National Aeronautics and Space Administration

FY23 Topic Areas Research and Technology Development (TRTD)

Realistic and Computationally Efficient 3D Full-Wave Model for Multistatic Scattering from Vegetated Terrains at P/L Band

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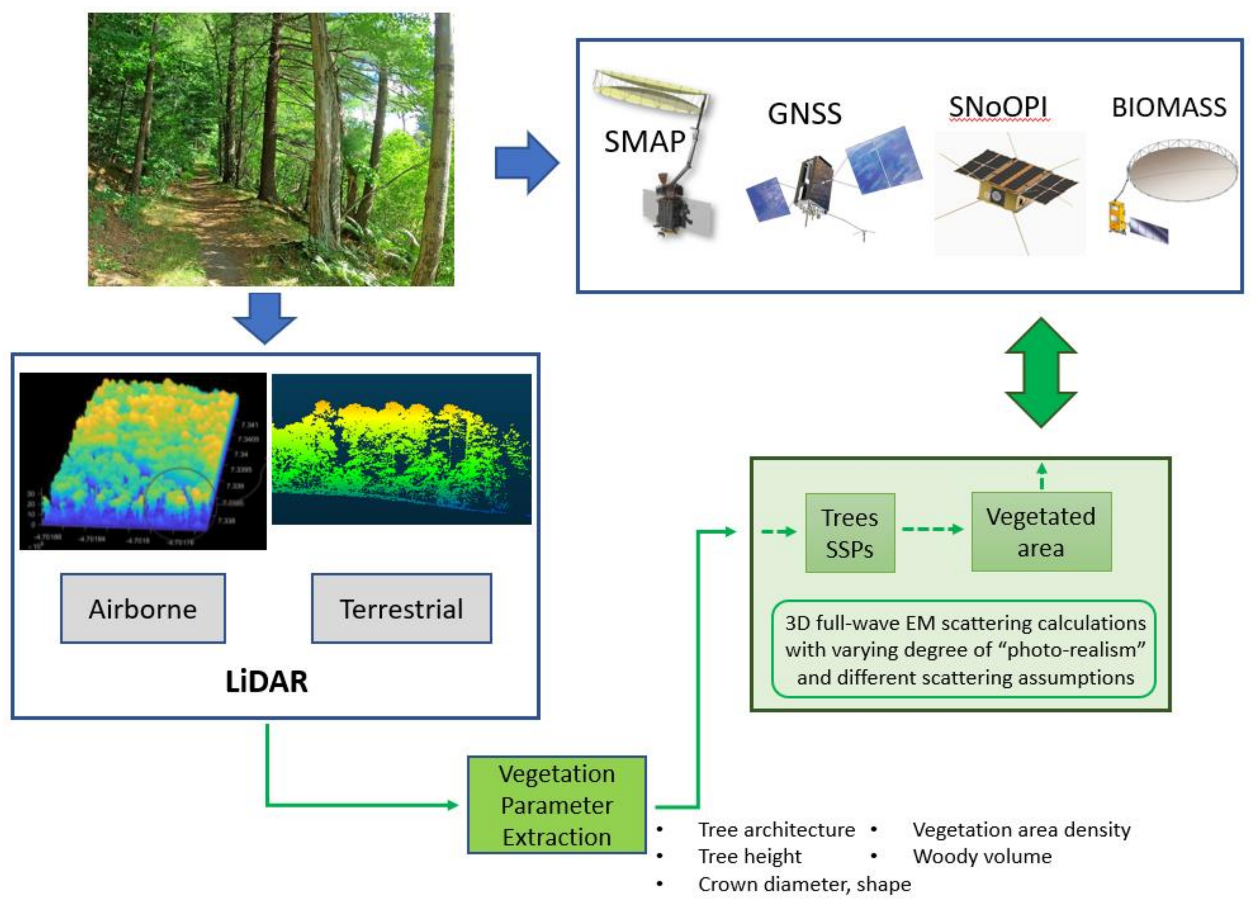
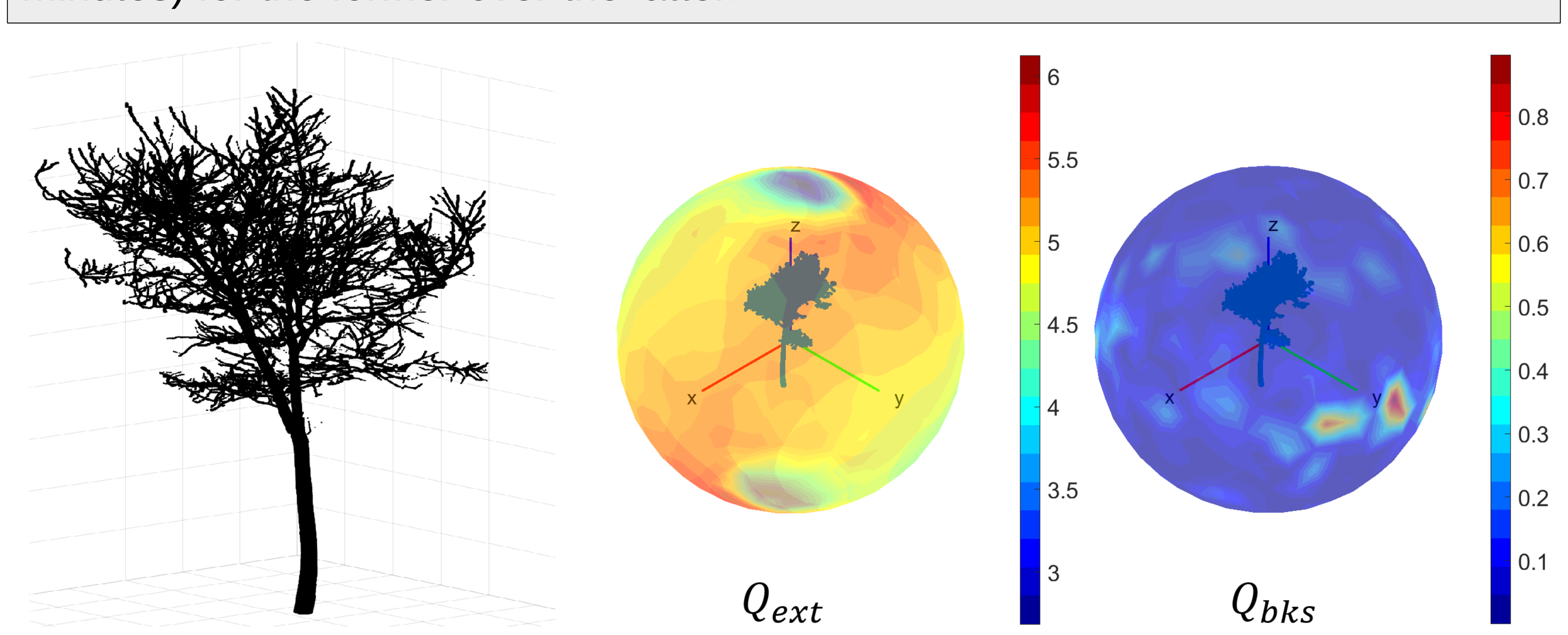
Strategic Focus Area: Modeling and Simulation

Objectives: The main objective is to develop and validate a 3D coherent full-wave model of electromagnetic (EM) scattering from realistic vegetation scenes that accounts for the vertical and horizontal heterogeneity and wave interactions among vegetation elements and between the vegetation and the soil. We aim to achieve an improved understanding of microwave properties of moderately to densely vegetated landscapes and their effects on surface and rootzone soil moisture, forest fire severity, and biomass retrieval using spaceborne multiple frequency (e.g., P and L bands) microwave measurements. While we address the research gaps with the EM models, we will determine the required model accuracy to radio-realistically mimic microwave measurements by comparing the different model's resulting scattering quantities, from dielectric mixing to full-wave models. To achieve this, we build on our advanced capabilities in 1) modeling realistic tree structures from LiDAR data and 2) calculating at a reasonable computational cost the full-wave EM scattering by realistic vegetation. The ultimate goal is to better understand the impact of the complex features of a vegetated scene on P- and L-bands measurements, and thus advance root-zone soil moisture (RZSM) and vegetation water content (VWC) retrieval.



The vegetation & EM scattering modeling constitute our field of action to determine the "radio-realism" and optimize the agreement between calculated scattering and measurements

Approach/Results: One major achievement of the current fiscal year is using LiDAR-derived vegetation structures along with our full-wave efficient scattering solution to investigate radio-realism for vegetation single scattering properties (SSPs) at P-band. Quantitative Structure Models (QSMs)-based algorithms enable us the reconstruction of realistic tree architecture from raw LiDAR. Then, we use our scattering model MIDAS (for MoM Integral-equation Decomposition for Arbitrarily-shaped Scatterers) to calculate SSPs of voxelized LiDAR-based realistic tree shapes, for a large number of incident directions. These results were validated in comparison with simulations using the commercial software FEKO. We note a good agreement between MIDAS and FEKO with a significant computational advantage (a few days vs a few tens of minutes) for the former over the latter.



(left) A "photo-realistic" reconstruction of a Witham Wood tree of height of h=20 m using TreeQSM, voxelized at a resolution d=5 cm. (right) Variation of the tree extinction and backscattering efficiency factors as function of the incident direction

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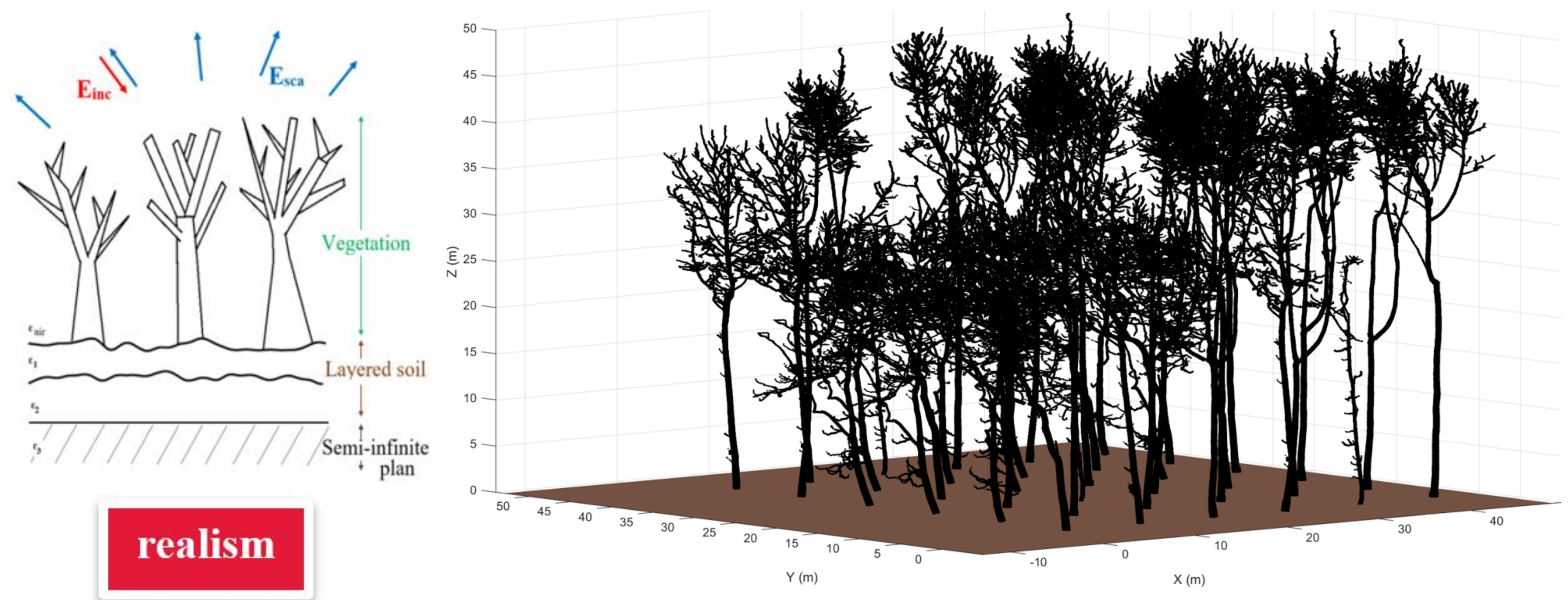
Brief Background: The uncertainty on the physical and scattering properties of realistic vegetation scenes is a major challenge for physical, quantitative microwave remote sensing of forests' parameters such as VWC and RZSM under vegetation. Our ability to monitor vegetation dynamics with P- and L-band signals is constrained by the application of sophisticated electromagnetic models, not by technology. Most scattering models represent the vegetation as consisting of a homogenous cloud, discarding tree structure and variations in vegetation geometrical and dielectric properties vertically and horizontally. These simplifications result in errors in retrieving or interpreting measurements. Overcoming the current gap in accurate full-wave models necessarily entails improving our understanding of the vegetation "radio-realism" at P- and L-bands, namely the degree of detail of the vegetation needed to mimic accurately the scattered signals at these frequencies.



realism + VIE/MoM + CBFM

In each point r of the forest scene, the total electric field E satisfies the VIE given by

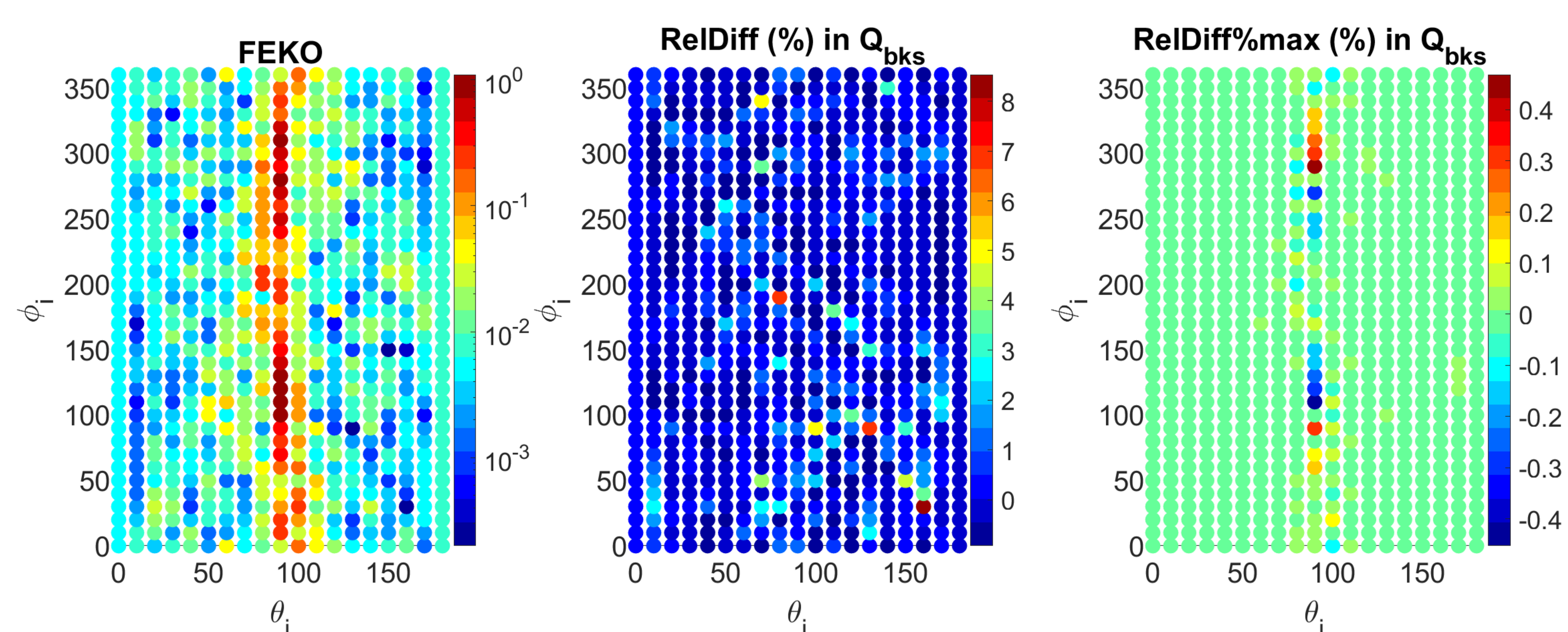
VIE $$E(r) = E_{inc}(r) + (k_0^2 + \nabla\nabla.) \int\int\int_{\Omega} \chi(r')\, \underline{\underline{G}}(r, r') E(r') dr'$$

where E_{inc} is the incident electric field, $\chi(r') = (\varepsilon(r') - \varepsilon_0)/\varepsilon_0$ is the dielectric contrast at a source point, $\underline{\underline{G}}(r, r')$ is dyadic Green's function of the two-layered media (free space and the ground), and Ω is the domain occupied by the scatterers (tree trunks and main branches).

MoM $$\bar{E}(\bar{r}) = \sum_{n=1}^{N} \sum_{q=1}^{3} E_q^n\, \bar{F}_q^n(\bar{r}) \qquad Z\,E = E^{inc}$$

The optimal approach to take advantage of the realistic improved representation of the forest scene consists in employing exact numerical methods capable of calculating the full-wave EM scattering from arbitrarily shaped and heterogeneous objects.

The goal is to leverage the computational efficiency and versatility (to the geometry of the scatterer) of MIDAS to determine the "radio-realism" at P- and L-bands. Simply put, we aim to assess the impact of shape simplification of the tree on its scattering behavior, to 1) optimally refine and polish-up our QSM simplification algorithms, and 2) generate a high utility database of simplified "radio-realistic" geometries and accurate SSPs of realistic trees of different species, dimensions and compositions. This is all the more important in view of the fact that the simplified geometries and accurate SSPs are required keys to success for classical radiative transfer (RT) and Distorted-wave Born Approximation (DBA)-based approaches and more recent full-wave solutions.



Relative difference (%) in backscattering efficiency factors calculated with MIDAS and FEKO for a LiDAR-derived realistic Wytham winter tree

Significance/Benefits to NASA/JPL: Accurately characterizing EM scattering by large realistic complex and heterogeneous forest scenes at P- and L-bands is of significant interest to many present and future NASA programs:
1) P-band Signals of Opportunity (SoOp) reflectometry as an emerging low-cost technology for P-band soil moisture and snow water sensing, represented for example by the CubeSat mission SNOOPI, and the Synthetic Aperture Radar (SAR) SoOpSAR concept. 2) L-band Global Navigation Satellite System Transmissiometry (GNSS-T) which emerged recently as a promising method for retrieving vegetation water content. 3) Wildfire monitoring and prevention through quantification of pre-fire fuel characteristics and structure represented by the Technology Development for Support of Wildfire Science and Disaster Mitigation (FireTech) program.

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