Analysis of SMOS brightness temperature and vegetation optical depth data with coupled land surface and radiative transfer models in Southern Germany

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General statement:

The paper presents SMOS validation activities carried out at one of the ESA key SMOS Cal/Val sites in the Upper Danube Catchment. In situ and airborne radiometer data from a campaign (3 weeks) as well as simulated data from coupled land surface and radiative transfer models (7 months) are compared with SMOS data. Focus is put on L1c brightness temperatures as well as L2 optical depth data. Results from land surface/radiative transfer model and SMOS L2 soil moisture product validations are picked up from previous studies and put in context with the current work.
The presented analyses are carried out thoroughly. They reveal interesting results which are mostly discussed in detail. However, at the current stage, parts of the paper appear quite lengthy, several sentences do not flow well, and there are seesaw changes between subjects leading to lots of unnecessary repetitions. Thus, beside the language, the structure should be significantly improved in order to facilitate the readability and better bring out the impressive amount of work that has been conducted.
Thereby, some major issues include:
- better separation of methods and results
- make more clear which are findings picked up from previous studies and which are new findings
- generally give more information on the spatial scales of the individual data sets
I suggest major revisions to address the points given in the comments below. I apologize that there are several overlaps between my comments and the comments of referee #1, as I wanted to do my review unpersuaded…

Detailed comments

P=page, L=line number

Abstract

P5390,L8: 'with good results' – maybe give few quantitative results instead. *Expression removed. The RMSE of the BT data is given.*

1. Introduction

I like the way you start your introduction. But overall I think it is very long and you seem to repeat yourself several times. Also, to me it appears that while the objectives and the followed approach are indeed mentioned, they are spread throughout the text so it is not easy to have a clear overview of what has been done. Please try to write this section a bit more concise and structure it better. *The second part of the Introduction has been completely restructured to make it clearer and more concise.*
P5392,L.7: To my knowledge Gruhier et al. 2010 are not presenting SMOS data *Correct, this was a mistake. The reference has been changed.*
P5392,L14-24: I clearly agree with you on that point. Additionally, maybe you could state which SMOS product versions were used for these analyses? Over time several

adjustments have been made in the processor. So, if not consistently data from the same reprocessing was used, you could mention that the improvements in the agreement with in situ data can additionally be attributed to this. *Agreed. This has been added as the algorithms are updated regularly. The cited study by Dall'Amico et al. used reprocessed data in 2010. This detail has not been added to the text as it is not relevant for this paper that deals only with 2011 data.*

P5393,L13-14: you already mention on P5393,L9 that soil moisture and optical depth are retrieved simultaneously. Could you possibly give few details on what vegetation optical thickness is? Not every reader might be fully familiar with it *As the optical depth is already mentioned in the title of the manuscript, it should be familiar to every reader. It is explained in detail in section 2.4.2. Explaining it in the Introduction is beyond the scope of this chapter as several referees have already stated that the Introduction is quite long.*

P5394,L3-6: you already write this on P5391-92,L26-27/1-4. Instead, I would find it important to mention the issue of uncertainties related to such modeling approaches. *Correct. This has been erased to make the Introduction more concise as requested by several referees. The uncertainties are discussed below.*

P5394,L16-17: you already mention the same on P5393,L14 *Correct, removed.*

P5394,L22-25: From what you write it is not clear to me at this point whether you are actually presenting any analysis regarding this issue. *This has been changed.*

P5394,L25-27: For me it would be more logic to include this information further above where you write that potential causes for the apparent problems in the SMOS L2 soil moisture data from Southern Germany are assessed in the current work (P5394,L9-10). *Done*

P5394-95,L28-29/1-11: I think it would be meaningful to first introduce the study site and the available data before you talk about the goals and conducted analysis (P5394,L7-27). Also, could you possibly add a bit more information here about the spatial scales of the different data? *Done*

P5395,L16-26: I do not think this paragraph is necessary. I would integrate the description of your approach (the information that is not already mentioned) further above where you already talk about this. *This paragraph has been shortened. But I think it is necessary to understand the structure of the paper.*

2. Material and methods

Personally, I think it would be better to split this chapter in two, i.e. 2. Data and 3. Methods, as you have so many subchapters. *Agreed. Done*

Figure 1: I like your overview. Could you possibly add some information on the different spatial scales of the data sets? *Done*

2.1. Study area and in situ data

P5396,L15: Define the SMOS footprint size. I assume you here refer to the approximate spatial resolution of 43 km which you mention in the introduction, but explain this a bit better, since the area observed by SMOS at one snapshot in time is much larger... You could maybe also point to Section 2.3 where you go more into detail. *The sentence has been rephrased to make this clearer*

P5396,L16-18: I know what you mean here, but maybe consider rephrasing as I think it is a bit dangerous to simply say that agricultural land is homogeneous since it is made up of so many patches of differing conditions regarding growing stages, crop types etc. *Done*

P5397,L3-7: I think this should be rephrased to make it clearer. I assume you use the additionally mentioned grid points in your studies as well? *Done. Yes.*

P5397,L7-9: I would move this information to the paragraph where you already address the soil moisture profile stations (i.e. P5396,L24). Maybe state which sensor type is used, how sensors are installed (horizontally vs. vertically), and give few details on calibration/sensor accuracy, or add a reference where this information can be found. *Done*
Figure 2: You could maybe illustrate the SMOS footprint for grid point 2027099? *As I am not talking about the footprint any more I decided to leave this out. It would only confuse people.*

2.2. Airborne data
P5397,L15: Could you possibly give an approximate coverage instead of writing 'a representative portion of a SMOS footprint'? *Done*
P5397,L16: Could you add some references that demonstrate the mentioned thorough validation of the EMIRAD radiometer? *Done*
P5397,L22: In case of SMOS you mention the values used as thresholds (P5399,L4). Could you do the same here in case of EMIRAD? *Done*
P5397,L25-28: This section is named 'airborne data' – it is a bit akward to suddenly find a description of ground data here…One possibility could be to move it to Section 3.1 (P5408,L12-13).*Agreed. Moved to section 2.1*
P5398,L1-2: Could you give some more details on this. Please explain as well how you average the data for comparison with SMOS data and accordingly, what area this data covers. I think it is very important. I am not sure that I fully got the concept and therefore, had problems to understand the following paragraphs: **Section 2.5.1,P5406,L11-17**; **Section 2.5.2,P5406-5407,L24-25/1-2**; **Section 3.2.1,P5410,L5-16** *Done*

2.3. SMOS data
Please mention which SMOS L1c and L2 product versions you use, i.e. original/reprocessed data?
P5398,L13-15: The study you mention was carried out in the U.S. Have you checked if it is really the same in Germany? *No, I have not checked that. As I write I want to avoid uncertainties that are related to differences between morning and evening overflights. I don't state there are any. It is known that the morning is ideal for soil moisture retrieval, there is not as much data about the evening.*
P5398,L21: I might be wrong, but to my knowledge the RFI flag in the L1c data does currently not really provide reliable information? *That is my experience too. Using the RFI flag does not sufficiently filter all RFI's, as stated in line 5/6 on page 5400. Therefore I apply additional filtering techniques as described on page5399 and following.*
P5400,L2: You mention in the introduction that SMOS observations are conducted in a multiangular fashion. However, (unless I read it over), you do not give the range of angles, which is of interest to the reader in connection with the here mentioned binning of the angular data. *I added the information to section 2.3.*
P5400,L9-10: Maybe just briefly explain what these parameters stand for. *Done*
P5400,L13-18: You already address this topic in the introduction. Could you possibly include the information (that is not already given) there and omit this paragraph here? *Done*

2.4. Coupled land surface and radiative transfer modeling
Generally, I think you mix methods and results a lot in this section. As you have actually created Section 3.1 'Model validation and L-MEB parameterization under local conditions' in the results section, could you possibly move your results there? *Done. I agree that Method and results were mixed up a bit. I restructured this.*

2.4.1 Land surface model PROMET

P5401,L22-28: Actually, several studies on the microwave emission depth have reported that at the 1.4 GHz frequency it is generally rather in the order of 1-3 cm (e.g. Raju et al. 1995, Laymon et al. 2001, Escorihuela et al. 2010, see below). Thus, in the future it could be interesting to investigate whether simulated data based on the 0-2 cm layer improves the agreement with the SMOS data.

• S. Raju, A. Chanzy, J.-P. Wigneron, J.-C. Calvet, Y. Kerr, L. Laguerre, "Soil moisture and temperature profile effects on microwave emission at low frequencies," Remote Sensing of Environment, vol. 54(2), pp. 85-97, 1995.

• C.A. Laymon, W.L. Crosson, T.J. Jackson, A. Manu, and T.D. Tsegaye, "Ground-based passive microwave remote sensing observations of soil moisture at S-band and L-band with insight into measurement accuracy," IEEE Transactions on Geoscience and Remote Sensing, vol. 39(9), pp. 1844-1858, 2001.

• M.-J. Escorihuela, A. Chanzy, J.-P. Wigneron, and Y. Kerr, "Effective soil moisture sampling depth of L-band radiometry: A case study," Remote Sensing of Environment, vol. 114, pp. 995-1001, 2010.

This is an interesting point that is being discussed. I will consider it more thoroughly in my future work.

P5402,L1-5: Could you possibly give few qualitative results instead of writing 'with good results'? *This has been rephrased. The results that are important for the study are already mentioned.*

P5402,L18-24: You talk about nine soil moisture measuring stations while in Section 2.1 you talk about 7. Are these the same plus two additional? And regarding the regional scale handheld probe measurements, I assume you refer to the campaign measurements conducted in the five selected focus areas (roughly 3x7 km) and the regional scale soil moisture values are derived from a spatial average of all measurements per focus area? If so, state this clearer or then give the approximate spatial scale of the mentioned regional study. *Correct. I have clarified this now.*

P5402,L24-29: Personally, I would not use the term 'uncertainties' in this context. Here, you are dealing with the agreement between two different data sets (model and measurements), which both contain uncertainties. Thereby, model uncertainties stem from the choice of parameters, which when varied within a range of reasonable values result in a range of modeling results. *I agree that the term uncertainty can also have a different meaning. In this case I cite a paper titled: "Uncertainty Assessment of the SMOS Validation in the Upper Danube Catchment" and in the paper the uncertainties of the model (amongst others) are discussed. Therefore I cannot change the terminology here when I cite this paper.*

P5403,L3-7: Could you give a reference to the Global Soil Data Base? And maybe mention which soil type you are talking about. *Done*

P5403,L7-15: Again, I would not use the term 'model uncertainty' in this context. Furthermore, I am slightly confused, about the information given here. The values 'over all stations', do they refer to five stations or seven or nine? Why are you only giving an RMSE for the comparison over the whole test site and not an R2 as for the stations? And in Figure 3 you show comparison of modeled and measured soil moisture for the 5 stations within 20 km radius of the studied SMOS grid point and state that 'the deviations between both data sets are small'. Could you underline this statement with statistical values as done in the other cases? *Concerning the term uncertainty: see comment above. To stay consistent I cannot change the terminology here. I agree that this was written a bit complex. I restructured this passage and the study area description to make it clearer. All stations are all 9*

stations that have been analysed in the Upper Danube Catchment. For the comparison for the whole test site I compare data from the SMOS Validation campaign. As this data set comprises only a few days this data set is not considered to be large enough for calculating a correlation. I added more information to the data shown in Figure 3.

2.4.2 Radiative transfer model L-MEB

P5404,L15-16/Table 1: Please add the formula to derive the vegetation optical depth from LAI, otherwise it is not clear in Table 1 what b' and b'' are. And maybe add a column with the Tau Nadir value ranges in Table 1. This is also important in connection with your discussion in Section 3.1 (P5408,L15-21). *A short description of the parameters b' and b'' has been added. It is beyond the scope of this paper to describe L-MEB in great detail as this would require a lot of additional formulas (to explain e.g. Q_R, b', b'', NR_p, tt_p). Adding a column with Tau_nadir value ranges is not possible as I use a dynamic vegetation model in this study that produces different LAI and Tau values for every pixel depending on Weather, soil etc.*

P5404,L17-18: As it is not fully clear whether HR is really soil moisture dependent (see Escorihuela et al. 2010), I would slightly rephrase this sentence, i.e. '…is chosen as a function of soil moisture'. And maybe make clear that HR is part of the above-mentioned surface component used to modify the Fresnel reflectivity.

• M.-J. Escorihuela, A. Chanzy, J.-P. Wigneron, and Y. Kerr, "Effective soil moisture sampling depth of L-band radiometry: A case study," Remote Sensing of Environment, vol. 114, pp. 995-1001, 2010.

Agreed. Sentence has been rephrased. A short description of the roughness parameters has been added.

P5405,L3-8: I am a bit confused about the spatial scale of this study. You talk about 'local conditions'. However, while you use the term 'local scale' for individual soil moisture stations in Section 2.4.1 (P5402,L19-24), it seems to me that here you compare modeled and measured brightness temperatures averaged over the entire area? Can you give some information on this to make it clearer? *Agreed. This has been clarified now.*

P5405,L8-17: Are the comparisons with usage of the improved land surface model new results? And are these the statistics belonging to the data shown in Figure 4? *Yes. I made this clearer now by restructuring it.*

P5405,L17-19: You have already mentioned this in Section 2.2.*Agreed, removed.*

P5404,L21-23: Give the approximate footprint size of ELBARA II. Again, you use the term 'local conditions', but better make clearer what spatial scale you refer to…*Done.*

P5405,L27-29: You have already mentioned that in a similar fashion (P5404,L28-29), maybe only state once. *I don't understand what you mean. Both text passages state different things.*

P5406,L1-2: As for EMIRAD in Section 2.2, please explain this clearer.*Done*

2.5 SMOS L1c data analysis

2.5.1 Comparison with airborne brightness temperatures during the SMOS Validation Campaign 2010

P5406,L11-17: As becomes apparent in Section 3.2.1 and Figure 4, you also compared modeled brightness temperatures for the five days with airborne and SMOS data. Maybe add this information in this section. An idea for future work could be to extend this analysis around the campaign days by means of the modeled data in order to have more

days to compare with SMOS data and link it to the airborne data. *This is already mentioned in section 2.5. I have extended this analysis around the campaign days but no clear conclusions can be drawn from this.*
P5406,L17-21: I agree with you that the findings of the referenced study can be adapted as long as the prevailing land cover conditions in your study region are similar to the ones encountered in the other study region? *Yes the land cover conditions can be considered similar in both studies. 80% of the Skjern river catchment test site (Hobe) are under intensive cultivation, 10% are covered by forest and 6% by grass/heath and wetlands. The climate is temperate and the mean precipitation is 800-900mm (Bircher et al., 2012).*

2.6 SMOS optical depth analysis
P5407,L8-9: 'modelled values of optical depth using vegetation parameters from the dynamic vegetation model PROMET', do you here mean the Tau Nadir values calculated from the PROMET LAI, or did you retrieve Tau Nadir using L-MEB coupled to PROMET? Furthermore, I assume only Tau Nadir values of low vegetation are taken into account here as you earlier state that the SMOS optical depth data is only valid for the low vegetation class? *True, only low vegetation. I calculated Tau Nadir values from the PROMET LAI. I didn't do any retrievals with my coupled models in this manuscript.*

3. Results and discussion

3.1 Model validation and L-MEB parameterization under local conditions
P5407,L17: '…the land surface model PROMET and specifically the soil moisture submodel have been validated and work…' instead of 'has' and 'works' *Done*
P5408,L5-7: I would give the information on the encountered bias already in Section 2.2, where you introduce the airborne data set. However, as far as I read in Bircher et al. 2012, the bias was observed in the vertical 40 degree channel, not in the horizontal channel? And despite this fact, I do not understand how a systematic bias can explain a not constant offset as observed in the horizontally polarized TBs? *Done, I moved the information to 2.2. You are right. I removed the passages where I talked about the horizontal polarization being influenced by the bias..*
P5408,L8-9: '…but due to the uncertainties related with the EMIRAD bias this issue is not further investigated.', but the mentioned uncertainties only occur in one of the two 40 degree channels, so the other channel should still show reliable information, right? Could there possibly be scaling effects responsible for parts of the bias? Maybe you could discuss this a bit together with some information on the spatial coverage of the airborne and modeled data. *I agree. I added the discussion of the scaling effects.*

P5408-5409,L24-29/1-14: I think that rain interception by vegetation is a very likely explanation for the observed changes in the data on the last campaign day. While EMIRAD is measuring the standing water on the plant leaves, the model does not take them into account…*You are right. This has been pointed out more clearly now.*
Figure 4: Mention error bars (standard deviation), and make clearer what modeled and EMIRAD TBs represent (i.e. spatial average?) *Done.*

3.2 Analysis of SMOS L1c data

3.2.2 Comparison with modeled brightness temperatures for the year 2011

P5411,L7-11: I would also mention here explicitly that the described expected angular signatures are encountered for both polarizations in case of the modeled brightness temperatures. *Done*

P5411,L18-29: Be careful, here you draw the conclusion that the problems in the SMOS L2 soil moisture product are considered to not primarily originate from a retrieval problem, which is very risky without having analyzed the retrieval algorithm and its associated auxiliary data products.I agree with you that RFI most probably significantly contributes to the encountered deviations. However, if the agreement between in situ/model and SMOS data at the L2 level is better than at the L1c level, could this not also mean that the retrieval is playing some kind of 'tricks' to improve the results? *I agree that this section was a bit misleading. I rephrased this section. It is clearer now. Now I state that the L2 problems are not exclusively a retrieval problem. Because obviously there is already a pronounced problem in the L1c data that, at least, adds to other possible problems. Yes, it is possible that the retrieval plays some kind of tricks. But a variety of other reasons are also possible and I do not want to speculate about this. And, after all, the L2 product does not perform much better than the L1c product. I would rather say, they both perform poor.*

Then, in Section 3.3 (P5415,L4) you actually contradict yourself as you have obviously discovered a retrieval problem in that there is an unexpected strong correlation between soil moisture and the optical vegetation depth… *I rephrased that section too. When there is a lot of RFI, for sure this will (also) lead to problems in the retrieval. What I want to stress is that we do not ONLY have a retrieval problem (which would have been possible), but at least a serious RFI problem (in addition to possible existing retrieval problems).*

Another thing that caught my eye is the fact that the HR values in Table 1 are significantly higher than the value used in theSMOS soil moisture processor (0.1-0.2) for two of the three most frequent land covertypes (corn/maize and grass). Bearing in mind your statement in Section 3.1 (and I agreewith you) that an incorrect soil roughness parameterization could lead to an offset between model and measurements, I believe this could also be considered a potential error source. In fact, it could for example further lead to compensation of some other model parameters for the HR... You state that the radiative transfer modeling works reliably, but it seems to me that you have only validated it over a quite short study period of few days. Might it not also stand to reason that the less good agreement between modeled and SMOS Tbs could originate from model inaccuracies throughout the year - as the radiative transfer model is driven by the land surface model, there must be an error propagation resulting in higher uncertainties at the brightness temperature level compared to the soil moisture level? For the above reasons, I think you should rephrase your statement. *The statement has been rephrased. It is true that some of the used HR values are higher than the SMOS values, but they are all taken from literature that shows that these parameters work very reliably. Of course the SMOS parameterisation is a possible source of error for the SMOS L2 data. But if the HR parameter would be completely wrong, SMOS would not be able to deliver very good results e.g. in the US (see Jackson et al. 2012). It is also true that I validated the radiative transfer model on the SMOS-like scale only on a few days, which is not ideal. But it is hardly possible to get more validation data on such a scale and the environmental conditions changed very much during these days. I mention in the manuscript e.g. how much the vegetation is growing and how much the soil moisture changes during the first 4 days. Therefore I still consider this validation quite robust because it covers a very wide range of environmental conditions. If the HR value would be completely wrong we would not have deviations between model and measurement of a few K only. I demonstrated that e.g. in Schlenz et al. 2012b.*

P5412,L2-4: Could you possibly check this assumption by additionally comparing the

original L1c data? *This would be interesting but it is beyond the scope of this manuscript.*
Table 2: In the text you talk about 'bias', so maybe replace the word 'offset' in the table. Also make a clear link between your discussion and 'gain' in Table 2. Right now it is not clear what this refers to. *Done: I added information to explain the parameters.*
P5412,L7-26: I think you are jumping a bit back and forth here. You mention the PROMET standard deviations on L8-9 and then again on L18. Maybe try to structure this a bit better. *You are right. I restructured it.*
P5412-5413,L27-29/1-8: I am very sorry, here I am not able to follow your explanations. Why do you actually expect an increase in brightness temperatures in summer? *Because of the increasing soil temperatures in summer. I added this to the text.* When I look at the soil moisture in Figure 3, there is an increase in soil moisture. From that, would you not expect a decrease in the brightness temperatures? To me the mentioned sharp drop in Tbs at the beginning of June seems to quite well conincide with a steep increase in soil moisture. Actually, looking at Figure 3, I generally get the feeling that the course of SMOS Tbs seems to correspond (inversely) with the course of the soil moisture. But as I said, maybe I have misunderstood something here. Another explanation for such a clear drop in Tbs could also be a change between SMOS data processor versions (in case you are not using reprocessed data). *I explain this a bit more detailed now. Of course an increase in soil moisture should lead to a drop in brightness temperature, but, as I write, the model does not react as extreme to the increase in soil moisture as SMOS. If soil temperature does not change too much, the brightness temperature should always react inversely to the soil moisture evolution. During the first half of the year 2011 the L1c processor was not updated. I checked that.*

3.3 Analysis of SMOS optical depth Tau
P5414,L6-11: First you write the comparison looks similar when the two additional grid points are considered, followed by information on how the statistics and the seasonal behavior differ for each node. That does not fully make sense to me… *I agree that this was misleading. I rephrased this sentence now. I wanted to say that the statistics differ from ID to ID, but the big picture stays the same (SMOS Tau is too high and shows strange seasonal behaviour).*

4. Conclusion and outlook
Please check my previous comments regarding the information summarized in this section. Try to write the conclusions more concise, I think you are jumping a bit back and forth between subjects and are repeating yourself several times. *You are right. I restructured this section.*
P5416,L2-4: Maybe add here that you found the horizontally polarized SMOS TBs less reliable than the vertically polarized ones? *Done.*

Technical corrections:
Abstract,P5390,L1-5: Please rephrase this sentence, it seems a bit akward. *Done*
Section 1,P5393,L=1-5: Please rephrase this sentence, it seems a bit akward. *Done*
Section 1,P5395,L1-2: Please rephrase this sentence, it seems a bit akward. *Done*
Section 2,P5396,L8: maybe replace 'and':…L2 soil moisture with optical depth…. *Done*
Section 2.1,P5396,L24: 'subject to' instead of 'subject of' *Done*
Section 2.1,P5397,L3: Use plural 'The analyses…concentrate…' *Done*
Section 2.3,P5399,L3-6: Please rephrase this sentence, it seems a bit akward. *Done*

Section 2.3,P5399,L7: 'their expected range' instead of 'its' *Done*
Section 2.4.1,P5402,L11-17: Please rephrase these sentences, they seem a bit akward and very difficult to understand. *Done*
Section 2.4.2,P5404,L1-4: Maybe write in an enumerative fashion, i.e. '(1) soil emission…, (2) direct vegetation emission…, and (3) vegetation emission…' *Done*
Section 2.5.2,P5406-5407,L24-25/1-2: Please rephrase this sentence, it seems a bit akward. I would rather say '…from April to October 2011…'. *Done*
Section 2.6,P5407,L12: 'correlation between the two data sets' instead of 'for both' *Done*
Section 3.1,P5408,L16: 'parameterisations', plural… *Done*
Section 3.2.2,P5410,L2: 'SMOS L1c brightness temperatures', plural *Done*
Section 3.2.2,P5410,L26: add 'and both polarizations, respectively' *Done*
Figure 11: Change R2 to R as you use R throughout your work. *Done*
Table 2: Mention polarizations and maybe add April-October. *Done*