GNSS-T Forest Transmissivity Simulations based on LiDAR-derived Tree Structure

Mohammad Ehsanul Hoque and Mehmet Kurum
University of Georgia, Athens, GA, USA

***Abstract*—In this study, we calculate forest transmissivity using Global Navigation Satellite System Transmissometry (GNSS-T) techniques. The SoOp Coherent Bistatic (SCoBi) model is enhanced by incorporating LiDAR-derived tree architectures to simulate forest environments, capturing the detailed structure of trees and their influence on signal attenuation. Using quantitative structure modeling, we generate simplified cylindrical models of trees and simulate forests with varying tree spacing to represent dense and sparse conditions. Two forest models are examined: one focusing on primary tree constituents and another encompassing full tree complexity. Both stationary and moving GNSS-T techniques are employed to assess temporal and spatial variations in forest transmissivity. Additionally, the study investigates the role of the woody volume of different tree parts within the Fresnel zone which is related to water content and responsible for signal attenuation. Preliminary findings suggest notable differences in signal behavior between the forest types, highlighting the importance of tree structure in understanding microwave signal propagation. Overall, this research provides a basis for improving forest transmissivity modeling simulations to support better forest health monitoring.**

I. Introduction

Forests are vital for regulating global ecosystems, particularly in managing water and carbon cycles, and they help reduce wildfire risks by absorbing water and sequestering carbon through photosynthesis. Monitoring vegetation water content (VWC) is crucial for understanding forest health and its broader environmental impacts. One key metric for assessing forest health is vegetation optical depth (VOD), which measures the attenuation of microwave radiation as it passes through vegetation. VOD is directly correlated with water content in the forest canopy and serves as an important ecological indicator. However, traditional in-situ monitoring methods are often impractical in dense and heterogeneous forest environments, leading to an increased reliance on spaceborne microwave remote sensing technologies. GNSS-T, illustrated in Fig. 1, is a promising approach that uses the attenuation of microwave signals passing through forest canopies to estimate VOD, comparing signal strength from beneath the canopy to open-sky conditions [1].

Accurate modeling of microwave signal propagation and attenuation in forests requires capturing the distinct structure of trees. Existing models like the SoOp Coherent Bistatic (SCoBi) scattering model [2] use a uniform distribution of scatterers, which does not depict the actual architecture of forests. To overcome this limitation, we propose a framework that integrates detailed LiDAR-based reconstructions of forest structures. By replacing the uniform scatterer distribution with realistic forest architecture, our model more accurately simulates signal propagation and attenuation in complex forest environments.

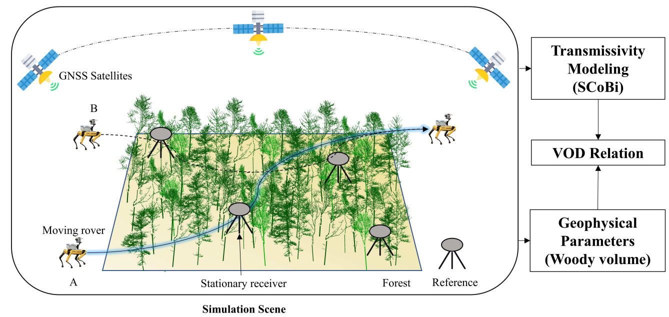

Fig. 1. Proposed framework for transmissivity modeling simulation. Simulation scene of a GNSS-T setup illustrated for both stationary and moving rover cases where the actual lidar scans are reconstructed to cylindrical shapes and artificial forest generated using individual tree instances

The primary contribution of this research is the development of a framework that generates a forest environment based on actual LiDAR tree scans. This information is then fed into the SCoBi model to retrieve accurate forest transmissivity and VOD. Additionally, We compare the geophysical parameter, woody volume in this case, which depends on the water content in tree constituents and affects signal attenuation. The volume is calculated for the significant parts of the tree within the Fresnel zone, the region around the direct signal path where wave interference occurs. We examine how different tree constituents influence attenuation and scattering by generating forests with varying structural complexity and tree spacing, simulating both dense and sparse forest environments.

II. Methodology

In this work, we aim to simulate forest transmissivity using the SCoBi model with LiDAR-derived tree architecture and analyze the relationship between VOD and geophysical parameters such as woody volume using a GNSS-T setup. This setup includes both stationary and moving rover scenarios to assess the impact of tree architecture on signal attenuation, as shown in Fig. 1. The proposed simulation framework reconstructs LiDAR tree scans into cylindrical structure model, which is then used to generate a forest for transmissivity calculations using the SCoBi model.

A. Data:

We use terrestrial LiDAR scans of trees from a publicly available dataset [3]. For this study, we utilized 500 tree scans from the data collected in leaf-off conditions to generate cylindrical reconstruction models of individual trees. Using these cylindrical models, we create a forest scene the forest by randomly distributing the trees within a specified area.

B. LiDAR derived Reconstructions:

LiDAR data are processed to capture detailed 3D scans of individual trees, which are reconstructed using quantitative structure modeling (TreeQSM) [4]. This process converts the tree architecture into cylinders shapes. Fig. 2(a) outlines the workflow for creating an artificial forest from individual tree reconstructions. The raw LiDAR scan of a single tree (Fig. 2b) is segmented and processed into a QSM reconstruction (Fig. 2c). To simplify the QSM model for transmissivity simulations, we merge consecutive cylinders that fall within a specific angular threshold and group them into orders based on volume, size, and shape. Each cylinder is then considered as a scatterer for the SCoBi model (Fig. 2d). Finally, multiple individual reconstructions are combined to create a 100m x 100m forest (Fig. 2e), where trees are randomly selected from the 500 individual tree models and placed within the forest area. Two forest models were developed: one with trunks and first-order parts, and another including all tree parts. Both were analyzed under two spacing setups: 5m (dense) and 10m (sparse).

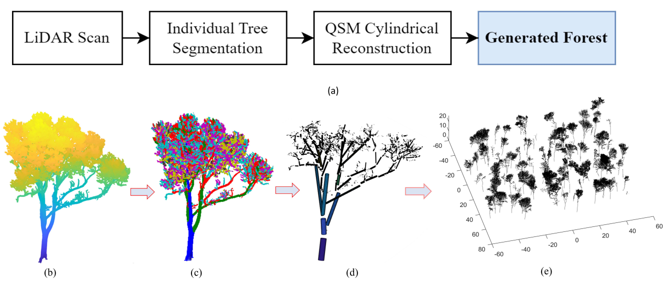

Fig. 2. (a) Workflow to reconstruct forest from individual lidar scans and QSM modeling, (b) Raw lidar scan of a single tree, (c) QSM reconstruction, (d) Simplification of the QSM model and (e) 100m x 100m forest generated from multiple individual reconstructions

C. Simulation scenarios analyzed:

We consider two GNSS-T scenarios: stationary and moving. In stationary setup, a passive receiver is placed in a fixed position within the forest. As satellite positions change, we obtain a temporal distribution of transmissivity at varying azimuth and elevation angles. On the other hand, on moving setup, a rover moves through the forest, capturing received power along its path. In both scenarios, a reference receiver is placed outside the forest in an open area to record the open-sky power density.

By comparing the power received within the forest to the reference power outside the forest, we calculate the forest's transmissivity and VOD. Additionally, for each simulation instance, we compute the woody volume within the Fresnel zone, which represents the elliptical area between the satellite transmitter and the receiver inside the forest.

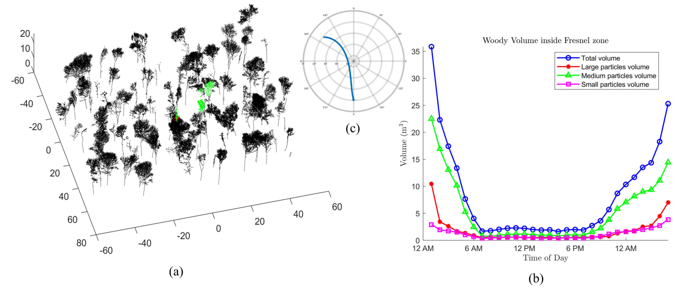

Fig. 3. (a) 100m x100m forest scene for stationary scenario; green portion of the trees illustrates volume under Fresnel zone for one instance and (b) variation of woody volume for the entire simulation (24hrs/10mins interval), (c) Position in skyplot for one satellite used in simulation

III. Results

In this study, we computed the woody volume for a stationary case. Fig. 3 shows the forest and woody volume of various tree parts inside the Fresnel zone for varying elevation angles over 24 hours for one satellite. The volume change over time as the satellite shifts will help explain variations in transmissivity in the same scenarios. The final results, including transmissivity calculations, will be presented at the conference.

IV. Conclusion

This paper presents a framework for forest transmissivity modeling that integrates LiDAR-derived tree reconstructions into the SCoBi scattering model, addressing the limitations of uniform scatterer approaches. By incorporating actual tree architecture into simulations, our method improves calculation of transmissivity modeling. We demonstrated that tree structure significantly affects VOD and geophysical parameters, such as woody volume, across both stationary and moving scenarios and varying forest models. The results highlight the importance of using real-world tree data for transmissivity modeling, with implications for forest health monitoring. Future work will refine tree reconstruction models for seasonal variations, and expand transmissivity analysis to include varying antenna polarizations and receiver heights.

References

[1] A. Ghosh, M. M. Farhad, D. Boyd, and M. Kurum, "A UGV-Based Forest Vegetation Optical Depth Mapping Using GNSS Signals," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 17, pp. 5093–5105, 2024. doi: 10.1109/JSTARS.2024.3365798. [Online]. Available: https://doi.org/10.1109/JSTARS.2024.3365798.

[2] M. Kurum, M. Deshpande, A. T. Joseph, P. E. O'Neill, R. H. Lang, and O. Eroglu, "SCoBi-Veg: A Generalized Bistatic Scattering Model of Reflectometry From Vegetation for Signals of Opportunity Applications," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 57, no. 2, pp. 1049-1068, Feb. 2019, doi: 10.1109/TGRS.2018.2864631.

[3] K. Calders *et al.*, "Terrestrial laser scanning data Wytham Woods: individual trees and quantitative structure models (QSMs)," Zenodo, Nov. 16, 2022. [Online]. Available: https://doi.org/10.5281/zenodo.7307956.

[4] A. Lau *et al.*, "Quantifying branch architecture of tropical trees using terrestrial LiDAR and 3D modelling," *Trees*, vol. 32, no. 5, pp. 1219–1231, May 2018. [Online]. Available: https://doi.org/10.1007/s00468-018-1704-1.