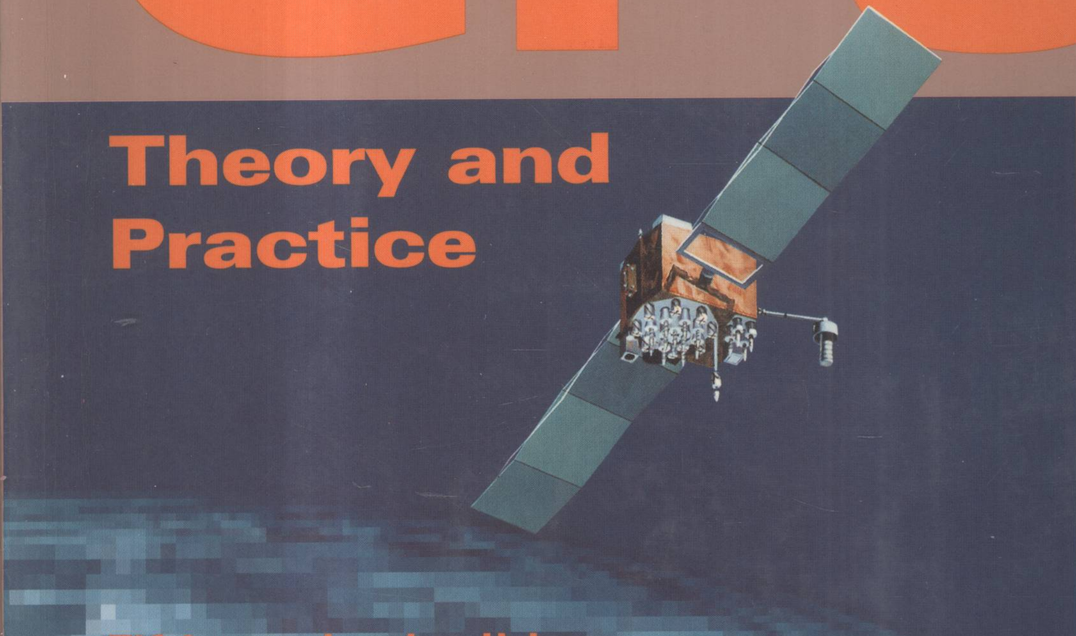
B. Hofmann-Wellenhof,
H. Lichtenegger, and J. Collins

GPS

Theory and Practice



Fifth, revised edition

SpringerWienNewYork

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Global Positioning System

Theory and Practice

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We dedicate this book to

Benjamin William Remondi

Foreword

This book is dedicated to Dr. Benjamin William Remondi for many reasons. The project of writing a Global Positioning System (GPS) book was conceived in April 1988 at a GPS meeting in Darmstadt, Germany. Dr. Remondi discussed with me the need for an additional GPS textbook and suggested a possible joint effort. In 1989, I was willing to commit myself to such a project. Unfortunately, the timing was less than ideal for Dr. Remondi. Therefore, I decided to start the project with other coauthors. Dr. Remondi agreed and indicated his willingness to be a reviewer.

I selected Dr. Herbert Lichtenegger, my colleague from the Technical University Graz, Austria, and Dr. James Collins from Rockville, Maryland, U.S.A.

In my opinion, the knowledge of the three authors should cover the wide spectrum of GPS. Dr. Lichtenegger is a geodesist with broad experience in both theory and practice. He has specialized his research to geodetic astronomy including orbital theory and geodynamical phenomena. Since 1986, Dr. Lichtenegger's main interest is dedicated to GPS. Dr. Collins retired from the U.S. National Geodetic Survey in 1980, where he was the Deputy Director. For the past ten years, he has been deeply involved in using GPS technology with an emphasis on surveying. Dr. Collins was the founder and president of Geo/Hydro Inc. My own background is theoretically oriented. My first chief, Prof. Dr. Peter Meissl, was an excellent theoretician; and my former chief, Prof. Dr.mult. Helmut Moritz, fortunately, still is.

It is appropriate here to say a word of thanks to Prof. Dr.mult. Helmut Moritz, whom I consider my mentor in science. He is – as is probably widely known – one of the world's leading geodesists and is currently president of the International Union for Geodesy and Geophysics (IUGG). In the fall of 1984, he told me I should go to the U.S.A. to learn about GPS. I certainly agreed, although I did not even know what GPS meant. On the same day, Helmut Moritz called Admiral Dr. John Bossler, at that time the Director of the National Geodetic Survey, and my first stay in the U.S.A. was arranged. Thank you, Helmut! I still remember the flight where I started to read the first articles on GPS. I found it interesting but I did not understand very much. Benjamin W. Remondi deserves the credit for providing my GPS instruction. He was a very patient and excellent teacher. I benefited enormously, and I accepted his offer to return to the U.S.A. several times. Aside from the scientific aspect, our families have also become friends.

The selection of topics is certainly different from the original book conceived by Dr. Remondi. The primary selection criteria of the topics were: relevancy, tutorial content, and the interest and expertise of the authors. The book is intended to be a text on GPS, recognizing the tremendous need for textual materials for professionals, teachers, and for students. The authors believe that it was not necessary to dwell on the latest technical advances. Instead, concepts and techniques are emphasized.

The book can be employed as a classroom text at the senior or graduate levels, depending on the level of specialization desired. It can be read, selectively, by professional surveyors, navigators, and many others who need to position with GPS.

May 1992 B. Hofmann-Wellenhof

Preface

The contents of the book are partitioned into 13 chapters, a section of references, and a detailed index which should immediately help in finding certain topics of interest.

The first chapter is a historical review. It shows the origins of surveying and how global surveying techniques have been developed. In addition, a short history on the Global Positioning System (GPS) is given.

The second chapter is an overview of GPS. The system is explained by means of its three segments: the space segment, the control segment, and the user segment.

The third chapter deals with the reference systems, such as coordinate and time systems. The celestial and the terrestrial reference frames are explained in the section on coordinate systems, and the transformation between them is shown. The definition of different times is given in the section on time systems, together with appropriate conversion formulas.

The fourth chapter is dedicated to satellite orbits. This chapter specifically describes GPS orbits and covers the determination of the Keplerian and the perturbed orbit, as well as the dissemination of the orbital data.

The fifth chapter covers the satellite signal. It shows the fundamentals of the signal structure with its various components and the principles of the signal processing.

The sixth chapter deals with the observables. The data acquisition comprises code and phase pseudoranges and Doppler data. The chapter also contains the data combinations, both the phase combinations and the phase/code range combinations. Influences affecting the observables are described: the atmospheric and relativistic effects, the impact of the antenna phase center, and multipath.

The seventh chapter is dedicated to surveying with GPS. This chapter defines the terminology used and describes the planning of a GPS survey, surveying procedures, and in situ data processing.

The eighth chapter covers mathematical models for positioning. Models for observed data are investigated. Therefore, models for point positioning and relative positioning, based on various data sets, are derived.

The ninth chapter comprises the data processing and deals with cycle slip detection and repair. This chapter also discusses phase ambiguity resolution. The method of least squares adjustment is assumed to be known to the reader and, therefore, only a brief review (including the principle of Kalman filtering) is presented. Consequently, no details are given apart from the linearization of the mathematical models, which are the input for the adjustment procedure.

The tenth chapter links the GPS results to a local datum. The necessary transformations are given. The combination of GPS and terrestrial data is also considered.

The eleventh chapter treats software modules. The intent of this chapter is not to give a detailed description of existing software and how it works. This chapter should help the reader decide which software would best suit his purposes. The very short sections of this chapter try to cover the variety of features which could be relevant to the software.

The twelfth chapter describes some applications of GPS. Global, regional, and local uses are mentioned, as well as the installation of control networks. The compatibility of GPS with other systems, such as Inertial Navigation Systems (INS) and the Global Navigation Satellite System (GLONASS), the Russian equivalent to GPS, is shown.

The thirteenth chapter deals with the future of GPS. Both critical aspects, such as selective availability and anti-spoofing, are discussed, along with positive aspects such as the combination of GPS with GLONASS and the International Maritime Satellite Communication Organization (INMARSAT). Also, some possible improvements in the hardware and software technology are suggested.

The hyphenation is based on Webster's Dictionary. Therefore, some deviations may appear for the reader accustomed to another hyphenation system. For example, the word "measurement", following Webster's Dictionary, is hyphenated mea-sure-ment; whereas, following The American Heritage Dictionary, the hyphenation is meas-ure-ment. The Webster's hyphenation system also contains hyphenations which are sometimes unusual for words with a foreign language origin. An example is the word "parameter". Following Webster's Dictionary, the hyphenation is pa-ram-e-ter. The word has a Greek origin, and one would expect the hyphenation pa-ra-me-ter.

Symbols representing a vector or a matrix are underlined. The inner product of two vectors is indicated by a dot "$\cdot$". The outer product, cross product, or vector product is indicated by the symbol "$\times$". The norm of a vector, i.e., its length, is indicated by two double-bars "$\|$".

Many persons deserve credit and thanks. Dr. Benjamin W. Remondi of the National Geodetic Survey at Rockville, Maryland, was a reviewer of the book. He has critically read and corrected the full volume. His many suggestions and improvements, critical remarks and proposals are gratefully acknowledged.

A second technical proofreading was performed by Dipl.-Ing. Gerhard Kienast from the section of Surveying and Landinformation of the Technical

University Graz. He has helped us with constructive critique and valuable suggestions.

Nadine Collins kindly read and edited the book in its final form, improving the flow and grammar of the text.

The index of the book was produced using a computer program written by Dr. Walter Klostius from the section of Surveying and Landinformation of the Technical University Graz. Also, his program helped in the detection of spelling errors.

The book is compiled based on the text system LaTeX. Some of the figures included were also developed with LaTeX. The remaining figures are drawn by using Autocad 11.0. The section of Physical Geodesy of the Technical University Graz deserves the thanks for these figures. Dr. Norbert Kühtreiber has drawn two of these figures, and the others were carefully developed by Dr. Konrad Rautz. This shows that theoreticians are also well-suited for practical tasks.

We are also grateful to the Springer Publishing Company for their advice and cooperation.

Finally, the inclusion by name of a commercial company or product does not constitute an endorsement by the authors. In principle, such inclusions were avoided whenever possible. Only those names which played a fundamental role in receiver and processing development are included for historical purposes.

May 1992 B. Hofmann-Wellenhof H. Lichtenegger J. Collins

Preface to the fifth edition

Today, writing a book on GPS is a completely different matter compared to the task eight years ago when this book was released for the first time. In these eight years, a tremendous improvement in GPS knowledge has occurred which would impact a conceptually new book. Topics have evolved which were not discussed a few years ago, like the third civil frequency, and by contrast, other topics have lost much of the importance of the earlier GPS years. The World Wide Web (WWW) is another feature with strong impact. Some GPS information may be more reliably downloaded in updated form from the internet than read in a book. Examples are the steadily changing satellite constellations and the RINEX format.

In the fifth edition, the afore-mentioned aspects have been considered to some extent. However, the overall structure of the former editions is retained since this was the request of many reviewers. In addition, the most recent advances in GPS technology like the decision to switch off Selective Availability (SA), the GPS modernization covering the new signal structure, improvements in the space and the control segment, and the augmentation of GPS by satellite-based and ground-based systems leading to future Global Navigation Satellite Systems (GNSS) are considered.

An exterior restriction was the limited number of pages of the book to keep a reasonable price. Figuratively, the more recent advances had to be implemented in exchange against subjects which might be considered well known. For this reason, we also had to reduce the list of references. With some exceptions like books and monographs, we treated this subtle matter by omitting all references "older" than 1990. This was relatively easy in cases where more recent publications of the authors were available but more critical if this was not the case. Thus, to avoid eliminating names of distinguished GPS pioneers, the person's name in connection with his fundamental idea is mentioned accordingly.

The authors are very grateful to Steve Nerem from the University of Texas at Austin for reporting us several errors we were not aware of. Steve wrote us in detail how to implement the corrections.

Similarly, the authors would like to thank the geodetic group of the Delft University of Technology, The Netherlands, headed by Peter Teunissen, for supporting us with many ideas and publications concerning the ambiguity resolution. Furthermore, Paul de Jonge and Christian Tiberius wrote us on the rank deficiency problem in some of our models. This letter arrived briefly before the release of the fourth edition and could not be implied adequately. The fifth edition fully encompasses this aspect. Thanks also to Kees de Jong for providing the figure on the SA discontinuity.

The authors would also like to thank Jan Kouba from the Geodetic Survey of Canada at Ottawa, Shin-Chan Han from the Ohio State University, Maria Tsakiri from the Curtin University of Technology at Perth, Australia, and Werner Oberegger, Austria, for some hints and advices. Thanks also to Walter Klostius, Norbert Kühtreiber, and Klaus Legat, all Graz University of Technology, for some help with the subject index and the figures.

The authors consider this edition the final one in the present structure; if another update should be required, the book will be written from the scratch. Your ideas for a future book and your advice is appreciated and encouraged.

August 2000 B. Hofmann-Wellenhof H. Lichtenegger J. Collins

Abbreviations

AFB	Air Force Base
AOC	Auxiliary Output Chip
AROF	Ambiguity Resolution On-the-Fly
A-S	Anti-Spoofing
AVL	Automatic Vehicle Location
C/A	Coarse/Acquisition
CBIS	Central Bureau Information System
CDMA	Code Division Multiple Access
CEP	Celestial Ephemeris Pole
CEP	Circular Error Probable
CGSIC	Civil GPS Service Interface Committee
CHAMP	Challenging Mini-satellite Payload
CIGNET	Cooperative International GPS Network
CIO	Conventional International Origin
CODE	Center for Orbit Determination in Europe
CORS	Continuously Operating Reference Station
CRF	Celestial Reference Frame
CSOC	Consolidated Space Operations Center
DARC	Data Radio Channel
DGPS	Differential GPS
DLL	Delay Lock Loop
DMA	Defense Mapping Agency
DME	Distance Measuring Equipment
DoD	Department of Defense
DOP	Dilution of Precision
DOSE	Dynamics of Solid Earth
DoT	Department of Transportation
DRMS	Distance Root Mean Square (error)
ECEF	Earth-Centered-Earth-Fixed
EGM	Earth Gravitational Model
EGNOS	European Geostationary Navigation Overlay Service
EOP	Earth Orientation Parameters
ERS	Earth Remote Sensing (satellite)
FAA	Federal Aviation Administration
FDMA	Frequency Division Multiple Access
FGCC	Federal Geodetic Control Committee
FOC	Full Operational Capability

FRP	Federal Radionavigation Plan
FTP	File Transfer Protocol
GBAS	Ground-Based Augmentation System
GDOP	Geometric Dilution of Precision
GEO	Geostationary Orbit (satellite)
GIC	GPS Integrity Channel
GIM	Global Ionosphere Map
GIS	Geographic Information System
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GOTEX	Global Orbit Tracking Experiment
GPS	Global Positioning System
GRS	Geodetic Reference System
HDOP	Horizontal Dilution of Precision
HIRAN	High Range Navigation (system)
HOW	Hand-Over Word
IAG	International Association of Geodesy
IAT	International Atomic Time
IAU	International Astronomical Union
ICRF	IERS (or International) Celestial Reference Frame
IERS	International Earth Rotation Service
IF	Intermediate Frequency
IGEB	Interagency GPS Executive Board
IGEX	International GLONASS Experiment
IGS	International GPS Service (for Geodynamics)
ILS	Instrument Landing System
INMARSAT	International Maritime Satellite (organization)
INS	Inertial Navigation System
IOC	Initial Operational Capability
ION	Institute of Navigation
IRM	IERS (or International) Reference Meridian
IRP	IERS (or International) Reference Pole
ISU	International System of Units
ITRF	IERS (or International) Terrestrial Reference Frame
ITS	Intelligent Transportation System
ITU	International Telecommunication Union
IUGG	International Union for Geodesy and Geophysics
IVHS	Intelligent Vehicle/Highway System
IWV	Integrated Water Vapor
JD	Julian Date
JPL	Jet Propulsion Laboratory

JPO	Joint Program Office
LAAS	Local Area Augmentation System
LEO	Low Earth Orbit (satellite)
LEP	Linear Error Probable
LORAN	Long-Range Navigation (system)
MEDLL	Multipath Estimating Delay Lock Loop
MEO	Mean Earth Orbit (satellite)
MIT	Massachusetts Institute of Technology
MITES	Miniature Interferometer Terminals for Earth Surveying
MJD	Modified Julian Date
MLS	Microwave Landing System
MRSE	Mean Radial Spherical Error
NAD	North American Datum
NAGU	Notice Advisories to GLONASS Users
NANU	Notice Advisories to Navstar Users
NASA	National Aeronautics and Space Administration
NAVSTAR	Navigation System with Timing and Ranging
NGS	National Geodetic Survey
NIMA	National Imagery and Mapping Agency
NIS	Navigation Information Service
NMEA	National Marine Electronics Association
NNSS	Navy Navigation Satellite System (or TRANSIT)
NSWC	Naval Surface Warfare Center
OCS	Operational Control System
OEM	Original Equipment Manufacturer
OTF	On-the-Fly
OTR	On-the-Run
PCMCIA	PC Memory Card International Association
PDD	Presidential Decision Directive
PDOP	Position Dilution of Precision
PLL	Phase Lock Loop
PPS	Precise Positioning Service
PRC	Pseudorange Correction
PRN	Pseudorandom Noise
RAIM	Receiver Autonomous Integrity Monitoring
RDS	Radio Data System
RF	Radio Frequency
RINEX	Receiver Independent Exchange (format)
RRC	Range Rate Correction
RTCM	Radio Technical Commission for Maritime (services)
RTK	Real-Time Kinematic

SA	Selective Availability
SBAS	Satellite-Based Augmentation System
SD	Selective Denial
SEP	Spherical Error Probable
SERIES	Satellite Emission Range Inferred Earth Surveying
SINEX	Software Independent Exchange (format)
SLR	Satellite Laser Ranging
SNR	Signal-to-Noise Ratio
SPOT	Satellite Probatoire d'Observation de la Terre
SPS	Standard Positioning Service
SV	Space Vehicle
TACAN	Tactical Air Navigation
TCAR	Three-Carrier Ambiguity Resolution
TDOP	Time Dilution of Precision
TEC	Total Electron Content
TLM	Telemetry (word)
TOPEX	(Ocean) Topography Experiment
TOW	Time-of-Week (count)
TRF	Terrestrial Reference Frame
TT	Terrestrial Time
TVEC	Total Vertical Electron Content
UERE	User Equivalent Range Error
UHF	Ultra High Frequency
URL	Uniform Resource Locator
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
USNO	U.S. Naval Observatory
UT	Universal Time
UTC	Universal Time Coordinated
UTM	Universal Transverse Mercator (projection)
VDOP	Vertical Dilution of Precision
VHF	Very High Frequency
VLBI	Very Long Baseline Interferometry
VOR	VHF Omnidirectional Range (equipment)
VRS	Virtual Reference Station
WAAS	Wide Area Augmentation System
WADGPS	Wide Area Differential GPS
WGS	World Geodetic System
WRC	World Radio Conference
WWW	World Wide Web

Numerical constants

GPS signal frequencies		
$f_0 =$	10.23 MHz	fundamental frequency
L1 =	1 575.42 MHz	primary carrier frequency
L2 =	1 227.60 MHz	secondary carrier frequency

WGS-84		
$a =$	6 378 137.0 m	semimajor axis of ellipsoid
$f =$	1/298.257 223 563	flattening of ellipsoid
$\omega_E =$	$7\,292\,115 \cdot 10^{-11}\,\mathrm{rad\,s^{-1}}$	angular velocity of the earth
$GM =$	$3\,986\,004.418 \cdot 10^{8}\,\mathrm{m^3\,s^{-2}}$	earth's gravitational constant
$b =$	6 356 752.314 25 m	semiminor axis of ellipsoid
$e^2 =$	$6.694\,379\,990\,13 \cdot 10^{-3}$	first numerical eccentricity
$e'^2 =$	$6.739\,496\,742\,26 \cdot 10^{-3}$	second numerical eccentricity

Various constants		
$c =$	$299\,792\,458\,\mathrm{m\,s^{-1}}$	velocity of light
$\omega_E =$	$7\,292\,115.1467 \cdot 10^{-11}\,\mathrm{rad\,s^{-1}}$	untruncated angular velocity
CD =	January 6.0, 1980	Civil date of GPS standard epoch
JD =	2 444 244.5	Julian date of GPS standard epoch

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