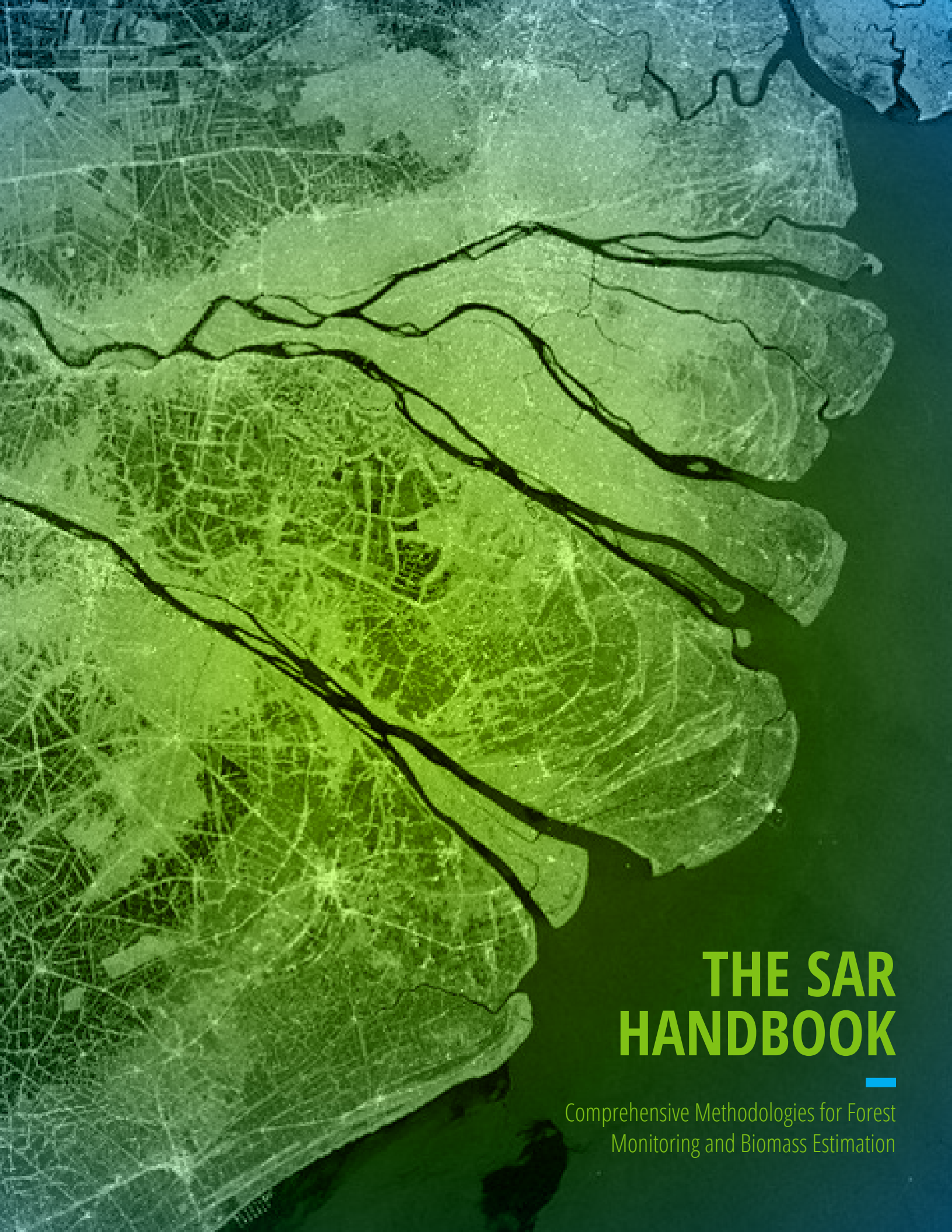

# THE SAR HANDBOOK

Comprehensive Methodologies for Forest Monitoring and Biomass Estimation

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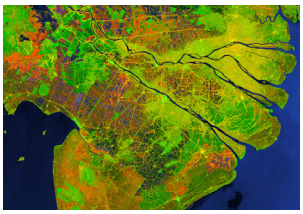

**COVER IMAGE:** The Mekong Delta in southern Vietnam, as seen by Sentinel-1 C-band SAR on November 26, 2018. (Jeremy Nicoll, Alaska Satellite Facility, contains modified Copernicus Sentinel data 2018, processed by ESA).

Africa Ixmucane Flores-Anderson · Kelsey E. Herndon · Rajesh Bahadur Thapa · Emil Cherrington
Editors

# The Synthetic Aperture Radar (SAR) Handbook: Comprehensive Methodologies for Forest Monitoring and Biomass Estimation

Preface by Juliann Aukema & Sylvia Wilson
Foreword by Daniel Irwin

# CONTENTS

# ACKNOWLEDGEMENTS

The development and completion of this Handbook would not have been possible without the direct support and collaboration of the SERVIR-Global family, including SERVIR Hubs from West Africa, Eastern & Southern Africa, Hindu Kush Himalaya, and Lower Mekong, the team at the SERVIR Science Coordination Office, NASA scientists and the world-renowned SAR experts authoring this book.

The editors of this SAR Handbook immensely appreciate the interagency support received, which made possible to conduct needs assessments, gather key attendees at workshops and training events, and develop relevant, hands-on training tutorials.

Below, we would like to recognize not only the authors of each of the chapters, but also all the team members involved in reviewing, editing and directing content for the theory-focused and respective training tutorial sections. This collaborative process made it possible to generate applied content that we expect to be a game-changer for the remote sensing community wanting to use SAR data for forest monitoring and biomass estimation.

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*Scoping Meeting (February 21-22, 2017, Huntsville, AL)*
Rajesh Bahadur Thapa (ICIMOD, Nepal), Kabir Uddin (ICIMOD, Nepal), Anastasia Wahome (RCMRD, Kenya), Phoebe Odour (RCMRD, Kenya), Bako Mamane (AGRHYMET, Niger), Kadidia Yero (AGRHYMET, Niger), Paul Bartel (AGRHYMET, Niger), Nguyen Hanh Quyen (ADPC, Thailand), David Saah (Spatial Informatics Group, USA), Sassan Saatchi (NASA JPL, USA), Alessandro Baccini (Woods Hole Research Center, USA), Bruce Chapman (NASA JPL, USA), Paul Siqueira (University of Massachusetts, Amherst, USA), Josef Kellndorfer (Earth Big Data, USA), Hans Andersen (USFS, USA), Sasha Gottlieb (USFS, USA), Sylvia Wilson (USGS, USA), Johan Pontus Olofsson (Boston University, USA), Gustavo Galindo (IDEAM, Colombia), Evan Notman (USAID, USA), Dan Irwin (SERVIR SCO), Ashutosh Limaye (SERVIR SCO), Eric Anderson (SERVIR SCO), Krishna Vadrevu (SERVIR SCO), Raymond French (SERVIR SCO), Emil Cherrington (SERVIR SCO), Lee Ellenburg (SERVIR SCO), Francisco Delgado (SERVIR SCO), Billy Ashmall (SERVIR SCO), Lance Gilliland (SERVIR SCO), Bill Crosson (SERVIR SCO), Emily Adams (SERVIR SCO), Rebekke Muench (SERVIR SCO), Kelsey Herndon (SERVIR SCO)
Organizers: Africa Flores, Emil Cherrington, Krishna Vadrevu, Paula Link, Emily Adams

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*Workshop: SAR basics and forest degradation; Deforestation detection (Regions: West Africa, Hindu Kush Himalaya)*
Subject Matter Experts: Franz Meyer, Josef Kellndorfer
SERVIR Hub POCs: Bako Mamane, Rajesh Bahadur Thapa
Follow-on workshop trainers: Rebekke Muench, Begum Rushi
Training Tutorial Reviewers: Kelsey E. Herndon (Meyer)
Rebekke Muench, Andrea Nicolau (Kellndorfer)

*Workshop: Forest stand height (Region: Mekong)*
Subject Matter Expert: Paul Siqueira
SERVIR Hub POC: Nguyen Hanh Quyen
Follow-on workshop trainer: Krishna Vadrevu
Training Tutorial Reviewers: Helen Baldwin, Sarva Pulla, Yang Lei

*Workshop: Mangrove and sampling design (Region: Eastern & Southern Africa)*
Subject Matter Experts: Marc Simard, Hans Andersen
SERVIR Hub POC: Phoebe Odour
Follow-on workshop trainers: Emily C. Adams, Kenneth Mubea
Training Tutorial Reviewers: Africa Flores-Anderson (Anderson), Katherine Strattman (Simard)

*Workshop: Biomass (Region: Hindu Kush Himalaya)*
Subject Matter Expert: Sassan Saatchi
SERVIR Hub POC: Rajesh Bahadur Thapa
Follow-on workshop trainer: Emil Cherrington
Training Tutorial Reviewer: Rajesh Bahadur Thapa

A final close-out meeting took place to bring the SAR experts, scientists from SERVIR-Hubs and relevant agencies together to address the main deliverables and provide additional content for chapters and trainings. We would like to acknowledge the meeting participants for their key contributions:

*Close-Out Meeting (November 5-6, 2018, Huntsville, AL)*
Franz Meyer (ASF, USA), Josef Kellndorfer (Earth Big Data, USA), Paul Siqueira (University of Massachusetts, Amherst, USA), Sassan Saatchi (NASA JPL, USA), Marc Simard (NASA JPL, USA), Hans Andersen (USFS, USA), Rajesh Bahadur Thapa (ICIMOD, Nepal), Kenneth Mubea (RCMRD, Kenya), Anastasia Wahome (RCMRD, Kenya), Sasha Gottlieb (USFS, USA), Gustavo Galindo (IDEAM, Colombia), Eric Anderson (SERVIR SCO), Kelsey Herndon (SERVIR SCO, USA), Africa Flores-Anderson (SERVIR SCO, USA), Leah Kucera (SERVIR SCO, USA), Emil Cherrington (SERVIR SCO, USA), Emily Adams

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# PREFACE

On behalf of both the U.S. Agency for International Development (USAID) and the U.S. Geological Survey (USGS), and specifically on behalf of the SilvaCarbon initiative, we are proud to share with you the following Handbook, the product of a collaboration between SilvaCarbon and the SERVIR program. Established in 2010, SilvaCarbon represents the US contribution to the Global Forest Observation Initiative (GFOI), itself a collaborative effort supporting countries in using Earth observation data for monitoring forests. SilvaCarbon's implementing agencies include USAID, the U.S. Department of State, the U.S. Forest Service (USFS), the USGS, the U.S. Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the Smithsonian Institution. This Handbook also represents an important contribution from a number of U.S.-based experts in Synthetic Aperture Radar (SAR), as well as experts from SERVIR's global network of hubs.

The motivation for this Handbook is to translate knowledge gained from decades of research in SAR into practical guidance to countries on how SAR can be used for different aspects of forest monitoring, reporting, and verification (MRV) for REDD+. There has been growing interest in applying this technology to land cover mapping and monitoring in the tropics, where seasonal and permanent cloud cover make detecting deforestation and forest degradation very challenging.

Radar data historically was known for being costly and complicated to use. However, with new datasets becoming available and open source, such as SENTINEL -1 from the European Space Agency (ESA), the fusion of optical and radar data becomes an option for sustainable and replicable methods. The drawback is the lack of historical radar data to include in historical baselines. However, the sooner SAR data is included in National Forest Monitoring Systems, the sooner it will be considered historical data in the future.

One of the GFOI's focus activities is providing 'Methods & Guidance' documentation to support countries' forest monitoring activities. This Handbook thus fits into that context as an important contribution to methods & guidance, especially since the body of available datasets and tools has been growing. One anticipated resource is the joint U.S. / India NISAR satellite mission whose launch is expected in the next few years.

The handbook walks you through the principles of SAR data applications from the beginning, starting from how to access the data and perform basic processing techniques. It describes how to use SAR data to map deforestation and forest degradation and how to estimate forest height. It also provides guidance on the best methods for using SAR to map and monitor forest biomass. It includes a chapter that exemplifies the use of radar for mapping mangrove forests. It concludes with the important issue of choosing a sampling design while using SAR data for biomass estimation.

The handbook was first conceptualized as an outcome from a workshop hosted by SERVIR. This workshop brought together scientists, program managers, and country practitioners to identify challenges on using SAR data, gaps where SAR data is not available, and potential areas where SAR could fill the gap in forest monitoring for remote sensing data. Thanks to the efforts of the SERVIR team, especially Africa Flores for managing the overall initiative, the scientists involved in the development of the handbook, and the SilvaCarbon team, this handbook offers a set of tools and operational methods that will streamline efforts to assist countries to build robust, transparent, replicable and verifiable Monitoring, Reporting and Verification Systems.

We therefore invite you to take advantage of this important resource, and feel free to provide us with feedback on how the Handbook can be improved, as we hope that this will evolve into a truly living document. We also take this opportunity to recognize the contributions of the subject matter experts who drafted the bulk of the Handbook, our counterparts from the respective SERVIR hubs across the globe, and our partners at NASA's SERVIR Science Coordination Office. Thank you.

**Juliann Aukema**
*SilvaCarbon Coordinator, USAID*

**Sylvia Wilson**
*SilvaCarbon Coordinator, USGS*

# FOREWORD

Two years ago, a group of scientists and practitioners representing a dozen countries across Africa, Asia, and the Americas identified a pressing need and opportunity for the applied Earth observations and international development communities. Global and national commitments to sustainable landscape management—including forests, mangroves, and the biomass they store and $CO_2$ they capture—has challenged scientists and resource managers to develop and implement new, accurate, and cost effective monitoring and reporting systems. Field measurements combined with satellite remote sensing techniques have provided industry-standard inputs into monitoring, reporting, and verification systems. In the last decade, critical access to satellite data has skyrocketed, thanks largely to public releases of over 40 years of Landsat data from the NASA and USGS, along with the European Space Agency's (ESA) free and open data policies under the Copernicus Sentinel series. However, data access alone does not guarantee appropriate use. Tools and training are important steps in ensuring adequate capacity at individual and institutional levels.

This Handbook represents a joint contribution from the U.S. government-led SilvaCarbon initiative, and the joint NASA-USAID SERVIR program, to support global capacity building endeavors as called for by the Global Forest Observations Initiative (GFOI). SERVIR's global network of international technical centers of excellence, known as "SERVIR Hubs", played a crucial role in defining needs and initial expansion of Synthetic Aperture Radar (SAR) capacity. SERVIR Hubs have deep knowledge of existing national and regional capacities in remote sensing for forestry and biomass monitoring, which articulated the critical gaps addressed in this Handbook.

A common challenge that the applied remote sensing community faces in forestry and landscape monitoring are clouds. For years, SAR promised all-weather, day-and-night capability, but at a steep cost. Until the launch of the Sentinel-1 series by ESA's Copernicus Program and the release of archived ALOS-1 imagery by JAXA, SAR data were effectively inaccessible and inappropriate for national and regional level forestry and biomass monitoring. The forthcoming NASA and Indian Space Research Organization (ISRO) SAR mission, NISAR, will only add to the free access of SAR data.

The series of chapters in this handbook are authored by leading global experts in SAR remote sensing fundamentals and applications in this field, and co-developed with professionals who thrive at the transition of research to applications for societal benefit. Through careful testing and curation, these materials are meant to complement existing national, regional, and global methods in forestry and biomass estimation. We are proud to share this as a multilateral contribution to improve the use of free satellite data toward better monitoring and management of our terrestrial environments.

**Daniel Irwin**
*SERVIR Global Program Manager, NASA*

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She is the NASA representative for the SilvaCarbon initiative, and is leading the collaboration between SERVIR and SilvaCarbon to create applied knowledge and capacity throughout the SERVIR network on the use of Synthetic Aperture Radar (SAR) for forest monitoring and biomass estimation.

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