学 位 論 文 審 査 の 要 旨

博士（環境科学）　　　　　　　　氏　名　RAJAT

審査委員　　主査　准教授　Ram Avtar
　　　　　　副査　教授　露崎　史朗
　　　　　　副査　教授　渡邉　悌二
　　　　　　副査　教授　根岸　淳二郎
　　　　　　副査　准教授　石川　守

学 位 論 文 題 名

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 cover approximately 31% of Earth's land surface and provide crucial ecosystem services, including climate regulation, nutrient cycling, biodiversity support, and cultural and aesthetic benefits. However, human activities have led to significant deforestation, converting vast forest areas into other land uses, while the remaining forests face degradation from overgrazing and logging. Together, deforestation and forest degradation contribute approximately 17% of global carbon emissions, underscoring the urgency of implementing effective mitigation strategies. Advancements in remote sensing technologies with the availability of multi spatio-temporal data have enhanced the ability to monitor forests and their biophysical parameters at a large scale. Optical remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS), Landsat, and Sentinel satellites have been instrumental in estimating forest biomass. However, current monitoring systems rely on cloud-free imagery and cannot penetrate the dense canopy of the tropical forest, limiting their utility in tropical regions. Assessing forest degradation remains challenging in tropical forests due to its complex and dynamic nature. Synthetic aperture radar (SAR) has emerged as a complementary tool to optical sensors, with the ability to provide cloud-free data and sensitivity to vegetation's structural, geometric, and dielectric properties. Thus, SAR data can be used to track forest changes under diverse environmental conditions.

This thesis introduces an algorithm for estimating forest above-ground biomass (AGB) using L-band fully polarimetric SAR (PolSAR) data. The approach leverages seven-component scattering power decomposition (7SD) and random forest regression (RFR) for AGB estimation. Data from the ALOS-2/PALSAR-2 sensor were used to extract seven scattering powers, which served as inputs for the model. Field measurements validated the biomass estimates, with results from the Shivamogga forest site showing a root mean squared error (RMSE) of 21.94 Mg/ha and a relative RMSE of 19.46% which outperformed the existing model based on the SAR backscattering coefficient. This model was further tested in the Tundi forest area, yielding a relative RMSE of 22.9% during cross-validation. These findings demonstrate the utility of scattering powers derived from L-band PolSAR data for biomass estimation in tropical forests.

To improve estimation accuracy, this study further explored integrating multi-frequency SAR data and canopy height measurements. L-band data from ALOS-2/PALSAR-2 and C-band data from RADARSAT-2 were combined with canopy height data from the Global Ecosystem Dynamics Investigation (GEDI) mission. By leveraging the complementary characteristics of the SAR frequencies and the canopy height information provided by GEDI, the model achieved higher precision. The multi-sensor model was applied to the Shivamogga forest, where a random forest algorithm combined 7SD scattering powers and GEDI-derived height data. Validation against field measurements yielded an RMSE of 16.06 Mg/ha and a relative RMSE of 14.24%. These results highlight the advantages of multifrequency SAR scattering powers with forest height data to achieve more accurate biomass estimation.

While full PolSAR data provide valuable insights, their limited temporal resolution and spatial coverage prompted the development of a novel method for dual-polarization SAR (dual-PolSAR) data. This study developed a four-component scattering power decomposition (DP-4SD) method, which uses a covariance matrix composed of four independent parameters. Tested on dual-PolSAR data from the Haldwani forest and San Francisco, the model demonstrated classification accuracy of 85.69% and 93.66%, respectively. It showed fewer unclassified samples compared to existing models, improving the interpretation of polarimetric information for land-use and land-cover mapping. The DP-4SD model was further adapted for forest monitoring by developing a Forest Disturbance Index (FDI). FDI effectively captured biomass dynamics in highly disturbed forest areas, validated by an RMSE of 21.844 Mg/ha and a relative RMSE of 21.84%. These results underscore its potential for tracking forest health and monitoring disturbance trends in vulnerable regions.

The examination committee recognized that this thesis developed an algorithm to estimate the forest biomass using SAR data that can be extended for practical implications for forest monitoring and biomass estimation. By addressing challenges such as deforestation, forest degradation, and land-use change, this study contributes to sustainable forest management and climate change mitigation. This study also developed a novel dual pol 4SD decomposition technique to overcome the data availability challenges of the full PolSAR data. In addition, Mr. Rajat maintained a strong academic record throughout his Ph.D. studies and publications. Based on this evidence, the committee concluded that he is eligible for the degree of Doctor of Philosophy (Environmental Science).