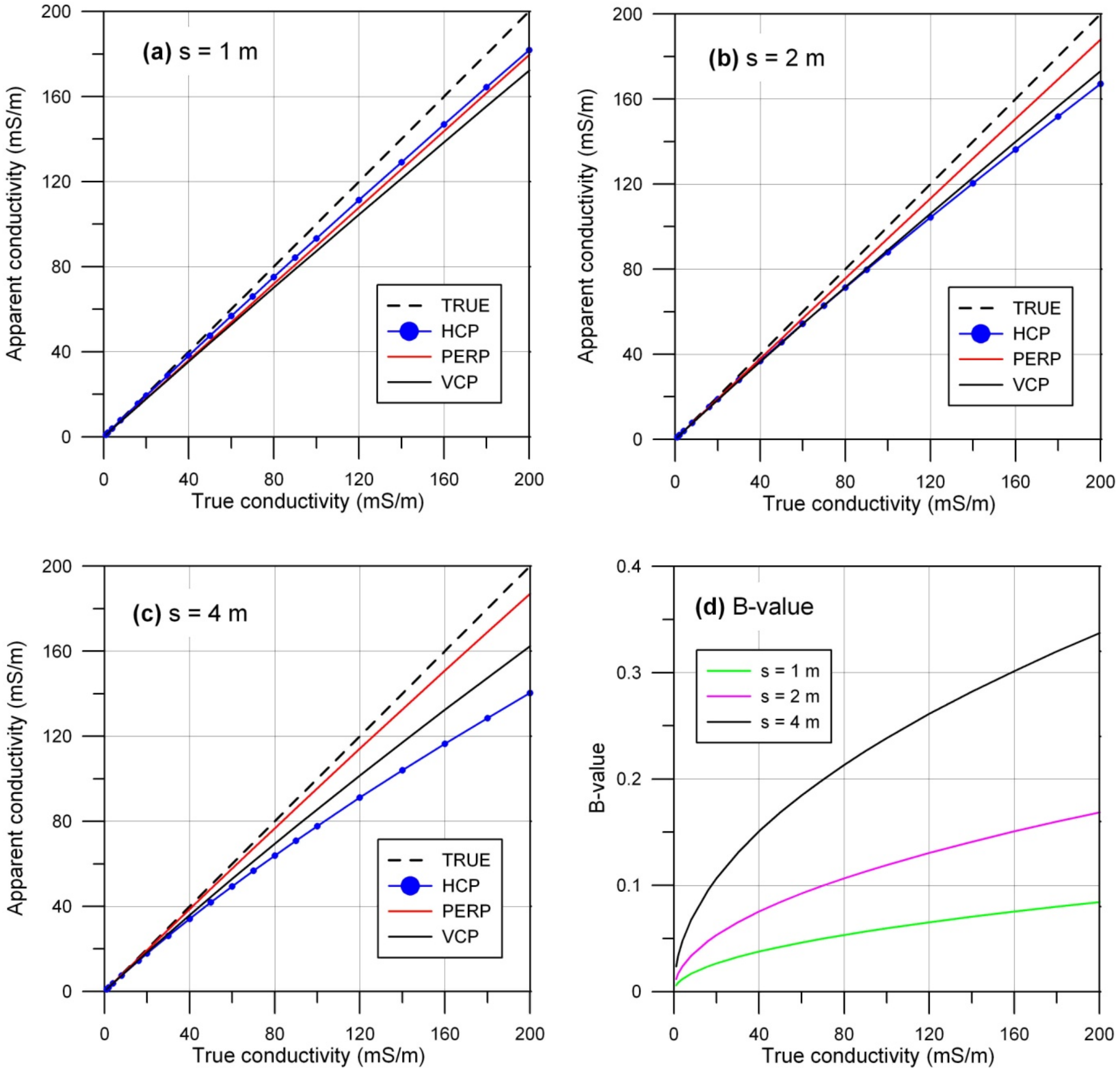

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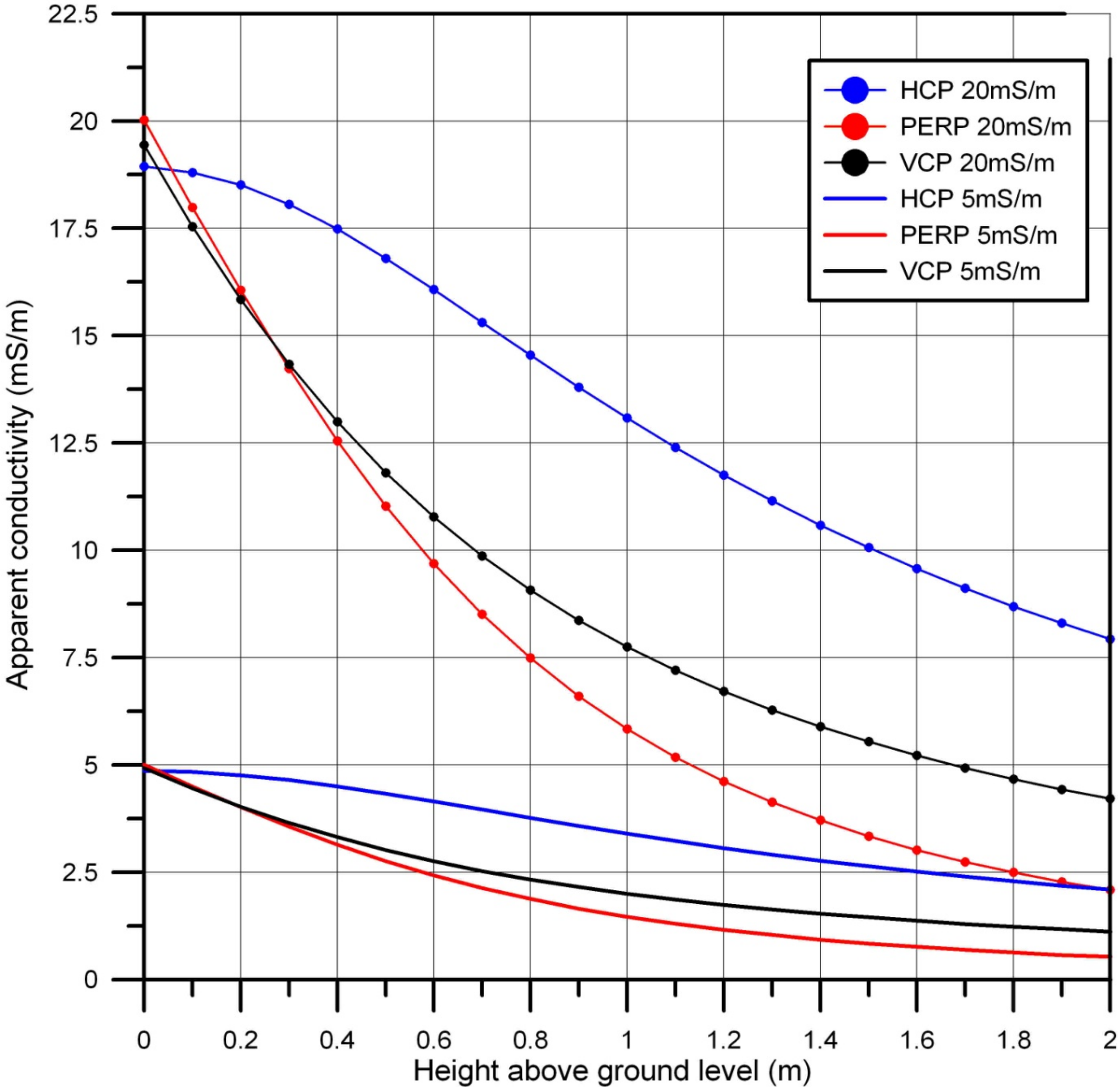

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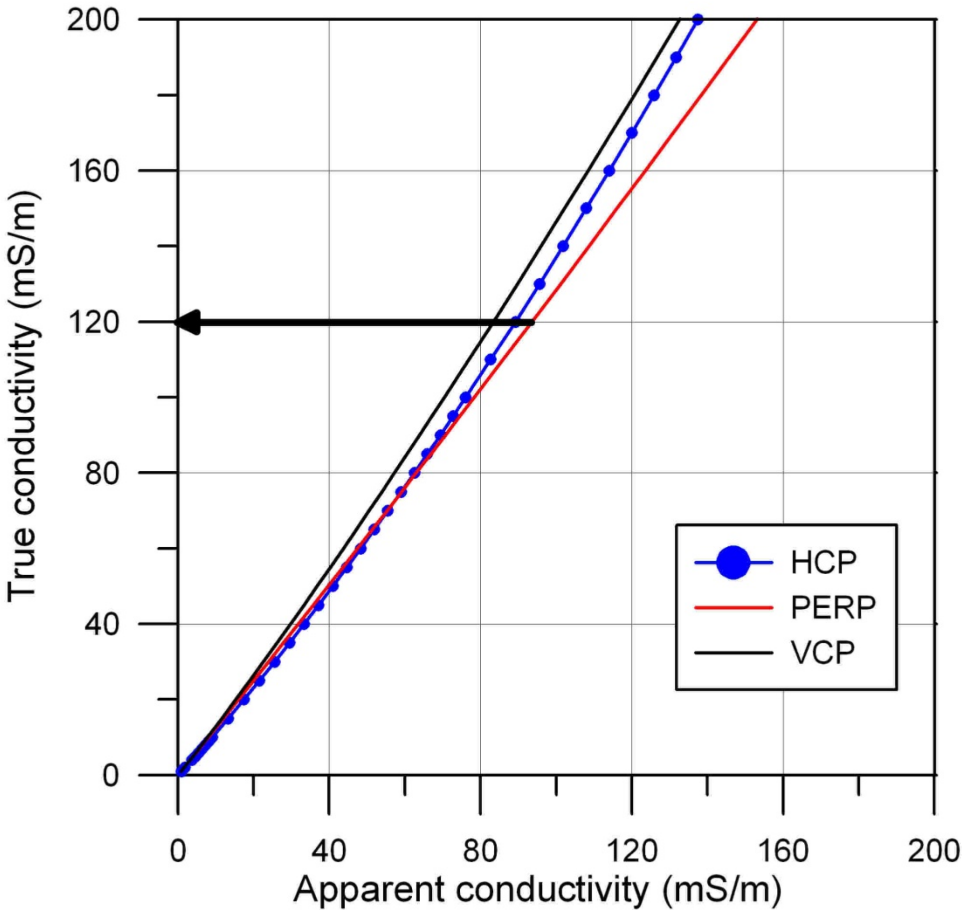

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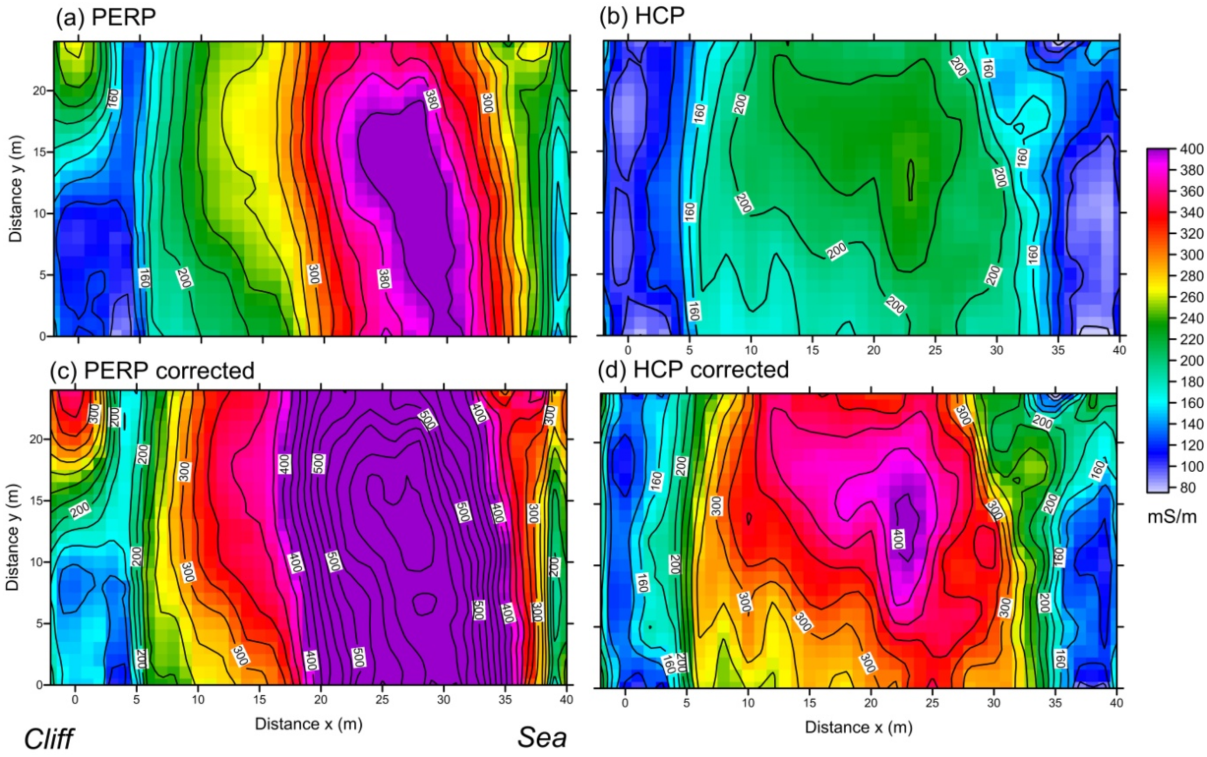

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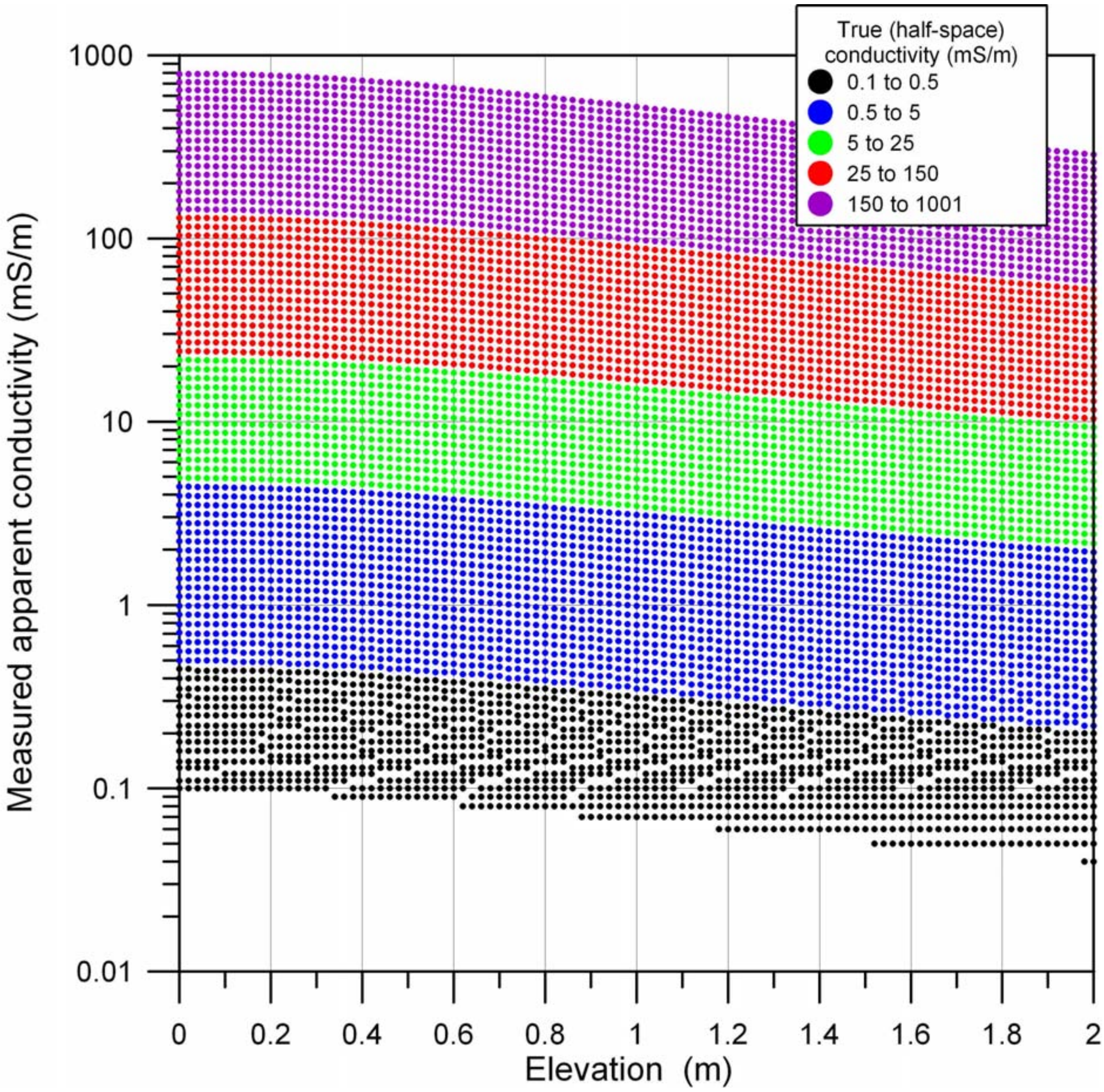

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