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 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.
The ultimate goal is to better understand the impact of the complex features of a vegetated scene, including vegetation and soil, on P- and L-band measurements, and thus advance soil moisture (SM) and vegetation water content (VWC) retrieval.

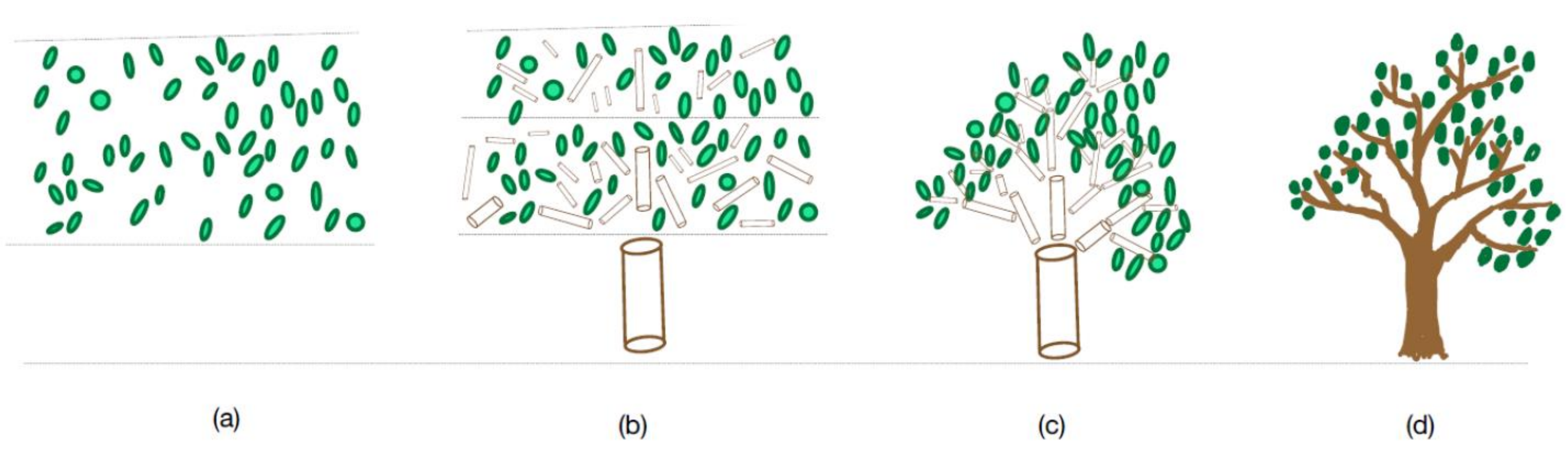

Illustration of tree implementations at different degrees of "photo" realism: (a) dielectric mixing model representation, (b) & (c) Discrete Born Approximation (DBA) representation with different degrees of realism, (d) The photo-realistic architecture of the full wave solution

Approach/Results: A 3D full-wave model for bistatic scattering from forest has been previously developed, based on the volumetric integral equation (VIE) method. To make this solver a useful tool for the forward scattering modelers, and SM and VOC retrieval algorithm developers at P and L band, we are working on 1) improving the vegetated scene representation in terms of geometry and dielectric heterogeneity of its elements, 2) optimizing the computational capabilities of the MoM/CBFM solution so that it can efficiently simulate bistatic scattering from the more realistic forest or agricultural terrain and 3) validate the model using collected data from controlled field experiments.
We improved tree geometry modeling by leveraging prior efforts on tree species definition, classification, and realization (by Razi Ahmed for PolSARProSim+). We are working on building a vegetation models database from different tree and short vegetation generation tools (PolSARProSim+, Arbaro, space colonization algorithm, recursive fractal algorithm).
We Implemented the first basic version of the MoM/CBFM algorithm by incorporating recent MIDAS computational performance enhancements to the previous scattering model. We also made good progress in numerically implementing and validating the multilayer dyadic Green's function (MLDGF), computed via Sommerfeld integrals.

Significance/Benefits to NASA/JPL: The present effort will help better exploit the forest signatures of current and upcoming missions such as SMAP, NISAR, ICESat-2, and SWOT, and emerging technologies such as Global Navigation Satellite Systems (GNSS) Transmissometry (GNSS-T) and Signal of Opportunities (SoOp). We expect the full-wave EM simulations and their validation using SMAPVEX'22 to provide a clearer understanding of the impact of the complex features of a vegetated scene, and thus the vegetation VWC and VOD, on the scattered signals, to make the best use of collected microwave land surface measurements.

Acknowledgments: Thanks go to co-I Kurum MSU (Mississippi State University) team members Dylan Boyd, Suraj Yadav, and Abesh Ghosh, for their work on DBA-based scattering model and the ground-truth data analysis.

National Aeronautics and Space Administration

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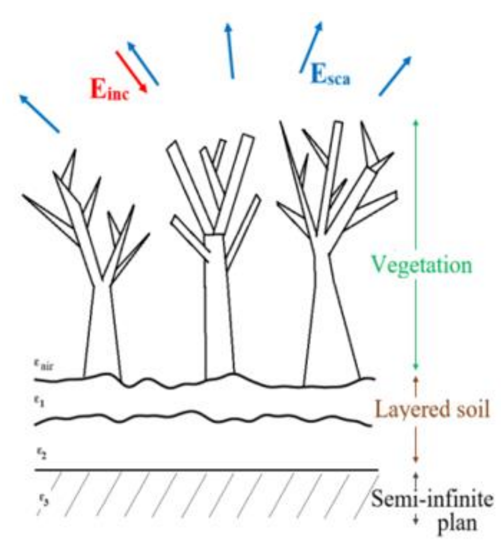
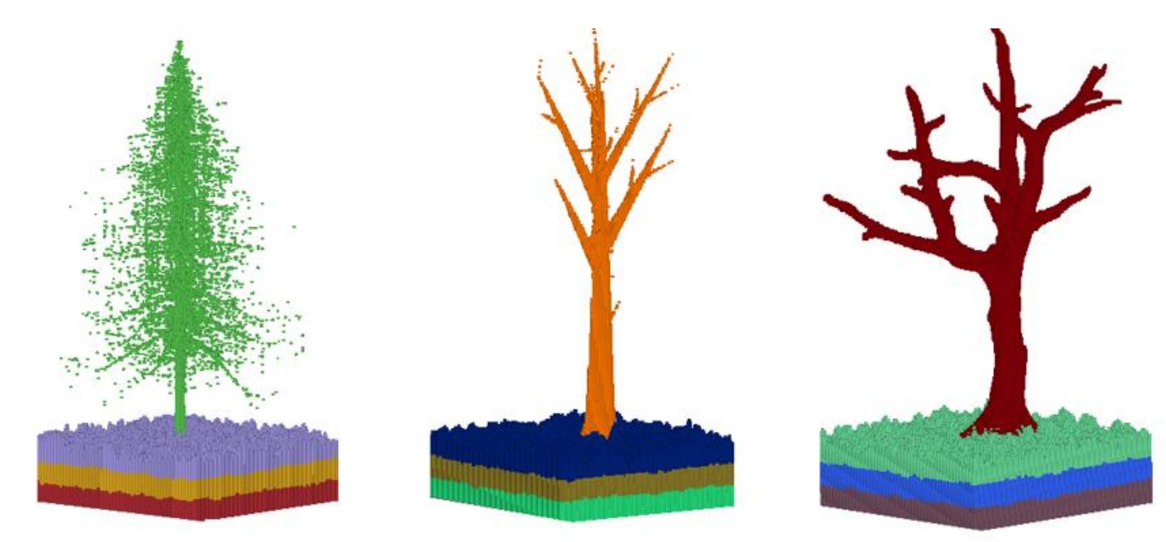
Clearance Number: CL#00-0000
Poster Number: RPC#

Brief Background: There is still a gap to be filled by accurate and efficient numerical 3D coherent models for scattering from realistic complex vegetated scenes. This gap is partially a result of the often-unbearable computational cost of full-wave accurate modeling of scattering by arbitrarily shaped and heterogeneous forest elements, e.g. realistic trees and plants, rough surface, and layered soil medium. We believe that owning a "radio-realistic" full-wave model of EM scattering by vegetated terrains, will significantly leverage several ongoing NASA technologies and research efforts for retrieval of soil moisture and vegetation properties over areas with large VWC using the P- and L-band signals.





Example : Three different models of tree of height 7.8, 7.5 and 6.9 m placed over a 3-layers soil medium of side length L = 4 m and depth d = 1.2 m

realism + **VIE/MoM** + **CBFM**

In each point $\boldsymbol{r}$ of the forest scene, the total electric field $\boldsymbol{E}$ satisfies the VIE given by

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

where $\boldsymbol{E}_{inc}$ is the incident electric field, $\chi(\boldsymbol{r}') = (\varepsilon(\boldsymbol{r}') - \varepsilon_0)/\varepsilon_0$ is the dielectric contrast at a source point, $\underline{\underline{\boldsymbol{G}}}(\boldsymbol{r},\boldsymbol{r}')$ 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).

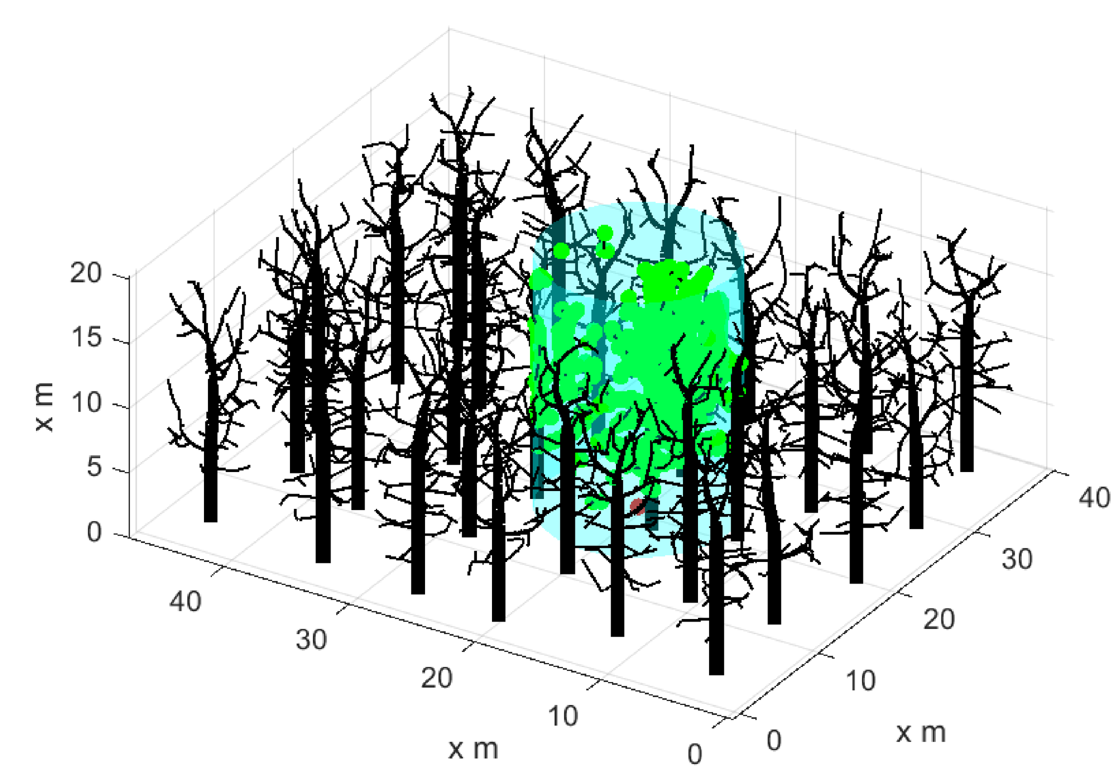
MoM $$\overline{E}(\overline{r}) = \sum_{n=1}^{N}\sum_{q=1}^{3} E_q^n \, \overline{F}_q^n(\overline{r})$$

$$Z\,E = E^{inc}$$

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. This is achieved by the use of the method of Moments (MoM) combined with a direct solver-based domain decomposition method.

We implemented and configured FEKO simulations to validate our scattering model once operational. This started with importing to FEKO realistic tree geometries, generated using Arbaro.
In order to vary the degree of realism of our EM scattering models, Dr. Kurum's team is working on improving their fully parametric first-order scattering model to bring it to the next stage of realism and use it to simulate simulating scattering and propagation of GNSS signals under a forest canopy.
With regard to validation, Dr. Kurum's team has been processing SMAPVEX's IOP-1 Global Navigation Satellite System (GNSS) Transmissometry (GNSS-T) data at selected sites, including GPS, GLONASS, Beidou, and Galileo satellites, and generated forest transmissivity and vegetation optical depth (VOD) heatmaps averaged to different angular bins at both SMAPVEX'22 locations.

Example of Quaken tree model by Arbaro imported to FEKO after cleaning using Hypermesh.



Forest scene generated by a space colonization algorithm to simulate a GNSS-T configuration where the red dot indicates the receiver position, and particles within the field of view are marked as green

Publications:

- Fenni, I., Roussel, H., Kurum, M., Boyd, D., Haynes, M.S. and Haddad, Z.S., Development and Optimization of a Full-wave Model for Multistatic Scattering from Vegetated Terrains at P/L Band. IEEE PIERS, Prague 2023
- Yadav, S.,Ghosh D.,Boyd, D. and Kurum M., 2023. A realistic framework of GNSS-T for simulating scattering and propagation of GNSS signals under a forest canopy. IEEE PIERS, Prague 2023

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