CHAPTER 1

INTRODUCTION

Over the last decade, the development and application of GNSS (global navigation satellite system) has been unabatedly progressing. Not only is the modernization of the U.S. GPS (global positioning system) in full swing, the Russian GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema) system has undergone a remarkable recovery since its decline in the late 1990s to be now fully operational. The first static and kinematic surveys with the Chinese Beidou system are being published, and the signals of the European Galileo system are being evaluated. While many individuals might look back on the exciting times they were fortunate to experience since the launch of the first GPS satellite in 1978, there are many more enthusiastic individuals gearing up for an even more exciting future of surveying and navigation with GNSS. Yes, it seems like a long time has passed since sunset admirers on top of Mount Wachusett, seeing a GPS antenna with cables connected to a big "machine" in a station wagon were wondering if it would "take off," or if you were "on their side," or regular folks in a parking lot approaching a car with a "GPS" license plate were wondering if you had "such a thing."

Much has been published on the subject of GNSS, primarily about GPS because of its long history. Admirably efficient search engines uncover enormous amounts of resources on the Internet to make an author wonder what else is there to write about. We took the opportunity of updating GPS Satellite Surveying to add strength by including two additional authors, while looking at rearranging the material in a way that reflects the maturity and permanency of the subject and de-emphasizes the news of the day or minor things that may have gotten the early pioneers of GPS excited.

Perhaps the most visible outcome of the rearrangement of the material for this edition is that GNSS in earnest starts only in Chapter 5, which may come as a surprise to the unexpected reader. However, if was determined that first presenting the geodetic and statistical foundations for GPS Satellite Surveying would be more efficient, and then focusing on GNSS, thus taking advantage of having the prerequisites available and not being side-tracked by explaining essential fill-in material. Therefore, there are two chapters devoted to least-squares estimation, followed by a chapter on geodesy. These three chapters clearly identify the traditional clientele this book tries to serve, i.e., those who are interested in using GNSS for high-accuracy applications. The other chapters cover GNSS systems, GNSS positioning, RTK (real-time kinematic), troposphere and ionosphere, and GNSS user antennas. There are nine appendices.

Chapter 2, least-squares adjustment, contains enough material to easily fill a regular 3-credit-hour college course on adjustments. The focus is on estimating parameters that do not depend on time. The material is presented in a very general form independently of specific applications, although the classical adjustment of a geodetic or surveying network comes to mind as an example. The approach to the material is fairly unique as compared to a regular course on least squares because it starts with the mixed model in which the observations and the parameters are implicitly related. This general approach allows for an efficient derivation of various other adjustment models simply by appropriate specifications of certain matrices. Similarly, the general linear hypothesis testing is a natural part of the approach. Of particular interest to surveying applications are the sections on minimal and inner constraints, internal and external reliability, and blunder detection.

Chapter 3, recursive least squares, represents new material that has been added to this fourth revision. In particular in view of RTK application where the position of the rover changes with time, it was deemed appropriate to add a dedicated chapter in which the estimation of time-dependent parameters is the focus. Consequently, we changed the notation using the argument of time consistently to emphasize the time dependency. A strength of this chapter is that it explicitly deals with patterned matrices as they occur in RTK and many other applications. Apart from the term "recursive least squares," other terms might be "first-order partitioning regression" or "Helmert blocking," that express the technique applied to these patterned matrices. Although Chapters 2 and 3 are related since there is only one least-squares method, Chapter 3 stands on its own. It also could serve easily as a text for a regular 3-credit-hour college course.

Chapter 4 is dedicated to geodesy. It provides details on reference frames, such as the ITRF (international terrestrial reference frame), as well as the transformation between such frames. The geodetic datum is a key element in this chapter, which is defined as an ellipsoid of defined location, orientation, and size and an associated set of deflection of the vertical and geoid undulations. Establishing the datum, in particular measuring gravity to compute geoid undulations, is traditionally done by geodesists. The fact that here it is assumed that all this foundational material is given indicates that geodesy is treated not as a science by itself in this book but rather as an enabling element that supports accurate GNSS applications. As the "model for all," we present the three-dimensional (3D) geodetic model, which is applicable to networks of any size and assumes that the geodetic datum is available. In addressing the needs of surveying, the topic of conformal mapping of the ellipsoidal surface is treated in great detail. This includes, as a transitional product encountered along the way, computations on the ellipsoidal surface. It is well known that computing on the conformal mapping plane is limited by the area covered by the network since distortions increase with area. Additionally, the respective computations require the geodesic line, which is mathematically complicated, and the respective expressions are a result of lengthy but unattractive series expansions. Clearly, an attempt is made to point out the preference of the 3D geodetic model when there is the opportunity to do so.

Chapter 5, finally, introduces the various GNSS systems. In order to provide background information on satellite motions, the chapter begins with an elementary discussion of satellite motions, the Kepler elements that describe such motions, and the particularly simple theory of normal orbits, i.e., motion in a central gravity field. The disturbing forces that cause satellites to deviate from normal orbits are discussed as well. However, the material is not presented at the level of detail needed for accurate satellite orbit determination. We assume that orbit determination will continue to be handled by existing expert groups and that respective products will be available either through the broadcast navigation message or the International GNSS Service (IGS) and other agencies in the form of precise and/or ultra-rapid ephemeris and satellite clock data. This chapter includes new material on GPS modernization and on the GLONASS, Galileo, and Beidou systems. In the meantime, interface control documents are available for all these GNSS systems and posted on the Internet. The reader is advised to consult these documents and similar publications that expertly address the space segment.

Chapter 6 discusses in detail the various GNSS positioning approaches conveniently in “one place.” It begins with specifying the fundamental pseudorange and carrier phase equations. All relevant functions of these observables are then grouped and listed without much additional explanation. These functions are all well known; exceptions might be the triple-frequency functions. We introduce the “across” terminology in order to more easily identify the specific differencing. As such, we have the across-receiver, across-satellite, and across-time observation (single) differences, and then the traditional double-difference and triple-difference functions. A separate section is dedicated to operational details. That section includes everything one needs to know when carrying out high-accuracy positioning with GNSS. We especially stress the “GNSS infrastructure” that has established itself to support users. By this, we mean the totality of GNSS services provided by government agencies, user groups, universities, and above all the IGS and the (mostly) free online computing services. IGS provides products of interest to the sophisticated high-end GNSS user, while the computation services are of most interest to those responsible for processing field data. This is indeed a marvelous GNSS infrastructure that is of tremendous utility.

As to the actual GNSS positioning approaches, Chapter 6 is concerned with three types of approaches, each having been assigned a separate section. The first section deals with navigation solution, which uses the broadcast ephemeris, and the traditional double-differencing technique with ambiguity fixing for accurate positioning. The double differences are formed on the basis of the base station and base satellite concept to conveniently identify the linear dependent double differences. We note that the reason for the popularity of the double-difference functions is the cancelation of common mode errors, such as receiver and satellite clock errors and hardware delays, as well as the tropospheric and ionospheric impacts on the carrier phases in the case of short baselines. The formation of double-difference functions is briefly contrasted with the equivalent undifferenced approach in which only the nonbase-station and nonbase-satellite observation contains an ambiguity parameter, while each of the others contains an epoch-dependent parameter. The latter approach results in a large system of equations that can be efficiently solved by exploring the pattern of the matrices.

In the second section, we discuss PPP (precise point positioning), CORS (continuous operating reference stations), and the classical differential correction that applies to RTK and PPP-RTK, which has been gaining popularity. In the case of PPP, the user operates one dual-frequency receiver and uses the precise ephemeris and satellite clock corrections to determine accurate position; the known drawback of the technique is long station occupation times. The use of the "classical" differential pseudorange and carrier phase correction is also well established, in particular in RTK. The differential correction essentially represents the discrepancies of the undifferenced observations computed at the reference stations. The user receives the differential correction of one or several reference stations and effectively forms double differences to determine its precise position. In the case of PPP-RTK, biases are transmitted to the user. These biases represent the difference of the satellite biases (clock error and hardware delay) and the base station bias (clock error and hardware delay). The user applies the received biases to the observations and carries out an ambiguity-fixed solution for precise point positioning. The advantage of the PPP-RTK approach is that the biases only primarily depend on the changes of the base station clock. Therefore, if the base station is equipped with an atomic clock, the variability of the transmitted biases can be reduced. Using the classical differential correction, the RTK user needs to estimate $(R-1)(S-1)$ ambiguities, where R and S denote the number of receivers (reference plus rover) and satellites involved, whereas the PPP-RTK user only needs to estimate $(S-1)$ ambiguities. In the case of PPP-RTK, some of the work is shifted to the reference network since it computes the biases relative to the base station, whereas the differential corrections refer to the respective reference station and not a specific base station.

In the third section, we deal with TCAR (three carrier phase ambiguity resolutions). This technique is an extension of the popular dual-frequency technique of computing the wide-lane ambiguity first and independently from the actual position solution. In the case of TCAR, one uses triple-frequency observations to resolve the extra-wide-lane, wide-lane, and narrow-lane ambiguities first.

Additionally, a separate section is dedicated to ambiguity fixing. First, the popular LAMBDA (least-squares ambiguity decorrelation adjustment) technique is discussed in detail. This is followed by material on lattice reduction. It was deemed important to add material to see how other disciplines deal with problems similar to ambiguity fixing in GNSS, and in doing so remaining open-minded as to other possible efficient solutions, in particular as the number of ambiguities increases when eventually all visible satellites of all systems are being observed.

Chapter 7 is dedicated to RTK. Since RTK includes static positioning as a special case, it is considered the most general approach. The technique is applicable to short baselines and long baselines if all effects are appropriately modeled. The chapter refers to a practical implementation of RTK algorithms that uses the formalism of recursive least squares given in Chapter 3, uses across-receiver differences as opposed to double differences, and is designed to include observations from all GNSS systems. Its recipes for software implementations are intended for specialists in geodetic software design. All examples are illustrated by way of real data processing.

Chapter 8 deals with the troposphere and ionosphere. The material is presented in a separate chapter in order to emphasis the major contribution of GPS in sensing the troposphere and ionosphere and, conversely, to understand the major efforts made to correct the observations for ionospheric and tropospheric effects in positioning. In addition to dealing with tropospheric refraction and various models for zenith delays and vertical angle dependencies, some material on tropospheric absorption and water vapor radiometers has been included. The chapter ends with a brief discussion on global ionospheric models.

Chapter 9 represents a major addition to this edition of the book. It is well known that multipath is affecting all GNSS positioning techniques, whether based on carrier phases or pseudoranges, since it is directly related to the ability of the user antenna to block reflected signals. Also realizing that geodesist and surveyors typically are not experts in antenna design, it was thought that a dedicated chapter on GNSS user antennas would provide an important addition to the book. We maintained the terminology and (mostly) also the notion that is found in the antenna expert community in the hope that it would make it easier for GPS *Satellite Surveying* readers to transition to the respective antenna literature if needed. Existing texts are often found to be too simple to be useful or too difficult for nonspecialists to understand. As an example of our approach, the Maxwell equations appear in the first section of the chapter but actually are not used explicitly except as support in the appendices. However, the majority of expressions are thoroughly derived and the respective assumptions are clearly identified. In several instances, however, it was deemed necessary to provide additional references for the in-depth study of the subject.

Chapter 9 is subdivided into seven sections. These sections deal with elements of electromagnetic fields and waves, antenna pattern and gain, phase center variation, signal propagation through a chain of circuits, and various antenna types and manufacturing issues and limitations. The material of this chapter is supplemented by six appendices which contain advanced mathematical material and proofs in compact form for readers who enjoy such mathematical depth. In general, the material is presented with sufficient depth for the reader to appreciate the possibilities and limitations of antenna design, to judge the performance of antennas, and to select the right antenna for the task at hand, in particular for high-accuracy applications.

Depending on one's view, one might consider GPS an old or new positioning and timing technology. Considering that the first GPS satellite was launched in 1978, one certainly can see it as old and well-established technology. However, given that new applications of GPS, and now we need to say GNSS, are continuously being developed, it is certainly also fair to characterize this as new technology. Whatever the reader's view might be, it is impossible to trace back all instances of important developments in GNSS unless, of course, one is willing to write a dedicated book on the history of GNSS. Nevertheless, the "pioneering years" of GPS were extremely uplifting as progress could be measured by leaps and bounds, and results were achieved at a level of quality that one had not expected. We present a brief, and probably subjective, review with a slant toward surveying of the major events up to the year 2000. Today, of course, progress continues to be made, in particular as other GNSS systems become operational; the progress is, however, now smooth and less steep.

Table 1.1 lists some of the noteworthy events up to the year 2000. GPS made its debut in surveying and geodesy with a big bang. During the summer of 1982, the testing of the Macrometer receiver, developed by C. C. Counselman at M.I.T., verified a GPS surveying accuracy of 1 to 2 parts per million (ppm) of the station separation. Baselines were measured repeatedly using several hours of observations to study this new surveying technique and to gain initial experience with GPS. During 1983, a first-order network densification of more than 30 stations in the Eifel region of Germany was observed (Bock et al., 1985). This project was a joint effort by the State Surveying Office of North Rhein-Westfalia, a private U.S. firm, and scientists from M.I.T. In early 1984, the geodetic network densification of Montgomery County (Pennsylvania) was completed. The sole guidance of this project rested with a private GPS surveying firm (Collins and Leick, 1985). Also in 1984, GPS was used at Stanford University for a high-precision GPS engineering survey to support construction for extending the Stanford linear accelerator (SLAC). Terrestrial observations (angles and distances) were combined with GPS vectors. The Stanford project yielded a truly millimeter-accurate GPS network, thus demonstrating, among other things, the high quality of the Macrometer antenna. This accuracy could be verified through comparison with the alignment laser at the accelerator, which reproduces a straight line within one-tenth of a millimeter (Ruland and Leick, 1985). Therefore, by the middle of 1984, 1 to 2 ppm GPS surveying had been demonstrated beyond any doubt. No visibility was required between the stations, and data processing could be done on a microcomputer. Hands-on experience was sufficient to acquire most of the skills needed to process the data—i.e., first-order geodetic network densification suddenly became within the capability of individual surveyors.

President Reagan offered GPS free of charge for civilian aircraft navigation in 1983, once the system became fully operational. This announcement can be viewed as the beginning of sharing arrangements of GPS for military and civilian users.

Engelis et al. (1985) computed accurate geoid undulation differences for the Eifel network, demonstrating how GPS results can be combined with orthometric heights, as well as what it takes to carry out such combinations accurately. New receivers became available—e.g., the dual-frequency P-code receiver TI-4100 from Texas Instruments—which was developed with the support of several federal agencies. Ladd et al. (1985) reported on a survey using codeless dual-frequency receivers and claimed 1 ppm in all three components of a vector in as little as 15 min of observation time. Thus, the move toward rapid static surveying had begun. Around 1985, kinematic GPS became available (Remondi, 1985). Kinematic GPS refers

TABLE 1.1 GPS Development and Performance at a Glance until 2000

1978	Launch of first GPS satellite
1982	Prototype Macrometer testing at M.I.T.
	Hatch's synergism paper
1983	Geodetic network densification (Eifel, Germany)
	President Reagan offers GPS to the world "free of charge"
1984	Geodetic network densification (Montgomery County, Pennsylvania)
	Engineering survey at Stanford
	Remondi's dissertation
1985	Precise geoid undulation differences for Eifel network
	Codeless dual-band observations
	Kinematic GPS surveying
	Antenna swap for ambiguity initialization
	First international symposium on precise positioning with GPS
1986	*Challenger* accident (January 28)
	10 cm aircraft positioning
1987	JPL baseline repeatability tests to 0.2−0.04 ppm
1989	Launch of first Block II satellite
	OTF solution
	Wide area differential GPS (WADGPS) concepts
	U.S. Coast Guard GPS Information Center (GPSIC)
1990	GEOID90 for NAD83 datum
1991	NGS ephemeris service
	GIG91 experiment (January 22–February 13)
1992	IGS campaign (June 21−September 23)
	Initial solutions to deal with antispoofing (AS)
	Narrow correlator spacing C/A-code receiver
	Attitude determination system
1993	Real-time kinematic GPS
	ACSM ad hoc committee on accuracy standards
	Orange County GIS/cadastral densification
	Initial operational capability (IOC) on December 8
	1–2 ppb baseline repeatability
	LAMBDA
1994	IGS service beginning January 1
	Antispoofing implementation (January 31)
	RTCM recommendations on differential GPS (Version 2.1)
	National Spatial Reference System Committee (NGS)
	Multiple (single-frequency) receiver experiments for OTF
	Proposal to monitor the earth's atmosphere with GPS (occultations)
1995	Full operational capability (FOC) on July 17
	Precise point positioning (PPP) at JPL
1996	Presidential Decision Directive, first U.S. GPS policy
1998	Vice president announces second GPS civil signal at 1227.60 MHz
	JPL's automated GPS data analysis service via Internet
1999	Vice president announces GPS modernization initiative and third civil GPS signal at 1176.45 MHz
	IGDG (Internet-based global differential GPS) at JPL
2000	Selective availability set to zero
	GPS Joint Program Office begins modifications to IIR-M and IIF satellites

to ambiguity-fixed solutions that yield centimeter (and better) relative accuracy for a moving antenna. The only constraint on the path of the moving antenna is visibility of the same four (at least) satellites at both receivers. Remondi introduced the antenna swapping technique to accomplish rapid initialization of ambiguities. Antenna swapping made kinematic positioning in surveying more efficient.

The deployment of GPS satellites came to a sudden halt due to the tragic January 28, 1986, *Challenger* accident. Several years passed until the Delta II launch vehicle was modified to carry GPS satellites. However, the theoretical developments continued at full speed. They were certainly facilitated by the publication of Remondi's (1984) dissertation, the very successful First International Symposium on Precise Positioning with the Global Positioning System held at the National Geodetic Survey, and a specialty conference on GPS held by the American Society of Civil Engineers in Nashville in 1988.

Kinematic GPS was used for decimeter positioning of airplanes relative to receivers on the ground (Mader, 1986; Krabill and Martin, 1987). The goal of these tests was to reduce the need for traditional and expensive ground control in photogrammetry. These early successes not only made it clear that precise airplane positioning would play a major role in photogrammetry, but they also highlighted the interest in positioning other remote sensing devices carried in airplanes.

Lichten and Border (1987) reported repeatability of 2–5 parts in 10^8 in all three components for static baselines. Note that 1 part in 10^8 corresponds to 1 mm in 100 km. Such highly accurate solutions require satellite positions of about 1 m and better (we note that today's orbit accuracy is in the range of 5 cm). Because accurate orbits were not yet available at the time, researchers were forced to estimate improved GPS orbits simultaneously with baseline estimation. The need for a precise orbital service became apparent. Other limitations, such as the uncertainty in the tropospheric delay over long baselines, also became apparent and created an interest in exploring water vapor radiometers to measure the wet part of the troposphere along the path of the satellite transmissions. The geophysical community requires high baseline accuracy for obvious reasons, e.g., slow-moving crustal motions can be detected earlier with more accurate baseline observations. However, the GPS positioning capability of a few parts in 10^8 was also noticed by surveyors for its potential to change well-established methods of spatial referencing and geodetic network design.

Perhaps the year 1989 could be labeled the year when "modern GPS" positioning began in earnest. This was the year when the first production satellite, Block II, was launched. Seeber and Wübbena (1989) discussed a kinematic technique that used carrier phases and resolved the ambiguity "on-the-way." This technique used to be called on-the-fly (OTF) ambiguity resolution, meaning there is no static initialization required to resolve the ambiguities, but the technique is now considered part of RTK. The navigation community began in 1989 to take advantage of relative positioning, in order to eliminate errors common to co-observing receivers and make attempts to extend the distance in relative positioning. Brown (1989) referred to it as extended differential GPS, but it is more frequently referred to as wide area differential GPS (WADGPS). Many efforts were made to standardize real-time differential

GPS procedures, resulting in several publications by the Radio Technical Commission for Maritime Services. The U.S. Coast Guard established the GPS Information Center (GPSIC) to serve nonmilitary user needs for GPS information.

The introduction of the geoid model GEOID90 in reference to the NAD83 datum represented a major advancement that helped combine GPS (ellipsoidal) and orthometric height differences and paved the way for replacing much of leveling by GPS-determined heights. More recent geoid models are available.

During 1991 and 1992, the geodetic community embarked on major efforts to explore the limits of GPS on a global scale. The efforts began with the GIG91 [GPS experiment for International Earth Rotation Service (IERS) and Geodynamics] campaign and continued the following year resulting in very accurate polar motion coordinates and earth rotation parameters. Geocentric coordinates were obtained that agreed with those derived from satellite laser ranging within 10 to 15 cm, and ambiguities could be fixed on a global scale providing daily repeatability of about 1 part in 10^9. Such results are possible because of the truly global distribution of the tracking stations. The primary purpose of the IGS campaign was to prove that the scientific community is able to produce high-accuracy orbits on an operational basis. The campaign was successful beyond all expectations, confirming that the concept of IGS is possible. The IGS service formally began January 1, 1994.

For many years, users worried about the impact of antispoofing (AS) on the practical uses of GPS. AS implies switching from the known P-code to the encrypted Y-code, expressed by the notation P(Y). The purpose of AS is to make the P-codes available only to authorized (military) users. The anxiety about AS was considerably relieved when Hatch et al. (1992) reported on the code-aided squaring technique to be used when AS is active. Most manufacturers developed proprietary solutions for dealing with AS. When AS was implemented on January 31, 1994, it presented no insurmountable hindrance to the continued use of GPS. GPS users became even less dependent on AS with the introduction of accurate narrow correlator spacing C/A-code receivers (van Dierendonck et al., 1992), since the C/A-code is not subject to AS measures. By providing a second civil code on L2, eventually a third one on L5, and adding new military codes, GPS modernization will make the P(Y)-code encryption a nonissue for civilian applications, and at the same time, provide enhanced performance to civilian and military users.

A major milestone in the development of GPS was achieved on December 8, 1993, when the initial operational capability (IOC) was declared when 24 satellites (Blocks I, II, IIA) became successfully operational. The implication of IOC was that commercial, national, and international civil users could henceforth rely on the availability of the SPS (Standard Positioning Service). Full operational capability (FOC) would be declared on July 17, 1995, when 24 satellites of the type Blocks II and IIA became operational. Also, Teunissen (1993) introduced the least-squares ambiguity decorrelation adjustment (LAMBDA), which is now widely used.

The determination of attitude/orientation using GPS has drawn attention for quite some time. Qin et al. (1992) report on a commercial product for attitude determination. Talbot (1993) reports on a real-time kinematic centimeter accuracy surveying system. Lachapelle et al. (1994) experiment with multiple (single-frequency) receiver configurations in order to accelerate the on-the-fly ambiguity resolution by means of imposing length constraints and conditions between the ambiguities. While much attention was given to monitoring the ionosphere with dual-frequency and single-frequency code or carrier phase observations, Kursinski (1997) discusses the applicability of radio occultation techniques to use GPS in a general earth's atmospheric monitoring system (which could provide high vertical-resolution profiles of atmospheric temperature across the globe).

The surveying community promptly responded to the opportunities and challenges that came with GPS. The American Congress on Surveying and Mapping (ACSM) tasked an ad hoc committee in 1993 to study the accuracy standards to be used in the era of GPS. The committee addressed questions concerning relative and absolute accuracy standards. The National Geodetic Survey (NGS) enlisted the advice of experts regarding the shape and content of the geodetic reference frame; these efforts eventually resulted in the continuously operating reference stations (CORS). Orange County (California) established 2000 plus stations to support geographic information systems (GIS) and cadastral activities. There are many other examples.

Zumberge et al. (1998a,b) report single-point positioning at the couple-of- centimeters level for static receivers and at the subdecimeter level for moving receivers. This technique became available at the Jet Propulsion Laboratory (JPL) around 1995. The technique that requires dual-frequency observations, a precise ephemeris, and precise clock corrections is referred to as precise point positioning (PPP). These remarkable results were achieved with postprocessed ephemerides at a time when selective availability (SA) was still active. Since 1998, JPL has offered automated data processing and analysis for PPP on the Internet (Zumberge, 1998). Since 1999, JPL has operated an Internet-based dual-frequency global differential GPS system (IGDG). This system determines satellite orbits, satellite clock corrections, and earth orientation parameters in real time and makes corrections available via the Internet for real-time positioning. A website at JPL demonstrates RTK positioning at the subdecimeter for several receiver locations.

Finally, during 1998 and 1999, major decisions were announced regarding the modernization of GPS. In 2000, SA was set to zero as per Presidential Directive. When active, SA entails an intentional falsification of the satellite clock (SA-dither) and the broadcast satellite ephemeris (SA-epsilon); when active it is effectively an intentional denial to civilian users of the full capability of GPS.