学 位 論 文 内 容 の 要 旨/Dissertation Abstract

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学 位 論 文 題 名/Title of Dissertation

Development of radar polarimetry techniques for forest biomass retrieval and disturbance detection
(森林バイオマス推定と撹乱検知のためのレーダーポラリメトリ技術の開発)

Forests occupy approximately 31% of Earth's land surface and provide a wide range of essential ecosystem services. They play a crucial role in regulating climate, supporting nutrient cycling, offering diverse flora and fauna habitat, and providing aesthetic and cultural benefits. However, the unsustainable exploitation of natural resources driven by anthropogenic demands has resulted in the conversion of millions of hectares of forestland into other land-use categories. In addition to deforestation, the quality of the remaining forest cover is often compromised by degradation, driven by factors such as overgrazing, logging, and pollution. Deforestation and forest degradation account for approximately 17% of global carbon emissions, underscoring the critical need for effective mitigation strategies. In response, various international initiatives have been established to promote the conservation and sustainable management of forest resources. One such initiative is the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program launched by the United Nations Framework Convention on Climate Change (UNFCCC). This program encourages the development of robust methodologies for Monitoring, Reporting, and Verification (MRV) of forest cover and carbon stocks as well as the establishment of Reference Levels (RLs) for tracking changes over time.

The availability of open-access remote sensing data such as MODIS, Landsat, and Sentinel series data has facilitated the creation of operational products for monitoring deforestation. However, existing monitoring systems often struggle to detect small-scale forest disturbances and rely heavily on cloud-free imagery. Forest degradation remains a significant challenge owing to the dynamic and complex nature of forest ecosystems. Synthetic Aperture Radar (SAR) has emerged as a complementary tool for forest monitoring to address the limitations of optical sensors. SAR's ability to penetrate cloud cover and its sensitivity to the structural, geometric, and dielectric properties of vegetation make it effective for tracking forest changes under varying environmental conditions.

The first objective introduced the L-band Fully Polarimetric SAR Algorithm for Forest Biomass Retrieval using 7SD and Random Forest Regression for forest above-ground biomass (AGB) estimation. As part of this research, L-band Polarimetric SAR (PolSAR) data were used to develop a model for forest biomass estimation. Biomass was estimated using fully polarimetric ALOS-2/PALSAR-2 datasets and field AGB measurements. To estimate the forest AGB, the algorithm employs a seven-component scattering power decomposition (7SD) and random forest regression (RFR) machine-learning approach. By implementing the 7SD model, seven scattering powers were extracted from the ALOS-2/PALSAR-2 inverted for the above-ground biomass. Field data were used to

validate the estimated biomass using this model. The above-ground biomass in Shivamogga, estimated using the model, was consistent with that measured in the field. The root mean squared error (RMSE) and relative RMSE with respect to mean AGB were 21.94 Mg/ha and 19.46, respectively, which are within acceptable ranges. The model was also used for cross-validation in Tundi Forest, where the relative RMSE with respect to the mean AGB was 22.9. I proposed a novel approach for estimating the AGB in tropical forests using the scattering power generated from L-band fully polarimetric data.

To further improve the accuracy of the biomass estimation using SAR data, this study also investigated the potential of using multifrequency SAR data from ALOS-2/PALSAR-2 (L-band) and Radarsat-2 (C-band) with canopy height from the Global Ecosystem Dynamics Investigation (GEDI) to enhance the accuracy of above-ground biomass (AGB) estimation in tropical forests. The integration of the L- and C-band SAR data improves the precision of biomass estimates by leveraging the complementary characteristics of each frequency. This research focused on the Shivamogga forest, employing full polarimetric SAR data from both L- and C-band sensors, alongside canopy height data from GEDI. A random forest algorithm was used for biomass estimation, incorporating scattering powers derived from seven-component scattering power decomposition and forest height measurements from the GEDI as input variables. The model's performance was validated against field measurements, yielding a root mean squared error (RMSE) of 16.06 Mg/ha and a relative RMSE of 14.24%, indicating enhanced estimation accuracy. These findings demonstrate the value of integrating the scattering power with canopy height information for AGB estimation. The synergy between structural information from SAR scattering and vertical insights from forest height data results in more comprehensive and reliable biomass assessments.

There is the limitation of the temporal resolution and spatial coverage of the full PolSAR data. To extend the scattering power decomposition to the dual-PolSAR data, this study introduces a novel four-component scattering power decomposition method for dual-PolSAR data. The increasing availability of dual-polarimetric synthetic aperture radar (PolSAR) data has led to a significant increase in its application over the past few decades. Model-based decomposition, combined with polarimetric information extraction from PolSAR data, plays a crucial role in target identification and classification. In this context, the covariance matrix [C], composed of four independent parameters, was used as the input for dual-pol four-component scattering power decomposition (DP-4SD). A novel 4SD model was tested using dual-polarimetric SAR data from space-borne ALOS-2/PALSAR-2, and its performance was evaluated against that of existing scattering power decomposition methods. The performance of the proposed 4SD model was assessed using dual-polarization data from Haldwani Forest and San Francisco to evaluate its classification capabilities within a single class (forest) and across various land-use and land-cover classes in San Francisco. The overall classification accuracy achieved was 85.69% for the Haldwani forest and 93.66% for San Francisco, with fewer unclassified samples compared with the existing model. The 4SD model demonstrates superior classification accuracy and enhances the interpretation of polarimetric information, indicating its potential to significantly improve land-use and land-cover mapping using dual PolSAR data.

This research work further extended the four-component scattering power decomposition model (4SD-DP) to forest monitoring by developing a novel Forest Disturbance Index (FDI). The FDI was validated against observed biomass changes in highly disturbed forest areas to ensure reliability. The validation results demonstrated a root mean squared error (RMSE) of 21.844 Mg/ha and a relative RMSE of 21.84%, indicating the effectiveness of the model in capturing biomass dynamics in areas undergoing significant forest disturbance. These results underscore the potential of FDI as a tool for monitoring forest health and tracking degradation trends in vulnerable regions.

The concluding chapter synthesizes key findings, emphasizing their practical implications for forest management, conservation policies, and environmental monitoring. These results offer valuable insights for addressing deforestation, forest degradation, and land encroachment, which are critical issues for many countries facing similar ecological pressures. Furthermore, this study highlights the importance of leveraging remote sensing technologies for sustainable forest management and climate change mitigation.