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Assessing dual-channel multi-year active microwave-based vegetation optical depth in temperate forest ecosystems

Florian M. Hellwig^{1,2}, Anke Fluhrer², Konstantin Schellenberg^{3,4,2}, Paul Vermunt⁵, Benjamin Lecart⁶, François Jonard⁶, Markus Zehner³, Thomas Weiß⁷, David Chaparro⁸, Clémence Dubois⁹, Moritz Link¹⁰, Jan Bliefernicht¹, Harald Kunstmann^{1,11}, and Thomas Jagdhuber^{2,1}

¹University of Augsburg, Institute of Geography, Department of Regional Climate and Hydrology, Augsburg, Germany (florian.hellwig@uni-a.de)

²German Aerospace Center (DLR), Microwaves and Radar Institute, Wessling, Germany

³Max-Planck Institute for Biogeochemistry, Department of Biogeochemical Processes, Jena, Germany

⁴Friedrich Schiller University Jena, Department for Earth Observation, Jena, Germany

⁵University of Twente, Enschede, Netherlands

⁶University of Liège, Department of Geography, Liège, Belgium

⁷University of Rostock, Geodesy and Geoinformatics, Rostock, Germany

⁸Centre for Ecological Research and Forestry Applications (CREAF), Cerdanyola del Vallès, Spain

⁹German Aerospace Center (DLR), Institute of Data Science, Jena, Germany

¹⁰University of Valencia, Image Processing Laboratory (IPL), Valencia, Spain

¹¹Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany

Forest water dynamics can be assessed on large spatio-temporal scales using satellite-based remote sensing. Vegetation optical depth (VOD), which indicates the vegetation's attenuation of microwaves, contains mainly information on the dry biomass, structure, and water content of the vegetation. Water dynamics can be reflected in short-term variations in VOD. Currently, VOD is operationally retrieved using passive microwave sensors, such as AMSR-2, SMAP, and SMOS, or radar-based sensors, such as ASCAT, with a coarse spatial resolution (tens of kilometers), which hinders the understanding of complex landscapes and is a major obstacle for VOD validation using ground sensors. To overcome this shortcoming of spatial resolution, we utilize synthetic aperture radar (SAR) sensors, such as Copernicus Sentinel-1 (S1) C-band (5.504 GHz), which enables a much higher spatial resolution (tens of meters).

This study aims to estimate spatially high-resolution SAR-based VOD across different forest ecosystems, using both VH and VV polarizations, and ultimately assess forest water dynamics. We employ soil and vegetation physical scattering models (De Roo et al., 2001; Ulaby & Long, 2014) and constrain the effective scattering albedo (ω), which indicates the ratio of scattering to absorption of vegetation. In our dual-channel approach, we utilize *in situ* soil moisture from forest ecological observatories and co-polarized S1 backscatter as direct model inputs, and characterize the vegetation structure (ω) using cross-polarized S1 backscatter to estimate SAR-based VOD. We test our approach across two deciduous broadleaf and three evergreen needleleaf forest ecosystems in Central Europe for up to three years (2023-2025). In addition, we compare our SAR-

based VOD with VOD estimates from Global Navigation Satellite System-Transmissometry (GNSS-T), derived from a pair of *in situ* receivers: one located at the top of the canopy and one on the ground for each test site (Brede et al., 2025). We validate our approach using *in situ* plant gravimetric moisture content (m_g ; $[\text{kg}_{\text{water}}/\text{kg}_{\text{wet biomass}}]$) measurements of the tree canopy and remote sensing-based leaf area index. We will also transfer our dual-channel approach to the agricultural site of the Land-Atmosphere Feedback Initiative (LAFI) and other ecosystems in a later step. In the end, spatially high-resolution satellite-based SAR-based VOD enables not only analyses of forest water dynamics but also small-scale up to stand-based assessments of plant hydraulics.

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