GPS for Geodesy

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GPS for Geodesy

Second Completely Revised and Extended Edition
with 127 Figures and 32 Tables

Springer

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Cataloging-in-Publication Data applied for
GPS for geodesy / Alfred Kleusberg, Peter J.G. Teunissen, [eds.]. -- 2nd ed.
"Contains the edited lecture notes of the International School GPS for Geodesy in Delft, The Netherlands, March 2-8 1997"--Pref. Includes bibliographical references and index
ISBN-13: 978-3-642-72013-0 e-ISBN-13: 978-3-642-72011-6
DOI: 10.1007/ 978-3-642-72011-6
1.Global Postioning System--Congresses. 2. Geodesy--Congresses. 3. Surveying--Congresses. I. Kleusberg, Alfred. II. Teunissen, P. J. G.
QB275.G65 1998

Typesetting: Camera-ready by Jasmine van der Bijl
Cover design: design & production, Heidelberg
SPIN:10635190 32/3020-5 4 3 2 1 0 - Printed on acid -free paper

PREFACE TO SECOND EDITION

This second edition contains the edited lecture notes of the 2nd International School **GPS for Geodesy** in Delft, The Netherlands, March 2-8, 1997. The school was again held at the excellent facilities of the DISH Hotel, and organized with the knowledgeable help of Frans Schröder of the Netherlands Geodetic Commission. It attracted 60 geodesists and geophysicists from around the world.

The 2nd school was organized using the successful formula of the first school. Following the rapid developments in GPS geodesy, new topics were added to the original lecturing program. These include GPS quality control, active GPS reference stations, long-distance kinematic GPS and atmospheric models from GPS. The expanded program was presented by the team of experts of the first school and three invited guest lecturers.

The typescript of the lecture notes of this second and enlarged edition was edited by Frank Kenselaar and Jasmine van der Bijl of the Department of Geodetic Engineering of the Delft University of Technology. They succeeded in transforming the original lecture notes to one coherently formatted manuscript.

The 2nd school received the same generous support as the first school. This support is gratefully acknowledged.

January 1998
Delft, The Netherlands — Peter Teunissen
Stuttgart, Germany — Alfred Kleusberg

PREFACE

This monograph contains the revised and edited lecture notes of the International School **GPS for Geodesy** in Delft, The Netherlands, March 26 through April 1, 1995. The objective of the school was to provide the necessary information to understand the potential and the limitations of the Global Positioning System for applications in the field of Geodesy. The school was held in the excellent facilities of the DISH Hotel, and attracted 60 geodesists and geophysicists from America, Asia, Australia and Europe.

The school was organized into lectures and discussion sessions. There were two lecture periods in the morning and two lecture periods in the afternoon, followed by a discussion session in the early morning. A welcome interruption to this regular schedule was a visit to the European Space Research and Technology Centre (ESTEC) in Noordwijk in the afternoon of March 29. A tour of the Noordwijk Space Expo and the ESA satellite test facilities, and presentations by ESTEC personnel of GPS and GNSS related activities at ESTEC, provided a different perspective to space geodesy.

The school had the support of the International Association of Geodesy, the Netherlands Geodetic Commission, the Department of Geodetic Engineering of the Delft University of Technology, the Department of Geodesy and Geomatics Engineering of the University of New Brunswick, and the Survey Department of Rijkswaterstaat. This support is gratefully acknowledged.

The organization of the International School began in early 1994, with the knowledgeable help of Frans Schröder of the Netherlands Geodetic Commission. Throughout the year of preparation and during the school, Frans Schröder looked after student registration and organized facilities, and thereby ensured the success of the school.

The International School **GPS for Geodesy** would not have been possible without a team of dedicated lecturers of international reputation with expertise in GPS geodesy. The lecturers were willing to agree beforehand to a shared responsibility for parts of the school presentation and the preparation of the corresponding lecture notes. All authors tried to adhere to a common notation throughout the chapters of the lecture notes, and avoided unnecessary repetitions.

The typescript of these lecture notes was edited by Wendy Wells of the Department of Geodesy and Geomatics Engineering of the University of New Brunswick. She received expert help on Chapter 8 from Jasmine van der Bijl of the Department of Geodetic Engineering, Delft University of Technology. Ms Wells succeeded in producing a coherently formatted manuscript from bits and pieces created with three different word processors on two different computer platforms.

January 1996
Fredericton, Canada — Alfred Kleusberg
Delft, The Netherlands — Peter Teunissen

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INTRODUCTION

The topic of these lecture notes of the International School **GPS for Geodesy** is the description of the use of the Global Positioning System (GPS) measurements for geodetic applications. The term geodetic applications is used in the sense that it covers the determination of precise coordinates for positions in a well defined reference system, and the monitoring of temporal changes of these coordinates.

These lecture notes are organized in sixteen chapters, each of which begins with the full address of the author(s), and a section introducing the theme of the chapter. After the main body of text, each chapter is concluded by a summary section and a list of references. The individual chapters have been written independently, and they can also be read and studied independently. Their sequence, however, has been arranged to provide a logical and coherent coverage of the topic **GPS for Geodesy**.

Chapter 1 introduces global reference systems for Cartesian and ellipsoidal coordinates and local reference frames, and their basic relation to the GPS measurements. Transformations between and motions of the Celestial and Terrestrial Reference Frames are described. Time systems are introduced to provide an independent variable for the description of motion and earth deformation. The concepts and realizations of Conventional Reference Systems are explained.

The topic of Chapter 2 is the description of the computation of GPS satellite orbits, and the dissemination of GPS satellite ephemerides. Starting from the equations of motion for satellites, first the Keplerian orbit is introduced and then generalized to include the pertubations resulting from non-central forces. Various sources of orbital information to GPS end users are described, and the chapter is concluded with a brief introduction of the effect of unmodelled orbit errors on positions determined from GPS measurements.

Chapter 3 introduces the GPS signal, its components, and its generation in the satellites' circuitry. The aspects of signal propagation from the satellite to the GPS receiver are described, including the effects of refraction, multipath, and scattering. Chapter 4 begins with an introduction to the basic building blocks of a GPS receiver, and shows how pseudoranges and carrier phases are being measured in the receiver circuits. The chapter is concluded with a discussion of the measurements errors in these two observables.

Chapter 5 starts from the complete non-linear observation equations for pseudoranges and carrier phases and introduces a number of different linear combinations, in order to eliminate, reduce, and/or emphasize parts of the equations. Following this exploratory analysis, the observation equations are linearized with respect to the parameters to be determined. Basic properties of the linearized equations in the context of single point positioning and relative positioning are discussed, with particular emphasis on parameter estimability.

Chapters 6 through 8 present details on the adjustment and testing of GPS data. Practical and methodological aspects of GPS data processing are discussed in Chapter 6, and methods for GPS quality control are presented in Chapter 7. The quality control procedures are developed for both batch solutions and recursive

solutions. The process of finding and validating the correct integer carrier phase ambiguities is discussed in Chapter 8. This chapter introduces the theory of integer least-squares and outlines various ambiguity search strategies, including the process of ambiguity decorrelation.

Chapters 9 through 16 present details on the use of GPS measurements for the spectrum of geodetic applications. There might be a number of ways of structuring these applications; we have chosen to start with single-receiver applications followed by multi-receiver applications for which the network scale is used as the criterion. Accordingly we begin with two chapters, Chapter 9 and Chapter 10, on the use of a single receiver. The first chapter discusses the components of an active GPS reference station, together with its potential on-line and off-line applications. Chapter 10 proceeds to discuss single site solutions through linearization of the observation equations. Also included is a presentation of the direct solution of pseudorange equations without the requirement of a priori information.

Chapter 11 discusses short distance GPS models. In the context of these Lecture Notes, "short" means that atmospheric and orbital errors do not significantly affect the accuracy of the positioning results, and do not have to be included explicitly. In order to retain the full capability of GPS in networks of larger scale (typically between 50 km and 1000 km), the atmospheric refraction effects and inaccuracies of the GPS satellite orbits need to be explicitly included. The corresponding mathematical models for the GPS measurements and procedures for the estimation of geodetic parameters are outlined in Chapters 12 and 13. The first of these two chapters considers large scale network solutions with applications for monitoring crustal deformation, while the second chapter concentrates on the positioning of moving platforms over long distances so as to assist large-area surveys with remote-sensing instruments on board ships or aircraft.

The last three chapters of this book discuss the Global Positioning System for applications on a global scale. Chapter 14 discusses the estimation of various parameters of interest for geodynamics applications, together with the necessary link to the determination and maintenance of global reference systems. Chapter 15 discusses the contribution of GPS to atmospheric modelling. In this scenario, the ionospheric and tropospheric delays are seen as remotely sensed data related to atmospheric parameters, with the possibility to recover some or all of these parameters through proper GPS data analysis. Finally, the last chapter of this book puts GPS in perspective by discussing its role in space geodesy, now and in the future.