Thesis title

Submitted in partial fulfillment of the requirements
of the degree of

Doctor of Philosophy

by

Student Name
(Roll No. 19XXXXXXX)

Supervisors:

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Centre of Studies in Resources Engineering
INDIAN INSTITUTE OF TECHNOLOGY BOMBAY
2019

Dedicated to my beloved parents.

Thesis Approval

This thesis entitled **Thesis title** by **Student Name** is approved for the degree of **Doctor of Philosophy**.

Examiners:

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Declaration

I declare that this written submission represents my ideas in my own words and where others ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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CERTIFICATE OF COURSE WORK

This is to certify that **Student Name** (Roll No. 19XXXXXXX) was admitted to the candidacy of Ph.D. degree on 16 July 2015, after successfully completing all the courses required for the Ph.D. programme. The details of the course work done are given below.

S.No	**Course Code**	**Course Name**	**Credits**
1	GNR 647	Microwave Remote Sensing	6
2	GNR 618	Remote Sensing and GIS Applications to Cryosphere	6
3	GNRS 01	Seminar	4
4	HS 699	Communication and Presentation Skills	PP
		Total Credits	**16**

IIT Bombay

Date: Dy. Registrar (Academic)

Abstract

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List of Abbreviations

AGU	Adaptive Generalized Unitary transformation
API	Application Programming Interface
BSC	Backscattering Coefficient
SAR	Synthetic Aperture Radar
CTD	Coherent Target Decomposition

List of Symbols

μ	Magnetic permeability
μ_0	Magnetic permeability of free space
ε	Relative complex dielectric constant
$\varepsilon^{'}$	Real part of dielectric constant
$\varepsilon^{''}$	Imaginary part of dielectric constant
ε_s	Snow surface dielectric constant
ε_v	Snowpack volume dielectric constant
κ_e	Volume extinction coefficient
κ_a	Absorption coefficient
κ_s	Scattering coefficient
δ_p	Penetration depth
δR	Slant range resolution of SAR data
δR_g	Ground range resolution of SAR data
$\mathbf{c}$	Speed of light
λ	Wavelength
τ	Pulse length of SAR signal
β	Bandwidth of the SAR signal
θ	Orientation angle
θ_i	Incidence or local incidence angle
θ_r	Local refractive angle
δA	Azimuth resolution of the SAR data

L	SAR antenna length
$\mathbf{E}(\mathbf{r},t)$	Electric field vector
$\mathbf{E^s_{pq}}$	Scattered field vector
$\rho(\mathbf{r},t)$	Volume density of free charges
$\mathbf{g_E}$	Stokes vector
g_0	Total power of the wave
g_1	Power in the linear horizontal or vertical polarized components
g_2	Power in the linearly polarized components at tilt angles ψ= 45° or 135°
g_3	Power in the left-handed and right-handed circular polarized component
$[\mathbf{J}]$	Jones matrix
$\boldsymbol{U_2}$	Unitary matrix (SU_2)
λ_1, λ_2	Non-negative real eigenvalues
A_W	Wave anisotropy
A_p	Particle anisotropy
H_W	Entropy
$[\mathbf{S}]$	2×2 Sinclair matrix
$\boldsymbol{k}$	3-D Pauli target vector
$\{\Psi_P\}$	Pauli spin matrix set
$\{\Psi_L\}$	Lexicographic matrix basis set
$\boldsymbol{\Omega}$	Lexicographic target vector
$[\mathbf{T}]$	3×3 Coherency matrix
$[\mathbf{C}]$	3×3 Covariance matrix
T^*	Matrix transpose with complex conjugation (superscript)
$\langle ... \rangle$	Spatial or temporal ensemble average
σ°	Backscattering coefficient
σ^0_{hh}	Backscattering coefficient of HH polarization

σ^0_{vv}	Backscattering coefficient of VV polarization
σ^0_{vvhh}	Correlation coefficient between VV and HH polarization
α_1	Dominant scattering magnitude
$[\mathbf{T_2}]$	2×2 coherency matrix
m_E	Effective DOP
$m_E^{\mathbf{opt}}$	Optimized AGU-Dop
p_{max}	Touzi optimum Dop (maximum)
p_{min}	Touzi optimum Dop (minimum)
$\chi_t^{\mathbf{opt}}$	Optimum polarization angles (ellipticity)
$\psi_t^{\mathbf{opt}}$	Optimum polarization angles (orientation)
s	RMS surface roughness

Chapter 1

Introduction

1.1 Background

Write some intro here. How to cite a figure. It is shown in Figure 1.1.

Snow is classified as wet or dry depending upon the amount of liquid water content. Dry snow consists of ice particles and air, whereas wet snow contains liquid water as a third component. Microwaves strongly respond to this change in liquid water content in snow (Hallikainen et al., 1986). The estimation of snowpack parameters requires a good understanding of the scattering mechanisms from the snowpack. Scattering from the air-snow surface and the uppermost layers are effective for wet snow estimation. The attenuation of a propagating EM wave is given in terms of the volume extinction coefficient (κ_e) and the penetration depth is defined as, $\delta_p = 1/\kappa_e$.

Figure 1.1: Test image include graphix.

1.2 Motivation

- SAR polarimetry is a very active research area in radar remote sensing in which there is an increased need to explore the potential for quantitative estimation of bio-/geo-physical parameters.

- Many works have reported the study of snow parameters using SAR data, among which very few studies barely attempted to retrieve any quantitative (for example snow wetness, snow density, snow grain size etc.) information.

- There is no proven precise methodology for the estimation of snowpack parameters using full polarimetric SAR data over the Indian Himalayan region.

- The data obtained from the new generation advanced full-polarimetric SAR sensors along with the advanced polarimetric decomposition techniques, provide an opportunity to develop improved algorithms for snow pack parameters estimation.

1.3 Research objectives

In this thesis, polarimetric SAR data is used for the estimation of snowpack parameters over the Indian Himalayan region. In this context algorithms have been developed for the estimation of snow wetness, snow surface dielectric constant and density,

1(a). Estimation of snow wetness from dual polarimetric $(\mathrm{HH}+\mathrm{VV})$ coherent X-band data.

1(b). Estimation of snow wetness from full polarimetric $(\mathrm{HH}+\mathrm{HV}+\mathrm{VH}+\mathrm{VV})$ SAR data.

1(c). Estimation of snow surface dielectric constant from full polarimetric $(\mathrm{HH}+\mathrm{HV}+\mathrm{VH}+\mathrm{VV})$ SAR data.

2. Estimation of snow density from full polarimetric $(\mathrm{HH}+\mathrm{HV}+\mathrm{VH}+\mathrm{VV})$ C-band SAR data.

These objectives are accomplished and implemented over the Indian Himalayan region for which data is acquired over the study area and field measurements were recorded during January to March 2012-2014. In the Indian Himalayan region, snowfall normally occurs during December to March from an altitude of 2000 m above the mean sea level. The expected snow wetness during Jan.– Feb. is around 2–6 % by volume because of fresh snowfall and average minimum temperature. The snow density variation mainly depends on the temperature which produces the snow melt-freeze cycle. In the Indian Himalayan region, the mean minimum temperature in the month of January is around -15°C-0°C and the mean maximum temperature in the month of June is around 20°C-30°C. The mean high and low temperatures in the month of February over the study area are around 11°C and -1°C respectively.

1.4 Thesis outline

The subject matter of the thesis is presented in the following five chapters,

- ✓ Chapter-1 gives an overview of the advantages of polarimetric SAR systems for snowpack parameters estimation. It also describes an outline of the snowpack parameters and their characteristics with respect to the electromagnetic waves, and also emphasizes the motivation of this research and objectives.

- ✓ Chapter-2 elucidates the principle and important parameters of a SAR system and the characteristics of snowpack parameters. Thorough investigations of snowpack characterization studies, PolSAR decomposition techniques and their advancements are included in this chapter.

- ✓ Chapter 3 describes all the new developments of methodologies for the estimation of snow parameters from available SAR systems in separate subsections. All the new developments are presented with detailed flowcharts and derivations. The detailed description about the study area, in-situ field data collection and the data sets used for this study are incorporated in this chapter.

- ✓ Chapter-4 discusses the results obtained from all the algorithms and are presented in separate subsections along with detailed investigations using topographic and observatory measurements. Multi-temporal analyses of the results is also included in this chapter.

- ✓ Chapter-5 highlights the new findings obtained by the utilization of SAR polarimetric data and conclusions arising out of this complete study are elucidated. The scope for future and continuation of this research work are also reported.

Chapter 2

Review of Literature

2.1 Introduction

In this Chapter, the emphasis of the discussion is on retrieval of snowpack parameters using spaceborne polarimetric SAR images. The principle and the imaging geometry of SAR system is described and a brief overview of the polarimetric SAR concepts are presented. A comprehensive exploration of all major factors affecting the SAR signal backscattered by the snow surface is discussed as available in the literature till date.

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Chapter 3

Development of Algorithms and Methodologies

In this chapter, all the new algorithms developed during the course of this work for the estimation of snow parameters from polarimetric SAR systems are explained. All the new methodologies are presented with detailed flowcharts and derivations. The detailed description about the study area, in-situ field data collection and the data sets used for this study are also incorporated in this chapter.

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Chapter 4

Results and Discussions

In this Chapter, the results obtained from all the algorithms are presented in separate sub-sections along with the detailed investigations using topographic and observatory measurements. Multi-temporal analyses of the results are also presented.

4.1 Snow wetness from dual polarimetric data

In this section, the results obtained from the proposed snow wetness estimation method for dual-polarimetric coherent (HH/VV) SAR data (*i.e.,* TerraSAR-X) Chapter 3 are presented.

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Chapter 5

Summary and Conclusions

In this thesis, the utilization of complete polarimetric SAR information for the estimation of snowpack parameters is described. Snow parameters in mountain areas are particularly sensitive to changes in environmental conditions. Timely gathering information about snow parameters and their temporal and spatial variability represents a significant contribution in climatology, local weather, avalanche forecasting and for the hydropower production in high mountainous areas. Conventional and ground-based methods represent only exact location measurements of field observations which may or may not be representative of a large area or basin. Due to the strong spatial and time-dependent dynamics of snow cover, frequent observation cycles are necessary. The sensitivity of microwave scattering to the characteristics of snowpack makes RADAR remote sensing a boon to understand a wide range of environmental issues related to the physical condition in high mountainous areas. Especially, the potential for retrieving snow parameters with a high spatial and/or temporal resolution corresponds to become an important input to snow avalanche forecasting, hydrological and meteorological modeling.

Synthetic aperture radar (SAR) imaging technology is one of the most important advances in space-borne radar remote sensing during recent decades. In the present investigation, dual- polarimetric (HH/VV) coherent TerraSAR-X (X-band) and full polarimetric Radarsat-2

(C-band) datasets have been used. Manali- Dhundhi region of Indian Himalaya is considered as a study area for this research work. Field data was collected synchronous with the satellite passes (Appendix-II). Snow parameters such as wetness, density, depth and snow permittivity have been measured using the snow fork instrument over the study area. Detailed analyses of Microwave interaction with snow covered terrain and different scattering mechanisms are described in **??**, in order to understand the physical characteristics of snowpack parameters.

In this thesis, four major algorithms were presented for the estimation of snow wetness, snow surface dielectric constant and snow density. The algorithms have been proposed and validated using polarimetric SAR data and near real time in-situ measurements. The methodologies have been clearly explained in Chapter 3 comprising of four separate sections. The results obtained from these approaches have been meticulously presented with detailed discussions in Chapter 4 pertaining to the corresponding sections.

- A new methodology for the estimation of snow wetness using dual- polarimetric (HH/VV) coherent high frequency (9.6 GHz) SAR data has been proposed.

- A new novel algorithm has been proposed to estimate snow wetness from full polarimetric SAR data. The proposed model was applied to Radarsat-2 fine resolution full-polarimetric data sets acquired over the Indian Himalayan region for three consecutive years.

- Snow surface dielectric constant estimation methodology from full-polarimetric SAR data is proposed. The dominant scattering type amplitude (α_{s1}) is used to characterize dominant snow.

- At final, a new methodology for snow density estimation from C-band full–polarimetric SAR data is proposed. The generalized volume parameter is derived from the double unitary transformation of the coherency matrix.

- These research works have been assimilated in the HimSAR software toolbox which is under development and expansion for the cryospheric applications using polarimetric SAR data. This toolbox will be helpful for the cryospheric scientific community to utilize, explore and contribute to the further development of this open source toolbox.

5.1 Contributions

During this course of research work, four major contributions were made in-terms of new algorithms development for the estimation of snowpack parameters.

- A new snow wetness estimation algorithm is developed for dual.
- A new novel algorithm has been developed to estimate snow wetness using full polarimetric SAR data.
- Snow surface dielectric constant estimation methodology has been developed for full-polarimetric SAR data.
- A new methodology for snow density estimation from C-band full–polarimetric SAR data is developed.

5.2 Scope for future research

- The proposed snowpack parameters estimation algorithm can be extended for multi frequency SAR data by considering all possible scattering mechanisms.
- Particularly for the estimation of snow density where the snowpack volume scattering has only been considered for the Radarsat-2 C-band data.

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Appendix A

HimSAR: A Snowpack Parameters Estimation Toolbox

A.1 Introduction

HimSAR (the word *hima* means snow in Sanskrit) is an endogenous snowpack parameters estimation and standalone toolbox containing the novel methodologies developed during this doctoral study. Apart from this it also contains the conventional SAR data processing algorithms and the widely used decomposition methodologies available in the literature. Moreover, it also contains algorithms for snowpack parameters estimation from single, dual and full- polarimetric SAR data.

A.2 Functionalities

Many pre and post-processing steps are included along with the snowpack parameter estimation algorithms in this HimSAR toolbox.

Appendix B

Snow Fork Measurements

Field campaigns were conducted to collect near-real time in-situ snowpack parameter measurements with the Radarsat-2 fine resolution quad polarimetric (FQ) data acquisitions using snow fork instrument. These measurements are listed with the corresponding GPS locations for consecutive three winter seasons from 2012 to 2014 in the month of February over the study area.

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List of Publications

International Journals

1. Bhattacharya. A, **Surendar. M**, 2016,"Enhanced Target Detection and Improved Scattering Power Decompositions Using the Optimized Coherency Matrix from Full-Polarimetric SAR Data ", *Geoscience and Remote Sensing Letters, IEEE*, (Under revision)

2. **Surendar. M**, Bhattacharya. A, Singh. G, Yamaguchi. Y, 2016,"Estimation of snow surface dielectric constant from polarimetric SAR data ", *Journal of Selected Topics in Applied Earth Observations and Remote Sensing, IEEE*, (Under revision)

3. Pandey. P, **Surendar. M**, Bhattacharya. A, Ramanathan. A.L, Singh. G, Venkataraman. G, 2015,"Qualitative and quantitative assessment of TanDEM-X DEM over western Himalayan glaciated terrain ", *Geocarto International*, (In Press)

International Conferences

1. Banerjee, B, De. S, **Surendar. M**, Bhattacharya, A, 2016 "An Unsupervised hidden markov random field based segmentation of polarimetric SAR images", *Geoscience and Remote Sensing Symposium (IGARSS), IEEE International*, (submitted)

2. Deo. R, **Surendar. M**, Rao. Y.S, Gedam. S.S, 2013 "Evaluation of interferometric SAR DEMs generated using TanDEM-X data", *Geoscience and Remote Sensing Symposium (IGARSS), IEEE International*, pp.2079-2082, 21-26 July 2013 doi:10.1109/IGARSS.2013.6723221.

3. **Surendar. M**, Bhattacharya. A, Singh. G, Venkataraman. G, Bharathi, P.A, 2013 "Snow wetness estimation from polarimetric SAR image", *Progress In Electromagnetics Re-*

search Symposium (PIERS), Stockholm, Sweden, Aug. 12-15, 2013, pp.678-682.

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Acknowledgments

I wish to record a deep sense of gratitude to **Prof. ..**, my supervisor for his valuable guidance and constant support at all stages of my Ph.D study and related research.