CHAPTER 1
Introduction and Rationale

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ABSTRACT

This Synthetic Aperture Radar (SAR) handbook of applied methods for forest monitoring and biomass estimation has been developed by SERVIR in collaboration with SilvaCarbon to address pressing needs in the development of operational forest monitoring services. Despite the existence of SAR technology with all-weather capability for over 30 years, the applied use of this technology for operational purposes has proven difficult. This handbook seeks to provide understandable, easy-to-assimilate technical material to remote sensing specialists that may not have expertise on SAR but are interested in leveraging SAR technology in the forestry sector.

This introductory chapter explains the needs of regional stakeholders that initiated the development of this SAR handbook and the generation of applied training materials. It also explains the primary objectives of this handbook. To generate this applied content on a topic that is usually addressed from a research point of view, the authors followed a unique approach that involved the global SERVIR network. This process ensured that the content covered in this handbook actually addresses the needs of users attempting to apply cutting-edge scientific SAR processing and analysis methods. Intended users of this handbook include, but are not limited to forest and environmental managers and local scientists already working with satellite remote sensing datasets for forest monitoring.

1.1 Background

As highlighted by the Global Forest Observation Initiative (GFOI) in their Methods and Guidance Document (MGD) (GFOI 2017), SAR datasets have proven useful as a source of activity data for forest Monitoring, Reporting, and Verification (MRV) systems at national and regional levels. SAR datasets can provide substantial aid to MRV systems, particularly in areas with persistent cloud cover, due to the sensor's all-weather capability (Reich et al. 2016).

The MGD also highlights the potential of SAR datasets with higher spatial resolution (<5 m) to characterize forest canopy. SAR captures different target parameters than optical sensors, therefore providing unique information that complements standard optical remote sensing methods. A helpful analogy would be that while the energy captured by optical sensors of a green leaf relates to its amount of chlorophyll (or "greenness"), the amount of microwave energy (part of the electromagnetic spectrum used in SAR) scattered by the leaf would be proportional to its size, shape, and water content (Woodhouse 2006). SAR indeed has a strong sensitivity to forest structure and biomass (Saatchi 2015).

GFOI's MGD also documents the limitations of optical data such as Landsat and MODIS to estimate forest biomass and to detect early regrowth of secondary vegetation, including a limited ability to expose small disturbances such as removal of individual trees (GFOI 2017). The main premise and recommendation of GFOI's MGD is to combine both remote sensing technologies, optical and SAR. However, the main limitation faced over and over by users is how to start ingesting SAR when its assimilation and analysis is rather difficult, considered highly sophisticated, and previously limited only to experienced professionals.

To clearly define the need for SAR technology for forest monitoring systems, a needs assessment was carried out within the SERVIR global network. SERVIR is a joint initiative between NASA and the U.S. Agency for International Development (USAID) that fosters the use of Earth observations to assess environmental conditions to improve decision-making actions.

Then, in collaboration with SilvaCarbon, a plan was designed and implemented to effectively address needs and knowledge gaps of remote sensing specialists working in MRV systems to use SAR. SilvaCarbon is an interagency technical cooperation program of the U.S. government to enhance the capacity of selected tropical countries in measuring, monitoring, and reporting on carbon in their forests and other lands. In addition, SilvaCarbon is the U.S. primary contributor to GFOI, where their activities focus on capacity building.

1.2 Limitations and Opportunities of Applying SAR Technologies

Multiple research efforts investigate empirical relationships between SAR backscatter and biophysical forest properties, particularly aboveground biomass (Woodhouse 2006, Reich et al. 2016). Yet there are a number of limitations that are well summarized by GFOI's MGD in using SAR for biomass estimation:

- Depending on wavelength, rapid saturation of

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the signal at low aboveground biomass stock (~50–100 t C/ha) (Gibbs et al. 2007)
- Increased errors due to terrain
- Rainfall and soil moisture effects
- Localized algorithm development focused on a single biome or mono-species stands
- Lack of consistency in estimates as a function of sensor parameters

Of particular concern is the limited transferability of algorithms within and between different forest structural types (GFOI 2017). **Chapter 5** of this handbook addresses this particular topic in depth. Though these limitations may confine some applicability of SAR technology, this handbook addresses them effectively and provides users with practical information to facilitate the appropriate use of SAR data for accurate results. It explains state-of-the-art methods not only with theory but also with hands-on exercises.

The use of SAR datasets to accurately monitor processes of deforestation, land and forest degradation, and secondary forest regrowth (Hoekman & Quinonez 2000) has produced promising results that should not be overlooked. **Chapter 3** provides practical information on change detection and forest degradation analysis. All chapters provide key information that addresses the listed challenges in working with SAR data. Practical workflows are also included to provide SAR analysis tools specific for stated user needs and forest monitoring applications.

With publicly available C-band data from the Sentinel-1 mission (Malenovský et al. 2012, Berger et al. 2012) since 2014, the outlook of SAR operational use has changed significantly, and in the most promising way. This, in addition to the forthcoming availability of public L-band data from NISAR and TanDem-L, completely changes the game in terms of potential operational use of SAR datasets. Previously designated Research and Development (R&D) topics by GFOI (2013) now use SAR for forestry applications such as change detection within forest land, near-real time forest change indicators, and forest stratification.

This previous R&D has enabled current and operational use of SAR for these applications. This handbook strives to provide technical materials to facilitate these new resources into operational use.

1.2.1 FROM NEEDS TO PRACTICE

Though extremely useful and educational, the most complete literature available on SAR is constrained mainly to textbooks (Woodhouse 2006, Shimada 2018) and does not focus on an applied approach needed by technicians to start processing SAR datasets. In addition, there are a number of studies and peer-reviewed publications (Moreira et al. 2013, Hoekman & Quiriones 2000) that add to the wealth of knowledge, but also lack applied content that facilitates uptake of SAR technology. This handbook represents a comprehensive resource for using SAR datasets for forestry and biomass applications, and also augments recent efforts to generate reference documentation for interpreting SAR datasets (CEOS 2018), given its applied focus that includes processing workflows for specific forestry applications.

The content of this handbook has been driven by the needs of the community (see **Sec. 1.3**), and as such, is strongly focused on forest biomass estimation. However, it also covers a range of topics from basic preprocessing to change detection, including mangrove monitoring, Forest Stand Height (FSH), and sampling design for uncertainty estimation. Given that current state-of-the-art methods use SAR data for forest biomass estimation as well as the ongoing research on how to better understand forest backscatter signals (Brolly & Woodhouse 2012), this handbook clearly describes the limitations and advantages of using SAR for specific forest applications. It also conveys in practical and understandable terms the main considerations and concepts technical users should be aware of when analyzing SAR data. It is the authors' intent to generate applied knowledge by leveraging the wealth of research knowledge that has been gathered over the past 30 years.

SERVIR and SilvaCarbon are committed to strengthening the technical capacity of users working on forest monitoring applications, and as new SAR missions are launched and new technologies emerge, it becomes crucial to join efforts to achieve this goal.

1.3 Needs Assessment

1.3.1 WHO IS SERVIR?

SERVIR operates through established technical organizations (called hubs) with unique sets of capabilities, including political buy-in from member countries, technical expertise in remote sensing, geographic information systems, and database management, along with strong relationships with stakeholders. Science within SERVIR is coordinated through the Science Coordination Office (SCO) at NASA Marshall Space Flight Center. All SERVIR activities and projects are user-driven and involve stakeholders who play a key role in service development and uptake. SERVIR's network of hubs includes:

- Eastern and Southern Africa, with the regional hub at the Regional Center for Mapping of Resources for Development (RCMRD) in Nairobi, Kenya;
- Hindu-Kush Himalaya, with the regional hub at the International Center for Integrated Mountain Development (ICIMOD) in Kathmandu, Nepal;
- Lower Mekong River, with the regional hub at the Asian Disaster Preparedness Center (ADPC) in Bangkok, Thailand;
- West Africa with the regional hub at Centre Regional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle (AGRHYMET) in Niamey, Niger; and
- Amazonia, with the regional hub based at the International Center for Tropical Agriculture (CIAT) in Cali, Colombia. Because this is the newest hub in the SERVIR network and the agreement to start activities did not take effect until December 2018, it was not included in the development of this material.

SERVIR hubs are comprised of recognized experts in their respective regions for satellite remote sensing and have developed multiple applications related to SERVIR's thematic areas, including food security and agriculture, water and water-related disasters, weather and climate, and land cover/land use. Forest monitoring is one of the common threads among the services SERVIR hubs provide in the land cover/land use change thematic area. SERVIR's stakeholders have identified forest biomass estimation using remote sensing as a key need.

Measurements of forest biomass can advance the understanding of forests in the global carbon cycle (Pan et al. 2011). In addition, forest biomass estimates are useful to support the implementation of Reducing Emissions from Deforestation and forest Degradation

(REDD+) initiatives in different regions of the world.

Demand to enhance forest monitoring systems by incorporating additional satellite datasets and to derive forest biomass has increased due to newly available satellite datasets that incorporate SAR technology (De Sy et al. 2012). Currently, there are free and open historical archives (2006–2011) of the Advanced Land Observing Satellite-1 (ALOS-1) SAR datasets, and Sentinel-1 has been providing free and open SAR imagery since 2014. In addition, new forthcoming missions such as NISAR, Biomass, and TanDEM-L will also provide free and open SAR data.

The recent widespread availability of SAR data coupled with the need to overcome cloud cover in most SERVIR regions highlight the need for understanding how these new and free SAR satellite resources might be leveraged, especially in the context of open source and freely available software for land cover and use applications (Brovelli at al. 2018). **Figure 1.1** shows cloud coverage over the five SERVIR regions, including the most recent SERVIR-Amazonia hub.

The SilvaCarbon program provides targeted technical support to countries in the process of developing and implementing national forest and landscape monitoring systems. SilvaCarbon leverages state-of-the-art science and technology to advance the generation and use of improved information related to forest and terrestrial carbon. It is within this context that SERVIR and SilvaCarbon joined efforts to generate state-of-the-art technical materials that will make meaningful contributions to support these countries' efforts to measure, monitor, and report on carbon in their forests.

Although the potential of SAR data is well recognized, the current level of expertise in operational use of SAR data for LCLUC applications, forest mapping/monitoring, and (more specifically) biomass estimation is limited in SERVIR regions. This limitation not only applies to scientists in the SERVIR network, but is also observed worldwide (Reich et al. 2016).

SERVIR hubs have advanced expertise in using optical remote sensing for land cover mapping, which is reflected in the multiple LCLUC projects executed over the years (http://catalogue.servirglobal.net). SERVIR hubs and their partners have requested support to increase their capacities to process and analyze SAR data for forest monitoring and biomass estimation applications.

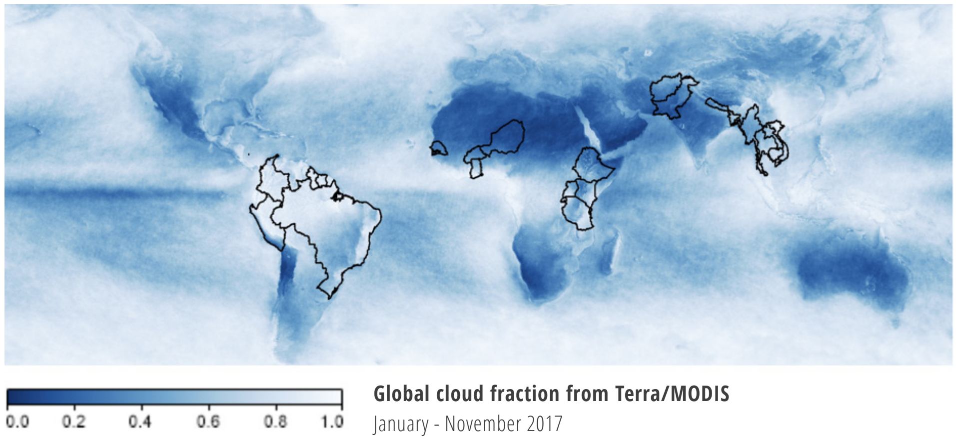

Figure 1.1 *Cloud coverage for year 2017 over SERVIR regions*

The SERVIR SCO performed a needs assessment across the SERVIR hubs to collect information on current capacity, main services, and requests on land cover/land use change applications. This needs assessment inspired an effort to work with SAR data for forest applications. The authors recognize that their focus in the SERVIR network does not represent a thorough global needs assessment; however, it likely provides a good representation of the needs facing remote sensing specialists around the globe in forest monitoring applications (**Table 1.1**).

In addition, due to the authors' collaboration with SilvaCarbon, the focus of this handbook is to contribute to and to be in alignment with their objectives, which include enhancing the capacity of countries for forest MRV systems. Through this collaboration, the authors aim to address user needs through the development of a distinctive product that could serve

SERVIR REGION & HUB	PRIMARY STAKEHOLDERS	CURRENT RS TECHNOLOGY USED FOR MRV SYSTEMS	RELEVANT SAR CAPABILITIES	POTENTIAL APPLICATIONS
West Africa AGHRYMET	Ghana Forestry Commission, University of Ghana	Monitoring permanent plots for AGHRYMET (GCCA Project, starting support for countries to establish national forest MRV systems	Matching ancillary data with the RS (SAR) within a pilot site, upscaling to cover all of the West African sub-region.	Integration of SAR to support MRV systems Estimation of forest biomass in West Africa
Eastern & Southern Africa RCMRD	Kenya Forest Service, Kenya Water Towers Agency, Kenya Marine and Fisheries Institute, Kenya REDD+, CIFOR, other agencies	Freely-available optical RS used; complicated by persistent cloud cover	Gain knowledge to start processing SAR data in general. This knowledge will go a long way in supporting the countries as well as in the provision of data that can be used by the relevant authorities in decision making.	Forest biomass estimation. Forest monitoring in cloudy regions Support for REDD+ MRV
Hindu Kush-Himalaya ICIMOD	FRTC - Nepal, DFPS - Bhutan	Optical RS Object-based image analysis Optical RS for MRV dev	Strength on capturing biomass estimates Gain knowledge to process SAR data and develop biomass estimation models	Forest biomass estimation to support national communications to UNFCCC for assessing carbon fluxes Accurate forest biomass estimation
Mekong ADPC	Forest Inventory and Planning Institute of Viet Nam	For Activity data: using medium resolution optical satellite images (Landsat and Sentinel 2) For Emission factors: using National systematic sample plots	Basic SAR processing (Sentinel 1) and application in mapping to recognized forest/ nonforest	Using SAR to improve volume-based estimation for forest quality, monitoring forest degradation Applied SAR for operation on forest change detection, forest plantation monitoring Forest biomass estimation

GCCA: Global Climate Change Alliance
FRTC: Forest Research and Training Centre
DFPS: Department of Forests and Park Services

Table 1.1 *List of needs to apply SAR technology in SERVIR regions as identified by each SERVIR Hub during the needs assessment process.*

to lower the barrier and create wise users of SAR technology. Therefore, building from that expertise, the authors have focused on capacity building.

Training SERVIR hubs and their partners on the use of SAR data will further strengthen their remote sensing capabilities. Researchers in the SERVIR network represent a link between national agencies, user groups and the global user/producer community, and NASA scientists; thus, we envision that engagement with SERVIR network researchers on SAR data capacity building and training activities will maximize benefits, in addition to complementing their current optical remote sensing methods with SAR methodologies.

1.4 Objectives

The main objective of this handbook is to provide practical guidance on the application of SAR technology for forest monitoring and biomass estimation. It addresses a gap that would otherwise exist on how to process SAR imagery for practical forest applications that can benefit from incorporating SAR technology. More specific objectives include:

- Disseminate practical knowledge on using SAR imagery for forest mapping/monitoring and biomass estimation
- Generate applied theoretical and hands-on materials that will enhance operational uptake of SAR technology for forest monitoring and biomass estimation
- Support SilvaCarbon objectives in developing good practices and approaches for using SAR data for MRV systems

1.5 SERVIR Approach

To meet the goals described above, SERVIR followed the next steps:

1. Scoping workshop with SAR experts and SERVIR user community
2. Define main topics for training and subsequent handbook
3. Recruit subject matter experts on SAR applications (SAR experts) to provide training and develop applied documentation
4. "Train the trainer" approach:
   - Generate descriptive training material using open source software
   - Hold sequential training events based on regional needs
   - Trainees repeat training at their centers
   - Review and update training materials per feedback collected at training events

Rather than creating another product—such as a local or regional biomass product for a given region that later becomes outdated and which nobody can replicate—the authors chose to develop a strong capacity building approach, enabling and strengthening technical capacities of users to create such a product. This entailed work with world-renowned SAR experts that are also the authors of individual chapters in this handbook. These experts also created training tutorials that are included in the appendices of this handbook and on the handbook webpage.

To identify the main technical topics this handbook addresses, the authors conducted a scoping meeting in February 2017, where SAR experts and technical experts on forest applications from SERVIR regions came together. This scoping meeting served to select topics for technical training that became the main topics addressed in this handbook. Hence, as portrayed in **Table 1.2**, the trainers of these international workshops are the authors of the main technical chapters in this handbook (**Chapters 2–7**). The content they cover in their chapters and training tutorials have been tested at hands-on workshops and reviewed by remote sensing specialists of the SERVIR global network and other SAR specialists to ensure functionality and usability.

Main deliverables include:

- **SAR Handbook of Applied Methods for Forest Monitoring and Biomass Estimation**—The SAR Handbook consists of eight chapters that include theory and background on a wide range of topics related to monitoring forests with SAR, as well as appendices that include step-by-step guides to applying the theory to practice. The authors envision this resource being used to develop forest applications and for capacity-building efforts. Chapters can be used together as a relatively complete and cohesive source of information on monitoring forests with SAR, or each chapter can stand alone as a resource on specific topics.
- **Hands-on training materials**—The SAR Handbook website hosts the materials necessary to complete the training described in the appendices. It includes PDFs of the handbook and step-by-step instructions, PowerPoint presentations to complement the training, scripts to process SAR data, and ancillary datasets, such as lidar and in-situ measurements.
- **One-pagers**—The editors have identified the need for quick reference guides for various SAR topics, since no such reference exists for using SAR to monitor forests. The editors developed a number of one-page documents that provide clear and easy-to-read summaries of important SAR concepts discussed more in-depth within

SAR EXPERT	TRAINING	HOSTING HUB(S)	LOCATION & DATES
Franz Meyer Univ. of Alaska Fairbanks **Josef Kellndorfer** Earth BigData	SAR Basics, Forest Degradation & Deforestation	1)West Africa 2) Hindu Kush-Himalaya	Niamey, Niger (Jan 29 - Feb 2, 2018) Kathmandu, Nepal (Feb 12-16, 2018)
Paul Siquiera Univ. of Mass. Amherst	Forest Stand Height	Mekong	Bangkok, Thailand (Mar 12-16, 2018)
Marc Simard CalTech/NASA JPL **Hans Andersen** US Forest Service	Mangroves, Sampling Design	Eastern & Southern Africa	Nairobi, Kenya (April 16-20, 2018)
Sassan Saatchi CalTech/NASA JPL	Biomass Estimation	Hindu Kush-Himalaya	Kathmandu, Nepal (April 30-May 4)

Table 1.2 *List of global SAR capacity building workshops for international partners in Africa and Asia.*

the handbook. These one-pagers include "SAR Data Access and Availability," "SAR Vegetation Indices," "SAR Preprocessing Steps," "SAR for Biomass Estimation," and "SAR for Forest Stand Height (FSH) Estimation." Digital versions of these one-pagers can be found on the handbook webpage or in the handbook appendices.

- **Technical videos**—The editors have developed short animated videos to simplify and clearly communicate complex concepts found within the handbook. These include an introduction to SAR concepts (wavelength, penetration depth, polarization, etc.), FSH estimation, and biomass estimation.

1.6 What to Expect

This handbook was developed to generate applied knowledge on using SAR for forest applications. The content has been generated by world-renowned experts on the topic and vetted, tested, and reviewed by a community of applied remote sensing users. It covers basic concepts to understand how SAR technology works and identifies some of the best practices and approaches to estimating forest change, biomass, and stand height; to mapping mangroves and estimating their biomass; and to sampling design for uncertainty estimation of biomass maps.

All the training tutorials use open source software and programming languages to process and analyze SAR datasets. This was a requirement that was fulfilled by the SAR experts that generated the materials.

This handbook is comprised of eight chapters in total, including this introductory **Chapter 1** and the following:

- **Chapter 2**, Spaceborne Synthetic Aperture Radar – Principles, Data Access, and Basic Processing Techniques. Author: Franz Meyer—This first technical chapter explains basic concepts to start using SAR datasets. It covers basic preprocessing and the peculiarities of SAR imagery, which enables an understanding of how these datasets are interpreted. This chapter also provides a comprehensive inventory of past, current, and planned SAR sensors.
- **Chapter 3**, Use of SAR Data for Mapping Deforestation and Forest Degradation. Author: Josef Kellndorfer—This chapter focuses on the applications of SAR imagery for forest change detection. It discusses how SAR backscatter changes due to sensor and target parameters, with an emphasis on forest targets. It also explains an approach for time series analysis for forest change detection.
- **Chapter 4**, Forest Stand Height. Author: Paul Siqueira—This chapter discusses the estimation of Forest Stand Height (FSH) through the use of spaceborne SAR, especially at L-band repeat-pass Interferometric SAR (InSAR). It covers the theory and software, and provides examples for the use of repeat-pass InSAR for FSH estimation.
- **Chapter 5**, SAR Methods for Mapping and Monitoring Forest Biomass. Author: Sassan Saatchi—This chapter provides a summary of the methodologies and techniques for estimating forest aboveground biomass. The content covers state-of-the-art SAR remote sensing approaches for characterizing vegetation structure and biomass estimation, and provides resources for future developments in the technology and emergency methodologies.
- **Chapter 6**, Radar Remote Sensing of Mangrove Forests. Author: Marc Simard—This chapter addresses the use of SAR imagery to monitor changes in the mangrove forest extent. The state-of-the-art radar remote sensing techniques to measure and monitor mangrove forest structure are also covered in this chapter.
- **Chapter 7**, Sampling Designs for SAR-Assisted Forest Biomass. Author: Hans Andersen—This chapter discusses sampling design and statistical modeling/estimation frameworks to provide a sound, statistically rigorous assessment of the uncertainty of forest biomass maps. It provides examples for efficiently using expensive field plot data and more extensive use of less expensive, remotely sensed information.
- **Chapter 8**, Perspectives on the Future Application of SAR in Forest and Environmental Monitoring. Authors: Emil Cherrington et al.—This chapter discusses future and emerging applications of SAR for forest and environmental monitoring, and also reflects on how SAR is currently being used across a range of applications. This chapter discusses how this is expected to change due to the growing public availability of SAR data and platforms to process and analyze radar data. It also discusses how SERVIR regional hubs are applying SAR technology, and how the SERVIR global network can be important resource centers in support of SilvaCarbon and GFOI to aid in articulating and addressing new environmental monitoring challenges.

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