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Error Detection in Personal Satellite Navigation

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Abstract

Personal positioning repeatedly occurs in severely degraded signal conditions, which sets a challenge for all error detection methods. Compared to ideal positioning conditions, the average signal condition is weaker and every tracked signal is more invaluable, simultaneously. Therefore, discarding a signal is a non-favored decision which is also often difficult to make as the combination of signal condition and satellite geometry is complex. Expert decision-making is required when the satellite subset is selected for positioning.

This thesis proposes new methods for error detection in satellite navigation, and aims to serve as an up-to-date survey of existing methods. The focus of the thesis being in personal positioning, another objective is to find ways to utilize possible cellular connection in error detection.

New methods outside the traditional family of fault detection algorithms, which are based on data self-redundancy tests, are presented. After representing the required preliminaries about satellite positioning, the thesis continues by introducing *satellite signal condition analysis* and *environment detection analysis*, which both employ probabilistic reasoning methods, including Dempster-Shafer theory. Then, *the weighted satellite geometry measure, KDOP*, and the error detection method based on that, are presented, and the essential feature of non-monotonicity of KDOP is addressed. This is followed by a consideration on *the utilization of cellular network in the perspective of coarse integrity monitoring* and reference position delivery. All the implemented algorithms were tested with real satellite navigation (and cellular) data as batch processing.

According to the obtained results, the proposed methods succeed in bringing new information about the positioning conditions to support different decision-making tasks of the receiver, and they are suitable for error detection. The approach of the KDOP method presents novelty by combining the subset satellite geometry and signal condition factors into one quality parameter of a position estimate. The presented method of cellular position databases supports error detection task in a complementary manner utilizing cellular connection of a GNSS receiver.

Preface

The work presented in this thesis was carried out during the years 2001-2006 at the Institute of Digital and Computer Systems, Tampere University of Technology, and at Nokia Corporation, Technology Platforms, Tampere, Finland (2003-2004).

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In His love, in Tampere, October 2006

Hanna Sairo

Contents

List of Publications

This thesis consists of the following publications, given in a reverse chronological order:

[P1] Sairo, H., Takala, J. Selective Combining in Personal Satellite Navigation. To appear in *IEEE Magazine Aerospace and Electronic Systems*. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2006.

[P2] Sairo, H., Syrjärinne, P. Creation and Utilization of Cellular Information Databases. Report 01-06. ISBN 952-15-1637-2, Tampere University of Technology, Tampere, Finland, Aug. 2006. 22 p.

[P3] Sairo, H., Akopian, D., Takala, J. Weighted Dilution of Precision as a Quality Measure in Satellite Positioning. *IEE Proc. Radar Sonar Navigation.* 150(6), 2003. London, UK: Institution of Electrical Engineers, 2003. pp. 430-436.

[P4] Sairo, H., Kuusniemi, H., Takala, J. Combined Performance of FDI and KDOP Analysis for User-Level Integrity Monitoring in Personal Satellite Navigation. In *Proc. 11th IAIN World Congress*. Berlin, 21-24.10.2003. Bonn, Germany: The International Association of Institutes of Navigation, 2003.

[P5] Sairo, H., Syrjärinne, J., Takala J. Multiple Level Integrity Monitoring with Assisted GPS. In *Proc. the 15th International Technical Meeting of the Satellite Division of Institute of Navigation, ION GPS 2002.* Portland, OR, Sept. 24-27, 2002. Fairfax, VA: Institute of Navigation, 2002. pp. 2129-2134.

[P6] Sairo, H., Syrjärinne, J., Takala J. Environment Detection with Assisted GPS. In *Proc. the 58th Annual Meeting of Institute of Navigation, ION AM 2002.* Albuquerque, NM, June 24-26, 2002. Fairfax, VA: Institute of Navigation, 2002. pp. 122-131.

[P7] Sairo, H., Syrjärinne, J., Leppäkoski, H., Saarinen, J. GPS Integrity Reasoning Using Dempster-Shafer Theory. In *Proc. the 14th International Technical Meeting of the Satellite Division of Institute of Navigation, ION GPS 2001.* Salt Lake City, UT, Sept. 11-14, 2001. Fairfax, VA: Institute of Navigation, 2001. pp. 3029-3035.

List of Abbreviations

AGPS	Assisted GPS
C/A	Coarse / Acquisition (code)
CDMA	Code Division Multiple Access
CID	Cell Identity
CS	Control Segment
DOE	Date of Ephemeris
DOP	Dilution of Precision
EDOP	East DOP
EGNOS	The European Geostationary Navigation Overlay Service
FAA	Federal Aviation Administration
FDI	Fault Detection and Isolation
GCI	Global Cell Identity
GDOP	Geometric DOP
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile communications
HDOP	Horizontal DOP
HSGPS	High Sensitivity GPS
HOW	Hand-Over Word
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IM	Integrity Monitoring
INS	Inertial Navigation System
ION	Institute of Navigation
KDOP	Weighted DOP (non-monotonic)
L1	Link 1 GPS Frequency
L2	Link 2 GPS Frequency
LAAS	Local Area Augmentation System

LAC	Location Area Code
LOS	Line-of-sight
LS	Least Squares
LSB	Least Significant Bit
MCC	Mobile Country Code
MS	Mobile Station
MSB	Most Significant Bit
MNC	Mobile Network Code
NDOP	North DOP
OCS	Operational Control Segment
PDOP	Position DOP
PPS	Precise Positioning Service
PRN	Pseudorandom Noise
P(Y)	Precision (encrypted) (code)
RF	Radio Frequency
RSS	Root Sum Squared
SMLC	Serving Mobile Location Centre
SMS	Short Message
SPS	Standard Positioning Service
SV	Space Vehicle
TDOP	Time DOP
TEC	Total Electron Content
TLM	Telemetry Word
TOE	Time of Ephemeris
UHF	Ultra-High Frequency
URA	User Range Accuracy
UTC	Universal Coordinated Time
WAAS	Wide Area Augmentation System
WCDMA	Wideband CDMA
WDOP	Weighted DOP or WLS-DOP (monotonic)
WLAN	Wireless Local Area Network
WLS	Weighted Least Squares

List of Symbols

Preliminaries

f_{L1}	GPS Frequency L1
f_{L2}	GPS Frequency L2
k	index of a satellite
K	total number of satellites
ρ	pseudorange
r	the geometric range between the satellite and the receiver antenna
Δt_u	the advance of the receiver clock in relation to GPS system time
Δt_s	the advance of the satellite clock in relation to GPS system time
d_I	the delay associated with the transmission of the signal through the ionosphere
d_T	the delay associated with the transmission of the signal through the troposphere
$\varepsilon_{\rho,\ \mathrm{EPH}}$	the ephemeris error component in the pseudorange
$\varepsilon_{\rho,\ \mathrm{NOISE}}$	the error component due to receiver noise in the pseudorange
$\varepsilon_{\rho,\ \mathrm{MULTIPATH}}$	the error component due to multipath effect in the pseudorange
(x, y, z)	user position
$\mathbf{x}$	user position
$\left(x^{(k)}, y^{(k)}, z^{(k)}\right)$	position of the satellite k

$\mathbf{x}^{(k)}$	position of the satellite k
$b = c\Delta t_u$	clock bias term
ε_ρ	the combined error term of the pseudorange
φ	carrier phase measurement
λ	the carrier wavelength
f	the carrier frequency
N	the integer ambiguity
ε_φ	the combined error term of carrier phase measurement
$\mathbf{x}_0$	initial user position estimate
b_0	initial clock bias estimate
$\Delta\mathbf{x}$	the corrections to be applied to the initial position estimate
Δb	the unknown corrections to be applied to the initial estimates
$\Delta\rho^{(k)}$	the correction to be applied to the pseudorange measurement of the satellite k
$\rho^{(k)}$	the pseudorange measurement of the satellite k
$\rho_0^{(k)}$	the initial pseudorange measurement (estimate) of the satellite k
$\mathbf{1}^{(k)}$	the unit vector directed from the user position to the satellite k
$\Delta\boldsymbol{\rho}$	pseudorange measurement vector
$\Delta\mathbf{x}_b$	user position vector that is augmented with the clock bias term
$\mathbf{G}$	the geometry matrix, sized $K \times 4$
$SSE(\cdot)$	function: the sum of squared errors
$\mathbf{g}_i$	i th row of the geometry matrix $\mathbf{G}$
$\mathbf{W}$	the weighting matrix

$\mathbf{R}_\rho$	the pseudorange correlation matrix
$\Delta\mathbf{x}_{b,W}$	the weighted position solution
σ_ρ	the satellite 1-sigma pseudorange error
$\mathrm{cov}(\cdot)$	function: covariance
$E(\cdot)$	function: expectance value
$\mathbf{I}$	the identity matrix
σ_x^2	the component of the position solution covariance in the x coordinates / axis, variance of position in the x coordinates
σ_{xy}^2	the component of the position solution covariance in the x, y coordinates; variance of position in the the x, y coordinates
$\mathbf{D}$	equals $\left(\mathbf{G}^T\mathbf{G}\right)^{-1}$
$\mathbf{F}$	coordinate system transformation matrix
φ	latitude
λ	longitude

Error Sources in Satellite Navigation

a_{f0}	the clock bias
a_{f1}	the clock drift
a_{f2}	the frequency drift, or aging
t_{oc}	the clock data reference time
t_{GPS}	current GPS system time epoch
Δt_r	the correction due to relativistic effects
TEC	total electron content

A_1 the night-time value of the zenith ionospheric delay (fixed at $5 \cdot 10^{-9}$ s)

A_2 he amplitude of the cosine function for daytime values,

A_3 the phase corresponding to the peak of the cosine function (fixed at 50 400 s, or 14.00 local time)

A_4 the period of the cosine function

Observables in Error Detection

σ_R the radial component of one-sigma predicted ephemeris error

σ_A the along-track component of one-sigma predicted ephemeris error

σ_C the cross-track component of one-sigma predicted ephemeris error

σ_t one-sigma predicted satellite clock error

σ_m one-sigma general modeling error

N_U URA index

X_U URA value

t_{GPS} GPS system time

t_{doe} date of ephemeris

t_{toe} time of ephemeris

q Boltzmann’s constant

B bandwidth

T_E the effective noise temperature

P_{NOISE} noise power

F free-space loss factor

λ the carrier wavelength

L the transmitter-to-receiver distance

Methods for Selective Combining

$\mathrm{P}(A)$	Probability distribution of the variable A
$\mathrm{P}(A \mid B)$	Probability distribution of the variable A when given evidence B
$\mathrm{Bel}(A)$	belief function of the variable A
$m(B)$	measure of belief committed to proposition B
$\mu(A)$	membership function of the variable A
$\mathbf{w}$	the residuals vector

Methods for Position Confirmation

$\mathbf{x}_i$	measurement of the user position with index i
N_{MEAS}	number of measurements
$\boldsymbol{\mu}_{N_{MEAS}}$	the sample mean
$C_{N_{MEAS}}$	the unbiased sample covariance
$N_{MEAS,WEIGHTED}$	adjusted number of measurements
$h(\cdot)$	function

Part I: Introduction

1 Introduction to Thesis

1.1 Personal Satellite Navigation

Satellite navigation, originated from military scene, has reached everyday use of a growing audience and is now being employed, e.g., in emergency positioning. For a long time, satellite navigation implied Global Positioning System (GPS). Maintained by the United States, GPS is the only fully functional global navigation satellite system (GNSS), as the Russian GLONASS maintains its struggle for a full satellite constellation, and GALILEO of European Union is still under its way. However, when complete, GALILEO (and GLONASS) will revolutionize the field of satellite positioning by doubling the number of satellites for the majority of the users.

Personal positioning is defined as positioning of an individual (positioning of vehicles, ships, planes, and military units are excluded). As positioning devices have been developed into small portable units similar to cellular phones, *handsets*, personal positioning has been predicted to become a significant business [Bro04], [Kap05]. There are several methods that have been proposed for personal positioning. Integrated or autonomous solutions of technologies such as standalone satellite positioning, cellular-supported a.k.a. assisted satellite positioning [Dig01], internet-augmented satellite positioning [Che03], independent cellular positioning (of which many variant technologies exist) [Spr01], inertial positioning [Col03], [Far99], and positioning methods employing Wireless Local Area Networks (WLAN) [Sin04] have been proposed.

While personal positioning can be required under any circumstances imaginable, it is typical that positioning is attempted with variant speed and occasional stops in urban environments, including indoor areas, partially covered indoor areas, and urban canyons, which can be defined as locations with narrow sky-view due to the surrounding buildings. Signals can be reflected, distorted, and/or attenuated. An attenuated signal can be decoded if the receiver has a higher sensitivity level, or lower signal acquisition limit. All in all, the resulting situation is that the signals to be used in position computation typically have significant differences in noise levels in personal positioning.

The aforementioned settings of personal positioning motivate the research of fault detection methods. It is inevitable that there will be erroneous signals which will decrease the positioning accuracy. Furthermore, it is inevitable that occasionally these error-bound signals have to be used in order to obtain a position estimate (at all). However, the recognition of a distorted, erroneous satellite signal can be used to adjust position estimation, either by weighting or exclusion of a signal. Intelligent methods are required to first identify the faulty satellite signal and secondly to make the appropriate decision of further action.

Another motivation for studying fault detection rises from the plurality of position information. As several sources of position information are available, the reliability and quality of this information becomes more important. The information about the quality of each position estimate becomes a necessity if these pieces of information are to be combined.

1.2 Main Concepts

The topic of this thesis is *selective combining* which is one of the challenging tasks in GNSS receivers. In this task, the satellite signal set producing the most accurate position is determined and the accuracy of positioning with this chosen set is defined. The term *satellite selection* has been used in [Nav96], [Kih94], and [Par01]. However, the term satellite selection can be confused with signal acquisition performed in base-band signal processing in a receiver [Mor99] and, therefore, the new term is proposed in this thesis (originally in [P1]).

Selective combining is closely related to *integrity monitoring* (IM), which refers to the receiver's ability to produce timely warnings about the reliability of the system [Par96b]. Integrity is a characteristic of a navigation system relating to the trust that can be placed in the correctness of information supplied by the navigation system [Och02].

The word *integrity* has a strong contextual reference to aviation navigation. Aviation requirement specifications of accuracy, availability, and integrity for GPS navigation have been directing the development of the receivers, also the development of integrity monitoring methods. Federal Aviation Administration (FAA) has set integrity requirements related to, e.g., precision approach categories. In personal positioning, there are no official integrity requirements, although there are accuracy requirements: the FCC mandate E911 in the US and the respective European regulation E112, which both concern emergency positioning accuracy.

Integrity of positioning can be separated from *quality* of positioning. Integrity refers to a phenomenon that can be observed but not greatly affected. The Space and the Control Segments in

GNSS positioning are beyond users' influence. User can only observe that signals of particular integrity are available for positioning at a specific time instant. Quality, in turn, is related to the receiver's performance under the prevailing circumstances. Thus, quality of positioning can be affected by the user segment. In other words, GNSS receivers are of different quality, and these receivers observe signals from a GNSS system having a certain level of integrity. Additionally, quality, in this context, translates at least partly to *accuracy*, which is in (some) cases a controversial goal with integrity [Lan99]. [Obe99] even proposes a design strategy with integrity as a starting point, not accuracy.

Integrity and quality are joined when the questions are simple: "Is my position trustworthy? How accurate is it? Which satellites should I use to have the least-faulty position estimate?" At the user level, it is sensible to answer these questions as precisely as possible, regardless of the source of an error. As mentioned in [Wal95], it is essential to have the IM process at the user level, since this is the only place where all information used to form the position solution is present. In other words, there is no feedback from the IM process to the receiver to influence the receiver operations.

1.3 Thesis Outline

This compound thesis comprises of two parts. Part I delivers the motivation, the background, and the previous work on the topic. Part II contains the obtained results of the author's research.

In Part I, the foundations for the presented ideas are laid in Chapters 2-5. Chapter 2 presents, in brevity, the fundamental elements of GNSS systems. Chapter 3 includes notational preliminaries and mathematical models, which will be repeatedly referred to in the latter text. Chapter 4 describes the error sources in satellite navigation. Chapter 4 ends with a few words about the effects of GPS modernization and the emerging GALILEO to the error budgets.

Chapter 5 categorizes the various data observables that are available for error detection. A satellite system produces different health parameters, intended to warn users about system malfunctions. Device related (i.e. receiver and user related) parameters and computational parameters, requiring minor data processing, are also summarized. Finally, a few words are spent on what remains unknown in spite of these observables.

After the foundations, Chapters 6 and 7 elaborate on the error detection methods. Chapter 6 addresses the methods that are available for user-level selective combining. These methods include signal condition analysis, dilution of precision (DOP) analysis, and traditional fault detection algorithms.

Chapter 7 elaborates on the position verification methods which can be utilized in coarse integrity monitoring and obtaining reference position. Chapter 8 gives a summary on the publications, which form the second part of the thesis. Finally, the concluding chapter of the thesis, Chapter 9, lists the main results and few future considerations.

2 Overview of Global Navigation Satellite Systems

Chapter 2 describes briefly the elements of Global Navigation Satellite Systems (GNSS) to give a sufficient background for the following Chapters. Being the only fully functional GNSS system, Global Positioning System (GPS) is in the focus, and GALILEO and GLONASS are addressed only shortly. The same policy will be followed in the remaining Chapters of the thesis as well. The presented overview is based on the following references: [Hof01], [Kap96], [Kap05], [Mis01], [Par96a], and [Par96b].

2.1 Global Positioning System

Traditionally, the GPS system has been presented in the tripartition to the Space, Control, and User Segments, and this partition is here followed.

2.1.1 Space Segment

The nominal satellite constellation being 24 satellites, the Space Segment consists currently of 30 satellites [GPS06]. Presenting different *satellite generations*, the satellites orbit the Earth at the average altitude of 20200 km with the speed of 3.87 km / s. The satellites are arranged in six orbital planes, which are inclined at 55 degrees relative to the equatorial plane and named from A to F. The period of an orbit is approximately 12 hours. The orbits are nearly circular and the ground tracks are stationary. The nominal GPS constellation is designed to cover the globe with minimum of four simultaneously visible satellites.

A summary of the satellite generations is given in Table 2.1. Each new batch of the satellite generations has been designed to provide additional capabilities. The unit cost of a satellite has reduced during this evolution while at the same time the design life has lengthened from 7.5 years (Block II) to 15 years (Block IIR-M).

2.1.2 Control Segment

Being funded by the Department of Defense of the United States, GPS is maintained by the (Operational) Control Segment, (O)CS. The CS consists of five monitor stations, four ground antenna upload stations, and the Operational Control Center. These facilities are located around the globe. The CS maintains each satellite in its orbit through small commanded maneuvers, makes corrections and adjustments to the satellite clocks as needed, commands major relocations in the event of satellite failure, tracks the GPS satellites, and generates and uploads the data to the satellites.

Figure 2.1 illustrates a simplified view of the GPS satellite payload. The GPS upload station sends the satellite the ephemeris information regarding the satellite orbit, and the exact position in that orbit vs. time. In addition, a satellite clock correction term is included. This term calibrates the offset of the satellite clock relative to the GPS system time. These data are uploaded to the satellite through an S-band telemetry and command system [Par96a].

Table 2.1 A summary of the satellite generations.

Satellite Generation	**Block I**	**Block II**	**Block IIA** (“advanced”)	**Block IIR** (“replenishment”)	**Block IIR-M** (“modernized”)
First launch	1978 (-1985)	1989 (-1990)	1990 (-1997)	1997	Sept 2005
Design life (yrs)	4.5	7.5	7.5	10	15
Inclination of orbital plane	63 deg	55 deg	55 deg	55 deg	55 deg
Weight (kg)	845	1500	1500	2000	1700
Other information	There were 11 Block I satellites in total.	Contrary to Block I, not all signals are available to civilian users.	Mutual communication capability added. Some satellites can be tracked by Laser ranging.	Improved facilities for communication and intersatellite tracking.	New M-code signal (not yet officially operational).
Number of the satellites in the current constellation	0	2	14	12	2

2.1.3 User Segment

The main categories of the GPS User Segment are military and civilian user, for whom all the signals are not available. Only the civilian use of GPS is of interest in this thesis. The applications of satellite navigation are diverse, and that diversity is matched by the type of receivers today with hundreds of GPS receiver models in the market [Mis01]. However, common operation of a receiver can be described. A generic block diagram of a GPS receiver is shown in Fig. 2.2 [Kap96]. Most receivers have multiple channels, typically 12, whereby each channel tracks the transmission from a single satellite. The received radio frequency (RF) signals are filtered by a band-pass prefilter to minimize noise. After amplification and down-conversion, the signals are sampled and digitized.

The samples are forwarded to digital signal processor where there are typically 12 parallel channels, each containing code and carrier tracking loops. A processor controls the receiver through operational sequence, starting with signal acquisition, which is followed by signal tracking and data collection.

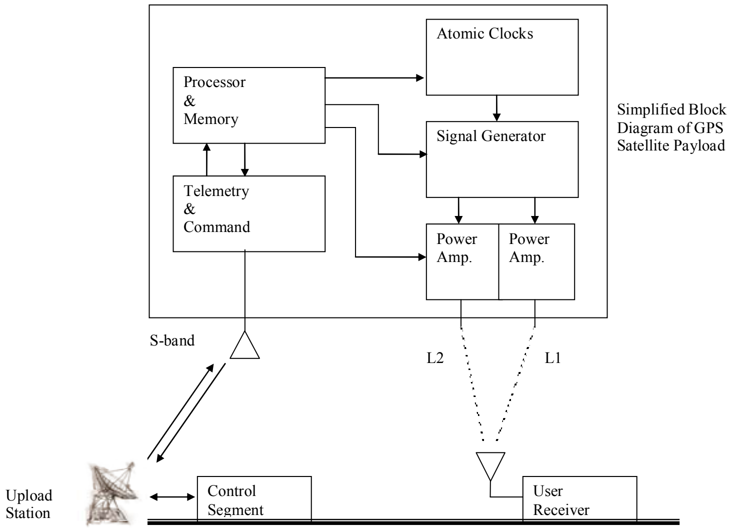

Figure 2.1 Simplified GPS satellite payload functional diagram [Par96a].

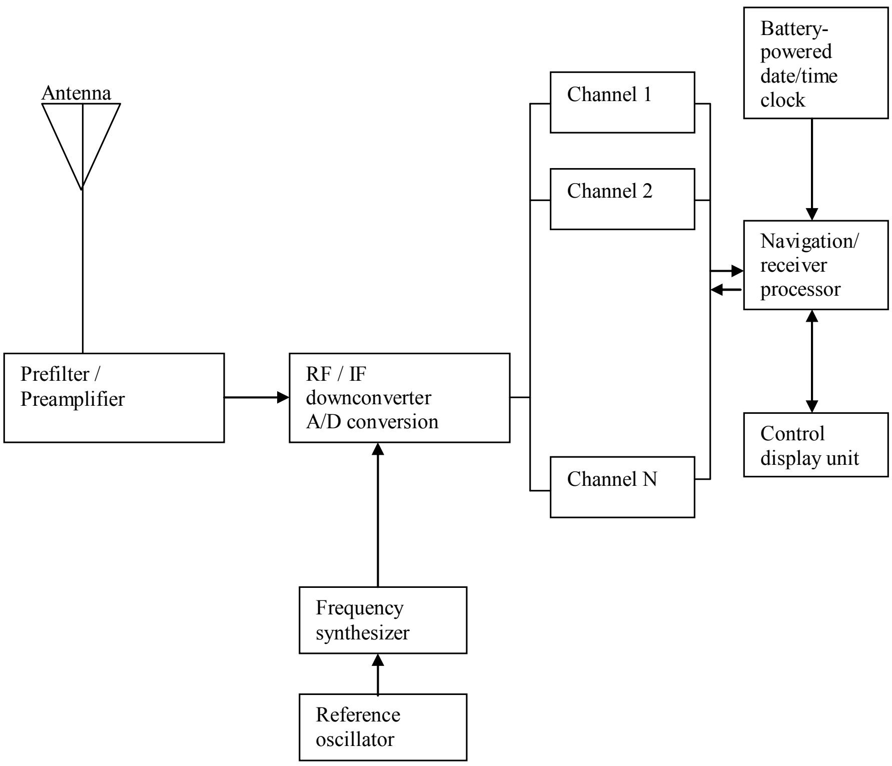

Figure 2.2 A generic GPS receiver [Kap96].

2.2 GPS Signals

Each GPS satellite transmits continuously using two radio frequencies in the L-band. These frequencies are referred to as Link 1 (L1) and Link 2 (L2). The L-band covers frequencies between 1 GHz and 2 GHz, and is a part of the ultra-high frequency (UHF) band [Mis01]. The GPS frequencies are the primary frequency L1 (f_{L1} = 1575.42 MHz) and the secondary frequency L1 (f_{L2} = 1227.60 MHz) [Kap96]. All the satellites transmit at the same two carrier frequencies but their signals do not interfere significantly with each other because of the unique pseudorandom noise (PRN) sequences. The structure of the signal is examined in more detail in the following.

2.2.1 Signal Structure

There are three parts in both of the GPS signals: carrier, code, and data.

Carrier

Carrier signal is a RF sinusoidal signal with frequency f_{L1} or f_{L2}.

Code

The ranging code is the very key to positioning with GPS. It is a unique sequence of zeroes and ones assigned to each satellite which allows the receiver to determine the signal transmit time. These sequences are called *pseudo-random noise* sequences or *PRN codes*. Having an appearance of a random signal, these codes are generated with great sophistication to obtain the special properties needed to avoid signal interfering with another satellite signal on the same frequency. The sequences are a selected set of Gold codes, which have the desired auto-correlation and cross-correlation features [Gol67]. The PRN sequences are nearly orthogonal to each other, so they are nearly uncorrelated for all shifts, i.e., the cross-correlation between them is weak. Equally important is that the auto-correlation of the PRN sequences is almost zero all shifts except the zero shift. Thus, code division multiple access (CDMA) signaling is utilized in GPS.

Two different codes are transmitted: a coarse / acquisition code or *C/A-code* and a precision (encrypted) code or *P(Y)-code*. Both C/A-code and P(Y)-code are modulated on L1, but on L2 there is only P(Y)-code. To limit the access for authorized users, the P-code has been encrypted since 1994. Therefore, the majority of GPS equipment receive only L1 signal. The P(Y)-code provides higher accuracy and it is referred to as *Precise Positioning Service (PPS)* when again *Standard Positioning Service (SPS)* is available without authorization.

Each C/A-code is a unique sequence of 1023 bits or *chips*. This sequence is repeated every millisecond. Thus, the chipping rate of C/A-code is 1.023 MHz. P-code is a very long sequence of

10230 chips, and the chipping rate is 10.23 MHz, which is also the frequency of the atomic standards aboard the satellites.

Data

Navigation data is a binary-coded message which contains satellite health status data, ephemeris data, satellite clock bias parameters, and an almanac which in essence is ephemeris data with reduced accuracy. The navigation message is transmitted at 50 bits per second, with a bit duration of 20 ms [Mis01].

To receive the entire navigation message, or a *Master Frame*, takes 12.5 minutes. The Master Frame consists of 25 frames, which are further divided into five *subframes*, which have different information contents:

- Subframe 1: satellite clock corrections, health indicators, age of data
- Subframes 2-3: satellite ephemeris parameters
- Subframe 4: ionosphere model parameters, universal time (UTC) data, almanac and health status for satellites numbered 25 and higher
- Subframe 5: almanac and health status data for satellites numbered 1-24

A subframe comprises 10 words, 30 bits each. The first two words of each subframe are Telemetry Word (TLM) and Hand-Over Word (HOW). The TLM contains a fixed 8-bit synchronization pattern and 14-bit message. The HOW provides time information required to access P(Y)-code segment.

2.3 GPS Measurements and GPS Positioning

GPS provides code phase measurements (from the code tracking loop), carrier phase measurements (from the carrier tracking loop), and Doppler frequency measurements (from the frequency tracking loop). In the following, the code and carrier phase measurement models are presented, but to describe how these measurements are formed in the receiver is beyond the scope of this thesis, refer to [War95] and [Bra99].

2.3.1 Code Phase Measurements

The code phase measurement can be converted to the transit time of the signal from a satellite to the receiver. This transit time is defined as the difference between signal reception time as determined by the receiver clock, and the transmission time as marked on the signal.

This is measured as the amount of time shift which is required to align the C/A-code replica (generated at the receiver) with the signal received from the satellite. Once this transit time is multiplied by the speed of light, the pseudorange is formed. This is only *pseudo*range as the measurement of the transit time is biased due to the fact that the satellite clock and the receiver clock are not synchronized. Therefore, both timing measurements must be taken to a common time reference, or *GPS system time*.

The signal transit time varies between 70 ms and 90 ms. As mentioned, the C/A-code is 1 ms long, and the pseudorange is ambiguous in whole milliseconds. However, the millisecond corresponds 300 km in range, so if the user has a rough estimate about the current location, this ambiguity is easy to solve. In Chapter 7, the significance of the reference position is returned to.

Pseudorange measurements can be corrected using parameters from the navigation message. Satellite clock offset relative to the GPS system time, relativistic effects, and ionospheric delay can be accounted for with navigation message data. Additionally, tropospheric error can be modeled and pseudorange measurements can be *smoothed* with less-noisy carrier phase measurements to reduce the effects of multipath and measurement noise.

2.3.2 Carrier Phase Measurements

The carrier phase measurement is the difference between phases of the receiver-generated carrier signal and the carrier received from a satellite at the instant of the measurement [Mis01]. This instant of measurement can be selected, so the measurement is indirect.

The carrier phase measurement can be converted into delta pseudorange (average pseudorange rate or velocity) and into integrated Doppler measurement (continuous cycle count after an arbitrary starting point). The integrated Doppler measurement is equal to pseudorange if the ambiguity of whole cycles is resolved. The estimation of the number of whole cycles is referred to as *integer ambiguity resolution*. Once solved, this leads to centimeter-level positioning accuracy (provided there is a precise reference available as well).

2.4 Assisted GPS

Conventional GPS positioning needs auxiliary methods to survive under difficult positioning conditions. The basic idea of *assisted* GPS (AGPS) is that information is delivered to a GPS receiver, and this additional information enables to release resources which then can be used to enhance the receiver performance. Methods of assisted GPS grew out of a need to simultaneously reduce the time to produce a position solution and increase the sensitivity of the receiver, as formulated in [Kap05]. A reference receiver is needed in creation of the *assistance data* as well as the means to deliver the assistance data to the GPS receiver.

As assistance data enhances the receiver sensitivity, a related term is *High Sensitivity GPS* or HSGPS, used e.g. in [Lac03]. The term HSGPS does not separate the factors (assistance or enhanced receiver technology) which make the receiver more sensitive but emphasizes the new positioning conditions brought by the greater sensitivity, i.e. the lower acquisition thresholds of the receiver.

Two versions of assisted GPS exist: In *Mobile Station (MS)-assisted GPS*, the handset delivers measurements to the network which then computes the position estimate. In *MS-based AGPS,* the handset computes its position autonomously. In relation to the work presented in this thesis, MS-based AGPS is of more interest. The improvements brought by AGPS (vs. stand-alone GPS) are an important motivator of the presented work.

2.4.1 Assistance Data Delivery

Assistance data can be delivered to the GPS receiver via a wireless link. *Network assistance* is a generally accepted term to define assistance data delivered via a cellular network [Kap05]. In [LaM02], short messages (SMS) via a cellular link are proposed for assistance data transmission. More importantly, assistance data has also been included in GSM standards, point-to-point messaging [Ets05a] and broadcast messaging [Ets05b], and in a WCDMA standard [Ets06]. [Syr01] elaborates on the types of assistance messaging.

The standards define the delivery of the assistance data within the communication between the MS and the Serving Mobile Location Centre (SMLC). When the protocol is put to use, the assistance data is delivered to the receiver quickly whenever the receiver is in cellular network coverage area.

2.4.2 Assistance Data

Assistance data is the key to shorter time-to-first-fix (TTFF) and enhanced receiver sensitivity. Assistance data may include the following pieces of information, as listed in [Dig02], [Kap05], and the above-mentioned cellular standards:

- A list of visible satellites, their elevation and azimuth angles
- Reference user position
- Reference GPS system time
- Part(s) of the navigation message: ephemeris, almanac

- Information derived from ephemeris: predictions of Doppler frequencies and Doppler rates
- Predictions of code phase
- Integrity information
- Differential GPS corrections
- Ionospheric model
- UTC model

The list is redundant, as a mobile receiver will only use a subset of this information in attempting to acquire the requisite number of satellites for a fix [Kap05].

2.4.3 Performance Enhancement

According to [Yil02], the performance of assisted GPS is enhanced vs. stand-alone GPS, since

- the time-to-first fix is reduced due to the reduced frequency bin search space in signal acquisition
- the receiver sensitivity is enhanced as the search space has been predicted and more time (per frequency bin) can be used for searching the noisy signals
- real-time integrity warnings about failed satellites are delivered promptly via a cellular connection, as the Control Segment cannot deliver the information with equal latency

In conventional GPS; the navigation message must be received without interruptions for 18 to 30 seconds, which is a challenge in difficult signal conditions. Pseudoranges can be estimated from much shorter data sets [Mis01]. Therefore, critical parts of the navigation message have been proposed to be sent over cellular links to the GPS receiver. E.g. in [Ako02], the time of transmission (satellite clock) part of the navigation message is sent in the form of network assistance.

At least two alternatives exist for sending and receiving navigation data bits over the network: predicting the navigation data bits (*bit prediction*) and guessing the navigation bits. Bit prediction means that the constant preamble of the navigation message subframe is predictable with time. In guessing the navigation data bits, a hypothesis corresponding to each possible bit transition is formulated, and parallel integrations are performed, with the integration resulting in the largest signal correlation peak determined to be the correct bit sequence [Kap05].

2.5 Other GNSS Systems

In addition to GPS, there are two other satellite navigation systems: European GALILEO, and Russian GLONASS. These systems are not-operational and semi-operational, respectively. In addition to global systems, there are regional satellite positioning systems, e.g. Chinese BeiDou System which differs significantly from GPS, GALILEO, and GLONASS as it employs two-way range measurements.

2.5.1 GALILEO

The still-almost-non-existent European GNSS system, GALILEO, is being funded by the European Union, and it will be the first global non-military GNSS system. According to the current plans, the GALILEO constellation will include 30 satellites. The first GALILEO launch of an in-orbit-validation satellite was in December 2005 and the first launches of operational GALILEO satellites are scheduled to be in 2008. The full functionality is estimated to be reached in 2012. GALILEO is designed to be interoperable with GPS and three topics in interoperability are emphasized: signal structure, geodetic coordinate frame, and time reference system. When completed, GALILEO will provide more diversity in the offered levels of service than GPS:

- An open service, which is free for all users,
- a commercial service combining high-accuracy positioning service with value-added data,
- safety-of-life service,
- public regulated service for authorized users, and
- support for search and rescue [Kap05].

Additionally, the main extension of Galileo compared to GPS consists in the implementation of a segment for integrity monitoring [Ins06]. GALILEO system is described in more detail in [Gal05] and [Kap05], and further presentation is here omitted. However, GALILEO's upcoming effect to error budgets in personal positioning is returned to in Chapter 4.

2.5.2 GLONASS

The Russian GNSS system, GLONASS is run by the Russian Space Forces. Currently, there are 16 satellites (of which 5 are switched off) in the constellation [Glo06], which is designed to include 24 satellites in 3 orbital planes in circular orbits at the altitude of 19100 km. Before the launch of GALILEO program, the combined use of GPS and GLONASS has been an active research area (e.g. [Bes95], [Mis91]) which now seems to have dimmed down at least in the number of related publications, as shown in Fig. 2.3.

The price of a GNSS receiver is greatly affected by the number of frequencies it is to receive, so it is easy to see why GLONASS is dropping out as the GALILEO with 30 satellites is coming. However, GLONASS should be on its way to its revival so that there are 18 satellites in orbit in 2008. Furthermore, also GLONASS is being modernized, and the first modernized GLONASS satellite has been launched in 2004 [Zin05].

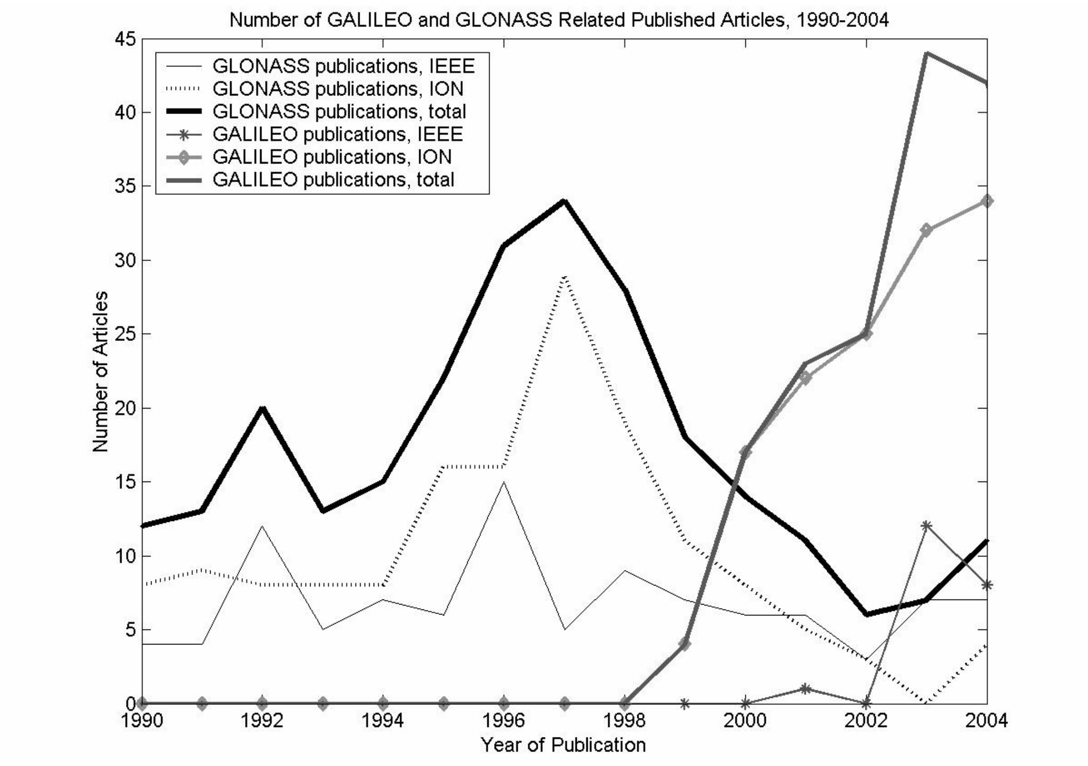

Figure 2.3 The number of ION and IEEE publications reflects the change brought by GALILEO in the field of satellite navigation. ION stands for Institute of Navigation, and IEEE for Institute of Electrical and Electronics Engineers, Inc.

3 Preliminaries

Before entering the topic of the thesis, preliminary definitions are given to provide fluent reading. After introducing the notation of the thesis, the signal models and position estimation by using the Least Squares approach are presented. Lastly, related performance measures are defined.

3.1 Notations

Following a common practice, all vector and matrix variables are in bold, e.g., **v** and **A**, the matrix quantity being in capitals. The Euclidean norm of a vector is marked with double vertical bars such as in $\|\mathbf{v}\|$. The *i*th diagonal element of a matrix **A** is written as a_{ii}. The transpose and the inverse of a matrix are marked as superscripts as in $\mathbf{A}^T$ and $\mathbf{A}^{-1}$, respectively. The symbol **1** identifies a unit vector, whose Euclidean norm equals one. The expectation value and the covariance of a measure are expressed as $E(\cdot)$ and $\mathrm{cov}(\cdot)$, respectively.

3.2 Signal Models

3.2.1 Pseudorange Model

The model of the pseudorange ρ must account for all the error sources as follows:

$$\rho = r + c\left[\Delta t_u - \Delta t_s\right] + d_I + d_T + \varepsilon_{\rho,\,\mathrm{EPH}} + \varepsilon_{\rho,\,\mathrm{NOISE}} + \varepsilon_{\rho,\,\mathrm{MULTIPATH}} \tag{3.1}$$

where

r is the geometric range between the satellite and the receiver antenna [m],

c is the speed of light [m/s],

Δt_u is the advance of the receiver clock in relation to GPS system time [s],

Δt_s is the advance of the satellite clock in relation to GPS system time [s],

d_I is the delay associated with the transmission of the signal through the ionosphere [m],

d_T is the delay associated with the transmission of the signal through the troposphere [m],

$\varepsilon_{\rho,\text{ EPH}}$ is the ephemeris error component [m],

$\varepsilon_{\rho,\text{ NOISE}}$ is the error component due receiver noise [m], and

$\varepsilon_{\rho,\text{ MULTIPATH}}$ is the error component due multipath effect [m].

Given that the satellite clock offset Δt_s is accounted for (as will be explained in more detail in Section 4.1.1), the model of the pseudorange ρ is

$$\rho = r + c\Delta t_u + d_I + d_T + \varepsilon_{\rho,\text{ EPH}} + \varepsilon_{\rho,\text{ NOISE}} + \varepsilon_{\rho,\text{ MULTIPATH}}\,. \quad (3.2)$$

Next, let us define the user position as $\mathbf{x} = (x, y, z)^T$ and the position of satellite k, $k = 1,\ldots, K$, as $\mathbf{x}^{(k)} = \left(x^{(k)}, y^{(k)}, z^{(k)}\right)^T$. Then, the geometric range r between the user and the satellite k is

$$r^{(k)} = \sqrt{\left(x^{(k)} - x\right)^2 + \left(y^{(k)} - y\right)^2 + \left(z^{(k)} - z\right)^2} = \left\|\mathbf{x}^{(k)} - \mathbf{x}\right\|. \quad (3.3)$$

By substituting this into Eqn. (3.2), we obtain the pseudorange measurement of the satellite k as

$$\rho^{(k)} = \left\|\mathbf{x}^{(k)} - \mathbf{x}\right\| + b + \varepsilon_\rho \quad (3.4)$$

where $b = c\Delta t_u$ is the clock bias term and $\varepsilon_\rho^{(k)}$ is the combined error term given as

$$\varepsilon_\rho = d_I + d_T + \varepsilon_{\rho,\text{ EPH}} + \varepsilon_{\rho,\text{ NOISE}} + \varepsilon_{\rho,\text{ MULTIPATH}}\,. \quad (3.5)$$

3.2.2 Carrier Phase Model

In a similar fashion, the error sources are accounted for in the model of carrier phase measurement φ, which is now expressed in the units of cycles:

$$\varphi = \lambda^{-1}\left(r - d_I + d_T\right) + f\left(\Delta t_u - \Delta t_s\right) + N + \varepsilon_\varphi \quad (3.6)$$

where λ is the carrier wavelength [m],

f is the carrier frequency [Hz],

N is the integer ambiguity [number of cycles], and

ε_φ is the combined error term of carrier phase measurement [fractional part of a cycle].

3.3 Position Estimation

Estimating the position from the obtained measurements is the heart of satellite navigation. To do this, the method of least squares is typically employed. In the following, the linear model for position estimation and its solution with the least squares algorithm is presented. Further reading on the method of least squares is in the thorough work by Krakiwsky [Kra90].

3.3.1 Least Squares Method

Let there be pseudorange measurements from K satellites, each modeled as a nonlinear equation (3.1) [Mis01]. There are four unknowns in each equation: the user clock bias and the three components of user position. A simple approach to solve these K equations is to linearize them about an approximate user position and solve the equations iteratively.

First, let the initial user position estimate and the initial user clock bias be $\mathbf{x}_0$ and t_{b_0}, respectively. The clock bias can be expressed in the units of length as $b_0 = ct_{b_0}$. Then

$$\rho_0^{(k)} = \left\|\mathbf{x}^{(k)} - \mathbf{x}_0\right\| + b_0 . \tag{3.7}$$

Let the true position and the true clock bias be $\mathbf{x} = \mathbf{x}_0 + \Delta\mathbf{x}$ and $b = b_0 + \Delta b$, respectively, where $\Delta\mathbf{x}$ and Δb are the unknown corrections to be applied to the initial estimates. Now, utilizing the Taylor series of a vector norm*, a system of linear equations can be developed as

$$\begin{aligned}
\Delta\rho^{(k)} &= \rho^{(k)} - \rho_0^{(k)} \\
&= \left\|\mathbf{x}^{(k)} - \mathbf{x}_0 - \Delta\mathbf{x}\right\| - \left\|\mathbf{x}^{(k)} - \mathbf{x}_0\right\| + \left(b - b_0\right) + \varepsilon_\rho \\
&\approx -\frac{\left(\mathbf{x}^{(k)} - \mathbf{x}_0\right)}{\left\|\mathbf{x}^{(k)} - \mathbf{x}_0\right\|} \cdot \Delta\mathbf{x} + \Delta b + \varepsilon_\rho \\
&= -\mathbf{1}^{(k)} \cdot \Delta\mathbf{x} + \Delta b + \varepsilon_\rho
\end{aligned} \tag{3.8}$$

$^*f(\mathbf{x}) = \|\mathbf{x}\| = \mathbf{x}^T\mathbf{x}$; $\dot{f}(\mathbf{x}) = \frac{-\mathbf{x}}{\|\mathbf{x}\|}$; Taylor series approximation: $f(b) - f(a) = \dot{f}(\xi)(b-a), a < \xi < b$;
now $a = \mathbf{x}^{(k)} - \mathbf{x}$; $b = \mathbf{x}^{(k)} - \mathbf{x} - \Delta\mathbf{x}$

where $\mathbf{1}^{(k)}$ is the unit vector directed from the user position to the satellite *k*.

As there are *K* satellites, there are *K* equations, which can be written in matrix notation as

$$\Delta\boldsymbol{\rho} = \begin{bmatrix} \Delta\rho^{(1)} \\ \Delta\rho^{(2)} \\ \vdots \\ \Delta\rho^{(K)} \end{bmatrix} = \begin{bmatrix} \left(-\mathbf{1}^{(1)}\right) & 1 \\ \left(-\mathbf{1}^{(2)}\right) & 1 \\ \vdots & \vdots \\ \left(-\mathbf{1}^{(K)}\right) & 1 \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta b \end{bmatrix} + \boldsymbol{\varepsilon}_{\rho} \tag{3.9}$$

$$\Delta\boldsymbol{\rho} = \mathbf{G}\begin{bmatrix} \Delta\mathbf{x} \\ \Delta b \end{bmatrix} + \boldsymbol{\varepsilon}_{\rho} \overset{\Delta\mathbf{x}_b = \begin{bmatrix} \Delta\mathbf{x} \\ \Delta b \end{bmatrix}}{=} \mathbf{G}\Delta\mathbf{x}_b + \boldsymbol{\varepsilon}_{\rho} \tag{3.10}$$

where **G** is a (*K* x 4) matrix, which is referred to as *the geometry matrix* or, less commonly, *the visibility matrix* [McK97], [Mis01] or (in a more general context) *the design matrix* [Kra90]. This matrix characterizes the user-satellite geometry, which is of great importance to the positioning accuracy, as will be presented in the latter chapters. If the rank of the geometry matrix is less than four, the equation system cannot be solved.

When assuming identically Gaussian distributed and zero-mean measurement errors, the Least Squares method can be used to find a solution which fits the measurements best, i.e., a solution which minimizes the sum of squared error (*SSE*) defined by

$$SSE\left(\Delta\mathbf{x}_b\right) = \boldsymbol{\varepsilon}_{\rho}^T\boldsymbol{\varepsilon}_{\rho} = \sum_{i=1}^{m}\left(\Delta\rho_i - \mathbf{g}_i\,\Delta\mathbf{x}_b\right) = \left(\Delta\boldsymbol{\rho} - \mathbf{G}\Delta\mathbf{x}_b\right)^T\left(\Delta\boldsymbol{\rho} - \mathbf{G}\Delta\mathbf{x}_b\right) \tag{3.11}$$

where $\varepsilon_\rho = \Delta\rho$ - $\mathbf{G}\Delta\mathbf{x}_b$.

To minimize the error, we follow the straightforward method presented in [Jan97] by setting the derivative of the squared error $\dot{SSE}\left(\Delta\mathbf{x}_b\right)$ zero. First, we can expand $SSE\left(\Delta\mathbf{x}_b\right)$ as

$$\begin{aligned} SSE\left(\Delta\mathbf{x}_b\right) &= \left(\Delta\boldsymbol{\rho} - \mathbf{G}\Delta\mathbf{x}_b\right)^T\left(\Delta\boldsymbol{\rho} - \mathbf{G}\Delta\mathbf{x}_b\right) \\ &= \Delta\boldsymbol{\rho}^T\Delta\boldsymbol{\rho} - 2\Delta\boldsymbol{\rho}^T\mathbf{G}\Delta\mathbf{x}_b + \Delta\mathbf{x}_b^T\mathbf{G}^T\mathbf{G}\Delta\mathbf{x}_b. \end{aligned} \tag{3.12}$$

The derivative of $SSE\left(\Delta\mathbf{x}_b\right)$ is

$$\dot{SSE}\left(\Delta\mathbf{x}_b\right) = -2\mathbf{G}^T\Delta\boldsymbol{\rho} + 2\mathbf{G}^T\mathbf{G}\Delta\mathbf{x}_b \tag{3.13}$$

which is set to zero, yielding that the squared error is minimized when

$$\mathbf{G}^T\mathbf{G}\Delta\mathbf{x}_b = \mathbf{G}^T\Delta\boldsymbol{\rho}. \tag{3.14}$$

Now, as the rank of the geometry matrix was assumed to be 4, $\mathbf{G}^T\mathbf{G}$ is non-singular, and

$$\Delta\hat{\mathbf{x}}_b = \begin{bmatrix}\Delta\hat{\mathbf{x}} \\ \Delta\hat{b}\end{bmatrix} = \left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T\Delta\boldsymbol{\rho} \tag{3.15}$$

and this results in new estimates of the user position and clock bias, which are

$$\begin{aligned}&\hat{\mathbf{x}} = \mathbf{x}_0 + \Delta\hat{\mathbf{x}}, \text{ and}\\ &\hat{b} = b_0 + \Delta\hat{b}.\end{aligned} \tag{3.16}$$

The position calculation is continued iteratively with the new estimates, which can be used as the linearization point. This is continued until an end criterion is reached.

3.3.2 Weighted Least Squares Method

To obtain a Weighted Least Squares (WLS) estimate, the measurements are weighted in relation to their error contribution. Then, the error function to be minimized is

$$SSE\left(\Delta\mathbf{x}_b\right) = \left(\Delta\rho_i - \mathbf{g}_i\Delta\mathbf{x}_b\right)^T\mathbf{W}\left(\Delta\rho_i - \mathbf{g}_i\Delta\mathbf{x}_b\right) \tag{3.17}$$

where $\mathbf{W}$ is the weighting matrix. The measurement errors are still assumed to be Gaussian distributed with zero-mean, but they are not necessarily identically distributed or independent of each other [Kap05]. If the de-correlation of pseudorange errors is assumed but the equality of errors is not, the error correlation matrix is diagonal

$$\operatorname{cov}\left(\Delta\rho\right) = \mathbf{R}_\rho = \begin{bmatrix}\sigma_1 & 0 & \cdots & 0\\ 0 & \sigma_2 & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & \sigma_K\end{bmatrix}. \tag{3.18}$$

The error is minimized if the weighting matrix $\mathbf{W}$ is the inverse of the pseudorange correlation matrix $\mathbf{R}_\rho$. The position estimate is then

$$\Delta\mathbf{x}_{b,W} \overset{\mathbf{W}=\mathbf{R}^{-1}}{=} \left(\mathbf{G}^T\mathbf{R}_\rho^{-1}\mathbf{G}\right)^{-1}\mathbf{G}\mathbf{R}_\rho^{-1}\Delta\boldsymbol{\rho}. \tag{3.19}$$

3.4 Accuracy Metrics

This section describes a small number of accuracy metrics which are commonly used in satellite navigation.

3.4.1 Accuracy Metrics and Geometry

Estimates of position errors can be computed as a function of satellite geometry and 1-sigma range error. The geometry is measured with a quantity called *dilution of precision (DOP)*, of which different variants exist. The respective metrics allow two-dimensional position error estimation in horizontal and vertical directions, three-dimensional position error estimation, and user clock error estimation. In previous work, such analysis of timing accuracy has been presented, e.g., in [Gle05], and the relationship of vertical positioning error and vertical DOP (VDOP) is elaborated on in [Lev94].

3.4.2 Definition of DOP

The concept of Dilution of Precision is the idea that the position error that results from the measurement errors depends on the user/satellite relative geometry. The more favorable the geometry, the lower is the DOP. The formal derivation of the DOP relations in GPS begins with the linearization of the pseudorange equations which was already presented. Let us start with the definition of the covariance of the position solution

$$\operatorname{cov}\left(\Delta\mathbf{x}_b\right) = E\left(\Delta\mathbf{x}_b \Delta\mathbf{x}_b{}^T\right). \tag{3.20}$$

By substituting (3.16) into (3.20) and considering the user/satellite geometry fixed (which is reasonable for short time intervals), we obtain

$$\begin{aligned}\operatorname{cov}\left(\Delta\mathbf{x}_b\right) &= E\left(\left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T\Delta\boldsymbol{\rho}\Delta\boldsymbol{\rho}^T\mathbf{G}\left(\mathbf{G}^T\mathbf{G}\right)^{-1}\right)\\ &= \left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T\operatorname{cov}\left(\Delta\boldsymbol{\rho}\right)\mathbf{G}\left(\mathbf{G}^T\mathbf{G}\right)^{-1}.\end{aligned} \tag{3.21}$$

Usually, the DOP computation is non-weighted: the components of $\Delta\boldsymbol{\rho}$ are assumed identically distributed and independent and have a variance equal to the square of the satellite 1-sigma pseudorange error σ_ρ. With these assumptions, the covariance of $\Delta\boldsymbol{\rho}$ is a diagonal matrix $\mathbf{R}_\rho = \sigma_\rho\mathbf{I}$ and the covariance of the position solution is

$$\operatorname{cov}\left(\Delta\mathbf{x}_b\right) = \left(\mathbf{G}^T\mathbf{R}_\rho\mathbf{G}\right)^{-1} = \left(\mathbf{G}^T\mathbf{G}\right)^{-1}\sigma_\rho. \tag{3.22}$$

The covariance matrix is expanded in component form

$$\operatorname{cov}\left(\Delta \mathbf{x}_b\right)=\begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xb} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} & \sigma_{yb} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 & \sigma_{zb} \\ \sigma_{xb} & \sigma_{yb} & \sigma_{zb} & \sigma_b^2 \end{bmatrix} \tag{3.23}$$

where x, y, and z refer to coordinate directions, and b refers to user clock bias in units of length. The components of the matrix $(\mathbf{G}^T\mathbf{G})^{-1}$ quantify how pseudorange errors translate into components of the covariance $\Delta \mathbf{x}_b$.

The most general DOP parameter is *Geometric Dilution of Precision* or GDOP which is defined as

$$GDOP=\sqrt{\frac{trace\left(\operatorname{cov}\left(\Delta \mathbf{x}_b\right)\right)}{\sigma_\rho^2}}=\sqrt{\frac{trace\left(\left(\mathbf{G}^T\mathbf{R}_\rho\mathbf{G}\right)^{-1}\right)}{\sigma_\rho^2}}=\sqrt{trace\left(\left(\mathbf{G}^T\mathbf{G}\right)^{-1}\right)}, \tag{3.24}$$

and equivalently

$$GDOP=\frac{\sqrt{\sigma_x^2+\sigma_y^2+\sigma_z^2+\sigma_{ct_b}^2}}{\sigma_\rho}. \tag{3.25}$$

A relationship for GDOP is obtained in terms of the components of $(\mathbf{G}^T\mathbf{G})^{-1}$ by expressing $(\mathbf{G}^T\mathbf{G})^{-1}$ $= \mathbf{D}$ in component form

$$\mathbf{D}=\begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ d_{21} & d_{22} & d_{23} & d_{24} \\ d_{31} & d_{32} & d_{33} & d_{34} \\ d_{41} & d_{42} & d_{43} & d_{44} \end{bmatrix} \tag{3.26}$$

thus GDOP can be given as

$$GDOP=\sqrt{d_{11}+d_{22}+d_{33}+d_{44}}\ . \tag{3.27}$$

3.4.3 Non-weighed DOP Measures

In addition to GDOP, there are many other DOP parameters which are useful in characterizing the accuracy of various components of the position/time solution. These are named *position dilution of* *precision* (PDOP), *horizontal dilution of precision* (HDOP), *vertical dilution of precision* (VDOP), and *time dilution of precision* (TDOP), and they are defined as follows:

$$\text{PDOP} = \sqrt{d_{11} + d_{22} + d_{33}}\ , \tag{3.28}$$

$$\text{HDOP} = \sqrt{d_{ee} + d_{nn}}\ , \tag{3.29}$$

$$\text{VDOP} = \sqrt{d_{uu}}\ \text{, and} \tag{3.30}$$

$$\text{TDOP} = \frac{\sqrt{d_{44}}}{c}, \tag{3.31}$$

where d_{ee} , d_{nn} , and d_{uu} are diagonal elements of the matrix $\tilde{\mathbf{D}} = \mathbf{FDF}^T = \begin{bmatrix} d_{ee} & d_{en} & d_{eu} \\ d_{ne} & d_{nn} & d_{nu} \\ d_{ue} & d_{un} & d_{uu} \end{bmatrix}$ where in turn $\mathbf{F} = \begin{bmatrix} -\sin(\lambda) & \cos(\lambda) & 0 & 0 \\ -\sin(\varphi)\cos(\lambda) & -\sin(\varphi)\sin(\lambda) & \cos(\varphi) & 0 \\ \cos(\varphi)\cos(\lambda) & \cos(\varphi)\sin(\lambda) & \sin(\varphi) & 0 \end{bmatrix}$ as given in [Mis01]. This matrix multiplication transforms the earth-centered earth-fixed coordinates to local East-North-Up coordinate frame that is fixed to (latitude φ , longitude λ).

3.4.4 DOP Based Accuracy Approximations

The horizontal position error can be characterized with *distance root mean square* (drms), which is defined by the formula

$$\text{drms} = \sqrt{\sigma_N^2 + \sigma_E^2}\ , \tag{3.32}$$

where σ_N^2 and σ_E^2 are the north and east position error variances, respectively. Drms can be expressed also as

$$\text{drms} = \text{HDOP} \cdot \sigma_\rho \tag{3.33}$$

if the position error is assumed to be a zero-mean random variable.

If the two-dimensional error distribution is close to being circular, then the probability that the horizontal error is within a circle of radius 2 drms ranges between 0.95 and 0.98 [Kap05]. “2 drms” is a commonly used accuracy metric as the 95% limit for the magnitude of the horizontal error [Kap05].

Another widely-used metric for horizontal errors is *circular error probable (CEP).* CEP is defined as the radius of a circle that contains a certain percentage of the error distributions when centered at the correct location. Commonly, the percentages of 50, 80, 90, and 95 are used. As given in [Col06], CEP is defined as

$$CEP_{p\%}\left(\boldsymbol{\varepsilon}\right) = e \Leftrightarrow P\left(\left\|\boldsymbol{\varepsilon}\right\| \leq e\right) = \frac{p}{100} . \tag{3.34}$$

There are approximation formulas for CEP, which can be used under the assumption that the horizontal error has zero-mean two-dimensional Gaussian distribution. The approximation formulas are listed in Table 3.1.

Table 3.1 CEP approximation formulas [Kap05].

Metric	**Approximation Formula**	**Equal Form**
CEP50	0.75 HDOP σ_ρ	$0.75\sqrt{\sigma_N^2 + \sigma_E^2}$
CEP80	$1.28 \cdot \mathrm{HDOP} \cdot \sigma_\rho$	$1.28\sqrt{\sigma_N^2 + \sigma_E^2}$
CEP90	$1.6 \cdot \mathrm{HDOP} \cdot \sigma_\rho$	$1.6\sqrt{\sigma_N^2 + \sigma_E^2}$
CEP95	$2.0 \cdot \mathrm{HDOP} \cdot \sigma_\rho$	$2.0\sqrt{\sigma_N^2 + \sigma_E^2}$

4 Error Sources in Satellite Navigation

As our ability to obtain accurate position in satellite navigation is dependent on our ability to control and eliminate positioning errors, it is vital to understand the nature of the error sources in positioning. Two factors affect the positioning accuracy: pseudorange error and the satellite geometry. As given in [Kap05], the accuracy of a position solution can be estimated by multiplying the pseudorange error factor with a geometry factor.

This chapter addresses the error sources of the range measurement, and the geometry is addressed in Chapter 5. In the following, the traditional division of the infrastructure of satellite positioning into three segments is obeyed in the error source analysis.

4.1 Errors Originating in the Space Segment

4.1.1 Satellite Clock

GPS satellites contain atomic clocks that control all onboard timing operations. The GPS satellite clocks are Rubidium and Cesium clocks (oscillators), which have stabilities of about 1 part in 10^{13} over a day [Par96a]. Although these atomic clocks are very stable, the clocks are not completely synchronized with the GPS system time. The deviation Δt_s can be approximately 1 millisecond at maximum, which is equivalent of a 300 km range error in the respective pseudorange. However, the one-sigma values of the ranging errors due to satellite clock error are on the order of 1.1 m [Kap05]. The difference between the error induced by clock instability and the effective error is explained by the clock correction transmitted by the Control Segment. It delivers the correction terms to the satellites to be further broadcasted in the navigation message to the receivers. These correction parameters are implemented by the receiver using the 2nd order polynomial

$$\Delta t_s = a_{f0} + a_{f1}\left(t_{GPS} - t_{oc}\right) + a_{f2}\left(t_{GPS} - t_{oc}\right)^2 + \Delta t_r \qquad (4.1)$$

where

a_{f0} is the clock bias [s],

a_{f1} is the clock drift [s/s],

a_{f2} is the frequency drift, or aging [s/s^2],

t_{oc} is the clock data reference time [s],

t_{GPS} is the current GPS system time epoch [s], and

Δt_r is the correction due to relativistic effects [s].

Since the parameters are fitted estimates of the actual satellite clock errors, some residual error remains. In [How05], a statistic is proposed which helps to create more accurate clock-correction parameters.

4.2 Errors Originating in the Control Segment

4.2.1 Ephemeris Prediction Error

Ephemeris errors result when the GPS navigation message does not transmit the correct satellite location. As illustrated in Fig. 4.1, there are three components in the ephemeris error: radial component, which is typically the smallest, tangential and cross-track errors may be larger by an order of a magnitude [Kap96a]. This is fortunate because the error in a pseudorange measurement is the projection of the satellite position error vector on the line-of-sight (LOS), which depends mostly upon the radial component.

The ephemeris data, for which the Control Segment responds, is a prediction of the real satellite orbit vs. time. Therefore, a residual error remains always even if the system is functioning properly. In the navigation message, the ephemeris is updated every two hours but it remains valid for four hours, after which the error grows significantly [Yil99]. According to [Kap05], the 1-sigma ephemeris error is 0.8 meters.

The Control Segment monitors the growth in parameter errors by comparing the broadcast ephemeris values to the best current estimates available. If the estimated range error for a satellite exceeds a threshold, “a contingency data upload” is scheduled [Mis01]. Similarly to clock correction parameters, an initiative has been made to enhance the accuracy of the ephemeris parameters [Mal97].

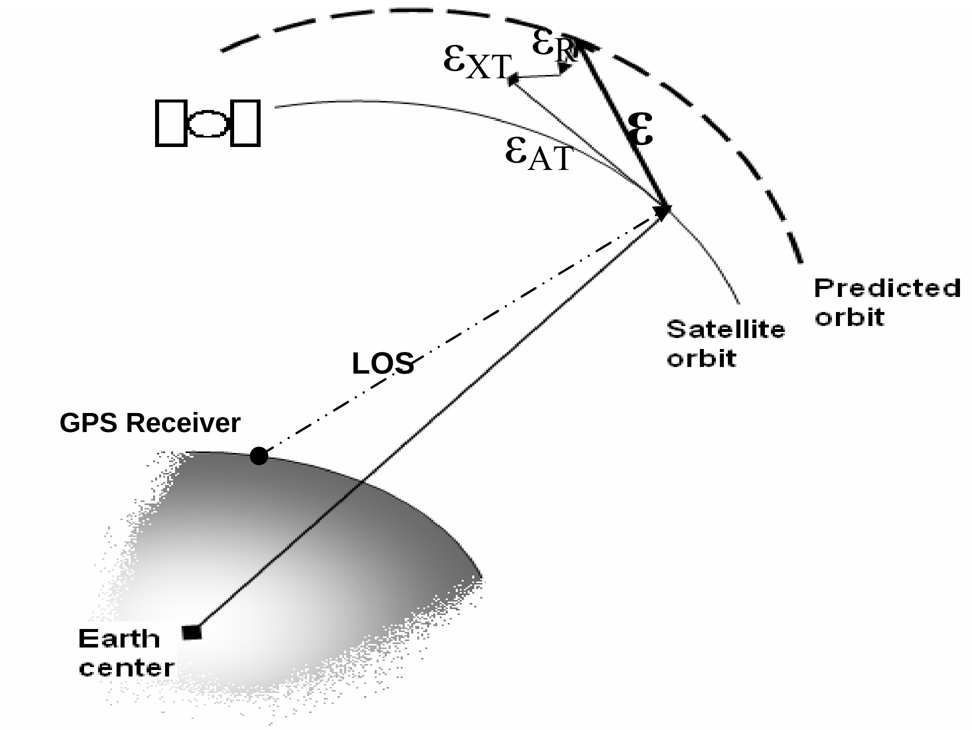

Figure 4.1 Ephemeris error components in the radial (R), tangential (T), and cross-track (XT) directions [Mis01], of which the radial component has the biggest influence on the pseudorange error.

4.3 Errors Originating in the User Segment

The radiopath of the signal from the satellite to the receiver has several interfering elements. The traveling distance of GPS and GALILEO signals is between 20 000 km and 26 000 km. 95 % of the travel path can be estimated to be in a vacuum. When the signal reaches the altitude of 1000 km, it enters *the ionosphere*. At the height of 40 km, *the troposphere* is encountered. Both these layers induce an error to the satellite signals. After atmospheric propagation distractions, the signals are typically reflected, attenuated, blocked, or distorted by obstacles before reaching the antenna. The user may also reside indoors. Then the signals have to be received through windows or walls. The characteristic attenuations due to walls and foliage have been studied extensively in [Gol98]. The user environment-born errors are described as *receiver noise* and *multipath errors.*

4.3.1 Ionospheric Delay

The propagation medium affects the travel time of the signal from a satellite to the receiver and as this travel time is the very key parameter in satellite positioning, it is important to model the induced uncertainty. Caused by the sun's radiation, the ionosphere is a region of ionized gases. As the sun is the origin of the phenomenon, the effect of the ionosphere changes between night and day and also solar activities have an effect on satellite positioning. A method has been suggested to provide timely warnings about the accuracy degradations caused by solar activities [Sko02].

The speed of propagation of a radio signal in the ionosphere depends on the number of free electrons in its path. The related observable is defined as *the total electron content* (TEC), which is the number of electrons in a tube of 1 m^2 cross section extending from the receiver to the satellite. The modulation of the GPS signals is *delayed* in proportion to the number of free electrons encountered. The phase of the radiofrequency carrier, or carrier phase φ, is *advanced.* When expressed in the units of length, these effects have same magnitude but opposite sign. Thus, the ionospheric delay can be expressed as

$$d_{I,\rho} = \frac{40.3 \cdot \text{TEC}}{f^2} = -d_{I,\varphi} \tag{4.2}$$

where TEC is the total electron content and f is the frequency (L1 or L2) [Mis01].

A user can account for ionospheric delay by using a Klobucher model whose parameters are transmitted in the navigation message. The zenith ionospheric delay estimate at local time t_{local} is given by

$$\frac{d_{I,Zenith}}{c} = \begin{cases} A_1 + A_2 \cos\left(\dfrac{2\pi\left(t_{local} - A_3\right)}{A_4}\right), & \text{if } \left|t_{local} - A_3\right| < A_4/4 \\ A_1, & \text{otherwise} \end{cases} \tag{4.3}$$

where A_1 is the night-time value of the zenith delay (fixed at $5 \cdot 10^{-9}$ s), A_2 is the amplitude of the cosine function for daytime values, A_3 is the phase corresponding to the peak of the cosine function (fixed at 50 400 s, or 14.00 local time), and A_4 is the period of the cosine function.

Similarly to clock error and ephemeris parameters, the Control Segment adjusts the parameters A_2 and A_4 to reflect the prevailing ionospheric conditions. This model has been estimated to reduce range measurement errors by 50 %. At mid-latitudes, the remaining error in zenith delay can be up to 10 m during the day and much worse during heightened solar activity [Mis01].

The path length of a signal depends on the elevation angle of the satellite and it must be accounted for in the form of *an obliquity factor*. The obliquity factor depends on the geometry between the user, the satellite, and the estimated ionospheric height. Therefore, it is a function of elevation angle. Finally, the current ionospheric delay can be estimated by multiplying the zenith delay with the obliquity factor.

A user equipped with a dual-frequency (L1, L2) GPS receiver can estimate the ionospheric delay from the measurements, and essentially eliminate the ionosphere errors. However, few personal positioning devices are multi-frequency receivers, and most users must still rely on the broadcast model.

4.3.2 Tropospheric Delay

Tropospheric delay is the effect of the neutral (non-ionized) atmosphere, and it includes the effect of both the stratosphere and the troposphere. The neutral atmosphere is a non-dispersive medium to radio waves up to frequencies of 15 GHz. In other words, the tropospheric delay is not dependent on the frequency. Therefore, the effect of troposphere is the same for L1 and L2 carriers, and the error elimination by using the dual frequency method cannot be used [Hof92].

The speed of propagation of GPS signals in the troposphere is lower than in free space and, therefore, the apparent range to a satellite appears longer, typically 2.5-25 meters [Mis01]. The extent of the tropospheric delay depends upon the refractive index of the air mass along its path, which in turn depends on the densities of the dry air constituents and water temperature. However, meteorological measurements are rarely available to the navigator. Therefore, usually the tropospheric delay is estimated upon average meteorological conditions at the user's location. A model of *standard atmosphere* and user's latitude and longitude are used in the delay estimation. There are several tropospheric models, of which the Hopfield model [Hop69] and the Saastamoinen model [Saa73] have been recognized to be accurate.

4.3.3 Receiver Noise and Resolution

Random measurement noise, called receiver noise, includes several error sources: noise introduced by the antenna, amplifiers, cables, and the receiver, multi-access noise (i.e., interference from other GPS signals and GPS-like broadcasts from system augmentations), and signal quantization noise.

A receiver cannot follow changes in the signal waveform perfectly and, therefore, there are delays and distortions. A receiver sees a waveform which is the sum of the GPS signal and randomly fluctuating noise. This results in the fact that the fine structure of a signal can be masked by thermal noise, especially if the signal-to-noise ratio is low (which is often the case in personal positioning, as mentioned earlier) [Mis01]. A typical 1-sigma value of receiver noise error is 0.1 meters [Kap05].

4.3.4 Multipath

Multipath is one of the major error sources, as the magnitude of the error can be even 100 meters although the 1-sigma error value is 0.2 meters [Kap05]. With multipath, a signal arrives at the receiver (or the phase center of the antenna) via multiple paths due to reflections from the Earth and nearby objects. Figure 4.2 illustrates the phenomenon. The degradation of the pseudoranges is caused by the distorted detection of the correlation peak by the presence of the indirect signal or the reflected version of the signal. A reflected signal is a delayed and usually weaker version of the direct signal. The subsequent code and carrier phase measurements are for the sum of the received signals. Thus, multipath affects both code and carrier measurements, but the magnitude of the errors differ significantly [Mis01].

The multipath effect can be combated with three different approaches [Hof92]:

- antenna siting, and other antenna-related mitigation techniques [Cou99],
- improved receiver technology, and
- signal and data processing.

The primary defense against multipath is to locate the antenna away from reflectors, but this is not always practical. Additionally, the antenna can be designed to lower the contribution of some types of reflections, e.g. from the ground below the antenna. Multipath generally arrives along with signals from satellites at low elevation angles. Therefore, antenna pattern gain could be designed to attenuate incoming signals at low elevation angles (as well as those from the ground). However, again the decision to discard signals with low elevation angles may be too costly to make, as this may prohibit navigation altogether in typically difficult personal positioning conditions.

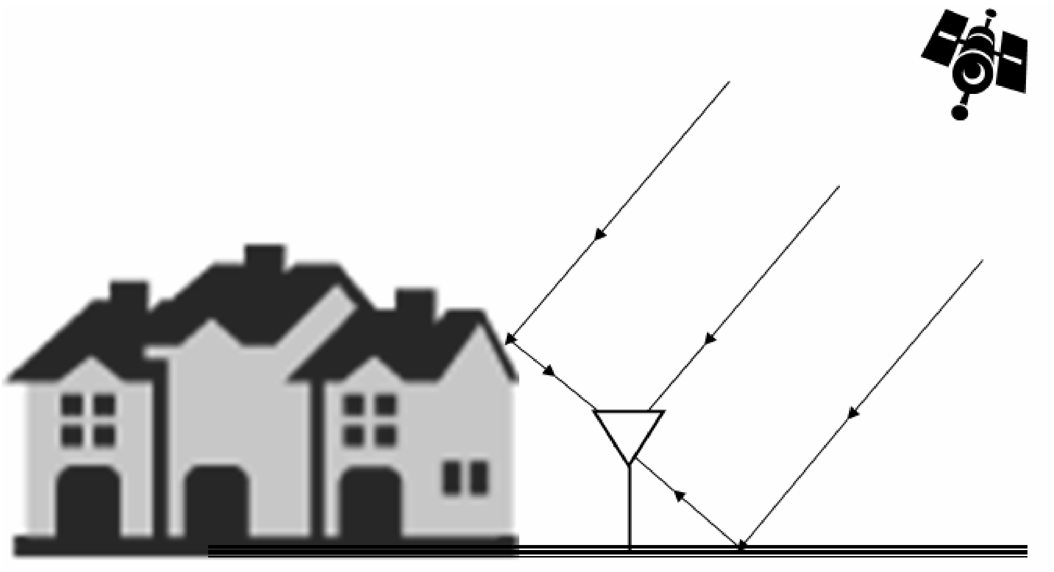

Figure 4.2 Multipath effect. The satellite signal is received via three paths, of which one is direct and two others are reflected, one from ground, and the other from a building.

Improving the receiver technology for multipath reduction includes narrow correlator spacing [Bra01], and extending the multipath estimation delay lock loop [Dov04]. GPS modernization and GALILEO bring new signal structures which enable different multipath mitigation as well [Nun05].

Numerous methods investigate multipath mitigation by signal and data processing: exploring the signal-to-noise ratio [Axe96], using multiple reference stations [Ray01], and using data combinations [Hof92].

4.4 Error Budgets

In Table 4.1 a summary of pseudorange errors in a form of an error budget is given. Contemporary values are given according to [Kap05], and for comparison, the respective estimates dating back to 1996 are presented in the right-most column, picked from [Kap96]. Table 4.1 shows that the root-sum-squared (RSS) error has reduced from 8.0 m to 7.1 m as the accuracy of GPS has improved in ten years due to development in both system and receiver technology. The use of root-sum-squared (RSS) addition of the error components is justified under the assumption that the errors can be treated as independent random variables such that the variances add or, equivalently, the 1-sigma total error is the RSS of the individual 1-sigma values [Kap05].

The dominating error source seems to be the ionosphere. The ionospheric error is the residual error after applying the broadcast ionospheric delay corrections, which were introduced in Section 4.3.1. However, the ionospheric errors are highly correlated among satellites. This results in the fact that the respective positioning error is less than predicted by using the estimate “DOP times the pseudorange error”.

Currently, GPS is being modernized. The first GPS satellite which transmits also the new signals was launched in September 2005 and it has been usable since December 2005. The first GALILEO satellite was launched in December 2005. Both GPS modernization and the combined use of GALILEO and GPS will affect the obtained accuracy.

GPS modernization program includes the addition of three civil signals. The L1C signal will be available in Block III satellites, and the L2C signal and the L5 signal in satellite Blocks IIR-M and IIF, respectively. The L5 signal resides at 1176.45 MHz and it is intended for safety-of-life use applications [Kap05]. These signals will provide civil users the ability to correct for ionospheric delays by making dual frequency measurements, which will increase user accuracy significantly as Table 4.1 shows.

The combined use of both GALILEO and GPS will improve the positioning accuracy when compared to only-GPS positioning. As summarized in [McD02], GALILEO-GPS interoperability will provide improvements in availability (especially at high latitudes), integrity, and accuracy. The improved accuracy of autonomous code-based positioning is estimated to be 5-10 m. The improvement is a direct consequence of the improved geometry: the nominal horizontal dilution of precision is estimated to drop from 1 to 0.7 and the nominal vertical dilution of precision is coming down from 3 to 2 (Chapter 6 addresses the dilution of precision more closely).

Table 4.1 GPS Standard Positioning Service typical pseudorange error budget for nominal signals. Due to small differences in the manner of presentation in the columns of the year 1996 and 2005, the ionospheric error seems to have grown over years, which it obviously has not done.

Segment Source	**Error Source**	**1-sigma error (m) [Kap05]**	**1-sigma error (m) [Kap96]**
Space / Control	Broadcast Clock	1.1	3.0
	L1 P(Y) – L1 C/A group delay	0.3	-
	Broadcast ephemeris	0.8	4.2
	Other	-	1.0
User	Ionospheric Delay	7.0	5.0
	Tropospheric Delay	0.2	1.5
	Receiver Noise and Resolution	0.1	1.5
	Multipath	0.2	2.5
	Other		0.5
System UERE	**Total (RSS)**	**7.1**	**8.0**

5 Observables in Error Detection

Chapter 5 lists observables that are suitable for error detection of satellite navigation. These parameters are divided into three groups: 1) those generated by the GPS Control Segment, 2) those generated by a receiver, and 3) those which require minor data processing (and are generated by a receiver). In other words, any information outside the receiver or the system is not included, although error detection solutions employing a third-party system have been proposed or are in use. Such systems include augmentation systems such as European EGNOS, and American WAAS (Wide Area Augmentation System), and currently research-use-only LAAS (Local Area Augmentation System). Additionally, wireless networks are possible providers of integrity data as it was explained in Chapter 2 in more detail. Chapter 5 ends with a few words used on what remains unknown or unreachable despite the observables.

5.1 Parameters Generated by the GPS Control Segment

GNSS systems produce signal health indicator parameters that are available to the user and that can be used in integrity monitoring. Following coherently the policy of the thesis, it is now focused only on data parameters produced by GPS. Having been created by the Control Segment, health indicators are sent in the navigation message.

5.1.1 User Range Accuracy

User Range Accuracy (URA) is a prediction of the signal accuracy, and it is created by the Control Segment. URA index is sent in the subframe 3 of the navigation message. In 1999, URA computation was updated which made URA a more reliable signal health indicator [Riv00]. However, URA is only a prediction of errors for which the Space and Control Segments are responsible, e.g. clock and ephemeris errors. Therefore, it does not include any user-dependent errors, naturally. The URA value may vary over a given subframe fit interval, but the URA index N_U reported in the navigation message corresponds to the maximum value of URA anticipated over the fit interval [Nav00]. The URA value is based on recent historical data and, therefore, it has the best accuracy immediately after an upload. This upload takes place every two or four hours (*fit interval*). Only the URA index is available to the user, but there is a simple formula to turn this index back into an URA value. The URA value means that accuracy is “not better than X_U meters”. URA value X_U is computed from the URA index N_U as given:

- If the value of N_U is 6 or less, $X_U = 2^{(1+N_U/2)}$,
- if the value of N_U is 6 or more but less than 15, $X_U = 2^{(N_U-2)}$,
- if the value of N_U is 15, it will indicate the absence of accuracy prediction.

The URA value is estimated by the Control Segment with the following relation:

$$URA = \sqrt{\sigma_R^2 + \frac{1}{16}\sigma_A^2 + \frac{1}{16}\sigma_C^2 + \sigma_t^2 + \sigma_m^2} \tag{5.1}$$

where σ_R is the radial component of one-sigma predicted ephemeris error,

σ_A is the along-track component of one-sigma predicted ephemeris error,

σ_C is the cross-track component of one-sigma predicted ephemeris error,

σ_t is one-sigma predicted satellite clock error, and

σ_m is one-sigma general modeling error.

5.1.2 Health Bits

Health bits are another satellite condition parameter delivered in the navigation message. Subframe 1 contains a 6-bit health indicator that refers to the transmitting satellite. The most significant bit (MSB) summarizes the health of the navigation message and the five least significant bits (LSBs) indicate the health of the signal components. Additionally, the subframes 4 and 5 contain two types of signal health information, describing the health of the navigation data, and of the signal components. Health bits are described in detail in [Nav00].

5.1.3 Date of Ephemeris

Date of ephemeris describes the age of the ephemeris data, more precisely it tells the time from ephemeris reference epoch [Nav00]. Ephemeris data is a prediction of satellite positions where the satellite orbit is modeled as a modified elliptical orbit with correction terms to account for different perturbations [Par96a]. These perturbations concern the argument of latitude, orbit radius, angle of inclination; and rate of change of right ascension and inclination angle. The parameters for this model are changed periodically to give a best fit to the actual satellite orbit. Transmission interval is two hours for time of ephemeris, but the fit interval is four hours, so data can be used up to four hours without big errors. However, ephemeris data, according to [Kap96 p. 206], begins to deteriorate rapidly after about three hours. After four hours, if the ephemeris is not updated, the error begins to increase dramatically [Yil99]. Transmission interval can also be one hour for some satellites.

Date of ephemeris t_{doe} is the difference between GPS system time t_{GPS} (at the time of transmission) and ephemeris reference time t_{toe} as given by Eqn. (5.2). The ephemeris reference time is called *as time of ephemeris (TOE)* [Par96a].

$$t_{doe} = t_{GPS} - t_{toe} \tag{5.2}$$

Thus, date of ephemeris tells the time from ephemeris reference epoch [Nav00]. According to [Nav96], pseudorange error tends to be at a minimum following a new navigation message upload. An upload takes the DOE to have a maximum value, because the fit interval is four hours and the minimum is fitted to be in the middle of the fit interval (two hours after upload). As it was mentioned the transmission interval is two hours and, therefore, DOE holds only negative values. The smaller the absolute value of DOE, the closer the system time is to ephemeris reference time, and the less there is difference between the actual ephemeris and the ephemeris used in calculations.

5.2 Parameters Created by the Receiver

5.2.1 Carrier to Noise Ratio

Carrier-to-noise ratio (*C/No*) is usually a trustworthy parameter about the signal condition, and one of the key parameters that determines receiver performance [Par96a]. *C/No* is important for determining whether the code and carrier tracking loops are in lock, controlling the response of the receiver to low *C/No* environment, and determining the *C/No* environment in order to assess or predict receiver performance [Gro05].

The signal levels received in indoors are inevitably lower than those received in outdoors. Especially, if a signal is received directly (line-of-sight) in indoors, the direct signal may be weaker than reflected signals. Thus, while indoors, carrier-to-noise ratio does not necessarily tell the “truth” about signal condition – the weaker signal is in fact the correct signal. Therefore, the reasoning about signal condition cannot be based on the mere carrier-to-noise ratio. However, it remains true that the lower the *C/No*, the more there are errors in the signal.

C/No is measured at the input of the receiver and it is usually given in dB/Hz. Typical *C/No* values range from 35 to 55 dB/Hz in line-of-sight conditions or under foliage. Next, the computation of *C/No* is now addressed briefly following the formulation in [Bra99]. Firstly, noise power can be calculated as

$$P_{NOISE} = qT_E B \tag{5.3}$$

where q is Boltzmann's constant, B is the bandwidth in Hz, and T_E is the effective noise temperature in Kelvin. For a typical GPS receiver T_E is 513 K. Given that the bandwidth is 50 Hz and noise power is –184.5 dBW. The bandwidth is 50 Hz because the signal of interest occupies the bandwidth of navigation data.

The coarse/acquisition (C/A) signal is transmitted at an effective level of 26.8 dBW. The signal loses power when traveling through space. This free-space loss factor is defined as

$$F = \left(\frac{\lambda}{4\pi L} \right)^2 \tag{5.4}$$

where λ is the carrier wavelength and L is the transmitter-to-receiver distance, which can be approximated to be $2 \cdot 10^7$ m. This gives us that the free-space loss factor is –182.4 dB. It is assumed that atmospheric loss is 2.0 dB, but in fact it can be less than 0.3 dB [Kap96]. Summarizing these estimating figures in Table 5.1, we obtain the result that the minimum received power is –157.6 dBW, which fits the design specification of required minimum received power -160 dBW.

Finally, with these approximations *C/No* value is –157.6 -(-184.5) = 26.9 dB. As it was mentioned, normally *C/No* value is given in dB/Hz. This means that C/No is normalized to a 1 Hz bandwidth to achieve a *C/No* that does not depend on the bandwidth. Thus, in this example the ratio in dB/Hz is $C/No = 10\log_{10}\left\{ 10^{26.9/10} \cdot 50 \right\} = 43.9 \text{ dB/Hz}$.

Making the *C/No* measurement is not straight-forward in weak signal conditions because long averaging times are necessary but not desirable as they lead to time lags in *C/No* measurements, as formulated in [Gro05] where three different methods of measuring the *C/No* are given.

Table 5.1 Satellite to receiver link budget.

Minimum transmitted power P	26.8 dBW
Free-space loss factor F	182.4 dB
Atmospheric attenuation A	2.0 dB
Minimum received power S = P – F – A	**-157.6 dBW**

5.2.2 Elevation Angle

Carrier to noise ratio has been used in signal weighting, giving more credit for signals with better *C/No*. In a similar fashion, elevation angle has been used for weighting the signals [Par96]. Elevation angle correlates with the distance that the satellite signal has to travel before reaching the receiver. Atmospheric effects are especially deteriorating when elevation angle is below 10 degrees. Multipath errors, reflections, and blockage of the signal are more likely when the elevation angle is low. In error modeling, this effect is partly accounted for with the obliquity factor as it was explained in Chapter 4.

In many cases, elevation angle and carrier-to-noise ratio are correlated. However, again, there are cases that break this correlation. In indoor positioning, the low-elevation signal may reach the signal through a window, and higher-elevation signals have to penetrate concrete walls, thus they become more attenuated than the low-elevation signal.

5.3 Parameters Requiring Minor Data Processing

5.3.1 Differential Parameters

Differential data observables reveal positioning faults when a sudden change in the evolution of the observable occurs. Abrupt increase or decrease in the change between two time-successive measurements reveals a possible error in data processing. Usually the difference between the previous and the current elevation or azimuth angle remains quite constant from epoch to epoch. Therefore, abrupt changes in the elevation or azimuth angles reveal errors in user or satellite position. If the change occurs in all angle values, then the error is in user position. On the other hand, if the change is related to only one or other limited number of satellites, then the error is in satellite position, which is, however, very rare.

Differencing over time takes us a step closer to *filtering.* Kalman filtering is widely used in satellite navigation applications to integrate position data from two or more sources or to integrate carrier and code measurements. However, filtering does not make the task of integrity monitoring obsolete: in [Jan00], a method is proposed to combine adaptive measurement covariance estimation and fault detection with an extended Kalman filter. In [Lep06], position estimates, which have been processed through fault-detection-algorithm, are Kalman-filtered. Kalman filtering, being related to satellite navigation, is a vast topic and, therefore, omitted here. A detailed presentation of the topic is found in [Bro97].

5.3.2 Velocity

Velocity of the user can be computed from the Doppler frequency as presented in [Kap96]. Velocity can also be derived from successive position fixes or from successive pseudoranges. Thus, comparison of different velocity estimates can be used for error detection. In addition to this, a sudden change in velocity may also be used as an error indicator, at least when it is known that the receiver is used by a person and/or that he is walking/cycling/driving and, therefore, there is a limit to the accelerations that may occur.

5.4 What Remains Unknown or Unreachable?

Having listed the possible observables which can be used in error detection, it is recognized that some errors cannot be modeled completely through these observables. Additionally, it remains to consider what cannot be reached with them (at all).

5.4.1 Multipath

In spite of the observables, positioning conditions that are affected by multipath phenomenon are difficult to predict or to identify. Obviously, there are methods to battle multipath, as given in Chapter 4. However, multipath remains a phenomenon which deteriorates navigation accuracy. Multipath is especially dominating in urban and indoor positioning [Bre05] where the antenna is in a handset, which is presumably in a pocket, in a bag, or next to user's ear [Dig01] and antenna siting cannot really be considered as a multipath mitigation method.

5.4.2 Near-Far Problem

The near-far problem (hearability problem) is another inherent situation that cannot be helped with any integrity monitoring or selective combining methods. In short, the near-far problem is one of detecting and receiving a weaker signal amongst stronger signals. The weaker signal cannot be "heard" as the stronger signals are "too loud". When navigation is augmented with pseudolites, overcoming the near-far problem is a primary challenge [Mad01]. In conventional GPS positioning, near-far problem is not very typical as all the signals hold a similar power. Instead, with high sensitivity GPS or assisted GPS, the signal levels differ greatly at times, which makes positioning vulnerable to the near-far problem [Lóp05]. This is especially true in indoors.

5.4.3 Geometry of the Satellite Subset

The geometry of the selected satellite subset is beyond the user's influence. The user can discard a satellite from the set but adding signals to improve the geometry is obviously impossible, unless pseudolites are used. As the geometry of the current constellation subset determines (with signal condition) the accuracy of the position estimate, it is important to include geometry analysis to error detection. The main tool for geometry analysis is the *dilution of precision* which will be addressed, along with other error detection methods, in the next chapter.

6 Methods for Selective Combining

Selective combining is a task of choosing the satellite subset, which results in the most accurate position estimate. In other words, out of M visible satellites, N satellites must be chosen, where $M \geq N$ as long as there is at least M channels in the receiver. The term selective combining emphasizes the comparison between different subsets.

In the following, all the methods that are available for this task at the user-level (after baseband processing) are listed. As mentioned in [Wal95], it is important that selective combining or integrity monitoring is carried out in the user-level because this is the only place where all information used to form the position solution is present. The importance of careful consideration of satellite subset selection has been addressed also in [Kih94].

6.1 Signal Condition Analysis

As the accuracy of a position estimate is a product of satellite geometry and pseudorange error, signal condition is of great interest. Signal condition determines the error in the pseudorange. Signal condition can be estimated from some of the observables presented in Chapter 5.

6.1.1 Probabilistic Reasoning

In probabilistic signal condition analysis, a probability distribution is associated with an observable quantity. Thus, a realized value of an observable can be interpreted as a probability of non-erroneous signal.

When multiple observables or parameters are available, the probabilities can be combined to form a joint probability of a non-erroneous signal. Ideally, the observables or *attributes* should be completely de-correlated in order to form the joint probabilities. However, this is not case. But the level of correlation between the attributes (which will be addressed shortly) is difficult if not impossible to estimate precisely. Therefore, the theory is compromised to find out something, even if that something is distorted slightly with a bias due to cross-correlation between input parameters.

To estimate signal condition, all the factors affecting the signal should be presented. The attributes have to account for different pseudorange error sources. To do this, the characteristics of the observables must be transformed into mathematical expressions, i.e., functions. Table 6.1 gives a summary on attributes which can be used for user-level signal monitoring and pseudorange error estimation. The Publication [P7] presents one possibility to turn these attributes into characteristic functions.

These functions are combined in a fashion determined by the theory employed. In the following, three suitable methods for joint signal condition analysis are proposed.

Table 6.1 Attributes and respective pseudorange error sources.

Pseudorange Error Source	**Attribute describing the error contribution**
Multipath	*C/No,* correlation peak shape, cycle slips
Noise	*C/No*, Elevation
Atmospheric effect	Elevation
Clock correction accuracy	User Range Accuracy (URA)
Ephemeris parameters accuracy (system-related ephemeris error)	User Range Accuracy (URA)
Ephemeris (user-related ephemeris error)	Date of ephemeris

6.1.2 Methods of Combining Information

Bayesian theory [Pea88], Dempster-Shafer Theory [Dem67], [Dem68], [Sha74], and diverse arithmetics of Fuzzy Logic [Jan97] are all methods, which extend or generalize expert decision making by using concepts of a probability or a partial belief in expressing relations. These *soft computing* methods can be utilized in estimation of the signal condition. Table 6.2 summarizes the function types and fusion methods. The resulting estimate of the signal condition is an abstract number, which itself does not have a meaning. However, a quantitative measure of signal condition could be used as a weight function in position estimation. Author's results are presented in [P7]. A similar approach has been proposed in [Var00] where Bayesian reasoning was proposed. [Nav96] describes *a figure of merit* which, in a similar fashion, combines information about several observables and is used for satellite subset selection.

Table 6.2 Comparison of three different combination methods in signal condition analysis.

Approach	Bayesian	Dempster-Shafer	Fuzzy Logic
Function Unit	Probability distribution $P(A)$	Belief function $\mathrm{Bel}(A)=\sum_{B\subset A} m(B)$ where $m(B)$ is a measure of belief committed to proposition B	Membership function $\mu(A)$
Fusion	Bayes' rule	Dempster's Rule	Fuzzy union, intersection functions
Fusion Algorithm	$P(C)=$ $P(A\mid B)=\frac{P(B\mid A)P(A)}{P(B)}$ which is the probability of A when given evidence B	$m(C)=m_1(A)\otimes m_2(B)$ $=K\sum_{A_i\cap B_j=C} m_1(A_i)m_2(B_j)$ where K is a normalization factor	Different possibilities. E.g. Union $\mu(C)=\max(\mu(A),\mu(B))$ and intersection $\mu(C)=\min(\mu(A),\mu(B))$
Result	Probability	Belief and uncertainty estimates	Membership value(s)

6.1.3 Environment Detection

GPS can be used for revealing the characteristics of surroundings of a receiver. The motivation for the study presented in [P6] is to find out is it possible to use the information about the receiver environment to enhance the performance of the receiver. The possible approaches are

- triggering between different possible positioning technologies (GPS, INS, WLAN, BlueTooth) in time to avoid erroneous position estimates from GPS, or
- a database of logged environment data about the surroundings which could be used to preventing multipath as it occurs repeatedly in a similar fashion at the same place (at the same time of day). Alternatively,
- the receiver can "remember" the difficult positioning environments and request special help from another source once entering again the difficult positioning neighborhood.
- Even further, the assistance data to the receiver could be localized, including information about blockages which could then be used in avoiding multipath.

The idea of environment detection is simple. The surroundings of a GPS receiver are divided into (e.g.) eight sectors. As the azimuth and elevation angles of the satellites are available from the receiver, the blocking degree of each sector is estimated on the basis of a priori information about satellites that should be visible in that sector. There are different possibilities to obtain the a priori information: from almanac data, from assistance ephemeris data, or from a model of ephemeris data stored to receiver's memory. Figure 6.1 illustrates the idea. The publication [P6] presents results of the test experiments. GALILEO will make the resolution of the proposed method better as the

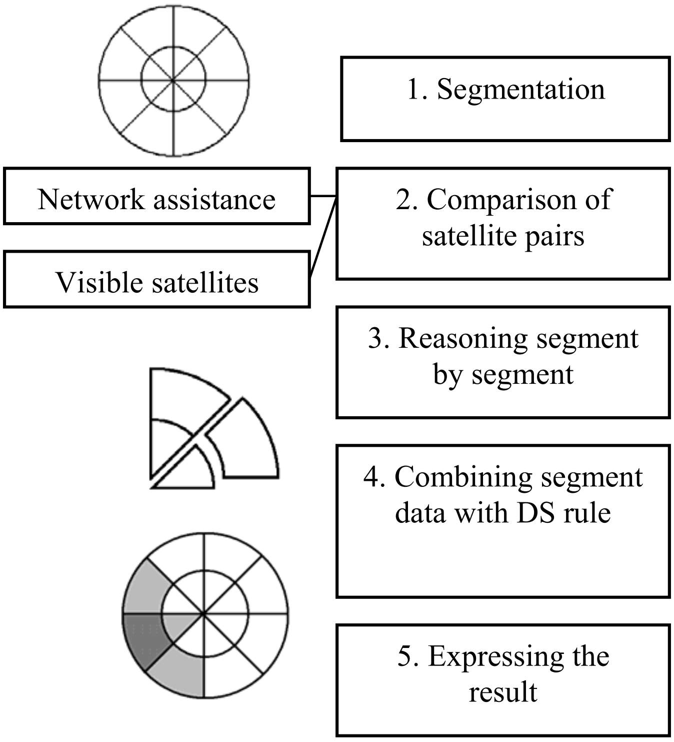

Figure 6.1 Environment of the receiver is divided into sectors, after which the status of each sector is analyzed.

number of satellites is doubled. Use of directional antennas would enable an enhancement to the method as well.

6.2 DOP Methods

Dilution of precision (DOP) is one of the most used and most studied GPS performance measures. Originally, DOP values (or predictions of them) were used for scheduling GPS data collection experiments [Mis01]. At that time, GPS constellation was not yet full. Despite the fact that today GPS navigation is completely different from those days, DOP measure remains to be a fundamental element in describing the current positioning conditions. Dilution of precision describes how badly the precision of the range measurements has diluted due to the current geometry of the selected satellite subset. Hence, DOP describes the goodness of the current satellite geometry with one numeric value.

Dilution of precision is not only GPS related term. In fact, GDOP concept has been introduced prior to GPS in the context of hyperbolic positioning [Fre73], and also studies of GDOP computation and GDOP bounds have been presented prior to GPS [Lee75a], [Lee75b]. In fact, the dilution of precision can be analyzed in any multilateration positioning method. Currently, the term is used in a similar fashion in cellular network positioning as in [Mes99] and [Chi04].

6.2.1 DOP in Previous Work

Geometric DOP (GDOP) and all DOP parameters have been analyzed thoroughly in previous work. In 1980's and still in early 1990's, the GPS receivers had less channels for tracking than they do today, and GDOP was an important analysis tool to select the optimum set of (e.g.) four satellites [Kih84]. The minimization of GDOP with four satellites was recognized to be (almost) equal to finding the maximum volume of a tetrahedron defined by four unit vectors directed to the selected satellites, as illustrated in Fig. 6.2. It is proved n [Hsu94], that this relation is indeed an approximation.

In [Cha94], it is proved that in addition GDOP matrix being the covariance of the linearized LS errors, GDOP is actually the Cramer-Rao bound on estimates of position and clock bias (assuming that pseudorange errors are Gaussian). [Pha01] proposes a recursive satellite subset selection method that is based on GDOP and an integrity constraint. DOP is also an important analysis tool in constellation design [Pir05], planning of combined use of different satellite systems [Con05], or combined use of pseudolites with a satellite system [McK97].

In previous work, DOP bounds have also been of interest [Par96a], [Yar00] which is explained by the small number of channels. The most commonly referred bound is GDOP (with four satellites) being greater than or equal to $\sqrt{2}$.

6.2.2 Monotonicity of DOP

As proved in [Yar00], the increasing the number of satellites will only reduce the GDOP, so GDOP is monotonically decreasing. In the Publication [P3], it is proved that a weighted version of GDOP is also monotonically decreasing. This fundamentally limits the ways that these parameters can be employed in satellite subset selection. However, fault detection methods based on the DOP measures are needed, since signal parameter masks cannot evaluate the importance of the particular signal to the current geometry and, therefore, they may decrease the overall navigation availability critically. Fortunately, a non-monotonic weighted DOP can also be formed. The both weighted DOP versions (a monotonic one and a non-monotonic one) are addressed in the following.

6.2.3 WDOP

The monotonic weighted GDOP is now named WDOP to emphasize its connection to the Weighted Least Squares (WLS) estimate, where the measurements are weighted in relation to their error contribution, as it was explained in Section 3.3.2. WDOP (or WLS-DOP) is given by

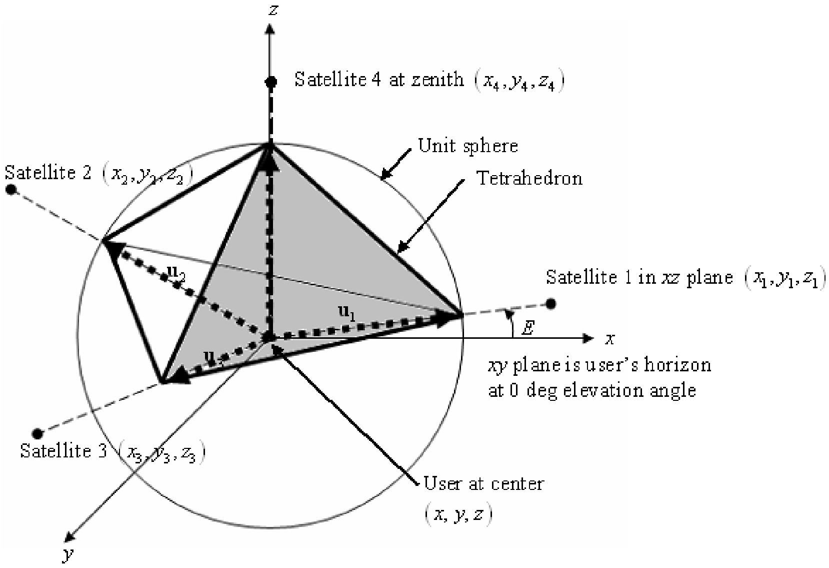

Figure 6.2 The maximum volume of the tetrahedron, defined by four unit vectors, approximates the minimum GDOP of the respective satellite subset

$$WDOP = \sqrt{trace\left(\operatorname{cov}\left(\Delta \mathbf{x}_b\right)\right)} = \sqrt{trace\left(\left(\mathbf{G}^T \mathbf{R}_\rho \mathbf{G}\right)^{-1}\right)}. \tag{6.1}$$

In [Mis01], the WDOP measure is also mentioned (but the term WDOP is not used, [Mis01] p. 186). Further on it is explained that this weighted DOP measure would reflect the structures of both the geometry and measurement errors but that would not be intuitive or simple anymore. Therefore, weighted DOP would be difficult to use for decision making.

6.2.4 KDOP

The non-monotonic weighted DOP is named KDOP. The term KDOP is mentioned in [Nav96], but the same measure occurs also as EDOP in [Par96] after elevation as the elevation angle is used in the weighting. KDOP is defined as follows

$$KDOP = \sqrt{trace\left(\left(\mathbf{G}^T \mathbf{G}\right)^{-1} \mathbf{G}^T \mathbf{R}_\rho \mathbf{G} \left(\mathbf{G}^T \mathbf{G}\right)^{-1}\right)}. \tag{6.2}$$

KDOP equals WDOP if $\mathbf{G}$ is invertible, which is rarely the case, and never when there are five or more satellites. The non-monotonicity of KDOP is apparent from the results in [P3].

6.2.5 Using KDOP for Fault Detection

The non-monotonicity of KDOP enables its use in fault detection. The KDOP follows the same principle as the non-weighted DOP: the more favorable the geometry (and now also the signal quality), the lower is the KDOP. Therefore, the satellite subset with the smallest KDOP value is chosen. The KDOP fault exclusion algorithm is simply the following:

> A satellite s_i is excluded when KDOP (with s_i) > KDOP (without s_i). If several satellite exclusions of a single (different) satellite yield a KDOP value lower than that of the entire in-view constellation, then the satellite subset with the lowest KDOP value is chosen.

As presented in [P3], the fault detection is possible with KDOP. It is shown that positioning errors can be successfully eliminated with the proposed method. However, it is recognized that the positioning accuracy is further improved if KDOP method is combined with another fault detection method with a different approach, as presented in [P4]. Such other methods are obviously the traditional fault detection algorithms which (usually) do not consider the signal quality in error detection. In the following, a brief summary on the existing methods is given.

6.3 Traditional Fault Detection and Isolation Methods

A summary on previous work on fault detection methods in satellite navigation is unavoidably also a brief outline of the history of the development of these methods. The vastness of the topic forces to limit the following to give only a skin-deep outline on the existing methods. For more detailed information, refer to [Glo88], [Par96b], [Obe96], and [Kuu05].

6.3.1 The Requirements and the Motivations

The key driver to the development of fault detection algorithms was the aviation requirements set by the American authorities. Federal Aviation Administration (FAA) required the aviators to be able to determine the availability and integrity of GPS prior to the flight [RTC88]. RTCA Special Committee 159, a Federal advisory committee to the FAA, pursued development of techniques to provide integrity for airborne use of GPS. Two methods have been developed: the wide area augmentation system (WAAS) and *receiver autonomous integrity monitoring* (RAIM).

The objective of the traditional RAIM methods has been to identify integrity of a GNSS system that is independent of the user. The hypothesis is that system integrity failures occur only a couple of times a year as given in [Kap96], and historical failure rate of GPS satellites or ephemeris uploads to those satellites has been very low, one event in 18-24 months [Kap05].

Instead, in personal positioning, the need for fault detection rises from the user segment. RAIM can be adjusted to personal positioning [Kuu05], but according to [Kap05], a handset receiver cannot be generally expected to perform its own RAIM function, since signal reception conditions may be poor [Kap05 p. 553].

6.3.2 The Snap-Shot RAIM

RAIM is a technique that uses an over-determined solution to perform a consistency check. To be over-determined, there has to be measurements available from at least five satellites. A basic approach goes under the name *a snap-shot RAIM* algorithm. In a snap-shot RAIM scheme, all the needed measurements are from the same time instant, when again *filtering schemes* use both past and present measurements. Such methods have been proposed originally in [Bro86] and later, e.g., in [Tsa02].

There are three snap-shot schemes: the Least-Squares Residuals method [Par88], the Parity method [Stu88], and the Range-Comparison method [Lee86]. These schemes have been proved equivalent [Bro92]. The Least-Squares Residuals algorithm is derived in the following in likeness of the formulation in [Par96b].

The Least Squares solution can be used to predict the measurements in accordance with

$$\left(\text{predicted }\boldsymbol{\rho}\right) = \mathbf{G}\hat{\mathbf{x}}_b \tag{6.3}$$

Then, the residuals vector is formed and named $\mathbf{w}$:

$$\begin{aligned}\mathbf{w} &= \boldsymbol{\rho} - \left(\text{predicted }\boldsymbol{\rho}\right) = \boldsymbol{\rho} - \mathbf{G}\hat{\mathbf{x}}_b \\ &= \boldsymbol{\rho} - \mathbf{G}\left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T\boldsymbol{\rho} = \left[\mathbf{I} - \mathbf{G}\left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T\right]\boldsymbol{\rho}\end{aligned} \tag{6.4}$$

This linear transformation takes the pseudorange measurement $\boldsymbol{\rho}$ into the resulting residual vector. The sum of squares of the residual vector plays the role of the basic observable in the Least-Squares RAIM, and it is named SSE or sum of squared errors:

$$SSE\left(\mathbf{y}\right) = \mathbf{w}^T\mathbf{w} \tag{6.5}$$

This basic observable is used for failure detection. As SSE is non-negative and scalar, the decision making is simple when a threshold is defined. Similarly, any other scalar variable which is monotonically related to SSE can also be used as the test statistic, and indeed, usually the test statistic is of the form:

$$\sqrt{\frac{SSE(\mathbf{y})}{K-4}} \tag{6.6}$$

where K is the number of satellites. Chi-square statistics can be used to find a threshold value for this test statistic.

6.3.3 Recent Developments

Today, the role of RAIM in its original environment, aviation, is different from the original. WAAS is the primary integrity monitoring system, and RAIM is a back-up solution in situations where WAAS is unavailable [FAA05]. Despite its role as a back-up system, RAIM methods are continuously studied.

Evidently, GALILEO will revolutionize also the RAIM approach by doubling the number of visible satellites to a GPS/GALILEO user but simultaneously the probability of a faulty satellite is increased as well. The combined use of GALILEO and GPS in the RAIM approach has been studied in [Bel05] and in [Lee05] in a WAAS context.

Availability of exclusion, or the lack of it, has been recognized as the problem of the traditional snap-shot approach. Recent RAIM studies include a new improvement to RAIM availability by barometer aiding, proposed by the originators of the RAIM filtering scheme [Bro05a]. In this novel method, the measurements are weighted non-uniformly as they are in the KDOP exclusion method, too. The inventors named this method NIORAIM and propose it also for two-fault detection [Bro05b]. Detection of multiple faults is more difficult than detection of a single fault and is addressed lately also in [Wan05] and [Mac05]. The advent of GALILEO encourages the research on two or multiple fault detection. Aviation requirements still drive RAIM development in [Nik05] where too better availability is aimed for.

7 Methods for Position Confirmation

Chapter 7 considers methods that are suitable for *position confirmation*. Especially, it is focused on a database method which requires cellular connection to be available in the navigation device.

7.1 Position Confirmation

7.1.1 Definition

The term *position confirmation* is introduced by the author to define an approach where the feasibility of a position estimate is verified or confirmed by using selected resources and methods. Checking the feasibility of a position estimate translates to obtaining a reference position estimate which is then compared to the current position estimate. The comparison is coarse as the accuracy of the reference is worse than normal navigation accuracy (which could be said, at least, to be better than 50 meters). The employed methods vary depending on the application and current navigation conditions.

7.1.2 Purpose

Position confirmation is needed in two tasks of a satellite positioning receiver:

- Verifying or obtaining *the initial reference position*, which is needed in signal acquisition, initialization of the Least Squares algorithm, and linearization of the pseudorange measurements (as in Eqn. (2.5))
- Excluding gross positioning errors, i.e. coarse integrity monitoring

Additionally, position confirmation is an independent positioning method, which can complement satellite navigation in case satellite navigation is not available, and a position estimate is crucially needed. In a similar fashion, [Yil02] proposes cell identification positioning to be a default positioning method in case network positioning or satellite positioning fail.

7.2 The Significance of the Initial Reference Position

An initial receiver position or, here, reference position, is needed in the receiver in two tasks: signal acquisition and computation of the first fix.

7.2.1 Signal Acquisition

In signal acquisition, the receiver must find the frequency and code phase of the signal before it can lock onto it. Obviously, the L1 frequency is known, but the received GPS signals are shifted in frequency due to the relative receiver-satellite motion. This is called the Doppler frequency shift. Knowing the satellite position and velocity and the initial receiver position reduces the number of frequency bins to be searched, because the receiver is able to estimate the satellite Doppler frequency shift instead of searching over the whole possible frequency range [LaM02].

7.2.2 Computation of the First Fix

It is typical that a GPS receiver estimates its position by using the Least Squares (LS) algorithm iteratively until a position fix is found (it is also a matter of designer's definition that when the fix is declared to be found). Chapter 3 presented the basic LS procedure. Besides the iterative Least Squares, closed-form solutions of the trilateration equations have also been suggested in GPS positioning in [Ban85], [Col99], and [Pac03]. However, the LS approach has remained dominant.

When the satellite navigation receiver is operating to compute the first fix, an initial estimate of the receiver location, a starting point, is needed for the search. This starting point is the linearization point. According to [Nar98], the center of the Earth is a good initial guess. This may seem to be far away from the actual user location, but the direction cosines in the geometry matrix are not so vulnerable to errors in user location. Using the center of the Earth ([0,0,0] in ECEF) as the initial guess is good for robustness when the very first fix is searched for in stand-alone GPS. After that, the previous estimated fix can be used as the linearization point [Ako06]. A correct estimate of user location benefits the iterative least squares search.

7.2.3 Excluding Gross Errors

A reference position can be used for detecting gross positioning errors, or coarse integrity monitoring. In [Kap05], the same idea is expressed as *horizontal position domain constraints to the LS solution*. After detection of an error, the current solution can be discarded and the computation re-started, and again, an initial reference point would be useful.

7.3 Reference Position from Cellular Network

This section considers three approaches to obtain position information from a cellular network: network assistance approach, which requires communication with an assistance server; approach of cellular position databases, which can be utilized independently by the user (once the database has been created first); and finally other database-based approaches. Positioning methods which are based on cellular signaling (including e.g. Enhanced Observed Time Difference (EOTD), and Advanced Forward Link Trilateration (AFLT)) are excluded.

7.3.1 Network Assistance

When a reference position is needed, it would be ideal to have the possibility to request a reference position from a third party. This is plausible via a cellular connection to a reference server. The server can choose the to-be-delivered coordinates on the basis of a given keyword (e.g. a city name), or other identification key. Thus, the reference position is a part of network assistance, which was introduced in Chapter 2. An assistance server has been implemented e.g. in [LaM02], where the assistance data was in Hypertext Transfer Protocol (HTTP) format and it was bit packed into the short (SMS) messages. More importantly, the cellular standards include the delivery of a reference position in network assistance data [Ets05a,b, Ets06], [Yil02].

7.3.2 Cellular Position Databases

The concept of cellular position databases is very simple and based on the fact that cellular networks (GSM, CDMA, WCDMA) consist of a number of radio cells, each served by *a base station* which serves mobile terminals in a particular geographical area in its vicinity, employing particular frequencies. The cells are tagged with *a cellular identity* which identifies them in the network.

Cellular identity information and respective position information can be organized to a database format, which associates one particular cell identity with a position estimate *(latitude, longitude, altitude)*. The database is stored, e.g., to the phone memory. Thus, the database covers a particular geographical area.

There are two options for obtaining the database: The user can either create it himself or the database can be downloadable from a third-party-server via a wireless connection. The size of the downloadable database file depends naturally on the number of included cells. A large number of cells can be stored without consuming too much memory, as a cell area estimate can be expressed with few parameters, as it will be shown later on. Furthermore, a user may update and enlarge the downloaded database himself. Obviously, to be able to create and/or update a database, the user must be equipped with a GPS (or GNSS) receiver.

7.3.3 Other Database Positioning Methods

Location fingerprinting is another database positioning method, which is used in WLAN positioning and similar methods have been proposed also for cellular systems in, e.g., [Aho03], [Lai01], and [Zim04] where power delay profiles or measurement prediction patterns are organized to a database structure. Similarly to these previously presented methods, the cell-identity method circumvents the environment related problems in network positioning. As cellular network is available also in locations where GNSS signals are greatly attenuated, the cell-identity method is complementary in nature in relation to satellite positioning.

7.4 Creation of Cellular Position Databases

To create a cellular position database, cell identity information must be associated with a particular geographic area. A point location must also be given to the cell to enable updating of the cell model. A procedure to create such a cellular position database is described in the following.

7.4.1 Cellular Identity

In GSM networks, a cell is unambiguously identified by its *Global Cell Identity* (GCI) from other cells. There are four parts in the GCI, and they are usually presented in the following order of sequence: Mobile Country Code (MCC), Mobile Network Code (MNC), Location Area Code (LAC), and Cell Identity Code (CID).

Each part of the GCI specifies further the location of the cell. First one, the country code (MCC), tells in which country the cell is. Next part of the GCI, the network code (MNC), identifies the network operator of the current cell. The location area code (LAC) is typically shared by tens or hundreds of cells. The cells with the same LAC code cover a continuous land area. Finally, the cell identity code (CID) specifically identifies the cell in the LAC area. CID is not unambiguous by itself, i.e. the mere CID is not enough to reveal the location of the cell. The other three components of the GCI are needed to unambiguously identify the cell.

7.4.2 Data Collection

Dedicated measurement scans are necessary to collect enough data for cell modeling. Information is obtained about the current position of the user, and the (simultaneously) *serving* cell of the user and the GCI of the cell.

The *serving* cell is the cell which handles all the phone traffic of the user. To find out that which cell is visible in which location point, a cellular terminal is coupled with a GPS receiver. The coverage area of a cell is mapped by moving around in the presumed area and in its vicinity. More reliable cell modeling is achieved when moving (walking, driving) in the cell area is systematically planned and carried out. Figure 7.1 illustrates the idea of dedicated measurement scans.

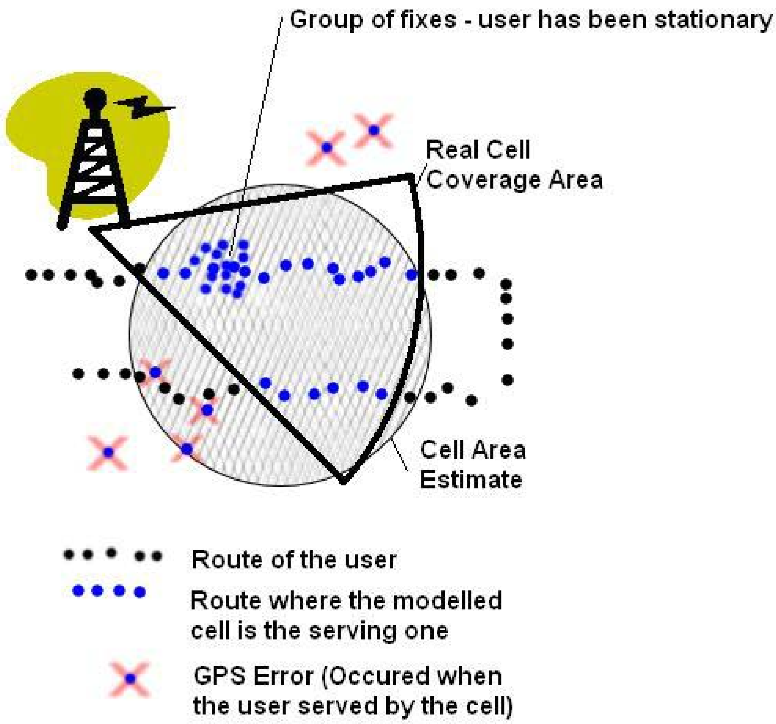

Figure 7.1 Dedicated routes are traveled by foot or by car to cover the cell area properly. GPS errors may distort the cell model but are escaped with a proper algorithm.

7.4.3 Cell Types

When modeling the position and coverage area of a cell, it must be acknowledged that there are cells of many types. Cell coverage area is usually illustrated as a hexagonal, but the real cell coverage varies considerably depending on the base station antenna beam, the terrain, the siting of the cell's antenna, intervening buildings, landmarks, and barriers.

There are *circular cells* and *selective cells* of different shapes of which the most common one is the sectored cell, where coverage is confined to individual 60-deg or 120-deg sectors. *Umbrella cells* cover a larger area as they are intended for fast-moving users to avoid a large number of handovers [Red95].

The maximum cell size is approximately 35 km. The maximum distance between a base station and a mobile is half the maximum burst delay, which is 75.5 km, which yields a limitation on the cell size [Red95]. A typical cell in downtown is significantly smaller than the maximum-sized, the cell range being from tens or hundreds of meters to a few kilometers.

7.4.4 Modeling the Cell Areas

For user, it is not possible to know what type of cell is serving at each moment. Therefore, a model that can represent all types of cells is used. A circle, the simplest model, is an obvious choice to represent a cell coverage or "visibility" area, i.e., the area where the particular cell is usable by the network users.

Two possibilities are considered in modeling a cell coverage area when a collection of data pairs (*GCI, location*) is available for model creation: *circle model* and *probabilistic model*.

Circle Model

Cell area is modeled as a circle which includes all the position fixes observed while the particular cell is the serving cell of the user. The center point of the circle is reported as "the position point" that is associated with the GCI.

Probabilistic Model

The probabilistic model aims to create the most probable position of the user in a specific cell coverage area. Therefore, a sample mean of the position fixes is chosen as the position point and as the center point of the modeled cell circle. Given the entire set of N_{MEAS} (> 1) recorded measurements of the position $\mathbf{x}_i$, the sample mean $\boldsymbol{\mu}_{N_{MEAS}}$ is computed as

$$\boldsymbol{\mu}_{N_{MEAS}} = \frac{1}{N_{MEAS}} \sum_{i=1}^{N_{MEAS}} \mathbf{x}_i \quad . \tag{7.1}$$

When the sample mean is used as an estimate of the expectation value, the unbiased sample covariance $C_{N_{MEAS}}$ is given by

$$\mathbf{C}_{N_{MEAS}} = \frac{1}{N_{MEAS} - 1} \sum_{i=1}^{N_{MEAS}} \left(\mathbf{x}_i - \boldsymbol{\mu}_i\right)\left(\mathbf{x}_i - \boldsymbol{\mu}_i\right)^T . \tag{7.2}$$

A cell coverage area can now be expressed by a setting the cell radius as the CEP_{95} range estimate within which 95% of the fixes are included. (CEP was defined in Section 3.4.4.)

In the circle model, all position fixes contribute to the reported cell size and thus, if a position fix is an erroneous outlier far away from the correct position, it distorts the cell size to be bigger than it really is. In the probabilistic model, the reported cell size is not affected by single outliers. The results in [P2] tell that the probabilistic cell model offers better positioning accuracy.

7.4.5 Memory Consumption

Table 7.1 summarizes how many bits are needed to store parameters of one GSM cell into the database. As shown, the cell can be described completely in less than 43 bytes. One hundred cells would then require 4.3 kilobytes which is a small figure considering that mobile phones are equipped with significant data processing capabilities. Furthermore, one hundred cells would easily cover a medium-sized city center as hinted by the results in [P2].

Table 7.1 The memory consumption of parameters of a single cell.

Cell Parameter	**Memory Consumption (bits)**
MCC	10
MNC	10
LAC	16
CID	16
Cell Model Parameters	< 208
Cell Position (lat, lon)	2 x 32
Cell Position (altitude)	16
Total	**< 340 bits < 43 bytes**

7.4.6 Adjustments to the Algorithms

Several problematic conditions can occur during database formation. A part of these conditions can be accounted for by minor changes in the cell modeling algorithm.

Problems Related to Network: Mobile Cells

There are “mobile” cells, which are transported to an area requiring extra network capacity, e.g., a rock concert in a stadium. In addition, network cells can be placed on mobile location, e.g., trains. Thus, any particular position cannot be associated with a cell, or at least significantly larger uncertainty area must be modeled.

Problems Related to Network: Changing Cell Identities

Network operator can change cell identities of network cells when the network is re-organized for administrational or other reasons. Therefore, continuous updating of the databases is required.

Users, who are equipped with GPS receivers, can participate in database updating, e.g., by sending their database collections to the third party who in turn maintains a database server or such.

Problems Related to User Mobility: Stationary User

If the user remains stationary for long periods of time while he is logging data for the database creation, then there will be a lot of data with essentially the same information (same position, same GCI). Thus, the distribution of the data is concentrated in one place. If the probabilistic model is used, this results in a distorted cell model, meaning that the cell is modeled to be smaller than it really is and possibly centered biasedly.

The obvious solution is to recognize the instants when the user is not moving, and omit the database updating for those time instants. The recognition of movement requires velocity information which is usually available from a GPS receiver.

Yet another enhancement is to "freeze" the updating parameter to some predetermined threshold value, so that it does not grow too large, even if the user remains stationary for long periods of time (and the real number of updates keeps growing), e.g. as follows

$$N_{MEAS,\,freezed} = \begin{cases} N_{MEAS}, & N_{MEAS} < 100 \\ 100, & N_{MEAS} \geq 100 \end{cases}. \tag{7.3}$$

If the updating parameter is too large, the following updates are nearly negligible in the probabilistic model, as it can be understood from Eqn. (7.2).

Problems Related to User Mobility: Variant Velocity of the User

If the GPS receiver logs the fixes of the user with constant time intervals, the speed of the user determines the geometrical distance between adjacent logged fixes. Obviously, the greater the speed of the user, the longer the distance between fixes. On the other hand, if the user is moving slowly, then the adjacent fixes are close to each other. If the user travels first, e.g., by car and then switches to walking while still in the same cell coverage area, there are fewer fixes from the car-driven path than from the walked path. Thus, the cell area that is walked through is emphasized in the cell modeling vs. the area that was driven through. Therefore, the velocity of the user must be used as an adjusting parameter in the cell updating algorithm.

A simple solution to do this velocity-adjustment would be to skip (some of the) fixes as the speed is decreased and to use only every second, third, or fourth fix to update the cell. In other words: the cell estimate is updated only when “necessary”, and the speed of the user is used to determine when the update is necessary.

Another possibility to adjust cell updating is to weight the updating parameter N_{MEAS} by the speed of the user:

$$N_{MEAS,WEIGHTED} = h\left(N_{MEAS}, \|\dot{\mathbf{x}}\|\right) \tag{7.4}$$

After weighting function, the parameter $N_{MEAS,WEIGHTED}$ is no longer equal to the number of measurements. The bigger the $N_{MEAS,WEIGHTED}$, the smaller the effect of each new update, and thus the weighting could be, e.g.

$$h\left(N_{MEAS}, \|\dot{\mathbf{x}}\|\right) = \frac{N_{MEAS}}{\|\dot{\mathbf{x}}\|}. \tag{7.5}$$

This makes the parameter $N_{MEAS,WEIGHTED}$ smaller, when the speed of the user increases.

In Case the Serving Cell is not in the Database: Neighbor Cells, Previous Cell

Neighbor cells are those around the serving cell, which are, in addition to the serving cell, also “visible” to the mobile phone, but are not used currently. It is possible to log the Global Cell Identities of the neighbor cells as well as the one of the serving cell. Therefore, the respective locations of the neighbor cells are available (as long as these cells are found in the database). In the field tests, it was tried to weight the position estimate of the cell center to the direction of the neighbor cells. However, this did not have a positive effect to the accuracy. It is concluded that the accuracy of the serving cell location is indeed dominating, and neighbor cells do not bring enough information to make this location estimate better. However, neighbor cells can have a crucial significance if the currently serving cell is not found in the database, but one or more neighbor cells are. In a similar fashion, previous serving cell can be used. If the current serving cell is not found in the database, the previous serving cell still leads to a reasonable estimate about the user location.

In Case the Serving Cell is not in the Database: LAC Database

In case the serving cell is not found in the database, nor any of its neighbors are, a position estimate can be given that is based on the LAC of the cell. *LAC database* would obviously provide a much worse accuracy than a database utilizing the complete GCI. However, an estimate with some accuracy is better than nothing. As there are tens or hundreds of cells in one location area and, therefore, they share the Location Area Code, the worst-case accuracy of the estimate would be tens of kilometers.

7.4.7 Obtained Accuracy

The results of the test runs are presented in [P2] and [Sai05]. The obtained median accuracy is 86 meters at its best and the average accuracy is between 100-300 meters. This is surely enough for position confirmation and even for independent positioning. However, the field tests were carried out only in city areas where the network is dense. In rural areas, the accuracy would be 1-10 kilometers, which would be sufficient for reference position accuracy. Similar results would be obtained in other European GSM networks as well. Although the urban accuracy is delightfully good, the theoretical accuracy of a cell ID-based method would be even better. This is due to the fact the nearest base station is not always the serving one. Again, the described situation occurs typically in city areas, where the network is dense.

The database method is an extremely reliable positioning method as long as the database is up to date and the user in network coverage area. Given these, there are no error sources or biases affecting the positioning accuracy or availability.

8 Summary of Publications

In this Chapter, the research problem is defined. This research problem has been addressed in seven publications, which are summarized and categorized. Finally, the author's contribution to each publication is specified.

8.1 Problem Formulation

The main objective of the thesis is to find *novel methods for error detection in satellite navigation* which are outside of the traditional approach of fault detection and isolation (FDI) methods or RAIM (receiver autonomous integrity monitoring) methods which use data self-redundancy tests. The methods should

- consider all factors affecting the positioning accuracy,
- be appropriate in personal satellite navigation, and
- provide new information which can be used in improving positioning accuracy.

Fault detection is closely related to the problem of finding error-causing signals. *Selective combining* is the task of selecting the satellite subset in the best possible way. The decision-making process in selective combining is not a trivial task of "just choosing the best signals". Instead, controversy is met and trade-offs must be made while searching for the "optimal" selection (and what is "optimal" is to be defined).

Selective combining aims to provide the best accuracy available with the currently visible satellite signal set. Accuracy is affected by two factors: geometry of the selected satellite subset and the satellite signal errors. The combination of the two is complex. As pointed out in [Cha94] in a slightly different context, "attempting to legislate an optimal solution is like declaring π to be 3 – makes computations easier but does not result in trustworthy outcome".

Many fault detection methods are methods of comparison between subsets. This results in high computational burden as there are many possible satellite combinations and that, inevitably, the

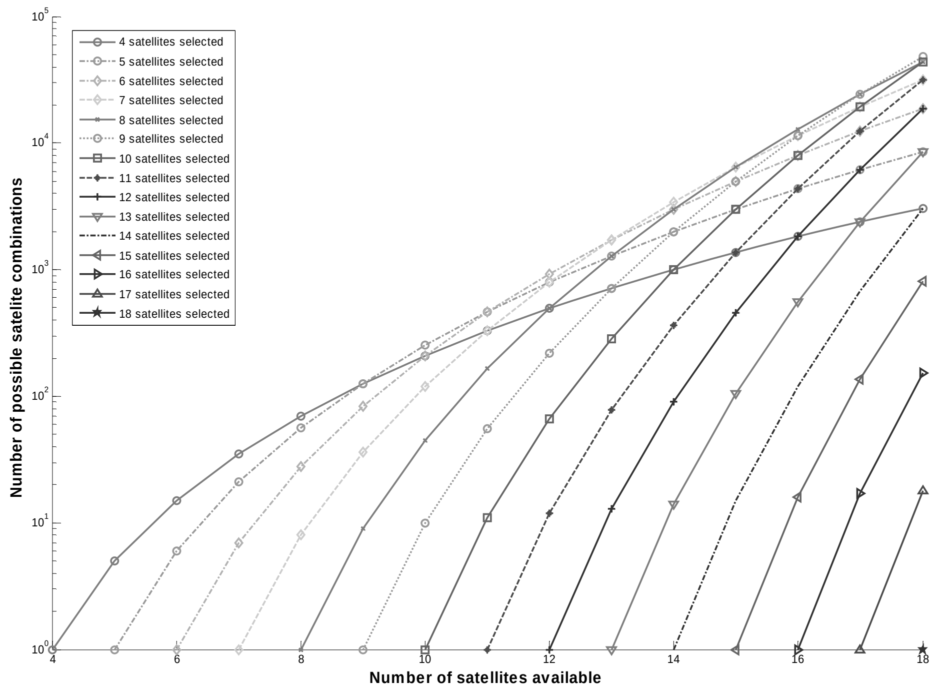

Figure 8.1 Number of possible satellite combinations increases rapidly as the number of satellites increases.

number of operands is high. In the future, there are even more satellites and more possible combinations, when GALILEO is operational. For example, if there are 12 visible satellites, there are nearly 800 combinations to select 8-12 satellites (up to four erroneous satellite signals may easily occur in urban environments). The increasing number of possible combinations is illustrated in Fig. 8.1. In [Par01], even a suboptimal method for subset selection is proposed where processing time is saved.

The motivation for integrity monitoring, or selective combining, in personal positioning arises from the user segment. Satellite navigation is exposed to interfering signals and severe signal degradations in urban environment: multipath, signal reflections, and signal attenuations due to constructions and foliage are common. Indoor positioning is another, yet more challenging, urban positioning platform. The signal noise levels of the received signals vary greatly in these environments, especially when high-sensitivity receivers, with lower acquisition thresholds, are used (with conventional receivers the low-powered signals are just not received). However, the enhanced sensitivity is a necessity under the conditions of the described urban environment [Dig02]. Thus, the objective is to find novel approaches which account for these special features of personal satellite navigation. These novel methods can be used in complementary fashion with the more traditional approaches.

The objective has been approached from four different directions:

- satellite signal condition analysis,
- satellite subset condition analysis,
- environment information gathering, and
- utilization of cellular connection.

The developed methods are presented in the Part II of this compound thesis, which consists of seven publications. The author is the main author of six publications and an equal co-author (out of two) in the Publication [P4].

8.2 Categorization of the Publications

8.2.1 Generally on Selective Combining

The Publication [P1] presents a tutorial on the methods available for user-level selection of the satellite signals. The article introduces selective combining, starting from the past framework of satellite navigation, and continues by explaining how selective combining is tightly coupled with integrity monitoring within the GNSS system. After this, the methods are categorized and briefly presented. The methods include different algorithms and various data parameters and computed parameters.

8.2.2 The KDOP Method

The KDOP method is addressed in the Publications [P3] and [P4], which are elaborated on the following. In addition to these, the KDOP method is mentioned also in [P5].

The Publication [P3] proposes a weighed geometry measure for satellite fault detection task. In this article, two different versions of weighted DOP are formed, KDOP and WDOP. WDOP is proved monotonically decreasing and KDOP non-monotonic in respect of the number of satellites. The non-monotonicity of KDOP is exploited in the proposed exclusion method. The exclusion method does not require any artificial rejection threshold to be created. Using real GPS data, the proposed exclusion method was tested in Matlab simulations. The results state that the proposed method can reduce the positioning error and/or computational load of the receiver.

In the Publication [P4], the combined performance of two different user-level integrity-monitoring methods is analyzed. A FDI method based on the traditional least-squares residuals RAIM and the KDOP method are presented. The principles of the FDI method and KDOP isolation are compared, and their combined performance is studied through real-life navigation tests analyzed in a Matlab environment. The results indicate that the FDI method and KDOP isolation detect different error situations and, therefore, they complement each other as user-level integrity control methods for personal satellite positioning.

8.2.3 On Integrity Monitoring

Monitoring GPS integrity is mainly about finding the possibly error causing signals, and then deciding about further actions in position computation. Integrity monitoring has been addressed in the Publications [P5] and [P7].

In the Publication [P5], a sequential approach to integrity monitoring is proposed. In this method, different checks form a method that was named multiple level integrity monitoring, which includes both signal condition checks and verification of satellite combination geometry. The proposed procedure is the following: First, signals that are very likely, if not certainly, erroneous are excluded. Then, if geometry is acceptable, weighted positioning is carried out. The proposed method presents novelty especially by proposing an angle value check for ephemeris data verification in assisted GPS.

In the Publication [P7], an expert system for GPS signal integrity reasoning is created. This expert system reasons the level of integrity of the received pseudorange signals as seen by the GPS receiver. The reasoning is accomplished by the Dempster-Shafer theory. For the sake of comparison, a reasoning system applying Bayesian theory is also created. The presented approach gives qualitative information about the integrity of the pseudoranges before they are used in the position solution. This approach does not need refined or preprocessed information to determine integrity. Measurement redundancy is not needed as in RAIM. Integrity reasoning is based on data that is always, or at least usually, available from the received satellite signals. The reasoning system was implemented using Matlab. The results for pseudorange signal integrity were plausible. They state that the expert system gives refined information about the integrity level of signals and this information can be used for weighting the pseudorange measurements or picking the good and the bad satellites.

8.2.4 On Environment Detection

The Publication [P6] presents a method for detecting the GPS receiver environment. The objective was to recognize structural characteristics of the receiver environment in a manner that would alleviate the recognition of the location. The information about the receiver environment is useful in detection of multipath conditions and, for instance, in emergency call positioning, when position information is vague. The basic idea of the environment detection is the comparison between the a priori information about the satellites and the currently visible satellites. Based on this idea and using the Dempster-Shafer theory, a reasoning system was developed, and tested with real data. The results state that the obtained information about the receiver environment does not describe the environment in detail, but the obtained information about the environment was correct: the characteristics of the simulation locations were detected.

8.2.5 The Role of Cellular Network in Integrity Monitoring

The Publication [P2] presents a method for creation of cellular information databases, where Global Cell Identities (GCIs) are associated with position information. The data pairs (GCI, position) are organized in a database, which is then used for positioning. Methods for creating and updating such databases are presented. The Publication [P2] describes field tests carried out with a cellular phone connected to a GPS receiver. First, a database is created with dedicated measurement scans and then the created database is tested in positioning. According to analyzed field test data, the obtained accuracy is 100-300 meters in city areas. In addition to independent positioning, the presented database method is suitable for coarse integrity monitoring and for obtaining referential position to support satellite positioning.

8.3 Author’s Contribution to the Published Work

In the following, the author’s contribution to the published work is clarified per publication. There are seven publications and the author has acted as the main author of six of them. The co-authors have seen these descriptions and agree with the author. None of the publications have been used as a part of another persons’ academic thesis or dissertation.

Publication [P1]: The idea of a tutorial on selective combining was author’s. The author received valuable comments by J. Takala which resulted in significant improvements in the manuscript. The author’s contribution includes an up-to-date survey on all existing integrity monitoring methods on user level in satellite positioning. A similar study has not been published in previous work. The work presents a novel categorization of the methods which helps the reader to familiarize himself with the topic in an unforeseen fashion.

Publication [P2]: The presented research was a joint effort of the authors and carried out at Nokia Technology Platforms. The author's contribution includes

- further development of the algorithms (which already existed) related to cell modeling and database construction. Implementation of them with Matlab and C-language,
- the further development included the solutions to problems in the database formation caused by stationary user and by variant velocity of the user,
- analysis of positioning accuracy and availability of the created database method. This included adjustments to the algorithms in a form of cell limits, neighbor cell weighting, and time averaging methods,
- active participation to field testing,
- analysis of the collected data and the obtained results, and
- the manuscript.

P. Syrjärinne's contribution includes:

- preliminary studies and planning of the approach,
- the original algorithms in cell modeling, and implementations of them,
- further development of the cell models,
- analysis of the obtained results,
- active participation in field testing, and
- valuable comments on the manuscript.

Publication [P3]: The original ideas were created in interaction with the author and D. Akopian in discussions. J. Takala gave vitally valuable comments on the manuscript. The author

- created the algorithm,
- tested the algorithm with real data,
- analyzed the results,

- wrote the proof of WDOP monotonicity after a correspondence with D.Akopian, and
- wrote the publication of which she received invaluable comments from the co-authors D. Akopian and J. Takala.

Publication [P4]: This publication was a joint effort by the author and H. Kuusniemi. The contribution of the author and H. Kuusniemi was equally important. In [P4], two methods were combined. The combined methods were the KDOP method and the adjusted FDI, which were developed by the author and H. Kuusniemi, respectively. The author

- developed the KDOP method,
- planned and carried out the combination of the algorithms with H. Kuusniemi,
- tested the resulting new error detection method with real data in co-operation with the co-author, and
- wrote the respective parts of the publication.

Publication [P5]: The co-authors J. Syrjärinne and J. Takala gave invaluable comments on the manuscript. The author’s contribution includes

- the original idea of using sequential approach to integrity monitoring,
- using differences of adjacent values of observables to error detection, and
- the manuscript.

Publication [P6]: The original idea of studying environment detection was given by J. Syrjärinne. Similar study has not been published elsewhere. The co-authors J. Syrjärinne and J. Takala gave invaluable comments of the manuscript. The author

- took the idea further by generating all the related algorithms,
- created the test scenarios,
- implemented and tested the algorithms with real data,
- analyzed the results, and
- wrote the manuscript.

Publication [P7]: The original approach of using data fusion methods in integrity monitoring was proposed by J. Syrjärinne. Valuable comments on the manuscript were received from J. Syrjärinne, H. Leppäkoski, and J. Saarinen. The author's contribution includes

- specifying how to use the Bayes and Dempster-Shafer algorithms in the context,
- further study and implementation of the Bayesian and Dempster-Shafer algorithms,
- testing of the method,
- analysis of the results, and
- the writing of the manuscript.

9 Conclusions

In the concluding paragraph of this thesis, the significance of the work is addressed, and a few proposals for the future development of error detection in personal positioning are given.

9.1 Main Results

The main contributions of the presented work are the following:

- The weighted DOP a.k.a. KDOP satellite exclusion method,
- a probabilistic method for environment detection with GPS, and
- a database method for position confirmation and independent cellular positioning.

The KDOP method was introduced by the author to be used as a fault detection method that combines signal health indicators and a consideration for the satellite geometry. The method presents novelty in its nature as the combination of the two aspects, signal condition and subset geometry, has not been combined in similar fashion in previous work. A related contribution is that it was proved that the other weighed (WLS-) DOP measure or WDOP is monotonically decreasing, which means that it cannot be used for satellite exclusion tasks in a similar fashion that KDOP can.

The study on environment detection also presents novelty in its approach by setting a goal to find information about the characteristics of receiver environment from GPS signals. Similar study has not been published elsewhere. The environment of the receiver was divided into sectors, and the blocking degree of each sector was analyzed with probabilistic methods. The results state that although the detection of the environment remains non-descriptive, the approach succeeds in bringing new information about the receiver environment, and this information can be used to support decision-making in different tasks of the receiver.

Lastly, the presented cellular database positioning method is suitable for coarse integrity monitoring, for obtaining referential position in satellite positioning, and for constraining the position estimation which results in smaller number of iteration rounds. The method is also valid for independent cellular positioning. From the error-detection point-of-view, the database method is a novel approach as it combines cellular and satellite navigation data, and supports error-detection with cellular connection.

9.2 Future Recommendations

Discarding an acquired, tracked, and data-decoded satellite signal is an expensive decision to make when the performance of a GPS receiver is the currency. Therefore, the benefits of selective combination methods should be studied thoroughly to prove their value. GALILEO will make the scene different with the new 30 satellites. Then, even under the most difficult positioning conditions, there are on the average (at least in theory) twice as many chances to acquire a satellite signal as there are today. Thus, the decision to discard a satellite could be made at a lesser cost.

Now that GALILEO is still on its way, urban satellite navigation will often provide positioning conditions so severely degraded, that in many cases discarding a satellite signal is not an acceptable choice. This issue has been brought up also in [Kap05]. Therefore, weighting of the signals according to their error contribution is the remaining option in order to minimize the error. This means that careful modeling of the pseudorange errors is required. Kalman filtering, which is widely used in satellite navigation, benefits from careful weight/error modeling.

When considering the further development of the methods of selective combination, the secret is in the fusion of signal condition and geometry analysis. The topic has been addressed in this thesis via the KDOP approach, and also in previous work (weighted RAIM in [Wal95], and more recently in [Bro05a]). However, the topic should be taken further by making realistic signal condition/geometry scenarios of personal positioning, and testing the methods to find a fitting model of pseudorange error. In previous work, unrealistic and artificial assumptions have been made about the signal errors, and then the fault detection algorithms have been tested with these assumptions. This mistake was made by the author in the research presented in [P5] and [P7] since, e.g., the errors induced by the broadcast-URA and -DOE are very rare. It is simple to discard signals which have been flagged to be invalid. In addition, after discarding them, all the real problems remain. To summarize what is needed to develop fault detection methods further is to create better error models of the combined signal condition / geometry conditions. A similar recommendation has been given in [Bel05].

Besides GALILEO, another giant-step for personal GNSS positioning is the close co-operation of cellular networks and the receiver. Network assistance provides support for the receiver in the most crucial tasks, all reducing the time to first fix. The proposed method of cellular databases offers a simple yet effective way to provide a reliable reference position immediately or with short latency. However, the role of cellular networks in error detection could be taken a lot further by setting the network connection as a channel for differential corrections and other integrity/error correction data, as it has been already proposed in the cellular AGPS standards.

Bibliography

[Aho03] Ahonen, S., Laitinen, H. Database Correlation Method for UMTS Location. In *Proc. 57th IEEE Semiannual Vehicular Technology Conference.* Vol. 4. Jeju, South Korea, April 22-25, 2003. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2003. pp. 2696 - 2700.

[Ako02] Akopian, D., Syrjärinne, J. A Network Aided Iterated LS Method for GPS Positioning and Time Recovery without Navigation Message Decoding. In *Proc. IEEE Position Location and Navigation Symposium IEEE PLANS 2002.* Palm Springs, CA, April 15-18, 2002. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2002. pp. 77 – 84.

[Ako06] Akopian, D. Private correspondence. January, 2006.

[Axe96] Axelrad, P., Comp, C.J., Macdoran, P.F. SNR-based multipath error correction for GPS differential phase. *IEEE Transactions on Aerospace and Electronic Systems.* 32(2), 1996. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1996. pp. 650 – 660.

[Bel05] Belabbas, B., Gass, F. RAIM Algorithms Analysis for a Combined GPS/GALILEO Constellation. In *Proc. ION GNSS 2005.* Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 1781-1788.

[Bes95] Beser, J., Balendra, J., Erpelding, E., Kim, S. Differential GLONASS, Differential GPS and lntegrated Differential GLONASS/GPS - Initial Result. In *Proc. ION GPS 1995*. Palm Springs, CA; Sept. 12-15, 1995. Fairfax, VA: Institute of Navigation, 1995. pp. 507-515.

[Bra99] Braasch, M.S., van Dierendock, A.J. GPS Receiver Architectures and Measurements. *Proceedings of the IEEE.* 87(1), 1999. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1999. pp. 48-64.

[Bra01] Braash, M.S. Performance comparison of multipath mitigating receiver architectures. *IEEE Proceedings of Aerospace Conference 2001*. Vol. 3. Big Sky, MT, March 10-17, 2001. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2001. pp. 1309 - 1315.

[Bre05] Brenner, J., Di Cintio, A., Genghi, A. Keeping a Stand-Alone Receiver on the Road in Hard Urban Environment. In *Proc. ION GNSS 2005*. Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 2649-2660.

[Bro04] Broughton, D. GNSS - A Users' Perspective in 2010. In *IEEE Proc. 46th International Symposium Electronics in Marine ELMAR 2004*. Zagreb, Croatia, June 16-18, 2004. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2004. pp. 1-4.

[Bro86] Brown, R.G., Hwang, P.Y.C. GPS Failure Detection by Autonomous Means Within the Cockpit. In *Proc. ION AM 1986*. Seattle, WA. June 24-26, 1986. Fairfax, VA: Institute of Navigation, 1986. pp. 5-12.

[Bro92] Brown, R.G. A Baseline GPS RAIM Scheme and a Note on the Equivalence of Three RAIM Methods. *Navigation*. 39(3), 1992. Fairfax, VA: Institute of Navigation, 1992. pp. 301-316.

[Bro97] Brown, R.G., Hwang, P.Y.C. *Introduction to Random Signal and Applied Kalman Filtering with Matlab Exercises and Solutions*. New York NY: John Wiley and Sons. 1997. 461 p.

[Bro05a] Brown, R.G., Hwang, P.Y.C. RAIM FDE Revisited: A New Breakthrough In Availability Performance With NIORAIM (Novel Integrity-Optimized RAIM). In *Proc. ION NTM 2005*. San Diego, CA, Jan 24-26, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 654-665.

[Bro05b] Brown, R.G., Hwang, P.Y.C. NIORAIM Integrity Monitoring Performance In Simultaneous Two-Fault Satellite Scenarios. In *Proc. ION GNSS 2005*. Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 1760-1771.

[Cha94] Chaffee, J., Abel, J. GDOP and the Cramer-Rao Bound. In *Proc. IEEE Position, Location, and Navigation Symposium*. Las Vegas, NV, April 11-15, 1994. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1994. pp. 663 – 668.

[Che03] Chen, R., Toran-Marti, F., Ventura-Traveset, J. Access to the EGNOS Signal in Space Over Mobile-IP. *GPS Solutions*. 7(1), 2003. Berlin, Germany: Springer-Verlag, 2003. pp. 16-22.

[Chi04] Chin-Der, W., Ming-Hui, L. Data Fusion Methods for Accuracy Improvement in Wireless Location Systems. In *Proc. IEEE Wireless Communications and Networking Conference WCNC*. Vol. 1. Atlanta, GA, March 21-25, 2004. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2004. pp. 471-476.

[Col03] Collin, J., Mezentsev, O., Lachapelle. G. Indoor Positioning System Using Accelerometry and High Accuracy Heading Sensors. In *Proc. ION GPS 2003*. Portland, OR, Sept. 9-12, 2003. Fairfax, VA: Institute of Navigation, 2003. pp. 1164-1170.

[Col06] Collin, J. *Investigations of Self-Contained Sensors for Personal Navigation*. Dissertation. Tampere, Finland: Tampere University of Technology, 2006.186 p.

[Con05] Constantinescu, A., Landry, R.Jr. GPS/GALILEO/GLONASS Hybrid Satellite Constellation Simulator, GPS Constellation Validation and Analysis. In *Proc. ION AM 2005*. Cambridge, MA, June 27-29, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 733-744.

[Cou99] Counselman, C.C., III. Multipath-rejecting GPS antennas. *Proceedings of the IEEE*. 87(1), 1999. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1999. pp. 86 – 91.

[Dem67] Dempster, A.P. Upper and Lower Probabilities Induced by a Multivalued Mapping. Annals of Mathematical Statistics. 38, 1967. Beachwood, OH: Institute of Mathematical Statistics, 1967. pp. 325-329.

[Dem68] Dempster, A.P. A Generalization of Bayesian Inference. Journal of the Royal Statistical Society. Series B, 30(2), 1968. London, UK: The Royal Statistical Society, 1968. pp. 205-247.

[Dig01] van Diggelen, F. Global Locate Indoor GPS Chipset & Services. In *Proc. ION GPS 2001*. Salt Lake City, UT, Sept. 11-14, 2001. Fairfax, VA: Institute of Navigation, 2005. pp. 1515-1521.

[Dig02] van Diggelen, F. Indoor GPS theory & implementation. In *Proc. IEEE Position Location and Navigation Symposium*. Palm Springs, CA, April 15-18, 2002. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2002. pp. 240 - 247.

[Dov04] Dovis, F., Pini, M., Mulassano, P. Multiple DLL architecture for multipath recovery in navigation receivers. In *Proc. IEEE 59th Vehicular Technology Conference*. Vol. 5. Milan, Italy, May 17-19, 2004. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2004. pp. 2848 – 2851.

[Ets05a] ETSI TS 144 031, V6.8.0, Digital cellular telecommunications system (Phase 2+); Location Services (LCS); Mobile Station (MS) – Serving Mobile Location Centre (SMLC) Radio Resource LCS Protocol (RRLP), 2005.

[Ets05b] ETSI TS 144 035, V6.0.0, Digital cellular telecommunications system (Phase 2+); Location Services (LCS); Broadcast network assistance for Enhanced Observed Time Difference (E-OTD) and Global Positioning System (GPS) positioning methods, 2005.

[Ets06] ETSI TS 125 331, V7.2.0, Universal Mobile Telecommunications System (UMTS); Radio Resource Control (RRC), Protocol Specification, 2006.

[FAA05] FAA (Federal Aviation Administration) Satellite Navigation Library. SatNav News, Spring/Summer 2005. Available at http://gps.faa.gov/Library , on 13th January, 2006.

[Far99] Farrell, J., Barth, M. *The Global Positioning System and Inertial Navigation*. New York, NY: McGraw-Hill, 1999. 340 p.

[Fre73] Frenkel, G. Geometric Dilution of Precision (GDOP) in Position Determination Through Radio Signals. *Proceedings of the IEEE*. 61(4), 1973. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1973. pp. 496-497.

[Gal05] GALILEO Web Page, European Commision, Energy and Transport.Available at: http://europa.eu.int/comm/dgs/energy_transport/galileo/index_en.htm, on 16th January 2006.

[Gle05] Glennon, E.P., Bryant, R.C. Solution of Timing Errors for AGPS. In *Proc. ION GNSS 2005*. Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 136-141.

[Glo88] *Global Positioning System, Papers published in NAVIGATION. Red Book on RAIM.* Volume V. Alexandria, VA: The Institute of Navigation. 1988. 380 pages.

[Glo05] Current GLONASS Constellation, Coordinational Scientific Information Center, Russian Ministry of Defence. Available at http://www.glonass-ianc.rsa.ru/pls/htmldb/f?p=202:1:352199159053339417::NO, on 27th October, 2006.

[Gol67] Gold, R. Optimal binary sequences for spread spectrum multiplexing. *IEEE Information Theory*. 13(4), 1967. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1961. pp. 619-621.

[Gol98] Goldhirsg, J., Vogel, W.J. *Handbook of Propagation Effects for Vehicular and Personal Mobile Satellite Systems.* The Johns Hopkins University, Applied Physics Laboratory, 1998.

[GPS06] Current GPS Constellation, U.S. Naval Observatory, available at http://tycho.usno.navy.mil/gpscurr.html, on 4th October, 2006.

[Gro05] Groves, P.D. GPS Signal to Noise Measurement in Weak Signal and High Interference Environments. In *Proc. ION GNSS 2005.* Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 643-658.

[Hof01] Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J. *GPS, Theory and Practice.* 5th ed. Wien: Springer, 2001. 382 p.

[Hop69] Hopfield, H.S. Two-quartic tropospheric refractivity profile for correcting satellite data. *Journal of Geophysical Research.* 74(18), 1969. Washington, DC: American Geophysical Union, 1969. pp. 4487-4499.

[How05] Howe, D.A, Beard, R.L., Greenhall, C.A., Vernotte, F., Riley, W.J., Peppler, T.K. Enhancements to GPS operations and clock evaluations using a “total” Hadamard deviation. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*. 52(8), 2005. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2005. pp. 1253 – 1261.

[Hsu94] Hsu, D.Y. Relations Between Dilutions of Precision and Volume of the Tetrahedron Formed by Four Satellites. In *Proc. IEEE Position Location and Navigation Symposium*. Las Vegas, NV, April 11-15, 1994. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1994. pp. 669 – 676.

[Ins06] Webpage of the Institute of Geodesy and Navigation, University FAF Münich, available at http://www.ifen.unibw-muenchen.de/research/index.htm on 27th October, 2006.

[Jan97] Jang, J.-S.R., Sun, C.-T., Mizutani, E. *Neuro-Fuzzy and Soft Computing.* Upper Saddle River, NJ: Prentice Hall. 1997. 614 pages.

[Jan00] Jang, C.-W., Juang, J.-C., Kung, F.-C. Adaptive fault detection in real-time GPS positioning. *IEE Radar Sonar Navigation.* 147(5), 2000. London, UK: Institution of Electrical Engineers, 2000. pp. 254-258.

[Kap96] Kaplan, E.D. (ed). *Understanding GPS, Principles and Applications*. Boston: Artech House, 1996. 554 p.

[Kap05] Kaplan, E.D., Hegarty, C. J. *Understanding GPS, Principles and Applications*. 2nd edition. Boston: Artech House, 2005. 703 p.

[Kih84] Kihara, M., Okada, T. A Satellite Selection Method and Accuracy for Global Positioning System. *Navigation.* 31(1), 1984. Fairfax, VA: Institution of Navigation, 1984. pp. 8-20.

[Kih94] Kihara, M. Study of a GPS satellite selection policy to improve positioning accuracy. *Proc. IEEE Position, Location, and Navigation Symposium.* Las Vegas, NV, April 11-15, 1994. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1994. pp. 267-273.

[Kra90] Krakiwsky, E.J. *The Method of Least Squares: A Synthesis of Advances.* Calgary, AL: The University of Calgary, 1990. 115 p.

[Kuu05] Kuusniemi, H. *User-Level Reliability and Quality Monitoring in Satellite-Based Personal Navigation.* Dissertation. Tampere, Finland: Tampere University of Technology, 2005. 180 p.

[Lac03] Lachapelle, G., Kuusniemi, H., Dao, D., MacGougan, G., Cannon, M.E. HSGPS Signal Analysis and Performance Under Various Indoor Conditions. *In Proc. GPS 2003*. Portland, OR, 9-12 September, 2003. Fairfax, VA: The Institute of Navigation, 2003. pp. 1171-1184

[Lai01] Laitinen, H., Lähteenmäki, J., Nordström, T. Database correlation method for GSM location. In *Proc. IEEE VTC 53rd Vehicular Technology Conference.* Vol. 4. Rhodes, Greece, May 6-9, 2001. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2001. pp. 2504 – 2508.

[LaM02] LaMance, J., DeSalas, J., Järvinen, J. Assisted GPS: A Low-Infrastructure Approach. *GPS World Magazine*. 13(3), 2002. Eugene, OR: Questex Media Group, Inc., 2002. pp. 46-51.

[Lan99] Langley, R.B. The Integrity of GPS. *GPS World Magazine*. 10(6), 1999. Eugene, OR: Questex Media Group, Inc., 1999. pp. 60-63.

[Lee75a] Lee, H.B. A Novel Procedure For Assessing The Accuracy of Hyperbolic Multilaterition Systems. *IEEE Transactions Aerospace and Electronic Systems.* 11(1), 1975. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1975. pp. 2-15.

[Lee75b] Lee, H.B. Accuracy Limitations of Hyperbolic Multilaterition Systems. *IEEE Transactions Aerospace and Electronic Systems.* 11(1), 1975. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1975. pp. 16-29.

[Lee86] Lee, Y.C. Analysis of Range and Position Comparison Methods as a Means to Provide GPS Integrity in the User Receiver. In *Proc. ION AM 1986.* Seattle, WA, June 24-26, 1986. Fairfax, VA: Institute of Navigation, 1986. pp. 5-12.

[Lee02] Lee, Y.C., van Dyke, K.L. Analysis Performed in Support of the Ad-Hoc Working Group of RTCA SC-159 on RAIM/FDE Issues. *Proc. ION NTM 2002.* San Diego, CA, Jan. 28-30, 2002. Fairfax, VA: Institute of Navigation, 2002. pp. 639-654.

[Lee05] Lee, Y.C., Braff, R., Fernow, J. P., Hashemi, D., McLaughlin, M.P., O'Laughlin, D. GPS and Galileo with RAIM or WAAS for Vertically Guided Approaches. In *Proc. ION GNSS 2005*. Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 1801-1825.

[Lep06] Leppäkoski, H., Kuusniemi, H., Takala, J. RAIM and Complementary Kalman Filtering for GNSS Reliability Enhancement. *Proc. IEEE Position Location and Navigation Conference PLANS 2006.* San Jose, CA, April 25-28, 2006. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2006, pp. 948-956.

[Lev94] Leva, J.L. Relationship between Navigation Vertical Error, VDOP, and Pseudo-range Error in GPS. *IEEE Trans. Aerospace and Electronic Systems.* 30(4), 1994. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1994. pp. 1138-1142.

[Lóp05] López-Risueño, G., Seco-Granados, G. C/No Estimation and Near-Far Mitigation for GNSS Indoor Receivers. In *Proc. 61st IEEE Vehicular Technology Conference*. Vol.

4. Stockholm, Sweden, 30 May-1 June, 2005. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2005. pp. 2624-2628.

[Mac05] Macabiau, C., Gerfault, B., Nikiforov, I., Fillatre, L., Roturier, B., Chatre, E., Raimondi, M., Escher, A.-C. RAIM Performance in Presence of Multiple Range Failures. In *Proc. ION NTM 2005.* San Diego, CA, Jan 24-26, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 779-791.

[Mad01] Madhani, P.H., Axelrad, P. Mitigation of the Near-Far Problem by Successive Interference Cancellation. In *Proc. ION GPS 2001.* Salt Lake City, UT, Sept. 11-14, 2001. Fairfax, VA: Institute of Navigation, 2001. pp. 148-154.

[Mal97] Malys, S., Larezos, M., Gottshalk, S., Mobbs, S., Winn, B., Feess, W., Menn, M., Swift, E., Merrigan, M., Mathon, W. The GPS Accuracy Improvement Initiative. *Proc. ION GPS 1997.* Kansas City, MO; Sept. 16-19, 1997. Fairfax, VA: Institute of Navigation, 1997. p 375-384.

[McK97] McKay, J.B., Pachter, M. Geometry Optimization for GPS Navigation. In *Proc. the 36th IEEE Conference on Decision and Control.* Vol. 5. San Diego, CA, Dec. 10-12, 1997. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1997. pp. 4695-4699.

[Mes99] Messier, G.G., Nielsen, J.S. An Analysis of TOA Based Locations for IS-95 Mobiles. In *Proc. IEEE VTS 50th Vehicular Technology Conference.* Vol. 2. Amsterdam, the Netherlands, Sept. 19-22, 1999. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1999. pp. 1067-1071.

[Mis01] Misra, P., Enge, P. *Global Positioning System; Signals, Measurements, and Performance.* Lincoln, MA; Ganga-Jamuna Press, 2001. 390 p.

[Mis91] Misra, P., Bavliss, E., Lafrey, R., Pratt, M., Hogaboom, R. Integrated Use of GPS and GLONASS in Civil Aviation Navigation II: Experience With GLONASS. In *Proc. ION GPS 1991.* Albuquerque, NM, Sept. 11-13, 1991. Fairfax, VA: Institute of Navigation, 1991. pp. 321- 331

[Mor99] Moreau, M. Axelrad, P., Garrison, J., Kelbel, D., Long, A. GPS Receiver Architecture and Expected Performance for Autonomous GPS Navigation in Highly Eccentric Orbits. In *Proc. ION AM 1999.* Cambridge, MA, June 28-30, 1999. Fairfax, VA: Institute of Navigation, 1999. pp. 653-665.

[Nar98] Nardi, S., Pachter, M. GPS estimation algorithm using stochastic modeling. In *Proc. the 37th IEEE Conference on Decision and Control*. Vol. 4. Tampa, FL, Dec. 16-18, 1998. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 1998. pp. 4498 – 4502.

[Nav96] *Navstar GPS User Equipment Introduction*. Public Release Version. September 1996.

[Nav00] Navstar GPS Interface Control Document, ICD-GPS-200C. Available at: http://www.navcen.uscg.gov/ftp/policy/icd200/icd200cw1234.pdf, on 6th December, 2005.

[Nik05] Nikiforov, I., Roturier, B. Advanced RAIM Algorithms: First Results. In *Proc. ION GNSS 2005*. Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 1789-1800.

[Nun05] Nunes, F.D., Sousa, F. Leit, J. Improving Multipath Mitigation in GPS/Galileo BOC Signals with Gating Functions. In *Proc. ION AM 2005*. Cambridge, MA, June 27-29, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 498-507.

[Obe96] Ober, P.B. *Integrity Monitoring*. Information Paper. Delft: Delft University of Technology, 1996. 81 p.

[Obe99] Ober, P.B. Towards High Integrity Positioning. In *Proc. ION GPS 1999*. Nashville, TN, Sept. 14-17, 1999. Fairfax, VA: Institute of Navigation, 1999. pp. 2113-2120.

[Och02] Ochieng, W.Y., Sheridan, K.F., Sauer, K., Han, X. An Assessment of the RAIM Performance of a Combined Galileo/GPS Navigation System Using the Marginally Detectable Errors (MDE) Algorithm. *GPS Solutions*. 5(3), 2002. Berlin, Germany: Springer-Verlag, 2002. pp. 42-51.

[Pac03] Pachter, M., Thao, Q.N. An Efficient GPS Position Determination Algorithm. *Navigation*. 50(2), 2003. Fairfax, VA: Institute of Navigation, 2003. pp. 131-142.

[Par96] Park, C., Kim, I., Lee, J.G., Jee, G.-I. A Satellite Selection Criterion Incorporating the Effect of Elevation Angle in GPS Positioning. *Control Eng. Practice*. 4(2), 1996. Oxford, UK: Elsevier. pp. 1741-1746.

[Par01] Park, C.-W., How, J.P. Quasi-optimal Satellite Selection Algorithm for Real-time Applications. In *Proc. ION GPS 2001*. Salt Lake City, UT, Sept. 11-14, 2001. Fairfax, VA: Institute of Navigation, 2001. pp. 3018-3028.

[Par88] Parkinson, B., Axelrad, P. Autonomous GPS Integrity Monitoring Using the Pseudorange Residual. *Navigation.* 35(2), 1988. Fairfax, VA: Institute of Navigation, 1988. pp. 255-274.

[Par96a] Parkinson, B. Spilker, J.J. (eds) *Global Positioning System: Theory and Applications, Volume I*, Washington, DC: American Institute of Aeronautics and Astronautics, Inc., 1996. 793 p.

[Par96b] Parkinson, B. Spilker, J.J. (eds) *Global Positioning System: Theory and Applications, Volume II*, Washington, DC: American Institute of Aeronautics and Astronautics, Inc., 1996. 643 p.

[Pea88] Pearl, J. *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*. San Francisco, CA: Morgan Kaufmann Publishers, Inc, 1988. 552 p.

[Pha01] Phatak, M.S. Recursive method for optimum GPS satellite selection. *IEEE Transactions Aerospace Electronic Systems*. 37(2), 2001. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2001. pp. 751–754.

[Pir05] Píriz, R., Martín-Peiró, B., Romay-Merino, M. The Galileo Constellation Design: A Systematic Approach. In *Proc. ION GNSS 2005*. Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 1296-1306.

[Ray01] Ray, J.K., Cannon, M.E., Fenton, P. GPS code and carrier multipath mitigation using a multiantenna system. *IEEE Transactions on Aerospace and Electronic Systems.* 37(1), 2001. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2001. pp. 183 – 195.

[Red95] Redl, S., Weber, M., Oliphant, M. *An Introduction to GSM.* Norwood, MA: Artech House, 1995. 379 p.

[Riv00] Rivers, M.H. The 2 SOPS User Range Accuracy (URA) Improvement and Broadcast Interfrequency Bias (TGD) Updates. In *Proc. ION GPS 2000*. Salt Lake City, UT, Sept. 19-22, 2000. Fairfax, VA: Institute of Navigation, 2000. pp. 2551-2555.

[Saa73] Saastamoinen, J. Contribution to the Theory of Atmospheric Refraction. *Bulletin Géodésique*. 107, 1973. Berlin, Germany: Springer-Verlag, 1973. pp. 13-34.

[Sai05] Sairo, H., Syrjärinne, P. Creation and Utilization of Cellular Position Information Databases. Submitted to *IEEE Trans. Wireless Communications*, November 2005.

[Sha76] Shafer, G. A *Mathematical Theory of Evidence*. Princeton, NJ: Princeton Univ. Press, 1976. 297 p.

[Sin04] Singh, R., Guainazzo, M., Regazzoni, C. S. Location determination using WLAN in conjunction with GPS network (Global Positioning System). In *Proc. IEEE VTC 59th Vehicular Technology Conference 2004.* Vol. 5. Milan, Italy, May 17-19, 2004. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2004. pp. 2695 – 2699.

[Sko02] Skone, S., El-Gizawy, M., Shrestha, S.M. Space Weather Predictions Service for Safety-Critical GPS Applications. In *Proc. IEEE Position Location and Navigation Symposium*. Palm Springs, CA, April 15-18, 2002. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2002. pp. 156 – 163.

[Spr01] Sprito, M.A. On the accuracy of cellular mobile station location estimation. *IEEE Vehicular Technology*. 50(3), 2001. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2001. pp. 674-685.

[Stu88] Sturza, M.A. Navigation System Integrity Monitoring Using Redundant Measurements. *Navigation.* 35(4), 1988. Fairfax, VA: Institute of Navigation. pp. 483-501.

[Syr01] Syrjärinne, J. *Studies on Modern Techniques for Personal Positioning*. Dissertation. Tampere, Finland: Tampere University of Technology, 2001. 180 p.

[Tsa02] Tsai, Y.-H., Chang, F.-R., Yang, W.-C. Moving Average Filters for Faster GPS Receiver Autonomous Integrity Monitoring. In *Proc. ION NTM 2002*. San Diego, CA, Jan 28-30, 2002. Fairfax, VA: Institute of Navigation, 2002. pp. 666-675.

[Var00] Vartiainen, T., Syrjärinne, J., Saarinen, J. Bayesian Approach to Satellite Selection. *Proc. EUSIPCO 2000, X European Signal Processing Conference*. Tampere, Finland, Sept. 5-8, 2000. Tampere: Tampere University of Technology, 2000. pp. 2257-2260.

[Wal95] Walter, T., Enge, P. Weighted RAIM for Precision Approach. In *Proc. ION GPS 1995.* Palm Springs, CA, Sept. 12-15, 1995. Fairfax, VA: Institute of Navigation, 1995. pp. 1995-2004.

[Wan05] Wang, Y. FDE and Positioning Performance in a Multi-Fault Scenario Using GPS and Galileo. In *Proc. ION GNSS 2005.* Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 1772-1780.

[War95] Ward, P. The Natural Measurements of a GPS Receiver. In *Proc. ION 51st Annual Meeting*. Colorado Springs, CO, June 5-7, 1995. Fairfax, VA: Institute of Navigation, 1995. pp. 67-85.

[Yar00] Yarlagadda, R., Ali, I., Al-Dhahir, N., Hershey, J. GPS GDOP metric. *IEE Proc. Radar Sonar Navigation.* 147(5), 2000. London, UK: Institution of Electrical Engineers, 2000. pp. 259-264.

[Yil99] Yilin, Z. *Simplified GPS Assistance Protocol*. Motorola, Inc., 1999.

[Yil02] Yilin, Z. Standardization of Mobile Phone Positioning for 3G Systems. Standards Report. *IEEE Communication Magazine.* July 2002. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2002. pp. 108-116.

[Zim04] Zimmermann, D., Baumann, J., Layh, A., Landstorfer, F., Hoppe, R., Wolfle, G. Database Correlation for Positioning of Mobile Terminals in Cellular Networks Using Wave Propagation Models. In *Proc. IEEE 60th Vehicular Technology Conference*. Vol. 7. Los Angeles, CA, Sept 26-29, 2004. New York, NY: Institute of Electrical and Electronics Engineers, Inc., 2004. pp. 4682 – 4686.

[Zin05] Zinoview, A.E. Using GLONASS in Combineed GNSS Receivers: Current Status. In *Proc. ION GNSS 2005.* Long Beach, CA, Sept. 13-16, 2005. Fairfax, VA: Institute of Navigation, 2005. pp. 1046-1057.

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