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978-0-521-76054-6 - Digital Satellite Navigation and Geophysics: A Practical Guide with GNSS Signal Simulator and Receiver Laboratory
Ivan G. Petrovski and Toshiaki Tsujii
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## Digital Satellite Navigation and Geophysics

Bridge the gap between theoretical education and practical work experience with this hands-on guide to GNSS. A clear, practical presentation of GNSS theory is provided, with emphasis on GPS, GLONASS, and QZSS, together with the key applications in navigation and geophysics.

Whether you are a practicing engineer, a researcher, or a student, you'll gain a wealth of insights from the authors' 25 years of experience in the GNSS field. You'll also get hands-on user experience with a bundled real-time software receiver and signal simulator, enabling you to create your own GNSS lab for research or study.

Numerous practical examples and case studies are provided, which you can explore using the real signal data provided or generated by you using the signal simulator. Also covered are issues related to GNSS signal propagation and its use in geophysics, including ionosphere mapping, atmosphere monitoring, scintillation measurements, earthquake prediction, and more.

**Ivan G. Petrovski** works on GNSS applications development at iP-Solutions, Japan. He has been involved in the GNSS field for more than 25 years. Prior to working at iP-Solutions, he worked as Associate Professor with Moscow Aviation Institute (MAI), as Japan Science and Technology Agency (STA) Fellow with Japan National Aerospace Laboratory (NAL), directed the Institute of Advanced Satellite Positioning in Tokyo University of Marine Science and Technology (TUMST), and led GNSS-related R&D for DX Antenna and GNSS Technologies Inc. He received his Ph.D. in aerospace navigation from MAI in 1993.

**Toshiaki Tsujii** is the Head of Navigation Technology Section, Aviation Program Group, at the Japan Aerospace Exploration Agency (JAXA), where he has been investigating aspects of satellite navigation and positioning for more than 20 years. He was at the Satellite Navigation and Positioning (SNAP) Group, University of New South Wales, Australia, as a visiting research fellow from 2000 to 2002. He received his Dr. Eng. in applied mathematics and physics from Kyoto University in 1998.

This book provides an excellent introduction to satellite navigation and the technologies that make it possible. The authors set forth both fundamentals and practical aspects in a manner that allows even newcomers to GNSS to utilize it effectively. The topics covered in this book address the most important elements of current-day GNSS applications.
*Sam Pullen, Stanford University*

# Digital Satellite Navigation and Geophysics

## A Practical Guide with GNSS Signal Simulator and Receiver Laboratory

IVAN G. PETROVSKI
*iP-Solutions, Japan*

TOSHIAKI TSUJII
*Japan Aerospace Exploration Agency (JAXA)*

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# Foreword

I built my first crystal radio kit when I was 9 years old. I became hooked on radio technology, even at that tender age, and later went on to build other radios as a teenager, including a shortwave receiver from a kit. I learned how radios worked by building them and tinkering with them. I learned much later on that the famous American physicist, Richard Feynman, also had an interest in radios when he was 11 or 12. He would buy broken radios at rummage sales and try to fix them. That's the way he learned how they worked. As he says in the first chapter of his book *Surely You're Joking Mr. Feynman!–Adventures of a Curious Character*, 'The sets were simple, the circuits were not complicated . . . It wasn't hard for me to fix a radio by understanding what was going on inside, noticing that something wasn't working right, and fixing it.' As we know, Feynman went on to unravel the nature of quantum mechanics amongst other accomplishments. And, all his life, he took great pleasure in finding things out.

My interest in radio and electronics together with a love of physics led me eventually into a teaching and research career in space geodesy and precision navigation. Over the years, I have been involved with a number of mostly radio-based space geodetic techniques. As a Ph.D. student, I worked with very long baseline interferometry (VLBI) and satellite Doppler (the US Navy Navigation Satellite System or Transit) and as a postdoctoral fellow at MIT, I worked with lunar laser ranging data and was introduced to one of the very first civil GPS receivers: the Macrometer™. Upon arriving at the University of New Brunswick's then Department of Surveying Engineering in 1981, it was back to satellite Doppler. But within a year or two, GPS captured my attention and it has been virtually my sole interest ever since.

While most of my writing about GPS has been for journals, the proceedings of technical meetings and *GPS World* magazine, I was fortunate to be a co-author of one of the first, if not *the* first, textbooks on GPS: *Guide to GPS Positioning*, published by Canadian GPS Associates in 1986. It was a technical best-seller, with over 12 000 copies sold worldwide in the English version alone.

There have been many advances in GPS technology since that seminal book was published. In fact, with the almost simultaneous development of the Russian GLONASS satellite navigation system and, more recently, the initial development of the European Galileo system, the Chinese BeiDou/Compass system, the Japanese Quasi-Zenith Satellite System (QZSS), and a number of satellite-based augmentation systems, we now need to use the term 'global navigation satellite systems' or GNSS. And GPS itself is going through a modernization exercise with the introduction of new signals, new satellite designs, and new ground infrastructure.

Much of the research associated with current developments in GNSS is published, in a timely fashion, in technical papers in journals and meeting proceedings. But these papers, typically written by experts for other experts, are often difficult for students to follow – especially those just starting out in the field. There is still the need for good textbooks about GPS and the other GNSS, and there are several currently in print. They do a good job of explaining the theory of how GNSS work but there are very few resources matching the theory to actual receivers so that a student, for example, might learn by doing as I did years ago when learning how shortwave radios worked. In part, this is due to the fact that modern GNSS receivers are extremely complex devices and most are not designed to be teaching tools.

With their new book, Ivan Petrovski and Toshiaki Tsujii have filled this education gap. *Digital Satellite Navigation and Geophysics: A Practical Guide with GNSS Signal Simulator and Receiver Laboratory* is not only a text that clearly describes the generation of GNSS signals and how they are processed by a receiver, but it is also accompanied by both a GNSS software signal simulator and a software GNSS receiver. Now it is possible to learn how GNSS work *by doing*. After reading about an aspect of signal design, transmission, propagation or reception, the student can simulate it and see how a receiver responds to it, immediately seeing 'cause and effect.'

The uniqueness of the book is revealed, in part, by the words in its title. Let's start with 'digital.' The authors carefully and clearly describe the generation, transmission, and reception of GNSS signals, which are inherently digital, although modulated onto radio-frequency (RF) analogue carriers. And, in a modern GNSS receiver, the front end includes an analogue to digital (A/D) converter that transforms the signal to baseband where it can be manipulated in a totally digital way. The authors thoroughly discuss the generation of GNSS signals in the satellites and in signal simulators, as well as the operation of the receiver's RF front end, including A/D conversion, and baseband processing. Not only are the legacy GPS signals fully described, but also those of modernized GPS, GLONASS, QZSS, and Galileo.

Then 'satellite navigation and geophysics.' GNSS users can be very broadly classified into two groups: navigators whose positioning needs can be met by using pseudorange measurements on one frequency to achieve metre-level accuracies and high accuracy users, including surveyors, engineers and scientists who make use of the more precise carrier-phase measurements (in addition to pseudoranges), typically on two frequencies. Positioning accuracy at the centimeter-level or better is often the goal. The authors not only describe the various aspects of GNSS for navigation, but also for the more demanding applications including some of those in geophysics. The use of GNSS for ionospheric scintillation monitoring, for measuring Earth rotation and assessing tectonic plate motion are all discussed.

And finally 'practical guide.' The authors present not only the theory of how GNSS signals are generated and processed under ideal conditions, but also how a receiver responds to various real-world effects such as ionospheric disturbances and multipath. And these and other factors can be studied with a hands-on approach using the software signal simulator and software receiver. The authors provide several case studies and most chapters end with a relevant student project. A useful feature of the book is the schematic or flowchart, repeated at intervals, showing how each chapter is related to the operation of a GNSS receiver or its applications.

Ivan Petrovski and Toshiaki Tsujii are experts in GNSS. Ivan has been in the GNSS field for almost 30 years. He worked as an Associate Professor with the Moscow Aviation Institute (State University of Aerospace Technologies) before being invited in 1997 by the Japan Science and Technology Agency to join the National Aerospace Laboratory as a research fellow. Subsequently, he was Head of R&D at GNSS Technologies Inc. and Director of the Institute of Advanced Satellite Positioning at Tokyo University of Marine Science and Technology. Since the fall of 2007, he has been developing a real-time software GNSS receiver, a signal simulator, and instant positioning technology at iP-Solutions, Tokyo, Japan.

Likewise, Toshiaki has had a long association with GNSS. As Head of the Navigation Technology Section of the Operation and Safety Technology Team in the Japan Aerospace Exploration Agency, he has been investigating aspects of satellite navigation and positioning for more than 20 years. In addition to GNSS aircraft navigation, his group is working on airship- and helicopter-based pseudolite applications.

I had the pleasure of working with both Ivan and Toshiaki when they authored an article for my *GPS World* 'Innovation' column on a significant advance in GNSS technology: instant GPS positioning. That article introduced the iPRx snapshot software receiver for instant positioning to the GNSS community. And, it is the academic version of a new generation of that receiver, along with the companion ReGen signal generator, that is bundled with this book.

Like Richard Feynman, I have always taken pleasure in finding things out – whether it be why the sky is blue or how the atmosphere affects GNSS signals. And, with new signal structures being introduced along with new ways of acquiring and tracking those signals, I'm still learning how a GNSS receiver works. This book will help.

Professor Richard B. Langley
Department of Geodesy and Geomatics Engineering
University of New Brunswick, Fredericton, New Brunswick, Canada

# Preface

This book is about ***global navigation satellite systems*** (GNSS), their two main instruments, which are a receiver and a simulator, and their applications. The book is based on an operational off-the-shelf real-time software GNSS receiver and off-the-shelf GNSS signal simulator. The academic versions of these tools are bundled with this book and free for readers to use for study and research.

The GNSS is probably unique in that it combines such a diverse variety of humanity's technological achievements. In order to understand a system better one needs to look at it from a wider perspective. Therefore we always try to present a theory behind each aspect of GNSS in general, which not only allows a better understanding of GNSS, but may also make it useful for specialists engaged in other fields.

The book structure is schematically presented on Figure P.1. Chapter 1 describes general methods of using GNSS. Chapter 2 looks at GNSS satellites and deals with their orbital mechanics. Chapter 3 discusses GNSS signals and how they are generated in satellites, simulators, and pseudolites. Chapters 4,7,10 describe GNSS signal propagation. Chapter 4 looks at where the GNSS signals are in relation to other electro-magnetic signals and how their specifics affect their propagation. Chapter 7 deals with multipath and Chapter 10 is devoted to the very interesting subject of signal scintillation. Chapters 5 and 6 describe in detail a software GNSS receiver front end and a baseband processor. Chapter 8 treats the subject of creating and improving various GNSS observables. Chapters 9,11,12 discuss how these observables are used in navigation and geophysics applications.

Among all GNSS we discuss first of all the US GPS, which is the main tool in satellite navigation and geophysics. We also consider the Russian GLONASS, which after a few years of being a partially filled constellation has now achieved full operational status, providing not only adequate coverage, but also new signals on L2 and L3. Even during the years of partial availability GLONASS was nevertheless regularly used in geodetic applications. Now GLONASS is also entering mass markets of cellular phone applications, car navigation, and so on. We also describe general principles and main features of the European Galileo, those which make it different from other GNSS. The space devoted to Galileo in this book is rather limited because we feel that the system is not yet finalized: the signal structure, the design, and even some concepts, particularly those related to open and restricted access signals, may yet be changed. Nonetheless, we think that the book provides enough information on GNSS in general for a reader to start work with the Galileo system and its applications.

 

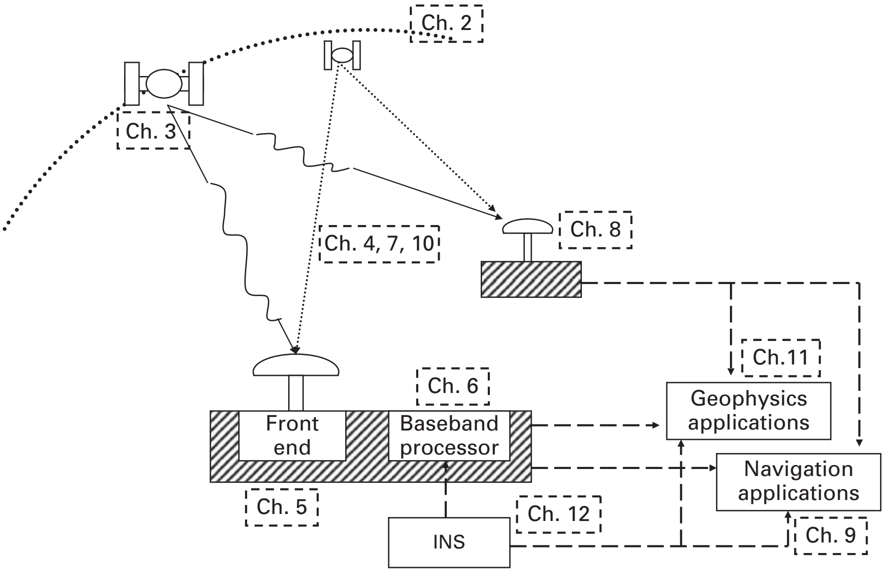


**Figure P.1** Structure of the book.

We have tried to make this book ***unique in several respects***:

1. We have tried to implement a practical and systematic approach to GNSS theory and technology. It is based on our experience in creation and usage of software, and in GNSS receivers and signal simulators in particular in airborne applications.
2. The book is accompanied by ***free academic versions*** of a ***real-time software receiver*** and ***signal simulator***.
3. Matching ***hardware*** for the bundled software is described and readily available for interested users. For example, a ***receiver front end*** allows the bundled receiver real-time positioning with live satellites.
4. The book website contains ***prerecorded flight test data***, including ***GPS signal records*** and matching ***INS raw data*** outputs, which readers can process with the receiver while working with the book examples and projects.
5. In this book we describe a GNSS simulator design. An understanding of how a GNSS simulator works gives insights into the operation of real satellite systems. A simulator is a widely used tool nowadays for R&D, testing, and in manufacturing.
6. We have tried to make this book fun to read. There are many interesting facts hidden in the philosophical and physical backgrounds of GNSS, which are rarely or never discussed.
7. We have tried to structure this book to be as useful as possible for both students and experienced engineers alike. The book contains all the material necessary to understand GNSS in depth.
8. Throughout the book we try to give clear physical explanations of various important phenomena, such as why code delay and phase advance of GNSS signals are opposite in sign and equal in value, why ionospheric scintillation amplitude and phase cross-correlation has a negative value, and so on.

In conclusion, we would like to acknowledge some friends and colleagues who have helped us along the way.

First we would like to thank those who helped us with material for this book, especially:

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– Professor Chris Rizos and many colleagues at the Satellite Navigation and Positioning (SNAP) Group, University of New South Wales, Australia, for their professional advice and discussions during and after my stay at the group.

I would also like to express hearty thanks to my wife and children: Kayoko, Honami, Yukino, Gousuke, and Yuto, for their encouragement and support.

Chapters 1–6 were written mostly by Ivan Petrovski, Chapters 8,9,12 mostly by Toshiaki Tsujii, and Chapters 7,10, and 11 by us both.

Although we have endeavored to avoid errors, some may have found their way into this book. The process of continuous refinement is a never-ending task.

*Ivan Petrovski, Toshiaki Tsujii*



## Artist credits

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