

GNSS Remote Sensing

Remote Sensing and Digital Image Processing

VOLUME 19

Series Editor:

Freek D. van der Meer
*Department of Earth Systems Analysis
International Institute for
Geo-Information Science and
Earth Observation (ITC)
Enschede, The Netherlands*
&
*Department of Physical Geography
Faculty of Geosciences
Utrecht University
The Netherlands*

Editorial Advisory Board:

Michael Abrams
*NASA Jet Propulsion Laboratory
Pasadena, CA, U.S.A.*

Paul Curran
*University of Bournemouth, U.K.
Finland*

Arnold Dekker
*CSIRO, Land and Water Division
Canberra, Australia*

Steven M. de Jong
*Department of Physical Geography
Faculty of Geosciences
Utrecht University, The Netherlands*

Michael Schaepman
*Department of Geography
University of Zurich, Switzerland*

EARSeL Series Editor:

André Marçal
*Department of Mathematics
Faculty of Sciences
University of Porto
Porto, Portugal*

EARSeL Editorial Advisory Board:

Mario A. Gomarasca
CNR - IREA Milan, Italy

Martti Hallikainen
*Helsinki University of Technology
Finland*

Håkan Olsson
*University of Zurich, Switzerland
Swedish University
of Agricultural Sciences
Sweden*

Eberhard Parlow
*University of Basel
Switzerland*

Rainer Reuter
*University of Oldenburg
Germany*

For further volumes:

<http://www.springer.com/series/6477>

Shuanggen Jin • Estel Cardellach • Feiqin Xie

GNSS Remote Sensing

Theory, Methods and Applications

 Springer

Shuanggen Jin
Shanghai Astronomical Observatory
Chinese Academy of Sciences
Shanghai, China
People's Republic

Estel Cardellach
Institut d'Estudis Espacials de Catalunya
(ICE/IEEC-CSIC)
Barcelona, Spain

Feiqin Xie
Texas A&M University-Corpus Christi
Corpus Christi
TX, USA

ISSN 1567-3200

ISBN 978-94-007-7481-0

ISBN 978-94-007-7482-7 (eBook)

DOI 10.1007/978-94-007-7482-7

Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2013950927

© Springer Science+Business Media Dordrecht 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

The Global Navigation Satellite System (GNSS) has provided an unprecedented high accuracy, flexibility and tremendous contribution to navigation, positioning, timing and scientific questions related to precise positioning on Earth's surface, since Global Positioning System (GPS) became fully operational in 1994. Since GNSS is characterized as a highly precise, continuous, all-weather and near-real-time microwave (L-band) technique, additional more applications and potentials of GNSS are being explored by scientists and engineers. When the GNSS signal propagates through the Earth's atmosphere, it is delayed by the atmospheric refractivity. GNSS radio occultation together with ground GNSS have been used to produce accurate, all-weather, global refractive index, pressure, density profiles in the troposphere, temperature with up to the lower stratosphere (35–40 km), and the ionospheric total electron content (TEC) as well as electron density profiles, to improve weather analysis and forecasting, monitor climate change, and monitor ionospheric events. Therefore, GNSS has great potentials in atmospheric sounding, meteorology, climatology and space weather.

In addition, surface multi-path is one of main error sources for GNSS navigation and positioning. It has recently been recognized, however, that the special kind of GPS multi-path delay reflected from the Earth's surface, could be used to sense the Earth's surface environments. A recent interesting result on fluctuations in near surface soil moisture has been successfully retrieved from the ground GNSS multi-path, fairly matching soil moisture fluctuations in soil measured with conventional sensors. In addition, the space-borne GNSS received delay of the GNSS reflected signal with respect to the rough surface could provide information on the differential paths between direct and reflected signals. Together with information on the receiver antenna position and the medium, the delay measurements associated with the properties of the reflecting surface can be used to produce the surface roughness parameters and to determine surface characteristics. The Bistatic radar using L-band signals transmitted by GNSS can be as an ocean altimeter and scatterometer. A number of experiments and missions using GNSS reflected signals from the ocean

and land surface have been tested and applied, such as determining ocean surface height, wind speed and wind direction of ocean surface, soil moisture, snow and ice thickness.

Therefore, the refracted, reflected and scattered GNSS signals can image the Earth's surface environments as a new, highly precise, continuous, all-weather and near-real-time remote sensing tool, which is expected to revolutionize various atmospheric sounding, ocean remote sensing and land/hydrology mapping, especially for various Earth's surfaces and the atmosphere. With the development of the next generation of multi-frequency and multi-system GNSS constellations, including the US's modernized GPS-IIF and planned GPS-III, Russia's restored GLONASS, and the coming European Union's GALILEO system and China's Beidou/COMPASS system as well as a number of Space Based Augmentation Systems, such as Japan's Quasi-Zenith Satellite System (QZSS) and India's Regional Navigation Satellite Systems (IRNSS), more applications and opportunities will be exploited and realized using new onboard GNSS receivers on future space-borne GNSS reflectometry and refractometry missions in the near future.

GNSS Remote Sensing –Theory, Methods and Applications has been written as a monograph and textbook that guides the reader through the theory and practice of GNSS remote sensing and applications in the atmosphere, oceans, land and hydrology. This book covers Chap. 1: Introduction to GNSS, Chap. 2: GNSS Atmospheric and Multipath Delays, Chap. 3: Ground GNSS Atmospheric Sensing, Chap. 4: Ground-Based GNSS Ionospheric Sounding, Chap. 5: Theory of GNSS Radio Occultation, Chap. 6: Atmospheric Sensing using GNSS RO, Chap. 7: Ionospheric Sounding using GNSS-RO, Chap. 8: Theory of GNSS Reflectometry, Chap. 9: Ocean Remote Sensing using GNSS-R, Chap. 10: Hydrology and Vegetation Remote Sensing, Chap. 11: Cryospheric Sensing using GNSS-R and Chap. 12: Summary and Future Chances. Chapters 1, 2, 3, 4, 7, 10, 11 and 12 were contributed from Prof. Shuanggen Jin, Chaps. 5 and 6 were contributed from Dr. Feiqin Xie, Chaps. 8 and 9 and part of Chap. 11 were contributed from Dr. Estel Cardellach as well as some contributions from Rui Jin and Xuerui Wu.

This book provides the theory, methods, and applications of GNSS Remote Sensing for scientists and users who have basic GNSS background and experiences. Furthermore, it is also useful for the increasing number of next generation multi-GNSS designers, engineers and users community. We would like to thank Assistant Editor's help and Springer-Verlag for their cordial collaboration and help during the process of publishing this book.

Shanghai, People's Republic of China
Barcelona, Spain
Corpus Christi, TX, USA

Shuanggen Jin
Estel Cardellach
Feiqin Xie

Contents

Part I GNSS Theory and Delays

1	Introduction to GNSS	3
1.1	GNSS History	3
1.1.1	GPS	3
1.1.2	GLONASS	5
1.1.3	GALILEO	6
1.1.4	Beidou/COMPASS	7
1.1.5	Other Regional Systems	7
1.2	GNSS Systems and Signals	8
1.2.1	GNSS Segments	8
1.2.2	GNSS Signals	10
1.3	GNSS Theory and Errors	11
1.3.1	GNSS Principle	12
1.3.2	GNSS Error Sources	12
1.4	GNSS Observations and Applications	13
1.4.1	GNSS Observation Network	13
1.4.2	GNSS Applications	14
	References	16
2	GNSS Atmospheric and Multipath Delays	17
2.1	Atmospheric Refractivity	17
2.2	GNSS Atmospheric Delays	18
2.2.1	Neutral Atmospheric Delays	18
2.2.2	Empirical Tropospheric Models	19
2.3	GNSS Ionospheric Delay	20
2.3.1	The Ionosphere	20
2.3.2	GNSS Ionospheric Delay	21
2.3.3	Empirical Ionospheric Models	24

- 2.4 GNSS Multipath Delay 25
 - 2.4.1 Multipath Effects 25
 - 2.4.2 Multipath Variations 27
 - 2.4.3 Surface Reflection Characteristics 29
- References 30

Part II GNSS Atmospheric Sensing and Applications

- 3 Ground GNSS Atmospheric Sensing 33**
 - 3.1 Introduction 33
 - 3.2 Theory and Methods 34
 - 3.2.1 Estimates of GNSS ZTD 34
 - 3.2.2 Mapping Functions 35
 - 3.3 ZTD Estimate and Variations 37
 - 3.3.1 ZTD Estimates from IGS Observations 37
 - 3.3.2 Multi-Scale ZTD Variations 40
 - 3.4 GNSS Precipitable Water Vapor 51
 - 3.4.1 GNSS PWV Estimate 51
 - 3.4.2 Comparison with Independent Observations 52
 - 3.4.3 Mean PWV Characteristics 53
 - 3.4.4 Seasonal PWV Variations 55
 - 3.4.5 Diurnal PWV Variations 57
 - 3.5 3-D Water Vapor Topography 57
 - 3.6 Summary 58
 - References 58
- 4 Ground GNSS Ionosphere Sounding 61**
 - 4.1 History 61
 - 4.2 GNSS Ionospheric Sounding 63
 - 4.2.1 DCB Determination 65
 - 4.2.2 TEC Estimate 70
 - 4.3 2-D Ionospheric Mapping 71
 - 4.3.1 Method of 2-D Ionospheric Mapping 71
 - 4.3.2 Applications of 2-D GNSS TEC 74
 - 4.4 3-D GNSS Ionospheric Mapping 79
 - 4.4.1 3-D Ionospheric Topography 79
 - 4.4.2 Validation of GNSS Ionospheric Tomography 81
 - 4.4.3 Assessment of IRI-2001 Using GNSS Tomography 82
 - 4.4.4 Ionospheric Slab Thickness 85
 - 4.4.5 3-D ionospheric Behaviours to Storms 88
 - References 90
- 5 Theory of GNSS Radio Occultation 93**
 - 5.1 Introduction 93
 - 5.1.1 Radio Occultation in Planetary Sciences 93
 - 5.1.2 GNSS Radio Occultation in Earth Sciences 94

- 5.2 Principle of GNSS Radio Occultation 98
 - 5.2.1 Atmospheric Refraction 99
 - 5.2.2 Geometric Optics Approximation 100
 - 5.2.3 Spherically Symmetric Atmosphere Assumption 101
 - 5.2.4 Bending Angle and Refractive Index 102
- 5.3 GNSS Radio Occultation Processing 104
 - 5.3.1 Calibrating and Extracting GNSS RO Observables 104
 - 5.3.2 Bending Angle Retrieval 110
 - 5.3.3 Ionosphere Retrieval 113
 - 5.3.4 Neutral Atmosphere Retrieval 115
- References 117
- 6 Atmospheric Sensing Using GNSS RO 121**
 - 6.1 GNSS RO Atmospheric Sounding 121
 - 6.1.1 Parameters Retrieval from GNSS RO 121
 - 6.1.2 Dry Atmosphere Retrieval (Density, Pressure and Temperature) 122
 - 6.1.3 Moist Atmosphere Retrieval 123
 - 6.1.4 1D-Var (Variational Method) 124
 - 6.2 Characteristics of GNSS RO Observations 124
 - 6.2.1 Spatial Resolution (Vertical and Horizontal Resolution) . 126
 - 6.2.2 Accuracy and Precision Analysis 126
 - 6.2.3 Measurement Errors 127
 - 6.2.4 Calibration Errors 129
 - 6.2.5 Retrieval Errors 130
 - 6.2.6 Experimental Validation of RO Accuracy and Precision . 135
 - 6.3 Dynamic Processes Studies with GNSS RO 136
 - 6.3.1 Tropopause and Stratospheric Waves 137
 - 6.3.2 Tropical Tidal Waves 138
 - 6.3.3 Weather Front 138
 - 6.3.4 Tropical Cyclones (TC) 139
 - 6.3.5 Atmospheric Boundary Layer (ABL) 140
 - 6.4 Weather Prediction Applications 141
 - 6.4.1 GNSS RO Data Assimilation 141
 - 6.4.2 Operational Assimilation of GNSS RO in NWP Models 142
 - 6.5 Climate Applications 143
 - 6.6 Future Application of Radio Occultation 146
 - 6.6.1 Future GNSS and GNSS RO Missions 146
 - 6.6.2 Airborne and Mountain-Top GNSS RO 146
 - 6.6.3 LEO-to-LEO Occultation 149
 - References 150

7 Ionospheric Sounding Using GNSS-RO 159

7.1 Introduction 159

7.2 Ionospheric Inversion 159

7.2.1 Ionosphere Inversion Based on Doppler 161

7.2.2 Ionosphere Inversion Based on TEC 163

7.2.3 Recursive Inversion of TEC 164

7.2.4 Amplitude Inversion 165

7.3 Error Analysis 166

7.3.1 Measurement Errors 166

7.3.2 Data Processing Errors 167

7.4 Ionospheric Products 167

7.5 GNSS-RO Ionospheric Applications 168

7.5.1 Establishing Ionospheric Models 168

7.5.2 Ionospheric Tomography 168

7.5.3 Monitoring Ionospheric Anomalies 169

7.5.4 Ionospheric Scintillation 170

References 170

Part III GNSS Reflectometry and Remote Sensing

8 Theory of GNSS Reflectometry 175

8.1 Introduction 175

8.2 Multi-static System: Geometry and Coverage 177

8.3 Specular and Diffuse Scattering 178

8.4 Delay and Doppler 184

8.5 Reflectivity Levels and Polarization Issues 188

8.6 Scattering Theories 192

8.6.1 Kirchhoff or Tangent Plane Approximation (KA) 194

8.6.2 Summary of Other Methods 198

8.6.3 Received GNSS Scattered Fields 199

8.6.4 The Bi-static Radar Equation for GNSS
Modulated Signals 201

8.7 Noise and Coherence Issues 203

8.8 Systematic Errors 205

8.9 PARIS Interferometric Technique (PIT) 206

8.10 Observables 208

References 211

9 Ocean Remote Sensing Using GNSS-R 215

9.1 Altimetry 215

9.1.1 Group Delay Altimetry 221

9.1.2 Atmospheric Corrections 224

9.1.3 GNSS-R Ocean Altimetric Performance 225

9.2 Ocean Surface Roughness 227

9.2.1 Surface Modelling 228

9.2.2 Retrieval Approaches 234

References 236

- 10 Hydrology and Vegetation Remote Sensing**..... 241
 - 10.1 Introduction..... 241
 - 10.2 Hydrology GNSS-Reflectometry 242
 - 10.3 Hydrology Sensing from GNSS-R 243
 - 10.3.1 Waveform Correlation 243
 - 10.3.2 Interference Pattern Technique (IPT) 244
 - 10.3.3 Hydrology Sensing from GNSS 245
 - 10.3.4 GNSS-R Scattering Properties 246
 - 10.3.5 GNSS-R Polarization 247
 - 10.4 GNSS-R Forest Biomass Monitoring 248
 - 10.5 Summary..... 249
 - References..... 249
- 11 Cryospheric Sensing Using GNSS-R** 251
 - 11.1 Dry Snow Monitoring 251
 - 11.1.1 Dry Snow Reflection Model: Multiple-Ray
Single-Reflection 252
 - 11.1.2 Dry Snow Observable: Lag-Hologram 255
 - 11.2 Wet Snow Monitoring 257
 - 11.2.1 Observations from Space-Borne GNSS-R 257
 - 11.2.2 Observations from Ground GNSS-R 258
 - 11.3 Sounding the Sea Ice Conditions 259
 - References..... 259
- 12 Summary and Future Chances**..... 261
 - 12.1 Status of GNSS Remote Sensing 261
 - 12.1.1 Atmospheric Sensing 261
 - 12.1.2 Ocean Sensing 262
 - 12.1.3 Hydrology Sensing 262
 - 12.1.4 Cryosphere Mapping 263
 - 12.2 Future Developments and Chances 263
 - 12.2.1 More GNSS Networks and Constellations 263
 - 12.2.2 Advanced GNSS Receivers 263
 - 12.2.3 New Missions and Systems 265
 - 12.2.4 New and Emerging Applications 266
 - 12.3 Summary..... 267
 - References..... 268
- Index**..... 271

Acronyms

ABL	Atmospheric Boundary Layer
AGW	Acoustic Gravity Wave
ART	Algebraic Reconstruction Technique
AMSR-E	Advanced Microwave Scanning Radiometer for Earth Observing System
AODC	Attitude and Orbit Determination and Control
BDS	Beidou Navigation System
BOC	Binary Offset Carrier
BPSK	Binary Phase Shift Keying
C/A	Coarse/Acquisition
CAS	Chinese Academy of Sciences
CDMA	Code Division Multiple Access
CHAMP	Challenging Mini-satellite Payload
COADS	Comprehensive Ocean-Atmosphere Data Set
CL	Close-loop
CMONC	Crustal Movement Observation Network of China
CODE	Center for Orbit Determination in Europe
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CICERO	Climate Community Initiative for Continuing Earth Radio Occultation
CIT	Computerized Ionospheric Tomography
CYGNSS	CYclon GNSS
DCB	Differential Code Biases
DD	Double Difference
DDM	Delay-Doppler Map
DMC	Disaster Monitoring Constellation
DGPS	Differential GPS
DMC	Disaster Monitoring Constellation
DMSS	Directional Mean Square Slope
DNSS	Defense Navigation Satellite System

DOD	Department of Defense
DORIS	Doppler Orbitography Radio positioning Integrated by Satellite
DOT	Department of Transportation
ECMWF	European Centre for Medium-Range Weather Forecasts
EGNOS	European Geostationary Navigation Overlay Service
ESA	European Space Agency
EST	Equivalent Slab Thickness
EU	European Union
FFT	Fast Fourier Transform
FDMA	Frequency Division Multiple Access
FIO	Fourier Integral Operators
Galileo	Global Navigation Satellite System of EU
GAGAN	GPS Aided Geo Augmented Navigation
GAMIT	GPS analysis software by Massachusetts Institute of Technology
GBAS	Ground-Based Augmentation Systems
GDOP	Geometric Dilution of Precision
GEO	Geostationary Earth Orbit
GFZ	GeoForschungsZentrum Potsdam
GIPSY-OASIS	GNSS-Inferred Positioning System and Orbit Analysis
GLONASS	Global Navigation Satellite System of Russia
GMF	Global Mapping Function
GNSS	Global Navigation Satellite Systems
GO	Geometric Optics
GOLD-RTR	GPS Open-Loop Differential Real-Time Receiver
GPS	Global Positioning System
GPS/MET	GPS/Meteorology
GNSS-R	GNSS-Reflectometry
griPAU	GNSS Reflectometer Instrument for the Passive Advanced Unit
GRACE	Gravity Recovery and Climate Experiment
GTS	Global Telecommunication System
HFI	Hardy Function Interpolation
IAG	International Association of Geodesy
IIEC	Institute for Space Studies of Catalonia
IERS	International Earth Rotation Service
IEM	Integral Equation Method
IGS	International GNSS Service
IGOR	Integrated GPS and Occultation Receiver
IPT	Interference Pattern Technique
IPP	Ionosphere Pierce Point
IRNSS	India's Regional Navigation Satellite Systems
IRI	International Reference Ionospheric
ITRF	IERS Terrestrial Reference Frame
JPL	Jet Propulsion Laboratory
KA	Kirchho Approximations
KPO	KA in Physical Optics Approximation

KGO	Kirchhoff Geometrical Optics
LAAS	Local Area Augmentation System
LC	Linear Combination
LEO	Low Earth Orbit (satellite)
LHCP	Left-Hand Circular Polarization
LOS	Line-of-Sight
LS	Least Squares (adjustment)
MEO	Medium Earth Orbit
MIT	Massachusetts Institute of Technology
MSU	Microwave Sounder Unit
MSAS	Multifunction Satellite Augmentation System
MSS	Mean of the Square Slopes
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NMF	Niell Mapping Function
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
NOC	National Oceanography Centre
OCX	Operational Control System
PARIS	PAssive Reflectometry Interferometric System
PDF	Probability Density Function
PGGA	Permanent GPS Geodetic Array
PIT	PARIS Interferometric technique
PLL	Phase-Locked Loop
PNT	Positioning, Navigation and Timing
POD	Precise Orbit Determination
PPP	Precise Point Positioning
PWV	Precipitable Water Vapor
PRN	Pseudo-Random Noise
PVT	Position, Velocity and Time
RINEX	Receiver Independent Exchange
QZSS	Quasi-Zenith Satellite System
RFI	Radio Frequency Interference
RMS	Root Mean Square
RT	Radiative Transfer
RTK	Real-Time Kinematic
RO	Radio Occultation
RHCP	Right-Hand Circular Polarization
SA	Selective Availability
SAR	Synthetic Aperture Radar
SAC-C	Satellite de Aplicaciones Cientificas-C
SBAS	Ground- and Space-Based Augmentation Systems
SGR-ReSI	Space GPS Receiver-Remote Sensing Instrument
SHAO	Shanghai Astronomical Observatory

SLM	Single Layer Model
SMEX02	Soil Moisture Experiment 2002
SMIGOL	Soil Moisture Interference-pattern GNSS Observations at L-band
SMOS	Soil Moisture and Ocean Salinity
SMAP	Soil Moisture Active and Passive mission
SNR	Signal-to-Noise Ratio
SOL	Safety-of-Life
SSC	Surrey Space Centre
SSTL	Surrey Satellite Technology Limited
SD	Single Difference
SINEX	Software Independent Exchange (format)
SLM	Single Layer Model
SLR	Satellite Laser Ranging
SNR	Signal-to-Noise Ratio
SPM	Small Perturbation Method
SSA	Small Slope Approximation
SST	Satellite-Satellite Tracking
SSTL	Surrey Satellite Technology Limited
STD	Slant Tropospheric Delay
STEC	Slant Total Electron Content
SWH	Significant Wave Height
TEC	Total Electron Content
TriG	Tri-GNSS (GPS+Galileo+GLONASS)
TOPEX	Topography Experiment
TT&C	Tracking, Telemetry and Command
URSI	International Union of Radio Science
USAF	US Air Force
UT	Universal Time
VLBI	Very Long Baseline Interferometry
VMF	Vienna Mapping Functions
WAAF	Woodward Ambiguity Function
WGS	World Geodetic System
WVR	Water Vapor Radiometry
ZTD	Zenith Tropospheric Delay
ZHD	Zenith Hydrostatic Delay
ZWD	Zenith Wet Delay
Z-V	Zavorotny and Voronovich