Radar Interferometry

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RADAR INTERFEROMETRY

Data Interpretation and Error Analysis

by

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Preface

This book is the product of five and a half years of research dedicated to the understanding of radar interferometry, a relatively new space-geodetic technique for measuring the earth's topography and its deformation. The main reason for undertaking this work, early 1995, was the fact that this technique proved to be extremely useful for wide-scale, fine-resolution deformation measurements. Especially the interferometric products from the ERS-1 satellite provided beautiful first results—several interferometric images appeared as highlights on the cover of journals such as Nature and Science. Accuracies of a few millimeters in the radar line of sight were claimed in semi-continuous image data acquired globally, irrespective of cloud cover or solar illumination. Unfortunately, because of the relative lack of supportive observations at these resolutions and accuracies, validation of the precision and reliability of the results remained an issue of concern.

From a geodetic point of view, several survey techniques are commonly available to measure a specific geophysical phenomenon. To make an optimal choice between these techniques it is important to have a uniform and quantitative approach for describing the errors and how these errors propagate to the estimated parameters. In this context, the research described in this book was initiated. It describes issues involved with different types of errors, induced by the sensor, the data processing, satellite positioning accuracy, atmospheric propagation, and scattering characteristics. Nevertheless, as the first item in the subtitle "Data Interpretation and Error Analysis" suggests, data interpretation is not always straightforward. Especially when the interferometric data consist of a superposition of topography, surface deformation, and atmospheric signal, it is important to recognize the characteristics of these signals to make a correct interpretation of the data. In this work, I hope to contribute to improved error analysis and data interpretation for radar interferometry.

This book owes significantly to the people I had the pleasure to work with during the past several years. First of all, I would like to thank Roland Klees for making it all possible, for supporting me to work abroad for such a long time, and for his supervision. My room mates Bert "Mr. Doris" Kampes and Stefania Usai provided a nice working environment and enough food for lengthy discussions.

I learned a lot from the MSc-students, whom I had the pleasure to advise during the last couple of years. Jaron Samson, Yvonne Dierikx-Platschorre, Ronald Stolk,

Claartje van Koppen, and Rens Swart, your work has contributed significantly to the results described in this book. Appendix A is based on ideas to combine GPS data with SAR interferograms for the correction or estimation of atmospheric error. The GPS data processing and analysis in this appendix was performed by Ronald Stolk and André van der Hoeven, supported by Hans van der Marel and Boudewijn Ambrosius.

The meteorological interpretation of the radar interferograms was only possible due to the close collaboration with several meteorologists. At the Royal Netherlands Meteorological Institute (KNMI) Sylvia Barlag, Frans Debie, Arnout Feijt, and many others participated in these analyses. Arnout Feijt developed the Meteosat water vapor channel parameterization using the GPS time series for one of the case studies of chapter 6, which enabled the Meteosat-InSAR validation. I am highly indebted to Tammy Weckwerth at the National Center for Atmospheric Research in Boulder, Colorado, who devoted much of her time to the interferogram interpretation leading to our Science paper. Our discussions in Boulder, as well as our email-battles improved my understanding of meteorology significantly. Stick Ware, thanks for making the link! I was introduced into the wonders of SAR amplitude imagery by Susanne Lehner, Ad Stoffelen, and Ilona Weinreich. The conformity between the observed wind patterns and the water vapor distribution provided a consistent support for the interferogram interpretation.

During the years we performed several common research projects with the Physics and Electronics Laboratory of TNO. Marco van der Kooij (now at Atlantis Scientific) and Erik van Halsema introduced me to interferometry and the Groningen land subsidence project. In a later stage, Jos Groot and Roel van Bree had a significant influence on my understanding of airborne interferometry (PHARUS) and in the Tianjin land subsidence project with EARS. At the Survey Department of Rijkswaterstaat, Erik de Min, Jur Vogelzang, and Yvonne Dierikx actively pursued the “practical relevance” issue, which kept me on track from time to time.

During my stay at the Institut für Navigation at Stuttgart University, Karl-Heinz Thiel, Jürgen Schmidt, and dr. Wu enabled me to obtain valuable experience in interferometric data processing. My roots in the understanding of radar lie at DLR-DFD in Oberpfaffenhofen. I am grateful to Richard Bamler, Michael Eineder, Nico Adam, and many others for giving me the opportunity to work with them, which was pleasing in many ways. At Stanford University I owe much to Howard Zebker for his support and hospitality. Discussions with him, Paul Segall, Sjonni Jónsson, and Weber Hoen were always enlightening. Now at the University of Hawaii, Falk Amelung was my tutor in geophysics. Falk, aloha for the Cerro Prieto Friday afternoon analysis. I am indebted to Ewa Glowacka at CICESE, Ensenada, and CFE, Mexico for their support in the Cerro Prieto study. David Sandwell is gratefully acknowledged for inviting me to visit Scripps Institution of Oceanography, which was a great experience.

Many people contributed to the GISARE field experiment, including the meteorological, the leveling, the GPS, and the SAR processing part. Installing corner reflectors in frozen ground at –15°C requires special skills, we had a great team. Although the GPS-SAR experiment during the solar eclipse in 1999 failed to produce an ob-

servable ionospheric signal in the interferograms, it provided good experience thanks to all people contributing.

Special thanks go to Herman Russchenberg for his droplets, Michel Decré for fig. 2.1A, Riccardo Riva and Bert Vermeersen for the Izmit earthquake analysis, and Remko Scharroo for his precise satellite orbits.

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Freek van der Meer, series editor, and Petra van Steenbergen at Kluwer Academic Publishers are gratefully acknowledged for making the monograph publication of this work possible in the *Remote Sensing and Digital Imaging Processing* series.

This book could not have been completed without the research funds of the Cornelis Lely Stichting, the Survey Department of Rijkswaterstaat, the European Space Agency, the Fulbright program, the Universiteitsfonds, and Shell International Production and Exploration B.V. All ERS SAR data were kindly provided by ESA. Meteorological data were made available by the Royal Netherlands Meteorological Institute (KNMI). Maps and visualizations have been implemented in GMT (Wessel and Smith, 1998) and in Matlab™.

Finally, I would like to thank Ardis for her understanding and support and for all the time I stole from her. I'm excited about the future with the three of us.

Ramon Hanssen
Delft, December 2000

Summary

Within a decade, imaging radar interferometry has matured to a widely used geodetic technique for measuring the topography and deformation of the earth. In particular the analysis and interpretation of the interferometric data requires a thorough understanding of the principles of the technique, the (potential) error sources, and the error propagation. This book reviews the basic concepts of radar, imaging radar, and radar interferometry, and revisits the processing procedure for obtaining interferometric products such as a digital elevation model or a deformation map. It describes spaceborne repeat-pass radar interferometry using a linear or Gauss-Markoff model formulation, which relates the interferometric observations to the unknown geophysical parameters. The stochastic part of the model describes the dispersion of the observations in terms of variances and covariances. Especially the influence of spatially correlated errors as induced by the satellite orbits and by atmospheric path delay are discussed. Mathematical models are presented that describe the spatial variability in the interferometric phase due to turbulent mixing of atmospheric refractivity and due to vertical atmospheric stratification. Using 52 SAR acquisitions, a systematic inventory of the characteristics of atmospheric signal in the radar interferograms is performed, using complementary meteorological data for the interpretation. Scaling characteristics are observed, which can be conveniently used to describe the power spectrum and covariance function of the atmospheric signal. The final variance-covariance matrix for the radar interferometric data is presented, including these spatially varying error sources. A number of case studies on deformation monitoring, such as land subsidence, earthquake deformation, and artificial reflector movement serve as examples of the application of interferometry and its error sources. The feasibility of the technique for practical geodetic applications is evaluated in relation to the geophysical phenomena of interest, yielding rules-of-thumb for its utilization. Finally, a novel application of interferometry for atmospheric studies, termed Interferometric Radar Meteorology, is presented and discussed. Maps of the vertically integrated water vapor distribution during the radar acquisitions can be obtained with a fine spatial resolution and a high accuracy. Several demonstration studies of this meteorological application are presented.

Nomenclature

List of acronyms

1D	One-Dimensional
2D	Two-Dimensional
ALD	Azimuth Look Direction
ALOS	Advanced Land Observing Satellite
AMI	Active Microwave Instrument
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
AVHRR	Advanced Very High Resolution Radiometer
BTTB	Block-Toeplitz Toeplitz-Block
CFE	Comisión Federal de Electricidad, Mexico
CLARA'96	Clouds and Radiation experiment 1996
CMOD4	C-band Model 4 (empirically derived model function to relate normalized radar cross-section with wind speed and direction)
CNES	Centre National D'Etudes Spatiales
CPGF	Cerro Prieto Geothermal Field
CSA	Canadian Space Agency
CTRS	Conventional Terrestrial Reference System
DEM	Digital Elevation Model
DEOS	Delft Institute for Earth-Oriented Space Research
DFD	Deutsches Fernerkundungsdatenzentrum (German Remote Sensing Data Center)
DIAL	Differential Absorption Lidar
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center)
DPWV	Differential Precipitable Water Vapor
DUT	Delft University of Technology
ERS	European Remote Sensing Satellite
ESA	European Space Agency
fBm	Fractional Brownian Motion
FFA	Far Field Approximation
FFT	Fast Fourier Transform
FM	Frequency Modulated
GISARE	Groningen Interferometric SAR Experiment
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
IERS	International Earth Rotation Service
IGS	International GPS Service for Geodynamics
InSAR	Interferometric SAR / SAR interferometry
IPW	Integrated Precipitable Water
I/Q	In-Phase (real), Quadrature (imaginary)
IRM	Interferometric Radar Meteorology

ITRF	IERS Terrestrial Reference Frame
JERS	Japanese Earth-Resources Satellite
JPL	Jet Propulsion Laboratory
LOS	Line of Sight
LT	Local Time
MCF	Minimal Cost Flow
MIT	Massachusetts Institute of Technology
MSC	Mesoscale Shallow Convection
NAM	Nederlandse Aardolie Maatschappij B.V.
NAP	Normaal Amsterdams Peil (Dutch vertical reference datum)
NASA	National Aeronautics and Space Administration
NASDA	National Aeronautics and Space Development Agency (Japan)
NDVI	Normalized Differential Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
PAF	Processing and Archiving Center
PDF	Probability Density function
PLW	Precipitable Liquid Water
PRARE	Precise Range and Rate Equipment
PRF	Pulse Repetition Frequency
PWV	Precipitable Water Vapor
radar	Radio detection and ranging
RAR	Real Aperture Radar
RCS	Radar Cross Section
RH	Relative Humidity
RMS	Root Mean Square
RRF	Range Reference Function
SAR	Synthetic Aperture Radar
s/c	Spacecraft
SIR	Shuttle Imaging Radar, Spaceborne Imaging Radar
SLAR	Side Looking Airborne Radar
SLC	Single-Look Complex
SLR	Satellite Laser Ranging / (Side Looking Radar)
SNR	Signal-to-Noise Ratio
SPOT	System Probatoire d'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SWST	Sampling Window Start Time
TEC	Total Electron Content
TECU	Total Electron Content Unit
TID	Traveling Ionospheric Disturbance
UTC	Universal Coordinated Time
VLBI	Very Long Baseline Interferometry
VTEC	Vertical Total Electron Content
WGS84	World Geodetic Survey 1984
WV	Water Vapor
X-SAR	X-band Synthetic Aperture Radar

List of symbols

^{0}	Initialization value, usually determined for reference surface
$\mathbf{A}$	Design matrix
$\mathbf{A}_k$	Part of the design matrix corresponding to observation k
B	Baseline
$B_\parallel$	Parallel baseline
$B_\perp$	Perpendicular baseline
$B_\perp^0$	Perpendicular baseline for range to resolution cell on the reference surface
$B_{\perp,\mathrm{crit}}$	Critical (perpendicular) baseline
B_h	Horizontal baseline

B_v	Vertical baseline
B_A	Azimuth time bandwidth
B_R	Range bandwidth
B_{Dop}	Doppler bandwidth
c	Speed of light = 299792458 m/s
C	Structure function coefficient
$\mathbf{C}_{\hat{\mathbf{x}}}$	Variance-covariance matrix of the estimated parameters
$\mathbf{C}_{\varphi}$	Variance-covariance matrix
$\mathbf{C}_{\mathbf{s}}$	Variance-covariance matrix of atmospheric delay
D_a	Antenna width (m)
$D\{.\}$	Dispersion operator, second moment, or variance-covariance matrix
D_i	Fractal dimension for a i-dimensional signal
D_k	Slant deformation for observation k
D_χ	Structure function of parameter χ
$E\{.\}$	Expectation operator, ensemble average, first moment, or mean
e	Partial pressure of water vapor (hPa)
f	Frequency
f_0	Carrier (center) frequency
f_{D}	Doppler frequency
f_{DC}	Doppler centroid frequency
f_P	Pulse repetition frequency (PRF) (cycles/m)
f_ϕ	Fringe frequency
h_p	Altitude of point p
h_{sp}	Height of the sub-ionospheric point (m)
$h_{2\pi}$	Height ambiguity (m)
H	Altitude; Haussdorff measure
H_k	Topographic height for observation k
I	Integrated Precipitable Water
k	Wavenumber
L	Effective number of looks
L_a	Antenna length (m)
L1,L2	GPS carrier phase frequencies (Ll=l.57542 GHz, L2=l.22760 GHz)
L3	GPS ionospheric-free linear combination
m	Number of observations
n	Number of parameters (unknowns)
n_e	Electron content (m^{-3})
$n_{\parallel}$	Parallel error baseline
$n_{\perp}$	Perpendicular error baseline
N	Refractivity, Geoid height
pdf	Probability density function
P	Total atmospheric pressure (hPa)
P_χ	Power spectrum of parameter χ
$\mathbf{Q}_{\varphi}$	Real positive-semidefinite cofactor matrix
R	(Slant) range (m)
R_1	Slant range between reference (master) satellite and resolution cell (m)
R_2	Slant range between secundary (slave) satellite and resolution cell (m)
s_c	Chirp rate or Frequency slope (s^{-2})
$S_k^{t_i}$	Slant atmospheric delay for pixel k at t_i (m)
t	Time (s)
T	Temperature (K)
v	Velocity (m/s)
v	Hermitian product $y_1 y_2^*$
$v_{s/c}$	Velocity of spacecraft (m/s)
w_k	Integer ambiguity number
W	Liquid water content ($\mathrm{g\ m}^{-3}$)
$W\{.\}$	Wrapping operator $= \mathrm{mod}\{\phi + \pi, 2\pi\} - \pi$
W_a	Radar footprint width in azimuth (3dB)
$\mathbf{x}$	Vector of parameters
$\hat{\mathbf{x}}$	Best linear unbiased estimator of the unknown parameters $\mathbf{x}$

$\vec{X}_{s/c}$	State vector of spacecraft
y_i	Complex observation (phasor) i
$Z(u,v)$	Amplitude spectrum of interferogram (u and v are wavenumbers)
$Z'(u,v)$	Amplitude spectrum of filtered interferogram
α	Baseline orientation angle; Spectral exponent
β	Error baseline orientation angle; Spectral index
β_r	Angular beamwidth in range direction (rad)
β_a	Angular beamwidth in azimuth direction (rad)
γ	Coherence (complex)
γ_{geom}	Coherence reduction due to geometric (baseline) decorrelation
γ_{DC}	Coherence reduction due to Doppler centroid decorrelation
$\gamma_{\mathrm{temporal}}$	Coherence reduction due to temporal decorrelation
γ_{vol}	Coherence reduction due to volume decorrelation
$\gamma_{\mathrm{processing}}$	Coherence reduction due to processing induced decorrelation
$\gamma_{\mathrm{thermal}}$	Coherence reduction due to thermal noise
Γ_χ	Semi-variogram of parameter χ
$\partial\theta$	Change in look angle
Δ_a	Focused azimuth resolution
Δ_r	Slant range resolution
ΔR	Slant range difference
$\Delta R_{\mathrm{defo},p}$	Slant range difference due to deformation
$\boldsymbol{\epsilon}$	Vector of observation errors
ζ	Local terrain slope w.r.t. reference surface (positive towards the radar): $\zeta = \theta_{\mathrm{inc}} - \theta_{\mathrm{loc}}$
θ	Look angle
θ_{inc}	Incidence angle, defined with respect to the global vertical at the scene
θ_{loc}	Local incidence angle, defined with respect to the local vertical at the scene: $\theta_{\mathrm{loc}} = \theta_{\mathrm{inc}} - \zeta$
ϑ	Reference phase (rad)
κ	$4\pi/\lambda$
λ	Radar wavelength
Λ	Geographic longitude in WGS84
μ	Mean
ρ	Local earth radius (m); Horizontal distance between two resolution cells.
ρ_χ	Autocorrelation function of parameter χ
σ^2	a priori variance factor
σ^0	"Sigma nought" or Radar Cross Section (RCS). Average power reflectivity or scattering coefficient per unit surface area
τ	Pulse length
τ_c	Effective pulse length
ϕ	Absolute interferometric phase, including reference phase
ϕ^{w}	Wrapped interferometric phase, including reference phase
Φ	Geographic latitude in WGS84
ϕ_r	Off-center beam angle in range direction (rad)
ϕ_a	Off-center beam angle in azimuth direction (rad)
ϕ_s	Squint angle (rad)
ϕ_N	Phase noise (rad)
φ	Absolute interferometric phase, reference phase subtracted
φ^{w}	Wrapped interferometric phase, reference phase subtracted
φ_k	Stochastic phase observation
$\boldsymbol{\varphi}$	Real stochastic vector of observations
ψ	Phase (rad)
ψ_{scat}	Scattering contribution to the phase value (rad)
Ω_k	Ratio between $B_\perp$ of deformation pair and $B_\perp$ of topographic pair
$\mathbb{N}$	Set of natural numbers
$\mathbb{R}$	Set of real numbers
$\mathbb{Z}$	Set of integer numbers
$\mathbb{C}$	Set of complex numbers
$\mathscr{F}$	Fourier transform