Chapter 7

Conclusion, Summary and Future Work

7.1 Conclusion

The present study undertaken in this thesis explored the use of optical and microwave remote sensing methodologies in conjunction with data analysis to extract biophysical parameters related to vegetation and soil surface characteristics. Various satellites with multi-sensor capabilities in microwave and optical bands, such as Sentinel-1A and Sentinel-2, are thoroughly examined across different polarizations and spectral bands. The objective of this study is to develop resilient algorithms for the efficient monitoring of vegetation and soil moisture. The analysis of the effectiveness of these algorithms included a range of frequencies and polarizations in order to get a comprehensive understanding of the complex interaction processes between electromagnetic radiation (EMR) signals and diverse surface characteristics of the Earth. The influence of various factors on the backscattering response of Synthetic Aperture Radar (SAR) from different crops and soil moisture content has been observed. These factors include the frequency, polarization, and angle of incidence of the SAR system, as well as the growth stages of vegetation, canopy structure, leaf orientation, vegetation water content, dielectric constant, and soil surface properties. Consequently, the investigation of backscattering behavior has become a pivotal element in the precise examination of vegetation and soil properties. The successful assessment of the interaction between EM radiation signals and the Earth's surface requires the combination of both system characteristics and surface attributes in this modeling technique.

The objective of developing algorithms for vegetation and soil is to minimize the presence of unknown model parameters, hence addressing the complexity associated with inversion processes. Significant insights are obtained via the use of multi-sensor satellite data, microwave scattering algorithms, and machine learning techniques in the modeling of backscattering for the recovery of biophysical parameters and the evaluation of soil moisture.

7.2 Summary

A summary of the results and significant contributions outlined in the study undertaken and provided within this thesis is as follows:

In **Chapter 3**, the study focused on developing an LAI retrieval model for wheat crops using Sentinel-2 (S2) optical Top of Atmosphere (TOA) and Sentinel-1 SAR data. The Bayesian-based Gaussian Process Regression (GPR) algorithm was trained with S2 TOA bands and S1-derived DpRVI images to estimate LAI. Comparison with an ANN-based SNAP biophysical processor revealed that while SNAP-derived LAI correlated well with ground data, it slightly overestimated with higher error due to possible residual errors in BOA data from atmospheric correction. The TOA-GPR model showed better results with improved correlation and lower error compared to SNAP-derived LAI, while the S1-based DpRVI-GPR model demonstrated the most accurate LAI estimation among the three models. This study underscores the potential of machine learning approaches, particularly using SAR datasets, to overcome optical data contamination issues for retrieving biophysical parameters.

In **Chapter 4**, the study enhanced the traditional Water Cloud Model (WCM) for surface and vegetation mapping using C-band Sentinel-1 SAR data and in-situ measurements of LAI, soil moisture, and surface roughness. Novel modification to the traditional WCM was incorporated. The modified WCM (mWCM) incorporated a novel scaling constant and a new vegetation-soil interaction term to improve the backscattering coefficient's accuracy. Results showed mWCM outperformed the simplified WCM. The interaction term's significance varied with LAI; its impact increased notably above an LAI of 2.0 m^2m^{-2}. The modifications increased R^2 between estimated and observed backscattering coefficients, with improved LAI estimation. Reductions in RMSE are observed, particularly notable for VV polarization in soil moisture estimation. Cross-polarization data proved more sensitive to vegetation, while co-polarized data are influenced by surface properties.

In **Chapter 5**, the study introduced a novel approach for estimating LAI using dual-polarimetric SAR data, combining Freeman-Durden decomposition's volume power metrics with polarization degrees. This method notably improved LAI estimation, especially for systematically grown crops like wheat. Unlike traditional models relying on assumptions about vegetation elements' shape and size, the volume power metric offers precise vegetation structure details. It provides direct measures of volume scattering, reducing dependency on assumptions and enabling more accurate assessments of crucial vegetation properties. While this study emphasized volume decomposition, further enhancements in surface properties can be achieved by considering surface and double-scattering components. This approach holds promise for enhancing our grasp of vegetation dynamics, essential for agriculture, ecology, and forestry applications.

In **Chapter 6**, a novel method deriving the VH polarization backscattering coefficient for the IEM model aims to estimate LAI from SAR data (VV and VH polarization) and optical datasets. To merge LAI data from both sources, deep learning, PCA, and regression techniques were utilized. Results revealed the superior accuracy of the deep learning approach. The deep learning model quickly converged to an optimal solution, indicating promising performance. This approach holds the potential to enhance LAI estimation accuracy from SAR and optical data, benefiting applications like agriculture and forestry monitoring. Future research might explore other deep learning models and incorporate additional SAR and optical data sources for further accuracy improvements.

These findings underscore the importance of continued research and development in remote sensing methodologies to further refine the monitoring and assessment of agricultural landscapes and soil conditions for sustainable resource management and precision agriculture applications.

7.3 Major takeaways from the research

The research presented in this work demonstrates significant advancements in remote sensing methodologies and their applications in vegetation monitoring and biophysical parameter retrieval. Each chapter introduces novel techniques tailored to address specific challenges in remote sensing analysis. The third chapter explores the potential of GPR in LAI of wheat crops, highlighting its effectiveness in heterogeneous environments like India. The fourth chapter proposes a mWCM to enhance LAI and SM retrieval accuracy using Sentinel-1 data, achieving improved performance compared to traditional approaches. In the fifth paper, a new approach for vegetation monitoring using VP analysis with dual-polarimetric SAR data is introduced, showing enhanced sensitivity to vegetation scattering and more accurate LAI estimation. Finally, in sixth chapter, fusion approach is proposed to enhance the retrieval accuracy of biophysical parameters. Rigorous validation with ground truth measurements ensures the reliability of the proposed methodologies. These findings hold promise for operational applications in agriculture, environmental monitoring, and land management, contributing to the development of reliable tools for Earth observation and resource management. However, it's essential to address limitations such as data availability and method scalability to further enhance the applicability and impact of these methodologies in remote sensing research and applications.

7.4 Limitation

In this work, following potential limitations can be identified:

- **Sensor Capability:** Not all satellite sensors are equipped with quad-polarization capabilities. Quad-polarization data provide additional information on the scattering mechanisms of targets, which can enhance the accuracy of biophysical parameter retrievals and classification tasks.
- **Satellite-insitu Temporal Discrepancies:** Ground truth measurements are typically collected at specific points in time during field campaigns, while satellite data may cover larger temporal extents. Temporal discrepancies between ground observations and satellite overpasses can introduce uncertainties, particularly if the environmental conditions change between ground measurements and satellite acquisitions.
- **Assumption of Homogeneity:** There is an underlying assumption of homogeneous scattering properties within the study areas. This assumption might not fully account for spatial variations in vegetation structure, soil properties, and other environmental factors, potentially leading to inaccuracies in the retrieved biophysical parameters, especially in heterogeneous landscapes.
- **Model Calibration Uncertainties:** The calibration of model parameters using specific algorithms, such as non-linear least square regression, might introduce uncertainties. If the training dataset used for calibration is not representative of the full range of environmental conditions encountered in the study area, it could affect the accuracy of the retrieved parameters.

- **Reliance on Empirical Relationships:** The reliance on empirical relationships for estimating biophysical parameters, such as LAI, based on modified radar metrics might limit the generalizability of the results to different vegetation types and environmental conditions.
- **Ground Truth Measurement Accuracy:** The accuracy of ground truth measurements used for validation purposes could introduce uncertainties. If these measurements are not representative of the entire study area or if there are errors in the measurement techniques, it could impact the validation process and the overall reliability of the results.
- **Spatial Resolution Limitations:** Remote sensing data used in the studies might have limitations in spatial resolution, potentially affecting the ability to capture fine-scale heterogeneity within the study areas. This limitation could influence the accuracy of the derived biophysical parameters, especially in areas with complex land cover patterns.

Addressing these limitations and acknowledging their potential impacts on the study outcomes can enhance the credibility and robustness of the research findings.

7.5 Future work

The evolution of optical and microwave remote sensing satellites will emphasize advancements in both finer spatial and temporal resolutions. These developments will also entail the utilization of multidimensional sensors across airborne and space-borne platforms. A crucial area for progress lies in deepening our understanding of how scattering occurs within vegetation canopies and soil layers. This understanding forms the groundwork for building more sophisticated microwave scattering models and algorithms.

The forthcoming research efforts will be geared towards refining these algorithms to significantly improve the accuracy of monitoring and retrieving crucial variables related to vegetation growth and soil surface parameters. Specifically, the focus will be on exploring and developing advanced higher-order microwave scattering models and algorithms. This exploration aims to unravel the complexities of scattering mechanisms within vegetation and soil layers, ultimately enhancing the precision and trustworthiness of remote sensing methods for analyzing and monitoring vegetation growth variables and soil surface parameters.

List of Publication

Published

1. **Singh, S. K.**, Prasad, R., Srivastava, P. K., Yadav, S. A., Yadav, V. P., and Sharma, J., 2023, "Incorporation of first-order backscattered power in Water Cloud Model for improving the Leaf Area Index and Soil Moisture retrieval using dual-polarized Sentinel-1 SAR data.", ***Remote Sensing of Environment***, 296, p.113756.

2. **Singh, S. K.**, Prasad, R., Tiwari, V. and Srivastava, P.K., 2023. "An improved volume power approach to estimate LAI from optimized dual-polarized SAR decomposition.", ***International Journal of Remote Sensing***, 44(18), pp.5736-5754.

3. **Singh, S.K.**, Prasad, R., Yadav, V.P., Yadav, S.A., Sharma, J. and Srivastava, P.K., 2022. "Synergy of dual–polarimetric radar vegetation descriptor and Gaussian processes regression algorithm for estimation of leaf area index.", ***International Journal of Remote Sensing***, 43(19-24), pp.6921-6935.

4*. Yadav, S.A., Prasad, R., Yadav, V.P., Verma, B., **Singh, S.K.**, Sharma, J. and Srivastava, P.K., 2022, "Far-field bistatic scattering simulation for rice crop biophysical parameters retrieval using modified radiative transfer model at X-and C-band.", ***Remote Sensing of Environment***, 272, p.112959.

5*. Yadav, S.A., Prasad, R., Srivastava, P.K., **Singh, S.K.**, Sharma, J. and Khamrai, S., 2022. "Time-series polarimetric bistatic scattering decomposition using comprehensive modified first-order radiative transfer model at C-band for vegetative terrain and validation.", ***International Journal of Remote Sensing***, 43(19-24), pp.7161-7180.

6*. Sharma, J., Prasad, R., Srivastava, P.K., **Singh, S.K.**, Yadav, S.A. and Yadav, V.P., 2021, "Roughness characterization and disaggregation of coarse resolution SMAP soil moisture using single-channel algorithm," ***Journal of Applied Remote Sensing***, 15(1), p.014514.

Note* 4, 5, and 6 works are not part of this thesis.

Unpublished

6. **Singh, S.K.**, Prasad, R., Prajapati B. K., and Srivastava, P.K., 2023, "Fusion of optical and SAR data using three approaches for the estimation of LAI with modified Integral Equation model". ***(under reveiw)***

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