Response to comments by Referee #1

This paper uses a pair of two ground-based GNSS receivers to estimate L-band VOD in a forested field. Similar configuration has been previously tested by others. Unique part of this study is for collection of a field data over a period of 8 months with analysis to get insights into vegetation response in different time scales such as hours-minutes for intercepted rainfall and dew, days-hours for canopy water content, and months-weeks for canopy structure. I think that the topic is very important for the community and the approach is very promising to monitor trees characteristics nondestructively in a continuous fashion. However, I have several major concerns on the VOD estimates, the model, and assumptions as they are the basis for the analysis.

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

(1) Polarization: The current setup measures the signal in RHCP-RHCP (RR) configuration, which might be significantly different from H-pol or V-pol VOD estimations from the satellites. This relation among various polarizations (RR, H or V pol) has not been established for VOD in the literature, so it is hard to interpret how RR-pol VOD estimates can be used for satellite data validation.

We agree that the relationship between VOD measured in a RHCP-RHCP configuration and VOD measured from H or V polarizations is poorly known. Existing studies have mostly compared VOD estimated at H and V polarizations and found that VOD_H and VOD_V can have an offset, even though temporal dynamics are in close agreement [Schwank *et al.*, 2021; Guglielmetti *et al.*, 2008; Kurum *et al.*, 2009a]. Our evaluation is that RR-pol VOD estimates would still be useful for comparison with satellite data especially in a relative sense (i.e. evaluation of the temporal dynamics or relative differences across sites) but otherwise, we would strongly advise against validating absolute values at this stage. We add the following text in section 6:

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)."*

(2) Model: The model used here is a dielectric mixing model, which is valid for electrically small constituents. At L-band, primary (even secondary) branches can violate the assumption. In addition, the model ignores the polarization, which could be significant for tree canopies with certain preferred oriented branches.

(3) Assumption: The current model ignores volume scattering. As the data suggests (from my own experience as well), the signals at high elevation under canopy could be

larger than the signal in open sky environment. This is a clear indication of volume scattering. The impact of volume scattering may vary from trees to trees and elevation angles to angles. Without physical modeling simulations for various scenarios, it would be difficult to develop methodologies to disentangle the direct signal from volume scattering.

Thank you for these comments, we fully appreciate these concerns.

A wide range of approaches has been used to relate 1) microwave-range measurements over forests to canopy attenuation, and 2) canopy attenuation to environmental variables of interest like biomass or water content. For instance, some past studies have directly related VOD to vegetation water content or biomass without considering a dielectric mixing model and/or have estimated VOD without taking into account the role of volume scattering [Rodriguez-Alvarez *et al.*, 2012; Vittucci *et al.*, 2019; Brandt *et al.*, 2018]. Other valuable approaches, like the tau-omega model, incorporate more knowledge from microwave radiative transfer theory [Frappart *et al.*, 2020], while still neglecting important aspects like volume scattering, which may be significant in some cases [Kurum *et al.*, 2009b; Feldman *et al.*, 2018].

It is of course possible to make use of more comprehensive formulations, which require making further assumptions regarding the size, density, shape, orientation, and distribution of the larger canopy elements. Using such more complex formulations, *Guerriero et al. [2020]* concluded that, for an experimental setup comparable to ours, direct signals largely dominate over volume scattering. In addition, they show that volume scattering produces signal fluctuations with timescale in the order of a few seconds that tend to average out with time integration. *Schwank et al. [2021]* analyse data from an upward-looking radiometer and also argue that volume scattering within the canopy plays a minor role at L-band and neglect it in their model of VOD. Obviously, this does not mean that scattering effects would be minor in all configurations, for instance, they are likely important to consider in a reflectometry (GNSS-R) experiment or when analysing below-canopy LHCP signals. Using the MIMICS model, *Steele-Dunne et al. [2012]* also concluded that leaf moisture is by far the dominant control on forest transmissivity at L-band for H and V polarizations (though branches and trunks do contribute significantly to backscatter). Thus, we believe using a dielectric mixing model valid for electrically small constituents such as leaves is acceptable, even though we agree with the reviewer that this assumption may be violated for larger elements.

In this study, our goal is primarily to showcase the potential of GNSS-based remote sensing for deriving useful information on vegetation biomass and water content. We document and discuss the limitations of our modelling approach at several points in the manuscript and aim at making all assumptions 100% transparent. Given the scope of the journal, the objectives of our study, the findings of both *Guerriero et al. [2020]* and *Steele-Dunne et al. [2012]*, and the available data, we believe our approach to be a reasonable compromise in terms of model complexity. Future work could certainly explore more complex formulations.

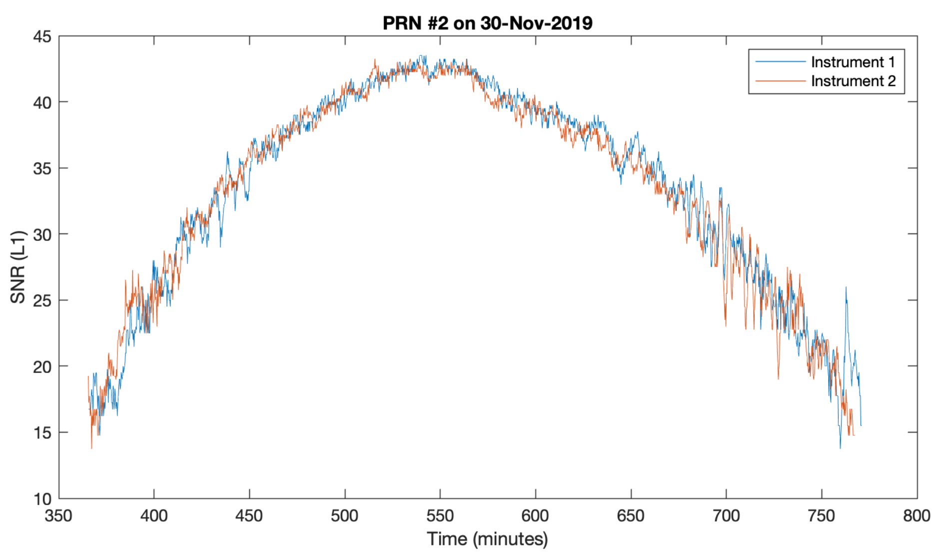
In response to the referee's concerns, we add these further statements to the manuscript.

(concerning the dielectric mixing model, L195): "While this may be true for leaves, this assumption may not hold for larger elements such as branches and trunks."

(later in the Methods section, L222): It is important to note that this simple formulation neglects several aspects, including volume scattering, which may be important in configurations with denser biomass (and also when interpreting RHCP backscatter or LHCP signals).

(inside a sentence of the conclusion, L709): In a further step, we use existing *simple* models of canopy microwave transmissivity and vegetation dielectric parameters [Ulaby and Long, 2014] to demonstrate the feasibility of using such GNSS-based VOD observations to derive information on canopy water content and aboveground dry biomass *(future work could certainly explore more complex formulations)*.

Finally, we would like to mention that observing slightly higher GNSS power at the subcanopy site compared to the open-sky reference does not necessarily indicate significant volume scattering. Even when placing two identical instruments within 2 meters of each other in an open-sky environment, small differences in measured signal power will unavoidably occur between the instruments (see below, data from an earlier test case with two Trimble NetRS instruments). These differences may arise from random noise, as well as non-random potential minor differences in antenna gain patterns, ground multipath effects, etc. Note that while these differences contribute some non-random noise in a hemispheric representation like the one shown in Figure 4a, they largely cancel out in our analysis of the hemispheric-integrated average.



Additional references (use a similar approach) to consider:

https://doi.org/10.1109/IGARSS47720.2021.9555155
https://doi.org/10.1155/2017/6941739

Thank you very much for making us aware of these, we have integrated them.

L125: *"Kurum and Farhad (2021) also tested it with mobile GNSS antennas and Zribi et al. (2017) used it to monitor sunflower canopies."*

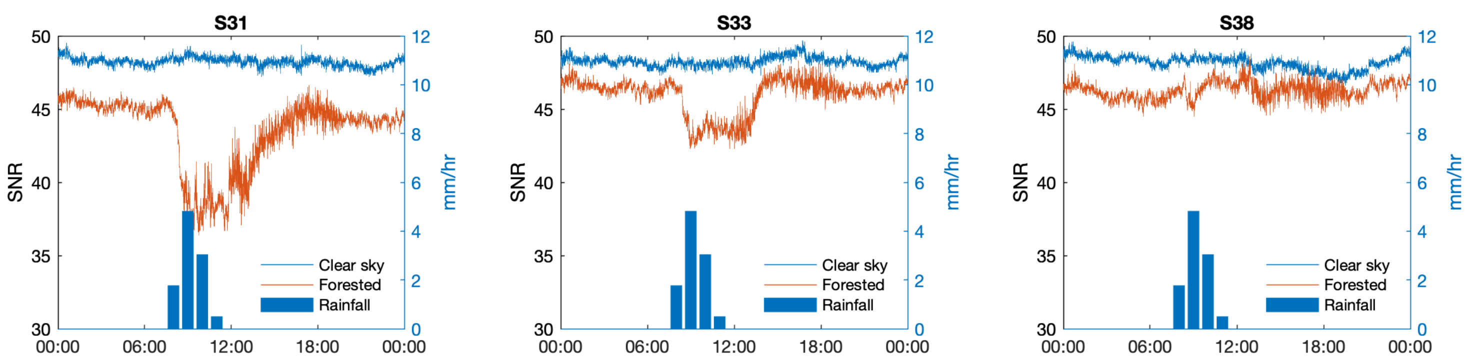
Specific Comments:

Page 1, Line 16: I think you meant "signal strength".

Thank you, corrected.

Page 1, Line 24: Have you checked the impact of rainfall and dew on the instrument? Any water on the antenna surface can change its radiation characteristics.

That's a very good point! Yes, we have looked at this question using the signal strengths of the 3 geostationary satellites of the SBAS/WAAS system which are also tracked by our receivers. Since these satellites have a fixed position in the sky their signal strength is usually very stable, which makes them ideal for looking at potential effects of water on the surface of the antenna. We found that the signal strength at the clear-sky site is unaffected by the rain event, even though the nearby surface wetness sensor was saturated. This suggests that water on the antenna surface is not a primary concern for our type of antenna.



Supplementary Figure 2. Signal strengths of the three geostationary SBAS/WAAS satellites measured at the reference and the forested sites during the rainfall event on May 18, 2020. The signal strength of the reference antenna remains stable, suggesting that the presence of water on the antenna surface does not cause strong perturbations (for our type of antenna). Note that the signal is attenuated differently for each satellite at the forested site because of the heterogeneous (and not gap-free) canopy density.

We will integrate this figure to the supplementary information and mention it in the main text.

L658: *"We could also establish that signal strength was likely not affected by the presence of intercepted water on the antenna itself (Supplementary Figure S2). »*

Page 2, Line 29: I think you meant "receiver systems".

Thank you, corrected.

Page 2, Line 40: I would say "continuously gathered network of ground truth data".

Changed to: *"a network of continuously gathered ground truth data does not exist yet"*

Page 2, Line 53: Replace "either or" with "both and" as both mentioned factors impact the transmissivity simultaneously.

Thanks for spotting this, corrected.

Page 3, Equation (1) : Add polarization symbol to this equation since VOD and gamma depends on polarization.

That's absolutely right, however we'd prefer to keep the generic version of that equation (i.e. as in *Frappart et al. [2020]* and many others). We modify the following statement instead:

L61: "where VOD represents an attenuation coefficient (specific to the observation wavelength *and polarization*)"

Page 4, Footnote: Coarse spatial resolution is not due to low signal energy. It is due to incoherent nature of the signal that requires real aperture antenna (limited in size).

Thanks, we aimed to span over a wide range of methods (from spaceborne radiometers to SAR). We clarified the sentence as follows: *"Drawbacks include a lower energy and longer wavelength, which usually translates into coarser spatial and/or radiometric resolution"*.

Page 5, Line 114: Please state the polarization of antennas used with these receivers here. In addition, receivers could be placed on the ground (without tripod) as long as they are levelled and cleared from the surrounding obstructions.

You're right, however in our case, placing them on the ground was not possible. We now mention the polarization at L156:

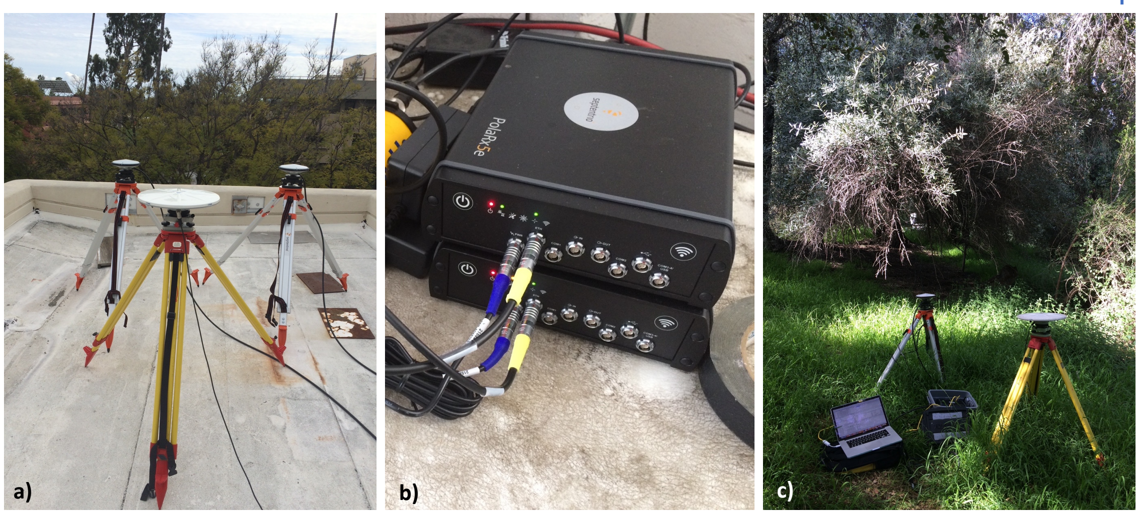
"At each site a Septentrio PolaRx5e GNSS receiver, connected to a PolaNt-x MF (RHCP) GNSS antenna, measured multi-constellation GNSS signals over the period of May 13 to December 10, 2020, with a logging rate of 15 seconds."

And the positioning at L738:

"It can even be placed on the ground (without a tripod) as long as it is level and free from obstructions."

Page 7, Lines 149 - 151: The pictures of receiver set-up would be useful to add to the manuscript.

Good idea. We add the following images as Supplementary Figure.



Supplementary Figure S3. (a) Antennas under test at the open-sky site (the PolaNt-x MF antennas are the smaller ones at the back). (b) Receivers. (c) Deployment at the forested site. The other larger Zephyr antenna (on the yellow tripod) was tested as a backup solution but was not used in the end.

Page 7, Line 156: Please state the polarization of the antenna.

Done.

Page 8, Line 179: This model is "dielectric mixing model". The physical model implies either "discrete scatter" based radiative transfer or wave theory, none of which are used in this paper. I would suggest not to use term "physical" for the model.

Thank you for this suggestion. We replace “physical model” with “dielectric mixing model”.

Page 8, Line 181: This is a major assumption which is not true for well-developed trees. Tree branches scatter and attenuate significantly while leaves attenuate mostly at L-band, so the received signal is expected to be a blend of both volume scattering and attenuation, depending on the vegetation, polarization, and incidence angle.

Yes, this assumption is discussed a few lines further at L191-198. Also see our response to the main comments discussing the literature supporting this assumption for our case and the three other statements we added to make these assumptions 100% transparent throughout the manuscript.

Page 8, Equation (4): This is repetition of Equation (1). I would define VOD here, instead.

We understand this comment. Our intention is for equation (1) to remain relatively generic as it appears in the introduction. In the methods, equation (4) provides one formulation (one among many possible) based the assumed dielectric mixing model. We’d like to keep these separate.

Page 8, Equation (5): This formula is applicable if inclusions are much smaller than wavelength as you correctly stated in the following paragraph. The formula can be applied to randomly oriented agricultural crops with no preferred scattering orientation and smaller than wavelength, but the validity region would be way off for tree canopies. The more descriptive formulation can be written as a function of forward scattering amplitudes of individual tree constituents. An example can be found at equation (8) of reference Guerriero et al. 2020.

We now mention this limitation explicitly at L195 (also see our response to the main comment for a discussion).

"While this may be true for leaves, this assumption may not hold for larger elements such as branches and trunks.”

Page 8, Line 196: That is correct that Guerriero et al. 2020 showed that coherent line-of-sight signal mostly dominates over volume scattering for RHCP-transmit RHPC-receive cases. However, it is hard to generalize this statement as this behavior can depend on the elevation, biomass, and type of trees. The question is if it is applicable to your case.

Our setup seems comparable to that of Guerriero et al. 2020 (their figure 3), with perhaps generally more randomly distributed canopy elements in our case. We agree that a more comprehensive investigation of the potential contribution of volume scattering to RHCP-transmit RHCP-receive cases in a wide variety of situations would be very welcome. Hopefully this can be the subject of future work. In the meantime, we now acknowledge these limitations at L222:

"It is important to note that this simple formulation neglects several aspects, including volume scattering, which may be important in configurations with denser biomass (and also when interpreting RHCP backscatter or LHCP signals)"

Page 9, Lines 231-214: This semi-empirical formula is developed for agricultural crops. It is not clear how it can be applied to trees, which are electrically much larger at L-band.

As mentioned in the text, this was investigated by *Chuah et al. [1995]*. They compared 3 different semi-empirical dielectric models against measurements made on leaves from rubber trees and oil palms. They conclude that the dual-dispersion model of Ulaby and El-Rayes provides good estimates in most cases. The same formula was used for forests in *Steele-Dunne et al. [2012]* for example.

Page 9, Line 220: I would call the dielectric mixing model approach as "zero-order" as the first order has completely different meaning in physical models such as RTE or wave theory.

We replace "first-order" with "simple" to avoid any misinterpretation.

Page 11, Lines 248-249: I would say "yield information on VOD" as stated at page 5, Line 116 as I stated above difference SNR can include some of the volume scattering.

We replace "mainly" by "for the most part". Also see our response to the main comments.

Page 12, Lines 260-261, Page 13, Lines 275-276: It is true that ground reflections would be small since your antenna is designed to reject reflected LHCP signals from the ground, but it would still receive volume scattering that comes from the upper hemispherical area of the antenna.

We modify the sentence at L260-261 as follows:

It should be noted that while the SNR measurement is dominated by the contribution of the direct (line of sight) signal, it also includes a comparatively weaker contribution from volume scattering and indirect multipath reflections (Bilich et al., 2007;Smyrnaios et al., 2013), the latter of which may contain information on soil water status for instance (Larson, 2016).

Page 13, Line 271: Not all GNSS systems are explicitly designed to reject such signals, but geodetic antennas are.

This is an important point. We modify the text as follows:

L271: … *"even though most geodetic ground-based GNSS systems are explicitly designed to reject such signals"*

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

Page 14, Equations, 10, 11: These need polarization subscripts.

We add the sentence:

"Note that in our case, this represents L-band VOD at RHCP polarization."

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

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