AUTHORS’ RESPONSE TO THE REVIEW COMMENT
by ANONYMOUS REFEREE #1

Manuscript **hess-2016-93** entitled

“Repeated electromagnetic induction measurements for mapping soil moisture at the field scale: validation with data from a wireless soil moisture monitoring network”

by Edoardo Martini, Ulrike Werban, Steffen Zacharias, Marco Pohle, Peter Dietrich, and Ute Wollschläger

We would like to thank the anonymous referee #1 for the valuable comments. In the following, we addressed all the comments.

Reviewer’s comment

“The paper in context describes a long term field experiment (conducted in the experimental station of Schäfertal, Central Germany) in which different wireless sensors (EM38-DD and SPADE ring oscillator) were utilized for measuring the so-called soil electrical conductivity (ECa). Changes of ECa, due to the time-variant soil properties, were monitored in order to capture changing soil conditions and to determine the source of this variability. The experimental campaign results in an extensive dataset with measurements in time and space. The persistence of spatial patterns was evaluated by calculating the Spearman rank correlation coefficient between the spatial patterns of ECa and the soil water content (θ). There is not a lot I can add to improve the quality of the paper. Only one more serious comment I have to make: the results of EMI-based ECa data analysis are site specific, therefore there is the necessity for a more robust soil characterization, which means the development of a more rigorous sensor calibration methodology to avoid misinterpretation. I am little bit worried about the poor correlation observed between the ECa and θ relationships of figure 4. Perhaps intrinsic limitations could exist in the EMI and SPADE sensor calibration which may limit the comparability of ECa-θ values. I urge the authors to discuss this issue in the paper prior publication.”

Authors’ response

We would like to thank the reviewer for this generally positive comment. First we need to clarify a misunderstanding that apparently occurred when the reviewer read the manuscript: the soil apparent electrical conductivity (ECa) was measured with the EM38-DD device only. The SPADE probes of the soil moisture monitoring network measure soil water content and soil temperature only. Hence, measurements of soil electrical conductivity (EC) are not available from the SPADEs. What we do in the paper is comparing EMI-measured ECa with soil moisture contents (not EC) measured with the SPADE sensors in the soil moisture monitoring network in order to further investigate the relationship between EMI-measured ECa and soil moisture. This comparison has been done by several other studies in the past except that in most of those studies no time series data and no depth-dependent temperature measurements for ECa correction were available. Hence, from our study we have generated an extensive dataset which allows more solid investigation of the relationship between ECa and θ.

We fully agree with the main comment from the referee, in which it was correctly highlighted that the results of EMI-based ECa data analysis are site specific. This is clear from previous studies as well as from our results. Site-specific in this respect means that EMI-measured ECa depends not only on soil moisture but on the whole suite of properties and states listed in the introduction of the manuscript including e.g. clay content and EC of the soil solution (EC_W). In addition, we aim at non-invasive field- or hillslope-scale mapping of soil moisture with EMI, hence we also have to consider spatial heterogeneity of all these properties and states throughout the site which are very likely to occur. Consequently, a calibration would be required for every point in space or at least for regions where properties/states are expected to change spatially. A proper calibration of ECa with respect to soil moisture which would also be suitable for soil moisture monitoring would only be possible if (i) state variables that induce co-dependencies on ECa (such as EC_W) would not change over time or could be excluded and (ii) the influence of the water content on ECa would be strong enough to significantly change ECa in a way that it is measurable with EMI. The measurements at our site indicate that (i) is very likely not the case and (ii) is at the limit of what is measurable with EMI after exclusion of as many co-dependencies as possible for our site.

We will add this paragraph to the discussion section in the manuscript, also in response to the comments of other reviewers.

Reviewer's comment

"In the following some general and specific comments for revision:

General comments:

1. The analysis also highlighted all the limits of taking EMI readings only at the soil surface to deduce the ECa vertical distribution along the soil profile. In fact, the study clearly revealed that this method is too sensitive to the changes over time of the vertical distribution of the local ECa along the soil profile. In different time frames, a different vertical distribution of the local ECa may still result in the same EMI measurement but with a different local (SPADE probe) readings. This induces the relative patters of variability of SPADE and EMI to change over time, so that even an effective calibration obtained at a given time frame cannot be extended immediately to other time frames. Accordingly, it is my opinion that of all the approaches now existing for deducing ECa distributions by EMI sensors, those based on multiple EMI measurements to be made at a succession of heights above the soil surface for each of the monitoring sites remain the best choice, as a sequence of measurements with different depth weightings guarantees more univocal information on the actual depth distribution of local ECa."

Authors' response

Here, again, we would like to point out that not ECa was measured with the SPADE sensors but soil moisture. Nevertheless, the reviewer makes an important point with respect to the different measurement volumes which indeed may influence the plotted relationships between EMI and θ. In our paper we first followed the procedure that has been adopted by most of the previous studies relating EMI measurements to soil moisture and directly compared the measured ECa to soil moisture content measured at the single SPADE observation depths while neglecting the different measurement volumes of both methods. Being aware that these do not really correspond to the EMI measurement volume we adopted a simple attempt for integrating the SPADE soil moisture readings from different depths by averaging the three values while weighting them with the depth sensitivity function for ECa of McNeill (1980). This is everything else but perfect as the function mentioned above assumes homogeneous and low soil conductivity over depth (which is rarely the case for real soils), hence the true sensitivity may be different. For an even better calibration, a proper integration of soil moisture values along the profile at such a field site with natural atmospheric forcing would only be feasible by using soil moisture and in the worst case also solute concentration profiles obtained with a calibrated soil hydrological model which would be an enormous effort for calibrating EMI measurements, in fact making the EMI measurements mostly redundant as soil moisture dynamics would be known already from the SPADEs and the model.

The reviewer suggests conducting a series of EMI measurements at different heights above the ground surface. Even more sophisticated methods are available today, such as multiconfiguration EMI, which are able to resolve conductivity profiles (e.g., von Hebel et al., 2014 and references therein). Nevertheless, we would like to point out again, that the major challenge with respect to field-scale mapping of soil moisture is not to obtain the conductivity profiles (we think the multiconfiguration EMI applications are very elegant to do so although possible limitations remain), but rather the separation of soil moisture from all the other properties and states that influence the EMI measurements.

We will improve the discussion on theses aspects in the revised manuscript.

References:

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

von Hebel C., Rudolf S., Mester A., Huisman J.A., Kumbhar P., Vereecken H. and Van der Kruk J.: Three-dimensional imaging of subsurface structural patterns using quantitative large-scale multi-configuration electromagnetic induction data. Water Resources Research. doi:10.1002/2013WR014864, 2014.

Reviewer’s comment

“2. To partly explain this site specificity, in the paper the authors must also evaluate the role of the different observation window of EMI sensors and of local scale sensors (SPADE probes) used for measuring local ECa values to be employed for EMI calibration.”

Authors’ response

Please refer to our comment above.

Reviewer’s comment

"3. Thus, in order to extract the predominant, high-variance signal, the authors must remove the noise of both the EMI and SPADE data series by filtering the original data through a Fourier's analysis. The technique can allow to identify characteristics that a calibration dataset should include to obtain more robust calibration parameters to be used for more effective predictions in other fields and other time frames.
In conclusion, I encourage the application of Fourier's analysis for the characterization of the presented time series of ECa and θ *measurements, in order to better interpret and speculate on their variability in space and time."*

Authors' response

The aim of a Fourier filtering is to remove the high frequency components from the signal. As described in section 2.4 of the manuscript, the discussion of the data is based on the ECa values "extracted" (that we called ECa_e in the manuscript) from the spatial maps (Fig 3a), as has been done in other published studies (e.g., Zhu et al., 2010). To take into account the small-scale variability of ECa, we decided to apply an adapted block-kriging approach for the spatialization of the measured data, with experimental variogram fitted separately for every sub-area of the hillslope site and for every measurement date. Such procedure ensures a site-specific smoothing of the experimental data which will lead to similar results as the Fourier analysis suggested by the reviewer.

Reference:

Zhu Q., Lin, H., and Doolittle, J.: Repeated electromagnetic induction surveys for determining subsurface hydrologic dynamics in an agricultural landscape. Soil Science Society of America J., 74, 1750-1762, doi:10.2136/sssaj2010.0055, 2010.

Reviewer's comment

"Specific comments:
1. The introduction is too long, I believe that this paragraph can be improved by making it shorter and more concise."

Authors' response

We agree with the reviewer that the introduction is quite long. However, in our manuscript we need to consider a number of different aspects linking in some way the theories and approaches of the soil hydrology and geophysics community.
We believe that all those parts are important to support our discussion. Therefore we would like to keep the introduction section as is, with small improvements as recommended by other reviewers.

Reviewer's comment

"2. Figures 3 and 4 are not readable in the form presented (especially figure 4). I believe that the dimensions of the figures in context should be increased."

Authors' response

We agree and will increase the size of figure 4 in the revised manuscript.