SATELLITE RADAR INTERFEROMETRY

Interferometric synthetic aperture radar (InSAR) is an active remote sensing method that uses repeated radar scans of the Earth's solid surface to measure relative deformation at centimeter precision over a wide swath. It has revolutionized our understanding of the earthquake cycle, volcanic eruptions, landslides, glacier flow, ice grounding lines, ground fluid injection/withdrawal, underground nuclear tests, and other applications requiring high spatial resolution measurements of ground deformation. This book examines the theory behind and the applications of InSAR for measuring surface deformation. The most recent generation of InSAR satellites has transformed the method from investigating 10s to 100s of synthetic aperture radar images to processing 1 000s and 10 000s of images using a wide range of computer facilities. This book is intended for students and researchers in the physical sciences, particularly for those working in geophysics, natural hazards, space geodesy, and remote sensing. This title is also available as Open Access on Cambridge Core.

DAVID T. SANDWELL is a professor of geophysics at Scripps Institution of Oceanography at the University of California, San Diego. His research is focused on marine tectonics, geodynamics, and the earthquake cycle using InSAR and Global Navigation Satellite System (GNSS). He is the author of more than 200 research papers and the book *Advanced Geodynamics: The Fourier Transform Method* (2022, Cambridge University Press). He is a member of the US National Academy of Sciences.

XIAOHUA XU is a professor of geophysics at the University of Science and Technology of China. His research is focused on earthquakes, faulting, crustal deformation, and tectonic geodesy.

JINGYI CHEN is an associate professor of aerospace engineering at the University of Texas at Austin. Her research is focused on the development of InSAR techniques for studying natural and induced seismicity, groundwater resources, natural disasters, and permafrost hydrology. She is a senior member of the Institute of Electrical and Electronics Engineers and a member of the American Geophysical Union.

ROBERT J. MELLORS is a researcher at Scripps Institution of Oceanography at the University of California, San Diego. His research is focused on enhancing geophysical sensing, including InSAR, global seismic instrumentation, muons, and photonic seismology. He is currently an advisor to the US Department of Energy (Advanced Research Projects Agency – Energy) on advanced energy technologies.

MENG WEI is an associate professor of oceanography in the Graduate School of Oceanography at the University of Rhode Island. His research is focused on tectonic geodesy, fault mechanics, coastal subsidence, and natural hazards. He has published more than 30 research papers and is a recipient of the Faculty Early Career Development Program award from the National Science Foundation.

XIAOPENG TONG is an associate researcher in the Institute of Geophysics, China Earthquake Administration, Beijing. He is a PhD from the Scripps Institution of Oceanography, University of California, San Diego. His research interests include InSAR, space geodesy, and crustal deformation.

JOHN B. DESANTO is a research scientist at the University of Washington. His primary interests lie in the fields of marine tectonics and subduction zone processes. He studies these regions directly by adapting geodetic techniques such as GNSS to the offshore environment.

QI OU is a lecturer at the University of Edinburgh. She applies big Earth observation data to understand multi-hazards induced by active tectonics, climate change, and anthropogenic activities. She is the author of several highly cited papers, a convener and speaker at the Seismological Society of America and American Geophysical Society conferences, and a recipient of a Discipline Hopping Award from UK Research and Innovation.

SATELLITE RADAR INTERFEROMETRY

Theory and Practice

DAVID T. SANDWELL
University of California, San Diego

XIAOHUA XU
University of Science and Technology of China

JINGYI CHEN
The University of Texas at Austin

ROBERT J. MELLORS
University of California, San Diego

MENG WEI
University of Rhode Island

XIAOPENG TONG
China Earthquake Administration

JOHN B. DESANTO
University of Washington

QI OU
University of Edinburgh

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre,
New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment,
a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of
education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781009606233

DOI: 10.1017/9781009606226

First published 2025

A catalogue record for this publication is available from the British Library

A Cataloging-in-Publication data record for this book is available from the Library of Congress

ISBN 978-1-009-60623-3 Hardback

Additional resources for this publication at www.cambridge.org/sandwell.

Contents

Preface and Acknowledgments

This textbook provides a comprehensive overview of satellite radar interferometry for mapping surface deformation from various phenomena, including earthquakes, volcanoes, landslides, glacier flow, ice grounding lines, ground fluid injection/withdrawal, and underground nuclear tests. It is designed for students and researchers in the physical sciences, who have completed courses in introductory physics, calculus, and computer science.

The book covers the physical principles, mathematical models, and algorithms used in Interferometric synthetic aperture radar (InSAR) processing from a geodetic perspective. Readers will gain insights into both the theoretical underpinnings and practical applications of InSAR, making it a valuable resource for understanding and utilizing this powerful remote sensing technology.

Chapter 1 discusses six types of remote sensing methods possible from Earth orbit and introduces radar interferometry as the optimal approach for measuring small surface deformation.

Chapter 2 explains the basic physics of radar imaging from orbital altitude, including the limits on accuracy, spatial resolution in the range and azimuth directions, and the fundamental limitation on swath width.

Chapter 3 details the kinematics of satellite orbits and their use in InSAR processing and its automation. It covers the six parameters needed to describe an orbit (Kepler elements or Cartesian state vector), transforming coordinates from an Earth-fixed frame to the satellite frame, and methods to calculate a centimeter-accuracy satellite trajectory from a sequence of state vectors.

Chapter 4 provides a comprehensive presentation of the commonly used range-Doppler algorithm for focusing complex backscatter data into a single-look complex (SLC) image.

Chapter 5 explains the process of forming an interferogram from two geometrically aligned SLC images and methods for extracting deformation and topography from the interferometric phase. It also covers critical baseline, geocoding, and geocoded SLCs.

Chapter 6 discusses the main methods for filtering complex interferograms and computing coherence and phase gradient.

Chapter 7 introduces the basic concepts and fundamental limitations (i.e., residues) of phase unwrapping. It presents three common unwrapping methods: the global Fourier transform method, the path-following branch-cut method, and the minimum cost flow method. Additionally, it covers methods for correcting integer ambiguities using phase closure within stacks of interferograms.

Chapter 8 explores a wide range of SAR operational modes, including polarization and wide swath modes. It reviews the fundamental limitation of the standard swath-mode acquisition and discusses three methods for increasing swath width: ScanSAR, terrain observation by progressive scans (TOPS), and SweepSAR for the upcoming NASA–ISRO–SAR mission.

Chapter 9 examines the three factors that affect radar range measurement: spatial and temporal variations of the dry and wet components of the troposphere, phase advance of radar waves through the ionosphere, and the solid Earth tides. It also discusses practical corrections and mitigation approaches.

Chapter 10 presents complementary approaches to measuring surface deformation by radar, including pixel offset tracking, multiple aperture interferometry, and burst overlap interferometry. The second part of the chapter discusses methods for extracting surface velocity and time series from a large set of interferograms, as well as identifying pixels that remain stable over long periods.

Chapter 11 highlights the need for ground control, such as Global Navigation Satellite System (GNSS) survey points, to bring InSAR deformation measurements into a geodetic reference frame. It also explains the theory for projecting vector GNSS displacement into scalar line-of-sight (LOS) InSAR displacement and the computation of strain rate from InSAR.

This textbook has been developed over the past two decades from a Space Geodesy class at Scripps Institution of Oceanography, as well as GMTSAR short courses at UNAVCO and EarthScope. Each chapter includes a set of exercises and solutions to highlight the important concepts.

The algorithms described in the book are implemented in a computer software package called GMTSAR, an open-source, InSAR processing system designed for users familiar with the Generic Mapping Tools (GMT). While the book references this specific software, the content is also relevant to any modern InSAR processing system.

GMTSAR software was developed over a period of 25 years to create a geodetically accurate, open-source InSAR processing system. Many individuals contributed to its development.

Howard Zebker (Stanford) provided the original FORTRAN code for the SAR processor. Evelyn Price (a University of California, San Diego (UCSD) student) translated this code into C, simplifying it while keeping the SAR-focusing algorithm unchanged. Price and Sandwell expanded this into a complete InSAR package by adding cross-correlation and phase modules. Paul Jamason (UCSD) wrote the preprocessors for ERS (CCRS and DPAF). Remko Sharro's (Delft University) getorb routines were used to compute precise orbits for proper focus, geolocation, and baseline estimation.

The GIPS package, developed by Peter Ford (the Massachusetts Institute of Technology), led to the creation of the SIOSAR system, which remained stable for 11 years. Sean Buckley, a student at UT Austin, developed the Envisat preprocessor. In 2010, GIPS was replaced by GMT modules. Rob Mellors (San Diego State University) developed the Advanced Land Observing Satellite preprocessing code, later translated by Matt Wei (a UCSD student) into the ERS and Envisat preprocessors. Mellors also wrote new software for image cross-correlation and Goldstein/Werner interferogram filtering.

Xiaopeng Tong (a UCSD student) tested and refined the codes, removing some approximations from SIOSAR. He also developed scripts for two-pass processing, stacking, and the time series (SBAS) C-code. The statistical-cost, network-flow algorithm for phase unwrapping C-code, written by Curtis Chen and Howard Zebker (Stanford), is used without modification.

Paul Wessel (University of Hawaii) enhanced GMT to process large binary tables and modified all the code to interface with GMT routines during his sabbatical at Scripps Institute of Oceanography in 2013. He also developed code for Keyhole Markup Language output for Google Earth. GMTSAR uses the GMT routines blockmedian and surface, developed by Walter Smith and Paul Wessel (Lamont-Doherty Earth Observatory). These routines are central to GMTSAR algorithms for transforming between geographic and radar coordinates.

Most recently, Xiaohua Xu (a UCSD student) and David Sandwell developed preprocessing and alignment codes for TOPS-mode interferometry, with assistance from Pablo Gonzalez (Leeds University, UK). Recent developments include InSAR corrections, GNSS integration by Katherine Guns, and common scene stacking by Katia Tymofyeyeva. Many users provided feedback and bug reports, helping to achieve a robust and stable software set.

Funding for research algorithms and code development was provided by the NASA Earth Surface and Interior program. The National Science Foundation Cyberinfrastructure for Sustained Scientific Innovation program supported code testing, hardening, and documentation (e.g., this book). EarthScope, formerly UNAVCO, supported GMTSAR short courses where lectures and homework problems were developed. Khalid Soofi supported the project through funding from

ConocoPhillips and by testing and developing the software. The National Geodetic Survey provided support for book development and open access publication. The Scripps Institution of Oceanography/UCSD provided many years of salary support for Sandwell to develop and publish the book.