Response to comments by Referee #2

This reviewer thanks the authors for efforts invested in the preparation of their manuscript. In this paper the authors overview an experimental set up where ground based GNSS receivers are used to passively monitor, primarily, vegetation water content or vegetation optical depth. The paper's topic has been the subject of some investigation in previous works in the relevant literature, but the authors discussion is extensive and offers a number of refreshing views on the topic. This reviewer does note a number of concerns outlined below, but would otherwise recommend accepting the manuscript after revision.

Thank you for the careful evaluation and the constructive review. We provide our point-by-point answers below.

Comments

1. Refer to [page 1] "The technique presented here has the potential to resolve two important knowledge gaps, namely the lack of ground truth observations for satellite-based VOD" - This reviewer is a little reluctant to agree with this assertion. While it is true that VOD estimates derived from spaceborne observatories will require some level of ground truth, measurements derived from the proposed sensors will also require ground truth estimates in the calibration of measurements made and validation of subsequent VOD estimates. The authors are encouraged to revise this statement placing the proposed technique in the appropriate context or elaborate to this reviewer on why they feel that the sensors are in situ data, or ground truth data independent. It is also important to note that it is difficult for the proposed techniques to really compete with the main impetus for having spaceborne receivers, namely their global coverage versus the proposed highly localized estimates.

Thank you for this comment. Our intention is not to compete with satellite microwave sensors, in fact it is primarily to support their development that we originally initiated this study. We fully agree with the reviewer that the proposed technique cannot compete with spaceborne receivers in terms of their global coverage and global relevance.

The comment on GNSS-based VOD being or not being ground truth is an interesting point. Maybe it is helpful to think of in situ soil moisture measurements, as they are today widely accepted as ground truth for satellite-based retrievals. Data from the International Soil Moisture Network is used extensively as ground truth by most centres. This data mainly relies on TDR probes which also need to be calibrated and evaluated against further measurements, for instance from gravimetric soil samples. Given this context, we do believe that GNSS-based VOD has in fact the potential to provide independent ground truth observations. This is not to say that one should expect GNSS-based VOD to match one-to-one with satellite retrievals. As the reviewer points out, we do not know yet how well GNSS-based VOD compares against other estimates of VOD. We now mention this more explicitly (see below).

L747: *"In particular, the degree to which GNSS-VOD at RHCP-polarization agrees with other VOD estimates at horizontal (H) or vertical (V) polarization is unknown. For instance, previous studies over forests have shown that H-pol VOD can differ from V-pol VOD, even though temporal dynamics are similar (Schwank et al., 2021;Guglielmetti et al., 2008;Kurum et al., 2009b)."*

The difference in scale and footprint between satellite and ground-based data also constitutes an important obstacle. This is already mentioned at L781: *"For example, arrays of GNSS receivers deployed within the spatial footprint of a satellite VOD grid cell (i.e. about 30 km) may serve to estimate a regional average VOD that would be suitable as ground truth for the satellite products."*

2. Refer to [page 2] "Microwave remote sensing methods are broadly categorized as either passive or active. Passive instruments (radiometers)" - The authors are encouraged to revise "Passive instruments (radiometers)" to something along the lines of Passive instruments (like radiometers). Any receiver that does not transmit its own signals or relies on signals transmitted by a none co-located system for sensing is by definition, passive. Radiometers are an example of passive instruments but a wide range of other platforms exist.

Thank you for pointing this out. We have made the suggested change.

3. Refer to [page 3] "Higher VOD values indicate that the canopy is less transparent to microwaves" - The authors are encouraged to generalize this statement to all "impinging or reflected radiation" given that higher VOD also attenuates visible light and IR in larger proportions.

Agreed. We replace with: *"Higher VOD values indicate that the canopy is less transparent to electromagnetic waves."*

4. Refer to [page 3] "But can hardly be validated, as systematic ground-based VOD observations do not exist at the moment" - It is important to make clear that this is not indicative of an inherent limitation in the ability of spaceborne receivers to provide VOD estimates, just a lack of field campaigns; something that could change in the future and so this reviewer does not regard this as a reasonable example of why the proposed methodology is superior to approaches based on spaceborne receivers' measurements.

Thank you for this comment. We fully agree with the reviewer's statement. We do not think the text argues that the proposed methodology is superior to spaceborne receivers. See for instance some of our current statements:

L42: "We then present a ground-based technique relying on Global Navigation Satellite Systems (GNSS) with the objective to address the lack of ground-based VOD observations."

L105: "Considering some advantages of microwave-range compared to visible-range observations, such studies have demonstrated the interest of VOD for monitoring vegetation dynamics from space (Konings et al., 2021)."

L756: "The results presented here suggest that GNSS-based VOD may have the potential to fill a key research gap in terms of linking satellite-based L-band VOD observations to ground observations."

5. Refer to [page 9] "(which GNSS antennas are designed to reject)" - The authors are encouraged to make clear that it is ground based GNSS antennas that are designed to receiver RHCP. This is important given that spaceborne GNSS-R receivers typically have antennas that are designed to receive LHCP antennas given GPS signal reflection (and polarization handedness reversal) off the Earth's surface.

This is an important point. We have made this clearer:

L198: *"(which most geodetic ground-based GNSS antennas are designed to reject)"*

L288: *"(note that in contrast, spaceborne GNSS reflectometry also relies on the LHCP signal)."*

6. Refer to [page 11] "from 102 individual GNSS satellites" - This reviewer is only aware of there being 24-32 operational GPS satellites or so, did the authors also use reflections from other GNSS constellations like Galileo, GLONASS and BDS?

Indeed, this is mentioned at L332 and L703. We now also mention it in the methods:

L156: "At each site a Septentrio PolaRx5e GNSS receiver, connected to a PolaNt-x MF (RHCP) GNSS antenna, measured multi-constellation (GPS, GLONASS, Galileo, BeiDou) GNSS signals …"

7. To make Figure 3(d) a little easier to follow, it may be useful to subject the series to a smooth (mean or median) smoothing filter in 15-1 hour increments. This may also aid in dampening the noise noted on page 14.

Yes, this is inherently what is done later in the analysis when hourly VOD time series are calculated. However, we would like Figure 3d to show the raw data and thus support the discussion on page 14.

> Once more this reviewer thanks the authors for efforts invested in the preparation of this manuscript and looks forward to their continued contribution.

> We thank the reviewer for their time and their constructive feedback!