

PREFACE

Remote sensing is the science and technology for detecting and monitoring the physical characteristics of an objects at Earth surface by measuring its reflected/scattered and emitted electromagnetic radiation (EMR) typically from the space-borne or air-borne platform. The Earth observation (EO) remote sensing satellites sense the Earth features in optical, infrared and microwave regions, which are least influenced by the Earth's atmospheric constituents.

Optical remote sensing images are eventually affected by haze and cloud present in the atmosphere. Therefore, the optical satellite-based study of vegetation and soil monitoring are not fully applicable during entire phenological stages. Due to availability of various microwave sensors on-board satellites which are least affected by the atmospheric constituents and day-night acquisition capability, the researcher has been developing the methodology for accurate monitoring of Earth's surface features. Moreover, the optical and microwave remote sensing satellite data provide complementary information and the combined use, either time-series or at different times during the crop growth season, can improve the estimation of biophysical parameters.

The microwave backscattering response of growth parameters of different crops and soil moisture (M_v) depends on the frequency, polarization and incidence angle of the incident synthetic aperture radar (SAR) signal. Unlike the optical remote sensing on-board sensors, the sensitivity of microwave signal to target dielectric and geometric properties made the SAR satellite data more useful for crop and soil parameters monitoring even in the cloudy conditions. The σ^0 (dB) measurements of the crop canopy/soil surface at multiple incidence angle, different polarizations and various microwave bands (L -, C - and X - bands) provide

better understanding of the sensitivity of crop backscatters such as shape, size, orientation, density and dielectric on the canopy scattering. The aim of the present research work was to study the backscattering mechanism of EMR from the different layers of vegetation and soil interfaces and modelling the σ^0 (dB) for the retrieval of crop growth parameters and soil moisture at VV and VH polarizations. The ample research has been carried out to developed the robust semi-empirical, empirical and physical algorithms for monitoring of crop growth conditions and retrieval of their biophysical parameters. However, due to the complexity of backscattering responses over the vegetation and soil surfaces, further modification and development of new methodology are highly needed. In this thesis, the potential of dual-pol SAR data was investigated for the retrieval of crop biophysical parameter and soil moisture for multiple crops over multiple test sites with varying agronomic practices. However, the monitoring of crop phenology and its parameters based on field measurements are often expensive, prone to enormous errors, and are unable to provide the real-time, spatially explicit information or forecasting of vegetation health conditions. The EO satellite provides temporally, spatially and repetitively monitoring of Earth surface targets for most of the globe.

Up to now, various multi-sensor Earth observation satellite mission has been launched for monitoring of Earth targets with fine spatio-temporal resolution. The SAR satellite data like Sentinel - 1A (C - band), ALOS - 2 (L - band), RADARSAT - 2 (C - band) and TerraSAR (X- band) have been launched from various space agencies for more accurate mapping of Earth surface features. These data were used for the extraction of valuable information about the Earth features from space platform at different incidence angle with complementary optical satellite data (Sentinel - 2, Landsat - 8 and MODIS). The study of

backscattering mechanism of land surface observations, at various frequencies, different polarization and fine spatio-temporal resolution, is becoming a subject of growing interest due to its capability to acquire the multi-dimensional information about the land use and land cover as and when required. However, till now, the limited physical and higher orders studies of backscattering mechanism of vegetation/soils in synergetic way has been investigated based on vegetation descriptors computed from Red-edge indices and radar vegetation index coupled with SAR and optical satellite data.

The σ^0 (dB) depends upon the several SAR parameters (wavelength, polarization and incidence angle) and surface parameters (dielectric constant, surface roughness, structure and orientation). Therefore, the high order (zero order, first order and radiative transfer model) backscattering modelling and the inversion of these models are computationally complex and tedious task for the retrieval of crop biophysical parameters. Therefore, a robust and high order backscattered (including intermediate effect through vegetation-soil interfaces) algorithms and novel radar vegetation index are highly needed for more accurate estimation of the biophysical parameters at various growth stages of the vegetation. To overcome the complex computational task, the hybrid optimization and inversion techniques are being extensively used in scientific and engineering research. The hybrid inversion technique was included in multi target random forest regression (MTRFR) and Genetic algorithm (GA) algorithm to feed in look up table (LUT) for robustness of the inversion steps in modified water cloud model (MWCM) and modified soil scattering model (MSSM). However, the scale invariant vegetation fraction (f_{veg}) showed promising result to weightage the correct amount of backscattering echoes from the vegetation and soil targets. The f_{veg} and the developed dual polarimetric radar vegetation index (generated from scattering vector matrix

(C₂) in the modified vegetation and soil microwave scattering algorithms showed the remarkable potential for more accurate monitoring of vegetation and soil parameters using satellite data. The performance of the developed microwave backscattering algorithm and some dual polarimetric radar vegetation index was also evaluated by computing the statistical parameters like root mean square error (RMSE), Nash Sutcliffe efficiency (NSE), coefficient of determination (R^2) and bias between the observed and retrieved values of the biophysical parameters and soil moisture.

The organization of present thesis work is divided in the following parts –

In the present thesis, the modelling and monitoring of SAR backscattering responses (σ^0 (dB)) were carried out for the retrieval of biophysical parameter and soil moisture in the vegetative and non-vegetative cover field. The co-polarization (VV) and cross polarization (VH) Sentinel - 1A SAR (C - band) and optical (Landsat - 8, Sentinel - 2, PROBA - V and MODIS) satellite images were used in this research work. The modified models for vegetation and soil microwave scattering algorithms were developed for accurate mapping and retrieval of crop growth parameter (LAI) and soil parameter at fine spatio-temporal resolution using complementary information computed from optical satellite data (i.e. f_{veg}).

The **1st chapter** describes the introductory background of remote sensing techniques and brief review of some research work carried out for modelling and monitoring the crops/vegetation and soil surface parameters by the retrieval of biophysical, soil surface parameters using physical, empirical and semi-empirical algorithms with different computational techniques.

The **chapter 2nd** describes an experimental procedure for the computation of LAI, soil moisture, root mean square height (s) and correlation length (l) during in-situ measurements.

It was also discussed about the details computation of σ^0 (dB) from SAR and different spectral indices (NDVI and Red - Edge Indices) from optical satellite data. Furthermore, the backscattering mechanism from vegetation canopy, soil surfaces and intermediate effect (multiple scattering from vegetation and soil layers) was discussed.

In the **3rd chapter**, the Red-Edge vegetation descriptors computed from Sentinel - 2 was assessed in a modified water cloud model (MWCM) for forward modelling using Sentinel - 1A SAR satellite data. The soil geometrical model was incorporated for the computation of soil backscattering according to soil roughness and moisture conditions. The modified Beer's law was chosen for the development of vegetation descriptors using various optical indices. The Red-Edge normalized difference vegetation index (NDVI_{RE}) has a better vegetation descriptor in optical regions to simulate the backscattered with higher potential in the forward modelling. The lower value of computed root mean square error (RMSE), higher correlation (R^2) and better NSE between the SAR derived and simulated σ^0 (dB) values showed high potential of developed index for the forward modelling simulation from the vegetation and soil layers.

The **4th chapter** describes the retrieval of LAI of wheat crop using time-series Sentinel - 1 A and Sentinel - 2 satellite data at co-polarization (VV) and cross-polarization (VH) channels of EMR signal. The MWCM and WCM semi-empirical models were evaluated for the robustness of modified vegetation model. The optimized unknown model parameters were computed using hybrid non-linear least square optimization algorithm at 95 % confidence level using training data sets. After the calibration of the MWCM, the modelled σ^0 (dB) values were simulated at VV and VH channels. The results indicated high potential of developed MWCM to provide improvements in the simulated σ^0 (dB) than that of old

WCM at both polarizations. Moreover, the LUT based inversion algorithm was applied for the retrieval of LAI for wheat crop at VV and VH polarizations. The performance indices (R^2 , RMSE and bias) authenticated the potential of MWCM to retrieve the LAI of wheat crop successfully. The estimated values of LAI by MWCM were found to show better correlation than those values of LAI obtained by WCM at VV and VH polarizations. The MWCM provided a substantial tool for the retrieval of biophysical parameters for wheat and barley crops by combining the potential of SAR and optical data.

In the **5th chapter**, the modified synergetic backscattering model for vegetation (i.e. MWCM) and direct scattering model for soil (i.e. MSSM) were developed for the retrieval of LAI over wheat and barley crops using C - band (5.405 GHz) Sentinel - 1A images whereas scale invariant f_{veg} parameter was computed from the Landsat-8 data. The non-linear least square optimization (constrained with derivative Jacobian matrix) technique was established for the calibration of proposed methodology. The inverse modeling results indicated a high potential of the proposed modified synergetic algorithms to retrieve LAI more accurately at finer spatio-temporal resolutions than the older semi-empirical and empirical approaches. In the forward modeling, the simulated $\sigma^0(dB)$ at VV polarization of the synergetic algorithm was found better than that of VH polarization. However, the retrieval performance of LAI values for inverse modeling scheme indicated higher R^2 and lower RMSE relationship with in-situ measurements at VV channel than that of well-established on-board PROBA - V and MODIS LAI satellite products. Therefore, this synergetic form of MWCM and MSSM models may provide a new tool for the more accurate mapping of biophysical parameters by coupling the recent advances of SAR and optical satellite data from space platform. Moreover, due to the limitation and unavailability of fine

spatial and temporal resolution LAI satellite data product, this modified developed algorithm could be used as an alternative approach to estimate the LAI over agricultural fields for ongoing and future SAR satellites missions.

In the **6th Chapter**, the potential of C- band SAR and improved inversion algorithms has been investigated for the accurate mapping and estimation of soil moisture (M_v) in two type of regions (vegetative and sparse vegetative covered fields). The semi-empirical MWCM backscattering model was developed by incorporating f_{veg} and LAI as vegetation parameters for the retrieval and mapping of M_v . The f_{veg} were computed using Landsat-8 satellite data in the vegetated and sparse vegetated soil sample fields. After the calibration of the MWCM, the MTRFR inversion algorithm was used for the retrieval of M_v in the study regions -1 and -2 during all the temporal changes followed by LUT techniques. The MTRFR algorithm has more capability to reduce the outlier noise and required minimum hyper-parameters as compared to others inversion algorithms like iterative optimization (IO), ANN and SVM. Therefore, the MTRFR based inversion algorithm developed in present thesis provided the better inversion tool as compared to inversion techniques applied in recent past to MWCM for the estimation of M_v . The results and statistical evidence showed high potential of the developed semi-empirical MWCM and improved inversion process to retrieve and mapping the spatio-temporal patterns of M_v more accurately using time-series Sentinel - 1A SAR data, which may become more time continuous with the constellation of Sentinel - 1A and Sentinel - 1B satellites in the near future.

In the **7th Chapter**, new and more emerging techniques have been incorporated in the high order microwave backscattering algorithm for the crop mapping and monitoring using dual polarimetric radar vegetation index (DpRVI), polarimetric radar vegetation index

(PRVI) and radar vegetation index (RVI). The 2×2 covariance matrix (C_2) was generated from the dual polarimetric Sentinel - 1 A SAR and ALOS - 2 SAR satellite data. The eigen-decomposition method was adopted for computing the non-negative eigen values (λ_1 and λ_2) of C_2 matrix. The eigen values quantify the dominancy of scattering mechanism from first order (VV polarization of direct scattering with no multiple scattering) and second and higher-order scattering (VH polarization with two or more reflections). The developed algorithm was parameterized using high and more robust Genetic optimization algorithm technique (GOAT). The simulated results from the developed high order backscattering algorithm demonstrated better performance of DpRVI than PRVI and RVI as vegetation descriptor in the microwave scattering algorithm.

Finally, the **8th chapter** describes the conclusions and future prospective of the research work of the present thesis. We envisage that this research would be able to develop more robust operational algorithms to retrieve the crop and soil parameters from the space-borne and air-borne sensors more authentically than ever before. The developed synergetic algorithm coupled with C- band SAR and hybrid computational methods may add a new dimension to the enhance the inversion accuracy and biophysical parameter retrieval accuracy which could lead to the clear understanding of remote sensing application over crop land using near future sensors from the space platform. Conclusions drawn through this research work shall find tremendous application in agriculture monitoring, agrometeorology and various agricultural missions (specially in our Indian perspective). Also, the further research work shall be continuing to other dual polarimetric (HH and HV) ALOS - 2 satellite data and quad-polarimetric (HH, VV, HV and VH) RADARSAT - 2 satellite data. The high order covariance matrix (C_2 and C_4) would be generated for more accurate study of complex

scattering from Earth targets (i.e. vegetation and soil surfaces) and develop the novel radar vegetation index (NRVI) as a robust vegetation descriptor in microwave scattering algorithm using on board L -, C - and X - bands SAR satellite data.