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利用雷达干涉技术监测区域地表形变

MONITORING OF GROUND DEFORMATIONS WITH RADAR INTERFEROMETRY

（中文摘要·英文版）

刘国祥 著

测绘出版社

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·北京·

内容简介

本书采取理论阐述、实验分析与实践验证相结合的形式，系统地讲述了卫星合成孔径雷达干涉(InSAR)遥感技术应用于大范围地球表面形变监测的基本原理、误差来源和误差传播模型，并主要针对精度和可靠性这两个方面展开讨论和分析。在地形数字高程模型误差的影响和控制、干涉相位图的先验滤波算法、基于地面控制点的卫星轨道数据(基线参数)精化、干涉模型的抗差估计等方面进行了深入研究，并提出了相应的改善精度和可靠性的方法与建议。基于多幅欧洲空间局卫星 ERS-1 和 ERS-2 合成孔径雷达图像，将上述方法和算法成功应用到香港填海区域地表沉降以及台湾西部地区的地壳形变的研究中，相关结果以图文并茂的形式展示在书中。

本书可作为高等院校及研究所测绘类专业研究生教学用书，亦可作为摄影测量与遥感、空间大地测量、工程测量和地球物理等专业的科技人员与高等院校师生的学习参考书。

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Foreword

The concept of synthetic aperture radar (SAR) was invented in 1950's, and consequently made the spatial resolution of radar imagery improved significantly. The first imaging SAR system of the world was born in 1960. We witnessed that a number of imaging SAR systems onboard either aircrafts or spacecrafts had been developed and enhanced over 50 years. In China, the airborne SAR technology has been evolved from scratch in recent 30 years. Since SAR sensors possess all-time and all-weather imaging capabilities, radar remote sensing with the use of SAR imagery becomes one of the key technologies which can provide us with the critical observations to understand the earth and other planets. The early applications of radar remote sensing are primarily involved in geology surveying and ecosystem monitoring with a single SAR image. In 1970's, the further advancement led to the birth of a novel technology—synthetic aperture radar interferometry (InSAR)—by combining the interferometry technique which had been well matured over decades in radio astronomy. It was first recognized that InSAR is capable of mapping topography and generating digital elevation model by mainly using interferometric phase information which can be extracted with a pair of SAR images acquired over the same region. As a further extension, a new methodology—differential SAR interferometry (D-InSAR)—was proposed by National Aeronautics and Space Administration (NASA) in 1989. D-InSAR can be remarkably applied to detect ground movements related to earthquake, volcanic movement, ice shift, urban subsidence and slope slide. It is by far considered as the unique remote sensing approach which can offer dense and accurate area-based deformation measurements.

Numerous international scientists and engineers in geoscience are currently doing intensive research on radar interferometry. Dr. Guoxiang Liu has focused on the sophisticated research direction of differential SAR interferometry, since he pursued the study for the degree of doctor of philosophy in the Hong Kong Polytechnic University. He has performed a systematic and in-depth research on both theoretical and practical issues in D-InSAR for the purpose of regional deformation mapping, and carried out a number of experiments of interferometric data processing and analysis by using SAR data collected by the satellites of European Space Agency (ESA). This book just shows his research fruits through which his enthusiastic and innovative attitude towards scientific research has been presented clearly. I am very gratified with the delightful situation that there are more and more young and excellent scholars growing up in China, who are making a brilliant figure in the remote sensing field.

This book concentrates on the analysis and discussion on two issues of D-InSAR in regional deformation mapping, i. e. , accuracy and reliability. On the basis of understanding all types of error sources in D-InSAR, the author first discusses the main factors affecting the accuracy of deformation measurements, and then proposes some algorithms and methodologies to improve the accuracy, which are well validated by using both simulated data and the real SAR images acquired by ESA satellites ERS-1/2. The reliability theory is also introduced to address the problems in interferometric modelling and to develop robust estimation methods, and thus enhancing the D-InSAR reliability. The proposed algorithms and methods are finally applied to two case studies of practical deformation mapping with ERS-1/2 C-band SAR images for Hong Kong new airport (subsiding) and Chi-Chi, Taiwan earthquake (crustal movement), respectively. The results obtained with the studies can offer a proper guidance for the similar applications elsewhere with D-InSAR.

For the integrity and combination of both theory and application on D-InSAR, this book is prepared with fine structure, distinct argument, and concise description. The theoretical and methodological results shown in the book should be helpful in China to push forward the advancement of radar interferometry technology. The Chinese small satellite carrying a radar sensor will be launched in the near future. We therefore believe that the applications with radar interferometry would have a great potential and present a prosperous situation in China. The Chinese government has always placed priority to monitoring deformation-related hazards or disasters caused by such as earthquake and slope slide. The conventional geodetic approaches for deformation detection are featured by high accuracy, but labor intensive like leveling and high cost like GPS. Moreover, their spatial resolution is often unsatisfactory due to the point-based measuring way. As D-InSAR offers the dense deformation measurements with area-based coverage, it will undoubtedly complement the conventional point-based geodetic tools. Therefore we hope the D-InSAR technology could be evolved as fast as possible to become a powerful tool for geoscience research and regional deformation monitoring.

In view of the above reasons, I would like to recommend this book to a wide variety of readers, including researchers, teachers, producers, and managers associated with geoscience. In the mean time, I hope the author of this book would continue to strive hard to make further progress and greater contribution towards the radar interferometry community.

Deren Li 李德仁

Aug. 8, 2005, Wuhan

序　言

20 世纪 50 年代，合成孔径雷达（SAR）概念诞生，致使雷达影像空间分辨率得到显著改善。1960 年，世界上第一个 SAR 成像系统问世。50 多年来，国际上飞机、航天飞机和卫星 SAR 成像系统发展蒸蒸日上。近 30 年内，我国机载成像雷达技术的发展从无到有，取得了长足进步。雷达成像具有全天候与全天时的技术特点，使雷达遥感成为对地观测和行星探测的关键技术手段之一。早期的雷达遥感大多基于单张 SAR 图像的灰度信息解译来进行地质调查与生态环境监测。20 世纪 70 年代，射电天文领域发展成熟的干涉技术被引入，合成孔径雷达干涉（InSAR）技术诞生了，主要针对 SAR 像对的相位信息进行分析与处理，可应用于制图与地面数字高程模型的建立。特别地，1989 年美国 NASA 首次提出差分雷达干涉（D-InSAR）的观点，可应用于地震形变、火山运动、冰川漂移、城市沉降以及山体滑坡的监测与研究。差分雷达干涉技术是迄今为止独一无二的高精度形变监测遥感手段。

目前，各国学者对雷达干涉这一新技术正竞相展开研究，国内外关注和从事 InSAR 研究的学者越来越多。刘国祥博士在香港理工大学攻读博士学位期间，不失时机地抓住了"差分雷达干涉技术"这一具有前沿性的研究方向，对应用差分雷达干涉测量区域地表形变的有关问题，进行了系统而深入的理论和方法研究，并使用欧洲空间局卫星 SAR 影像进行了实验。本书即是他进行这些研究的成果结晶，书中突出地体现了作者对相关科学研究的务实与创新精神。我为我国遥感领域不断地涌现出一批批崭露头角的年轻学者而感到欣慰与高兴。

本书主要围绕使用差分雷达干涉技术测量地表形变的精度与可靠性这两大问题展开研究与讨论。在系统分析各种误差来源的基础上，指出了影响形变测量精度的主要因素，提出了改善精度的相关算法，并使用模拟数据或真实卫星 SAR 影像数据进行了验证。将可靠性理论引入干涉模型估计中，并发展了抗差估计算法。使用多幅欧洲空间局卫星 ERS-1/2 SAR 影像数据，将这些方法和算法应用于两个实验区域，即香港机场沉降和台湾集集大地震，呈现了相关结果，并得到了诸多有指导意义的结论。

该书体系完整（含理论、技术、应用等方面），理论与实践相结合；全书结构、层次清晰，表达清楚、流畅，语言简练。本书所展示的理论研究与相关技术方法将对我国雷达干涉技术理论的进一步研究与技术发展起到促进和推动作用。随着我国自主研制的小型卫星 SAR 成像系统的即将升空，雷达干涉技术在我国的应用必将呈现一个崭新的局面。我国一直重视形变灾害（如地震与山体滑坡等）的监测工作，惯用的形变测量技术精度较高，但其劳动强度大（如大地水准网）、成本高（如 GPS 网）且空间分辨率较低，而具有高空间分辨率特征的差分雷达干涉技术可与这些惯用地面监测技术形成优势互补。因此，我们期望差分雷达干涉技术快速发展成为地球科学研究和形变灾害监测的强有力的空间对地观测手段。

基于以上理由，我愿向广大读者，包括科研、教学、生产和管理方面的读者推荐这本书。同时也希望作者继续努力，为雷达干涉技术的发展与完善作出更大的贡献！

李德仁

2005 年 8 月 8 日于武汉

Preface

The earth deformations can be caused by various reasons including the natural factors such as crustal movement and the human factors such as mining and groundwater withdrawal. For a long time, geodesists and geophysicists have always explored and developed some effective technologies and methods that can be applied to monitoring all types of ground deformations and even their potential hazards. Since 1970's, satellite synthetic aperture radar interferometry (InSAR) has been evolved as a very promising technology for mapping of the regional ground deformations. At present, the European and American countries are in strong competition to push the technology forward. In China, the relevant research work has just commenced, but it has drawn much attention and interest from the domestic scientists and engineers working in the field of surveying and mapping as well as the field of earth science.

InSAR is a nested-style abbreviation that is formed from "radio detection and ranging (radar)", "synthetic aperture radar (SAR)", and "SAR interferometry (InSAR)". Such abbreviation not only indicates the development course of InSAR, but also means that it is the synthesis of conventional SAR technique and interferometry technique that has been evolved over decades in radio astronomy. The deformation measurements derived by InSAR that can work day and night and under adverse weather conditions offer high sensitivity to displacement, fine spatial resolution and wide coverage. InSAR is therefore viewed as the unprecedented area-based approach for monitoring deformations, and thus can remarkably complement the existing low spatial resolution geodetic tools such as GPS, satellite laser ranging, very long baseline interferometry and precision levelling. It can provide rich measurements for geophysical modelling and inversion, interpretation of deformation mechanics, and even forecasting of deformation hazards. A number of experiments have demonstrated that InSAR is very useful in such fields as earthquake-related deformation, volcanic motion, ice-sheet shift, urban settlement and slope slide.

From 1999 to 2003, the author pursued his degree of doctor of philosophy (PhD) in the Hong Kong Polytechnic University (HKPolyU). During the period of time, the author successively took part in several research projects related to InSAR, which are funded by the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. B-Q406), the Research Funding Schema of HKPolyU (Project No. 87A7), the Postgraduate Research Funding of HKPolyU (Project No. GV-747), and the Open Research Funding of the National Key Laboratory of Wuhan University (Project No. WKL(00)0103). Afterwards, the author participated in two InSAR-related research projects funded by the Natural Science Foundation of China (Project No. 40374003, 50278082) as a principal investigator and a co-investigator, respectively. With the support of these projects, the author has conducted the in-depth research on radar interferometry. Currently, there are few books/monographs addressing InSAR, but the more and more scholars are eager to commence the use of InSAR. In view of these, the author would like to share his research experiences and results with a number of colleagues through the publication of a monograph that is primarily based on his PhD thesis. This monograph concentrates on the analysis and discussion on both accuracy and reliability of InSAR in deformation mapping, and proposes the algorithms and methodologies to improve the two aspects.

This book first reviews and summarizes the development history of InSAR, the state-of-the-art, and the theoretical backgrounds. The research results on both accuracy and reliability are then followed. There are ten chapters included in the book. Chapter 1 will introduce the issues, objectives and scopes of the research. Chapter 2 will review the development history of satellite InSAR, as well as the mathematical models and the application limitations of differential SAR interferometry when applied to regional deformation mapping. Chapter 3 will outline the procedures for extracting surface deformations with interferometric data. Chapter 4 will cover the analysis and modelling of the various errors in interferometric deformation measurements. Chapter 5 will investigate the propagation of the topographic errors in differential processing through simulation studies. Chapter 6 will be dedicated to enhancing interferometric quality by apriori filtering of the individual SAR images. Chapter 7 will present the methodology for the precise determination of baseline parameters. Chapter 8 will address the reliability and robustness in the interferometric modelling. Chapter 9 will treat two case studies of practical deformation mapping over some tropical regions with ERS-1/2 C-band SAR images, i. e. , the subsiding area reclaimed from the sea in Hong Kong and the crustal deformation field in the west of Taiwan. Chapter 10 will give the conclusions and recommendations based on the entire research work.

The author is very thankful to the grants mentioned above. Without these funding, the research work presented in this book could not have been performed successfully. Special thank goes to the monograph-publication funding from the National Surveying and Mapping Bureau as it makes possible the publication of this book. The editors are also gratefully acknowledged for their great efforts on editing this book.

I would like to express my sincere gratitude to my chief supervisor, Prof. Xiaoli Ding, as well as two co-supervisors, Prof. Yongqi Chen and Prof. Zhilin Li from HKPolyU. They set me off in the right research direction, and provided enlightening guidance during my candidature for PhD. Without their enthusiasm in scientific research, continuous support and great encouragement, I could not have successfully finished the research work and the book. Prof. Xiaoli Ding should be specially appreciated for his valuable recommendations provided during the preparation of this book and his careful modification made to the early manuscript. Several experts in geodesy and remote sensing should also be appreciated for their useful advices, comments, and encouragements, including Prof. Deren Li (Academician) from Wuhan University, Prof. Dawei Zheng from Shanghai Observatory, Prof. Wenxi Liu and Prof. Dingfa Huang from Southwestern Jiaotong University.

The author wishes that the publication of the book would be able to bring convenience to the numerous colleagues working in the relevant fields, and to promote the further research on the theory and application of InSAR. Although the author has attempted his best to prepare this book, there are still possibly some mistakes or improper descriptions appearing somewhere due to the limitation of the author's professional level. Your criticism and guidance are welcome.

Guoxiang Liu

December 2004, Chengdu

前　言

引起地球表面形变的原因很多，包括自然因素（如地壳运动）和人为因素（如采矿与城市地下水抽取）等。长期以来，测量学家和地球物理学家一直在探求监测各种地球表面形变及其灾害的有效技术和方法。20世纪70年代末发展起来的卫星合成孔径雷达干涉（synthetic aperture radar interferometry，InSAR）便是一项极具潜力的区域地表形变监测技术。目前，欧美国家对这一技术正竞相展开研究，我国对雷达干涉的研究仍处于起步阶段，但已引起了国内测绘界与地学界同仁们的极大兴趣和广泛关注。

"InSAR"是一个嵌套式的英文缩写，即 Radio detection and ranging（Radar，无线电探测和测距，简称雷达），Synthetic Aperture Radar（SAR，合成孔径雷达），Synthetic aperture radar interferometry（InSAR，合成孔径雷达干涉）。这一缩写方式大致说明了 InSAR 的发展历程，同时也表达了它是合成孔径雷达遥感成像与电磁波干涉两大技术的融合。InSAR 应用于地表形变探测具有高形变敏感度、高空间分辨率、几乎不受云雨天气制约，并具有空中遥感等突出的技术优势。它是迄今为止独一无二的基于面观测的形变监测手段，既可补充已有的基于点观测的低空间分辨率大地测量技术（如全球定位系统、激光测卫、甚长基线干涉测量和精密水准测量等），又可为地球物理模型反演研究、相关形变基理解释、甚至形变灾害预测提供丰富的观测数据，它已在研究地震形变、火山运动、冰川漂移、城市沉降以及山体滑坡等方面表现出极好的应用前景。

1999—2003年，作者在香港理工大学攻读博士学位期间，先后承担了香港政府研究基金项目（编号：B-Q406）、香港理工大学研究基金项目（编号：87A7）、香港理工大学博士学位研究基金项目（编号：GV-747）和武汉大学测绘遥感信息工程国家重点实验室开放研究基金项目（编号：WKL(00)0103），其后又主持和参予了国家自然科学基金项目（编号：40374003，50278082）。依托这些项目，对雷达干涉技术的理论与应用进行了系统而深入的研究，并取得了一系列的研究成果。考虑到目前国内外已出版的有关 InSAR 的书籍或专著较少，而关注和从事 InSAR 研究的学者越来越多，为此，作者决定出版此本专著，以期与广大相关学者和研究人员及时分享本人的研究经验和成果。本书在扩展本人博士论文的基础上，将主要围绕使用 InSAR 测量地表形变的精度和可靠性这两个方面展开讨论和分析，并提出改善它们的有效方法和建议。

本书在回顾和总结卫星 InSAR 的发展历史、国内外发展现状和理论背景的基础上，逐章陈述有关 InSAR 精度和可靠性这两方面的研究成果。全书共分为10章：第1章介绍了本书的研究目的和研究范围；第2章介绍了卫星 InSAR 的发展历史、差分干涉数学模型及其应用制约因素；第3章总结了使用卫星 InSAR 提取形变信号的数据处理方法和工作流程；第4章分析了卫星 InSAR 的误差来源，并发展了差分干涉的误差传播模型；第5章讨论了地形数据误差对形变精度的影响及控制措施；第6章和第7章分别发展了干涉相位数据先验滤波算法和卫星轨道（基线）数据精化算法；第8章涉及干涉模型的稳健估计理论与方法；第9章给出了卫星 InSAR 应用的研究实例，包括香港填海区域地表沉降以及台湾西部地区的地壳形变；第10章为结论与进一步研究建议。

作者感谢为本人进行 InSAR 研究工作而提供的各项研究基金的资助，没有这些实质性的资助，研究工作不可能顺利进行；同时也感谢测绘科技专著出版基金的资助，使本书才得以出版；此外，还要感谢为此书出版付出辛勤劳动的各位编辑。

作者对香港理工大学的三位导师丁晓利教授、陈永奇教授和李志林教授的悉心指导与帮助表示诚挚的谢意，并对丁晓利教授在本书写作过程中所提出的许多宝贵建议和悉心修改表示衷心的感谢。此外，作者还对武汉大学的李德仁院士、上海天文台的郑大伟教授、西南交通大学的刘文熙教授和黄丁发教授在本研究进行过程中所给予的建议、关心、支持与帮助表示诚挚的谢意。

作者期望本书的出版能给同行学者带来方便，对他们的研究工作起到借鉴作用，为推动我国 InSAR 理论与应用研究起到积极有益的影响。尽管作者已尽最大的热情和投入来完成本书，以不辜负将要面对的诸多读者，但由于作者水平所限，书中难免存在错误和不妥之处，敬请读者不吝赐教。

刘国祥

2004年12月于成都

CONTENTS

目 录

Chapter 1
Introduction

内容提要

卫星合成孔径雷达干涉(synthetic aperture radar interferometry, InSAR)是正在发展中的、极具潜力的微波遥感新技术,其诞生至今已近 30 年的时间。起初,它主要应用于生成数字高程模型和制图,后来很快被扩展为差分干涉技术并应用于测量微小的地表形变,并已在研究地震形变、火山运动、冰川漂移、城市沉降以及山体滑坡等方面表现出了极好的应用前景。

特别地,差分雷达干涉技术具有高形变敏感度、高空间分辨率、几乎不受云雨天气制约,并具有空中遥感等突出的技术优势。它是迄今为止独一无二的基于面观测的形变遥感监测手段,可补充已有的基于点观测的低空间分辨率大地测量技术(如全球定位系统——GPS)、甚长基线干涉——VLBI 和精密水准等)。目前,欧美国家对这一技术正竞相研究,我国对 InSAR 的研究仍处于起步阶段,但已引起了国内测绘界与地学界同仁们的极大兴趣和广泛关注。随着技术的成熟,InSAR 必将为地球物理研究和形变灾害监测提供一种全新的经济的空间对地观测新途径。

虽然卫星 InSAR 新技术已逐渐开始应用于大范围区域地表形变探测,但其基础理论研究仍需扩展和加强。本章陈述了本书将以改善 InSAR 的精度和可靠性两个方面作为总体研究目标,也明确指出了与总体目标相关的研究范围,同时给出了本书写作的组织结构。

1.1 Motivation

Statement of the Issues

The earth deforms in various forms either as part of a geodynamic process or due to the effect of an engineering activity such as a mining operation and ground liquid withdrawal. It is important to study the earth deformation either to better understand the dynamics of the earth or to help to prevent/reduce the adverse effects of hazards such as earthquakes, volcanic eruptions and ground settlement.

There is a wide range of methods for the measurement of earth deformations, among which satellite InSAR possesses some prominent advantages although the method is still at the stage of intensive experimentation. InSAR has over the past two decades or so been evolving remarkably and has become a very promising space-geodetic technique (Rosen et al. 2000, Liao et al. 2003, Wang et al. 2004). The current satellite InSAR systems use the repeat-pass mode of operation, i. e., a radar sensor onboard a satellite revisiting the same ground scene periodically to form interferometers between pairs of SAR data acquisitions. By combining SAR complex images acquired at two different times, phase differences (termed interferogram) between the two acquisitions are computed to determine precisely range (sensor-to-surface distance) changes due to surface motions for corresponding pixels of the image pair (Goldstein et al. 1987, Goldstein et al. 1989, Gabriel et al. 1989).

The InSAR technique features automated data processing, and all weather, night and day capability. The interferometric deformation measurements are of great interest to geophysicists due to their high spatial resolution, competent accuracy and wide coverage. The technique can greatly complement the point-based geodetic methods such as levelling and the global positioning system (GPS). The area-based deformation mapping can be carried out without much field work, and enables remote monitoring of regional deformation fields related to, e.g., ice sheet changes, plate tectonic motions and volcanic dynamics, and urban subsidence. Therefore InSAR is viewed as one of the most exciting members of the space-geodesy family (Bürgmann et al. 2000).

Although InSAR has been increasingly used to study worldwide earth deformations, much attention has been given to geophysical interpretation or inversion of such measurements (Massonnet et al. 1998), while less effort has been made to study the quality of such measurements (Hanssen 2001, Crosetto et al. 2002). With the advance of InSAR, especially when it is transiting from experimental stage to operational stage, there is an increasing demand for assessing and controlling the quality of interferometric deformation measurements, as the suitability and reliability of the products are often in question. The importance of quality assessment and control of InSAR systems has been recognised recently by a number of researchers (Massonnet et al. 1998, Gens 1998, Stevens 1999, Rosen et al. 2000, Bürgmann et al. 2000).

A common approach for assessing the quality of interferometric deformation measurements is to compare the measurements with other type of data such as GPS measurements (Murakami et al. 1996, Massonnet et al. 1998, Rosen et al. 2000). The method is useful for general assessment of the quality of the InSAR results. It however cannot reflect all the information on the quality of the measurements. Besides, little attention has been paid to the reliability aspect of interferometric results now.

This research focuses on the assessment and improvement of the quality of deformation measurements with repeat-pass satellite InSAR. Both the accuracy and reliability aspects of interferometric deformation measurements will be studied and presented in the monograph.

Objectives of the Study

The quality of InSAR measurements may be degraded by a number of error sources. First, interferometric deformation measurements strongly rely on the quality of radar observations, particularly the phase data. Phase noise may be resulted from such factors as temporal and spatial decorrelation (Li 1990, Zebker 1992). Enhancing the signal-to-noise ratio (SNR) in interferometric phase data can help to improve the accuracy of InSAR measurements and to aid intermediate data processing such as phase-ambiguity solution (called phase unwrapping). Second, in order to remove the topographic effects, i.e., the so-called differential processing, topographic data such as the external or interferometric digital elevation models (DEM) are required. The errors in such data also affect the accuracy of the final deformation product. Third, radar system parameters, such as the baseline parameters, should be known up to the mm-accuracy level. However, even the most accurate orbit data available are only accurate to 5～10 cm for satellites with imaging radars, e.g. the ERS-1/2 (Scharroo & Visser 1998). The combined effects of the random, systematic and gross errors in the various datasets may make InSAR measurements untrustworthy.

This monograph is dedicated to the analysis and improvement of the two most important performance aspects of InSAR, the measurement accuracy and reliability. The objectives of the research are defined as:

- Systematic study of the effects of the various errors on interferometric deformation measurements;
- Investigation of methods for improvement of the accuracy of interferometric deformation measurements, including enhancing the SNR of interferometric data and refining baseline parameters;
- Analysis of the reliability of interferometric deformation measurements and development of methods for dealing with gross errors in the datasets.

1.2 Scope of the Study

The various error sources in interferometric deformation measurements will be analysed and modelled to understand their effects. Uniform error models will be presented for the three interferometric differential approaches. The results obtained will be not only useful to analysing interferometric products, but also beneficial to interferometric designs.

The effects of errors in the topographic data are somehow special. For example, some researchers consider that the effects are systematic (Murakami et al. 1996, Massonnet & Feigl 1998), while the others think that they are random (Rosen et al. 1996, Tobita et al. 1998, Ferretti et al. 2000, Crosetto et al. 2002). A series of simulation studies will be carried out to show the different effects of the errors.

Some work has been done to mainly filter the interferogram to reduce the noise in the phase data (Goldstein et al. 1988, Goldstein et al. 1998), the so-called aposteriori filter. The apriori filters will be designed in this work to filter the noise in the individual SAR complex images. The approach can enhance radar coherence more naturally, hence reducing the kernel length of the aposteriori filter to avoid unnecessary resolution reduction. Although Prati & Rocca (1993) and Gatelli et al. (1994) have demonstrated the use of the apriori filters, they only focused on filtering in the range direction. Since spatial decorrelation in the azimuth direction may also occur (Hanssen 2001), adaptive filtering algorithms for both range and azimuth dimensions will be developed and their effectiveness evaluated. Their conditions for the application of filtering are also studied.

A new approach for precise baseline estimation based on ground control points (GCPs) and the least squares method is presented. It distinguishes from the other approaches (e. g. , Small et al. 1993, Kimura 1995, Joughin et al. 1996) in the methods for baseline modelling and estimation. Baseline modelling in this study is based on the ellipsoidal reference surface instead of the commonly used planar or spherical reference surface. A combined adjustment method is also proposed instead of the commonly used parametric adjustment. Different functional and stochastic models are derived for the approach. In addition, the effects of the distribution of GCPs will be investigated through a series of simulation studies.

The concept of reliability that has been applied in conventional geodesy and photogrammetry for some years will be introduced into interferometric data modelling. Two aspects of the study will be investigated in this connection, design of distribution of GCPs/tiepoints for better geometric strength for the purpose of gross error detection, and robust estimation of model parameters to mitigate the effects of gross errors.

1.3 Structure of the Monograph

Chapter 2 will review the "state-of-the-art" method of using repeat-pass satellite InSAR for regional deformation mapping. Chapter 3 will outline the procedures for extracting surface deformations with D-InSAR. The two Chapters serve to provide the essential background for the work introduced thereafter. Chapter 4 will cover the analysis and modelling of the various errors in interferometric deformation measurements. Chapter 5 will investigate the propagation of the topographic errors in differential processing through simulation studies. Chapter 6 will be dedicated to enhancing interferometric quality by apriori filtering of the individual SAR images. Chapter 7 will present the methodology for precise determination of baseline parameters. Chapter 8 will address the reliability and robustness in interferometric modelling. Chapter 9 will give two case studies of practical deformation mapping over some tropical regions with ERS-1/2 C-band SAR images.

Chapter 2
Regional Deformation Measurement and Satellite InSAR

内容提要

卫星 InSAR 既属于微波遥感新技术，又属于空间大地测量新技术，它在区域地表形变探测的应用上已表现出明显的技术优势。

从技术构成和历史的角度来看，InSAR 是在融合"合成孔径雷达遥感成像"与"电磁波干涉"两大技术的基础上发展起来的。雷达传感器主动发射具有固定波长的微波信号，接收并记录目标反射信号（包含目标反射能量信息和反映传感器到目标距离的相位信息），每一像素信息可用一个复数来表达，因此 SAR 图像也被称为复数图像。长时间以来，人们仅仅利用 SAR 图像的强度（灰度）信息，而抛弃了 SAR 图像的相位信息。早期的雷达遥感大多基于单张 SAR 图像的灰度信息来进行地质调查、极地冰川、土地利用、植被和生态环境监测等。进入 20 世纪 70 年代，射电天文领域发展成熟的干涉技术被引入，将覆盖同一地区的两张 SAR 图像联合处理并提取对应像素的相位差（干涉相位）信息，以此恢复目标形状如建立数字高程模型，从而导致了 InSAR 的诞生。随后的技术扩展结果是差分雷达干涉，用以探测地球表面的微小形变。1989 年，NASA/JPL 的 Gabriel 等首次提出卫星差分雷达干涉的观点并发表了对 California 某地区地面垂直位移观测的实验结果，这种高分辨率、高精度和覆盖范围大的独特技术特征以及这种形变数据应用的巨大潜力极大地刺激了 InSAR 技术的快速向前发展。

从原理上来看，InSAR 正是基于卫星轨道数据或基线参数，利用具有高敏感特性的干涉相位信号来提取和分离出有用信息如地表高程或地表形变的。将覆盖同一地区的两幅雷达图像对应像素的相位值相减（即一次差分）可得到一个相位差图，即所谓干涉相位图。这些相位差信息是地形起伏和地表形变（如果存在）等综合因素的体现。因此，InSAR 数据分析和处理的焦点是干涉相位，这一点与摄影测量和可见光、近红外遥感主要利用影像灰度信息来重建三维或提取信息技术是完全不同的。

目前，机载 InSAR 系统鲜有应用于探测地表形变的，而卫星 InSAR 系统在地表形变探测中应用较多。为分离出形变信息，具有显著影响的参考趋势面和地形起伏的相位贡献必须从初始干涉相位中去除，也就是所谓的二次差分。目前存在三种二次差分模式来提取形变图，即"两轨"、"三轨"和"四轨"模式。值得指出的是，InSAR 观测得到的地表形变是斜距（传感器—地表）方向上的一维位移量，而非地面目标的三维位移。

从实际应用来看，卫星重复轨道差分干涉主要受到两大因素的制约，即时间几何失相关引起的低相位信噪比和雷达成像时不同的大气条件引入的相位延迟。时间失相关常常导致形变测量（特别在植被覆盖区）失败，几何失相关限制了有效干涉像对的可用数量，而大气效应将大大降低形变结果的精度和可靠性。当前这两个棘手问题国际上都没有得到很好的解决，这无疑制约了 InSAR 在区域形变探测等方面的普及应用。

本章将简要回顾 InSAR 的发展历史，系统地介绍 InSAR 的基本观测量、干涉相位信号分解及其数学模型和用于形变探测的差分干涉方法。从理论上分析并比较了各种已有卫星 InSAR 系统对形变量的敏感程度，从实用上分析了它们的应用局限性。

2.1 Introduction

As a new space-geodetic technology, InSAR has been proven to be a promising tool for Earth