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Radar Remote Sensing for Crop Biophysical Parameter Estimation

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Foreword

It is a tremendous honor to have the opportunity to introduce this book, "Radar Remote Sensing for Crop Biophysical Parameter Estimation". As a research scientist with the Government of Canada, I have been passionate about advancing the use of Synthetic Aperture Radar (SAR) for agriculture monitoring because I strongly believe in the power of this technology. The growth of the world's population is accelerating at a time of increasing climatic uncertainty and among mounting calls for environmental stewardship. Measuring the current status of our agricultural landscapes, and monitoring how we are managing our agro-ecosystems, is an imperative. Crop production is under increasing pressures to feed the growing global population. Although there is no single solution, space-based imagery provides science-based data to monitor and respond to risks to agriculture, to manage landscapes, and to quantify crop production.

It has been 30 years since the European Space Agency launched the ERS-1 satellite. In the subsequent decades, efforts have accelerated to develop methods to exploit space-based SAR imagery to monitor agriculture. The SAR satellites of today are engineering marvels. Imaging modes are more sophisticated, with acquisition options to acquire data not only in single and dual polarizations but also in Fully Polarimetric (FP) and Compact Polarimetric (CP) configurations. In addition to these advancements in polarimetry, users of these space-based SAR satellites are able to see the Earth at incredible spatial detail and over large geographical extents. Such advanced sensors offer an extraordinary opportunity to monitor our changing landscapes. It is not simply the ability of microwave frequencies to observe the Earth regardless of cloud cover that draws users to SAR data for landscape monitoring. It is also a very unique way in which microwaves see vegetation and monitor crop growth. These remarkable advancements in SAR engineering have challenged researchers to find ways to exploit the full capability of these advanced SAR modes. Years of research have been convincing. SAR sensors have a vital role to play in monitoring soils and crops and in quantifying crop production. We are truly in the era of SAR.

This book is an impressive monograph complied by Dr. Mandal, Dr. Bhattacharya, and Dr. Rao from the Microwave Remote Sensing Lab, IIT Bombay (India). The authors unite the technical and practical aspects of SAR in the context of agriculture. The initial book chapters lead readers through the development and evaluation of physical and semi-empirical models of interest in characterizing scattering from vegetation. The theory behind radar scattering is incredibly important to comprehend for researchers tasked with developing new SAR methods for biophysical retrieval. Next, the authors provide a thorough accounting of advanced methods to retrieve indicators of crop productivity, from advanced SAR imaging modes. These include detailed descriptions of state-of-the-art methods to derive radar vegetation indices. Of additional importance, the authors assess methods to invert radar indices to estimate biophysical crop parameters, a practical consideration for wide area monitoring. These methods can be applied to retrieve leaf area index, plant area index and above-ground biomass, essential indicators of crop development, health, and productivity. In the spirit of open science, the authors include program codes of theoretical and semi-empirical models, calibration and inversion approaches, and radar vegetation indices. These codes will facilitate comparative analysis of these modeling approaches over diverse cropping systems and will strengthen the robustness of algorithms by the open science community. Most importantly, this openness will promote uptake of SAR-based approaches to monitor crops.

The Microwave Remote Sensing Lab, IIT Bombay, is a leader in the modeling of radar scattering for land monitoring. I have had the pleasure to collaborate with this exceptional team over the years, as they continue to make significant contributions to SAR science. Dr. Mandal, Dr. Bhattacharya, and Dr. Rao couple a review of scattering theory with discussions on scattering models to estimate crop condition and provision of algorithm codes. Given the scientific strength of this team and the breadth of the topics covered, this is a must-read book for anyone interested in learning how to apply SAR technologies to the challenges facing agriculture.

Ottawa, Canada
March 2021

Dr. Heather McNairn
Agriculture and Agri-Food Canada

Preface

Synthetic Aperture Radar (SAR) has been used in a wide range of applications. It has become increasingly popular due to its many advantages, such as capturing data day or night and seeing through clouds. SAR data has become vital for crop growth monitoring and agricultural inventory mapping. It is widely used in agricultural research to model vegetation and its associated scattering, followed by biophysical parameter estimation. Furthermore, it is gaining attention due to the availability of increased SAR satellites and the rapid expansion of the constellations of satellites. The connection between the sensitivity of microwave signals with crop biophysical parameters has led to numerous significant efforts devoted to the investigation of models for Electromagnetic (EM) wave interactions with crop canopies. In addition, Earth Observation (EO) data analytics for agricultural applications has established itself as an independent domain of research over several decades, with numerous renowned organizations, international consortia, and institutions focusing on utilizing and promoting these data sets.

Crop biophysical parameters such as foliar area (photosynthetically active components) and plant biomass are of particular interest for crop condition monitoring and production forecasts. Estimating bio- and geophysical parameters from EO data is imperative for developing applications on crop growth monitoring. Assimilating time series of SAR data-derived biophysical variables into agricultural monitoring frameworks could improve yield estimation. Unlike the optical remote sensing sensors, the sensitivity of microwaves to target dielectric and geometrical properties made the radar data useful for crop monitoring even in cloudy conditions. It leads us to identify critical, delicate links between crop biophysical parameter estimation and their operational scalability.

Among several studies carried out to retrieve these biophysical parameters from SAR data, the semi-empirical Water Cloud Model (WCM) has been extensively utilized to estimate these crop descriptors. Recognizing the ill-posed nature of such inversion strategies with the traditional approaches (viz., Iterative optimization—IO and Look-Up Table—LUT search techniques) for applications to large areas, the present research aims at developing a set of methodologies for crop biophysical parameter estimation using polarimetric SAR observables at various modes, e.g., dual-pol (VV-VH, HH-HV), quad-pol (HH-HV-VV), and compact-pol (RH-RV). Notably, estimating vegetation parameters from dual- and compact-pol SAR systems holds significant interest from an operational perspective for agricultural applications based on time series of satellite data. These could be globally obtained from multiple SAR satellites considering the rapid expansion of constellations of satellites such as Sentinel-1 A/B, Canadian RADARSAT Constellation Mission (RCM), SAOCOM (SAtélite Argentino de Observación COn Microondas), and the upcoming NASA-ISRO SAR (NISAR) mission.

The majority of our present research applies field experiments to test insights from SAR observations. These investigations are in the context of crop mapping and monitoring. The advancements of several research techniques and their applicability to agriculture using SAR remote sensing data sets are organized in several chapters. In addition, the research aims to find the best inversion approaches, which were investigated in a cross-site experiment setting through the Joint Experiment for Crop Assessment and Monitoring (JECAM) SAR inter-comparison experiment. In this approach, the potential of full-, compact-, and dual-pol SAR data for retrieval of crop biophysical parameters are investigated for multiple crops over different test sites with varying agronomic practices.

Another focus is drawn towards radar vegetation indices, which are gaining importance due to their immense capability as Analysis Ready Data (ARD) products. Similar to spectral indices (e.g., NDVI, EVI, etc.) that are well established in optical remote sensing, a vegetation index derived from SAR data is essential for crop growth monitoring. These radar-derived vegetation indices must be explainable to non-radar experts. They should be bounded within specific ranges to help discriminate between low and high vegetative conditions easily. This monograph presents innovative radar vegetation indices developed by utilizing advanced polarimetric scattering models for distinct acquisition modes (i.e., full-, dual-, and compact-pol). We propose three indices, namely the Generalized Radar Vegetation Index (GRVI), the Compact-pol Radar Vegetation Index (CpRVI), and the Dual-pol radar vegetation index (DpRVI). These indices are assessed across diverse cropping systems in several regions worldwide for crop condition monitoring, particularly the Copernicus Sentinel-1, the Canadian Radarsat Constellation Mission, and the upcoming NISAR L-band SAR system. The chapters primarily concentrate on developing practical, spatio-temporal crop development products to support downstream applications while considering the potential and scope of these new approaches. These would help users analyze EO products to understand crop dynamics, develop crop production risk assessment applications and inventory mapping, and validate them over diverse agricultural landscapes.

The book addresses a reasonably broad audience in EO, Remote Sensing, and Geoscience community. It will help graduate and postgraduate students recognize the importance of microwave remote sensing, remote sensing of vegetation, and geophysical parameter inversion techniques. It will also assist as a reference book for researchers and physical scientists working in radar remote sensing for agricultural crop mapping and monitoring and translating research into operation. We have made all program codes, simulation studies, and test sample data available for further research to benefit such researchers and the user community. The familiarity of the readers with EM wave theory, radar polarimetry, scattering physics, and crop phenology would help better appreciate the monograph. We shall be delighted to receive comments and suggestions from the readers.

Mumbai, India
May 2021

Dipankar Mandal
Avik Bhattacharya
Yalamanchili Subrahmanyeswara Rao

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This research monograph is the outcome of the activities primarily led by the first author since 2015 as a part of his doctoral research at the Microwave Remote Sensing Lab (MRSLab), Centre of Studies in Resources Engineering (CSRE), Indian Institute of Technology Bombay (IIT Bombay). The authors sincerely thank CSRE, IIT Bombay, for providing the necessary facilities to carry out all the research activities. All the authors are thankful to Dr. Juan M. Lopez-Sanchez, University of Alicante Spain, and Dr. Heather McNairn, Agriculture and Agri-Food Canada (AAFC), for numerous insightful conversations at all phases of research which contributed to the development of the contents for several chapters of this monograph.

We are thankful to various funding agencies, especially the Ministry of Education (formerly the Ministry of Human Resource Development—MHRD), the Government of India, the Shastri Indo-Canadian Institute (SICI), and the GEO-Amazon AWS Cloud Credit program. Dr. Dipankar Madal wants to acknowledge SICI for bestowing him with the prestigious Shastri Research Student Fellowship (SRSF) 2018–2019, which allowed him to accomplish a particular portion of the research work as a visiting researcher at Agriculture and Agri-Food Canada (AAFC) and Carleton University, Ottawa, Canada.

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Quite a few figures and tables in the monograph have appeared in some of our publications in several peer-reviewed articles. We are thankful to Elsevier, Taylor and Francis, and IEEE for permitting us to reuse the same. We offer our most sincere gratitude to the long-temporal in situ data collection team members from MRSLab, Bidhan Chandra Krishi Viswavidyalaya, and Andhra Pradesh Space Application Centre (APSAC) over several Indian test sites. We are grateful to ESA and associates for providing the PolSARPro and SNAP Toolbox for the preprocessing of SAR data sets. The authors want to thank Mr. Divya Sekar Vaka, MRSLab, for his generous support and suggestions in SNAP graphs processing and many command-line codes. Several friends and colleagues, including Dr. Vineet Kumar, Mr. Narayana Rao Bhogapurapu, Mr. Divya Sekar Vaka, Mr. Subhankar Mandal, to name a few, have been kind enough to provide their quality time and energy to assist in the preparation of this monograph.

This monograph would not have been conceivable without the endless support and encouragement of our beloved family members.

Contents

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Dr. Dipankar Mandal received his B.Tech. degree in agricultural engineering from Bidhan Chandra Krishi Viswavidyalaya, India, in 2015, and M.Tech + Ph.D. dual degree in Geoinformatics and Natural Resources Engineering from the Indian Institute of Technology (IIT) Bombay, Mumbai, India, in 2020. He was a visiting researcher with the Agriculture and Agri-Food Canada (AAFC), Ottawa, Canada, and Carleton University, Ottawa, from October 2018 to February 2019. As a visiting researcher, he contributed to the Synthetic Aperture Radar (SAR) Intercomparison experiment for crop biophysical parameter estimation within the Joint Experiment for Crop Assessment and Monitoring (JECAM) network of GEO Global Agricultural Monitoring. His research interests include applications of SAR polarimetry for crop classification, vegetation biophysical parameter estimation, deriving radar vegetation indices and yield forecasting. Dr. Mandal was a recipient of the Shastri Research Student Fellowship 2018–2019 Award by the Shastri Indo-Canadian Institute, India.

Dr. Avik Bhattacharya received his integrated M.Sc. degree in Mathematics from the Indian Institute of Technology (IIT) Kharagpur, India, in 2000, and a Ph.D. degree in remote sensing image processing and analysis from Télécom ParisTech, Paris, France, and the Ariana Research Group, Institut National de Recherche en Informatique et en Automatique (INRIA), France, in 2007. He is currently a professor with the Centre of Studies in Resources Engineering, Indian Institute of Technology Bombay, India. Before joining IIT Bombay, he was a Canadian Government Research Fellow with the Canadian Centre for Remote Sensing (CCRS) in Canada. His current research interests include SAR polarimetry, statistical analysis of polarimetric SAR images, radar remote sensing applications in agriculture, cryosphere, urban and planetary studies. Dr. Bhattacharya was a recipient of the Natural Sciences and Engineering Research Council of Canada visiting Scientist Fellowship with the Canadian national laboratories from 2008 to 2011. He is the Editor-in-Chief of IEEE Geoscience and Remote Sensing Letters (GRSL).

Dr. Yalamanchili Subrahmanyeswara Rao received his M.Sc. degree in physics from Andhra University, Andhra Pradesh, India, in 1982, and the Ph.D. degree in passive microwave remote sensing of soil moisture from the Indian Institute of Technology (IIT) Bombay, India, in 1992. He joined the Centre of Studies Resources Engineering, IIT Bombay, in 1985, as a senior research assistant and then became a research scientist in 1999. During 2005–2009, he was a senior research scientist and then an associate professor from 2009 to 2014. He is currently continuing as a professor. He worked in passive and active microwave remote sensing for several applications, viz., soil moisture, vegetation dynamics, flood mapping and land use/land cover. He has participated in several space-borne campaigns to collect synchronous ground-truth data and has experience handling various datasets for several applications. His research interests include the application of polarimetry for geophysical parameter retrieval and SAR interferometry for digital elevation models and displacement map generation.

Chapter 1
Introduction

1.1 Background

Crop monitoring is crucial to understand its production at local and regional levels. Several countries have their operational management systems that monitor crops and forecast yields at national and regional scales (Baruth et al. 2008; Wu et al. 2014; Parihar and Oza 2006; Chipanshi et al. 2015). These systems operate within a season by collecting timely information on crop conditions, meteorological data, and related production presumptions. Satellite imagery can provide complementary synoptic details on spatial and temporal variations for crop growth and phenology stages. After decades of extensive research and development, optical remote sensing technology has led to well-established operational crop monitoring frameworks that are efficiently utilized for seasonal crop yield modeling. Crop biophysical parameters derived from optical remote sensing satellite data used in the operational monitoring framework are either vegetation parameters (e.g., Leaf Area Index (LAI), vegetation water content, chlorophyll concentration) or vegetation indices (Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), etc.).

Although optical remote sensing data has been successfully used in such an operational framework (e.g., MODIS vegetation products), these systems are restricted to data acquisition under clear sky conditions, which is seldom the case, mainly during the Indian subcontinent monsoon season. Cloud cover creates blind spots when monitoring crop phenological development. In this context, the Synthetic Aperture Radar (SAR) data are of significant interest for agricultural applications due to its ability to monitor crops under all weather conditions and the sensitivity of the microwave signal to the dielectric and geometrical properties of the target.

This versatility makes SAR technology a reliable option for space agencies to continually monitor land, coastal, and ocean environments. The SAR signal response is affected by crop canopy characteristics which vary during the phenological stages of

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the crop. Therefore, it is expected that SAR data can discriminate crop growth stages depending upon the sensitivity to several biophysical parameters (LAI, biomass, canopy height). Significant consideration has been provided to the application of SAR for agricultural monitoring due to the increased availability of data from satellite-based SAR systems operating at C-band (e.g., ERS-1/2, ENVISAT, RADARSAT-1 and -2, RISAT-1, Sentinel-1a, and -1b), L-band (e.g., ALOS and ALOS-2) and X-band (e.g., TerraSAR-X, etc.). However, direct SAR observables (i.e., backscatter coefficients) or any other derived parameters (e.g., scattering decomposition parameters Cloude and Pottier 1996) cannot be immediately utilized within the actual optically driven models at an operational level.

A reasonable step forward would be to derive vegetation metrics from SAR data similar to those derived from optical sensors (e.g., LAI or biomass). Then assimilating a time series of SAR data-derived biophysical variables into agricultural monitoring frameworks could improve yield estimates. A dense time-series SAR data could be collected from multiple SAR satellites, considering the rapid expansion of constellations of satellite missions, such as the Sentinel-1, SAOCOM, Canadian RADARSAT Constellation Mission (RCM) and the forthcoming NASA-ISRO SAR (NISAR), ROSE-L, and the commercial Capella X-SAR and ICEYE. The individual observation swaths of these sensors could be coordinated to provide wide-swath coverage, facilitating the generation of detailed crop inventories.

1.2 Motivation

SAR data has become crucial in the pursuit of diverse agricultural applications and has been mainly utilized for crop biophysical parameter estimation (Le Toan et al. 1997; Inoue et al. 2002; Chakraborty et al. 2005; Hosseini et al. 2015; Fieuzal and Baup 2016; Dave et al. 2017; Kumar et al. 2018; Chauhan et al. 2018). Besides, it is gaining considerable importance due to the availability of multiple SAR satellites and the rapid expansion of satellite constellations. The relationship between the sensitivity of microwave signal with crop biophysical parameters has led to substantial effort devoted to investigating physical models of SAR signal interaction with crop canopies.

In this context, a semi-empirical model, such as the Water Cloud Model (WCM) proposed by Attema and Ulaby (1978) has been widely used for agricultural applications (Prevot et al. 1993; Inoue et al. 2002; Dabrowska-Zielinska et al. 2007; Hosseini and McNairn 2017). It has been extensively used to retrieve vegetation parameters, given its relative simplicity to model and retrieve these parameters.

Simulation of these interactions with a complex canopy is quite challenging and has been improved in several studies by incorporating various realizations of canopy descriptors (Lievens and Verhoest 2011; Kweon and Oh 2015; Tao et al. 2016). In addition to simulation, model inversion could influence retrieval accuracy due to the ill-posed nature of the WCM inversion. Different combinations of LAI, biomass, and soil moisture can generate identical backscatter intensity leading to unstable and potentially inaccurate inversion performance. Similar simulation and inversion have been established for an operational scale using optical remote sensing data (Myneni et al. 2002; Baret et al. 2007; Verrelst et al. 2012). However, to date, little attention has been given to inversion approaches using SAR data-driven LAI estimates. Hence, there is an urgent need to explore the potential for estimating crop biophysical parameters using SAR data.

Several methods (e.g., iterative optimization, a Look-Up Table (LUT) search method, and regression-based approaches) have been used in various studies to overcome the ill-posed nature of the model inversion problem. However, there is no proven single best inversion approach to estimate biophysical parameters from vegetation models using full and dual polarimetric SAR data. Another critical aspect of such model inversion-based biophysical parameter estimation is the data volume and limited study with computation constraints. Due to the large data volume collected by new dual-pol SAR systems, exploration of processing chains for crop inventory map generation at a larger scale is limited. Moreover, the data obtained from the new generation dual- and compact-pol SAR sensors provide an opportunity to develop improved algorithms for radar vegetation indices to monitor crop conditions.

1.3 Key Objectives

The monograph features research directions to develop a set of methodologies for crop biophysical parameter estimation using polarimetric SAR observables across a wide range of crops combined with varied agricultural practices. The major objectives considered here are as follows:

- Revisiting physical, empirical, and semi-empirical models for scattering from vegetation and their evolution.
- Crop biophysical parameter retrieval using full- and dual-pol SAR data.
    - Investigation of inversion approaches for crop biophysical parameter estimation from WCM.
    - Joint estimation of crop biophysical parameters with multi-target inversion approaches.
    - Crop inventory mapping with dual-pol SAR data for operational scalability.
- Crop biophysical parameter retrieval using compact-pol SAR data.
    - Investigation of modified WCM and a novel PolSAR decomposition to estimate crop biophysical parameter from compact-pol SAR data.
- Quantitative assessment of the potential of novel radar vegetation indices for crop growth monitoring with full-, dual-, and compact-polarimetric SAR data.

1.4 Book Organization

The monograph is organized in the following eight chapters:

- This chapter provides an overview of the crop biophysical parameter retrieval from remote sensing context. It also emphasizes the motivation of this research and its objectives.
- Chapter 2 illustrates the principle and presents a few essential parameters for a SAR system. The concepts of SAR polarimetry, different polarimetric acquisition modes, and target decompositions are discussed concisely.
- Chapter 3 describes the characteristics of crop growth descriptors in the context of radar measurements. Thorough investigations of vegetation characterization studies, vegetation modeling, and inversion approaches and their advancements are reported in this chapter.
- In Chap. 4, the evolution of semi-empirical techniques starting from the dielectric slab model to the WCM and its modified versions are provided with their theoretical development. A section is dedicated to evaluating the theoretical aspect of WCM parameterization from several physical models. State-of-the-art inversion approaches are sequentially presented.
- In Chap. 5, the assessment of multi-target inversion approaches for the WCM are presented with sufficient validation data sets with full- and dual-pol SAR data. In a cross-site experiment strategy, the best inversion approaches are investigated. Also, the utility of cloud computing platforms to generate crop inventory maps is investigated.
- Chapter 6 describes the methodology for crop biophysical parameter estimation using compact-pol SAR data. The simulated RADARSAT Constellation Mission (RCM) data sets are utilized to estimate biophysical parameters, and a comparison study is presented versus existing approaches.
- Chapter 7 includes the methodologies involved in the proposed radar vegetation indices for full-, compact-, and dual-pol SAR systems. Detailed investigations are performed by temporal analysis of VIs using in situ measurements of crop biophysical parameters.
- In Chap. 8, the proposed methodologies and the discussions of results, including critical findings of these studies, are summarized. The future scopes of the research works are presented successively, following the conclusion based on substantial extracts and understanding of the subject of interest.

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Chapter 2
Basic Theory of Radar Polarimetry

2.1 SAR Imaging Principles

Synthetic Aperture Radar (SAR) is an active imaging system that transmits pulses in the microwave region of the electromagnetic spectrum and measures the backscatter signal from the objects. The objects (or targets) are then spatially resolved based on the time delay of the received pulses (Woodhouse 2005). SAR operates either on an airborne or spaceborne moving platform that looks sideways to determine targets unambiguously. Due to the side-looking geometry of SAR, it acquires a two-dimensional (2-D) image that contains both magnitude and phase information of the scattering from the target. The typical geometry of the radar imaging system is shown in Fig. 2.1.

In Fig. 2.1, it is shown that the radar moves with a velocity V_{sat} in the azimuth direction (y) at a height H km from the Earth surface. It transmits microwave pulses in the range direction (x) perpendicular to the azimuth direction, with an incidence angle θ_i. The area spreading from near slant range to far slant range represents the swath width W_s of an imaging mode. The swath width depends on the imaging mode. Several imaging modes, such as the ScanSAR, StripMap, Spotlight, and TopSAR, are utilized in various SAR systems (Slade 2018). For example, the Spotlight imaging mode acquires data with a high resolution over an area, while the ScanSAR mode covers a wide area with coarser resolution (Moreira et al. 2013). The spatial resolution of a SAR system is defined for both range and azimuth directions. The range resolution (R_r) is defined as Eq. (2.1).

$$R_r = \frac{c\tau_w}{2}, \tag{2.1}$$

where c is the velocity of the EM wave and τ_w is the pulse width of the transmitted signal. Please note that the factor $1/2$ is used since the pulse travels two-way, and the resolution is measured in distance units. To increase slant range resolution, linear frequency modulated signal, i.e., a chirp signal is transmitted instead of a simple pulse. So, the Eq. 2.1 can otherwise be expressed as Eq. 2.2.

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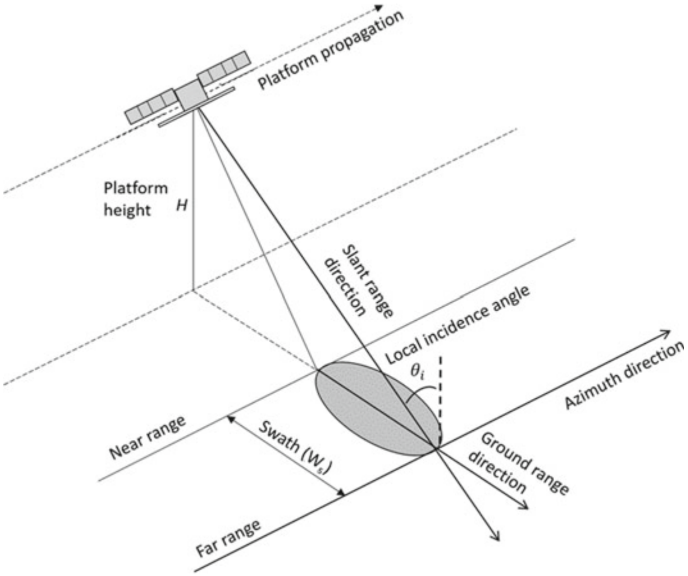

Fig. 2.1 Radar (real aperture) imaging geometry

$$R_r = \frac{c}{2B_p}, \tag{2.2}$$

where, B_p is the bandwidth of the transmitted signal. In Eq. (2.1), τ_w is replaced with $1/B_p$ as it provides an effective pulse length. From Eq. (2.2), it is apparent that larger bandwidth gives a better range resolution (Woodhouse 2005). However, the range resolution is defined in the radar slant range. This resolution is projected on the ground to determine the ground range resolution using the following relation given in Eq. (2.3),

$$R_{rg} = \frac{R_r}{\sin \theta_i}, \tag{2.3}$$

where R_{rg} is the ground range resolution and θ_i is the angle of incidence.

A large antenna array can be synthesized electronically, i.e., a synthetic aperture, with a narrow beam. It can be seen in Fig. 2.2 that with the constant motion of the radar platform, it transmits repetitive frequency modulated chirp signals at each point determined by the Pulse Repetition Frequency (PRF) and subsequently receives the return pluses. The radar signal is recorded at each point along the synthetic antenna (aperture) of length L_a.

For the synthetic antenna, the azimuth resolution (R_{az}) of a radar system is described as given in Eq. (2.4)

$$R_{az} = \frac{l_a}{2}, \tag{2.4}$$