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 #1

Received and published: 24 July 2019

This paper uses a model based virtual reality to determine the number of in-situ stations required to assess L-band soil moisture data. The paper is well written and is easy to read. There is a strong story through the paper leading the conclusions.

Reply: Thank you very much.

There are some minor technical revisions required (provided on the pdf) as well as three other revisions which would help to improve the quality of this already strong paper:

- It would be interesting to see the comparison to actual in-situ soil moisture data to answer the question: is the theoretical number of stations ok when faced with real insitu measurements? For this you would need to have a study area containing a high density of in-situ stations covering the SMAP period. I think it is worth checking if such a comparison could be done or if not recommending it for future research.

Reply: dall'Amico et al., 2012 is cited in Line 52 to show the comparison result between in-situ measurements and satellite products. Other references like Chen's 2017/2018, etc., which indirectly discuss this kind of comparison, are now also added. Line 86: "It is suggested that the core validation sites are met with the 0.04 cm3/cm3 accuracy in terms of unbiased RMSE while the bias will be hard to eliminate. Establishing ground monitoring networks…" and Line 128: "Another case study close to the VR region shows that the bias can reach 0.2 cm3/cm3 over the Upper Danube catchment (dall'Amico et al., 2012)"

- I would have expected a little more discussion on the impact of topography as well as the sand and clay fraction. There seems to be some spatial patterns in the results which correspond to these.

Reply: Line 439-443 is added to address this point as 'Topography also affects the soil moisture and TB distribution, but it is difficult to infer the impact of landuse and vegetation because soil properties determine both the water holding capacity and the plant cover. In practice, soil moisture monitoring networks avoid complex terrain. Homogenous terrain and landscape lead to an overestimation of satellite soil moisture product accuracies.'.

- The study is currently done over a small area in Germany. More information on why this site is chosen is required and more, importantly, the applicability of the results of this study to other areas would be useful for the reader.

Reply: Lines 461-470 are added to make the motivation hopefully more clear "This study isolates the sampling density issue from other factors and is a test of the current Cal/Val network standard without pre-knowledge of the site. The SMAP team suggests 15 sites for a 36 km by 36 km grid-size (Colliander et al., 2017b), and this study agrees with this configuration for typical mid-latitude European regions from the sampling error perspective. For a 36 km by 36 km grid-size, the required sampling sites would range from about 36 (6 km) to 4 (17 km). However, five sites for 9 km by 9 km and three sites for 3 km by 3 km will miss the 70 % confidence level requirements over this area. Since SMAP's 9-km and 3-km soil moisture products are from a combination of passive and active microwave signals, which have lower accuracy than the passive one(Entekhabi et al., 2010), their Cal/Val campaigns shall determine sampling distances with less confidence level". The landscape simulated by VR01 contains considerable land cover variability (Figure 1), thus our conclusions would apply also to other sites and the typical satellite Cal/Val sites, in particular, except, e.g. for mountainous areas.

Please also note the supplement to this comment: https://www.hydrol-earth-syst-sci-discuss.net/hess-2019-192/hess-2019-192-RC1-supplement.pdf

Reply: Thank you. All comments in the supplement are replied to accordingly. Please see our revised manuscript and the replies in the supplement pdf file.

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

Received and published: 30 July 2019

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)”

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

Received and published: 6 August 2019

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

$$\text{sampling density} = \frac{1}{\text{sampling distance}^2} \tag{1}$$

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.