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Depth sounding with the EM38–detection of soil layering by inversion of apparent electrical conductivity measurements

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Abstract

The EM38 electro-magnetic induction instrument is widely used for soil mapping in precision agriculture. Added value can potentially be obtained by using the instrument to detect soil layering by depth sounding. Layer conductivities can be estimated from depth sounding data by an optimization procedure called inversion. Inversion is based on a geophysical forward model, which calculates apparent conductivities (measured from the surface) from specific conductivities of the soil layers. Results of inversion can be non-unique due to the fact that different combinations of layer conductivities can generate the same apparent conductivity (principle of equivalence). This also causes high sensitivity to measurement errors. Synthetic data and measurements from fifty plots on two test-sites were analysed. 1D depth sounding with the EM38 cannot sufficiently detect vertical soil variation within 1 m depth but is suitable to indicate the general trend within 2 m depth.

Keywords: EM38, depth sounding, soil layering, electrical conductivity, inversion, principle of equivalence

Introduction

Apparent electrical conductivity (ECa) of soils measured with the EM38 (Geonics, Canada) has been related to many important soil properties and thus found to be useful in research as well as in practice. The EM38 is widely used for geo-electrical soil mapping and is probably the most popular soil sensor in precision agriculture. There has been a lot of published research on the EM38 in the proceedings of the European and the International Conferences on Precision Agriculture. The EM38 is regularly used for mapping lateral variations of ECa. Nevertheless, vertical variations of soil properties are important as well, e.g. for estimating rooting depth, available water capacity and for modelling nitrogen dynamics. One can try to detect soil layering by two measurements with the EM38 arranged in a horizontal and vertical orientation (H-mode, V-mode). Unless there are very large contrasts in conductivity, it is very difficult to separate two soil layers in this way and it is even impossible to distinguish more than two layers. To better assess soil layers by surface methods, it is necessary to survey the soil with a larger number of different penetration depths. In geophysics, this kind of procedure is known as vertical electrical sounding (VES) (Parasnis, 1997). As described below, depth sounding with the EM38 can be accomplished relatively easily within a few minutes. So, the idea is to combine mapping of horizontal soil variations with VES data to explore the vertical variations at selected sites to further improve the soil survey. If the resulting depth profiles of EC are reliable, this might further extend the usage of the EM38 in precision agriculture. In this study, VES with the EM38 is evaluated by simulation experiments and by investigations on two test sites.

Theory

VES was first developed for galvanic coupled electrical resistivity measurements where depth of investigation (DOI) is controlled by the spacing of the electrodes. The EM38 is based on electromagnetic induction (EM) where a primary electrical field is induced by a transmitter coil (dipole) and the soil response is sensed by a receiver coil (Parasnis, 1997). With EM methods, DOI can be controlled by coil spacing, coil orientation, frequency of the induced current and by height of the probe above the ground. In geophysics, depth sounding by EM methods is usually done by variation of frequency, coil spacing and/or coil orientation. While the EM38 has fixed coil spacing and frequency, the only options to control DOI are coil orientation and height above ground. Thus VES with the EM38 is performed by lifting the instrument step by step above the ground (McNeil, 1980, Borchers *et al.*, 1997). While lifting the instrument, the relative influence of deeper soil layers on the measurements increases (Figure 1). Layer conductivities are derive from the VES data by computational methods which are called inverse modelling or simply inversion. Inversion summarizes a large number of numerical methods which are used to estimate inputs given a mathematical model and observed outputs. Due to the limited space, inversion is not explained here in detail. For in-depth treatment, the reader is referred to the literature (Borchers *et al.*, 1997; Hendrickx *et al.*, 2002; Vogel, 2002). The basic idea of inversion is to calculate possible VES curves based on known physical laws describing the influence of the specific electrical conductivity (EC) of soil layers on the ECa measured above the soil surface. The formulae of the physical laws are called the forward model. The results of forward modelling are compared with the actual measurements and when they are different, estimations for input parameters are adjusted by means of numerical routines.

According to McNeill (1980), the forward model of the EM38 is based on the cumulative depth response curves for the V-mode (R_V) and the H-mode (R_H)

$$R_V(z) = (4z^2 + 1)^{-0.5} \tag{1}$$

$$R_H(z) = (4z^2 + 1)^{0.5} - 2z \tag{2}$$

where z is the depth. The cumulative response curves are integrals of the depth response curves as visualized in Figure 1. From the cumulative depth response curves, a linear forward model is derived

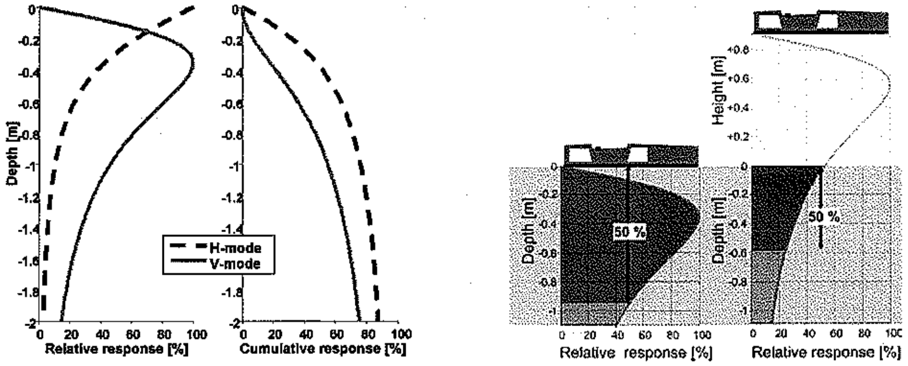

Figure 1. Relative and cumulative depth response (left). Principle of depth sounding with the EM38 in the V-mode (right): the influence of the upper layers is decreasing when the instrument is lifted.

which can be written in matrix form where K is the matrix of coefficients and σ is a vector of the layer conductivities. With d as the vector of observed ECa values at the surface, inversion can now be written as a minimization problem for linear least squares with non-negative constraints:

$$\min\|K \cdot \sigma - d\|^2 \qquad \sigma \geq 0 \tag{3}$$

Inversion of VES faces two problems: non-uniqueness of the solution and ill-posedness[1] of the parameter matrix. Non-uniqueness of the solution is due to the fact that different conductivity distributions may lead to very similar VES curves (principle of equivalence, Parasnis 1997; Lück *et al.* 2005). Inverse problems are ill-posed when small errors in the data d may cause large variations in the inversion results (Borchers *et al.* 1997). To overcome the sensitivity to errors in d, so called regularization is applied which forces the solution of the inversion to have some desirable properties:

$$\min\|K \cdot \sigma - d\|^2 + \lambda^2\|L \cdot \sigma\|^2 \tag{4}$$

where $\|K \cdot \sigma - d\|^2$ is the fit-to-data functional for calculating the residual error and $\lambda^2\|L \cdot \sigma\|^2$ is the regularization functional for calculating the regularization error. The regularization functional forces the estimated σ of adjacent layers to be more similar. The degree of smoothing is controlled by the regularization parameter λ. Regularization has to be balanced between the preservation of details and the smoothing of noise.

A basic assumption of the forward model is that σ is constant within each layer and that no lateral variations appear. Another assumption is the low induction number hypothesis (McNeill, 1980). This implies that the response of an EM38 is only linearly related to the conductivity of the soil when conductivities are below 100 mS/m. On soils with higher conductivities, non-linear forward models have to be considered (Hendrickx *et al.*, 2002).

Materials and methods

Inversion programs

Different inversion programs were used in order to test the influence optimisation algorithms and parameter settings. IX2D is a commercial inversion program developed by Interpex (Golden, USA). For smooth inversion, it uses a ridge-regression least-squares inversion procedure. The parameters of the program were fixed to a four-layer model at 2 m depth, minimal thickness of a layer was 0.1 m, initial guess for all layer conductivities was 10 mS/m. Three MATLAB (The MathWorks, USA) implementtations of inversion algorithms based on a linear forward model by Borchers *et al.* (1997) were tested. The original algorithm uses the "lsqnonneg" MATLAB solver for non-negative least-squares constraints problems (linear least squares with non-negativity constraints). In a second version, "lsqnonneg" was replaced by the "fminunc" MATLAB built-in routine which uses a Quasi-Newton algorithm. Additionally we implemented a gradient projection conjugate gradient method (GPCG) based on modified codes provided by John Bardsley and described by Bardsley and Vogel (2003). According to Deidda *et al.* (2003), the GPCG method can solve EM38 inversion without regularization. The influence of the regularization parameter λ was tested by repeated inversions with different parameter settings (0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1 and 2).

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[1] Ill-posedness is a mathematical term which describes the situation when the numerical solution of a problem is highly sensitive to changes in the input parameters. An ill-posed problem is indicated by a big condition number.

Simulation studies

To investigate the performance of the inversion algorithms and to understand the influence of errors on inversion, Monte Carlo simulation studies with synthetic profiles were carried out (Figure 2). Two types of errors were considered: height errors (constant shift) and measurement errors (random normal distributed error).

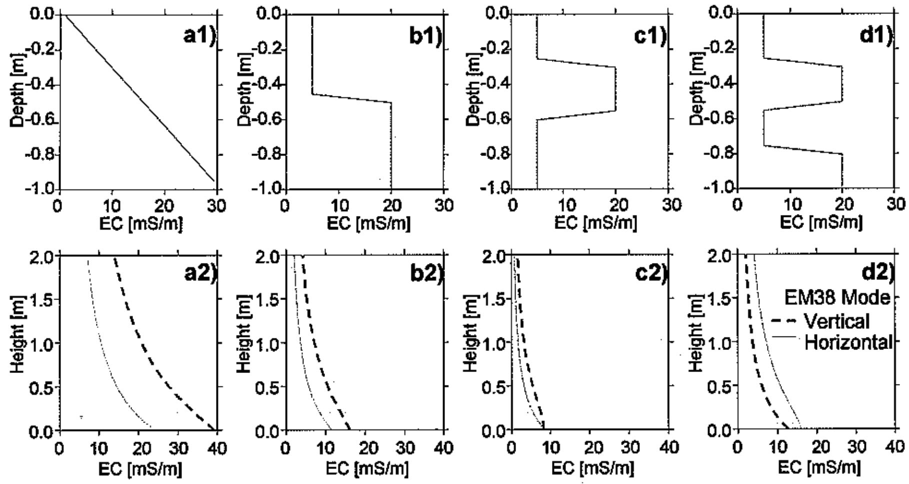

Figure 2. Synthetic models of specific conductivity depth profiles (a1 to d1, upper row) and their corresponding apparent conductivity sounding curves (a2 to d2, lower row)

Instrumentation

For EM depth sounding, a standard EM38 was used. It was mounted on a wooden stand which allowed placement at different heights up to 2 m. At the first test site (Bornim), height increments of 0.1 m were used, at the second site (Scheyern) increments were enlarged to 0.2 m. As measurements in Bornim were made on a warm (about 20 °C) and sunny day, the instrument was thermally insulated by a Styrofoam box. To prevent electromagnetic distortion by cables linked to an automatic datalogger, readings were manually written down. The operator was wearing metal-free clothes and shoes. Readings were taken in the horizontal and the vertical mode. A total of 50 depth soundings were made, 32 in Bornim in June 2005 and 18 in Scheyern in Sept. 2005.

The direct-push probe ERM (Earth Resistivity Meter, Eijkelkamp, The Netherlands) was used as a reference for the upper meter. The ERM is a galvanic-coupled resistivity instrument (GCR). The tip of the probe consists of four electrodes which measure electrical resistivity via direct soil contact by the four-point method (Parasnis, 1997). The probe senses a volume of about 80 cm^3. Readings were taken every 0.05 m down to 1 m beginning at 0.1 m depth. To compare ERM measurements with EM38 inversion results, inversions for three sets of layers were calculated and ERM values were averaged accordingly: a high resolution set with layers of 0.01 m thickness, a medium resolution set with 0.02 m layers, and a coarse set with three layers between 0, 0.3, 0.6 and 1.0 m. The latter set of layers corresponds to the German standard depths from where soil samples are taken for soil nutrient analysis. Analysing different sets of layers should indicate whether the number of the target layers has an influence on the quality of inversion.

A GeoTom (GeoLog, Germany) multi-electrode system was used as a second reference for readings beyond 1 m. The GeoTom is a GCR instrument for surface geophysical prospecting based on the four-point method. Up to 100 electrodes were placed in 0.5 m intervals along the transects and switched in a Wenner configuration (Parasnis, 1997). Eight electrode spacings were evaluated to obtain readings up to about 2 m depth. The measurements were inverted by RES2DINV (Geotomo Software, Malaysia). RES2DINV performs 2D inversion accounting for values from neighbouring VES. In previous studies we have observed a high correlation between inverted GeoTom readings and the ERM within 1 m depth (Kendall's τ was 0.703, Pearson's r was 0.871). Thus we assumed that the GeoTom was producing reliable results for depths greater than 1 m as well and could serve as a reverence.

Correlation

Inversion results were compared with other field data by Kendall's tau rank correlation coefficient (τ). τ is more robust than Pearson's r and does not assume linear relationships.

Test sites

The first test site at Bornim is situated in north-east Germany, 30 km west of Berlin. Geology was formed by the last ice age 10,000 years ago. The site it is a part of a landscape garden and is covered by tall herb vegetation which is mown once or twice a year. The dominant soil type is Dystric cambisol. Soil texture is dominated by loamy sand varying from sand to loamy sand and sometimes clay in lenses and at the bottom of the profile. Elevation of the test site varies between 40 and 43 m resulting in a gentle slope facing to the north. Investigations were carried out on a transect of 159 m length which was arranged along the terrain slope and along the gradient of soil texture. Plots for VES with the EM38 were placed with a spacing of 5 m along the transect.

The second test site is Scheyern, located in southern Germany, 30 km north of Munich. The 150 ha of arable farmland were part of the project "Munich research association for agricultural ecosystems (FAM)" (http://fam/weihenstephan.de/). Parent material originates from the tertiary and quaternary period, while the relief results from quaternary processes. Investigations were carried out on four transects (80 to 220 m). Texture ranges from gravel and sand to clay (lenses). Soil types are Kolluvisols (Udifluvents), Brown Earths (Eutrochrepts), Pelosols (Vertic Eutrochreps). Plots for VES were arranged irregularly on the transects.

Results

Sensitivity analysis

Small errors can have a large influence on the inversion results. This is due to the principle of equivalence and ill-posedness. Figure 3 illustrates this by the inversion of three simulated measurements (based on the three layer model c1 in Figure 2) with a constant height error of 0.03 m and random measurement errors of 0.1 mS/m for the V-mode and 0.3 mS/m for the H-mode. The standard deviations used in this simulation have been obtained by repeated measurements. The influence of the errors can be ranked as follows: height error 1.0, V-mode measurement error 0.7, H-mode measurement error 0.2. Regulation reduced the effects of errors by a relative factor of -0.3. Increasing regularization improved the overall fit, but at the expense of details (good fits became worse, see Figure 4b and c). Analysis of model a1 (Figure 2) showed that inversion of data from constantly increasing (or decreasing) ramp-like EC profiles fails with or without regularization. Only depth soundings from soils with distinct layering could successfully be inverted. This was confirmed by observations in practice (Figure 4a).

Inversion algorithms

In the presence of noise, no big differences between the inversion algorithms were observed. Only with error-free data, the GPCG procedure could reveal conductivities of layered profiles without regularization and thus produced better results.

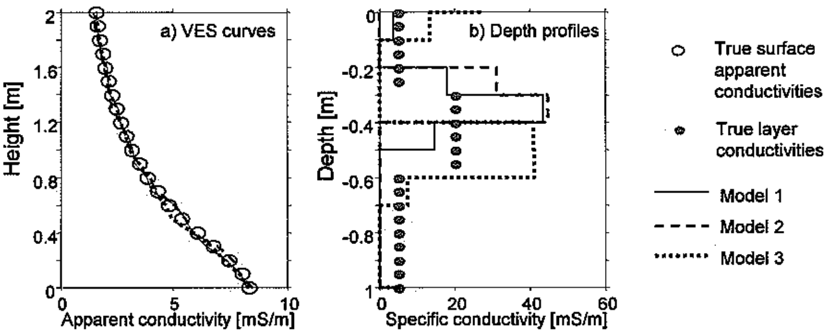

Figure 3. Principle of equivalence and ill-posedness. (a) Forward modelling: True values (empty circles) and models fitted to V-mode data with small errors. (b) Layer conductivities: True values (filled circles) and estimates by inversion.

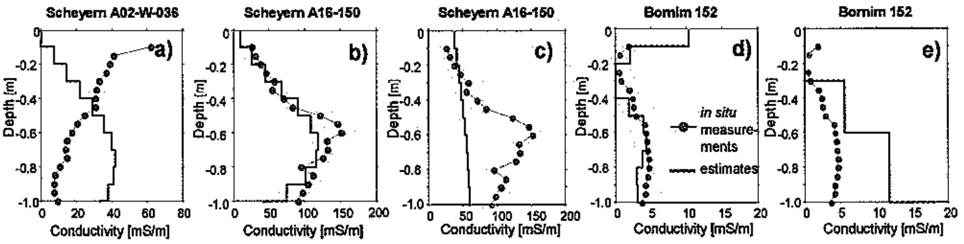

Figure 4. Example for inversion results with GPCG. (a) Bad estimate due to a ramp-like profile, (b) good estimate with λ = 0.05, (c) bad estimate due to smoothing by λ = 2, (d) good estimate with λ = 0.005, (e) bad estimate due to smoothing (λ = 2) and coarse layer resolution.

Practical results

In Scheyern, the overall relationship between ERM and EM38 inversion results were all negative and mostly poor. No matter which regularization parameter or set of layers, correlations were in the range of -0.05 to -0.2. In Bornim, all correlations were positive. The best result (0.25) was achieved with the regularization parameter set to 2 and with the high resolution set of layers. Correlations in Bornim generally increased with the regularization parameter, but this was not always consistent. Reducing the number of predicted layers did not improve the results (Figure 4d and e).

Correlation between inversion results of EM38 and GeoTom for 2 m depth achieved τ of more than 0.6 on both test sites with λ = 2. Examples are given for Bornim in Figure 5. Regarding the pseudo-sections derived from EM38 VES (Figure 5b to d), it should be mentioned, that the large lateral variations around 100 were caused by a metal water pipe. While the electromagnetic induction method was very sensitive to metal, the GCR based GeoTom was not disturbed.

Discussion

Simulation studies and practical observations confirm the problems of inversion of EM38 data due to the principle of equivalence and ill-posedness. Inversion can be improved by regularization. However, the regularization factor λ has to be chosen with care. While overall correlation increases with increasing λ, the estimates for particular profiles can become worse because of the loss of details. Thus, λ should be set individually for each profile. However, this can be very time consuming; also, the selection of an appropriate λ is difficult. Borchers *et al.* (1997) suggest the

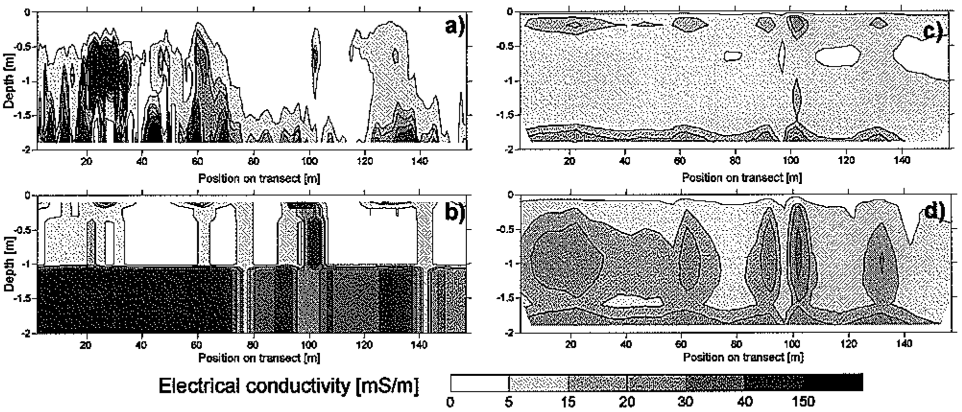

Figure 5. Inversion results for the transect in Bornim. (a) GeoTom, (b) EM38 with IX2D, (c) EM38 with GPCG and λ = 0.001, (d) EM38 with GPCG and λ = 0.05.

L-curve criterion, but Deida *et al.* (2003) showed that this can be misleading, a finding which was confirmed by our own results (not presented here).

Correlations with the ERM for 1 m depth were relatively poor while correlations with inverted GeoTom values for 2 m depth were significantly better. This can be due to a number of reasons: first, variability of the *in situ* measurements is higher because of the smaller soil volume under investigation while the GeoTom senses larger soil volumes increasing with depth; second, the GeoTom values were likewise results of inversions and thus subjected to smoothing; third, lateral variations near the surface can violate the assumption about lateral homogeneity of σ in the forward model. In this case, V-mode measurements will conflict with H-mode measurements due to their different depth of investigation. In these situations, inversion of V-mode data only can lead to better estimates.

In some cases, we have observed very high conductivities which came close to the 100 mS/m limit of the low induction number hypothesis. In these cases, the linear forward model we have used might be inappropriate. Hendrickx *et al.* (2002) have shown that the use of a nonlinear forward model could very much improve inversion results for depths up to 3 m in the presence of very conductive layers. However, they stated as well that inversion results for depths up to 1.5 m differed only about 1% for linear and nonlinear forward models. While the effective penetration depth of the EM38 is about 1.5 m the effect of measurement errors becomes much larger than the effect of model errors when depths below 1.5 m are considered.

Conclusions

1D inversion with the EM38 turns out to be rather difficult. Due to the principle of equivalence and due to the fact that measurement errors cannot be avoided, inversion results will always be uncertain. Results for 1 m depth are not very reliable while general trends within 2 m depth are detected with a greater certainty. Results could probably be improved when 2D inversion is applied in a similar way as with the GeoTom data. However, this would involve VES with an EM38 along a transect in a stop-and-go mode. Such an approach is not cost-effective for mapping of large agricultural fields. A solution could be the development of multi-electrode resistivity or multi-coil EMI systems for continuous kinematic measurements of multiple depths.

References

Bardsley, J.M. and Vogel, C.R. 2003. A Nonnegative Constrained Convex Programming Method for Image Reconstruction. SIAM Journal on Scientific Computing 25 (4) 1326-1343.

Borchers, B., Uram, T. and Hendrickx, J.M.H. 1997. Tikhonov Regularization of Electrical Conductivity Depth Profiles in Field Soils. Soil Science Society of America Journal 61 1004-1009.

Deidda, G.P., Bonomi, E. and Manzi, C. 2003. Inversion of electrical conductivity data with Tikhonov regularization approach: some considerations. Annals of Geophysics 46 549-558.

Hendrickx, J.M.H., Borchers, B., Corwin, D.L., Lesch, S.M., Hilgendorfer, A.C. and Schlue, J. 2002. Inversion of Soil Conductivity Profiles from Electromagnetic Induction Measurements: Theory and Experimental Verification. Soil Science Society of America Journal 66 673-685.

Lück, E., Rühlmann, J. and Spangenberg, U. 2005. Physical Background of soil EC mapping: laboratory, theoretical and field studies. In: Proceedings of the 5th European Conference on Precision Agriculture, ed. J.V. Stafford, Wageningen Academic Publishers, The Netherlands, pp. 417-424.

McNeil, J.D. 1980. Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers. Technical Note TN-6. Geonics Limited: Mississauga, Canada.

Parasnis, D.S. 1997. Principles of Applied Geophysics. Fifth edition. Chapman & Hall: London, 456 pp.

Vogel, C.R. 2002. Computational Methods for Inverse Problems. SIAM: Philadelphia, PA, USA, 183 pp.