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It is certified that the work contained in the thesis titled **"Scattering model for land bio-geophysical parameters retrieval and validation using multi-frequency bistatic scatterometer measurements"** by **Mr. Yadav Suraj Amarbahadur**, Roll Number **17171010**, has been carried out under my/our supervision, and this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of the **Doctor of Philosophy (Ph.D.)** in **Physics**.

Signature:

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Declaration

I, **Yadav Suraj Amarbahadur**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Prof. Rajendra Prasad** from July 2017 to June 2022 at the **Department of Physics**, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers whenever and wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any others' work, paragraphs, text, data, results, etc., reported in journals, books, magazines, dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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Signature of the Head of the Department

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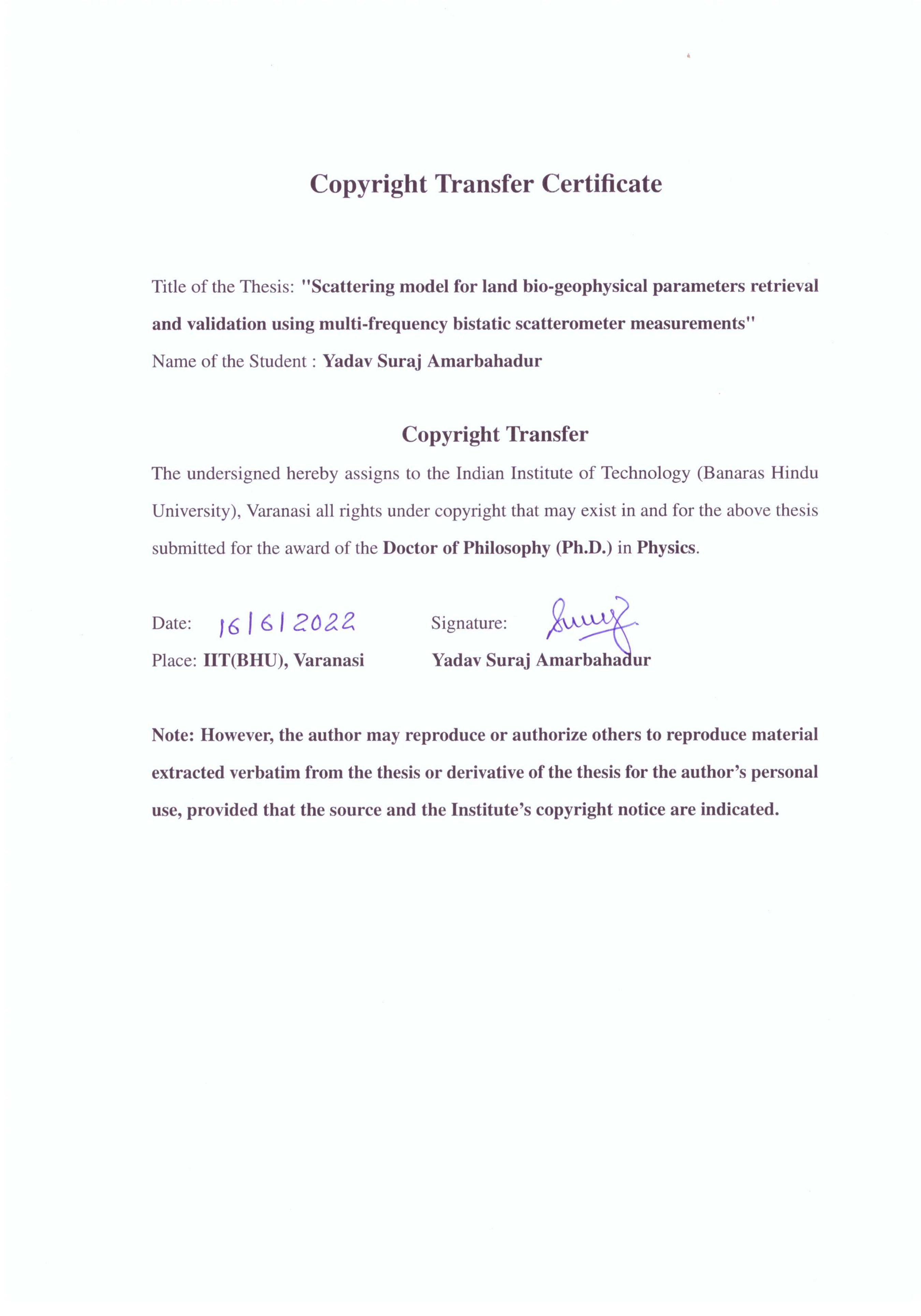

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Department of Physics, IIT (BHU) **Yadav Suraj Amarbahadur**

Abstract

The remote sensing phenomenon is based on the principle of getting information about the object without any physical contact. Remote sensing techniques for Earth observation have become a reality with the development of space-borne sensors. Microwave in remote sensing is widely promoted due to their ability to penetrate cloud, even the top layer of the soil surface, as well as provide day and night coverage of Earth features. The use of the microwave region of the electromagnetic spectrum in remote sensing has different capabilities that enhance remote sensing technologies utilized in other spectral regions. For instance, microwave interaction mechanism with different Earth surface features is usually governed by their structural (i.e., size, shape, orientation, and density) and physical (i.e., leaf area index, water content, biomass, soil moisture, and dielectric constant) properties.

In microwave remote sensing, the amount of energy scattered off the target is the key to understanding the target properties and is represented by the target scattering coefficient. In the last few decades, significant advancements have been made in developing theoretical microwave scattering models for interpreting experimental data and field measurements to validate the model. Our key research interests in bistatic radars for active remote sensing include the electromagnetic modeling, simulation, and data retrieval of vegetated fields and rough soil surfaces.

This thesis presents an optimization technique for an indigenously designed bistatic scatterometer system to interpret target scattering response and information retrieval of land bio-geophysical parameters. The theoretical microwave scattering model embedded with the geometric configuration of the bistatic scatterometer system, frequency, polarization, and physical properties of the target is developed and used to simulate the bistatic scattering coefficient of the target. The developed model is also utilized to interpret the experimental results and understand the interaction mechanism for microwave electromagnetic signals

with the complex targets, such as vegetated rough soil surfaces. The radiative transfer theory has been extensively used in the interpretation of the experimental data obtained from the vegetated rough soil surface at the ground altitude. The decomposition of the single and multiple scattering components utilizing the radiative transfer theory allows the interpretation of the dominant scattering component with respect to temporal change in the physical and structural properties of the target. For vegetative terrain, volume and multiple scattering play a crucial role at high frequencies of electromagnetic wave scattering. In addition, at low frequencies, the rough soil surface scattering plays an important role. The theoretical model emphasizes wave scattering from the rough surface when volume scattering is not considered. The parametric function and empirical relations are used to connect the scattering model with target parameters which facilitate efficient and accurate interpretation of the target information retrieval by inverting the model. The retrieval of the desired vegetation and land surface information helps to better understand the environmental dynamics at a local and global scale. Specifically, the possibility of bistatic radar for vegetation biophysical and soil moisture retrieval is explored using electromagnetic scattering models that give bistatic scattering simulations. The sophisticated electromagnetic scattering models are excellent for describing the complex scattering phenomenon based on physics, their structural properties, and mathematics, but it involves so many parameters that do not exist for each observed pixel for retrieval. Therefore, the inversion of these electromagnetic scattering models is computationally complex and tedious for desired target information retrieval. In the scientific field of remote sensing, machine learning approaches have also been employed to overcome the complexity of the electromagnetic scattering model. In our study, the potential of machine learning technique (i.e., support vector machine) is also evaluated for vegetation biophysical parameter retrievals.

The experimental findings presented in the thesis may be used as a reference to find the optimum parameters, such as incidence angle, polarization, and frequency, for

future advancements in the bistatic radar system to monitor vegetation/land scattering response more authentically ever before. The bistatic scattering simulation finding and retrieval of vegetation biophysical and land surface parameters utilizing the microwave scattering model have shown excellent potential for monitoring vegetation health and surface characteristics.

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Table of Contents

List of Figures

List of Tables

Nomenclature

List of Greek and Roman Symbols

λ	Wavelength
E	Energy
f	Frequency
GHz	Gigahertz (Unit of frequency)
c	Speed of light
$\hbar$	Reduced Planck's constant
μ	Micro
m	Meter
μm	Micrometer
mm	Millimeter
W	Watt
kg	Kilogram
K	Kelevin

T	Temperature
$^{\circ}C$	Degree celcius
σ	Stefan-boltzmann constant
λ_{max}	Wavelength of maximum spectral radiant exitance
$E_i(\lambda)$	Incident energy
$E_r(\lambda)$	Reflected energy
$E_t(\lambda)$	Transmitted energy
$E_a(\lambda)$	Absorbed energy
ρ_λ	Reflectance
α_λ	Absorptance
τ_λ	Transmittance
Δx	Horizontal spacing
Δz	Height spacing
$p(z)$	Probability density function
$z_i(x_i)$	Height profile at x_i values
$\rho(\zeta)$	Correlation function
$\hat{k}$	Wave vector direction
$\Delta\phi$	Phase difference
θ	Zenith angle

ϕ	Azimuth angle
η, ζ	Vegetation density
w	Scattering albedo
τ	Vegetation optical depth
σ_{pq}	Bistatic scattering coefficient at ‘pq’ polarization
$\hat{h}$	Horizontal polarization unit vectors
$\hat{v}$	Vertical polarization unit vectors
θ_i	Zenith incidence angle
ϕ_i	Azimuth incidence angle
θ_r	Reflected receiving angle
θ_s	Scattered receiving angle
ϕ_r	Reflected azimuth angle
ϕ_r	Reflected azimuth angle
P_p^i	p-Polarized power of incidence plane wave
P_q^s	q-Polarized power of spherically scattered wave
G_t/G_r	Gain of the transmitting/receiving horn antenna
G_{t0}/G_{r0}	Maximum gain of the transmitting/receiving antenna
L	Largest lateral dimension of the horn antenna
ρ_0	Reflectivity

Γ_{pq}, R_{pq}	Fresnels reflection coefficient
$P_q^s(std)$	Reflected power from a perfectly flat aluminum sheet
ϕ_{el}	Elevation beam-width of the horn antenna
ϕ_{az}	Azimuth beam-width of the horn antenna
R_i	Transmitter horn antenna range in specular direction
R_s	Receiver horn antenna range in specular direction
k_e	Extinction coefficients
k_a	Absorption coefficients
k_s	Scattering coefficients
I^i, I^-	Downwelling Intensity
I^r, I^+	Upwelling Intensity
h	Surface roughness parameter
γ^2	Two-way wave attenuation in the vegetative medium
R_c	Radius of curvature
f	Fields in the Kirchhoffs approximation
I	Ensemble average of scattered intensity
ε_m	Soil dielectric constant
$\varepsilon_m^{'}, \varepsilon'$	Real part of the soil dielctric constant
$\varepsilon_m^{''}, \varepsilon''$	Imaginary part of the soil dielctric constant

α	Shape factor
β	Texture factor
ρ_b	Bulk density
ρ_s	Particle density
ε_s	Solid soil matter dielctric constant
ε_{fw}	Free water dielctric constant
%	Percentage
x_i	Input features or training datasets
y_i	Observables
ξ_i, ξ_i^*	Slack variables
$\varepsilon, C, d, \gamma$	Hyper and kernel parameter of support vector regression algorithm

****

List of Abbreviations

NASA	National Aeronautics and Space Administration
SAR	Synthetic-Aperture Radars
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
HySIS	Hyperspectral Imaging Satellite
SLAR	Side-Looking Airborne Radar
ISAR	Inverse Synthetic-Aperture Radar
InSAR/IFSAR	Interferometric SAR
SRTM	Shuttle Radar Topography Mission
NSCAT	NASA Scatterometer
ASCAT	Advanced Scatterometer
SMAP	Soil Moisture Active Passive
SLR	Side-Looking Radar
SLAR	Side-Looking Airborne Radar
ESA	European Space Agency
GNSS-R	Global Navigation Satellite System- Reflectometry
IEM	Integral Equation Model
I2EM	Improved IEM
EMSL	Experimental Microwave Signature Laboratory

SPM	Small Perturbation Model
PO	Physical Optics
GO	Geometrical Optics
BRDF	Bidirectional Reflectance Distribution Function
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
PAD	Polarization Analogue and Digital
LAI	Leaf Area Index
PWC/VWC	Plant/Vegetation Water Content
FBm	Fresh Biomass
d or PH	Plant Height
N	Number of samples
m_v	Volumetric soil moisture
M	Amount of radiation emitted by object per surface area of black body in a unit time
A	Weins constant
RMS	Root Mean Square
s	RMS height
l	Surface correlation length

m	RMS slope
RTM	Radiative Transfer Model/Method
MRTM	Modified Radiative Transfer Model/Method
RTE	Radiative Transfer Equation
CCRS	Canada Centre for Remote Sensing
ComRAD	Combined RADar/RADiometer
UF-LARS	University of Florida L band Automated Radar System
UF-LMR	University of Florida L band Microwave Radiomete
BRCS	Bistatic Radar Cross-Cection
FSA	Forward Scattering Alignment
BSA	Back Scatter Alignment
RFOV	Radar Field Of View
UAVs	Unmanned Aerial Vehicles
GPS	Global Positioning System
DEM	Digital Elevation Model
VPF	Vegetation Phase Function
VOD	Vegetation Optical Depth
DAS	Days After Sowing
HG	Henyey-Greenstein

RMSE	Root Mean Square Error
R	Correlation coefficient
R^2	Squared Correlation coefficient
HH	Horizontal transmit - Horizontal receive
VV	Vertical transmit - Vertical receive
HV	Horizontal transmit - Vertical receive
VH	Vertical transmit - Horizontal receive
BiSCAT	Bistatic Scatterometer
$W_{Fresh\ veg}$	Weight of the fresh vegetation biomass
$W_{dry\ veg}$	Weight of the dry vegetation biomass
KA	Kirchhoff Approximation
DBA	Distorted Born Approximation
MIMICS	Michigan microwave Canopy Scattering
TOV	Tor Vergata
Bi-spec	Bistatic Specular
SVR	Support Vector Regression
CRMSE	Centered RMSE
SD	Standard Deviation

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