Springer Handbook *of* Global Navigation Satellite Systems

Teunissen
Montenbruck
Editors

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Springer Handbook of Global Navigation Satellite Systems

Peter J.G. Teunissen, Oliver Montenbruck (Eds.)

With 818 Figures and 193 Tables

Springer

Editors
Peter J.G. Teunissen
Curtin University
Department of Spatial Sciences
Perth, Australia
Perth, WA 6845, Australia

Oliver Montenbruck
German Aerospace Center (DLR)
Wessling, Germany
Münchener Str. 20
82234 Wessling, Germany

ISBN: 978-3-319-42926-7 e-ISBN: 978-3-319-42928-1
DOI 10.1007/978-3-319-42928-1
Library of Congress Control Number: 2017936757

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Production and typesetting: le-tex publishing services GmbH, Leipzig
Typography and layout: schreiberVIS, Seeheim
Illustrations: Hippmann GbR, Schwarzenbruck
Cover design: eStudio Calamar Steinen, Barcelona
Cover production: WMXDesign GmbH, Heidelberg
Printing and binding: Printer Trento s.r.l., Trento

Printed on acid free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

Satellite navigation has become an integral part of our modern-day society and is used by people all over the world. Before 2000, practically only one system was fully operational and available, the American Global Positioning System (GPS). Its Russian counterpart GLONASS, built up during the times of the Cold War in the 1970s and 1980s, had problems with the lifetime of its satellites and decreased to five satellites in the late 1990s. When in 2002 Europe decided to develop its own global satellite system called Galileo, a global race began. Very soon, around 2020, four global satellite navigation systems will be available (GPS – USA, GLONASS – Russia, BeiDou – China, Galileo – Europe), as well as two regional systems (IRNSS/NavIC – India, QZSS – Japan) and more than six augmentation systems. Furthermore, there are probably more to come.

One may wonder whether we need so many systems, yet, who wants to stay on the sidelines in this high-tech area? Satellite navigation with its precise positioning, navigation, and timing (PNT) information is an enabling technology and an important factor in the economic impact of new applications. Precise satellite navigation time is used in the critical infrastructure (telecommunications, power supply, etc.) of many countries, and restricted and encrypted PNT services are a major element in governmental tasks and military applications.

A satellite navigation system is not comparable to other space missions. It does not have a lifetime of, say, 10 years, as is the case with other dedicated space missions that fulfil a specific goal for a limited scientific or technical part of our society. Satellite navigation systems need 10 to 20 years to be built up and are meant to last for many decades in the future. Moreover, they affect the life of each citizen – space for everybody!

In recent years, only a limited number of new textbooks addressing satellite navigation as a whole have become available. The reason is obvious; many systems were under construction, and the authors often had to restrict themselves to the general theory of satellite navigation, to the fundamentals, in order not to write a book that would already be outdated at the moment of publication. Separate books covered satellite navigation receivers, orbit determination, or navigation applications.

With the present book, we have the first *Handbook of Global Navigation Satellite Systems,* aiming to give the reader a full overview of satellite navigation, starting from its fundamentals in the first part and covering in a total of seven parts the entire spectrum of satellite navigation knowledge and applications. Although some global satellite navigation systems are not yet fully completed, the Editors and authors were brave enough to include as much available information as possible.

Guenter W. Hein
Former Head of ESA's EGNOS and Galileo Evolution Dept. & Scientific Consultant of The European Space Agency

More than 60 authors – all international experts and specialists in their field – have put together the latest state-of-the-art knowledge in the field in approximately 1400 pages. The names of the authors read like the *who is who* in satellite navigation. This is really an exhaustive reference work for one of the key technologies of science and engineering in the future and for those who want to know more about the background for their satellite navigation applications. It must already have been a huge amount of work for the Editors to find the right specialists, to convince them to contribute to such a handbook, to harmonize the different chapters in order to avoid duplications, and last but not least, to describe everything in a consistent way using the same nomenclature. This was a remarkable management exercise with an excellent outcome! Many figures and photographs illustrate the text, completing the handbook as *the* reference and resource in satellite navigation.

It is also excellent that the book is not only published as a hardcover version, but also as an eBook, which will enable the reader to do a quick search in this big exhaustive work. Each of the 41 chapters also contains a list of references from which the interested reader can start to dig even deeper into the topics. Nothing is missing. There are even two annexes that show the different receiver and data formats and outline the various GNSS parameters.

Each of the seven major parts of the book covers distinct aspects of Global Navigation Satellite Systems.

The reader confronted with satellite navigation for the first time can find a very useful, quick overview in Chap. 1. A very clear description and definition of the coordinate reference systems used follows. The chapter on clocks and the relativistic effects on GNSS is excellent; it covers everything from theory to practical examples of clock data in space. Part A concludes with signal propagation in the atmosphere.

In Part B, the reader already finds a description of all the global, regional, and augmentation systems. The Editors have made great effort to reflect the latest status in the concluding developments of some of these systems.

Part C presents signal processing, receivers, and antennas, and the main effects: multipath and interferences. Even signal generators are described, a topic that is presently not well covered in the open literature.

In Part D, one can read all about the modern achievements in GNSS algorithms and, of course, about the LAMBDA method for the carrier-phase ambiguity resolution developed by one of the Editors in the past 15 years.

Part E entitled *Positioning and Navigation* shows the classical measurement modes of GNSS (absolute and differential positioning). All the new achievements of precise point positioning can be found here, as well the integration of GNSS with inertial navigation systems. The use of GNSS in aviation with its satellite-based augmentation systems and attitude determination is described here. Here, you can also find a description of all GNSS applications on land and sea, as well as in aviation and space.

Part F is dedicated to surveying, geodesy and geodynamics, the first users of GNSS and the most demanding ones in terms of accuracy.

Finally, in Part G *GNSS Remote Sensing and Timing*, some of highly specialized GNSS applications are addressed: tomography, GNSS altimetry, as well as time and frequency transfer.

The list of acronyms and abbreviations and the glossary at the end of the book are very valuable.

There is no doubt that this handbook will quickly become *the* reference manual in satellite navigation – it contains all facets of this high-tech field. The Editors and the many authors have put together an exhaustive book – it is hard to find anything missing. I can only congratulate them for such a fine handbook!

Guenter W. Hein

Preface

In the mid-1970s, a team of inspired engineers gathered around Brad Parkinson to devise a novel navigation system, which finally became known as NAVSTAR, the Global Positioning System, or briefly GPS. Despite all creativity and visionary thought, the fathers of GPS could hardly imagine that this system would literally change the world. Originally conceived as a means for providing instantaneous positioning and timing to the United States' armed forces around the globe, it was soon realized that GPS would be equally beneficial for a wide range of civil navigation applications and could likewise serve as a system-of-opportunity for diverse types of scientific investigations. The Global Positioning System ultimately became a blueprint for a whole family of space-based navigation systems subsequently established by Russia, China, Europe, and Japan, which all build on the same key principles and technologies.

In response to its widespread use and overall impact, GPS has certainly found due attention and coverage in the popular, educational, and scholarly literature. Numerous textbooks and monographs have been published over the years, but more than 20 years have passed since GPS technology and usage was last summarized in a single comprehensive encyclopedia. Since then, substantial progress has been made and the world of global navigation satellite systems has changed dramatically. Obviously, the number of global navigation satellite systems (GNSS) has increased notably and so has the number of signals and services made available to their users. In parallel, the concepts of GNSS signal and data processing have continuously matured. This has both enabled new levels of performance (in terms of accuracy and timeliness) as well as a wide range of new application areas.

With the above background, we gratefully accepted the publisher's invitation (and challenge) to compile a dedicated *Handbook of Global Navigation Satellite Systems*, which presents a complete and rigorous overview of the fundamentals, methods, and applications of GNSS from today's perspective. After 4 years of work, this endeavor has come to an end, and we are proud to present the result of this work to our readers. With more than 40 chapters and roughly 1400 pages, the new handbook provides an exhaustive, single-source reference work and a state-of-the art description of GNSS as a key technology for science and society at large. Key experts from a broad range of disciplines have contributed to cover the diverse aspects of GNSS and to summarize the respective body-of-knowledge. This includes fundamental principles and technologies but likewise addresses the latest developments in the field. Throughout the handbook, due attention has been given to the new and emerging navigation satellite systems and the way they affect GNSS data processing and utilization.

Overall, the Handbook is structured in seven distinct parts, each comprising a set of four to eight individual chapters with a common range of topics.

Part A starts with a primer on global navigation satellite systems (GNSS), followed by chapters that cover the fundamentals of GNSS. Reference systems that form the backbone of positioning and navigation are discussed, as well as the essentials of GNSS satellite orbits and attitude. These topics are followed by a treatment of radio signals and modulations for GNSS, as well as a chapter on high-performance ground and space clocks that form another GNSS key technology. The part concludes with a description of the physics of atmospheric signal propagation and the changes experienced by GNSS signals when passing through the ionosphere and troposphere.

Part B gives a detailed description of the global and regional navigation satellite systems that are currently operational and/or under development. In addition to GPS, it covers the Russian Global'naya Navigatsionnaya Sputnikova Sistema (GLONASS), the European Galileo system, the Chinese BeiDou System (BDS), the Japanese Quasi-Zenith Satellite System (QZSS), and the Indian Regional Navigation Satellite System (IRNSS/NavIC). The architecture, the navigation signals, the space and control segments, and the services and performances of each system are described as well as their planned evolution. This part also covers the fundamentals and operations of satellite-based augmentation systems (SBASs).

Part C focuses on GNSS user equipment as well related aspects of signal multipath and interference. It discusses the basic architecture of hard and software receivers together with their digital signal processing principles. A dedicated chapter is devoted to GNSS antennas, including design options, performance aspects, and calibration. The multipath environment and its impact on code and phase measurements are described along with relevant mitigation techniques. Sources of GNSS signal interference are examined, and a systematic treatment of jamming and spoofing is provided together with a review of interference detection and mitigation techniques. The part is concluded with an overview of the different GNSS simulators and a description of their key features.

Part D covers the fundamentals of the GNSS observation equations including the generic algorithms for GNSS parameter estimation and model validation. It starts with the basic observation equations for pseudorange, carrier-phase, and Doppler measurements, and continues with a discussion of linear combinations and their applications. Then the undifferenced GNSS model is developed and used to provide an overview of the various absolute and relative positioning concepts. This is followed by a treatment of the fundamental GNSS estimation, filter, and ambiguity resolution algorithms, together with the corresponding batch and recursive methods for GNSS model validation.

Part E describes different methods of GNSS positioning and navigation together with their various applications. The single-receiver, precise point positioning concept is discussed first, highlighting its adjustment procedure as well as the required models needed to correct for systematic effects. Then the methods of differential positioning are described, including DGNSS, real-time kinematics (RTK) and network RTK. This is followed by a presentation of GNSS attitude determination methods and a discussion of GNSS integration with inertial measurement units. Subsequently, dedicated chapters provide an overview of GNSS applications in land, marine, air, and space environments, along with a discussion of ground-based augmentation systems (GBAS).

Part F describes how GNSS is used in surveying, geodesy, and geodynamics. It starts with an overview of the International GNSS Service (IGS) and a description of the various GNSS products that it offers. For surveying, this part describes how GNSS is used as a tool by the land, engineering, and hydrographic surveyor; for geodesy, it focuses on the role of GNSS in the Global Geodetic Observing System (GGOS), including GNSS-based reference frame implementation, Earth rotation, and sea level monitoring. For geodynamics, it describes the concepts and models used to relate active processes within the Earth to surface deformation observed with GNSS.

Part G, finally, covers GNSS remote sensing and timing. It describes how GNSS tropospheric sensing from ground and space can be used for short-term weather forecasting and long-term climate research. It also describes how GNSS ionospheric sensing contributes to space weather studies and how it helps to mitigate GNSS performance degradation. Furthermore, this part describes the principles of GNSS reflectometry together with methods to retrieve geophysical information from GNSS signals scattered or reflected at the Earth's surface. It concludes with a description of how GNSS is used for accurate time and frequency dissemination and the comparison of distant clocks.

The main body of the book is complemented by an Annex that provides a detailed description of the most widely used GNSS data and product formats. It also offers a summary of relevant physical constants, key parameters of the GNSS constellations, and a compilation of the various GNSS signals. A Glossary covering GNSS-specific terminology is available at the end of the book to provide definitions of common terms that appear in the various chapters.

Overall, we are confident that the Handbook offers an invaluable source of knowledge for scientists, engineers, students, and institutions. It is likewise suited for readers who want to familiarize themselves with GNSS or one of its sub-disciplines and for experienced readers who aim at a deeper understanding of specific aspects. Unlike traditional textbooks, the individual chapters have been written by dedicated expert authors, who were selected based on their experience and background. Each chapter covers a specific aspect of GNSS in a largely self-contained manner and is thus well suited for standalone reading. However, individual chapters are still well connected through cross-references and follow a well-defined and transparent path for readers interested in studying all GNSS aspects in a step-by-step approach. Despite the overall size of the Handbook, space for each topic inevitably remains limited. Care has therefore been taken to complement each chapter with a thoroughly compiled list of bibliographic references covering both background literature and recent developments in the field. These may serve as a starting point for independent research and will enable readers to gain full insight into the numerous details of GNSS technology that cannot be addressed in a single-volume work.

At this stage, we would finally like to thank everyone who helped turn the vision of a new GNSS encyclopedia into reality. This includes, first of all, the more than 60 colleagues and authors who volunteered to contribute their expertise to this project. Despite a wealth of other duties, they all spent endless hours compiling the relevant information, preparing illustrating material, and adapting their work to the never-ending suggestions and change requests of the Editors. Their effort and patience have greatly contributed to achieving an up-to-date, concise, and consistent presentation of the whole world of GNSS in a single publication. We are also grateful to Ms Safoora Zaminpardaz of Curtin University, who assisted in the LaTeX conversion of numerous manuscripts and helped prepare various illustrations for the Handbook. Her assistance has taken substantial work off our shoulders and is thankfully acknowledged.

Our particular appreciation belongs to Ms J. Hinterberg and Ms J. Schwarz of Springer-Verlag, Heidelberg, as well as Ms A. Strohbach of le-tex, Leipzig, and her team for their excellent cooperation and continued support throughout all phases of this work. It was a great pleasure to work with them! Last but not least, we would both like to thank our families, who tolerated, without major complaints, that we stole so many hours from them to work on this project. We are more than grateful for their patience and the continued backing received over the past years.

Peter J.G. Teunissen — Perth, Australia
Oliver Montenbruck — Munich, Germany

About the Editors

Peter J.G. Teunissen is Professor of Geodesy and Satellite Navigation at Curtin University (CU), Australia, and Delft University of Technology (TU Delft), The Netherlands. He obtained his Doctorate degree from TU Delft in 1985, following which he received a Constantijn and Christiaan Huygens Fellowship of The Netherlands Organization for the Advancement of Pure Research (NWO). In 1988, he became full Professor at TU Delft and held various academic positions including Vice-Dean of the Faculty of Civil Engineering and Geosciences, Head of the Aerospace Engineering Department, and Science Director of the Delft Institute of Earth Observation and Space Systems. He currently heads the Curtin University GNSS Research Centre, where his research is focused on developing theory, models, and algorithms for high-accuracy geospatial applications of new global and regional satellite navigation systems. He has authored numerous journal papers and textbooks in his field. His pioneering contributions include statistical and numerical methods of integer inference theory, innovative algorithms for multi-GNSS precise parameter estimation, and the early characterization and utilization of the Chinese BeiDou, the Indian IRNSS, and the Russian GLONASS CDMA system. His scientific contributions have been recognized through various awards, including the Bomford Prize, the Steven Hoogendijk Prize, and the Alexander von Humboldt Award. He serves on the Editorial Boards of several journals and is past Editor-in-Chief of the Journal of Geodesy. He has an Honorary Degree from the Chinese Academy of Sciences and is a Fellow of the International Association of Geodesy (IAG), the UK Royal Institute of Navigation (RIN), the US Institute of Navigation (ION), and the Royal Netherlands Academy of Sciences (KNAW).

Oliver Montenbruck is Head of the GNSS Technology and Navigation Group at DLR's German Space Operations Center, Oberpfaffenhofen. He studied Physics and Astronomy and received his diploma from Ludwig Maximilians University Munich in 1987. After joining DLR, he worked as a flight dynamics analyst for geostationary spacecraft as well as other near Earth and deep space missions. He received his PhD from the Technical University Munich in 1991. In 2004, he started teaching at the same university, where he received his habilitation (second doctorate) in 2006 and where he is presently engaged as an Associate Lecturer. His research activities comprise space borne GNSS receiver technology, autonomous navigation systems, spacecraft formation flying, and precise orbit determination. More recently, he has been focusing on the characterization of new satellite navigation systems and multi-GNSS processing. Pioneering contributions in this field included GIOVE and GPS signal investigations based on high gain antenna measurements, the build-up of the Cooperative Network for GNSS Observation (CONGO), the evaluation of triple-frequency signals, as well as the early characterization and utilization of the Chinese BeiDou navigation system. Oliver Montenbruck chairs the Multi-GNSS Working Group of the International GNSS Service (IGS) and coordinates the performance of the MGEX Multi-GNSS Project (MGEX). He has authored various textbooks and numerous technical papers related to his diverse fields of work. His scientific contributions have been recognized through various awards, including the DLR Senior Scientist Award, the Institute of Navigation's (ION) Tycho Brahe Award, and the GPS World Leadership Award.

List of Authors

Zuheir Altamimi
Institut National de l'Information Géographique et Forestière (IGN)
Université Paris Diderot (LAREG)
Bâtiment Lamarck A et B, 35 rue Hélène Brion
75013 Paris, France
zuheir.altamimi@ign.fr

Felix Antreich
Federal University of Ceará (UFC)
Dept. of Teleinformatics Engineering
Campus do Pici – Bloco 725
CEP 60455-970, Fortaleza, Brazil
antreich@ieee.org

Ron Beard
US Naval Research Laboratory
Advanced Space PNT Branch
4555 Overlook Ave. SW
Washington, DC 20375, USA
ronald.beard@verizon.net

Alexey Bolkunov
Federal Space Agency (Roscosmos)
PNT Information and Analysis Center
4 Pionerskaya Street
141070 Korolyov, Russian Federation
alexei.bolkunov@glonass-iac.ru

Michael S. Braasch
Ohio University
School of Electrical Engineering & Computer Science
1 Ohio University
Athens, OH 45701, USA
braaschm@ohio.edu

Thomas Burger
European Space Agency (ESA)
Galileo Project Office
Keplerlaan 1
2201 AZ, Noordwijk, The Netherlands
thomas.burger@esa.int

Estel Cardellach
Institute of Space Sciences
ICE (IEEC-CSIC)
Carrer de Can Magrans, S/N
08193 Cerdanyola del Valles, Spain
estel@ice.csic.es

James T. Curran
European Space Agency (ESA)
Keplerlaan 1
2201 AZ, Noordwijk, The Netherlands
jamestcurran@ieee.org

Pascale Defraigne
Royal Observatory of Belgium
Avenue Circulaire 3
1180 Brussels, Belgium
p.defraigne@oma.be

Bernd Eissfeller
Universität der Bundeswehr München
Inst. of Space Technology and Space Applications
Werner-Heisenberg-Weg 39
85577 Neubiberg, Germany
bernd.eissfeller@unibw.de

Gunnar Elgered
Chalmers University of Technology
Dept. of Earth and Space Sciences
Onsala Space Observatory, Observatorievägen 90
43992 Onsala, Sweden
gunnar.elgered@chalmers.se

Marco Falcone
European Space Agency (ESA)
Galileo Project Office
Keplerlaan 1
2201 AZ, Noordwijk, The Netherlands
marco.falcone@esa.int

Richard Farnworth
Eurocontrol Experimental Centre
Centre du Bois des Bordes – BP15
91222 Bretigny sur Orge, France
richard.farnworth@eurocontrol.int

Jay A. Farrell
University of California, Riverside
Dept. of Electrical and Computer Engineering
900 University Avenue
Riverside, CA 92521, USA
farrell@ece.ucr.edu

Jeff Freymueller
University of Alaska
Geophysical Institute
903 Koyukuk Drive
Fairbanks, AK 99775-7320, USA
jfreymueller@alaska.edu

A.S. Ganeshan
Indian Space Research Organization (ISRO)
ISRO Satellite Centre (ISAC)
Old Airport Road, Vimapura PIO
560017 Bangalore, India
asganeshan53@gmail.com

Steven Gao
University of Kent
School of Engineering and Digital Arts
Jennison Building
Canterbury, Kent, CT2 7NT, UK

Gabriele Giorgi
Technical University of Munich
Inst. for Communications and Navigation
Theresienstr. 90
80333 Munich, Germany
gabriele.giorgi@tum.de

Richard Gross
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109, USA
richard.s.gross@jpl.nasa.gov

Jörg Hahn
European Space Agency (ESA)
Galileo Project Office
Keplerlaan 1
2201 AZ, Noordwijk, The Netherlands
joerg.hahn@esa.int

André Hauschild
German Aerospace Center (DLR)
German Space Operations Center
Münchener Str. 20
82234 Wessling, Germany
andre.hauschild@dlr.de

Grant Hausler
Geoscience Australia
Cnr Jerrabomberra Ave & Hindmarsh Drive
Symonston, ACT 2609, Australia
grant.hausler@ga.gov.au

Christopher J. Hegarty
The MITRE Coporation
202 Burlington Road
Bedford, MA 01886, USA
chegarty@mitre.org

Thomas Hobiger
Chalmers University of Technology
Onsala Space Observatory
Observatorievägen 90
43992 Onsala, Sweden
thomas.hobiger@chalmers.se

Urs Hugentobler
Technical University of Munich
Satellite Geodesy
Arcisstr. 21
80333 Munich, Germany
urs.hugentobler@bv.tum.de

Todd Humphreys
The University of Texas at Austin
Aerospace Engineering and Engineering
Mechanics, W.R. Woolrich Laboratories, C0600
210 East 24th Street
Austin, TX 78712-1221, USA
todd.humphreys@mail.utexas.edu

Norbert Jakowski
German Aerospace Center (DLR)
Institute of Communications and Navigation
Kalkhorstweg 53
17235 Neustrelitz, Germany
norbert.jakowski@dlr.de

Christopher Jekeli
Ohio State University
School of Earth Sciences
125 South Oval Mall
Columbus, OH 43210, USA
jekeli.1@osu.edu

Gary Johnston
Geoscience Australia
Cnr Jerrabomberra Ave & Hindmarsh Drive
Symonston, ACT 2609, Australia
gary.johnston@ga.gov.au

Allison Kealy
University of Melbourne
Dept. of Infrastructure Engineering
Grattan Street
Parkville, 3010 VIC, Australia
akealy@unimelb.edu.au

Satoshi Kogure
National Space Policy Secretariat, Cabinet Office
QZSS Strategy Office
1-6-1 Nagata-cho, Chiyoda-ku
100-8914 Tokyo, Japan
satoshi.kogure.e7f@cao.go.jp

Jan Kouba
Natural Resources Canada
Canadian Geodetic Survey
588 Booth Street
Ottawa, ON K1A 0Y7, Canada
kouba@rogers.com

François Lahaye
Natural Resources Canada
Canadian Geodetic Survey
588 Booth Street
Ottawa, ON K1A 0Y7, Canada
francois.lahaye@canada.ca

Richard B. Langley
University of New Brunswick
Dept. of Geodesy & Geomatics Engineering
15 Dineen Drive
Fredericton, NB E3B 5A3, Canada
lang@unb.ca

Ken MacLeod
Natural Resources Canada
Canadian Geodetic Survey
615 Booth Street
Ottawa, ON K1A 0E9, Canada
ken.macleod@canada.ca

Moazam Maqsood
Institute of Space Technology
Dept. of Electrical Engineering
1 Islamabad Highway
44000 Islamabad, Pakistan
moazam.maqsood@ist.edu.pk

Michael Meurer
German Aerospace Center (DLR)
Institute of Communications and Navigation
Münchener Str. 20
82234 Wessling, Germany
michael.meurer@dlr.de

Oliver Montenbruck
German Aerospace Center (DLR)
Münchener Str. 20
82234 Wessling, Germany
oliver.montenbruck@dlr.de

Terry Moore
University of Nottingham
Nottingham Geospatial Institute
Triumph Road
Nottingham, NG7 2TU, UK
terry.moore@nottingham.ac.uk

Dennis Odijk
Fugro Intersite B.V.
Dillenburgsingel 69
2263 HW, Leidschendam, The Netherlands
d.odijk@fugro.com

Thomas Pany
Universität der Bundeswehr München
Inst. of Space Technology and Space Applications
Werner-Heisenberg-Weg 39
85577 Neubiberg, Germany
thomas.pany@unibw.de

Mark G. Petovello
University of Calgary
Geomatics Engineering
2500 University Drive NW
Calgary, AB T2N 1N4, Canada
mark.petovello@ucalgary.ca

Sam Pullen
Stanford University
Dept. of Aeronautics and Astronautics
Durand Building, Room 250
Stanford, CA 94305-4035, USA
spullen@stanford.edu

Sergey Revnivykh
RESHETNEV's Information Satellite Systems
Coporation
GLONASS Evolution Department
Mytischinskaya 3-16-60
129626 Moscow, Russian Federation
revnivykh@iss-reshetnev.ru

Anna Riddell
Geoscience Australia
Cnr Jerrabomberra Ave & Hindmarsh Drive
Symonston, ACT 2609, Australia
anna.riddell@ga.gov.au

Antonio Rius
Institute of Space Sciences
ICE (IEEC-CSIC)
Carrer de Can Magrans, S/N
08193 Cerdanyola del Valles, Spain
rius@ice.csic.es

Chris Rizos
The University of New South Wales
School of Civil & Environmental Engineering
High Street
Kensington, NSW 2052, Australia
c.rizos@unsw.edu.au

Ken Senior
US Naval Research Laboratory
Advanced Space PNT Branch
4555 Overlook Ave. SW
Washington, DC 20375, USA
ken.senior@nrl.navy.mil

Alexander Serdyukov (deceased)

Tim Springer
PosiTim UG
In den Löser 15
64342 Seeheim-Jugenheim, Germany
tim.springer@positim.com

Peter Steigenberger
German Aerospace Center (DLR)
German Space Operations Center
Münchener Str. 20
82234 Wessling, Germany
peter.steigenberger@dlr.de

Jing Tang
China National Administration of GNSS and Applications
17 Garden Road, Haidian District
100088 Beijing, China
blazingtangjing@163.com

Pierre Tétreault
Natural Resources Canada
Canadian Geodetic Survey
588 Booth Street
Ottawa, ON K1A 0Y7, Canada
pierre.tetreault@canada.ca

Peter J.G. Teunissen
Curtin University
Dept. of Spatial Sciences
Perth, WA 6845, Australia
p.teunissen@curtin.edu.au

Sandra Verhagen
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Stevinweg 1
2628 CN, Delft, The Netherlands
a.a.verhagen@tudelft.nl

Todd Walter
Stanford University, GPS Lab
496 Lomita Mall Room 250
Stanford, CA 94305-4035, USA
twalter@stanford.edu

Lambert Wanninger
Technical University Dresden
Geodetic Institute
Helmholtzstr. 10
01069 Dresden, Germany
lambert.wanninger@tu-dresden.de

Jan P. Weiss
University Corporation for Atmospheric Research
COSMIC Program
3090 Center Green Drive
Boulder, CO 80301, USA
weissj@ucar.edu

Jan Wendel
Airbus DS GmbH
Navigation and Apps. Programmes
Robert-Koch-Str. 1
82024 Taufkirchen, Germany
jan.wendel@airbus.com

Jens Wickert
GFZ German Research Centre for Geosciences
Dept. of Geodesy
Telegrafenberg
14473 Potsdam, Germany
wickert@gfz-potsdam.de

Jong-Hoon Won
Inha University
Faculty of Electrical Engineering
100 Inharo, Nam-gu
Incheon, 22212, Korea
jh.won@inha.ac.kr

Yuanxi Yang
China National Administration of GNSS and Applications
17 Garden Road, Haidian District
100088 Beijing, China
yuanxi_yang@163.com

Contents

List of Abbreviations

A

A-GNSS	assisted GNSS
A-PNT	alternative positioning navigation and timing
ABAS	aircraft based augmentation system
AC	analysis center
ACES	atom clock ensemble in space
ADC	analog-to-digital converter
ADEV	Allan deviation
ADF	automatic direction finding
ADOP	ambiguity dilution of precision
ADS	automatic dependent surveillance
AEP	architecture evolution plan
AFS	atomic frequency standard
AFSCN	air force satellite control network
AGC	automatic gain control
AGGA	advanced GPS/GLONASS ASIC
AIUB	Astronomical Institute of the University of Bern
AKM	apogee kick motor
AltBOC	alternative BOC
AM	amplitude modulation
ANTEX	antenna exchange (format)
AOCS	attitude and orbit control system
APL	airport pseudolite
APV	approach with vertical guidance
ARP	antenna reference point
ARW	angular random walk
ASIC	application specific integrated circuit
ATV	automated transfer vehicle
AUT	antenna under test
AWGN	additive white Gaussian noise

B

BAW	bulk acoustic wave
BC	Barker code
BCH	Bose–Chaudhuri–Hocquenghem (code)
BCRS	barycentric celestial reference system
BDS	BeiDou Navigation Satellite System
BDT	BeiDou time
BGD	broadcast group delay
BIH	Bureau International de l'Heure
BIPM	Bureau International des Poids et Mesures
BLUE	best linear unbiased estimation
BLUP	best linear unbiased prediction
BNR	bias-to-noise ratio
BOC	binary offset carrier
BPSK	binary phase-shift keying

C

CAPS	Chinese Area Positioning System
CASM	coherent adaptive sub-carrier modulation
CBOC	composite binary offset carrier
CCD	code-carrier divergence
CCIR	Comité Consultatif International des Radiocommunications
CDGNSS	carrier-phase differential GNSS
CDMA	code division multiple access
CEP	circular error probable
CFIT	controlled flight into terrain
CGCS	China Geodetic Coordinate System
CIO	celestial intermediate origin
CL	long code
CM	moderate-length code
CMC	code-minus-carrier
CMCU	clock monitoring and comparison unit
CMOS	complementary metal oxide semiconductor
CMS	constrained maximum success-rate
CNAV	civil navigation message
CODE	Center for Orbit Determination in Europe
COG	center-of-gravity
CoM	center-of-mass
CoN	center-of-network
CONUS	conterminous United States
COO	cell-of-origin
CORS	continuously operating reference station
COSPAS	Cosmicheskaya Sistema Poiska Avariynyh Sudo (space system for search of distress vessels and airplanes)
COTS	commercial-off-the-shelf
CPT	coherent population trapping
CPU	central processing unit
CRC	cyclic redundancy check
CRF	celestial reference frame
CRPA	controlled radiation pattern antenna
CRS	celestial reference system
CS	Commercial Service
CS	control segment
CSAC	chip scale atomic clock
CSK	code shift keying
CTP	conventional terrestrial pole

D

DAB	digital audio broadcast
DC	data center
DCB	differential code bias
DCFBS	digital cesium beam frequency standard
DD	double-difference

DDM	delay-Doppler-map
DEM	digital elevation model
DGNSS	differential GNSS
DH	decision height
DIODE	DORIS immediate orbit on-board determination
DLL	delay lock loop
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMA	Defense Mapping Agency
DME	distance measuring equipment
DOP	dilution of precision
DORIS	Doppler orbitography and radiopositioning integrated by satellite
DQM	data quality monitoring
DSP	digital signal processor
DVB	digital video broadcasting

E

EAL	Echelle atomique libre (free atomic scale)
ECEF	Earth-centered Earth-fixed
ECI	Earth-centered inertial
ECMWF	European Centre for Medium-Range Weather Forecasts
ECOM	Empirical CODE Orbit Model
EELV	evolved expendable launch vehicles
EGNOS	European Geostationary Navigation Overlay Service
EIRP	effective isotropic radiated power
EKF	extended Kalman filter
EO	Earth observation
EPB	equatorial plasma bubble
ESA	European Space Agency
EUV	extreme ultraviolet

F

FAA	US Federal Aviation Administration
FAR	full ambiguity resolution
FBR	front-to-back ratio
FCC	Federal Communications Commission
FDMA	frequency division multiple access
FE	front end
FEC	forward error correction
FFT	fast Fourier transform
FK5	Fundamental Katalog 5
FLDR	flicker drift
FLFR	flicker frequency (noise)
FLL	frequency lock loop
FLPH	flicker phase (noise)
FMS	flight management system
FNBW	first-null beam width
FOC	full operational capability
FOG	fiber optic gyroscope
FPGA	field programmable gate array
FRPA	fixed radiation pattern antenna
FTE	flight technical error

G

GAGAN	GPS-aided GEO Augmented Navigation
GAST	Greenwich apparent sidereal time
GBAS	ground-based augmentation system
GCC	Galileo Control Centre
GCRS	Geocentric Celestial Reference System
GDGPS	global differential GPS
GEO	geostationary Earth orbit
GFZ	Deutsches GeoForschungsZentrum
GGTO	GPS-to-Galileo time offset
GIM	global ionospheric map
GIOVE	Galileo In-Orbit Validation Element
GIS	geographic information system
GIVE	grid ionospheric vertical error
GLONASS	Global'naya Navigatsionnaya Sputnikova Sistema (Russian Global Navigation Satellite System)
GLST	GLONASS System Time
GMS	ground mission segment
GNSS	global navigation satellite system
GPS	Global Positioning System
GPST	GPS Time
GPT	global pressure and temperature (model)
GRAM	GPS receiver application module
GRAS	ground-based regional augmentation system
GRAS	GNSS receiver for atmospheric sounding
GST	Galileo System Time
GTRS	Geocentric Terrestrial Reference System

H

HDOP	horizontal dilution of precision
HEO	highly elliptical orbit
HOW	hand-over word
HPBW	half-power beam width

I

I/Q	in-phase/quadrature
IAU	International Astronomical Union
IB	integer bootstrapping
IBLS	integrity beacon landing system
ICAO	International Civil Aviation Organization
ICD	interface control document
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IEEE	Institute of Electrical and Electronics Engineers
IERS	International Earth Rotation and Reference Systems Service
IF	intermediate frequency
IFA	inverted-F antenna
IGP	ionospheric grid point
IGS	International GNSS Service
IGSO	inclined geo-synchronous orbit
IIP	instantaneous impact point
ILS	integer least-squares

ILS	instrument landing system
ILS	International Latitude Service
IMU	inertial measurement unit
INS	inertial navigation system
InSAR	interferometric synthetic aperture radar
IOD	issue-of-data
IODC	issue-of-data clock
IODE	issue-of-data ephemeris
IONEX	ionosphere exchange (format)
IOP	intensity optical pumping
IOT	in-orbit test
IOV	in-orbit validation
IPP	ionospheric pierce point
IR	integer rounding
IRI	international reference ionosphere
IRM	IERS reference meridian
IRNSS	Indian Regional Navigation Satellite System
IRP	international reference pole
ISB	intersystem bias
ISC	intersignal correction
ISS	International Space Station
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
ITS	intelligent transport system
ITU	International Telecommunication Union
IUGG	International Union of Geodesy and Geophysics

J

JAXA	Japan Aerospace Exploration Agency
JD	Julian day/date
JPL	Jet Propulsion Laboratory

K

KASS	Korean Augmentation Satellite System
KF	Kalman filter

L

L-AII	Legacy Accuracy Improvement Initiative
LADGNSS	local area differential GNSS
LAMBDA	least-squares ambiguity decorrelation adjustment
LEO	low Earth orbit
LEOP	launch and early orbit phase
LHCP	left-hand circular polarized
LIDAR	light detection and ranging
LNA	low-noise amplifier
LNAV	legacy navigation message
LOS	line-of-sight
LQG	linear quadratic Gaussian
LRA	laser retro-reflector array
LTT	laser time transfer

M

MAP	maximum a posteriori
MC	master clock
MCS	master control station
MDB	minimal detectable bias
MEMS	micro-electromechanical system
MEO	medium Earth orbit
MJD	modified Julian day/date
MLE	maximum likelihood estimation
MLS	microwave landing system
MMP	minimum mean penalty
MMS	Magnetosphere Multiscale Mission
MOT	magneto-optical trap
MPR	multipath rejection ratio
MQM	measurements quality monitoring
MS	monitoring station
MSAS	Multi-Function Satellite Augmentation System
MSS	mean squared slope

N

NAD	North American Datum
NANU	notice advisory to NAVSTAR users
NAQU	notice advisory to QZSS users
NASA	National Aeronautics and Space Administration
NCO	numerically controlled oscillator
NCP	North celestial pole
NDB	nondirectional beacon
NEP	North ecliptic pole
NGA	National Geospatial-Intelligence Agency
NH	Neuman-Hofman (code)
NIST	National Institute of Standards and Technology
NMCT	navigation message correction table
NMEA	National Marine Electronics Association
NMF	Niell mapping function
NOTAM	notice to airmen
NPA	nonprecision approach
NRL	Naval Research Lab
NSE	navigation system error
NUDET	nuclear detection (payload)
NWM	numerical weather model
NWP	numerical weather prediction

O

OCS	operational control system
OCX	next generation operational control segment of GPS
OCXO	oven controlled crystal oscillator
OEM	original equipment manufacturer
OS	Open Service
OSPF	orbitography and synchronization processing facility
OWCP	one-way carrier-phase technique

P

PAR	partial ambiguity resolution
PBN	performance based navigation
PBO	plate boundary observatory
PCB	printed circuit board
PCO	phase center offset
PCV	phase center variation
PDA	personal digital assistant
PDF	probability density function
PDOP	position dilution of precision
PF	particle filter
PHM	passive hydrogen maser
PLL	phase lock loop
PM	phase modulation
PMF	probability mass function
PNT	positioning, navigation and timing
POD	precise orbit determination
PPD	personal privacy device
PPP	precise point positioning
PPS	precise positioning service
PPS	pulse per second
PRC	pseudorange correction
PRN	pseudo-random noise
PSD	power spectral density
PVT	position, velocity and time

Q

QHA	quadrifilar helix antenna
QPSK	quadrature phase-shift keying
QZSS	Quasi-Zenith Satellite System

R

RAAN	right ascension of ascending node
RAFS	rubidium atomic frequency standard
RAIM	receiver autonomous integrity monitoring
RDSS	radio determination satellite service
RF	radio frequency
RFI	radio frequency interference
RFSA	Russian Federal Space Agency
RHCP	right-hand circular polarized
RINEX	receiver independent exchange (format)
RLG	ring laser gyroscope
RMS	root mean square
RNAV	area navigation
RNP	required navigation performance
RNSS	radio navigation satellite service
RNSS	regional navigation satellite system
RO	radio occultation
RRC	range-rate correction
RSS	root-sum-square
RTAC	Real-Time Analysis Center
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime Services
RTI	Rayleigh-Taylor instability
RTK	real-time kinematic
RTS	real-time service
RWDR	random walk drift
RWFR	random walk frequency (noise)
RWPH	random walk phase (noise)

S

SA	selective availability
SAASM	selective availability anti-spoofing module
SAR	synthetic aperture radar
SAR	search and rescue
SARPS	standards and recommended practices
SAW	surface acoustic wave
SBAS	satellite-based augmentation system
SD	single-difference
SDA	strapdown algorithm
SDCM	System for Differential Corrections and Monitoring
SDM	signal deformation monitoring
SDR	software defined radio
SEL	single event latch-up
SEU	single event update
SIGI	Space Integrated GPS/Inertial navigation system
SINEX	solution independent exchange (format)
SISO	single-input-single-output
SISRAD	signal-in-space receive and decode
SISRE	signal-in-space range error
SLAM	simultaneous location and mapping
SLR	satellite laser ranging
SLTA	straight line tangent point altitude
SNR	signal-to-noise ratio
SoC	system-on-a-chip
SOFA	standards of fundamental astronomy
SP3	Standard Product 3 (format)
SPAD	single photon avalanche diode
SPP	single point positioning
SPS	standard positioning service
SRP	solar radiation pressure
ST	system time
STEC	slant total electron content
SV	space vehicle
SVN	space vehicle number

T

TACAN	tactical air navigation (system)
TAI	International Atomic Time
TASS	TDRSS augmentation service for satellites
TCB	barycentric coordinate time
TCG	Geocentric Coordinate Time
TCXO	temperature compensated crystal oscillator
TDB	barycentric dynamic time

TDRSS	tracking and data relay satellite system
TDT	terrestrial dynamic time
TEC	total electron content
TGD	timing group delay
TID	total ionization dose
TID	traveling ionospheric disturbance
TIO	terrestrial intermediate origin
TKS	time keeping system
TLM	telemetry (word)
TMBOC	time multiplexed binary offset carrier
TOA	time-of-arrival
TRF	terrestrial reference frame
TT	terrestrial time
TTA	time-to-alert
TTFF	time-to-first-fix
TWSTFT	two-way satellite time and frequency transfer
TWTA	traveling wave tube amplifier

U

UAV	unmanned aerial vehicle
UDRE	user differential range error
UERE	user equivalent range error
UHF	ultra-high frequency
UMPI	uniformly most powerful invariant
UNAVCO	University NAVSTAR Consortium
UNB	University of New Brunswick
URSI	International Union of Radio Science
USGS	United States Geological Survey
USNO	United States Naval Observatory
UT	Universal Time
UTC	Coordinated Universal Time
UWB	ultra-wideband

V

VDB	VHF data broadcast
VDOP	vertical dilution of precision
VHF	very high frequency
VLBI	very long baseline interferometry
VMF	Vienna mapping function
VNA	vector network analyzer
VOR	VHF omnidirectional range
VPL	vertical protection level
VRE	vibration rectification error
VRW	velocity random walk
VSWR	voltage standing wave ratio
VTEC	vertical total electron content

W

WAAS	Wide Area Augmentation System
WAGE	wide area GPS enhancement
WGS	World Geodetic System
WHPH	white phase (noise)
WLS	weighted least-squares

Z

ZHD	zenith hydrostatic delay
ZTD	zenith troposphere delay
ZWD	zenith wet delay

Part A
Principles

Part A Principles of GNSS