TAMPERE UNIVERSITY OF TECHNOLOGY

OLLI LEHTINEN
BAROMETRIC ASSISTANCE SERVICE FOR ASSISTED GNSS RECEIVERS

Master of Science Thesis

Examiner: Professor Jarmo Harju
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ABSTRACT

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In the age of information the ability to navigate persons and equipment has become increasingly important. A rising number of applications and services depend on the precise positioning that is provided by global satellite positioning systems such as the GPS. However, most people using satellite-based positioning services are living in the most challenging surroundings for the satellite positioning systems – densely populated cities.

Fundamentally, satellite navigation is based on distance measurements from the receiver to satellite vehicles in orbit of the Earth. The receiver determines its location – latitude, longitude, and elevation – and the system time using the satellite positioning system. The determined location is only an estimate: residual errors induce inaccuracies to the determination process. At worst, the receiver may not be able to determine its position if not enough signals could be acquired. The performance of the receiver could be greatly improved if one or more of the geographic coordinates or the precise time could be obtained from another source with smaller error. One such source is Earth's atmospheric pressure which is relative to the altitude and from which a receiver can deduce its altitude if a reference pressure level is known.

To address the problem of unavailability and inaccuracy of positioning in urban environment, a barometric assistance service was designed and a respective software application was implemented. The implemented assistance service generates continuously time and location-dependent reference pressure data from high resolution weather forecasts that are calculated by the Finnish Meteorological Institute.

Receivers with the barometric sensor can download the assistance data from the service and utilize it to determine the current barometric altitude consistently and more accurately than a conventional receiver. Barometric altitude measurements improve the availability of the positioning service and reduce the time required for the first position estimate by decreasing the number of required satellite measurements.

TIIVISTELMÄ

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Paikannukseen ja navigointiin perustuvat laitteet, sovellukset ja palvelut ovat saavuttaneet kuluttajien suosion 2000-luvulla. Modernit navigointi- ja paikannussovellukset perustuvat satelliittipaikannusjärjestelmiin, kuten GPS:ään, jotka ovat käytettävissä ilmaiseksi maailmanlaajuisesti. Suuri osa paikannuspalvelujen käyttäjistä asuu tiiviisti rakennetuissa kaupungeissa – paikoissa, joissa satelliittipaikannus on virhealtteinta ja siten epätarkkaa.

Satelliittipaikannus perustuu paikannusvastaanottimen ja Maan kiertoradalla olevien satelliittien välisten etäisyyksien mittaamiseen. Mittausten perusteella vastaanotin määrittelee sijaintinsa – pituus- ja leveyspiirin sekä korkeuden merenpinnasta – sekä tarkan satelliittijärjestelmäajan. Laskettu sijainti on vain arvio, joka sisältää epätarkkuutta aiheuttavia jäännösvirheitä. Mikäli riittävästi satelliittisignaaleja ei pystytä vastaanottamaan, vastaanotin ei kykene määrittämään sijaintiaan. Vastaanottimen paikannuksen tarkkuutta on mahdollista parantaa, jos yksi tai useampi sijantikoordinaatti tai tarkka järjestelmäaika saataisiin mitattua tarkemmasta lähteestä. Yksi tällainen mittaus on Maan ilmakehän paineen suuruus, jonka perusteella korkeuden tarkka määrittäminen on mahdollista, jos tunnetun tason viitepaine on tiedetty.

Tässä työssä suunniteltiin ja toteutettiin ilmanpaineavustepalvelu ohjelmistoineen, jonka tarkoituksena on parantaa paikannuksen tarkkuutta ja saatavuutta erityisesti kaupunkiympäristöissä. Toteutettu avustepalvelu tuottaa aika- ja paikkariippuvaista avustetietoa, joka on laskettu Ilmatieteen laitoksen korkean erottelukyvyn sääennusteesta.

Vastaanottimet, joihin on liitetty barometri, voivat ladata palvelusta ilmanpaineavusteita ja käyttää niiden viitepainetietoa paikallisen korkeuden määrittämiseen tarkemmin kuin tavanomaiset vastaanottimet. Ilmanpaineeseen perustuva korkeusmittaus vähentää tarvittavien satelliittimittausten määrää, mikä parantaa paikannuspalvelun saatavuutta sekä vähentää aikaa, joka ensimmäisen paikka-arvion laskemiseen kuluu.

PREFACE

The work described in this thesis was carried out for Nokia Corporation during 2013. My supervisor MSc Kimmo Alanen is thanked for providing excellent working facilities and for supporting the work for this thesis.

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My deepest gratitude to my family – Irja and Timo Lehtinen – for all their support and encouragement over the years. Thanks to you, this all was made possible.

My beloved, Kaisa, is deeply thanked for sharing her life with a mere engineer and for encouraging me during the recent months – and in years to come!

And – finally! – to everyone who ever cast an eye on these pages or who lent an ear over coffee or a beer.

To you, dear Reader, I have reserved the following words:

From the moment I picked up your book until I laid it down, I was convulsed with laughter. Some day I intend reading it. – Groucho Marx

Tampere, 2nd of July, 2013,

Olli J. Lehtinen

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

API	Application Programming Interface
BDS	BeiDou Navigation Satellite System. A Chinese GNSS, formerly known as COMPASS.
BGD	Broadcast group delay
BPSK	Binary phase-shift keying
C/A	Coarse/Acquisition
CDMA	Code Division Multiple Access
C/N	Carrier-noise ratio
dB	Decibel
DoD	Department of Defense of the United States
DOP	Dilution of Precision
DSP	Digital Signal Processor
DSSS	Direct-Sequence Spread Spectrum
E112	A European service for making the location of the emergency caller available to the emergency services.
E911	An American counterpart of E112 (see E112).
ECMWF	European Centre for Medium-Range Weather Forecasts
EGM96	Earth Gravitational Model 1996. The model in which the geoid of WGS 84 is currently based on.
EGNOS	European Geostationary Navigation Overlay System. A European satellite-based augmentation system.
FCC	Federal Communications Commission

FDMA	Frequency Division Multiple Access
FMI	Finnish Meteorological Institute
FOC	Full Operational Capability
FTP	File Transfer Protocol
GAGAN	
GBAS	Ground-based Augmentation System
GDOP	Geometric Dilution of Precision
GEO	Geostationary orbit
GLONASS	Global Navigation Satellite System (rus. *Globalnaya Navigatsionnaya Sputnikovaya Sistema*). A Russian GNSS.
GNSS	Global Navigation Satellite System
GPS	Global Positioning System. An American GNSS.
GPST	GPS Time
GSA	European GNSS Agency of the European Union
GSO	Geosynchronous orbit
HIRLAM	High Resolution Limited Area Model
HTTP	Hypertext Transfer Protocol
ICD	Interface Control Document
IEEE	Institute of Electrical and Electronics Engineers
INS	Inertial Navigation System
IVS	In-vehicle system
IRNSS	Indian Regional Navigation Satellite System

ISA	International Standard Atmosphere
ISO	International Organization for Standardization
ITU	International Telecommunication Union
L band	Electromagnetic frequencies from 1 to 2 GHz
LBS	Location-based service
MCC	Mobile Country Code
MCS	Master Control Station
MEMS	Micro-electromechanical System
MEO	Medium Earth Orbit
MSAS	Multi-functional Satellite Augmentation System. A Japanese satellite-based augmentation system for GPS.
PND	Personal navigation device
PNT	Position, navigation, and timing
PPP	Precise point positioning
PRN	Pseudo-random noise
PVT	Position/velocity/time
QZSS	Quasi-Zenith Satellite System. A Japanese second-generation satellite-based augmentation system for GPS.
RF	Radio frequency
RNSS	Radio Navigation Satellite System
SBAS	Satellite-Based Augmentation System
SDR	Software-defined radio
SSH	Secure Shell

SV	Space vehicle
TAI	International Atomic Time (fr. *Temps Atomique International*)
TOA	Time of Arrival
TOW	Time of Week
TTFF	Time to first fix. Measured or estimated time to acquire GNSS signals and calculate a position.
UERE	User-Equivalent Range Error
UTC	Coordinated Universal Time
WAAS	Wide Area Augmentation System. An American satellite-based augmentation system.
WGS 84	World Geodetic System 1984. A global geocentric reference frame and collection of models.
WLAN	Wireless Local Area Network
WMO	World Meteorological Organization
XML	Extensible Markup Language

1. INTRODUCTION

Personal navigation has become a part of everyday life due to the increasing popularity of mobile phones with navigational capabilities. Particularly, the satellite-based positioning has enabled manufacturers to develop a variety of products with excellent performance in outdoors. As result, a whole ecosystem of location-aware applications and services has been developed. Generally, users of location-based services (LBSs) require accurate positioning promptly, which has led scientists and the positioning industry to develop methods to improve the existing satellite-based systems.

Satellite-based positioning is implemented with Global Navigation Satellite Systems (GNSSs), which provide signals that can be used to accurately locate the position of people, and to provide navigational information to moving vehicles such as automobiles, aircraft, and ships. However, requirements for accuracy, availability, and latency of LBSs – such as emergency services (E112, E911) and recreational services – are demanding for GNSS receivers based on bare satellite-based positioning, as the electromagnetic signals from space vehicles (SVs) suffer from, for example, path loss and multipath propagation in dense urban areas. During the course of the GNSS evolution a variety of augmenting methods, technologies, and services have been developed to enhance the system performance. In addition, some of these improvements can be utilized in indoor positioning in which technologies such as satellite-based positioning perform poorly.

This thesis introduces a method to improve the performance of GNSS receivers with the atmospheric pressure sensor by enabling them to estimate the altitude using barometric assistance data sent over the Internet. Particularly, the sensitivity of GNSS receivers is improved by allowing the receiver to utilize the local barometric altitude in position determination calculations. Additionally, the latency of the calculated position estimate is diminished. The method is realized in the implementation of a lightweight server-side software application for barometric assistance data calculation and distribution.

The structure of the thesis is as follows. Chapter 2 describes briefly GNSSs and the basics of satellite-based positioning. In Chapter 3, technologies that are used to improve the performance of civilian GNSS receivers are described. Chapter 4 presents a barometer and describes a method to determine altitude using atmospheric pressure. In addition, two positioning methods of utilizing barometers are introduced.

The implemented assistance service is presented in Chapter 5. Focal design decisions and implementation specifics are discussed in detail and relative results are shown. Chapter 6 provides conclusions of the thesis.

2. GLOBAL NAVIGATION SATELLITE SYSTEMS

A satellite-based system providing a global service for positioning and timing is known generally as a Global Navigation Satellite System – in short, a GNSS. To be able to provide a truly global service for terrestrial users GNSSs are implemented by employing Earth-orbiting SVs that continuously broadcast radio-navigational signals towards the Earth. These signals can then be received with inexpensive equipment without a cost, and contents of signals can be used to solve the position of the receiver.

The system architecture of a modern GNSS is three-fold: it includes a space segment, a ground-based control segment, and a user segment. The space segment consists of a constellation of SVs orbiting the Earth, the control segment monitors and operates SVs and supportive subsystems, and the user segment consists of a variety of receiver equipment for military and civil use. [1, pp. 32–36]. The operator of the GNSS is responsible for the first two and the development of user segment equipment and services is typically left to market forces.

The civilian GNSS market has grown rapidly during the 21st century because of the increased penetration in the core market segments: GNSS-enabled smartphones, personal navigation devices (PNDs), and in-vehicle systems (IVSs). The combined effect of improved positioning performance, the decreased size and price of GNSS chipsets, and the demand of positioning functionality makes it worthwhile for today's device vendors to include GNSS-solutions to a variety of core market devices in all price ranges. The European GNSS Agency (GSA) has estimated the GNSS shipments to grow on average 10% per year during 2010–2020 with global shipments exceeding 1 billion units before 2020. [2.]

In addition to civilian use, accuracy and especially availability of navigation are of strategic importance of modern military. In addition to advancements in GNSS technology and regional requirements, the provision of reliable positioning service for military has accelerated the development of independent GNSSs around the world. Different GNSSs are discussed in more detail in Section 2.1.

Data transmitted from SVs using radio signals are the basis for the accurate positioning and timing on and near the Earth. For a receiver to be able to estimate its position a number of these signals from different SVs must be acquired, decoded, and processed. Section 2.2 discusses GNSS signals in general, and in Section 2.3 a position estimate is calculated using data from GNSS satellites.

2.1 Satellite Constellations

The idea of satellite-based positioning was conceived after the launch of Sputnik I during the Space Race between the United States and the Soviet Union. The discovery led to the deployment of the two first-generation positioning systems: Transit of the U.S. (1964–1996) and Tsikada of the USSR (1974–). [3, pp. 2–10.] Positioning with Transit, for example, was based on the continuous measurement of the Doppler shift of the received signal during the 10–20 minute satellite pass which rendered the system unusable for aircraft and mobile users [1, pp. 19–20].

The development of the first GNSS – the NAVSTAR Global Positioning System (GPS) – began 1960s as a government follow-on program to Transit and the basic operation of GPS of today is virtually identical as the one proposed first on 1973 [3, p. 10]. GPS reached fully operational capability (FOC) in April 1995 with 24 SVs in circular Medium-Earth orbit (MEO).

The second GNSS in operation is Russian Federation's Global Navigation Satellite System (GLONASS, rus. ГЛОНАСС). Originally it achieved FOC in 1995 but the underfunded service degraded quickly when older satellites failed and were not replaced timely. During 2000's, Russian government has been restoring the service level of GLONASS by directing more funds to the project and repopulating the constellation with new SVs. [4, pp. 595–597.] FOC was achieved again on December 2011 [5]. Main features of currently operational GNSSs are presented in Table 2.1.

A satellite constellation is characterization of the set of orbital parameters for

Name	Owner	Type	SVs	Alt. (km)	Incl. (deg)	Period	FOC
GLONASS [3]	Russia	MEO	24	19 100	64.8°	11 h 15 min	Dec 1995 (Dec 2011)
GPS	U.S.	MEO	24	20 163	55°	11 h 58 min	Apr 1995

Table 2.1: *Fully operational GNSS constellations including the system owner country, the type of the constellation, the number of SVs (incl. spares), approx. altitude of SVs, the inclination of the orbital planes, the period of a full orbital cycle, and the date of FOC.*

the individual satellites in that constellation. The design of a constellation entails a selection of orbital parameters which optimize desired function of that system. [4, p. 43.] Satellite navigation particularly constrains constellation design by requiring a minimum of four SVs being in view of a user to provide necessary measurements for the user to determine real-time three-dimensional position and timing information (see Section 2.3). For example, satellite orbit altitude has several effects on perceived performance by end-users:

- The higher the orbit altitude, the greater fraction of the Earth is visible from an SV.
- Power flux density on the Earth is nearly independent of the orbit altitude because the SV antenna beamwidth is configurable to provide full coverage on the Earth.
- A low-orbit altitude and its corresponding short visibility time leads to a larger number of signal acquisitions by the receiver, and, in addition, larger Doppler shift must be tolerated by the receiver. [3, p. 38.]

Particularly, for low orbital altitudes – below 2 000 km in the Low Earth orbital zone (LEO) – the drag of Earth's atmosphere, which causes orbital decay, becomes significant [6, pp. 423–424], and, in addition, the oblate shape of the Earth causes perturbative torque to satellites on such low altitudes [6, pp. 156–159]. Unwanted implications of these effects require regular orbital corrections of SVs, that require expensive and heavy boosters and propellant on-board or other means to change the course. Orbital zones of the Earth are illustrated in Table 2.1. For a detailed discussion of the problem of constellation design, see [4, pp. 43–50].

Figure 2.1: *Altitudes of Low (LEO), Medium (MEO), and High Earth (HEO) orbital zones, and the geostationary orbit (GEO). The zero-level is Mean Sea-Level (MSL).*

GNSS constellations – including GPS and GLONASS – utilize orbital altitudes in the region called Medium Earth orbit (MEO; above 2 000–25 766 km). Altitudes around 20 000 km are popular among GNSSs because on that level nominal periods of orbits are close to 12 h sidereal day. For example, satellite vehicles of GPS have an altitude of 20 200 km. If a constellation with regional requirements is designed, an SV may be placed either on a Geosynchronous orbit (GSO) or the Geostationary orbit (GEO). GSOs have a period of *a sidereal day* (i.e., the time for the Earth to complete one revolution on its axis; 23 h, 56 min, 4.09054 s [6, p. 102]) which causes a satellite on a such orbit to appear at the same position in the sky after the period. A special case of a GSO is the GEO: an SV placed on the GEO maintains the same position relative to the Earth and appears to have the same position of the sky if looked at from the Earth. [3, p. 38.] In Figure 2.2 is an illustration of the GPS constellation.

In addition to two operational GNSSs, there are two GNSSs in development: Chinese BeiDou and European Union's (EU) Galileo. Also, Japan is developing a regional augmentation system called Quasi-Zenith Satellite System (QZSS), and Indian Regional Navigation Satellite System is being created in India. See Table 2.2 for current status of the systems.

2.2 Signal Characteristics

Positioning and timing service realized by a GNSS is based on radio signals broadcast from space to the Earth, which makes them passive systems by design. The role of SVs of a GNSS is to transmit these signals that have embedded in them, in the form

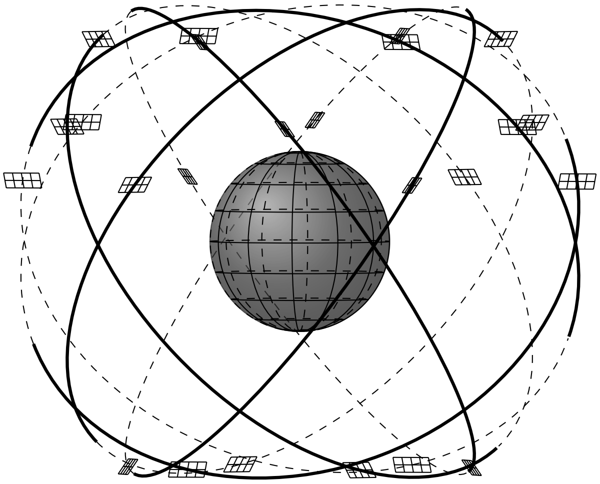

Figure 2.2: *The constellation of GPS looking directly at the Equator. The constellation has a total of 24 SVs on 6 orbital planes. Orbits have the inclination angle of* 55° *and the eccentricity of* 0.

Name	Owner	Status	Type	Min. FOC SVs	IOC	FOC (est.)
BeiDou	China	Testing	MEO+ GEO + GSO	$27 + 5 + 3$	-	2020
Galileo	EU	In-orbit validation (4 SVs) [7]	MEO	27	Est. 2015 (18 SVs) [8]	2020
QZSS	Japan	In-orbit verification (1 SV)	GSO (Asia-Pacific regional)	4	Jun 2011	Late 2010s
IRNSS	India	1st launch on June 2013 [9]	GEO + GSO (India regional)	$3 + 4$	-	2014

Table 2.2: *Status of planned GNSS and regional constellations. The status as of March 2013.*

of navigation data, both satellite positioning data as well as clock correction terms, so receivers on the Earth can determine both satellite time and satellite position at the time of transmission.

Navigation data are encoded as GNSS-specific navigation messages. The navigation data contain all the parameters that enable the user to perform positioning service. They are stored on board each satellite and broadcast world-wide by all the satellites of the GNSS constellation. Generally, the four types of data is needed to perform positioning [10, p. 44]:

- Ephemeris which are needed to indicate the position of the SV to the receiver
- Time and clock correction parameters that are needed for pseudorange measurements (see Section 2.3)
- Service parameters which are needed to identify the set of navigation data, SVs, and indicators of signal health
- Almanac which are needed to indicate the position of all the SVs of the constellation with reduced precision

GNSS SVs broadcast messages with different intervals depending on the importance of the message. For example, in GPS a message which includes an ephemeris, time and clock correction parameters, and service parameters is broadcast by each SV every 30 seconds and a full almanac message every 12.5 minutes [11]. Structures of navigation messages are defined in the signal-in-space specification of each GNSS. These specifications are commonly known as Interface Control Documents (ICDs).

Radio frequency (RF) signals broadcast from GNSS SVs utilize frequency bands allocated specifically for Radio Navigation Satellite Systems (RNSSs) by International Telecommunication Union (ITU). Currently allocated RNSS bands are listed in Table 2.3.

Frequency range (MHz)	Name	Type
1 164–1 215	E5–L5 band	Space-to-Earth
1 215–1 260	L2 band	Space-to-Earth
1 260–1 300	E6 band	Space-to-Earth
1 559–1 610	E1–L1 band	Space-to-Earth
2 483.5–2 500	S band	Space-to-Earth
5 000–5 010	C	Earth-to-space

Table 2.3: *Allocated radio frequency bands for GNSSs. The band names are commonly used but unofficial. [12; 13; 14; 15]*

Navigation messages are encoded to RF signals using digital modulation techniques – typically *binary phase-shift keying* (BPSK), *quadratic phase-shift keying* (QPSK), or *binary offset carrier* (BOC) method. To be able to broadcast multiple signals from a satellite constellation or even a single SV signals must be multiplexed.

Both frequency division multiple access (FDMA) and code division multiple access (CDMA) are utilized by GNSSs: signals of GLONASS use FDMA, and GPS, BeiDou, and Galileo CDMA – however, GLONASS is in process to convert its system to CDMA during 2010's.

In FDMA different carrier frequencies are used for different signals. The frequency range FDMA requires is linearly proportional to the number of signal required to be transmitted. In CDMA different signals are transmitted using a single carrier. Distinct signals are separated using special spreading codes; in GNSSs direct-sequence spread spectrum (DSSS) multiplexing is used. In DSSS an additional binary signal called spreading waveform – or pseudo-random noise (PRN) waveform – is added to BPSK signal. The PRN waveform is periodic, and the binary sequence used to generate the waveform over one period is referred to a *PRN code*. Parameters, other than the exact binary sequence, of a PRN code are the *chip period* (minimum time interval between transitions in the waveform), a *chip* (the portion of a waveform over a chip period), and the reciprocal of the chip period, the *chipping rate*. [4, pp. 113–116.]

In addition to spreading the signals, QPSK is usually used to transmit multiple signals simultaneously using the same carrier – for example, when a signal includes both data and pilot channels. Receiver that can reproduce the PRN code can distinguish corresponding coded waveform from the received, modulated signal. That is possible because of auto-correlation and cross-correlation properties of pseudo-random codes used with DSSS; see [1, pp. 268–279] for details. In Table 2.4 is presented summary of key technical parameters of GNSS signals for civilian use.

Position determination using a GNSS is possible only after GNSS signals are acquired and messages they are carrying decoded. Typical modern GNSS receiver designs are digital receivers, and usually implemented using a digital signal processor (DSP) or as a software-defined radio (SDR). SDR design and implementation is discussed in [11].

Acquiring a GNSS signal is based on the cross-correlation characteristic of high-rate chip code integrated into the data signal. At first, the digital intermediate frequency signal, which includes all of the in-view GNSS SV signals using the same

Signal name	Nominal carrier frequency (MHz)	Modulation	Multiplexing mode	Chip rate (Mchip/s)	Chip length
B1 (BeiDou)	1 561.098	QPSK	CDMA	2.046	2 046
E1 B (Galileo)	1 575.420	BOC	CDMA	1.023	4 092
E6 B (Galileo)	1 278.750	BPSK	CDMA	5.115	5 115
E5a (Galileo)	1 176.450	Alt-BOC	CDMA	10.230	10 230 × 20
E5b (Galileo)	1 207.140	Alt-BOC	CDMA	10.230	10 230 × 4
L1 C/A (GPS)	1 575.420	BPSK	CDMA	1.023	1 023
L1C (GPS)	1 575.420	BOC	CDMA	1.023	10.230
L2C Mod. (GPS)	1 227.600	BPSK	CDMA	0.5115	10 230
L2C Long (GPS)	1 227.600	BPSK	CDMA	0.5115	767 250
L5 (GPS)	1 176.450	QPSK	CDMA	10.230	10 230
L1 C/A (GLONASS)	1 602.000	BPSK	FDMA	0.511	511
L2 C/A (GLONASS)	1 246.000	BPSK	FDMA	0.511	511
L3 (GLONASS)	1 202.025	QPSK	CDMA	10.230	10 230

Table 2.4: *Signal characteristics for BeiDou [16], Galileo [10] (E5a and E5b signals are the side lobes of the wideband Galileo E5 signal). GLONASS [3] (FDMA subbands for GLONASS's L1 and L2 are calculated by adding the corresponding carrier frequency* $(-7...6) \times 562,5$ *kHz (L1) or* $(-7...6) \times 437,5$ *kHz (L2) [3; 17]) and GPS [18; 19; 11]. Values are given for civil signals and data channels.*

carrier, is dominated by noise. The signal is collapsed to baseband by removing the carrier (and Doppler shift) using numerically controlled oscillator. Baseband signal is correlated with the receiver synthesized chip sequence and its phase is aligned to produce maximum correlation between signals. From this signal SV navigation data can be sampled and further processed. [4, pp. 156–158.] After acquisition receiver moves to tracking mode in which carrier and code phase are tracked.

In CDMA, each SV uses an unique chip sequence (that is, a PRN code) so a receiver is aware which SV signals it has acquired. All FDMA signals of GLONASS use identical PRN code but the signals have different carrier frequencies. GNSS signals using longer chip code reduce cross-correlation to more acceptable level but acquisition time grows larger. On the other hand, long codes are much harder to guess which makes them usable as an encryption tool.

Even though the distance to SVs might be over 30 000 km, relatively small transmit power is used to broadcast position and timing signals to the Earth. The ICD of each GNSS define minimum received power for every signal which can be used as a basis for signal power budget calculations and receiver design. In Table 2.5 is listed minimum received power values for each GNSS signal.

Signal name	Minimum receiver power (dBW)	Reference antenna gain (dBi)	Minimum elevation angle
B1 (BeiDou)	−163	0	5°
E1 (Galileo)	−157	0	10°
E6 (Galileo)	−155	0	10°
E5 (Galileo)	−155	0	10°
L1 (GPS)	−158.5	3	5°
L1C (GPS)	−157	3	5°
L2 (GPS)	−158.5	3	5°
L5 (GPS)	−157	3	5°
L1 (GLONASS)	−161	3	5°
L2 (GLONASS)	−167	3	5°
L3 (GLONASS)	*N/A*	*N/A*	*N/A*

Table 2.5: *Minimum user-received signal levels, reference antennas and minimum elevation angles as is defined in corresponding ICDs. (An official signal plan for GLONASS L3 does not exist at the time of writing.)*

2.3 Estimating Position

A fundamental measurement made by a GNSS receiver is the apparent transit time of the signal from an SV to the receiver. The transit time is defined as the difference between signal reception time, as determined by the receiver clock, and signal transmission time at the SV, as marked on the signal. In CDMA-based GNSSs, the time difference is measured as the amount of time shift required to align the PRN code replica with the signal received from the SV. The measurement is biased due to the fact that the receiver and the SV clocks are not synchronized. The corresponding biased range – known as a *pseudorange* – is defined as the propagation time multiplied by the propagation velocity of the signal (for example, the speed of light). [1, p. 124.] This concept is known as the time of arrival (TOA) ranging. By measuring ranges from multiple sources, it is possible for the receiver to determine its position unambiguously. In Figures 2.3 (*a*) and (*b*) are illustrations of two and three transmitter systems.

In Figure 2.4, a user receiver's position with respect to the coordinate origin

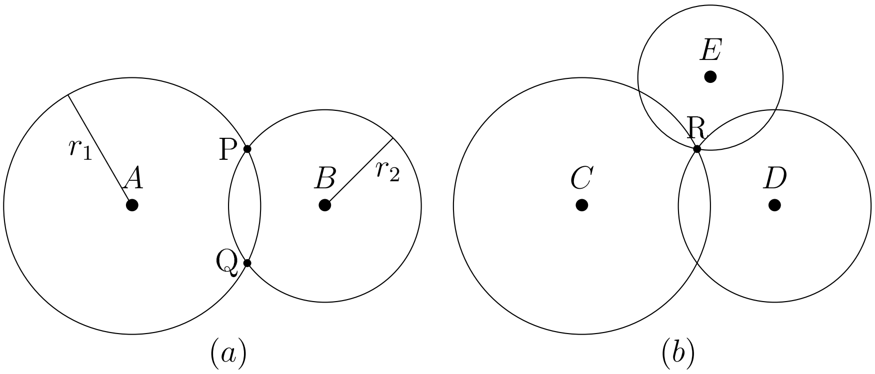

Figure 2.3: *In (a), sources A and B broadcast in two-dimension space. Receiver's clock is synchronized with those of at A and B. After receiving signals from A and B, the receiver calculates distances r_1 and r_2 using propagation times and determines its position either being at point P or Q. Respectively, in (b), with three sources C, D, and E broadcasting, the receiver can unambiguously determine its position at point R. [4, pp. 22–23.]*

is represented by vector $\bar{\mathbf{u}}$. User's position coordinates x_u, y_u, z_u are considered unknown. Vector $\bar{\mathbf{s}}$ represents the position of the SV relative to the coordinate origin, and it is computed from the ephemeris data broadcast by the SV. [4, pp. 51–54.]

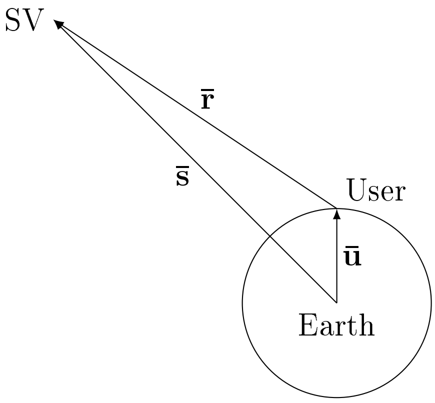

Figure 2.4: *Vector representation of user position.*

The SV-to-user vector $\bar{\mathbf{r}}$ is

$$\bar{\mathbf{r}} = \bar{\mathbf{s}} - \bar{\mathbf{u}} \tag{2.1}$$

The magnitude of $\bar{\mathbf{r}}$ is

$$||\bar{\mathbf{r}}|| = ||\bar{\mathbf{s}} - \bar{\mathbf{u}}|| \tag{2.2}$$

Let r denote the magnitude of $\bar{\mathbf{r}}$

$$r = ||\bar{\mathbf{s}} - \bar{\mathbf{u}}|| \tag{2.3}$$

The geometric distance r can be computed by multiplying the signal propagation time with the signal propagation velocity c (the speed of light in vacuum). If T_s denotes the system time at which the signal left the satellite and T_u the time when it reached the receiver, then

$$r = ||\bar{\mathbf{s}} - \bar{\mathbf{u}}|| = c(T_u - T_s) = c\Delta t \tag{2.4}$$

If the receiver clock and the satellite clock were perfectly synchronized (2.4) would yield the true distance. However, the receiver clock will generally have a bias error from the GNSS system time. Furthermore, satellite frequency generation and timing is based on precise free-running rubidium atomic clocks or passive hydrogen masers that are offset from system time. [4, pp. 52–53.]

Thus the pseudorange, denoted as ρ, contains (1) the geometric (that is, true) user-to-satellite range r, (2) the bias of the SV clock δt_s, and (3) the bias of the receiver clock δt_u, both related to system time of the respective GNSS. [4, p. 53] Pseudorange can be written as

$$\begin{aligned}\rho &= c\big[(T_u + \delta t_u) - (T_s + \delta t_s)\big] + \varepsilon_\rho \\ &= c(T_u - T_s) + c(\delta t_u - \delta t_s) + \varepsilon_\rho \\ &= r + c(\delta t_u - \delta t_s) + \varepsilon_\rho \end{aligned} \tag{2.5}$$

[4, p. 54] where ε_ρ accounts for modeling errors, such as satellite clock modeling error and orbit prediction error [1, p. 176].

The satellite clock bias from system time, δt_s, can be calculated by the GNSS ground control and corresponding corrections are broadcast from each SV to receivers as part of the navigation data. [4, pp. 52–54.] Hence, the previous equation can be expressed as

$$\rho = r + c\delta t_u + \varepsilon_\rho \tag{2.6}$$

GNSS signals propagate through free space with a constant speed of light c. Closer to the Earth's surface, at the height of about 1 000 km, signals enter an atmospheric layer known as the ionosphere where charged particles affect electromagnetic waves. Later, at height of about 40 km, signals enter the troposphere where signals encounter electrically neutral gaseous atmosphere. In these layers GNSS signals are refracted which changes propagation velocity. Changes in velocity introduces propagation delays (see [1, pp. 132–150] for detailed discussion). [1, pp. 125–126.] If ionospheric delay is denoted as I_ρ and tropospheric delay as T_ρ, Equation (2.6) can be expanded to

$$\rho = r + c\delta t_u + I_\rho + T_\rho + \varepsilon_\rho \tag{2.7}$$

The basic pseudorange measurement equation (2.7) is a basis for calculation of a PVT solution. As in Equation (2.1), let vectors $\bar{\mathbf{u}} = (x, y, z)$ and $\bar{\mathbf{s}}^{(k)} = (x^{(k)}, y^{(k)}, z^{(k)})$, for $k = 1, 2, ..., K$, represent the position of the user receiver and the position of the kth satellite. The user-to-satellite geometric range is

$$r^{(k)} = \left\|\bar{\mathbf{u}} + \bar{\mathbf{s}}^{(k)}\right\| = \sqrt{(x^{(k)} + x)^2 + (y^{(k)} + y)^2 + (z^{(k)} + z)^2} \tag{2.8}$$

Equation (2.7) can be rewritten for pseudorange to kth satellite as

$$\rho^{(k)} = \left\|\bar{\mathbf{u}} + \bar{\mathbf{s}}^{(k)}\right\| + b + \check{\varepsilon}_\rho^{(k)} \tag{2.9}$$

where $\check{\varepsilon}_\rho^{(k)}$ includes tropospheric and ionospheric propagation delays in addition to modeling errors, and b has replaced clock bias term $c\delta t_u$. [1, pp. 176–177.]

In order to determine user receiver's position, K pseudoranges to satellites are measured, each modeled as a nonlinear equation (2.9). In each equation are four unknowns: three coordinate components of $\bar{\mathbf{x}}$ and b. At a minimum four equations ($K \geq 4$) are needed to solve four unknowns. In other words, at least four simultaneous pseudorange measurements to GNSS SVs are required in order to estimate user's instantaneous position. [1, p. 178.]

Different ways exist to solve these equations. For a single-point solution, iterative techniques based on the Newton-Raphson method can be used (see [3, pp. 412–413] and [4, pp. 54–58]), and for continuous position determination Kalman filtering, in which a PVT estimate is formed based on a current measurement as well as previous position estimates, is usually applied (see, for example, [3, pp. 420–424]). [4, p. 55.] In these techniques it is usually required that the receiver can give a rough guess of its position as an initial value for calculations. Typical today's GNSS receivers calculate continuous PVT estimates with sampling intervals of approximately 1 second [4, p. 459].

2.4 Sources of Errors

In general, GNSS accuracy performance depends on the quality of the pseudorange and carrier phase measurements as well as broadcast navigation data. Furthermore, the fidelity of underlying physical model that related to these parameters is important. All in all, errors are induced throughout all parts of GNSSs: by control, space, and user segments.

When analyzing the effect of errors on accuracy, a fundamental assumption is usually made: the error sources can be allocated to individual pseudoranges and they can be viewed as effectively resulting an equivalent error in the pseudorange values [4, p. 301]. The effective accuracy of the pseudorange value is called as the user-equivalent range error (UERE).

The accuracy of the PVT solution can be expressed as the product of a geometry factor and a pseudorange error factor. The geometry factor, or the Dilution of Precision (DOP) value, expresses the composite effect of the relative user-satellite geometry on the PVT solution. A pseudorange error factor can be modeled as UERE in general case. [4, pp. 301–302.] Therefore, error in the PVT solutions can be estimated by the formula

$$Estimated\ Position\ Error = DOP \cdot UERE \tag{2.10}$$

which is derived and discussed in detail in Chapter 7 of [4].

Different kinds of errors perceived in GNSS can be grouped to following six classes: [3, p. 478]

1. Ephemeris data – Errors in the transmitted location of the SV

2. Satellite clock – Errors in the transmitted clock
3. Ionosphere – Errors in pseudoranges caused by ionospheric effects
4. Troposphere – Errors in pseudoranges caused by tropospheric effects
5. Multipath – Errors caused by reflected or diffracted signals entering the receiver antenna
6. Receiver – Errors in the receiver's measurement of range caused by the design (e.g., thermal noise and software accuracy)

Ephemeris errors result when the GNSS navigational message does not transmit the correct SV position. Ephemeris data is calculated in the ground control segment of the GNSS and uplinked to SVs in orbit for rebroadcast to users. Errors are introduced in a curve fit of the control segment's best prediction for each SV. For GPS, the effective pseudorange error due to ephemeris prediction errors is reportedly on the order of 0.8 m (1 σ) [4, p. 205].

All GNSS SVs contain high precision clocks on-board that control all timing operations, including broadcast signal generation. Even a small error in clock have a large effect: an offset of 1 ms translates to to a 300-km pseudorange error. The ground control segment calculates clock correction terms that are uploaded and rebroadcast as ephemerides were earlier. For example, for GPS residual errors in pseudorange vary typically from 0.3–4 meters, depending on the age of the broadcast data and the type of the satellite. [4, pp. 304–305.]

As discussed in the previous section, ionosphere and troposphere affect propagation velocity of signals entering Earth's atmosphere. In ionosphere – between 70 km and 1 000 km above the Earth – GNSS signals do not travel at the speed of light in vacuum. The modulation on the signal is *delayed* in proportion of free electrons encountered and is also proportional to the inverse of the carrier frequency squared ($1/f^2$). In addition, the phase of the carrier is *advanced* by the same amount because the same effects. [3, p. 479.] This phenomenon is known as *ionospheric divergence*. The ionospheric activity is closely related to solar activity. In addition, the ionization fluctuates daily with the day-night cycle. Almost three times as much ionospheric delay is incurred when viewing SVs at low elevation angles than at the zenith. Signals arriving at vertical incidence, the delay ranges from 10 ns (3 meters) at night to 50 ns (15 meters) during the day. For low elevation angles (0° to 10°), the delay ranges from 30 ns (9 m) up to 150 ns (45 m) respectively. A typical value for the residual ionospheric delay, averaged over the Earth and over elevation angles, is 7 meters (1 σ) [4, pp. 310–314.]

In troposphere the speed of GNSS signals is affected not because of electrons but variations in temperature, pressure, and humidity. When left uncompensated, the range equivalent of tropospheric delay can vary from about 2.4 meters for an SV at the zenith to about 25 meters for an SV at an elevation angle of approximately 5°. To compensate tropospheric delay measurements of local temperature and pressure must be available. [4, pp. 314–319.] For detailed discussions of ionospheric and tropospheric effects see Chapter 7.2 of [4].

One of the most significant errors incurred in the receiver is multipath. Multipath is the reception of reflected or diffracted replicas of the desired signals. Since the path traveled by the multipath signal is always longer than the direct path, multipath arrivals are delayed relative to the direct signals. Multipath reflections from nearby objects can arrive at short delays after arrival of the direct signal. Such multipath signals distort the correlation function between the received composite (direct path plus multipath) and the locally generated reference signal in the receiver. Also, multipath signals distort the composite phase of the received signal introducing pseudorange offsets. These offsets produce errors in calculations of PVT solutions. In worst case, the direct signal is shadowed by, for example, thick foliage which causes the receiver track only delayed multipath signals. [4, pp. 279–280.] Typical net impact to a moving receiver should be less than 1 meter for most cases [3, p. 480].

Typical modern receiver 1σ errors are smaller than a decimeter and negligible compared to those induced by multipath [4, p. 319]. Because of this insignificance and the variety of different receiver designs receiver-induced errors are not discussed here.

3. IMPROVEMENTS TO GNSS PERFORMANCE

Performance requirements of GNSS receivers can be divided to two groups. Firstly, time to calculate the first position – time to first fix (TTFF) – is of importance to users who require operational PNDs without an initial waiting period. Secondly, the accuracy of the PVT solution is what makes a GNSS usable or unusable. In following sections importance has been given to solutions that can be applied with mobile GNSS receivers, such as smart phones.

In Section 3.1 is described a standalone GNSS receiver whose performance is used as a baseline in the remaining sections. In these sections are summarized technologies and methods that improve GNSS performance. These solutions represent the most important ones suitable and available for civil use, thus excluding military and high precision solutions.

3.1 Standalone GNSS receiver

A standalone GNSS receiver is a receiver that determines its position using the data only from the GNSS satellites. In other words, a standalone receiver is a common satellite-navigation receiver without a network connectivity. The receiver may utilize one or more GNSS constellations to solve the PVT estimate.

If the receiver does not have up-to-date ephemeris (which includes clock correction terms) it is required to receive them from GNSS broadcasts. Steps of operation of a standalone receiver are:

1. Acquire at least four distinct GNSS signals
2. Listen each signal until ephemerides are received
3. Measure pseudoranges to each SV

4. Calculate a PVT solution.

Commonly used term for this kind of operation, where the receiver does not have data stored beforehand, is the *cold start*. The position solution can be calculated by a full sky search and by receiving clock correction and ephemeris data from the SVs. The TTFF is dependent to the time it takes ephemerides to be received.

For example, ephemeris data is transmitted every 30 seconds in the GPS L1 C/A signal. It takes 18 seconds to transmit the full ephemeris which means a receiver has to track the signal continuously for 18–36 seconds. Therefore, typical TTFFs are over 20 seconds. In bad signal conditions or with a mobile receiver signal may be lost before ephemeris data is received. In such cases the same or a new signal must be acquired and tracked until a new full ephemeris data is fully received.

In a *warm start* scenario, a receiver has valid ephemeris and clock correction data stored in memory. To calculate its position, it only needs to acquire enough (at least four) GNSS signals and calculate corresponding pseudoranges and the PVT solution. Typically TTFF is from a subsecond to a few seconds. [20.] The *hot start* is a scenario in which the warm start conditions apply and, in addition, accurate position and relatively accurate system time are known by the receiver. The PVT solution can be calculated without any information from GNSS navigation messages. [20.]

In addition to possibly high TTFF values, standalone receivers are affected by ionospheric and tropospheric delays to GNSS signals that cause errors to pseudorange measurements. The simplest correction to ionospheric delay is to use an internal diurnal model of these delays. As the effects in the ionosphere are mainly relative to the Earth's day–night cycle receivers can use the clock information in navigation messages to apply corrections to calculations. The effective accuracy of the diurnal modeling is about 2–5 m in ranging in temperate zones. [3, p. 479.] The receiver may also apply ionospheric correction parameters that are usually included into broadcast almanac messages if one has been received at the time of position calculations.

Tropospheric delay can not be compensated by a standalone receiver without knowledge of local temperature and atmospheric pressure, which are main causes for the effect. As discussed in previous chapter, corresponding incurred pseudorange error is from about 2.4 m to 25 m depending on user-satellite geometry.

3.2 Assisted GNSS

Assisted GNSS, or A-GNSS, is a method to provide GNSS receivers some of the required information to solve PVT solutions. An obvious improvement to the operation of a standalone receiver is to retrieve ephemeris and clock correction data with other means than receiving them as a payload of GNSS signals.

A-GNSS receivers, or *assisted receivers*, require connectivity to a data network to be able to download assistance data. For example, GNSS-enabled cellular handsets can use Wireless Local Area Networks (WLANs) or cellular data connectivity. Nowadays assistance data is downloaded over the Internet from servers of A-GNSS service providers. Service providers measure itself or buy the necessary data of corresponding GNSS or GNSSs they provide the service for. Service providers may offer additional corrections to GNSS broadcast data as well.

The advantage of A-GNSS is greatly improved TTFF latency because assisted receivers do not have to receive broadcast ephemerides and clock corrections anymore. Cold start TTFF values of a few seconds are usual for A-GNSS receivers with valid assist data. Secondly, the accuracy of the position solution improves because the receiver may utilize all SV signal it can acquire without the need for the reception of ephemerides which would require a relatively long tracking period. For example, the assistance service may include additional parameters or filter broadcast ephemeris anomalies out to improve the receiver performance.

A downside of A-GNSS is requirement of network connectivity. Assisted receivers need to download assist data every few hours to keep the data up-to-date and usable. If a suitable network is not available, assisted receivers can usually operate in an autonomous mode with reduced performance that of a standalone receiver.

3.3 Multi-GNSS Receivers

A receiver that can utilize signals from more than one GNSS at the same time is called a multi-GNSS receiver. For example, a multi-GNSS receiver that supports

GPS and GLONASS can receive and process signals concurrently from both of the systems. Position calculations are done using pseudorange measurements to SVs regardless of their source constellation.

The advantage of employing signals from multiple GNSSs is increased number of possibly visible SVs. Because each GNSS has its own constellation in orbit multi-GNSS receivers gain from each of those. Especially when the signal conditions are not optimal, the a larger number of usable SVs improves perceived performance of a multi-GNSS receiver compared to a single-GNSS device, which may have difficulty in acquiring direct-path signals.

If a multi-GNSS receiver is able to receive two different signals from one SV it can compensate ionospheric divergence. Delays induced in the ionosphere are relative to the frequency of the passing signal – therefore, it is possible to determine so-called ionospheric-free pseudorange to the SV. It is notable that single-GNSS receivers may apply this technique as well if they can receive and process multiple signals concurrently.

Changes to receiver design to enable support for multiple constellations are mostly focused to baseband and software implementations. GNSS carrier signal frequencies are concentrated to a narrow part of the radio spectrum, which allows receiving with a single antenna and simple bandpass filtering.

3.4 Sensor-assisted Positioning

The need to provide continuous navigation between update periods of a GNSS receiver, during periods of shading of the receiver antenna, and through periods of interference or similar effects is the stimulus for integrating GNSS receiver with various additional sensors [4, p. 459]. Popular sensors include, for example, inertial sensors, such as accelerometers and gyroscopes, magnetometers, and altimeters.

Sensory input is usually integrated to GNSS positioning through a use of a Kalman filter estimator (see [4, pp. 466–470] for details). There exists a few scenarios where sensory input is helpful. First, they may provide continuous measurements for PVT calculations even though GNSS reception is not possible. This kind of sensor-based navigation is generally known as *dead reckoning*. However, position estimates deteriorate quickly with inexpensive sensors with high drift.

Second, a method, referred to as prepositioning, is used to compute an a priori estimate of a signal's code phase using the integration filter's estimates of PVT and frequency error as an input. With prepositioning it is possible to do nearly instantaneous reacquisition of a lost signal. For example, this method has been used since the very first GPS receivers. [4, pp. 460–466.]

Sensory assistance from integrated sensors make a GNSS receiver more accurate than a receiver which uses GNSS as a single-source for navigation – be it an A-GNSS receiver or a standalone receiver. Position estimation is more accurate and consistent when additional sensory input is used to filter out GNSS anomalies – such as biased pseudorange measurements from multipath propagated signals – and to aid navigation by means of dead reckoning when GNSS signals are shadowed.

4. ALTITUDE DETERMINATION WITH BAROMETERS

First, this chapter describes the Earth's atmosphere and introduced pressure it exerts onto everything inside it. Furthermore, a description of an altitude determination based on atmospheric pressure measurements is given.

Later, Section 4.2 introduces the barometer, a device for measuring the atmospheric pressure. Section 4.3 describes two use-cases where barometers can be utilized in GNSS positioning.

4.1 Atmospheric Pressure

Pressure p is defined to equal the normal force exerted to a surface area, or

$$p = \frac{F_{\perp}}{A} \tag{4.1}$$

where A is the area of a finite plane surface, and $F_{\perp}$ is the net normal force (that is, perpendicular to the surface) exerted to that area. The standard unit of pressure is *pascal*, where

$$1\ pascal = 1\ Pa = 1\ N/m^2$$

One commonly used unit is the hectopascal (hPa) which equals 100 Pa. Other related units, used mainly in meteorology, are the bar, equal to 10^5 Pa, and the millibar, equal to 100 Pa. [21, p. 429.]

The atmosphere of the Earth is a layer of gases surrounding the planet Earth. It is held in place by the gravity of the planet. Dry air of the Earth's atmosphere is composed by nitrogen (78.09%), oxygen (20.95%), argon (0.93%), and other gases. The structure of the atmosphere can be divided to five principal layers: the exosphere, the thermosphere, the mesosphere, the stratosphere, and the troposphere.

In addition to the principal layers the ozone layer and the ionosphere can be distinguished by their properties. In Figure 4.1 is an illustration of the layers of the atmosphere.

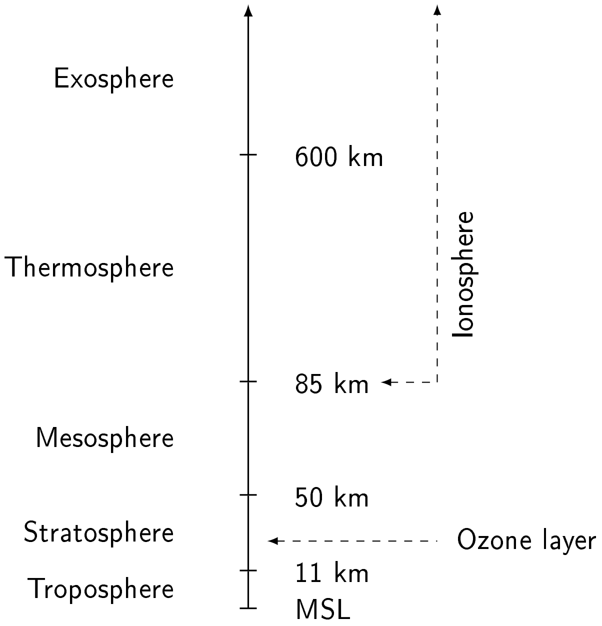

Figure 4.1: *The atmosphere of the Earth. The principal layers of the atmosphere starting from mean sea level are the troposphere, the stratorsphere, the mesosphere, the thermosphere, and the exosphere. The ozone layer (20..30 km), in which ultraviolet radiation is absorbed, is a part of the stratosphere. The ionosphere (50–1,000 km) is a region of the atmosphere which is ionized by solar radiation.*

The atmospheric pressure is the pressure of the Earth's atmosphere. This pressure varies with weather changes and with elevation. The standard atmosphere is an SI unit of pressure and it is defined to be exactly 101 325 Pa. [21, p. 429.]

The atmospheric pressure depends firstly on the mass of the air, secondly the area below the mass, and thirdly the height of the mass above the surface. This can be portrayed as an air column – see Figure 4.2. The mass of the air column is relative to the density of the air, which is not a constant but a variable depending on, for example, altitude and humidity.

The density of the air can be calculated using the ideal gas law

$$pV = nRT \tag{4.2}$$

where p is the absolute pressure of the gas, V is the volume of the gas, n is the

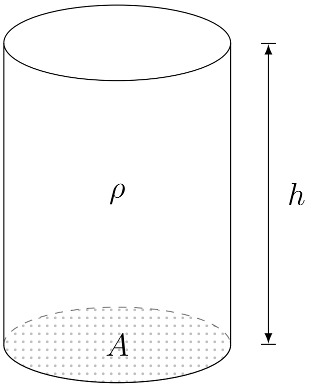

Figure 4.2: *A column of air of height h that exerts a force to the shaded area A. The mass of the air is relative to the air density ρ.*

amount of substance of the gas, T is the temperature of the gas, and R is the universal gas constant (R=8.3144621 J/molK). [21, pp. 499–501.] The amount of substance n in moles is equal to the total mass of the substance m divided by the molar mass M

$$n = \frac{m}{M} \tag{4.3}$$

so (4.2) can be written as

$$pV = \frac{m}{M}RT \tag{4.4}$$

$$\iff p = V\frac{m}{M}RT \tag{4.5}$$

The density ρ is defined to equal the ratio between the mass of the substance and its volume. By applying the density $\rho = {}^{m}/_{V}$, Equation (4.4) becomes

$$p = \rho\frac{R}{M}T \tag{4.6}$$

The relation between the universal gas constant R and the molar mass of the specific substance M can be expressed as a specific gas constant $R_{specific}$:

$$R_{specific} = \frac{R}{M} \tag{4.7}$$

Therefore, Equation (4.6) becomes

$$p = \rho R_{specific} T \tag{4.8}$$

$$\iff \rho = \frac{p}{R_{specific} T} \tag{4.9}$$

where ρ is the density of the gas, p is the absolute pressure of the gas, $R_{specific}$ is the specific gas constant of the gas, and T is the temperature of the gas in kelvins.

The specific gas constant for dry air is 287.058 J/kgK. Therefore, for example, at 293.15 K (20 °C) and 101.325 kPa, dry air has density of 1.2041 kg/m^3.

The density of the air changes from the value of dry air if water vapor is added making the air humid. Counter-intuitively, increased humidity reduces the density of the air. This is based on the Avogadro's Law: The molar mass M of a compound is a mass of one mole, and it is equal to the mass m_s of a single molecule multiplied by Avogadro's number N_A (the number of molecules in a mole)

$$M = m_s N_A \tag{4.10}$$

The molar mass of dry air (28.97 g/mol) is larger than that of water vapor (18.02 g/mol). When applied to (4.6) and (4.9) the result for given values is that dry air is about three times as dense as water vapor. The calculations are summarized in Table 4.1.

	Dry air	Water vapor
Molar mass (kg/mol)	$28.97 \cdot 10^{-3}$	$18.02 \cdot 10^{-3}$
$R_{specific}$ (J/mol K)	278.00	461.40
Pressure (Pa)	101 325	
Temperature (K)	293.15	
Density (kg/m^3)	1.524	0.479

Table 4.1: *Calculated density values of dry air and water vapor with given molar masses. The densities are calculated at 20 °C and 101 325 Pa using Equations (4.3) and (4.9).*

In practice, the composition of the air is not homogeneous throughout the air column. Not only the humidity of the air changes but the ambient temperature as well. The rate of the change – called as the lapse rate – is not linear through all the layers of the atmosphere. For example, temperature decreases linearly when gaining altitude until the border of the troposphere and the stratosphere is reached after which the lapse rate is nearly zero to the midpoint of the stratosphere. Likewise, the pressure decreases linearly until the edge of the stratosphere where the rate grows to exponential.

The International Standard Atmosphere (ISA) is a model of how the pressure, temperature, and density of the Earth's atmosphere change over a range of altitudes. The ISA is an international standard published by the International Organization for Standardization (ISO). The ISA divides the atmosphere to layers similar to those of Figure 4.1 but with linear temperature distributions. For example, the standard defines the mean sea level temperature as 15 °C (288.15 K) and the lapse rate of temperature through the troposphere (from 0 m to 11 km) as −6.5 °K/km.

As seen in Equation (4.1) and in Figure 4.2 the height of the air column will affect the force exerted to the surface. Therefore, all else being equal, the larger the elevation of the surface area is, the smaller the pressure will be. The barometric formula is a formula which is used to model how the pressure of the air changes with altitude. It is a useful formula as it does not require the density to be known. It can be derived from the ideal gas law (Equation (4.2)) but using intermediate Equations (4.7) and (4.9) the density can be expressed as

$$\rho = \frac{M \cdot P}{R \cdot T} \tag{4.11}$$

where M is the molar mass of the air, P is the absolute pressure, R is the universal gas constant, and T is the temperature. Assuming all the pressure hydrostatic, applying basic equation of hydrostatics gives

$$\mathrm{d}P = -\rho g \ \mathrm{d}h = -\frac{M \cdot P}{R \cdot T} g \ \mathrm{d}h \tag{4.12}$$

where the gas pressure P is a function of the altitude h and g is the gravitational acceleration. Integration after reordering gives

$$\int \frac{\mathrm{d}P}{P} = -\int \frac{Mg}{RT} \ \mathrm{d}h \implies ln \ P = -\frac{Mg}{RT} h + ln \ C \tag{4.13}$$

and finally the barometric formula

$$P = C\ exp(-\frac{Mg}{RT}h) \tag{4.14}$$

The constant of integration C can be determined from the initial condition $P(h = 0) = P_0$ where P_0 is the average sea-level pressure. Therefore, the formula can be expressed as

$$P = P_0\ exp(-\frac{Mg}{RT}h) \tag{4.15}$$

where T is the difference in temperature between the sea level and the height h.

By substituting constants M, R, and $g = 9,81$ m/s^2, and applying the average sea-level values $P_0 = 101.325$ kPa and $T = 288.15$ K to Equation (4.15), a function $P_{MSL}(h)$ can be formed:

$$P_{MSL}(h) = 101350\ exp(-0,000119 \cdot h) \tag{4.16}$$

For example, above 150 meters of the sea level the pressure is 99 556.95 Pa (supposing an average temperature of 15 °C). Commonly used rule-of-thumb is the pressure decrease of about 12 Pa for every meter in altitude.

The *mean sea-level pressure* (MSLP) is the atmospheric pressure at the average sea level. It is usually formed by reducing the pressure value, which is measured at a given elevation on land, to the sea level assuming the lapse rate of temperature 6.5 K/km. MSLP is the atmospheric pressure used in common weather reports and forecasts. By using the common reference level (that is, the mean sea-level) makes the reports meaningful and comparisons possible because they are not dependent on geographic location – in particular, the altitude. Weather maps using isobars are a good example of the usage of MSL pressure.

4.2 Overview of Barometers

An instrument used to measure atmospheric pressure is called a barometer. Barometer designs vary from simple water-based Göethe barometers (named after Johann Wolfgang Von Göethe, a German writer who first built such a device) and mercury barometers to commonly seen aneroid barometers that are characterized by a telltale requirement of a tapping to force the pointer to move and reveal whether the pressure is falling or rising. More recent designs are based on micro-electro-mechanical systems (MEMS) that allow fabrication of digital barometer chips with sizes smaller or as small as 3×3×1 mm (see [22], [23]). Applications where MEMS-based barometers are commonly used include GNSS receivers, sport watches, and weather stations. MEMS barometers also guarantee higher degree of accuracy and reliability than earlier designs. [24.]

A pressure reading given by a barometer is specific for the point it is located. In other words, the measured pressure depends on the density of the air above and the altitude of the barometer. Therefore, the value a conventional barometer measures is called as the *absolute pressure.*

A measurement of absolute pressure can not be used to determine altitude without reference pressure level. An instrument for determining altitude is known as an altimeter. It calculates vertical distance in accordance with a predetermined reference level. The barometric altimeter follows this principle: it measures altitude in accordance with atmospheric pressure.

A typical application where barometric altimeters are used are aircraft altimeters. This kind of altimeters require the pilot to reset the reference value of the altimeter based on radio-transmitted aviation reports (known as METARs) sent from airfields. For example, an airfield 100 meters above MSL reports the atmospheric MSL pressure of 101.0 kPa. A pilot near the airfield resets aircraft's barometric altimeter accordingly. The pressure at the level of the airfield is 99.8 kPa (about 1.2 kPa less than the MSL pressure because of the elevation of the airfield). Therefore, if the absolute atmospheric pressure at the level of the aircraft is, for example, 90.0 kPa, the barometric altimeter reports the aircraft altitude as 817 m above the airfield:

$$\Delta p = 90.0\ kPa - 99.8\ kPa = -9.8\ kPa$$

$$h(aircraft) = \frac{\Delta p}{-1.2\ kPa/100\ m} \approx 8.17 \cdot 100\ m = 817\ m$$

where −1.2 kPa/100 m is the pressure lapse rate.

In addition to determining altitude, the barometer can be used to track changes in altitude. It is possible as the absolute pressure measured by the barometer changes with the altitude. However, utilizing this method over long time periods is not feasible because of the drifting caused by changes in weather.

4.3 Enhancing GNSS Positioning with Barometric Sensors

GNSS performance can be improved by integrating barometric sensor input to position determination calculations or using it in continuous navigation. Barometric altimeters are commonly used as an altitude tracking aid in GNSS receivers available commercially (see [25]). Barometer can be considered one of the enablers for indoor navigation. The altitude tracking method is described in the next section.

Another improvement to receiver performance is to assist the receiver-integrated barometer with a reference air pressure. This method improves especially receiver availability and altitude accuracy. Preliminary research and results regarding this method are done in [26]. Assisted receiver barometer is described in Section 4.3.2.

4.3.1 Tracking Altitude with Barometric Altimeter

Commonly seen enhancement in commercial GNSS PDUs – especially in receivers intended for hiking and similar activities – is the barometric sensor. Its output is used to continuously track changes of receiver altitude after an initial position determination. A GNSS receiver using this method to improve altitude accuracy does not require any knowledge of a reference pressure level as the barometer does not determine absolute altitude itself.

Receivers with barometric altitude tracking benefit from the accuracy of MEMS barometers. Resolution of pressure data of current MEMS barometers is around 1 Pa (less that 10 cm in altitude) [23]. This level of accuracy in altitude tracking makes barometers feasible instruments, for example, in indoor positioning where information about the user's floor in the building is required.

4.3.2 Improving Receiver Performance with Pressure Assistance Data

The barometer can be used as an altimeter in GNSS receivers if the reference pressure value is known by the receiver. Advantages are clear: where typical standard deviation of vertical GNSS position estimates are 10–50 meters in urban environment, receivers with barometers using reference pressure level assistance achieve an average of 95% improvement in the vertical accuracy [23].

If the reference pressure level is known the altitude of the receiver can be calculated using following equation:

$$h_{MSL} = \frac{P_{receiver} - P_{reference}}{L} \tag{4.17}$$

where $P_{receiver}$ is the absolute pressure measured by the receiver barometer, $P_{reference}$ is the MSL pressure reference value, and L is the lapse rate of the pressure (for example, -1.2 hPa/100 m or more precise value derived from Equation (4.15)).

When atmospheric pressure can change a few hPa over a course of an hour it is vital from the accuracy point of view that the reported reference level is valid at the time of its use. In addition, reference pressures are highly location-dependent which makes it pointless to generate, for example, nationwide assistance data. These facts make the utilization of assisted barometers difficult because accurate enough pressure reference data is not generally available.

In addition to improved vertical accuracy, GNSS receivers utilizing barometric assistance data benefit from improved sensitivity. The barometric altitude can be considered another pseudorange towards the center of the Earth. Therefore, as discussed in Section 2.3, the receiver is required to acquire signals only from three GNSS SVs as there is one unknown less. This improvement in receiver availability is important especially in poor signal conditions usually found in dense urban environment.

5. IMPLEMENTATION OF THE SERVICE

A barometric assistance service was designed and implemented as a part of this thesis. This chapter gives a detailed description of the aspects of the service itself as well as the essential inter-operable systems.

The next section discusses the reasons for the implementation of the service. Input data – from which the reference pressure assistance data is calculated – is described in Section 5.3. In Section 5.2, the requirements for the service are described. The structure of the service is represented in Section 5.4.

Section 5.5 provides the description of the algorithms and optimizations used during the assistance data calculations. Quality assurance is discussed in Section 5.6.

5.1 Background

Urban canyons and dense urban surroundings are a challenging environment for GNSS receivers. Even for assisted GNSS receivers, multipath propagation may deteriorate PVT estimates to unacceptable levels when users would require accurate position fixes starting from the first estimate the receiver gives.

Improvements to vertical accuracy of first position fix were described in Section 4.3.2. As there is available high resolution weather forecast data (see Section 5.3) which could be used as an input for the barometric assistance calculations, it was decided that an implementation of a barometric assistance service is required for further trials. Because the applicability of the service using the forecast data was unknown, the design of the service was set as lean as possible to allow rapid implementation phase which would make early transition to testing possible and, later on, the assessment of the feasibility of the barometric improvement method.

5.2 Requirements for the Service

The barometric assistance service is in practice a suite of software running on a server. Its primary task is to calculate barometric assistance data for GNSS receivers from weather forecast data. The assistance data is composed at least of time- and place-dependent atmospheric pressure reference level information. The service is mostly usable in dense cities which requires the service to be configurable to support a number of locations for which assistance data should be generated.

Using weather forecast data points (see Section 5.3) as assistance data without optimizations or simplifying would require bandwidth relative to the number of data points. Therefore, the generated assistance data should be an optimized subset of weather forecast data.

During the planning stage *configurability* and *maintainability* were identified as primary characteristics of the service. The implemented service software should be easily configurable as it allows trying out various different sets of options in testing to find out the most applicable combinations. Also, the reference assistance data to be produced is highly location dependent which requires, for example, a way to configure an arbitrary number of points-of-interest for the calculations. In other words, configurability makes it easy to change the way the service software works within limits.

Maintainability of the service was another identified requirement. It stands for the ease with which the software can be fixed (in case a found defect), changed to meet new requirements, or otherwise improved. Maintainable software should not require support from the original author but could be understood and maintained by a skillful person in art.

5.3 Atmospheric Pressure Forecast Data

Input data for the barometric assistance service is weather forecast data. Used forecasts are part of the research programme called High Resolution Limited Area Model (HIRLAM). HIRLAM is a research cooperation of European meteorological institutes, and its aim is to develop and maintain a numerical short-range weather forecasting system. [27.]

Forecasts based on the HIRLAM model are generated by the Finnish Meteorological Institute (FMI) four times a day. The forecast dataset is a two-dimensional grid of data points. The dataset consists of data points for every 0.067 decimal degrees vertically and horizontally (that is, forecast data points are modeled for about every 6.7 km). The HIRLAM dataset used in the barometric assistance service is a rectangular area from 36°N 11°W to 71.156°N 32.452°E and it consists of 336 690 separate data points.

The FMI has made its data sets as a free-or-charge Open Data service in the beginning of June 2013 [28]. The barometric assistance service accesses machine-readable HIRLAM forecast data using the Application Programming Interface (API) of the FMI Download Service which is defined in [29].

The forecast data is downloaded by the service in GRIBv1 (GRIdded Binary, version 1) format which is a standard data format defined by the World Meteorological Organization (WMO). GRIB – officially designated as FM 92-VIII Ext. GRIB – is a general-purpose, binary data exchange format for transmitting large volumes of gridded data over communications networks. It is suitable for machine-to-machine communications by definition. [30.]

The HIRLAM forecasts of MSL pressure and temperature (2 meters above ground) are downloaded by the assistance service. The MSL pressure forecasts are used to calculate time and location-dependent reference pressure levels which can be used as assistance data in GNSS receivers with the barometer.

5.4 System and Service Architecture

The barometric assistance service is a suite of various software applications running on a server machine connected to the Internet. The main application, which is responsible for processing and optimizing forecast data to assistance data, was designed and implemented as a part of this thesis. In addition, the service uses various other tools for auxiliary tasks, such as file downloading over the Internet.

A high-level diagram of the system architecture of the barometric assistance service and related systems is shown in Figure 5.1.

The forecast datasets are generated in the FMI four times a day. Forecast datasets

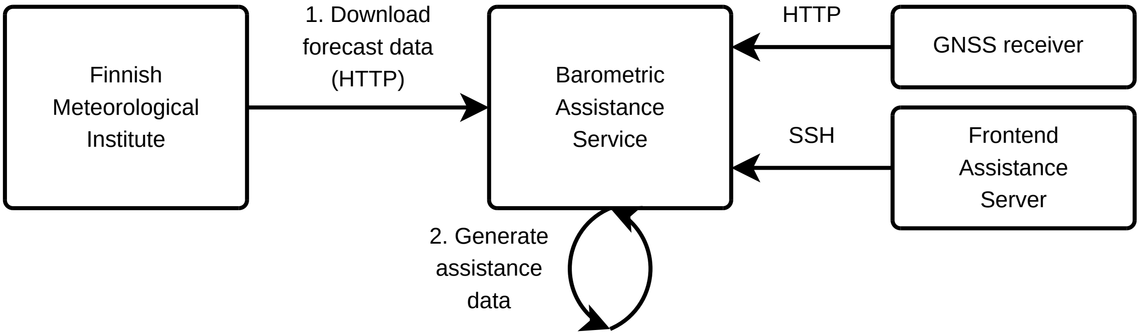

Figure 5.1: *Block diagram of the barometric assistance service and related systems. Input data for the service is (1) downloaded from the FMI using the Open Data API. Based on the forecasts, barometric assistance data is generated (2) locally by the service software. The assistance data is made available for download for the Internet clients: both Hypertext Transfer Protocol (HTTP) and Secure Shell (SSH) protocol are supported.*

are downloaded and saved to the hard disk of the assistance server as separate files four times a day (see (1) in Figure 5.1). Each saved file contains a dataset for one-hour time period. These files are used as an input for the barometric assistance application.

The assistance application calculates assistance data for each hour (see (2) in Figure 5.1). As required, the assistance data is generated only for defined areas to keep the assistance file size low. A configuration file, written in Extensible Markup Language (XML), contains, for example, an user-defined set of coordinate pairs of locations where barometric assistance data should be generated. An example configuration file is shown in Appendix A.2.

The configuration file is divided to a number of countries. Each country is identified by a Mobile Country Code (MCC) and each one includes an arbitrary number of coordinate pairs of points-of-interest for which assistance data is calculated. User must define the country, which the assistance data is generated for, by giving its MCC when the application is started.

The assistance application was implemented in C++ programming language. The implementation follows object-oriented programming paradigms such as data encapsulation using classes. In addition to Standard Template Library of C++ and ISO C libraries, the application makes use of a few third-party software libraries as well. These libraries are used as part of the main implementation or in auxiliary tasks, such as in unit testing. The list of utilized software libraries are listed in Table A.2 in Appendix A.1. In addition to the main application, a number of unit tests were implemented using Google's googletest testing framework (see [31]). The software documentation was created from the annotated comments in the source code using Doxygen.

The barometric assistance service was set up running on a server running Debian GNU/Linux distribution. In addition to default tools included in the Debian distribution, auxiliary software that were used are listed in Table A.1 in Appendix A.1.

5.5 Optimizing Assistance Data

As discussed it is impractical for the GNSS receiver to download all data points of each hour-long forecast. Considering smart phones, the automatic downloading of large volumes of data would increase data transfer fees and disturb functionality of applications that require network connectivity. Also, the processing of large datasets requires processing power which is scarce in battery-operated mobile receivers. Therefore, the required calculations are made by the barometric assistance server-side software.

The primary problem of converting forecast data to assistance data is ensuring the validity of the data used by the GNSS receivers. Especially the fact that the weather changes can be fast with rapidly fluctuating atmospheric pressure levels must be taken into consideration in the calculations. On the other hand, the optimization method must be straightforward and simple enough to be a feasible option in the application implementation.

The selected optimization method is based on the calculation of an average pressure reference value for an area around a center location. The average pressure for an area is calculated by increasing the size of the area until a pressure value of new data point differs from the average more than some predefined value. The method consists of following steps:

1. Search the closest forecast data point to the center point (which is read from the configuration file).

2. Increase the area around the center point by including more forecast data points and calculate arithmetic mean of pressure values.

3. Continue increasing the area until a pressure value which is to be included to the area differs from the average more than predefined limit.

The maximum pressure difference value can be passed to the assistance application as a command line option. In practice, the difference value will become the uncertainty of the optimization method. For example, with a value of 50 pascals, the uncertainty of the resulting assistance data is (at least) ±50 Pa, which translates to the error of ±4.2 meters in altitude. It is notable that this value of uncertainty excludes any bias in the forecast model or the offset in the receiver.

After the application has calculated an area with an average pressure within bounds it transforms the area to a circle. The radius of the circle is set equal to the shortest distance to the border of the calculated area. Now the location and time-dependent barometric assistance data can be expressed with following variables:

- Reference time (from which the assistance is valid)
- Latitude and longitude of the center point of the area of validity
- Radius of the (circular) area of validity
- Atmospheric pressure reference value (MSL)

Center point	Pressure (Pa, ±50)	Radius (km)	Area coverage (km^2)	Est. population (million)
Tampere (61.498 23.771)	101 556	45.3	6 447	0.4
Helsinki (60.170 24.931)	101 636	16.7	876	0.7
Oulu (65.017 25.467)	101 709	14.3	642	0.1
Berlin (52.5167 13.3838)	101 906	39.3	4 852	4
Hamburg (53.5653 10.0014)	101 683	21.1	1 399	2
Munich (48.1334 11.5667)	102 098	42.8	5 755	2

Table 5.1: *An extract of assistance data for selected cities in Finland and Germany. The data is for 06-Jun-2013 12:00–13:00 UTC. The uncertainty of pressure values is 50 Pa. In the table an effective area is calculated, for which each reference pressure value is valid. Lastly, an estimate of population living on the area is given.*

From these values the assistance application creates assistance files that are made available for the clients (see Figure 5.1) to download. The assistance application exports the assistance data in a binary format. The format is a proprietary assistance format specified by Nokia Corporation and it is not covered in this thesis.

In Table 5.1 contains an extract of assistance data for three Finnish and German cities. With current data format, the assistance data for each city takes 20 bytes per an hour (excluding message headers). For example, the reference pressure value calculated for Tampere in Table 5.1 was calculated from 572 forecast data points. If each of these points would use 4 bytes for the pressure value and 8 bytes for the coordinate pair, the total data amount would be about 6 900 bytes (per an hour) for the same area.

Preliminary testing of the barometric assistance service was conducted using a prototype receiver with an integrated barometer. The test was conducted comparing the results with another receiver which was identical with an exception of not using barometric assistance data. In Figure 5.2 the results of the altitude measurements of the conducted test are shown.

Figure 5.3 contains the results for the horizontal coordinates. The accuracy of the horizontal positioning has not visibly improved at least in tests in good signal conditions. However, the receiver that used the barometric assistance data performed more consistently and with better accuracy than the regular receiver. As seen in Figure 5.4, only a small improvement of about 1 second in TTFFs was noticed during the test.

5.6 Designing a Robust Service

The validity of the assistance data is of great importance. The object of the service is only to improve the receiver performance without a chance of degrading it with erroneous data. The service was designed to stop generating any assistance data in case discrepancies are found in the forecast data. If the GNSS receiver were to use assistance data an offset of, for example, 1 kPa from the true pressure, the first assisted position estimate would be off by about 80 meters.

One way the barometric assistance application tries to prevent plainly erroneous

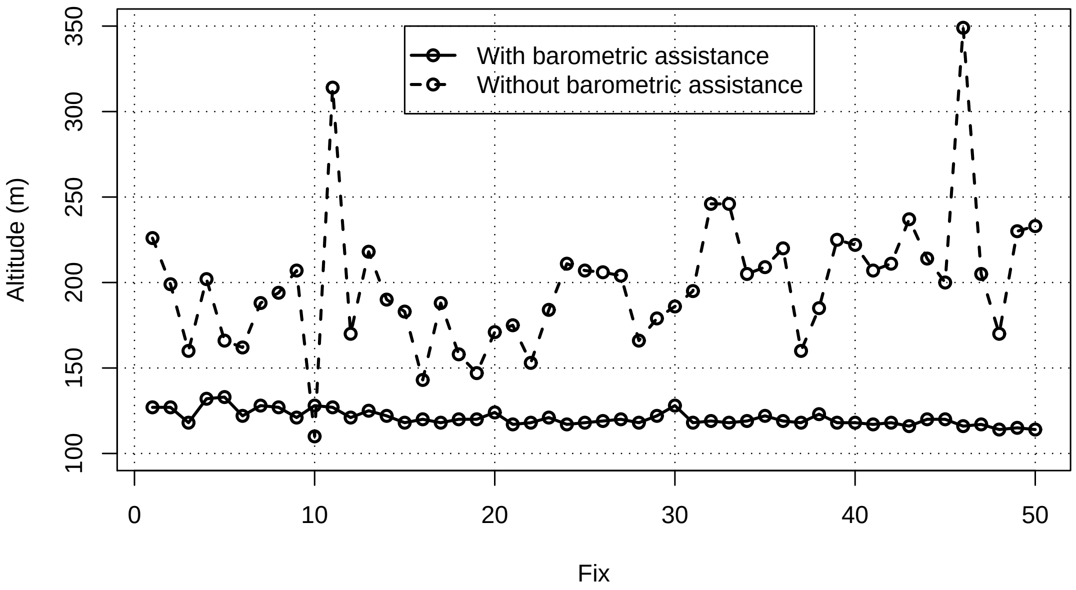

Figure 5.2: *Recorded altitudes of 50 distinct position fixes. Receivers were identical both were using regular assistance data. The receiver with the barometer has determined its altitude more accurately and consistently from the first fix on. Without the barometer the altitudes of the first position estimates are highly erroneous.*

values from affecting the assist data is to inspect the forecast data for exaggerated values. In normal conditions, atmospheric pressure fluctuates around 100±10 kPa: The highest atmospheric pressure ever recorded has been about 109.4 kPa and the lowest was about 87.0 kPa – both recorded in very extreme weather. The assistance application uses these values as limits to filter out possibly extreme weather or faulty data.

At the moment, there is no way to make sure the forecast data from the HIRLAM is not biased or plainly erroneous. This limitation could at least be amended by utilizing a network of local real-time weather stations and compare their atmospheric pressure measurements to the forecast data. This approach requires not only the weather stations itself but rather accurate measurements from them including the known elevation of the station.

A way to improve the assistance method would be by detecting strong inbound weather fronts from the future forecast data and exclude these area when calculating assistance data. As atmospheric pressure can change rapidly during such weather

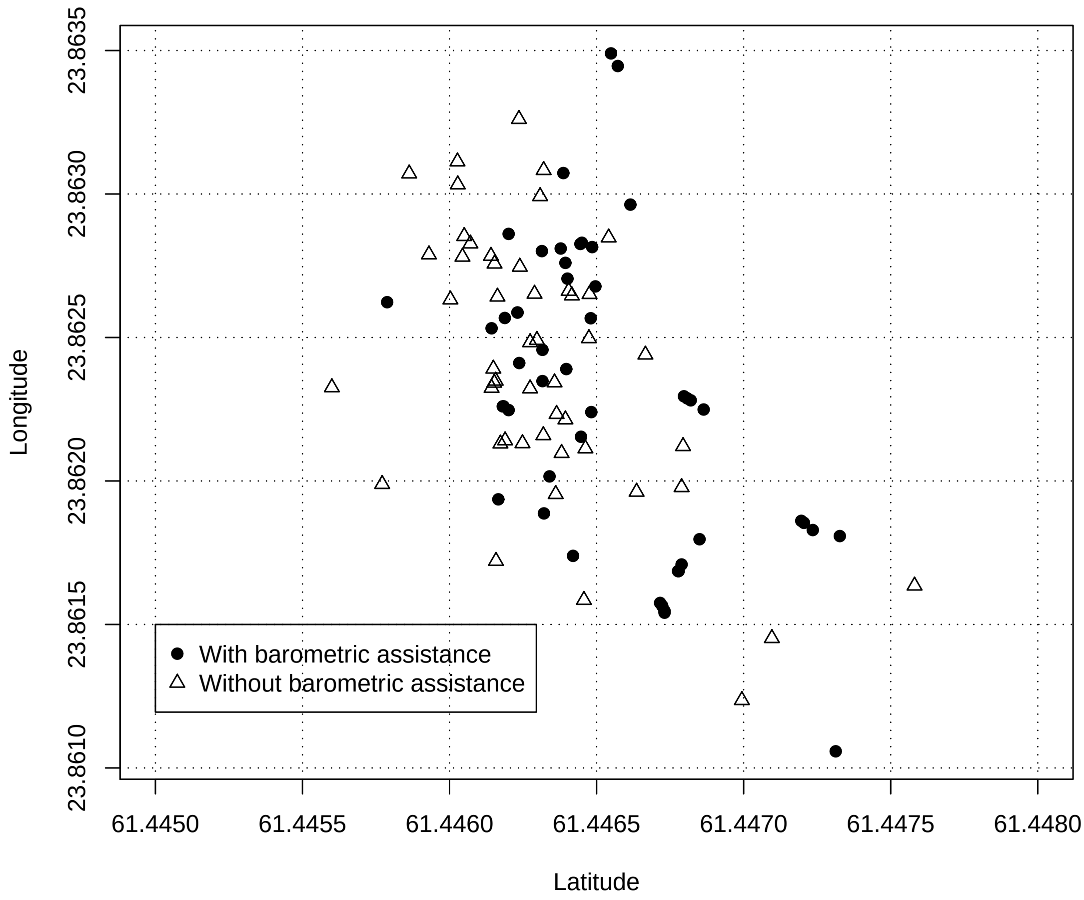

Figure 5.3: *Latitude and longitude of 50 distinct single position fixes during the conducted test. Receivers were identical and both were using regular assistance data. The receiver utilizing barometric assistance data does not generate visibly more accurate position estimates than the regular receiver.*

fronts, probability of erroneous reference pressure values would increase. In future research of the barometric assistance method the applicability of this improvement should be inspected.

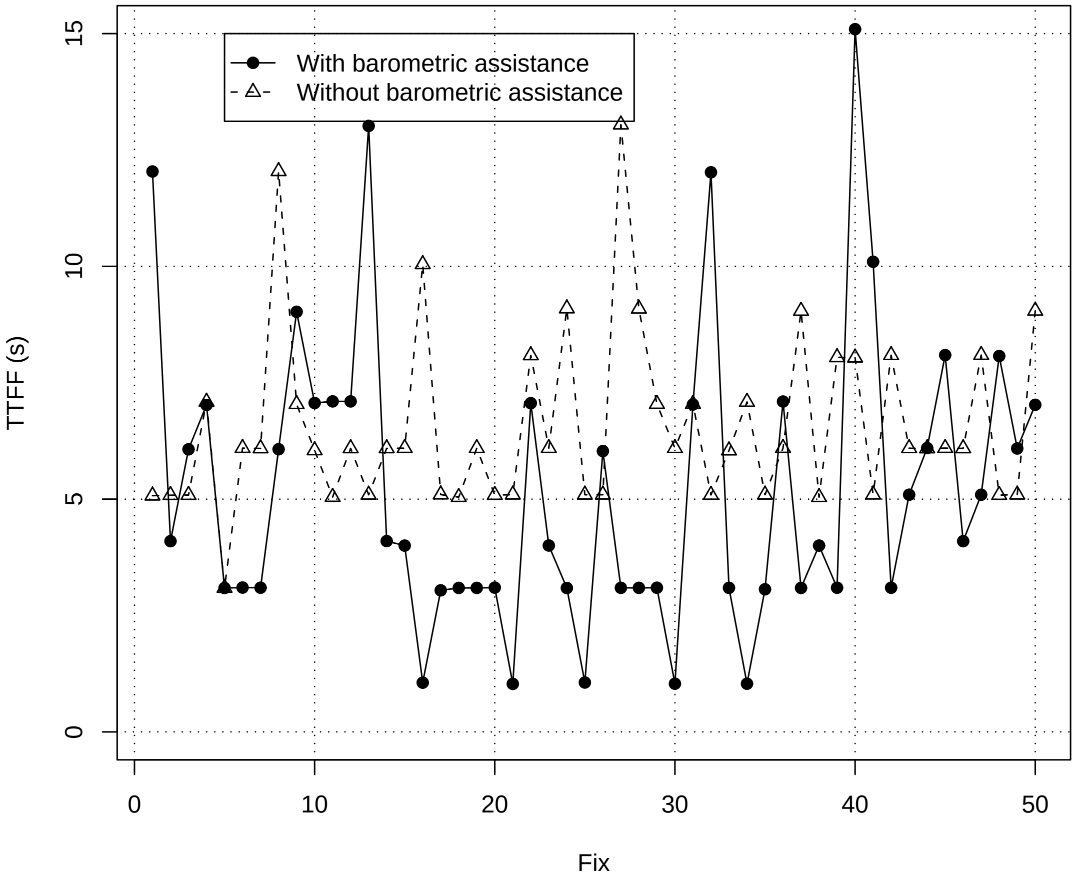

Figure 5.4: *Difference between time-to-first-fix values of two assisted receivers. In the test 50 single position fixes were recorded. Mean TTFF of the receiver utilizing the barometric assistance service was 5.27 seconds and for the receiver without the barometric assistance it was 6.56 seconds.*

6. CONCLUSIONS

In-market GNSS receivers suffer from poor signal conditions that are usually encountered in dense urban environment. The availability of the positioning service, the accuracy of the position estimates, and time-to-first-fix could all be improved in challenging surroundings if GNSS receivers could utilize altitude information from another source than the satellites of the positioning system.

The altitude determination from the atmospheric pressure is possible if a reference pressure at the specified level is known. If a receiver with an integrated barometer could determine its barometric altitude and use it as part of the positioning process the availability of the positioning service, the positioning accuracy, and time-to-first-fix would improve.

This thesis presented an implementation of a barometric assistance service which generates barometric reference data for GNSS receivers. As shown in the results, receivers utilizing the assistance data will be able to determine their positions more accurately and consistently especially in challenging surroundings. The assistance data was calculated from high resolution weather forecasts generated by the Finnish Meteorology Institute as part of the European HIRLAM project.

The implementation of barometric assistance service makes further research of the concept possible. Firstly, additional tests should be conducted in the field to ensure the applicability and feasibility of the concept in practice. Secondly, assuring the consistent quality of the generated assistance data requires further studies, especially the availability of forecast data with higher resolution should be surveyed. Thirdly, the possible sources of forecast data for the United States and Asia should be sought if the service is to be expanded towards the commercialized global service.

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A. APPENDICES

A.1 Additional software applications and libraries

Application	Function	Available
Apache HTTP Server	HTTP server for barometric assistance data	`http://httpd.apache.org/`
curl	Command line tool for making HTTP requests to the FMI Open Data service	`http://curl.haxx.se/`
Doxygen	Tool for generating documentation from annotated C++ source code.	`http://www.stack.nl/~dimitri/doxygen/`
OpenSSH server	SSH server for barometric assistance data	`http://www.openssh.org/`

Table A.1: *Notable secondary software applications used with the barometric assistance service. The list does not include standard applications included into typical GNU/Linux distributions.*

Library	Function	Available
Apache log4cxx	Logging framework for C++. Based on Apache log4j.	[32]
Boost Filesystem	Portable methods to query and manipulate filesystem paths, files, and directories.	[33]
googletest	Google's C++ test framework based on xUnit.	[31]
GRIB API	Methods for encoding and decoding GRIB (version 1 and 2) messages.	[34]

Table A.2: *Software libraries used in the barometric assistance service implementation. The list does not include C++ or C standard libraries.*

A.2 Example XML configuration file

Listing A.1: *An example of the XML configuration file which is used by the barometric assistance application.*

```
<?xml version="1.0" encoding="us-ascii"?>
<config>
  <log>
    <level>INFO</level> <!-- Logging level of log4j -->
  </log>
  <country code="244"> <!-- Finland -->
    <outfile>0.bin</outfile>
    <area>
      <name>Tampere</name>
      <latitude>61.498</latitude>
      <longitude>23.771</longitude>
    </area>
    <area>
      <name>Helsinki</name>
      <latitude>60.17</latitude>
      <longitude>24.931</longitude>
    </area>
    <area>
      <name>Jyvaskyla</name>
      <latitude>62.233</latitude>
      <longitude>25.733</longitude>
    </area>
  </country>
  <country code="262"> <!-- Germany -->
    <outfile>1.bin</outfile>
    <area>
      <name>Berlin</name>
      <latitude>52.516691</latitude>
      <longitude>13.383812</longitude>
    </area>
  </country>
  <country code="240"> <!-- Sweden -->
    <outfile>2.bin</outfile>
  </country>
  <!-- Mapping from Mobile Country Codes to arbitrary indices -->
  <mccmap>
    <mcc id="0">244</mcc> <!-- Finland -->
    <mcc id="1">262</mcc> <!-- Germany -->
    <mcc id="2">240</mcc> <!-- Sweden -->
  </mccmap>
</config>
```