Estimation of Belowground Biomass and Permafrost Active Layer Properties Using Radar and Lidar Measurements

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Science Objectives

This work directly responds to the Terrestrial Ecology Program's seeking to "strengthen the theoretical and scientific basis for measuring Earth surface properties using reflected, emitted, and scattered electromagnetic radiation," as well as the Program's goal to develop "the methodologies and technical approaches to analyze and interpret such measurements."

Specific objectives of this investigation are to:

1. Develop sophisticated radar scattering models adapted for Alaska and Western Canada permafrost landscapes that account for multilayer soils with a surface organic layer and vegetation roots, and intervening tundra and taiga vegetation. Use Lidar observations to parameterize above-ground vegetation structural properties.
    - Limited but judicious ground sampling is planned for this phase of the project.
2. Apply the model developed under Objective 1 to develop a regionally refined inverse algorithm to retrieve permafrost properties using dual-frequency P-band and L-band radar imagery; and
3. Use combined airborne radar remote sensing from AirMOSS and UAVSAR to retrieve and map belowground biomass, soil moisture profile, and active layer thickness (ALT), and assess the retrieval error and uncertainty using ground truth observations.

Expected Significance

1. Establish the joint use of P-band and L-band SAR, and in particular the AirMOSS and UAVSAR instruments, as a principal remote sensing and direct observation tool for quantifying the spatiotemporal distributions of root biomass as well as permafrost properties, including the subsurface soil moisture profiles, in the presence of tundra and taiga vegetation and their root systems;
2. Provide accurate and geospatially consistent information about active layer properties to ecosystem and carbon models of boreal and arctic regions; and
3. Based on the lessons learned about current airborne sampling strategies and to-be-determined uncertainties of products, provide input to future phases of the ABoVE implementation plan and recommend the required spatiotemporal sampling designs for remote sensing and in-situ observations to yield the optimum set of retrievable parameters along with quantified uncertainties and errors.

Impact to State of Knowledge

- This work develops remote sensing algorithms and produces permafrost products, including root biomass, using the ABoVE Foundational Airborne Measurements collected with airborne SAR. The target radar data sets are the Alaska and Canada circuits flown by the AirMOSS and the UAVSAR.
- The work, using a combination of two long-wavelength radars at L-band and P-band, will enable a much more realistic and accurate representation and retrieval of permafrost active layer properties, which would not be possible otherwise.
- No other remote sensing observation is expected to provide the proposed set of products, especially the root biomass, the information which is scarce in the Arctic.

References

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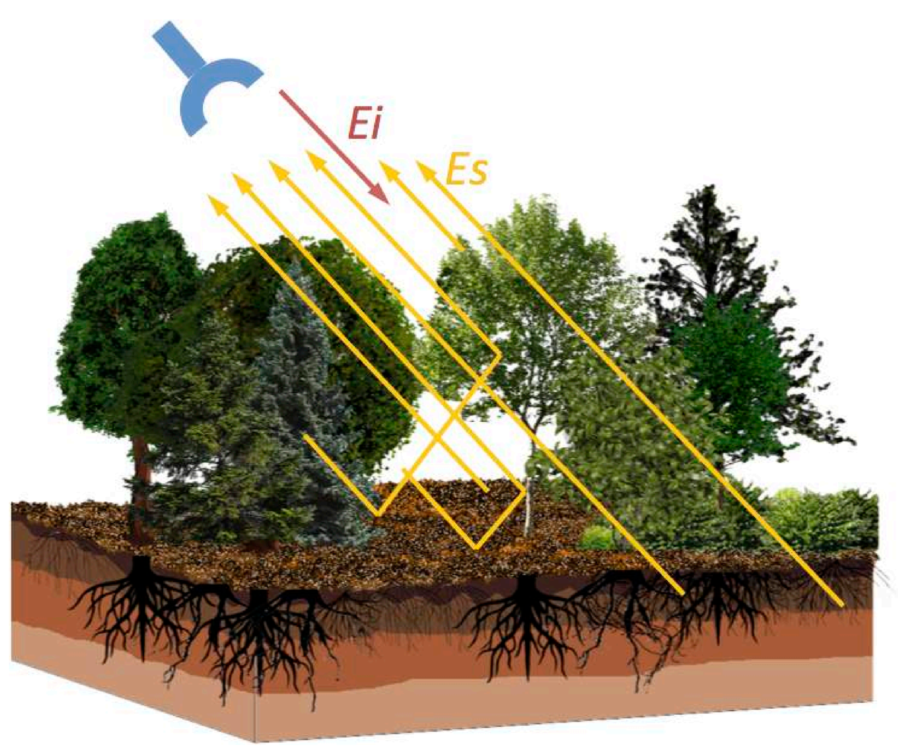
- Duan, X., and M. Moghaddam, "Full wave scattering from rough surfaces with buried inhomogeneities," in review, 2015.
- Burgin, M., D. Clewley, R. Lucas, and M. Moghaddam, "A generalized radar backscattering model based on wave theory for multilayer multispecies vegetation," *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 12, 2011.
- Tabatabaeenejad, A., M. Burgin, and M. Moghaddam, "P-band radar retrieval of subcanopy and subsurface soil moisture profile as a second order polynomial: first AirMOSS results," *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 2, 2015.

Technical Approach

Objective 1: Advance the current radar scattering model to include roots (belowground biomass) and surface organic layer; advance the surface and volume scattering modules



Final radar scattering model will include the permafrost interface, active layer, surface organic layer, vegetation roots, and tundra and taiga above-ground vegetation.

Inclusion of Shallow Roots

1. We will create a numerical representation of root distributions for the boreal taiga and arctic tundra vegetation. We will use these to parameterize the root module of the radar scattering model.
2. We will integrate the random-medium-based root model of Duan and Moghaddam (2011, 2015) into the current radar scattering model we used for the AirMOSS project.
3. We will test and verify results using simple special cases, and test backward compatibility. The component of the model impacted is the effective surface scattering module, since the roots cause a volume scattering contribution to the surface backscatter.

Inclusion of Surface Organic Layer

1. Dielectric models of organic soils are not as well studied as their mineral counterparts, but there are some examples available in the literature. We will carry out a detailed literature survey to determine which model is the best for the permafrost soils in the ABoVE domain.
2. The soil moisture profile that extends through both organic and mineral layers will be assumed to be represented by a function the parameters of which will be retrieved. This is already built in our layered medium models referenced above and used for AirMOSS retrievals.
3. The new soil model (that accounts for surface organic layer) will be integrated with the vegetation module. This task is mathematically straightforward, because of the modularity of the existing model.
4. Each of the above tasks will be tested and verified in simulation. This will include backward-compatibility as well as testing of new special cases that can be verified analytically (e.g., smooth surfaces for ground and idealized cylinders for tree stems).

Model Advancement for Surface Scattering and Volume Scattering

Benefiting from previous work, for the entire period of our project, we will keep improving the formulation of scattering within and from the branch layer in the current scattering model. The main focus of our forward model enhancement will be on inclusion of roots and organic layer. However, any improved module of the model will be easily incorporated into the current forest scattering model of Burgin *et al.* (2011).

Model Parameterization Using Field Measurements and Lidar

In order to use LVIS for model parameterization and validation, canopy height and vertical arrangement of canopy elements such as canopy height profiles (CHP) and vertical foliage profile (VFP) will be first derived from LVIS return waveform data using the established techniques. Mean canopy height and trunk height can then be obtained from the height indices. Other parameters such as diameter at breast height (DBH), primary branch density, and tree density will be estimated using canopy height indices and allometric equations if known for the dominant species in the study area.

Objective 2: Develop joint P- and L-band retrieval algorithm to estimate belowground biomass, soil moisture profile, and active layer thickness; quantify retrieval uncertainty

1. Based on the forward scattering modeling activity under Objective 1, we will determine the most important set of unknowns in terms of which the retrieval problem should be formulated. The set of unknowns will be found from a large set of simulations, sensitivity analysis with respect to model parameters, and our field work.
2. Given the three P-band channels and three L-band channels, we can retrieve at least six parameters. These parameters will be the belowground (root) biomass, thicknesses of the organic and mineral layers, and the soil moisture profile, which will be represented with a second-order polynomial and extends from the surface through both organic and mineral layers.
3. Since each frequency has its strengths and weaknesses with respect to depth and resolution of retrieval, we will develop regularization strategies to highlight the strengths and diminish the weaknesses.
4. The cost function is minimized using a global optimization scheme. We plan to continue using the simulated annealing method as it has proven very powerful and cost-effective throughout the AirMOSS project (Tabatabaeenejad *et al.*, 2015).
5. We will perform an extensive uncertainty analysis using the Monte Carlo method. This analysis will be carried out with respect to uncertainty in parameters that are considered known such as soil texture properties, aboveground vegetation parameters, and root dielectric assumptions.

Objective 3: Use the ABoVE Foundational Airborne Measurements from AirMOSS and UAVSAR to map permafrost structure properties; validate and assess retrieval error