

Table of Contents

List of Figures	xxi
List of Tables	xxv
Nomenclature	xxvii
1 Introduction	1
1.1 Background of the remote sensing	1
1.2 Concepts and basis of remote sensing	3
1.2.1 Electromagnetic radiation principle	4
1.2.2 Energy interaction in the atmosphere	8
1.2.3 Energy interaction with Earth surface features	11
1.3 Microwave for remote sensing	12
1.4 Overview of microwave sensor	14
1.4.1 Space-borne radars	15
1.5 Motivation	16
1.6 Research objective	20
1.7 Thesis outline	21
2 Literature review and the state-of-the-art	23
2.1 The role of scattering model	23

2.2	A review of land observations and surface scattering model	24
2.2.1	Land parameters observation	24
2.2.2	Smooth-surface criteria	28
2.2.3	Surface-scattering model	30
2.3	A review on vegetation observations and the volume scattering model	33
2.3.1	Vegetation observations	33
2.3.2	Volume scattering model	34
2.4	Scatterometers	37
2.5	State-of-the-art	39
3	Bistatic radar scattering	43
3.1	Introduction	43
3.2	Scattering Coordinate System	43
3.2.1	Forward Scattering Alignment (FSA) convention	45
3.2.2	Back Scattering Alignment (BSA) convention	46
3.3	Bistatic radar equation	47
3.4	Advantages of bistatic radar system	50
4	Far-field bistatic scattering simulation for rice crop biophysical parameters retrieval using modified radiative transfer model at X and C bands	53
4.1	Introduction	53
4.2	Far-field bi-spec scatterometer system	57
4.3	In-situ measurements and data acquisition of σ_{pq}^0	58
4.4	Proposed methodology	60
4.4.1	Problem geometry and approximation	60
4.4.2	Parametric Bi-spec radiative transfer model (RTM)	61
4.4.3	Parametric description of VPF and BRDF	64

4.5	Empirical formulation of the parametric bi-spec RTM	65
4.5.1	MRTM algorithm Implementation	66
4.6	Results and Discussion	67
4.6.1	Assessment of in-situ biophysical parameters of the rice crop and measured σ_{pq}^0 using bi-spec scatterometer measurement	67
4.6.2	Parameters selection and inversion of MRTM	70
4.6.3	Analysis on specular scattering components contribution in the total value of σ^0	74
4.6.4	Retrieval of LAI and PWC	77
4.7	Conclusion and summary	79
5	Vegetated surface-scattering model for X and L bands with application to leaf area index and soil moisture retrieval and validation	83
5.1	Introduction	83
5.2	Bi-spec scatterometer system and in-situ measurements description	85
5.3	Methodology	87
5.3.1	Problem formulation	87
5.4	Results and discussion	90
5.4.1	Model parameterization and optimization technique	92
5.4.2	Assessments of the bistatic scattering model results	94
5.4.3	Model inversion for LAI and m_v retrieval	96
5.5	Conclusion	96
6	Fully polarimetric bistatic scattering measurements from vegetation and sim- ulation using modified first-order radiative transfer model at C band	99
6.1	Introduction	99
6.2	Experimental data collection methods	102

6.2.1	Technical information of the C band Bistatic scatterometer system	103
6.2.2	Vegetation and land surface parameter measurements	104
6.3	Methodology	105
6.3.1	First order modified radiative transfer model	105
6.3.2	Kirchhoffs model for rough soil surface bistatic scattering	107
6.3.3	Dobson model for relative soil dielectric constant	109
6.3.4	Vegetation scattering components	110
6.4	Results and discussion	112
6.4.1	Experimental assessment and optimization of the BiSCAT system	112
6.4.2	Model calibration/validation datasets generation and optimization	115
6.4.3	Simulation results	116
6.4.4	Model validation	118
6.5	Conclusion	119
7	Bistatic radar scatterometers for studying vegetation scattering response and its parameter retrieval: A machine-learning study	121
7.1	Introduction	121
7.2	Methodology	125
7.2.1	Ground-based measurement description	125
7.2.2	Bistatic specular (Bi-spec) scatterometer system	126
7.2.3	Calibration	127
7.3	Statistical analysis	128
7.3.1	Support vector regression model	128
7.3.2	Validation check and evaluation of the performance	129
7.4	Results and discussion	130
7.4.1	Analysis of bi-spec scattering response and optimal parameters selection	130

7.4.2	Input data, output data, and training/testing samples	137
7.4.3	Inversion result	137
7.5	Conclusion	140
8	Conclusion and Future prospects	145
8.1	Summary	145
8.2	Future prospects	148
	List of Publications	149
	References	151

List of Figures

1.1	The electromagnetic spectrum	4
1.2	The characteristics of electromagnetic wave	5
1.3	The spectral distribution of energy radiated from blackbodies of various temperatures	6
1.4	Spectral characteristics of (Top) Energy sources, (Middle) Atmospheric transmittance, and (Bottom) Remote sensing system	10
1.5	The fundamental interaction between electromagnetic radiation and an Earth surface features	11
1.6	The attenuating effect of clouds, rain, snow, and clean air on the transmission of radio waves between space and the Earth's surface	13
2.1	(a) Random height variations superimposed on a periodic surface; and (b) Random height variations superimposed on a flat surface	25
2.2	(a) Normal incidence and (b) Oblique incidence	28
3.1	(a) Monostatic radar system and (b) Bistatic radar system	44
3.2	FSA Convention	45
3.3	BSA Convention	46
3.4	Geometric configuration of the bistatic radar system	48
4.1	Indigenous design of far-field bi-spec scatterometer system.	57

4.2	Sampling field conditions at various phenological stages of rice.	59
4.3	Schematic illustration of bi-spec scattering measurement geometry.	61
4.4	Schematic workflow for the modified radiative transfer model-based vegetation biophysical parameters retrieval.	66
4.5	Temporal response of in-situ observations, namely d, LAI, and PWC of rice crop.	68
4.6	Temporal and multi-angular scattering response value of measured σ^0 at (a) HH and (b) VV Polarization for X band; (c) HH and (d) VV Polarization for C band.	69
4.7	The temporal variation of the parameter g.	71
4.8	Simulation results of MRTM using LAI at (a) HH and (b) VV Polarization for X band; (c) HH and (d) VV Polarization for C band.	74
4.9	Simulation result of MRTM using PWC at (a) HH and (b) VV Polarization for X band; (c) HH and (d) VV Polarization for C band.	75
4.10	LAI retrieval through presented MRTM using LAI at (a) HH and (b) VV Polarization for X band; (c) HH and (d) VV Polarization for C Band.	78
4.11	LAI retrieval through presented MRTM using PWC at (a) HH and (b) VV Polarization for X band; (c) HH and (d) VV Polarization for C Band.	79
5.1	The bistatic specular scatterometer system.	85
5.2	Temporal variation in the measured σ_{pq}^0 at HH and VV polarization for X and L bands.	90
5.3	(a) Temporal variation of insitu measurements; and (b) Computed ϵ' at different m_v values using the Dobson model for X and L bands.	91
5.4	Temporal variation of the optimized parameter ν	94
5.5	The simulation results at HH and VV polarization for X and L bands.	95
5.6	LAI and m_v retrieval results	96

6.1	Condition of different phenological stages of wheat crop during the BiS-CAT measurements.	104
6.2	Visualization of the zero and First-order bistatic scattering contributions .	111
6.3	(a)-(d) The temporal and multi-angular behavior of measured bistatic scattering coefficient curves at C band for HH, VV, HV and VH polarizations.	112
6.4	(a) The temporal variation of the insitu land bio-geophysical parameters; (b) Variation of soil dielectric constant(ϵ_m) with m_v	113
6.5	The simulated results of co-polarized $\sigma_{HH/VV}^0$ using PWC as an auxiliary dataset for C band	116
6.6	The Q:Q plot between simulated $\sigma_{HH/VV}^0$ using the optimized modified radiative transfer model and measured σ_{pq}^0	118
7.1	The temporal variation of vegetation growth parameters of the transplanted paddy field during in-situ measurements.	131
7.2	Visualization of major coherent scattering components for the bistatic case..	131
7.3	Temporal pattern of σ^0 at a various specular angle of incidence ranging from 20° to 60° for X band (a) HH polarization (b) VV polarization. . . .	132
7.4	Temporal pattern of σ^0 at a various specular angle of incidence ranging from 20° to 60° for C band (a) HH polarization (b) VV polarization. . . .	132
7.5	(a) Estimated values of LAI by the SVR model using different kernels and in-situ LAI for paddy crop at X and C bands, and (b) Visualization of error estimates for LAI estimation by the Taylor plot.	140
7.6	(a) Estimated value of PH by the SVR model using different kernels and in-situ PH for paddy crop at X and C band, and (b) Visualization of error estimates for PH estimation by the Taylor plot.	141

7.7 (a) Estimated values of FBm by the SVR model using different kernels and in-situ FBm for paddy crop at X and C bands and (b) Visualization of error estimates for FBm estimation using the Taylor plot. 141

7.8 (a) Estimated values of VWC by the SVR model using different kernels and in-situ VWC for paddy crop at X and C bands and (b) Visualization of error estimates for VWC estimation using the Taylor plot. 142

List of Tables

4.1	Technical information of the bi-spec scatterometer system.	58
4.2	The correlation coefficient between the value of σ^0 and vegetation parameters at X band.	69
4.3	The correlation coefficient between the value of σ^0 and vegetation parameters at C band.	70
4.4	The optimal numerical values of MRTM's parameters using constrained non-linear least-square algorithm.	73
5.1	Specification of the bistatic scatterometer system	87
5.2	Land surface parameters	88
5.3	Correlation analysis between 8 measured σ_{pq}^0 with LAI and m_v	92
5.4	Optimized model parameters at 40° specular incidence angle	93
6.1	Land surface parameters	109
6.2	Correlation analysis between 8-measured fully-polarimetric σ_{pq}^0 with PWC and m_v	115
6.3	Optimized model parameters	116
7.1	Specification of the bi-spec scatterometer system.	126
7.2	The statistical parameters used to evaluate the performance indices of the developed SVR model.	130

7.3	The correlation coefficient between the value of σ^0 and vegetation parameters at X band	136
7.4	The correlation coefficient between the value of σ^0 and vegetation parameters at C band	136
7.5	Optimized parameters of support vector regression model using linear, polynomial and radial kernel for vegetation parameter estimation at <i>X_VV_40</i>	137
7.6	Optimized parameters of support vector regression model using linear, polynomial and radial kernel for vegetation parameter estimation at <i>C_HH_40</i>	138

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
$^{\circ}\text{C}$	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}	Fresnel's 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 Kirchhoff's approximation
I	Ensemble average of scattered intensity
ϵ_m	Soil dielectric constant
ϵ'_m, ϵ'	Real part of the soil dielectric constant
ϵ''_m, ϵ''	Imaginary part of the soil dielectric constant

α	Shape factor
β	Texture factor
ρ_b	Bulk density
ρ_s	Particle density
ϵ_s	Solid soil matter dielectric constant
ϵ_{fw}	Free water dielectric constant
%	Percentage
x_i	Input features or training datasets
y_i	Observables
ξ_i, ξ_i^*	Slack variables
ϵ, C, d, γ	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
