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 #2

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The authors use a virtual reality to estimate minimum requirements for in situ station density for satellite soil moisture and brightness temperature cal/val. The study is well executed, has interesting, impactful findings, and is generally well presented.

Reply: Thank you very much.

My lone concern is the lack of consideration of previous, related works and insufficient context for the conclusions presented here. Overall, I recommend the authors revisit the extensive literature devoted to understanding in situ sampling requirements for satellite soil moisture cal/val and provide a better, in-depth synthesis of this literature both in the introduction and conclusion/discussion sections.

Reply: Thank you for your suggestion. In the Introduction, we added information on a field campaign that took place in the Rur Catchment and on Chen's publications in 2017/2018/2019 about the TC/ETC method. The former one addresses a comparison between soil moisture measurements in the field and satellite soil moisture products and reports errors a larger than 0.2 cm3/cm3 bias (Line 126); a direct soil moisture comparison is therefore not recommended in that area. Several similar studies (Delwart et al., 2008; de Rosnay et al., 2006; Burgin et al., 2017; Kerr et al., 2016) are now cited as well; their result varies considerably and underline the importance of our study. The latter ones by Chen following the TC/ETC method are less compatible with our study because in the VR01 the representativeness of every variable in one grid is very clear. The variables in that grid represent precisely the mean value within the grid border. In Line 87 we summarize Chen's results: "Chen et al. (2017, 2018, 2019) suggest the utilization of TC (Triple collocation), which is a statistic method to characterize systematic biases and random errors, or ETC (Extended Triple collocation) to analyze the noise component in soil moisture observations, and to use correlation to evaluate the representativeness of soil moisture networks. They also suggest that the core validation sites should allow validating the retrieved soil moisture to an accuracy of 0.04 cm3/cm3 with a probability of 70% in terms of unbiased RMSE because the bias itself is hard to eliminate."

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 444-454 to make it clear.

Specific comments: The introduction is lacking sufficient review of past literature, despite a growing number of studies focused on in situ sampling requirements for satellite soil moisture cal/val. Recent examples include Molero et al 2017, Bhuiyan et al. 2018, and Chen et al. 2019, among others.

Reply: Molero et al. (2017), Bhuiyan et al. (2018), and Chen et al. (2019) are now added in the introduction. Molero et al. (2017) are introduced in Line 64-66. Bhuiyan et al. (2018) does not support 0.04 cm3/cm3 (as he said "Overall the soil moisture retrieval errors have exceeded SMAP's mission requirement (errors below 0.04 m3 m−3), with the exception of some sites of annual cropland as present at the Carman") and is juxtaposed with Jackson et al. (2012) and Crow et al. (2012) in Line 64. Chen et al. (2019) and other work from that group are introduced in Line 87-92.

The statement on lines 75 - 77 is technically true, but that does not preclude the authors from developing an in-depth synthesis of previous, related studies.

Reply: Thank you. We revised Line 77-92 to make our motivation stronger.

The same can be said for the Conclusion and discussion section, which consists of much more conclusion than discussion. Please expand this section to include a discussion of your findings in the context of previous studies examining sampling density and satellite soil moisture or brightness temperature cal/val, and how your findings build off of and/or improve on these previous studies.

Reply: Thank you for your suggestion. The Conclusion & Discussion are extended to judge better the improvements reached by our study compared to what is already known. See Line 421-433 which read now: "A major assumption in our study is that the estimation of soil moisture for an area with a diameter of about 400 m is possible, or in other words that a single station within a 400-m area is representative for its spatial average, an assumption also discussed in Famiglietti et al. (2008). Compared to the region analyzed in Famiglietti et al. (2008), our study uses a much more realistic terrain and excludes subjective factors in selecting suitable Cal/Val sites. Because of this, the soil moisture error in our study grows much faster with increasing sampling distance. We also find that the estimation of area-averaged brightness temperatures from a network of ground-based stations has a different error growth with increasing sampling distance compared to soil moisture despite an initial linear growth for both of them (compare Figures 3 and 6). Thus, a representative soil moisture network does not guarantee a representative radiometer network for the estimation of area-averaged brightness temperature, or that brightness temperatures computed for the soil moisture stations can be used for that estimate. But Figures 3 and 6 also show that sampling distances below 6 km still fulfill the 70th percentage requirement for keeping the sampling error below the nominal error."

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, as we explained above, and that a single soil moisture sensor can represent it. 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.

The statistical results in our study differ from those in Famiglietti et al. (2008) because our focus is on the satellite footprint scale and not the representativeness of one station within a network. For example, a particular sensor may not represent the true 400 m average, but one such sensor every 400 m may statistically sufficiently represent a much larger footprint. A similar concept is adapted in ensemble forecasts using members, e.g. with different physics packages, none of which is expected to be the truth (Lewis, 2005; Leutbecher and Palmer, 2008). Thus, our study can be considered as a complement to the study by Famiglietti et al. (2008)."

The suggestion concerning Cal/Val is taken up in Lines 481-490: "Our results are not only useful for the planning of ground-based soil moisture networks, they also contribute to a better understanding of the relation between brightness temperatures observed at the ground – or simulated at high resolution - and the ones observed from satellites apart from non-linearity effects of radiative transfer (e.g.,(Drusch et al., 1999)). The study allows, e.g., to quantify to what extent a bias between satellites brightness temperature and forward simulation could be explained by the spatial sampling (e.g., Figures 5, 8, and 11), and to understand the similarities and dissimilarities between observed soil moisture and brightness temperature time-series (Figures 4 and 7). Since ground-based soil moisture networks will always cover only certain parts of a satellite pixel, a bias must be expected between both. Biases in satellite and ground-based estimates of soil moisture can also be caused by the different representativeness of the latter for soil moisture and brightness temperatures."

Also, please include some discussion of how your findings - in virtual reality - could apply in or differ from reality. For example, most existing in situ networks do not sample soil moisture systematically within a pixel-area, but are often clustered within certain parts of the pixel. How could this affect determination of minimum sampling distances? Given your findings, how many SMAP core validation sites, for example, meet the recommended requirements for sampling distance?

Reply: Besides the discussion already added above, Lines 455-470 also addresses this issue.

Technical corrections: Line 18: by "better" do you mean "finer"?

Reply: Thank you - changed.

Lines 37-38: This is vague, yet overreaching statement. Effective in situ soil moisture observation at continental scale is possible depending on the application. Please refine this statement.

Reply: Thank you, and we also realized that the Former Soviet Union and China had established nationwide soil moisture monitoring networks. We altered the sentence to "…its in-situ observation applicable to numerical weather modeling is …"

Line 41: add comma separating "satellite" and "SMOS" Line 48: replace "set up" with "establish"

Reply: Thanks - these are revised accordingly.

Line 58: "better 15 observations" is oddly used here. Is this a direct recommendation from the reference, or are you simply arguing that more stations are better than fewer stations? Either way, I think it can be deleted without consequence.

Reply: Thanks – that sentence is deleted now.

Lines 61-68: Are these figures from some previous study or official recommendation? How did you arrive at these values?

Reply: Yes, these figures are cited from Colliander et al. (2017b) in our reference list. We added this reference in the revised manuscript.

Line 62: should be "should be sampled with at least eight stations"

Reply: Thank you. This part, as well as the other two in the following sentences, are revised.

Figure 1: could you report the PFT name along with or instead of the PFT number in the third panel, instead of referencing the PFT name in the caption?

Reply: PFT names are now moved from the caption to the third panel.

Line 229: replace "only" with "at least", and "70 percentile" should be "70th percentile" Line 323: "thus" is used too often in this sentence. Please throw in a "therefore" instead

Reply: We revised the text accordingly.

Line 327: replace "as an ideal footprint" with just "ideal" Lines 335-339: this is quite a long sentence, please consider rephrasing Line 360: should be "that represents" and not "which represents" line 361: add "is necessary" between "3 km" and "if we want..."

Reply: Thank you, we revised the text accordingly.

Molero, B., et al., 2018: Multi-Timescale Analysis of the Spatial Representativeness of In Situ Soil Moisture Data within Satellite Footprints. JGR: Atmospheres, 123(1), 3-21, https://doi.org/10.1002/2017JD027478

Bhuiyan, et al., 2018: Assessing SMAP Soil Moisture Scaling and Retrieval in the Carman (Canada) Study Site. Vadose Zone Journal, 17(1), https://doi.org/10.2136/vzj2018.07.0132

Chen et al., 2019: Uncertainty of Reference Pixel Soil Moisture Averages Sampled at SMAP Core Validation Sites. Journal of Hydrometeorology, https://doi.org/10.1175/JHM-D-19-0049.1

Reply: Thank you. Molero and Bhuiyanis are inserted in Line 62 to support recent research progress in this field. Chen et al., 2019, as well as Chen et al., 2017 and 2018 are added in Line 82 as “Chen et al., suggest TC (Triple collocation) and ETC (Extended Triple collocation) to analyze soil moisture noise, and use correlation to evaluate the representativeness of a soil moisture network (Chen et al., 2017;Chen et al., 2019;Chen et al., 2018)”