Review of manuscript HESS-2012-248, Three-dimensional monitoring of soil water content in a maize field using electrical resistivity tomography by L. Beff et al.

Our responses to reviewer comments are in blue in the text below. All comments have been taken into account and in almost all cases we directly followed the suggestions.

General comments

The manuscript HESS-2012-248 presents a study in which electrical resistivity tomography (ERT) was used in combination with time-domain reflectometry (TDR) to monitor the 3D soil water content (SWC) distribution under maize plants. The manuscript has two goals. Firstly, it is aimed to demonstrate the applicability and performance of a state-of-the-art 3D ERT setup for quantitative monitoring soil water redistribution under maize under field conditions. Secondly, the ERT image data were to be used to investigate soil water dynamics under maize plants under natural climatic and subsoil boundary conditions. Both goals are successfully tackled by the authors.

It is true that similar goals have already been topics in preceding studies, e.g. by Michot et al. 2003, Srayeddin et al. 2009 or Robinson et al. 2012 using surface-electrode ERT or by Garré et al. under semilaboratory conditions. However, Beff et al. 2012 are to my knowledge the first ones who successfully apply an advanced modern 3D ERT measurement layout in combination with TDR in a field for vadose zone water content monitoring under natural boundary conditions. The quality of their results is consequently unprecedented and for the first time allows for a quantitative visualization of the 3D spatio-temporal water dynamics in cropped soils under field conditions. The manuscript is therefore highly relevant for a publication in HESS.

The scientific methods are valid and clearly outlined with the exception that the influence of ERT-image resolution is not discussed. Such a discussion is crucial and should be included in the manuscript. Provided that this is done the (possibly slightly modified) conclusions of the manuscript would be sufficiently supported by the results. The description of experiments and calculations are sufficiently complete and precise to allow their reproduction by fellow scientists. The number and quality of the references is appropriate and the authors give proper credit to related work, an exception being some citations of former ERT studies which are cited in a wrong context (see below). The title clearly reflects the contents of the paper and the abstract provide a concise and complete summary.

The manuscript is well structured and clear. However, the language should be improved since it still contains some grammatical flaws (e.g. wrong article use) and strange word choices and is not always very precise. The mathematical formulae appear correct to me. However, some of the units are not given (see below).

I recommend a major revision.

We thank the referee for his/her positive and constructive comments on the paper. We significantly improved the discussion on the sensitivity of the ERT image, in agreement with reviewer comments, and showed that we have reliable images for supporting our analyses (see our responses below).

Specific comments

It should be worked out more clearly what the authors' new original contributions to research were. Quantitative interpretations of smoothness constraint ERT is never an easy task. Caveats should be given explaining why it was working well in this study and why no major mass balance errors (e.g. like in Singha, K., and S. M. Gorelick (2005), Saline tracer visualized with three-dimensional electrical resistivity tomography: Field-scale spatial moment analysis, *Water Resour. Res.*, *41*(5)) between ERT and alternatively derived water contents were observed.
We added a few sentences to describe the challenges of this study, including the quantitative approach, the fact that we work on water content in a cropped field and under natural boundary conditions. We will also mention possible problems as in Singha & Gorelick (2005), who observed an underestimation of their mass balance with ERT. They attributed this underestimation to two points (i) the reduced measurement sensitivity to far away from the electrodes and (ii) spatial smoothing (regularization) from tomographic inversion. In our study, we also observed a decrease of sensitivity with distance from electrode. But, by installing staggered deep electrodes, we increased the ERT sensitivity in the whole soil volume, which in turn reduced the impact of smoothness on the result. We think that the improved ERT resolution is the main reason for the good mass balance.

Moreover, Michot et al. (2003) suggested the use of in situ calibration to quantify SWC from ERT in field, due to the influence of the soil volume in the relationship calibration. In our study, we used a TDR calibration made in the same field in 2010, which could significantly improve our pedoelectrical relationship (and therefore the mass balance).

As the degree of regularization comprised within smoothness-constrained ERT images depends on the position of the image-voxel relative to the ERT electrodes, the electrode positions should be indicated in the ERT-images shown in the manuscript (see Friedel 2003; Day-Lewis, F. D., K. Singha, and A. M. Binley (2005), Applying petrophysical models to radar travel time and electrical resistivity tomograms: Resolution-dependent limitations, *Journal of Geophysical Research-Solid Earth*, *110*(B8).). An overview of the amount of smoothness in the different regions of the ERT images should be given, e.g. in form of an ERT sensitivity distribution. Since it appears from figure 3 that the borehole electrodes are not symmetrically arranged in space, it would be helpful for the interpretation of the ERT images to know the ERT sensitivity shown from above on the soil surface and in 1 or two depths. Also an integral measure of sensitivity for the averaged vertical cross-sections would be helpful.
Following the suggestion, we added the electrodes positions in the figures and a sensitivity analysis in the corrected document. The sensitivity analysis was added at the beginning of section "3.3.1 SWC spatial variability". A description of the equation was also added in the material and methods section. The added sections are presented at the end of this document.

p8536, l6: ".. validate the sensitivity of ERT..". It is misleading to use the term 'sensitivity' in this context because the ERT-sensitivity of a specific voxel normally refers to the hypothetical change in the measured transfer resistances associated with a change in bulk electrical resistivity of this voxel (see e.g. Kemna, A., J. Vanderborght, B. Kulessa, and H. Vereecken (2002), Imaging and characterisation of subsurface solute transport using electrical resistivity tomography (ERT) and equivalent transport models, *J. Hydrol.*, *267*(3-4), 125-146.)

We changed the sentence: "to check and validate the sensitivity of ERT for monitoring SWC distribution in a maize field during the late growing season" in "to check and validate how well ERT is able to monitor SWC distribution in a maize field during the late growing season"

p8538, l19ff:

a) "Binley, A., G. Cassiani, R. Middleton, and P. Winship (2002), Vadose zone flow model parameterisation using cross-borehole radar and resistivity imaging, *J. Hydrol.*, *267*(3-4), 147-159." did image water and solute transport in the deep vadose zone using borehole electrodes that extended more than 10 meters into the ground. A small uncropped soil column was used in the following study: "Binley, A., S. HenryPoulter, and B. Shaw (1996), Examination of solute transport in an undisturbed soil column using electrical resistance tomography, *Water Resour. Res.*, *32*(4), 763-769."

Thanks, we corrected this reference.

b) The lysimeter in Garre et al. 2010 was not yet cropped.

We were mistaken. In 2010, it was a tracer experiment in bare soil lysimeter and in 2011, a SWC experiment in cropped lysimeter. We corrected for it in the revision.

c) The study of Cassiani et al. 2006 may have been under a cropped field but aimed at detecting a tracer plume in the shallow and deeper groundwater, so it was not relevant for their experiment whether it was carried out under a cropped field or not

Yes, indeed, for the points c) and d), it does not matter whether the field was cropped or not. This is corrected it in the revision.

d) Kemna et al. (2002) monitored a tracer plume in the groundwater under a meadow in a depth of 8 meters below the soil surface.

e) Vanderborght et al. (2005) merely conducted a numerical experiment. The study only took place on their computers.

OK, we removed this reference.

p8540: It would be worthwhile knowing how high the maize plants were in the beginning of the experiment and how much they grew during the monitoring period.

Indeed, the maize development is a useful precision for the reader. The maize plants were well developed during the experiment. I added the plant size at the beginning and at the end of the experimental time and the flowering date.

p8540, l.7: Do you mean "horizontal spacing"?

Yes, we added "horizontal".

p8541, l8: "showed" would be more adequate than "proved".

OK, we changed it.

p8541, l9: Did you conduct the ERT and TDR measurements at the same time? Or did you disconnect the TDR multiplexers when carrying out the ERT measurements to prevent short circuits?

Thank you for this remark. We are aware that TDR and ERT measurements together could create short circuits. However, as the horizontal spacing between the ERT area and the TDR area was around 4m, we assumed that this distance was sufficiently large to neglect the effect of the short circuits on ERT measurements.

p8542, l6: it should be "normal and reciprocal mode".

OK, we changed it.

p8542, l9: "..contained 12664 measurements" Including or excluding reciprocals?
Including the reciprocal, we added this precision.

p8543,l11: "a constant value of 50 for lambda was chosen..". Explain why you chose 50 and not another value.
To choose the value of lambda, we realized several inversion tests with lambda going from 10 to 100. The value of 50 for lambda was the result of a compromise between the inversion quality (rrms and chi²) and the smoothness level of the images. High values of lambda overly smoothed the image and could not fit data appropriately (relatively high rrms and chi²). Low values of lambda fitted the data better but produced too much small-scaled anomalies that were not necessary.

p8544, eq. 5 and 6: Are both, the rrms and the chi2 needed here or is one of them sufficient? Furthermore, I do not understand how both, rrms and chi2 were "mostly close to the estimated error level" of 2.7% and 0.8 mV. Please explain this further.
The rrms and the chi² are both quality factors of the ERT inversion. Indeed it would have been sufficient to only mention the chi² because that's what we inverted for. However, many publications specify rrms values that are easier to interpret.

The sentence "The rrms and χ^2 of the ERT inversion were comprised 3.56% to 10.43% and 0.97 to 10.08, respectively, mostly close to the estimated error level" is probably not well formulated. With this sentence, we wanted to mention that the rrms and chi² level indicated that the error level is relatively well defined. Indeed, the rrms was below 9% and the chi² was below 3 excepted for the first data frame which was used as the reference for the inversion. We modified the sentence to render it more understandable.

p8544, equ.7: It should be stated explicitly that equation 7 requires that the solute electrical conductivity remains constant.
Thanks for this precision, we added it.

p8545, l13: Did you mean (Garré et al., 2010)?
We forgot to add this reference… It was Garré et al. (2008) and not (2006). The correct reference is:

Garré, S., Huisman, S., and Weihermüller, L.: Manual for TDR calibration, Agrosphere Institute, ICG IV, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany, 1-18, 2008.

p8465, section 2.6 (Validation of ERT soil water content): An approach for appraising the impact of the varying ERT image resolution with respect to the electrode positions should be included in this section, e.g. ERT-sensitivity distribution with respect to the row- and inter-row positions (see general comments).
We added a sensitivity analysis in the revised version of our paper. The added section can be found at the end of this document.

p8546, l12-21: This passage is not concerned with the ERT validation at all. It would better fit under section 2.2 (experimental plot).
This passage was related to ETC, which was explicitly used in the mass balance equation in section 2.6. We changed the position of this passage to section 2.2.

p8547, l3: Did you mean "ERT voxels corresponding to the TDR depths.."?
Yes, we modified the sentence to include this precision.

Figure 4: Please start the X-axis at 0. It took me several minutes to figure out how a reasonable parameterization of equation 7 could cut the y-axis (which it would not if the y-axis were at x==0).
OK, we modified the figure.

p.8548, l17-20: It should also be mentioned in the caption of Figure 5 that the ERT measurements corresponding to the cyan line were taken from the depth of the TDR probes (by the way: were they taken in the vicinity of the TDR probes?)
We added in caption of Figure 5 that the ERT SWC measurements in cyan correspond to ERT SWC at the TDR depths. As mentioned before, there was 4m between ERT and TDR area. So the measurements were not exactly taken at the same place.

Figure 5: The circles indicating the ERT measurements should be larger. Also the font size should be increased. Finally, I would find the time series shown in Figure 5 and in later figures much more intuitive if the months and days were shown instead of the DOYs.
We made all these modifications and we changed the time scale in all the following figures.

p8549, l27: Please mention again how many TDR probes were installed per depth.
OK, we mentioned it.

p8551, section 3.3.1: especially the spatial variability should be discussed also with respect with ERT sensitivity, as the spatial variability will appear to be smaller in regions with low ERT sensitivity (see e.g. Day-Lewis et al. (2005))
In section 3.3.1, we added a discussion on the ERT sensitivity. This section is resumed at the end of this document.

p8551, l11: better "topmost soil horizon"
OK, we made the modification.

p8552, l13: please explain in the material and methods what you mean by "root impact"
Thanks for this remark. We though it was understandable with the explanation given in the Material and methods. We added a few sentences to clearly explain our meaning of "root impact".

For performing the root profiles, we located a grid with 5 cm by 5 cm squares on the vertical soil profile. In each 5x5 cell, we counted the number of visible root segments. These root segments are part of the total root system, which reached/impacted this vertical plane, and are therefore called root impacts.

p8553, l7-8: is the discontinuity in the water depletion curve due to the use of two different Waxman-Smits-type law calibrations? This should be discussed.
Yes, the discontinuity was mainly due to the use of three pedoelectrical relationships. The discontinuity was visible at the interface of the soil horizons. We added a discussion on that point in the corrected document

p8553, l9-11: please explain in more detail what you mean by this statement. From looking at your figures I would rather say that it fits not too bad. (also see p8556, l12-14)
Between the first and the last ERT measurement time, water stock decreased by nearly 25 mm. In the soil profile, the SWC decrease was mainly observed in the second and third soil horizon while most of the roots were present in the first soil horizon. For this reason we

wrote that the shape of the soil water depletion profile did not reflect the root distribution. This is not a problematic observation per se, but a usual assumption made in some root water uptake models. However, if we compare the 2D map of SWC and the 2D distribution of root impacts, both show similar patterns.

p8556, l15-23: "At the beginning.." these explanations should already be given in section 3.3.3. If I understood correctly they are probably the main reason for why you observed different water uptake patterns in your study differ from the ones reported by Michot et al. (2005).

Your remark showed us that it was not sufficiently explicit in the section 3.3.3 that the soil was already relatively dry in surface and especially under the maize rows in our study. Indeed it is one important point on the difference in our results compared to the ones of Michot et al. (2003). Michot et al. (2003) observed a decrease of SWC mainly visible in the first soil horizon under the maize rows. In our study, the decrease of SWC during two short dry periods is mainly visible under the inter-rows area in the two first soil horizons. One explanation for the difference of results between Michot et al. (2003) and us is the initial SWC. The results obtained in our study should be taken into account only by considering the initial SWC, the meteorological conditions, the plant development and the soil properties. We clarified it in the corrected document.

Figure 6: a legend should be provided for this figure (the meaning of the different shades of grey should not only be explained in the caption.

Yes, this figure was not really clear. To clarify, we added a legend and used a colored scale instead of a grey scale.

Figure 8: The last two ERT measurements are the only ones which clearly underestimate the TDR values. Do you have any explanation for this?

Yes, indeed the two last ERT results at 10 cm under the maize rows underestimated the TDR values. At the other positions, TDR measurements were closed to ERT-SWC.

This underestimation could be due to a combination of different factors:

(i) There were only two TDR probes at this location and the TDR area was situated at 4m from the ERT area. The SWC spatial variability could partly explain the difference between the SWC measured by TDR and by ERT.

(ii) The sampling window of ERT below the maize row is broader than the TDR window. Therefore, because TDR were situated exactly under the maize rows, they can better fill the real SWC.

(iii) The smoothing effect of ERT inverted data which could have underestimated the increase of SWC induced by the rainy events. Many authors have reported the smoothing effect of ERT–inverted data on the determination of salt tracer breakthrough and concentration distribution (e.g. "Koestel, J., Kemna, A., Javaux, M., Binley, A., and Vereecken, H.: Quantitative imaging of solute transport in an unsaturated and undisturbed soil monolith with 3-D ERT and TDR, Water Resour. Res., 44, W12411, doi:10.1029/2007WR006755, 2008" or " Kemna, A., Vanderborght, J., Kulessa, B., and Vereecken, H.: Imaging and characterization of subsurface solute transport using electrical resistivity tomography (ERT) and equivalent transport models, J. Hydrol., 267, 125–146, 2002." or "Vanderborght, J., Kemna, A., Hardelauf, H., and Vereecken, H.: Potential of electrical resistivity tomography to infer aquifer transport characteristics from tracer studies: a synthetic case study, Water Resour. Res., 41, 1–23, 2005." Or "Garré, S., Koestel, J., Günther, T., Javaux, M., Vanderborght, J., and Vereecken, H.: Comparison of heterogeneous transport processes observed with electrical resistivity tomography in two soils, Vadose Zone J., 9, 336–349, 2010."

Figure 9: The black lines should be explained in the caption
OK, it is added.

Figure 10: Instead of showing all CV profiles, one may be enough to support your point. Instead, a comparison to the ERT sensitivity distribution (or image resolution) should be given. Temporal development of the SWC-CV would be better illustrated by 1D time-series, maybe from different depth.
Yes indeed, one CV profile is sufficient to show the SWC variability in the soil volume. Temporal development of the SWC-CV could be interesting to observe the evolution of the CV. However, in this study, we did not want to focus on the evolution of the SWC-CV. The goal was only to show the difference in CV in the x and y direction. Therefore, we would finally not show the temporal evolution of the SWC-CV and only showed one CV profile in x and y.

Figure 11: The difference in water content would become more obvious if colors would be used in this figure. It should be explained in the manuscript that the clear separation of the soil horizons stems from the use of three different pedophysical relationships (or, if this was not the case, this should be pointed out too).
OK, the Figure 11 was modified and is now with colors.

The explanation concerning the clear separation is also added in the new document at the end of section 3.3.2. This clear separation is obviously due to the use of three different pedoelectrical relationships. But, we should keep in mind that these three pedoelectrical relationships were obtained from measurements realized in the three pedologic soil horizons. And that the depths associated on each pedoelectrical relationship were based on the pedologic horizons.

Technical corrections

p8536: the abstract is started in the past tense and should remain in the past tense.
Yes, of course. We corrected the tenses.

p8536, l17: it should be "short dry periods"
Corrected

p8536: "At the opposite" is used several times in the manuscript. I am not an English native speaker so I may be wrong here, but it reads odd to me. I think that it is not an expression commonly used in English. "In contrast" may be more appropriate.
Corrected

There are similarly uncommon expressions throughout the manuscript which could easily be improved by letting an English native speaker read through the manuscript. Another example is "destroying variability" (p8437, l7). I will not list similar cases in the following.
We will pay specific attention to English uncommon expression. However, the expression "destroy variability" was used by other authors as for example "Teuling, A. J., and Troch, P. A.: Improved understanding of soil moisture variability dynamics, Geophys. Res. Lett., 32, 1-

4, 2005." or "Albertson, J.D., and Montaldo, N.: Temporal dynamics of soil moisture variability: 1. Theoretical basis, Water Resour. Res., 39, 1274, doi: 10.1029/2002WR001616, 2003".

p8537, l.9 " the rain repartition …, the drainage, the pollutant dispersion, …" as the processes are addressed in a general way I think the articles should be skipped. Again I have to admit that I may be wrong since I am not a native English speaker. In contrast, on p8540, l18 an article is needed: "The TDR method was used.."
Corrected

8538, l5: It should be "The advantage of these methods is their robustness.."
Corrected

8538, l6: It should be "gravimetric measurements are .."
Corrected

8538, l9: "are limited to a few cm"
Corrected

There are more similar mistakes throughout the manuscript which I will not explicitly state in the following.
We will pay attention to this type of mistakes

p8539, l7: in the introduction, the two goals are enumerated with (1) and (2). In the conclusions, (i) and (ii) are used instead. One of the two different enumerations should be used consistently.
Corrected

p8539, l.23: better "plough pan"
Corrected

p8542, l16: the units of R and e should be given. Likewise on the next page for rho and epsilon, the variables in equation two as well as U. I have not checked whether the units for all the other variables are given. If not, it should be done.
It was an oversight. We added the units in the corrected document.

p8543, l1: the sentence "Occam's inversion finds the smoothest distribution of logarithmized resistivities.." implies that Occam's inversion is necessarily connected with a smoothness constraint and with logarithmized resistivities. I am sure that the authors are aware that this is not necessary the case.
The sentence should be reformulated.
We reformulated this sentence in the corrected document.

p8554, l4ff: there is no reason to switch into present tense
Of course, there is no reason to switch into present tense. We corrected it in the new document.

p8554, l20: RWU is not defined
Thanks for this remark. We changed "RWU" in "root water uptake" in the corrected document.

p8555, l12-18: this part can be skipped.
Yes, indeed, this part could be skipped because it was already written in the "Material and methods" section.

p8555, l23-25: "We observed.." this sentence should be moved to a later section as it has nothing to do with aim (i) i.e. the validation of ERT.
Thanks, it is a wise advice. We moved this sentence to the section regarding SWC decrease.

p8556, l26: I think "excellent" is a bit exaggerated since the spatial resolution of ERT is rather limited (albeit superior to any other contemporary method which is applicable in the field)
Yes, indeed, "excellent" is exaggerated. As it is well explained by the reviewer, the spatial resolution of ERT is one of the highest that could be obtained in the field. Our comments were eased in the new document.

Section regarding ERT sensitivity and added in the corrected document

2 Material and methods

2.4 Electrical Resistivity Tomography

2.4.3 ERT inversion

[…]

ERT spatial resolution is a complex function of numerous factors, e.g., electrode layout, measurement schedule, data quality, imaging algorithm, electrical conductivity distribution (Kemna et al., 2002). To determine ERT spatial resolution, an indirect approach based on the sensitivity could be used (Binley and Kemna 2005, Kemna et al., 2002). The resolution is supposed to be low in model regions where sensitivity of the measurements is poor (Binley and Kemna 2005). In this study, we used the coverage which is like an overall or cumulative sensitivity. In analogy to linear tomography problems, it is the sum of all (absolute values of the) sensitivities for a given model parameter (Günther, 2004). Because the cell sizes were not equal for all model parameters, we weighted the coverage by dividing it for each cell *j* by its size, η_j (in m³). The coverage, cov_j (in log (m^{-3})), was calculated for each cell *j* of inverted resistivity as showed in Eq. 7. The obtained coverage was then normalized and logarithmized for the figures.

$$\mathrm{cov}_j = \frac{\sum_{i=1}^{N} \left| \frac{\partial f_i(\boldsymbol{m})}{\partial m_j} \right|}{\eta_j} \qquad (7)$$

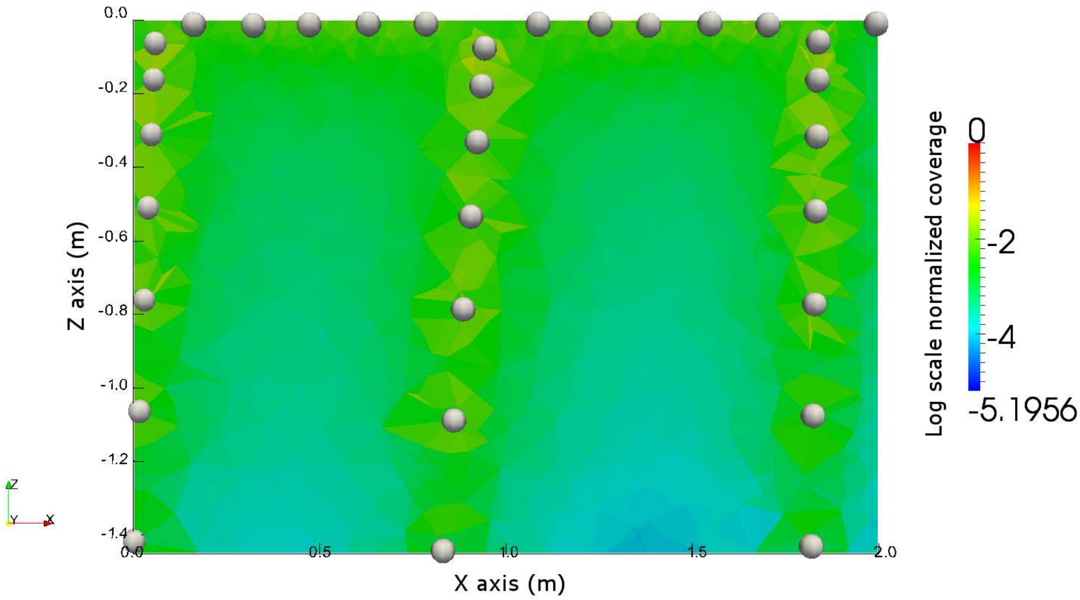
3 Results and discussion

3.3 Processes inducing SWC distribution

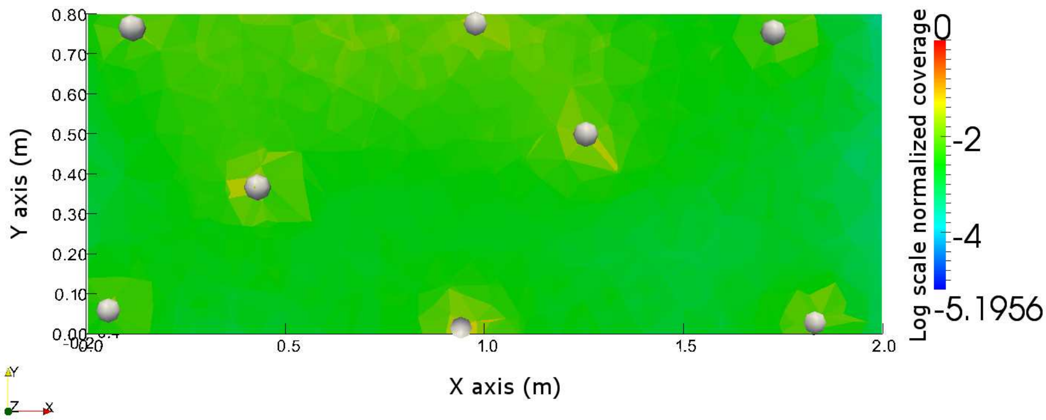
3.3.1 SWC spatial variability

Figure 1 presents the normalized logarithmic coverage of the 3D ERT inversion model, calculated with Eq. 7. To visualize the normalized logarithmic coverage distribution, one vertical section passing by three ERT electrodes sticks (y = 0.05 m (Figure 1 a)) and two horizontal sections (z = -0.15m (Figure 1 b) and -1.42m (Figure 1c)) were realized. We observed that coverage decreases with the distance from the electrodes and that the staggered position of the ERT electrodes did not deform the coverage distribution. Moreover, with the contribution of combined surface and stick electrodes, the coverage stayed relatively high in the whole soil volume (Figure 1 a) and deep stick electrodes increased the coverage till the bottom of the considered soil volume. However, the coverage stayed the lowest in the bottom of the soil volume. But with TDR measurements, we showed that the SWC variability is also lower with depth (Figs. 7 and 8). Huge resolution is therefore not so important in the deep soil horizon. Moreover with the TDR and ERT SWC comparison, we proved that the there was no major problem in the resolution. Indeed, if the coverage was too low, the inverted ERT measurements would badly predicted the hydrological processes as showed by Nguyen et al. (2009). In our study, the relationship between TDR

and ERT measurements was good as showed by Fig. 7. We then assumed that our coverage was sufficient, even in the deeper soil, to predict the hydrological process.
[..]
(a)



(b)



(c)

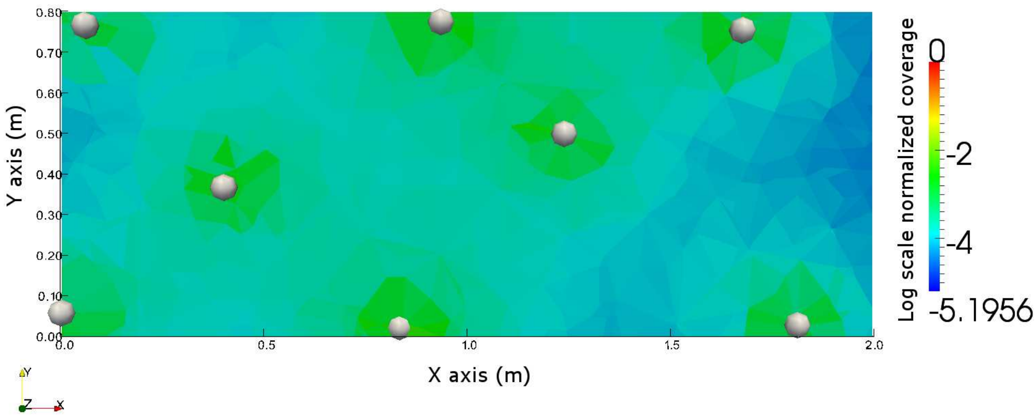


Figure 1: Normalized coverage sections at y = 0.05m (a), z = -0.15 m (b) and z = -1.42m (c) of the 3D ERT inversion model. The coverage was calculated using Eq. 7. The white balls represent the electrodes present in the considered sections.