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Quality assessment of SAR interferometric data

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ABSTRACT

Digital elevation models (DEMs) and the products derived from them are widely used for numerous applications within the geoscientific community. Radar interferometry is a new technique which can provide these digital elevation models. The increasing availability of digital elevation models has led to a growing need for assessing the quality of such models.

A common way to assess the quality of interferometrically derived DEMs is by comparison with a reference model. This is done assuming that the reference DEM is reliable and without any distortions. From the statistical point of view, the accuracy of the reference DEM should be at least one order better than the model to be tested. This study investigates the possibilities of assessing the quality of SAR interferometric data independent of any reference model.

After reviewing the technique of SAR interferometry, geometrical constraints and relevant parameters for the processing are identified. Potential applications of interferometrically derived DEMs and recent trends are also addressed. Factors influencing the quality of SAR interferometric data and the necessary steps for the processing of these data are then studied. The suitability of various data sets for SAR interferometry is investigated. Special attention is paid to the influence of each single processing step on the quality of the final interferometric product, and potential sources of error are identified. Technical details of available software packages for interferometric processing have been collected. Quality measures suitable for the assessment of DEMs are investigated focusing on the requirements of the end-product user. Some alternative techniques for the generation of digital elevation models are also described.

The key issue of this study is the development of an error propagation model as an alternative method for the quality assessment of SAR interferometric data. Results of the empirically implemented error propagation model and of the sensitivity study of the parameters used as input for the interferometric processing are evaluated. The sensitivity study emphasises the importance of good quality input data for obtaining results with the desired reliability. The empirical propagation model for the quality assessment of interferometric DEMs is applied to results from two test sites. The advantages and limitations of the empirical propagation model are pointed out and some useful recommendations for future studies are made. Finally it is concluded that the developed technique provides a useful tool for the quality assessment of SAR interferometric data.

ZUSAMMENFASSUNG

Digitale Geländemodelle und von ihnen abgeleitete Produkte finden weitreichende Anwendung in zahlreichen Geowissenschaften. SAR-Interferometrie ist eine neue Technik, die diese Geländemodelle zur Verfügung stellen kann. Die steigende Zahl von verfügbaren Geländemodellen führt zu einem wachsendem Bedarf, die Qualität dieser Modelle abzuschätzen.

Eine gebräuchliche Methode der Qualitätsabschätzung von interferometrisch erstellten Geländemodellen ist der Vergleich mit einem Referenzmodell. Dieser Vergleich beruht auf der Annahme, daß das Referenzgeländemodell zuverlässig ist und keine Verzerrungen beinhaltet. Statistisch gesehen sollte die Genauigkeit der Referenzgeländemodelle mindestens eine Größenordnung besser sein als das zu testende Modell. In dieser Arbeit wird die Möglichkeit der Qualitätsabschätzung von SAR-interferometrischen Daten unabhängig von irgendwelchen Referenzmodellen untersucht.

Nach einem Rückblick auf die interferometrische Technik werden die geometrischen Einschränkungen und die für die Datenverarbeitung relevanten Parameter identifiziert. Die potentielle Anwendung interferometrisch erstellter Geländemodelle und die jüngsten Entwicklungen werden vorgestellt. Faktoren, die die Qualität von SAR-interferometrischen Daten beeinflussen, sowie die zur Berechnung dieser Daten notwendigen Schritte werden eingehend untersucht. Spezielles Augenmerk wird dabei sowohl auf den Einfluß jedes einzelnen Verarbeitungsschrittes als auch auf die Qualität des interferometrischen Endproduktes gelegt. Dabei werden potentielles Fehlerquellen identifiziert. Technische Details der verfügbaren Softwarepakete für die interferometrische Datenverarbeitung werden zusammengestellt. Qualitätsmerkmale, die für die Bewertung von Geländemodellen geeignet sind, werden erforscht im Hinblick auf die Anforderungen der Benutzer des Endproduktes. Einige alternative Techniken zur Generierung von Geländemodellen werden ebenfalls beschrieben.

Ein Kernstück dieser Arbeit ist die Entwicklung eines Fehlerfortpflanzungsmodells als eine alternative Methode zur Qualitätsabschätzung von SAR-interferometrischen Daten. Ergebnisse eines empirisch umgesetzten Fehlerfortpflanzungsmodells und einer Sensitivitätsstudie der Parameter, die als Input der interferometrische Datenverarbeitung benutzt wurden, werden präsentiert. Die Sensitivitätsstudie unterstreicht die Bedeutung der hohen Qualität der Eingangsdaten, um die erwünschten, zuverlässigen Ergebnisse zu erhalten. Das empirische Fortpflanzungsmodell zur Qualitätsabschätzung interferometrischer Geländemodelle wird für die Ergebnisse von zwei Testgebieten angewendet. Die Vor- und Nachteile des empirischen Fehlerfortpflanzungs-modells werden aufgezeigt und einige hilfreiche Vorschläge für zukünftige Studien gemacht. Schließlich kann zusammenfassend festgestellt werden, daß die entwickelte Methode ein hilfreiches Werkzeug zur Qualitätsabschätzung SAR-interferometrischer Daten ist.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIRSAR	Airborne SAR
AODA	Attitude and Orbit Determination Avionics
ASF	Alaska SAR Facility
CCD	Charge-coupled Device (solid-state detector)
CCRS	Canada Center for Remote Sensing
CEC	Commission of the European Communities (Brussels)
CEOS	Committee on Earth Observation Satellites
CIS	Conventional Inertial System
CNES	Centre National D'Etudes Spatiales
CORISTA	Consorzio di Ricerca su Sistemi di Telesensori Avanzati
CPRF	Central Processing Reference Facility
CSR	Center of Space Research (Austin)
CTS	Conventional Terrestrial System
D-PAF	German Processing and Archiving Facility
DARA	Deutsche Agentur für Raumfahrtangelegenheiten (German Space Agency)
DASA	Deutsche Aerospace AG
DEM	Digital Elevation Model
DEOS	Delft Institute for Earth-Oriented Space Research
DLR	Deutsches Zentrum für Luft - und Raumfahrt (German Aerospace Research Establishment)
DOSAR	Dornier SAR
DTM	Digital Terrain Model
E-SAR	Experimental SAR
ERS-1	First European Remote Sensing Satellite
ERS-2	Second European Remote Sensing Satellite
ESA	European Space Agency
ESRIN	European Space Research Institute
GCP	Ground Control Point
GIS	Geographical Information System
GPS	Global Positioning System
I-PAF	Italian Processing and Archiving Facility
ICA	International Cartographic Association
INS	Inertial Navigation System
InSAR	Interferometric SAR
IRS-1C	Indian Remote Sensing Satellite
ITC	International Institute for Aerospace Survey and Earth Sciences
JERS-1	First Japanese Earth Resources Satellite
JPL	Jet Propulsion Laboratory
JRC	Joint Research Centre
LASER	Light Amplification by Stimulated Emission of Radiation
LIDAR	Light Detection And Ranging
MDA	MacDonald Dettwiler & Associates
MOMS	Modular Optoelectronic Multispectral Scanner
NASA	National Aeronautics and Space Administration (USA)

NASDA	National Space Development Agency (Japan)
NDCDB	National Digital Cartographic Data Base
NIMA	National Image and Mapping Agency (USA)
PAF	Processing and Archiving Facility
PRARE	Precise Range and Range Rate Equipment
PRF	Pulse Repetition Frequency
RADAR	Radio Detection and Ranging
rms	root mean square
RSL	Remote Sensing Laboratories
SAR	Synthetic Aperture Radar
SIR-C	Shuttle Imaging Radar (C-mission)
SLC	Single Look Complex
SNR	Signal-to-Noise Ratio
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
TIN	Triangulated Irregular Network
TOPSAR	Interferometric Radar Topographic Mapping Instrument
UK-PAF	British Processing and Archiving Facility
USGS	United States Geological Survey
WGS84	World Geodetic System from 1984
X-SAR	SAR in X-band

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1 INTRODUCTION

Digital elevation models (DEMs) are one of the most demanded products in the remote sensing community. Radar interferometry is a new technique for producing these digital elevation models. The increasing number of available DEMs stresses the importance of the quality assessment of these digital elevation models. First, the problems related to this assessment are identified. In this introductory chapter, the objectives of the research are defined and suitable research methods are proposed. Finally, the structure of the thesis is sketched out.

1.1 PROBLEM IDENTIFICATION

Radar interferometry is a technique for providing information about three-dimensional objects of the Earth's surface by using the phase content of the complex radar signal. The theoretical aspects of this technique are well studied and understood. With the availability of suitable data sets, especially after the launch of ERS-1 satellite, the potential of interferometric synthetic aperture radar (InSAR) for various geoscientific applications was investigated. Recent research mainly focuses on the limiting factors of this technique.

Radar interferometry is at the stage of becoming operational. In order to reach an operational level, there is an increasing need for quality measures for interferometric products since the user wants to know whether these products are suitable and reliable for his application. The focus of this study is on the quality assessment of digital elevation models because these are the most demanded interferometric product. DEMs are widely used within the geoscientific community e.g. for mapping purposes, geomorphological studies based on slope and aspect maps, and as a layer in geographical information systems (GIS) for combining relief data with thematic information. There is also a growing interest in the field of telecommunication. Therefore, DEMs have become key products on the market.

According to a study carried out by SPOT IMAGE (Guerre *et al.*, 1996), there is an increasing demand for high accuracy DEMs which cannot be satisfied by optical imagery. The problem of cloud coverage, especially in tropical areas, limits the suitability of optical images for the production of DEMs in some parts of the world. Radar interferometry could be the technique to fill this gap. Radar satellites such as JERS-1 and RADARSAT with their all-weather capabilities can provide nearly global coverage using on-board tape recording.

As mentioned before, DEMs are used in a wide range of applications. Despite this fact, there is still a lack of quality control. A standard procedure for this kind of assessment as well as generally accepted specifications about the accuracy of DEMs, e.g. in relation to the type of terrain or to the grid size, does not exist (Ackermann, 1996b). Research dealing with the problem of data quality is carried out in various fields. Recently, the United States Geological Survey (USGS) proposed standards for the collection, processing and quality control of DEM data for the entry into the National Digital Cartographic Data Base (USGS, 1997). The International Cartographic Association (ICA) established a commission on spatial data quality which defined seven elements to describe

the quality of data used in a GIS (Guptill and Morrison, 1995). Despite these efforts, quite a number of unsolved problems on how to treat the quality of spatial data still remain.

One of the common procedures for the quality assessment of a DEM, for example, is the comparison with a reference DEM (Lin *et al.*, 1994). This is done assuming that the reference DEM is correct and any differences are due to errors in the digital data (e.g. Giles and Franklin, 1996). Any distortions in the reference DEM remain undetected. Another critical aspect of this method is that, from the statistical point of view, the reference DEM should be one order better than the DEM to be evaluated. For an interferometrically derived DEM based on satellite data, which has on average a standard deviation of about five metres in the vertical direction (Zebker *et al.*, 1994b), a reference DEM with an accuracy of 50 centimetres is required.

1.2 OBJECTIVES AND RESEARCH METHODS

The work presented in this thesis was initiated by the CEC's Human Capital and Mobility Programme of the European Community entitled 'Synergy of Remotely Sensed Data'. The European Scientific Research Network also funded this research. Most of the network members are working in the field of geology or forestry where they combine different data sets in a synergistic way. Within this group there is a growing interest in SAR interferometric products as a complimentary data source. However, before combining these product with other data sources, the reliability of these data sets needs to be estimated.

The aim of this research is to develop a procedure for the quality assessment of SAR interferometric data. This procedure has to fulfil a number of requirements. Because suitable reference data sets are not always available, the quality control should exclude the comparison to any kind of reference, neither using a reference DEM nor ground control points (GCPs). Hence, the approach developed during this research had to be based on the quality estimation of the input parameters for the processing and also on the performance of the processing.

The focus of this research was on the quality assessment of SAR interferometric satellite data for several reasons. First of all, a large number of data sets acquired by the ERS satellites are available which are suitable for interferometric purposes and could be used for this investigation. Furthermore, the data sets have a certain level of quality, which is frequently controlled by ESA, and are processed to a CEOS standard format. The satellite systems have a configuration comparable to the airborne systems even though the latter are more complex in terms of equipment and performance (e.g. motion compensation). Thus, experience from this research could serve as a base for future studies on airborne systems. Finally, all the software packages commercially available are developed primarily to handle data sets from various satellite systems.

In this study a detailed review of the techniques used in SAR interferometry has been done. This served to identify the necessary input parameters involved in the processing. It also helped in understanding the role of different processing steps and possible sources of error. A sensitivity study was considered important as it provides information about the influence of each single input parameter on the performance of the interferometric

processing. The quality of the final output of the interferometric processing has been estimated by means of error propagation for two test sites.

In order to find suitable quality measures for SAR interferometric products, these products are defined precisely. It has to be clear which accuracy level is required in order to use an interferometric product for a certain application. The user requirements were studied to be able to provide the user with a quality measure which supports his decision on whether an interferometrically derived DEM is suitable for his application.

1.3 STRUCTURE OF THE THESIS

After this introductory chapter, the basics of SAR interferometry are reviewed in chapter 2. This includes a brief look at the InSAR history, a description of the techniques, the potential applications and the trends as well as the identification of the factors influencing the data quality.

The available data sets and interferometric processing steps such as co-registration, interferogram generation, phase unwrapping, conversion from phase to height information and geocoding of the digital elevation model are the subject of chapter 3. Each single processing step is described with emphasis on the quality aspect. Details of the available software packages are also discussed.

In chapter 4 the various alternative techniques for creating digital elevation models such as from contour lines, aerial photogrammetry, adapted radar techniques, stereoscopy using optical images and laser scanning are reviewed. The techniques for quality control are evaluated.

The factors influencing the interferometric processing such as the choice of data sets, the sensitivity of the input parameters and the processing algorithms are studied in chapter 5.

The theoretical background of error propagation and the implementation of the proposed method is developed in chapter 6. This includes the presentation of the results and a critical analysis of the advantages and limitations of this technique.

Chapter 7 concludes this thesis with final remarks and recommendations.