Interactive comment on "Required sampling-density of ground-based soil moisture and brightness temperature observations for calibration/validation of L-band satellite observations based on a virtual reality" by S. Lv et al.

Anonymous Referee #3

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The manuscript describes an analysis of uncertainty associated with soil moisture validation based on the sampling density of the ground truth network. The analysis is based on modeling of hydrological and radiative transfer features within a limited geographical area. The area was relatively small, but contained relatively significant land cover variability. On one hand, the analysis is based on modeling only without experiment data, which is clearly a weakness. On the other hand, the approach of the modeling allows evaluation of the ground sampling requirements in controlled scenar-ios which does make the study interesting and relevant for the community.

Reply: Thank you very much.

However, there is one major issue that needs to be corrected in the analysis. This is the effective assumption that single station within a 400-m resolution cell would represent the average soil moisture within the cell. Authors acknowledge as well that this leads to a (likely) underestimation of the sampling requirement, but do not offer any quantitative analysis on the effect of this assumption. Without a quantitative assessment of this effect, the main results of the manuscript do not hold much weight. Accounting for the soil moisture variability within the cells should not be too difficult using models developed in Famiglietti et al. (2008), for example, and should be included in the manuscript.

Reply: Thank you. This point is critical to our study. We further discuss this issue now after Line 398:

Our method is similar to Famiglietti et al. (2008) but contains several extensions. Firstly, the required station number for a certain accuracy is extended to brightness temperatures for which results are different compared to soil moisture. Secondly, our result does not contradict Famiglietti's study, which links the required sampling numbers to the mean soil moisture. Using a virtual reality like VR01, all influencing factors are included by trusting in the realism of the simulations. The soil volume observed by a soil moisture sensor (via measuring the soil dielectric constant using the capacitance/frequency domain technology) is about a sphere with a ten-centimeter diameter. Thus, Famiglietti et al. (2008) assume, that soil moisture is homogeneous within meters, and that a single soil moisture sensor can represent it since the distribution of soil moisture values in 2.5 m scale is similar to 16/100/800 m scales. It means the spatial divergence of soil moisture sampling is not reduced with a decreasing scale in his study. We assume that soil moisture estimations representative for 400 m wide areas can be done with good accuracy. Thus, overall, our estimations of required station densities are on the optimistic side. We added Line 417-433 to make it clear.

Other more minor comments will follow below.

Section 1

L39-40: The soil dielectric constant is strongly dependent on the soil moisture at other frequencies as well. The L-band is beneficial because its reduced sensitivity to surface roughness and vegetation compared to higher frequencies.

Reply: Thank you for your suggestion. We added this point to Line 38.

L46: “tens of kilometers” – here the reference is specifically to SMAP and SMOS and something like “40-km resolution range” could be used for more specificity.

Reply: “40-km resolution range” replaces now “tens of kilometers.”

L50-52: The references are not accurately placed here: Delwart et al. (2008) should be mentioned in relation to SMOS only, not SMAP.

Reply: Thank you very much. Delwart et al. (2008) is removed from the SMAP part.

de Rosnay et al. (2006) presents analysis based on SMOSREX which was conducted close to Toulouse, which is not mentioned in the text, only Spain and upper Danube catchment.

Reply: “SMOSREX (Surface Monitoring Of Soil Reservoir Experiment) in France” is now added in Line 50.

Lemaitre et al. (2004) is not that relevant compared to many others. dall’Amico et al. (2012) should be cited, especially as Danube was mentioned in the text. There is a SMOS assessment paper by Kerr et al. which should be cited too. Brown et al. (2008) is a SMOS related paper, not SMAP. Some of additional and very relevant SMAP Cal/Val papers are Colliander et al. (2017b), Chen et al. (2017; 2018), Burgin et al. (2017).

Reply: Lemaitre et al. (2004), Brown et al. (2008) are removed. Kerr et al. (2016),), Chen et al. (2017; 2018), Burgin et al. (2017), dall’Amico et al. (2012) are cited and discussed.

L55-56: “SMAP Cal/Val suggests” – Lv papers do not provide direct reference for this statement. . ..

Reply: Thank you for your suggestion. We split the sentence where the second part is discussed in Lv’s papers.

L61-66: What is the reference for all these numbers?

Reply: Colliander et al., 2017b is now added.

L71 & L72: “suggest” -> suggested

Reply: it is “suggested” in Line 78/79/83 now.

L80-81: The first indication that the soil moisture is essentially assumed homogeneous within the 400-m resolution cells.

Reply: it is revised as “This virtual reality allows us to arbitrarily vary the sampling resolution, at steps of 400 m by assuming that the area is homogeneous within 400 m.”

Section 2

L97: Please justify the selection of this location for the simulation study.

Reply: As also suggested by another reviewer, we clarify in Line 130 that “The area was selected by the research unit because of its heterogeneity in topography and land-use typical for midlatitude European river catchments; thus, it is also well suited for our study. The objective of the research unit is the setup and test of a strongly coupled data assimilation system with a fully-coupled regional terrestrial model. Their virtual reality run (VR01), the results of which we are exploiting in this study, is the so-called nature run from which the research unit draws the virtual observations to be assimilated in a lower-resolved model version using ensemble methods. The model area can be covered by about 15 x 20 SMOS pixels, which suffices for the statistical analyses performed to determine required sampling densities. There exist two soil moisture monitoring networks close to the domain, which are used for soil moisture validation studies with satellite-based L-band observations (Montzka et al., 2013). ".

Other than that (this part is not in print), the catchment is not special at all; several other catchments could also be used for the same purpose - in fact, the main reason is that the Neckar is part of FOR2131 where data assimilation of L-band TB is pursued. Besides, several of our group knew the area already, so it was easier to get started. FOR2131 is a project that FOR2131 will exploit the large potential of observations to improve predictions of states and fluxes in the Subsurface-Land surface-Atmosphere System (SLAS) to constrain its large degree of freedom. The overall goal of the Research Unit FOR2131 is an analysis and prediction platform of terrestrial systems on the mesoscale catchment scale built on multi-scale and multivariate data assimilation with fully coupled terrestrial system models.

Figure 1: Please include an outline of the Neckar catchment in the images.

Reply: Thank you for your suggestion. The outline is added now.

L113: SAI is not spelled out.

Reply: "SAI (Stem Area Index)" is added in Line130

L114: Please explain in a little more detail how the SAI is estimated for different land cover types.

Reply: As in Line 150-160, "The Leaf Area Index (LAI) for the specific plant classes is taken from MODIS estimates corrected for known biases (Tian et al., 2004). Instead of the tiling approach implemented in CLM, the dominant land use type for each grid-cell is used, because the resolution of 400 m is high enough to warrant this approach. The SAI (Stem Area Index) is estimated from the LAI by formulations slightly modified from those implemented in the CLM. For crops, SAI is just 10% of the LAI; thus, SAI is larger in summer than in winter. For all other types, SAI is 10% of LAI plus a "dead leaf" component. The "dead leaf" component is estimated empirically from the change of the LAI from the previous and current month. The "dead leaf" component is only a major contributor during fall, but even there the needle leaf trees, for instance, show only a small increase of SAI. The VR01 region is mostly covered by deciduous trees that have 1-2 months of high SAI because the dead-leaf component decays rather quickly. Details about SAI calculation in VR01 are described in Schalge et al., (2016), Lawrence and Chase, (2007), and Zeng et al., (2002)."

L119: Baroni et al. (2017) is missing from the reference list.

Reply: Sorry for missing it on the list.

L134: "soil sand and clay soil fractions" -> remove extra soil after "clay"

Reply: Thanks, it is removed now.

L137: Please specify that vegetation optical thickness depends on LAI in the CMEM. Please explain also how the relationship between the LAI and the vegetation optical thickness depend on the land cover type.

Reply: We add, "Depending on the particular Plant Functional Type (PFT) CMEM uses different parameters to calculate the vegetation optical thickness from the respective LAI" to make it clear.

L138: Please include a short explanation how the effective soil temperature is computed in CMEM?

Reply: The scheme by Lv et al. (2014) is implemented in CMEM and used in this study as “The new scheme is a discretization of the integral formulation and takes advantage of multi-layer soil temperature/moisture profile information with a wider range of soil properties. This advantage makes the new scheme more flexible to the land surface model data than field measurement that usually contains fewer layers.”

L148: SMAP makes the 6 AM overpass during the descending part of the orbit and SMOS makes it during the ascending part of the orbit.

Reply: it is revised as “…which corresponds to the approximate ascending/descending overpass time of SMOS/SMAP …”

L149: Please include the more detailed definition of “footprint”. Often the 3-dB beam width is used which results in the 40-km footprint, but I suppose the authors are referring here to the main beam.

Reply: Thank you, we added “that is defined by 3 dB contour of the main lobe.” and in Line 241 as “This sampling is applied to both soil moisture and brightness temperature with and without considering the satellite weighting function (Figure 2b)”

Figure 2: Please include the footprint centers also in the right-hand side plot for better illustration of the geometry.

Reply: Thank you for your suggestion. We add a pair of dash lines to show its center.

L162-163: This leaves a huge uncertainty to the results. I’m afraid without quantifying this uncertainty somehow the main results of the manuscript are not useful. See the above.

Reply: Thank you, and please check our reply to your major comments above.

L180: It seems to me the (i/0.4)ˆ2 is an approximation of the SC_ftd=106x106/(43/i)ˆ2 and should be the last term.

Reply: (i/0.4)ˆ2 is switched to the last term.

L171-192: I think there is some redundancy in this explanation and would encourage the authors to condense it.

Reply: Thank you for your suggestion, but we prefer the reserve this part. This part is critical to this study because we cannot achieve it with a completely random site selection. The combination methodology introduced in this section is similar to Famiglietti et al. (2008), who took a regular sampling distribution. There are a lot of dimensions that can define homogeneity in CLM, like soil type, lai, even elevation. Thus, to use another method rather than regular random sampling, we have to quantify the representativeness of each site with the average soil moisture/TB, which is hard to achieve. We used random sampling in our study, which more easily allows us to judge the statistical significance of our results. Even though the sampling distribution is regular, the samples at each resolution are sufficient for statistical analysis. It means the sampling approach in this study is enough to isolate the sampling density-error relationship in tens of km scale.

Section 3

L207: “below” –> less than

Reply: All the “below” that coming with a number are replaced with “less than”.

L222: Average sampling distance is not as relevant as the number of stations so I would recommend using that as the primary result and perhaps include the average sampling distance in the parenthesis.

Reply: The relation between average sampling distance and the number of stations (station density) only with methodology in Section 2. Thus, the sampling distance and sampling density are the same by Equation (6). This is also the scales configuration used in Famiglietti et al. (2008) which is further applied in setting up sampling numbers in the field. we add in Line 255-265 as "The relationship between the sampling distance (km) and the sampling density can be transferred by

$$\text{sampling density} = \frac{1}{\text{sampling distance}^2} \quad (1)$$

The sampling distance is more Intuitive because it reflects the overall sampling sites without decimal. The SMAP Cal/Val adopt a similar definition with integers for a specified grid size. For instance, 5/3 sites for a grid size of 9/3 km would be around 0.0617/0.3333 sites per km^2. Besides, the sampling density cannot be compared without giving a particular gird size. It means a sampling density for 3 km gird size shall not be compared with a value for 5 km gird size. The sampling distance is more compatible with the unit of km, which is also used to define the grid size in this study. We note here that the average grid size of the SMAP passive soil moisture product is 36 km x 36 km per pixel, which is somewhat less than for SMOS. the 43 km in all equations shall be exchanged by 36 km. ".

L226: "footprint" -> grid size

Reply: it is "grid size" now.

L228-235: This is at least partly redundant and not building on what was said on L61-68. Please try to describe the results in light of the rationale and motivation laid out in the introduction.

Reply: The text related to SMAP/SMOS is deleted from this part.

L243-245: Several studies have shown that intermediate soil wetness levels would create the most heterogeneous soil moisture distributions spatially. The exact behavior of the spatial variance is naturally scale, soil type and land cover dependent. Please address this issue.

Reply: Line 310-313 is rewritten as "The opposite occurs during dry periods because evaporation, draining, and runoff over various soil and land cover types tend to create spatially heterogeneous soil moisture distributions, which typically reaches its maximum at intermediate soil moisture levels (Brocca et al., 2010)."

Figure 4: The top plot is not described in the caption.

Reply: A short description "Precipitation in VR01 (upper panel)" is added.

Figure 4: "The grey intensity" – it is not clear what this refers to (same in Figure 7).

Reply: Sorry, the "grey" is updated to "color" now.

L261: Please describe the assumptions made in the CMEM that result in the 10 K and 5 K accuracies.

Reply: Thanks. As suggested by another reviewer, here we add Sabater et al. (2011) and Monerris Belda (2009), which discuss the relation between brightness temperature and surface condition. We also weak our tune here by adding “approximately”.

L268-277: In this paragraph, “already” is used multiple times and it is not the best word unambiguous description of the results.

Reply: These “already” are deleted.

L308-316: Again, use the introduction and remember to cite the appropriate studies when discussing these results.

Reply: Thank you, Colliander et al. (2017b) is cited again.

L322-323: “thus” used twice in the same sentence.

Reply: “and hence” replace “thus” here.

L326-332: Please discuss the mechanisms that make the spatial variance of soil moisture and brightness temperature increase with occurrence of forests according to your simulations. E.g., is soil moisture always different in forested areas as compared to non-forested areas? If so, what is the driver of this?

Reply: Sorry, we did not state that forest sites always have higher soil moisture errors than non-forest sites. Usually, forest sites are usually no site candidates for L-band soil moisture Cal/Val missions. However, we cannot remove the forest impact on redistributing soil moisture/TB map in an application. For example, while giving an accuracy of 0.04 cm^3/cm^3, users would apply soil moisture product over non-forest sites where the accuracy is estimated usually, but also the plants' covered area where accuracy is unknown. We add some words in Line 398-410 to make it clear. With a footprint size of 40 by 40 km, it is hard to exclude forest influences; thus, we have to take it into account, which is ignored in ground measurements.

Figure 11: To make the plots more readable, please change “selected” in the legends with something like “<15% forested”.

Reply: Figure 11 is updated.

Section 4

L357: What is the reference for this SMAP team suggestion?

Reply: Colliander et al. (2017b) is added here.

References

Burgin et al. (2017). A Comparative Study of the SMAP Passive Soil Moisture Product With Existing Satellite-Based Soil Moisture Products. IEEE TGRS.

Chen et al. (2017). Application of Triple Collocation in Ground-Based Validation of Soil Moisture Active/Passive (SMAP) Level 2 Data Products. IEEE JSTARS.

Chen et al. (2018). Global-scale evaluation of SMAP, SMOS and ASCAT soil moisture products using triple collocation. RSE.

dall'Amico et al. (2012). First Results of SMOS Soil Moisture Validation in the Upper Danube Catchment. IEEE TGRS.

Reply: These references are cited accordingly.