FAKULTÄT FÜR !NFORMATIK
Faculty of Informatics

Techniques and methods for the collection of location data and influencing factors on the accuracy of location measurements

DIPLOMARBEIT

zur Erlangung des akademischen Grades

Diplom-Ingenieur

im Rahmen des Studiums

Software Engineering & Internet Computing

eingereicht von

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Wien, 25. Juli 2015

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DIPLOMA THESIS

submitted in partial fulfillment of the requirements for the degree of

Diplom-Ingenieur

in

Software Engineering & Internet Computing

by

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to the Faculty of Informatics

at the Vienna University of Technology

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Vienna, 25th July, 2015

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Wien, 25. Juli 2015

Christopher Simerle

Acknowledgements

First of all I want to thank my advisors Simone Kriglstein and Margit Pohl for their great support during the writing of this thesis - their input, thoughts and help during the early stages were invaluable and they also always had a spare minute for discussion.

Furthermore I also want to give thanks to my parents, who supported me during the whole time and made all this possible.

On a final note I especially want to thank Magdalena, who always had an ear for my rants/problems and miraculously managed to keep my spirits high.

Kurzfassung

Mit dem Aufkommen einer neuen Generation von mobilen Geräten, wurden Millionen an unabhängigen Nutzern mit einer neuen Welt bekanntgemacht die sie so bis dato noch nicht kannten - der Welt der Location Based Services (LBS), der standortbezogenen Dienste. Heutzutage ist es schwer sich vorzustellen ohne Navigationsdienste, die rund um die Uhr erreichbar sind, auszukommen - sei es eine simple Suche nach einem neuen, unbekannten Hotspot via Google Maps oder das Navigieren bei einer Reise durch fremde Länder. Um dies alles zu ermöglichen braucht es jedoch Daten, standortbezogene Daten um genau zu sein. Das Ziel dieser Arbeit ist es eine schlüssig Übersicht zu präsentieren, wie diese Daten in der heutigen Zeit mit der Hilfe von mobilen Geräten wie Smartphones zustande kommen. Es wird aufgezeigt wie aktuelle Lösungsansätze und Technologien aussehen und funktionieren als auch dargelegt welche Vor- und Nachteile existieren bzw. welche Faktoren in welchem Ausmaß Einfluss auf die Genauigkeit der gesammelten Daten haben.

Die Arbeit beginnt mit einer ausführlichen Literaturanalyse, um aktuelle State-of-the-Art Lösungsansätze und Technologien bezüglich der Generierung von Standortdaten mit Hilfe von mobilen Geräten zu sammeln. Diese Ansätze werden dabei grob in globale und lokale Systeme unterteilt und beschrieben. Inkludiert in das Kapitel, welches sich mit lokalen System beschäftigt, ist dabei ein sehr kontroverses Thema - die komplexe Welt des Indoor Positionings, der Positionsbestimmung in Gebäuden, für welche aktuelle Lösungsansätze ausführlich diskutiert werden. Im Zuge dieser Analyse und der gewonnen Information wurden unterschiedliche Szenarien, die sich dabei zur Positionierung auf das Global Positioning System (GPS) verlassen, erstellt und ausgeführt. Ziel des Ganzen ist es die theoretische und praktische Genauigkeit der, von den mobilen Geräten erhobenen, Positionsdaten in den unterschiedlichen Szenarien zu evaluieren und zu vergleichen um zu sehen unter welchen Umständen diese vertrauenswürdig sind.

Abstract

With the advent of a new generation of mobile devices, millions of independent consumers were introduced to a new and wondrous world - the world of Location Based Services (LBS). Nowadays it is hard to imagine a world without a round the clock navigation service like Google Maps to find ones favorite hotspot or taking a trip across the country. However, to be able to navigate the world requires specific data, location data to be precise. The goal of this thesis is to provide a conclusive overview of how location data using mobile devices is gathered, the general approaches and technologies utilized as well as to show up influencing factors concerning the accuracy of this data.

The first part of this thesis deals with the state-of-the-art approaches, techniques and methods of gathering location data using mobile devices. To this end extensive literature research on the basis of constructive research was used, providing clear objectives and tasks, to give a conclusive overview on how this is accomplished using global systems as well as local systems. The chapter on Local Positioning System (LPS) also includes a very controversial topic - the complex world of indoor positioning - for which current approaches are discussed at length. Based on this information several different scenarios, which use the Global Positioning System (GPS) to provide the needed location data, were created. Goal of this undertaking is to examine and evaluate the actual accuracy values of location data gathered by different mobile devices. The contribution of this thesis is to see under which conditions the location data provided can be trusted and when not.

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CHAPTER 1

Introduction

1.1 Motivation and Problem Statement

Software services which use location data to control certain features, so called Location Based Services (LBS), have been around since 2000 but were mostly in commercial hands with heavy use of subscription-based business models. With the release of Apple's 3G iPhone and Android, Google's LBS-enabled operating system, however, developers were allowed to introduce millions of independent consumers to the world of location based services like Google Maps or Apples Find My Friends. According to a 2013 report from Pew Research Center, an American research institute based in Washington, D.C, almost three-quarters of U.S. smartphone users get realtime location based information on their smartphones. A solid 19% increase up from 55% in May 2011 [1].

While these numbers seem random they paint a clear picture - more and more people are using and, in some cases, are dependent on location based services and furthermore on location data when using mobile devices. Finding social events nearby, request the location of the nearest service or business (e.g., cash machines) or even aiding search and rescue efforts are just a few examples. Due to the fact that LBS are becoming more and more prominent, it is imperative that the methods and techniques providing this location data are accurate. Furthermore not only the gathering techniques must be solid but also the applications and services themselves should do their part to provide location information as precise as possible. The user of such a location based service or, generally speaking, an application which is dependent on location data, should know how this information is realized. This knowledge can prove helpful to decide when to use what location gathering technique or to turn it off completely to significantly reduce power consumption of the mobile device [2, 3].

1.2 Research Questions

Based on the motivation and problem description a number of research questions come up for which this research project should provide conclusive answers. One might sum up these questions to the overall goal of providing an answer on how location data is gathered using mobile devices and what factors can have negative affects on the accuracy of this data.

Q1: Which techniques and methods for the collection of location data using mobile devices are state-of-the-art?
The most important part of this thesis is to provide a conclusive overview of the current techniques and methods for the collection of location data which is accomplished through extensive literature research.

Q2: Do these techniques and methods have specific advantages and/or disadvantages in certain cases or can be negatively influenced?
This question is immediately triggered in response to the first question. In addition to the overview a clear and precise listing of all positive and negative aspects of every gathering technique as well as influencing factors concerning the location data are identified and presented.

Q3: How accurate are these techniques and methods?
The answer to this specific question will be provided in two parts - firstly through extensive literature research and in the case of Global Positioning System (GPS), through certain testing scenarios which are created based on respective strengths and weaknesses as well as typical end user utilization (e.g., finding services/businesses in the inner city). The test results are documented, evaluated and presented to reveal noticeable shortcomings in specific situations (weather, buildings, electric disturbances, etc.). To compile this information a small location based application for the Android operating system is used which monitors all relevant data like values for latitude and longitude or accuracy.

1.3 Methodology and Approach

The general approach of this thesis consists of three greater parts:

- The first part explores the current techniques and methods for gathering location information. Firstly the use of a Global Navigation Satellite System (GNSS), namely GPS, is addressed. The Chapter starts with a brief introduction in the general history of GPS. This section is deliberately kept short and serves only the purpose of introducing the novice reader to the topic of gathering location information and location based services. Afterwards the general mechanics of GPS are explained which includes a detailed look into the different segments and the basic workings of range measurements. Nowadays GPS is not the only available GNSS anymore, so a brief digression is taken to inform the reader about other satellite systems. This first Chapter will close with a detailed look into the influencing factors concerning the accuracy of satellite systems. Secondly, working alternatives to GPS are addressed, Local Positioning System (LPS) to be precise. As before with GPS, the general mechanics of the different possibilities concerning LPS are discussed as well as relevant shortcomings of every LPS method. To provide accurate information in the context of this first two Chapters, extensive reviews are conducted using specialized literature.

- The second part is the design of three different scenarios to assess the quality of gathered location data. These scenarios are modeled with reference to gathering methods and influencing factors which were identified in the previous parts as well as typical real world use of location based services. The general idea is to compare certain reference location data to measurements taken during the scenarios. The reference data is gathered by using a service provided by the land surveying office of the city of vienna called ”Geodatenviewer“ [4]. The geo-information provided by this service is accurate down to 25 centimeters and is therefore more than enough to provide viable reference points.

- The third part is the execution of the designed scenarios and the evaluation of the gathered data. Devices utilized for the scenario measurements are a Samsung Galaxy Nexus i9250, a HTC One SV as well as a Motorola Moto G2. The data collected during this scenarios is documented and afterwards presented to assess the actual accuracy.

1.4 General Structure

Following this introductory section the remainder of the thesis is structured as follows. Chapter 2 starts off with providing an insight into the thinking process during the literature research. It states the used strategy to find relevant information and why or why not certain literature was used. Included into this chapter are two major sections which cover the theoretical basis of state-of-the-art methods for gathering location data.

The first section deals with the ”grandfather“ of navigation - the GPS - and its origins. The roots of the now de-facto standard concerning navigation are explored and explained in great detail. Intensive literature research was used to provide an overview on how this GNSS operates, the different segments that are needed as well as a small digression into satellite systems developed by different countries. The section closes with a conclusive overview of the major influencing factors concerning the accuracy of measurements using a GNSS.

The second section in Chapter 2 deals with the positioning using LPS and furthermore with one of the great difficulties concerning navigation and LBS - indoor navigation. In this section the great range of possibilities is presented, dealing with state-of-the-art realizations of indoor positioning systems, starting with the inherent conundrum of complexity and specifications.

Chapter 3 describes the general design of the testing scenarios down the smallest detail to provide conceivable explanation as to why the different scenarios were designed the way they are. The general procedure as well as evaluation methods are explained in separate sections and the data gathered during these tests is evaluated, described and presented.

Chapter 4 is devoted to the discussion of the major findings of this thesis. These findings range from results of the literature research to the data collected with the help of the created scenarios. Goal of this section is to revise all the information gathered during this thesis and to provide a conclusive answer to the proposed research questions.

The last chapter of this thesis provides a conclusion on the results as well as the general topic and discusses further work and research which could be done in the near future.

CHAPTER 2

Literature Analysis

The actual literature research done during this thesis is adapted from the guidelines proposed in Kitchenham [5]. These guidelines are intended to assist PhD students or research groups with several members and provided helpful hints which aided during the research stages of the thesis. One goal of this extensive literature research was to collect information to be able to provide a conclusive overview on how gathering location data using mobile devices is accomplished using state-of-the-art techniques and methods. Furthermore this preceding research should supply helpful information for clear tasks and objectives necessary for the test and evaluation stages of the thesis.

In the beginning, after writing the abstract which would serve as a rough outline of the work, the actual research questions were very vaguely defined. So the first step, which is also considered the most important part, was to specify these questions. Having done this, the second logical step seemed to go to a great source and wealth of information - the university library of the Vienna University of Technology. After a few preliminary searches using the online service provided, in combination with the keyword "gps", it was clear that several recent books concerning the topic were available. To be more precise the first few searches all netted a total of 1.893 books on the topic of the Global Positioning System (GPS). Given the fact that GPS, or the navigation using satellites in general, is basically "ancient technology" the concern with recent releases was thought to be an issue at first. Fortunately the university library was in possession of several useful books from authors like Kaplan [6], Bauer [7] or Groves [8], with quite recent releases, none of them further back than 2006, so additional searches were constricted to the year 2000 and above. All in all the selection was reduced to 7 individual books which were chosen due to relevance, date of publication and a quick read through.

It also occurred that the information needed during this first part was available at first hand and, even better, with close to real time updates as it gets. GPS was and is a military project which basically has been overtaken by use cases in the private sector - so the U.S. government made information about it and related systems publicly available and does so to this day. This includes important information concerning the space and ground segment as well as services provided.

Incidentally one of these books, Samama [9], recovered during this first research exercise also contained detailed information about a later section in Chapter 2, namely positioning using a Local Positioning System (LPS). During the actual research for this part of the thesis yet another trip was taken to the university library this time involving keywords like “lps” or “local positioning systems”. Unfortunately these searches did not turn up quite the expected results, so the terms of the search had to be altered. Using keywords like “location based services”, “lbs”, “mobile computing”, “wlan positioning”, “bluetooth positioning” and “smart phone” alone or in combination, including a timing constraint from the year 2000 and upwards, yielded interesting and quite recent results like Chen [10], Brimicombe [11] or Werner [12].

Another great resource which has been used extensively during the course of this thesis was the Institute of Electrical and Electronics Engineers (IEEE) Xplore Digital Library. Other libraries like Association for Computing Machinery (ACM) or Springer were also used but not this extent, due to unsatisfactory results and, in some cases, access problems. Especially during the later stages of positioning using a LPS, most of the books found in the university library exhausted their usefulness due to the wide range of possibilities and complexity of the area. Only one, namely Samama [9],, provided tremendous help in figuring out a general approach to the topic of indoor positioning. Using this information, the IEEE Xplore Digital Library was utilized to its fullest to find current articles and papers to the solutions mentioned in the book - very often the keywords used in the search were nothing more than the actual name of the method like “infrared” or “uwb” in combination with ”indoor“ or ”indoor positioning“ to yield good results. After a few searches the results turned out to be even better, due the fact that several very recent studies have been conducted to provide exactly the information needed. The data provided in Werner [12] Koyuncu [13], Al-Ammar [14] and Dardari [15] proofed to be very helpful in providing a conclusive overview and validate that the information given in Samama [9] is still relevant.

2.1 GNSS - Global Navigation Satellite Systems

2.1.1 GPS - Global Positioning System

In the early 1960s various government organizations of the U.S, including the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA) and the Department of Transportation (DoT), were interested in developing satellite systems for three dimensional position determination. Although primarily thought to be a military project to overcome numerous shortcomings of predecessor navigational systems, the program known as NAVSTAR GPS became the cornerstone to many location based services millions of people use day in and day out [6].

2.1.1.1 A brief History of Navigation

The early 20th century witnessed an important introduction in the field of navigation - the so called radio navigation. This development was based on radios which enabled navigators the localization of shore-based transmitters, provided they were within a certain range. Based on this important discovery the DoD was very interested in developing a navigation system which would satisfy the needs of a broad spectrum of users. The cornerstone attributes of this system should be [16]:

- globally usable
- low susceptibility to weather effects
- highly available
- highly accurate

Based on this general idea the U.S. Navy as well as the Air Force began working with the concept of radio signals transmitted from satellites for the purpose of navigation and positioning. The Navy Navigation Satellite System, referred to as Transit, and another program called Timation, launched by the Naval Research Laboratory, were the results of these efforts [16].

Transit consisted of 7 low-altitude polar-orbiting satellites which broadcasted highly stable radio signals to a number of monitoring stations based on the earth, which were able to track these satellites and, if the need arose, could update certain orbital parameters. The signal transmitted by these satellites could now be used to determine the position of a user on earth by measuring the Doppler shift. Although the general idea of transit was the ability to locate ballistic missile submarines and other kind of watercraft on the ocean's surface, the system was made available to the public in 1967 and was quickly adopted by many commercial and private marine navigators. Transit provided great utility for general ship navigation but suffered from a number of drawbacks [9]:

- capability for positioning restricted to two-dimensions
- limited coverage caused by the intermittent availability of its signals
- hours of unavailability
- slow speed
- requirement of long observation times
- user velocity is not considered (must be calculated in manually)

All of these drawbacks made Transit basically useless for tracking aircraft or other fast moving vehicles. Nonetheless the satellite prediction algorithms developed for Transit as well as other developments are considered a vital stepping stone in the history of Global Positioning System (GPS). Transit was finally decommissioned on December 31, 1996 by the U.S. Government. An interesting side note is the fact that the whole concept for Transit only came into existence because of observations of the Russian satellite Sputnik, launched in 1957. A discovery of the Applied Physics Laboratory (APL) showed that the Doppler shift caused by the satellite was enough to determine the orbit. They also noted that using the same Doppler measurements and a known satellite orbit a determination of positions on earth should be possible [9].

The second project, Timation, was a space-based navigation system the Navy developed since the early 1960s. Backbone of this system were two satellites which were used to broadcast an accurate time reference for the use as a ranging signal to receivers on the ground. The general concept of Timation was to drive forward the development of high-stability clocks, time transfer and two-dimensional navigation which greatly contributed to the development of GPS. On May 31, 1967 Timation-1 was launched, laden with a highly stable quartz-crystal oscillator whereas later models used atomic clocks. Advantages of these were better frequency stability which extended the time during control segment up-dates and greatly improved prediction of orbits [6, 7].

During this time engineers at the Aerospace Corporation were looking into potential applications of space capabilities to meet critical military needs like the tracking and precise positioning of aircraft. These studies later became the so called System 621B after the Air Force formally requested the continuation of the research in October 1963. System 621B was able to provide not only two but three-dimensional navigation - namely latitude, longitude, and altitude - as well as a continuous service. Furthermore it made use of a new type of satellite ranging signal based on Pseudorandom Noise (PRN). The main advantage of this technique was the capability to reject noise, which in turn enables the system to reject most forms of jamming or deliberate interference. It enabled the satellites to transmit on the same frequency without negatively interacting with each other. In addition a further communication channel was added which allowed the exchange of certain information like satellite location and clock information. Several tests conducted by the Air Force at White Sands Proving Ground in New Mexico showed that PRN was accurate enough to pinpoint aircraft positions to within a hundredth of a mile [7, 17, 18].

The general vision of the Air Force back then consisted of a global system of 16 satellites in geosynchronous orbits. These satellites should follow specific pathways which extend 30 degrees north and south of the equator and allowed for 24h coverage of a specific region. Due to several competing initiatives from the other services concerning satellite navigation as well as the fact that by the late 1960s the U.S. Navy, Air Force, and Army were each working independently on navigation systems no real progress was made [19]. Each institution wanted to push its own idea forwards - Transit received several improvements and upgrades over the years while Timation was waiting for approval of further expansion. In the meantime the Army had proposed their own system called Sequential Correlation of Range (SECOR). Finally the DoD stepped in and issued a joint tri-service steering committee in 1968 called Navigation Satellite Executive Group (NAVSEG) which should spend the next few years ironing out the details and specifications of a satellite navigation system such as the number of satellites, altitude, communication techniques and of course the price tag. In April 1973, after 5 years of planning, the Deputy Secretary of Defense tasked the Air Force to combine the various existing concepts for satellite navigation into one system, the so called Defense Navigation Satellite System (DNSS), which should cover the views and needs of all affiliated services and should be developed by a Joint Program Office (JPO). Finally in September 1973 a new system was maturing that merged all the best ideas and features of the earlier projects [7, 17, 20]:

- signal structure and frequencies from System 621B
- satellite orbits based on Timation with higher altitude which increased the time period from 8 to 12 hours
- atomic reference clocks for which the Navy had already performed successful tests

The resulting system is known today as the Navigation System Using Timing and Ranging (NAVSTAR) Global Positioning System for which the DoD granted approval in December 1973 to proceed with a three-phase development of the NAVSTAR GPS [7, 17, 20]:

1. **Phase I: 1974 - 1979 Testing Phase**
   This phase should determine if the proposed system is suitable for the requirements stated by the U.S. government. In short these requirements state that a GPS user should have access to highly accurate information regarding his three-dimensional position, velocity as well as time anywhere on the planet regardless of being in motion or a complete standstill. Furthermore the system should be able to deliver this information continuously without interference from weather conditions. To this end several test satellites were brought into orbit to assess the military value. Additionally first base lines concerning investment and costing were established [7].

2. **Phase II: 1979 - 1985 Development Phase**
   During this phase the work force was concentrated toward technical development of the system. Additional prototype satellites were launched into orbit as well as improvements on the relay and receiver stations on the ground were made [7].

3. **Phase III: 1985 - 1995 Expansion Phase**
   Further improvements were made to bring the system closer and closer to its intended capacity. In February 1989 the first operational Block II satellite was launched into orbit. On July 17, 1995 the Air Force officially announced

   > "...that today the Global Positioning System satellite constellation has met all requirements for Full Operational Capability (FOC)." [7, p. 227]

   FOC means that 24 Block II/IIA satellites were in stable orbits, operational and tested for operational military performance. These 24 satellites have been in orbit since March 1994 but FOC was not declared until a year later [7].

From the beginning GPS was designed as a dual-use system, a system which could be used for civil as well as military purposes. Even prior to the announcement of the Air Force concerning FOC, GPS was used by a number of civil services - survey engineers started using GPS at a time where just a handful of satellites were in orbit [7].

2.1.1.2 GPS Services

GPS is designed as a dual-use service, which means it provides separate signals and services for military and civil users. These two services are called the Standard Positioning Service (SPS) and the Precision Positioning Service (PPS). It should be noted that the official accuracy values provided by these documents are very conservative and have to be taken with a grain of salt.

SPS - Standard Positioning Service

SPS as defined by the GPS Performance Standard is

> "...a positioning and timing service provided by way of ranging signals broadcast at the GPS L1 frequency. The L1 frequency, transmitted by all satellites, contains a coarse/acquisition (C/A) code ranging signal, with a navigation data message, that is available for peaceful civil, commercial, and scientific use." [21, p. 3]

SPS was designed to provide accuracy in a range of 5 to 10 meters [21].

PPS - Precision Positioning Service

PPS as defined by the GPS Performance Standard is

> "...a positioning and timing service provided by way of authorized access to ranging signals broadcast at the GPS L1 and L2 frequencies. The L1 frequency, transmitted by all Navstar satellites, contains a coarse/acquisition (C/A) code ranging signal, with a navigation data message, that is available for peaceful civil, commercial, and scientific use; and a precision (P) code ranging signal with a navigation data message, that is reserved for authorized use. The P-code will normally be cryptographically altered to become the Y-code. The Y-code will not be available to users that do not have valid cryptographic keys. Navstar satellites also transmit a second P- or Y- (P(Y)-) code ranging signal with a navigation data message at the L2 frequency. The navigation data message is identical across all codes and frequencies, but certain portions of the navigation data message will normally be cryptographically altered so as to not be available to users that do not have valid cryptographic keys." [22, p. 3]

The reason that PPS is transmitted on two frequencies, namely L1 and L2, is that it allows for a compensation of ionospheric delay which is caused by the transmission of the signal through the ionosphere of the planet. PPS was designed to provide accuracy in a range of 2 to 9 meters [22].

2.1.1.3 GPS Modernization

40 years after the initial phases of the GPS development the direction in which GPS is heading has altered tremendously from the original objective. More than 90% of its utilization stems from civil users and the U.S. government even declared the GPS service as Primary Means of (Radio-) Navigation for civil aviation. In 1996 U.S. President Bill Clinton issued a policy directive which declared GPS as a dual-use system after recognizing its importance in military as well as civil use cases. He guaranteed that GPS is and will continue to be free of charge. Several other factors were also important to further the cause of GPS development. The large number of civil users created a new kind of industry, one not seen before - the satellite navigation industry - creating thousands of new jobs. This in turn caused the demand for new and improved signals which would increase the user accuracy and reliability. In 1998 these demands were finally met when the White House officially declared to modernize GPS [7, 17].

The Rise and Fall of Selective Availability

The reason that Selective Availability (SA) came to be was that in the early stages of GPS design the engineers and researchers believed that the technologies and algorithms used were simply too difficult, complex and expensive for use outside of the military sector. Additionally those responsible firmly believed that the U.S. forces would held the GPS monopoly for years to come so only the P code was cryptographically protected but not the Coarse/Acquisition (C/A) code - the existence of the latter was simply kept secret. Similarly to the analysis of the Sputnik signals 1957 the decipherment of the bits in the C/A signal was considered an academic challenge amongst universities across the country and soon the researchers succeeded in their mission. They provided their findings to numerous entrepreneurs who in turn used the flourishing micro processor industry at the time to develop the first civil L1 GPS receivers - the GPS monopoly of the U.S. forces was broken [7, 17, 23].

The U.S. forces tolerated this "breach" and the decipherment of the C/A signal became the first important milestone in the development of civil GPS usage. The second milestone came with the downing of KAL007, a jumbo jet of Korean Airlines, in September 1983. Due to navigational errors the aircraft deviated from its intended course and crossed over into Soviet prohibited airspace and was ultimately shot down by an Interceptor aircraft of the Soviet Union near Moneron Island. To avoid such tragic incidents due to a lack of suitable radio navigation systems in the future acting U.S. president Ronald Reagan decided to officially support civil GPS utilization. This decision did not come without dilemma. Being the heyday of the Cold War several U.S. military strategists uttered their concern considering Mutually Assured Destruction (MAD) and the Window of Vulnerability, stating that civil GPS receivers might be used to increase first-strike capability. The pentagon therefore issued a directive of serious consequence - the birth of SA [7, 17, 23].

Task of SA was to deliberately worsen the measurement accuracy of civil GPS receivers to about 100 meters and the actual implementation of this "feature" was conceivably simple - the simulation of stochastic pathing and timing errors. With the help of the atomic clocks on board of the satellites, time values transmitted via the L1 frequency would deviate randomly from the norm signals given a specific range. This little addition had tremendous influence on the location data. Figures 2.1 and 2.2 show GPS horizontal and vertical pinpoint accuracy with SA turned on and off, respectively. On March 25, 1990 SA was eventually turned on and it should stay on for over 10 years. During this time though, the pressure from the american economy sector as well as the ever-growing number of civil GPS users grew, demanding the deactivation of SA. They argued that there was no justifiable cause given the ending of the Cold War and nuclear disarmament - the Window of Vulnerability was no more and so should SA. Finally in May 2000 an important first step of GPS modernization was taken, after U.S. president Bill Clinton issued a directive which discontinued the use of SA. Figure 2.3 shows a diagram of this historic event and the impressive improvements concerning horizontal and vertical accuracy of GPS the minute SA was shut down for good [7, 17, 23].

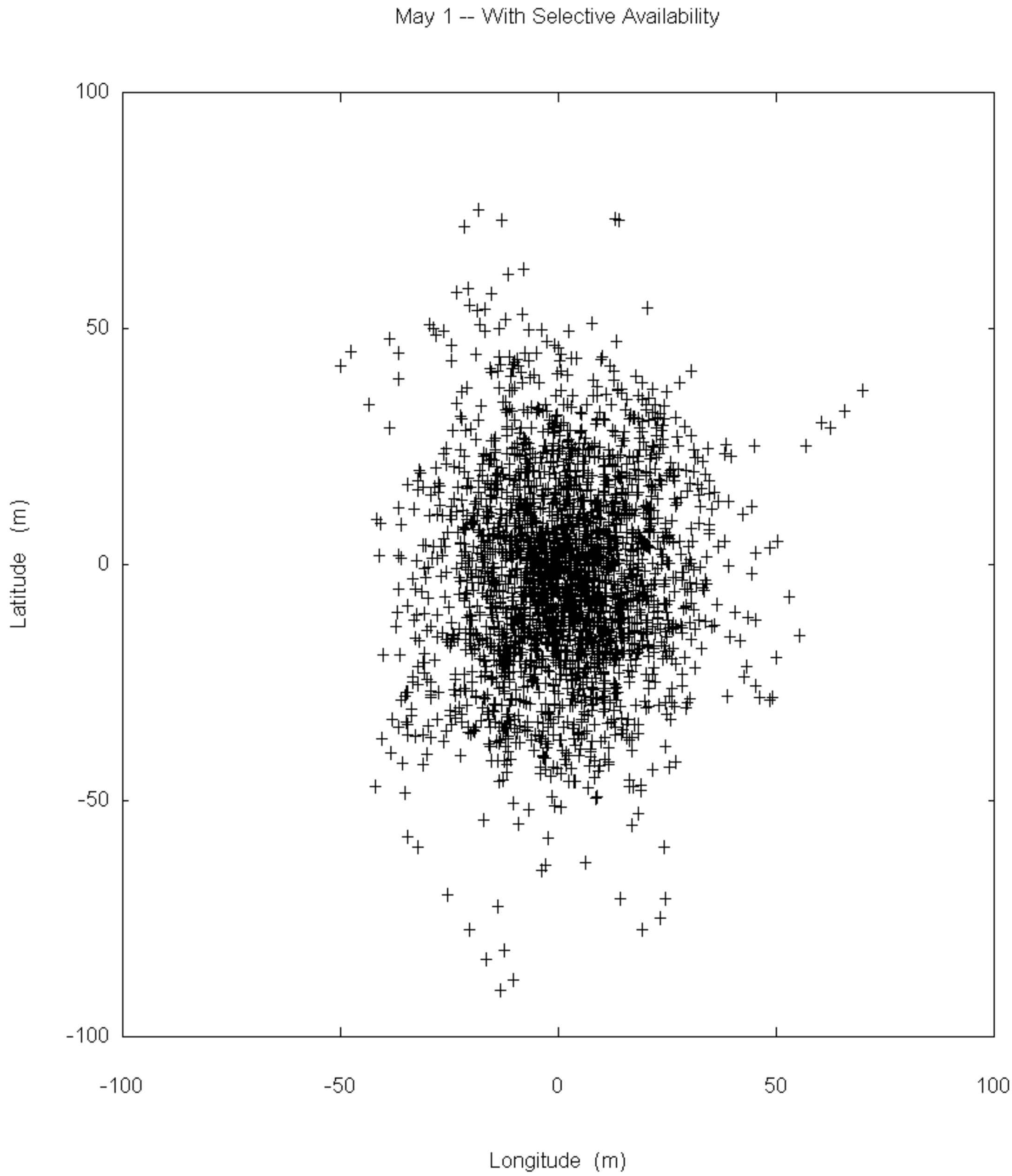

Figure 2.1: GPS Accuracy with SA on May 1, 2000 (image reprinted from [24]).

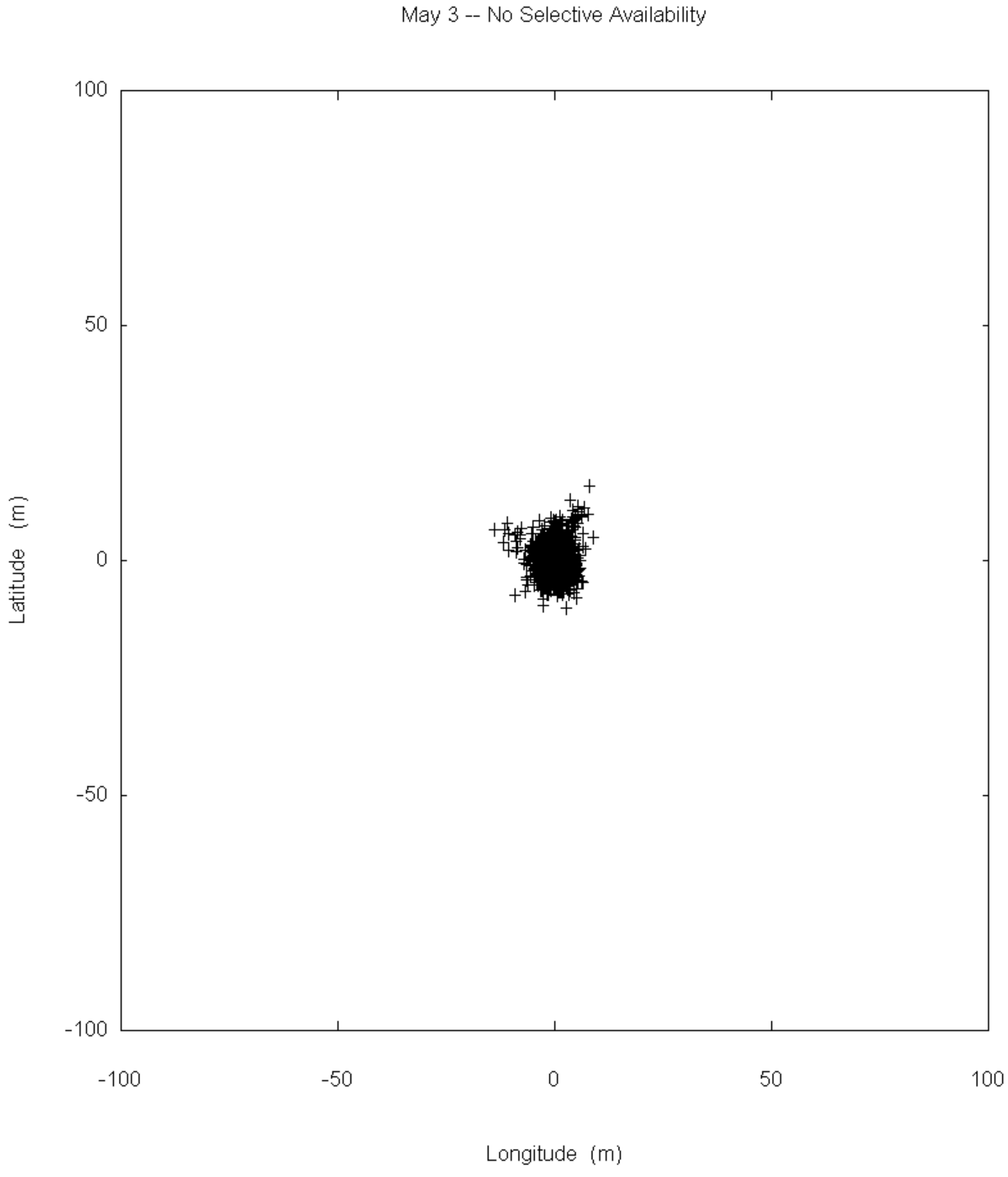

Figure 2.2: GPS Accuracy without SA an May 3, 2000 (image reprinted from [24]).

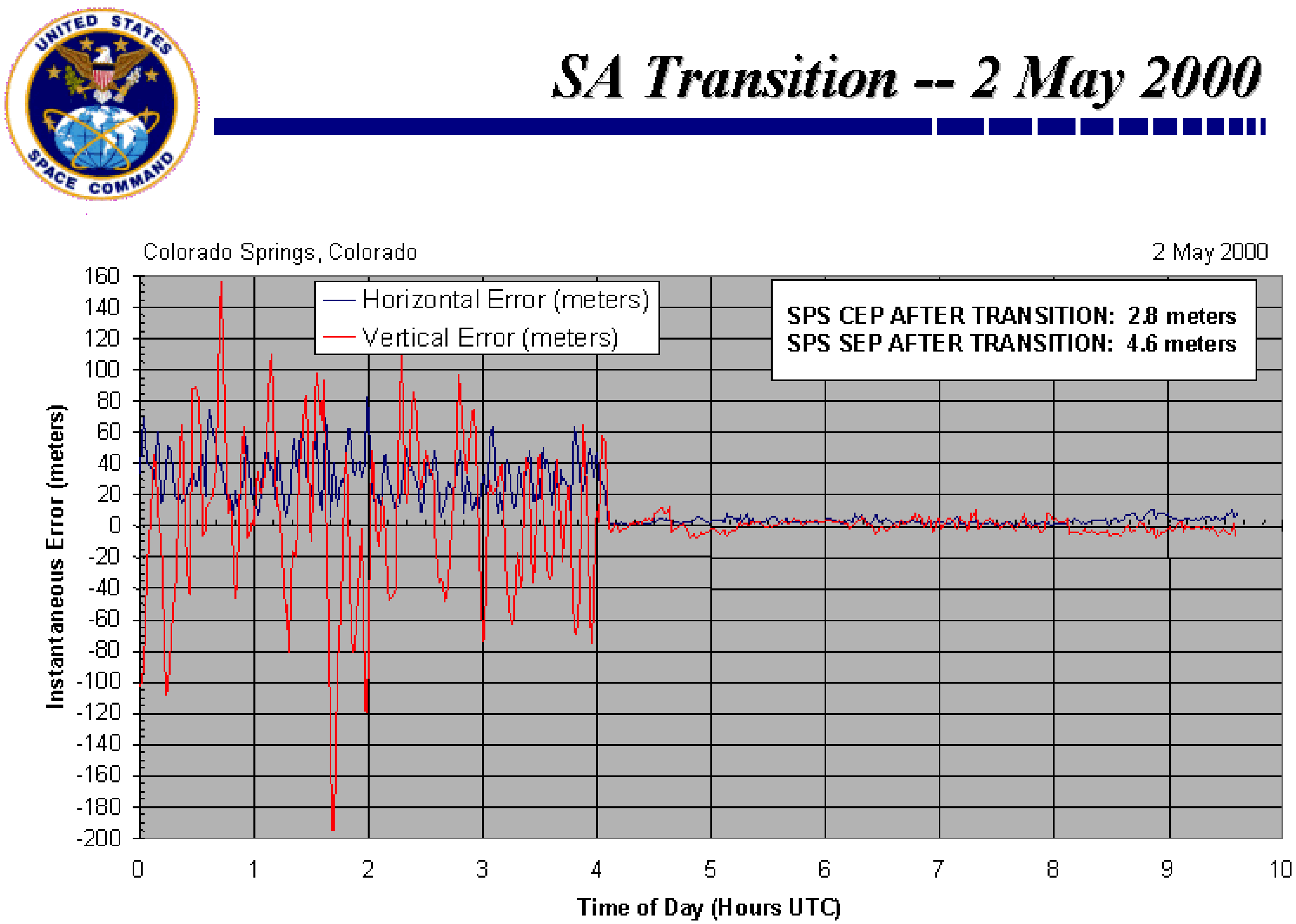

Figure 2.3: GPS Fluctuations Over Time on May 2, 2000 show a tremendous improvement of GPS accuracy, concerning vertical and horizontal errors, the minute SA was turned off (image reprinted from [24]).

2.1.1.4 GPS Segments

A satellite navigation system needs more than just the satellites in orbit to function properly. These necessary institutions are called segments and are depicted in Figure 2.4 as well as described extensively in the following sections. The architecture consists of three such segments, namely the space segment (also called satellite constellation), the control segment (also called ground segment) and the user segment. The first two are unique to every Global Navigation Satellite System (GNSS) like GPS or GALLILEO but the third segment is free to use a single or even multiple signals from different systems [6].

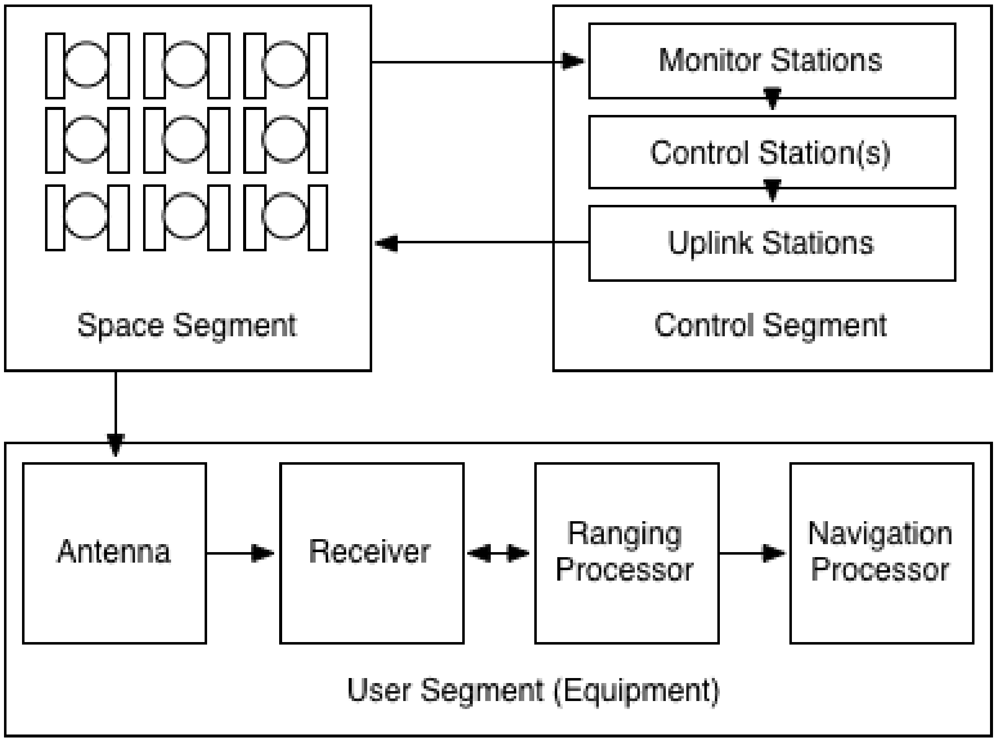

Figure 2.4: GPS Segments (modeled after [8]).

Space Segment

The satellites in orbit enable the user to perform range measurements using the transmitted signals. A typical GNSS signal is the modulation of a carrier with a ranging or spreading code - the PRN code - and in most cases a navigation message. It is possible for GPS to support an unlimited number of users simultaneously due to the fact the whole system design is passive. GPS satellites only broadcast navigation signals and the users are passively receiving them. The signal itself is modulated with data describing key factors like the position of the satellite or current time parameters. A satellite is equipped with a payload and a vehicle control system. It is important to note that GPS satellites include two payloads - the first payload is a navigation payload used for Position - Velocity - Time (PVT) whereas the second payload, called Nuclear Detonation Detection System (NUDET), is used to detect nuclear activities on earth. With the modernization program started in the 1990s, the ground as well as the space segment experienced different phases of upgrades. Concerning the space segment new satellites have been designed and launched in so called blocks. Table 2.1 shows an overview over legacy, current as well as future satellites, including design and signal details, belonging to the space segment of GPS. Specifications made by the U.S. government describe a baseline configuration of the satellite constellation consisting of 24 satellites, including 3 reserve satellites, orbiting on 6 planes with 4 satellites per plane as seen in Figure 2.5. Orbits are nearly round, oriented around the equator and are separated from each other by spaces of 60 degrees. The inclination with respect to the equatorial plane is 55 degrees. The height in which the satellites are orbiting is approximately 20.180km. Considering these variables the time it takes a GPS satellite to complete its orbit is about 1½ of a sidereal day, which means 11 hours, 58 minutes, and enables a 24h PVT service. Satellites in the fleet are referred to in different ways - one way is to assign each plane a unique letter, A to F, and the satellites on it from 1 to 4. The second approach is to use designated numbers assigned by the U.S. Air Force. The third and final way is represented by the configuration of the PRN code generators of each satellite. Due to the fact that these onboard generators are configured uniquely on each satellite, the transmitted C/A and P-codes are unique and can be used to identify the satellite [6, 25].

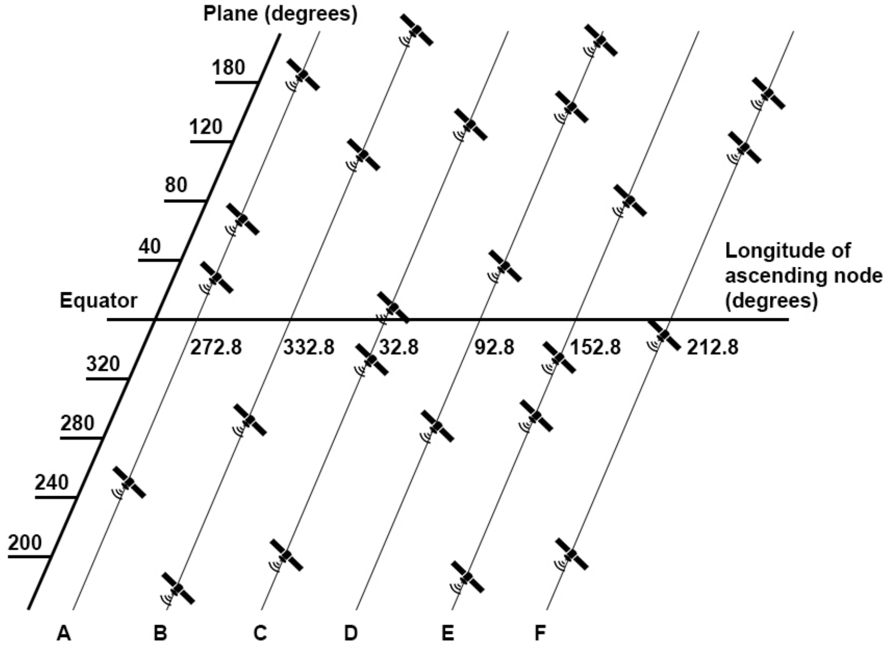

Figure 2.5: GPS Constellation on July 1, 1993 at 00:00 (modeled after [6]).

Legacy Satellites		Modernized Satellites		
Block IIA	Block IIR	Block IIR(M)	Block IIF	GPS III
2 operational	12 operational	7 operational	10 operational	in production
- C/A code on L1 - P(Y) code on L1&L2 - 7.5 year lifespan - Launched 1990-1997	- C/A code on L1 - P(Y) code on L1&L2 - On-board clock monitoring - 7.5 year lifespan - Launched 1997-2004	- All legacy signals - 2nd civil signal on L2 called L2C - New M code (military) for increased jam resistance - Flexible power levels for military signals - 7.5 year lifespan - Launched 2005-2009	- All IIR(M) signals - 3rd civil signal on L5 frequency called L5 - Advanced atomic clocks - Improved accuracy, signal strength, quality - 12 year lifespan - Launched since 2010	- All IIF signals - 4th civil signal on L1 called L1C - Enhanced signal reliability, accuracy, integrity - No S/A - 15 year lifespan - Launch planned for 2016

Table 2.1: Legacy and modernized space segment of GPS (modeled after [26]).

Control Segment

At the time of this writing the Control Segment (CS) consists of a Master Control Station (MCS), an Alternate Master Control Station (AMCS), 12 command and control antennas and 16 monitoring sites including installations from the Air Force Satellite Control Network (AFSCN) and the National Geospatial-Intelligence Agency (NGA) as depicted in Figure 2.6. The ground segment has received several updates and improvements since 2000 which more than doubled the monitoring sites and tripled the amount of antennas. This upgrade provides the CS with capability of continuous L-band tracking which was subjected to a 2 hour coverage outage only a few years ago.

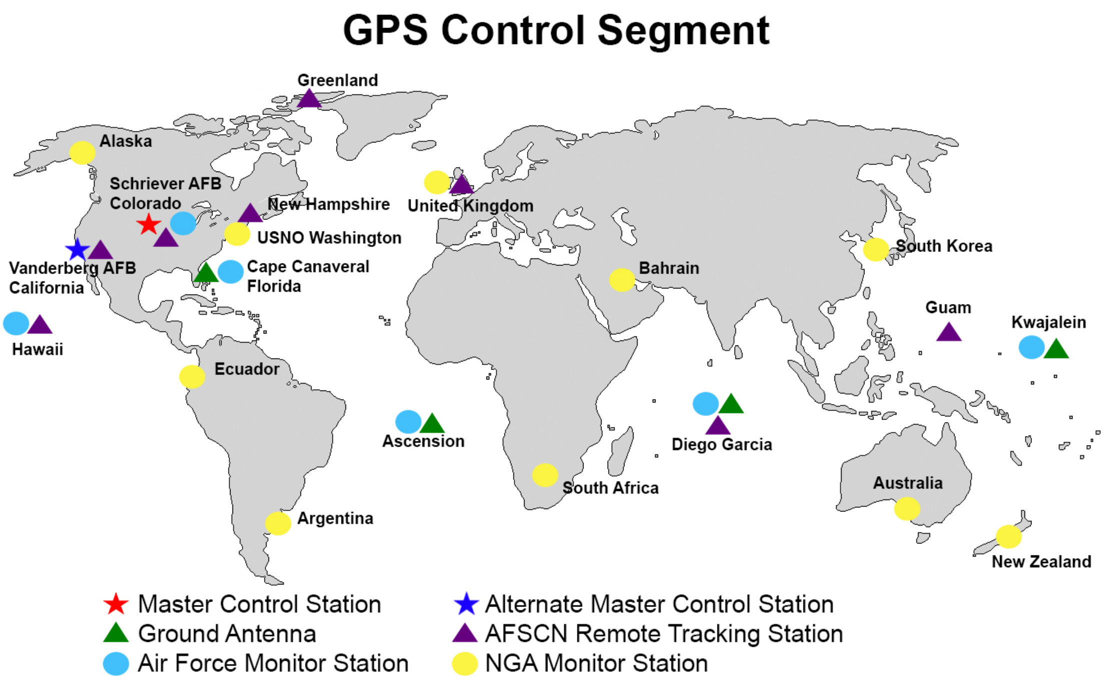

Figure 2.6: The GPS Ground Control Segment consists of a global network of ground facilities (modeled after [27]).

The CS provides several functions including:

- Monitoring satellite health and orbits including the authorization of maneuvers to maintain stable orbit
- Generating GPS navigation messages
- Monitoring and maintaining GPS timing service and synchronization to Coordinated Universal Time (UTC)
- Monitoring and maintaining navigation service integrity

- Verification and logging of navigation data delivered to the GPS user
- Activation and repositioning of satellites in case of system failures

The CS has the responsibility to maintain all the satellites in orbit and keep them functioning properly. This task is split into monitoring all satellite parameters - like the position of the solar panels, fuel levels for maneuvers, battery power levels - and the so called stationkeeping which is the maintenance of the proper orbital positions. Should a satellite stop functioning for any reason the CS has the authority to activate spare satellites if available to ensure full PVT capability. Furthermore the CS updates the navigation message of the satellites at least once per day - this includes the satellites clock, ephemeris, almanac and other indicators which are described later. These updates can come more frequently to reduce the space and/or control contributions to filter out range measurement error depending on wether improved accuracy is required [8].

User Segment

The final segment is used to process the L-band signals broadcast from the space constellation to determine PVT - typically referred to as GPS receivers. Compared to the first receivers designed and built in the mid to late 1970s which were primarily analog, large, bulky and heavy, todays receivers are often in form of a single chip the size of a few match heads. GNSS receiver architecture description can vary depending on the author, in this case it is modeled in four parts as seen in Figure 2.7 - the antenna, the receiver hardware, the ranging processor and the navigation processor [8].

A vital part of the receiver architecture, the antenna must possess peak sensitivity near the carrier frequency carrying the signals and enough bandwidth to pass those signals. Should the signals come from more than one frequency band the antenna can be sensitive to all required frequencies or multiple antennas may be utilized as well. This may lead to so called multipath problems which will be discussed in a later section. The final navigation solution, determining PVT, is based on a certain point, the so called electrical phase center. This point does not necessarily mean the physical center of the antenna and may even be a few centimeters outside of the antenna itself. This may seem irrelevant for the standard user but needs to be addressed for high-precision applications. Typical antennas for mobile devices such as smartphones are often designed for minimal space and resource consumption at the cost of performance [8].

The timing for GNSS user equipment is provided by a reference oscillator which supplies a frequency standard for the receiver clock as well as the various other oscillators used in the receiver front end and baseband processor. The receiver clock is used to provide a time reference for the ranging and navigation processor. A non critical GNSS system may use a quartz crystal oscillator but a temperature-compensated crystal oscillator is more common due to the frequency fluctuations as a result of temperature changes [28]. The analog signals from the antenna are processed by the receiver front end, the so called signal conditioning, and then digitized. It would go beyond the scope of this study to

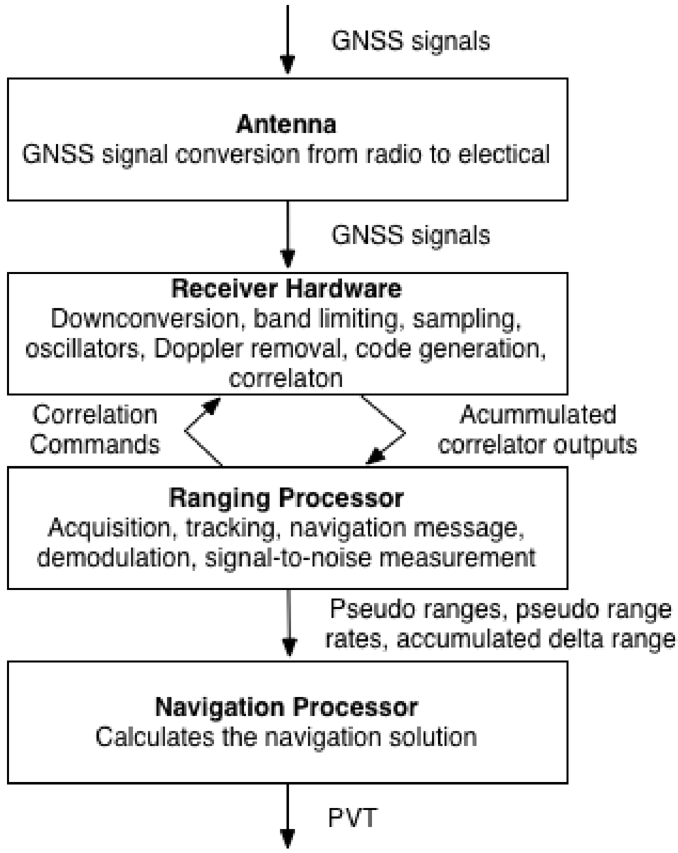

Figure 2.7: Functional diagram of the user segment of a GNSS (modeled after [8]).

provide more information on the technical details of a GPS receiver. The interested reader is referred to [6, 8].

2.1.1.5 GPS Signals, Navigation Message and Range Measurement

At the time of this writing the GPS system is in a fundamental transition, affecting all 3 segments, to accommodate for the new L2C and L5 signals provided by Block IIR(M) and IIF satellites, respectively. Currently there are 10 different navigation signals, transmitted over 3 different frequency bands known as L1, L2 and L5. Another frequency exists, called L3, but is only used for NUDET purposes. Due to the fact that the official state of these new signals is "pre-operational" and are still in testing, this section will describe only the currently used "legacy" signals in greater detail. However, the fundamental mechanics of modulation and demodulation of carrier wave, ranging codes and navigation message remain the same and therefore apply for the new signals as well [6, 8].

C/A Code

The C/A code is generated by a PRN generator with a length of 1023 bits at a clock rate of 1.023MHz, repeating every millisecond. This code is chosen from a given set of codes, the so called Gold Codes, which is unique for every satellite in the space constellation. Furthermore the Gold Codes are specifically designed to minimize cross-correlation which enables a identification of the satellite. The short length of the C/A code was intended to allow for an easier and faster signal acquisition process before switching to the more complex P code. The C/A code is available for all users on the L1 frequency and is not subject to encryption [6, 8].

P(Y) Code

The P code is generated by a PRN generator, as the product of 2 PRN codes, with a length of 6.1871E12 bits at a clock rate of 10.23MHz, which results in a total length of about 267 days or 38 weeks. The actual P code transmitted by each satellite is only part of this master P code, a unique snippet in the length of 7 days which repeats every week, resetting at midnight GPS time from Saturday to Sunday. Usually this P code is encrypted into the Y code with the help of an additional encryption code known only to PPS users. Primary reason for this encryption is the prevention of spoofing, the intentional broadcasting of similar signals to deceive the GPS receiver. Satellites in the space constellation have the capability of transmitting either the P or the Y code so it was made common practice to refer to it as the P(Y) code. P(Y) code is broadcast on both frequencies, L1 and L2. To cause less interference with the C/A code already present on L1 the P(Y) code is modulated 90 degrees out of carrier phase [6, 8].

Navigation Message

The actual navigation message, which contains data unique to each satellite as well as data which is common to all satellites, is multiplexed on top of the C/A code and P(Y) code, respectively. The complete navigation message is made up of 25 frames, each comprised of 1.500 bits of data, adding up to a total of 37.500 bits. Each of these 25 frames are further divided into 5 subframes, consisting of 300 bits as shown in Figure 2.8. Signals from the satellites are broadcast at a rate of $50^{\text{bits}}/_{\text{s}}$ which means one subframe is transmitted in 6 seconds and a complete frame in 30 seconds. The complete navigation message is transferred once every 12.5 minutes. To enable a precise calculation of a position on earth, exact information of the satellite positions is needed. Waiting for up to 12.5 minutes to receive critical satellite information is infeasible, of course, so to enable a quick fix the subframes 1 to 3 are comprised of the same information, consistent across all 25 frames. Subframes 4 and 5 contain data which is common to all satellites and less relevant for a quick fix [6, 8].

Both datasets, called ephemeris and almanac, describe the orbit and status of a satellite in the space segment. The reason for 2 such datasets is that almanac data is not very precise, may be several months old (up to 210 days) and contains orbital information for the

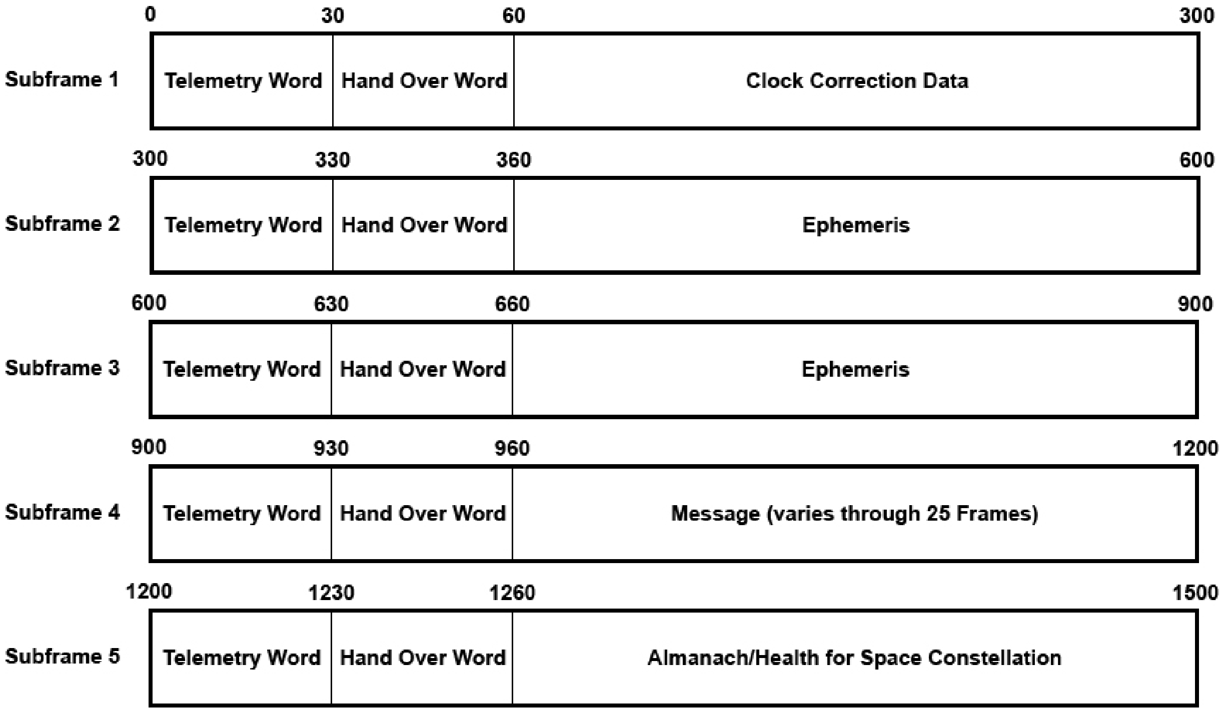

Figure 2.8: Subframes of a Navigation Message Frame (modeled after [8]).

whole fleet whereas ephemeris data is very precise, unique for a specific satellite and only valid for up to 4 hours. The almanac is broadcast repeatedly over 12.5 minute intervals whereas ephemeris data is broadcast every 30 seconds via the subframes. Almanac data is used for predicting approximate positions of visible satellites in aid for a signal fix. This information is only sufficient to determine viable satellites but not a complete and accurate position search. To this end the ephemeris data is downloaded directly from the specific satellites to provide the GPS receiver with enough information for a precise location lookup. It is important to note that the complete ephemeris dataset of a satellite is needed to be usable for a location search. Further data contained in the navigation message includes [6, 8]:

- The Telemetry Word (TLM) is used to mark the beginning of a new subframe and enable synchronization
- The Hand Over Word (HOW) provides GPS time and subframe identity within a frame
- Satellite Clock Calibration Data
- Ephemeris Data and Health of the broadcasting satellite
- Almanac Data and Health of the whole space constellation

- Coefficients for Atmospheric Effects
- Coefficients for the calculation of UTC

Correlation and Range Measurement

Task of the receiver hardware and ranging processor is to provide values for the so called pseudo-range which in turn is needed to calculate the receivers actual PVT values. To calculate its actual position a satellite navigation receiver will determine the ranges to at least four satellites in orbit as well as their actual positions at time of signal transmitting. The satellite signals are basically radio waves so the travel time it took from satellite to receiver can be simply multiplied by the speed of light to get the pseudo-range. Due to the fact that there are accuracy errors due to clock errors and other influencing factors the term pseudo-range is preferred to range for these kind of measurements. The actual math behind the measurement of the distance from a satellite boils down to the simple equation of velocity times travel time. In case of GNSS signals the velocity of a radio signal is the speed of light which is 299.792.458$^{m}/_{s}$ [29] but the timing problem is a bit tricky. First of all the time it takes a signal to reach the receiver is very short - assuming a satellite point blank overhead the broadcast signal would travel less than a tenth of a second which in turn means that very precise clocks are needed. But another, more urgent problem is the time synchronization - in order to provide an accurate measurement both the satellite as well as the receiver need clocks that allow for a synchronization down to the nanosecond. Equipping each receivers with a very pricey atomic clock would make GPS pretty much useless for civilian users, so the minds behind GPS came up with an effective solution. The aforementioned oscillators do not store an actual "current time" value but are constantly reset and used for calculations. As already mentioned satellites broadcast their signals using a specific ranging code. This code is not only known by the satellite but also by the receiver which in turn can generate this code locally. In a process which is called correlation the receiver adjusts the phase of the locally generated signal to match the incoming signal. These signals are designed in a way that [6, 8]:

- the correlation output peaks when the code is correlated with an aligned replica of itself
- the correlation output is at a minimum when the code is correlated with a misaligned replica of itself
- the correlation output is at a minimum when the code is correlated with another code of the same family, which means another GPS satellite signal

If the correlation process reaches a peak output the carrier and navigation data are recoverable from the transmission. The data in the navigation message can then be used to provide a first value for the pseudo-range. This is done using the time the subframes arrive at the receiver, marked by the TLM, as well as the actual GPS time which is encoded in the HOW. Using this approach a receiver has the potential to generate a new pseudo-range measurement every full subframe which means every 6 seconds. To provide a precise location for the receiver the ephemeris data of 4 or more satellites is required to calculate the exact location at transmission time which shown in Figure 2.9 and explained below [6, 8]:

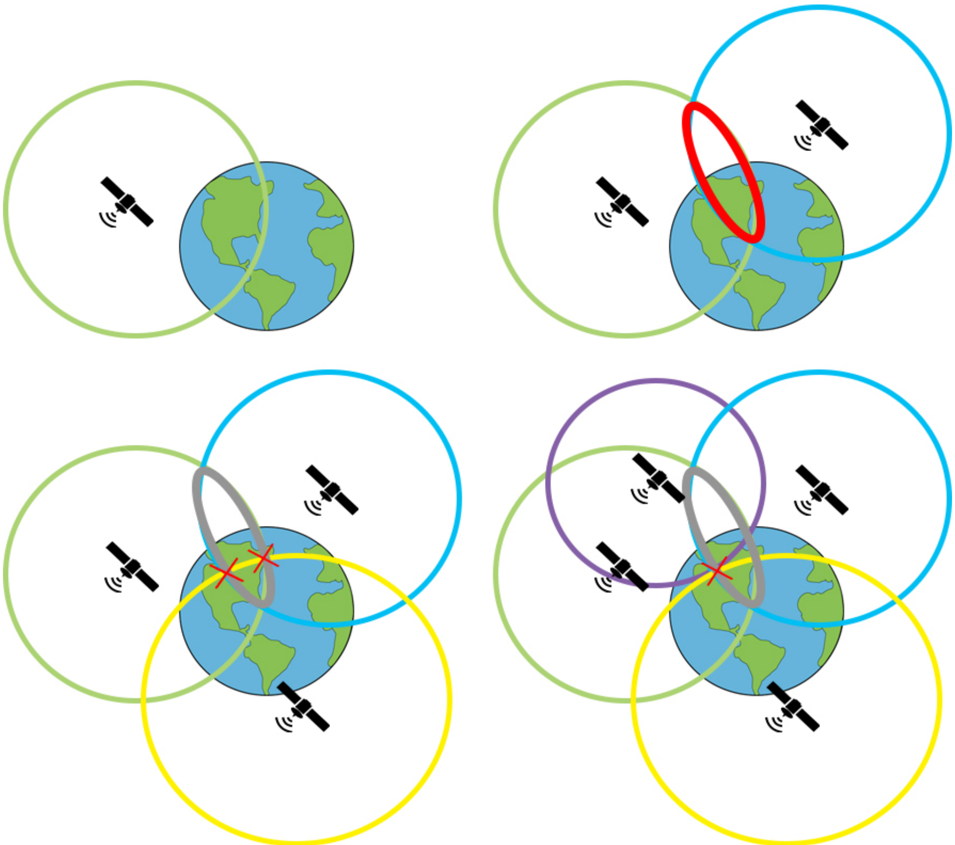

Figure 2.9: Determination of the receiver position using 4 satellites (modeled after [30]).

- **1 Satellite**
  The receiver compares the time encoded in the satellites signal to it's own internal clock to compute a distance to the satellite. Using only the information provided by 1 satellite the receiver can determine that it is somewhere on the surface of a sphere of a given radius. Due to the fact that the receiver has no information concerning the correct timing the range measurement comes with an error of unknown magnitude which in turn makes the measurement completely useless.
- **2 Satellites**
  Receiving the information from 2 satellites gives the receiver enough knowledge to compute 2 spheres which will intersect on a circle. It knows with certainty that

the actual position is somewhere on this specified circle but the magnitude of the measurement error is still unknown which renders this measurement useless as well.

- **3 Satellites**
  Given 3 satellite signals the actual position can now be narrowed down to 2 points on the aforementioned circle. In real world measurments one of those 2 points is usually not close enough to the surface of the earth to be considered valid and simply discarded. Assuming perfect clock timing on the receivers end this measurement would be all that is needed to provide location information but this is usually not the case. However, considering a fixed height value, possible in aircrafts or at sea, positioning with only 3 satellites can be a viable solution.

- **4 Satellites**
  Given a fourth signal the receiver is able to calculate another sphere that will disagree with the other measurements unless the receiver clock and the satellite clock are perfectly synchronized. This is the reason why the receiver clock does not use an actual time - it adjusts it's own clock until all spheres intersect at exactly 1 point. This in turn provides the receiver not only with an precise value for the location but also with a precise value for the time.

- **5 or more Satellites**
  A satellite count of 5 or more provides the receiver with the capability of different permutations - it can compute the location based on every possible combination of 4 of them. The variance between this location values gives a certain indication concerning the accuracy of the range measurement.

Measurements using at least 4 satellites provide the receiver with 4 equations calculating pseudo-range. If the receiver clock was actually perfectly synchronized to GPS time, the pseudo-range would be the actual range from receiver to satellite. Due to unknown offsets and/or clock errors this is rarely the case but fortunately this timing offset is the same for all satellites and can be seen as another unknown. The receiver is now in possession of 4 equations with 4 unknowns, namely the receiver location with the coordinates X, Y and Z as well as the time, which is solvable using various approaches like the least-squares or weighted least squares method [8].

2.1.1.6 GPS Reference Systems

Position

Reference System for GPS is the so called World Geodetic System 1984 (WGS84) which has become an established standard for navigation purposes since its introduction in the early 1980s. This system does not only provide a needed standard coordinate system for the planet but also a reference surface for altitude data, the so called datum or reference ellipsoid, and gravitationally balanced reference for the nominal sea level, the so called geoid. Furthermore important variables, needed for PVT calculations, are also part of the WGS84 as shown in Table 2.2 [7, 31].

The first implementation of WGS84 was realized from a large number of terrestrial sites, with accuracy at the level of 1 to 2 meters but successive adjustments and refinements have improved the system greatly over the years. With the GPS week #1150, which started on January 20th, 2002, coordinates used have been adjusted to the International Terrestrial Reference Frame (ITRF) coordinates with the help of the International Earth Rotation and Reference Systems Service (IERS). This greatly refined frame, called WGS84(G1150), improved accuracy to a level of a few centimeters [7, 31].

Parameter		Variable	Value
Ellipsoid	Semi-major axis	α	6.378.137,0m
	Flattening factor	f	1/298,257223563
Earth angular velocity		ω	7.292.115.0x10^-11 rad/s
Gravitational constant		μ	3.986.004,418x10^8 m^3/s^2
Speed of Light (Vacuum)		c	299.792.458 m/s

Table 2.2: The parameters of the WGS-84 ellipsoid after [31].

Time

GPS Time is a uniformly counting time scale which began at midnight in the night from May 1st to May 2nd in 1980 and is in sync with the UTC. Computation of time takes place in the form of weeks and seconds of a week from the starting point in 1980. Each week begins at the transition from Saturday to Sunday and each day of the week is numbered starting with 0 for Sunday and so on. Given these parameters the actual GPS time within a week is a number between 0 and 604.800 - this number stems from number of seconds per hour per day per week (60x60x24x7) [7, 8].

An important fact is that the world does not rotate smoothly which in turn forced the introduction of the so called leap second in July 1st, 1981. So to be precise, GPS time is not actually accurate to UTC time - at least not anymore. GPS time was set equal to UTC time back in 1980 but does not have leap seconds. So with every introduction of a leap second since the 1980s, UTC time fell behind and GPS time is now, at time of this writing, 17 seconds ahead [7, 8].

2.1.2 Other Global Navigation Satellite Systems

Another important factor that led to the final decision to modernize the GPS System was the need to stay internationally competitive. GPS should be globally available and free of charge, as promised, but the U.S. were and are still able to deny access to this system - it happened before in 1999 during the Kargil War [32] and it can happen again at any time. Many countries as well as the European Union (EU) saw the need for an own, independent version of GPS because one could not rely on a foreign government-controlled GNSS in hostile situations. Nowadays receivers combine the use of multiple GNSS systems to increase overall performance and robustness. The basic principle for other GNSS is essentially the same as GPS so the following sections only summarize and give a short overview of important cornerstones.

2.1.2.1 GLONASS

Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS), was originally developed as a military system by the Russian Aerospace Defense Forces during the 1970s. The design took place in parallel to GPS, started by the Soviet Union and continued by Russia after its demise. Similar to GPS, GLONASS should provide a service for military as well as civil use. Starting in 1982 more and more satellites were brought into orbit with finally reaching a full space segment of 24 satellites in 1995. Unfortunately, a decline in capacity during the second half of the 1990s brought the service to a low point with only 6 operational satellites in orbit by 2001. Finally a modernization program was initiated by President Vladimir Putin, which should make it top government priority and breath new life into the dying system. Initial Operational Capability (IOC) was reached again in 2010 and FOC by 2011, with a full constellation of 24 satellites including 3 active spares [8, 33, 34].

The GLONASS satellites orbit the earth at an altitude of 19.100km with an inclination of 64.8 degrees and an orbital period of 11 hours and 15 minutes. The space segment orbits the planet in 3 planes, with 8 evenly spaced satellites on each one, unlike GPS which operates in 4 planes. GLONASS was designed under the “21 satellite concept”, which means the performance of all satellites will be determined by ground control and the most suitable set of 21 satellites will be used. The 21 satellite constellation is able to provide a consistent coverage of over 97% of the earths surface while 18 satellites are needed to cover the whole territory of Russia. Due to the fact that the program started during the time of the Soviet Union, ground control installations are almost completely located in former Soviet Russia except for one station which is located in Brazil. The System Control Center is located in Krasnoznamensk and the Central Clock is found in Schelkovo near Moscow. GLONASS provides ephemeris and almanac data in the Earth Parameter System 1990 (PZ90) which is an Earth-Centered, Earth-Fixed (ECEF) reference frame and of similar quality compared to WGS84. Prior to August 1993 this data was provided using the Soviet Geodetic System 1985 (SGS85) for which concrete details have not been made public. The International GLONASS Experiment (IGEX-98) [35] made it possible to transform PZ90 coordinates to WGS84 coordinates. GLONASS time is in sync with the UTC but with a constant three-hour difference. In contrast to GPS, the system implements a time scale with the leap second, so timing corrections are made simultaneously with the insertion of a leap second [8, 33, 34].

One important fact is that in contrast to GPS and other GNSS systems, which use Code Division Multiple Access (CDMA) for their signals, GLONASS uses Frequency Division Multiple Access (FDMA). As already mentioned GPS satellites use so called PRN codes to distinguish themselves and make themselves identifiable. GLONASS satellites all broadcast the same code as their standard-precision signal but each satellite uses a different frequency for this transmission. Reason for the approach with FDMA was that in the early stages of the program implementations were very expensive and complex but promised better results considering the ever growing amount of signals which are broadcast on a single frequency using CDMA. Furthermore the system is considered to be more jamming resistant due the fact that a jammer would have to jam every single satellite frequency instead of just one. Since 2008 additional CDMA signals are under development for GLONASS which should provide interoperability with other GNSS but should not be seen as a replacement for the “old” FDMA signals [8, 33, 34].

2.1.2.2 GALILEO

Galileo, named after the Italian astronomer Galileo Galilei, is the GNSS developed and maintained by the EU and the European Space Agency (ESA). Once fully established Galileo should provide European nations an alternative to GPS and GLONASS in case of a shutdown of the public signals. As is the case with the other GNSS, Galileo will provide a basic service free of charge as well as a high precision service for commercial use. Galileo’s intended measurement error in horizontal as well as vertical position measurements should lie below 1 meter and provide better signal reception in higher latitudes, north and south. The first 2 Galileo satellites were launched in 2005 and 2008 respectively. GIOVE-A and GIOVE-B were part of the GIOVE mission for which the goal was to test the ground algorithms for orbit determination as well as time synchronization. Originally a third satellite, GIOVE-A2, was planned but cancelled due to the successful launch and operation of GIOVE-B. Following the GIOVE block was the In-Orbit Validation (IOV) block. The first 2 IOV satellites were launched in October 2011 with another 2 following in October 2012 which made an end-to-end validation possible, due to the 4 satellite principle. FOC with a full space segment should be reached by 2020 [6, 17, 8]. Galileo should not only provide a positioning service but also a unique Search and Rescue (SAR) function. This function should not only relay a distress signal but also inform the user that help is on the way [36].

Galileo satellites orbit the earth at an altitude of 23.222km with an inclination of 56 degrees and the ascending nodes separated by 120 degrees longitude. The space segment orbits the earth in 3 planes with 8 satellites per plane plus 2 spare satellites in case of failure which results in a total of 30 satellites. The constellation configuration at this altitude repeats itself exactly at the 10th day at which each satellite will have completed its orbit 17 times. The systems ground segment is spread all across Europe with additional Uplink Stations and monitor stations all around the globe. The Ground Control Center is located in Oberpfaffenhofen, Germany and the Ground Mission Center is located in Fucino, Italy. Galileo provides location data using the so called Galileo Terrestrial Reference Frame (GTRF) which was built by a consortium called the Galileo Geodetic Service Provider (GGSP). GTRF is an independent realization of the ITRF. Differences between WGS84, the reference frame of GPS, and GTRF should be of the order of centimeters which makes that accuracy considering ITRF virtually identical.

Galileo System Time (GST) is specified in a way that over the course of 1 year the difference between GST and Temps Atomique International (TAI) should be less than 50ns. TAI is an international atomic time scale based on an ongoing counting of the International System of Units (SI) second. At the time of this writing TAI is currently ahead of UTC by 36 seconds and ahead of GPS by 19 seconds [6, 7, 8].

2.1.2.3 BeiDou/COMPASS

The BeiDou Navigation Satellite System, which is named after the Big Dipper constellation which is known in Chinese as Běidǒu, is the GNSS currently under development by the China National Space Administration (CNSA). The BeiDou system actually consists of two individual constellations - an experimental test system called BeiDou-1 and a full scale GNSS called BeiDou-2 or COMPASS. The space segment of BeiDou-1 consists of 4 satellites which were brought into orbit in 2000, 2003 and 2007 respectively. Contrary to GPS, GLONASS or Galileo the satellites used, remained in a geostationary orbit which means they followed the earths rotation and makes them appear motionless at a fixed position in the sky. This principle made it possible to test the system with a limited number of satellites - 3 active and 1 spare - although with a limited coverage. After this successful first iteration, the second step was a regional system covering China and neighboring regions, starting with the first COMPASS satellite in 2007 with a continuous growth towards a complete global navigation system by 2020. BeiDou-2 as well will offer a free service, called Open Service (OS) and a so called Authorized Service (AS) which will provide better PVT accuracy for authorized users. The specification for the OS state a positioning accuracy within 10 meters, velocity accuracy within 0.2 $^{m}/_{s}$ and timing accuracy within 50ns. The specification for the AS states that it should work unimpaired even in “complex“ situations which are not otherwise specified [7, 17, 37].

The complete space segment of BeiDou-2 will consist of 35 satellites:

- 27 Medium Earth Orbit (MEO) satellites orbiting in 3 planes with 8 satellites per plane plus 1 spare satellites in case of failure. These satellites orbit the earth at an altitude of 27.840km with an inclination of 55 degrees and an orbital period of 12 hours and 56 minutes.
- 3 Inclined Geosynchronous Orbit (IGSO) satellites orbiting in 3 planes at an altitude of about 42.000km, 1 satellite per plane, with an inclination of 55 degrees and an intersection node of 118E.
- 5 geostationary satellites positioned at an altitude of about 42.000km at 58.75E, 80E, 110.5E, 140E and 160E respectively.

It can be assumed that the ground segment for BeiDou-2 is similar to the ground segments of other GNSS which consist of a MCS, several uplink stations as well as several monitor stations. Concrete technical and/or location data has not been made publicly available yet though [7].

BeiDou-2 provides location data using the so called BeiDou Coordinate System (BDC) which is consistent with the China Geodetic Coordinate System 2000 (CGCS 2000) which in turn is aligned with the ITRF. Differences between BDC and the GPS geodetic system are within an order of magnitude that can be neglected. BeiDou-2 uses the so called BeiDou System Time (BDT) as a time reference system which is an internal, continuous navigation time scale utilizing the SI second. BDT is in sync with UTC within an offset of 100ns and the actual time value is stated the Week Number (WN) and the Second of Week (SoW). From this follows that the largest unit used in BDT is exactly one week which is 604,800 seconds. BDT started at Sunday January 1, 2006 00h00m00s UTC [38, 39]

2.1.2.4 IRNSS

The Indian Regional Navigation Satellite System (IRNSS) is a satellite navigation system currently under development by the Indian Space Research Organisation (ISRO). FOC of the system should be provided by a space segment of 7 satellites, IRNSS-1A to IRNSS-1G. At the time of this writing, the first 4 satellites have been successfully launched into orbit [40] and the remaining 3 should be delivered by the end of 2016. 3 of these 7 satellites will be placed in geostationary orbits at 34E, 83E and 132E respectively. The other 4 are destined to be IGSO satellites orbiting in 2 planes, 2 satellites each, with an inclination of 29 degrees. These orbits are designed in a way that 2 satellites are above the equator and 2 below at all times. This will ensure a complete and continuous coverage of the Republic of India as well as neighboring regions. As with the other systems IRNSS shall provide a free service, called the Standard Positioning Service (SPS), and an encrypted service called Restricted Service (RS).

An important side note is the fact that the IRNSS does not completely qualify as a GNSS because, as the name of the system already suggests, it is not a global but a regional navigation system. The Indian Government is planning such a system though, consisting of 24 satellites, the so called Global Indian Navigation System (GINS). If and when this system will be available is unknown at the time of this writing [7, 17].

2.1.3 GNSS Error Sources

The determination of a users position and velocity values or the synchronization to the GNSS system time is not a trivial task and the warranty of a certain level of accuracy makes the whole situation even more intricate. Generally speaking the accuracy of a GNSS like GPS depends strongly on the pseudo-range and signal phase measurements as well as the transmitted navigational data. Furthermore the underlying model of the physical universe that enables the translation into real world data is also of great importance. An example would be the offset of satellite to user clocks which is a crucial part of the system. These kind of errors are not only introduced by the space segment alone but also the responsibility of the other segments which makes the topic of error sources and compensation methods even more important [6, 8].

To provide a viable assessment of the impact of certain errors on accuracy the term User Equivalent Range Error (UERE) was coined. The basic assumption hereby is that the error sources can be assigned to individual satellites and can be expressed as an equivalent error in the pseudo-range between a user receiver and a certain satellite. These UERE originate from different error sources and are therefore considered independent. The total value for UERE, which takes in account all error sources affecting a specific satellite, is calculated by summing up the squares of the individual UERE values of a specific error source and taking the square root of the result. Sometimes this total UERE is divided into 2 segments - the Signal in Space User Range Error (SISRE), which includes satellite clock and ephemeris prediction errors, and the User Equipment Error (UEE) which concerns itself with ionospheric model errors, tropospheric model errors or receiver noise [41]. Finally the actual accuracy of a PVT solution calculated by a receiver is determined by a simple estimation formula:

$$\text{Error in PVT solution} = \text{Geometry Factor} \times \text{Pseudo-Range Error Factor}$$

In this case the *Pseudo-Range Error Factor* is simply UERE for a specific satellite. The *geometry factor*, generally also known as Dilution of Precision (DOP), describes an effect on the PVT solution due to the fact of the satellite-to-user geometry for which an example is shown in Figure 2.10.

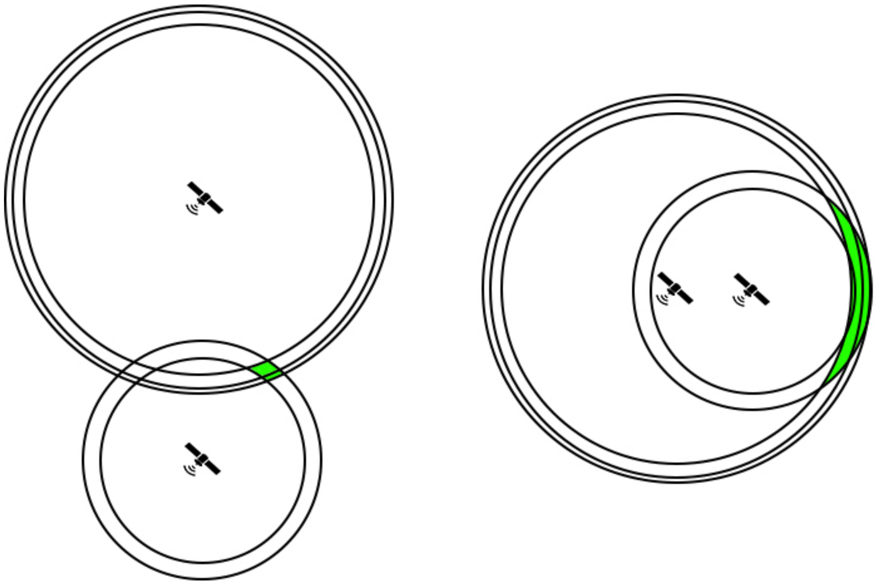

Figure 2.10: The effect of low and high DOP (modeled after [6]).

Clock offsets observed at the satellite as well as the receiver end translate directly into pseudo-range measurements. Signals broadcast from the satellite have to traverse through the planets atmosphere which influences the travel time of signal differently as if it were transmitted in a vacuum. The troposphere delays the signal propagation whereas the ionosphere actually expedites it - a phenomenon more commonly known as ionospheric divergence. Another point to consider are reflections - so called multipath effects - as well as hardware influences on the receiver side which can also delay or speed up signal components [42]. The following sections describe the major error sources in GNSS and the magnitude of the effect on the computed PVT solutions in greater detail [6, 8].

2.1.3.1 Satellite Clock and Ephemeris Errors

To be able to control onboard operations like the generation of the signal which is broadcast to earth, each satellite is equipped with a highly stable atomic clock. Despite this high standard of stability and accuracy the margin of error between the satellite onboard time and the actual GPS time can be as much as 1ms. This may seem irrelevant but as already mentioned during the discussion of the user segment, this small deviation can lead to a large pseudo-range measurement error due to the involvement of the speed of light. A deviation of 1ms therefore directly translates to an error of 300km [43]. To combat this error the MCS transmits so called clock correction parameters ever so often to the satellites which in turn transmit these to the users receiver. The receiver receives these correction parameters with the navigation message and calculate the clock error using the polynomial [6, 8]:

$$\delta_{clk} = \alpha_{f0} + \alpha_{f1} * (t - t_{oc}) + \alpha_{f2} * (t - t_{oc})^2 + \Delta t_r$$

where:

α_{f0} is the clock bias (s)
α_{f1} is the clock drift (s/s)
α_{f2} is the frequency drift (s/s^2)
t_{oc} is the clock data reference time (s)
t is the current time epoch
Δt_r stands for a correction of relativistic events (s), which will be discussed in a later section

α_{f0}, α_{f1}, α_{f2} are polynomial coefficients which are provided with the ephemeris data. $t - t_{oc}$ represents the time the signal takes to travel from the satellite to the user. Clock data and/or correction data degrade over time so logically these measurement errors which occur as a result of clock errors reach their nadir after a update from the control station which is done usually at least once a day. At Zero Age of Data (ZAOD) or shortly after, the normal clock errors lead to an offset of about 0.8 meters whereas 24 hours after the upload the clock error has increased and so has the measurement error - by up to 4 meters [44]. Beside other navigation data parameters the control segment also provides estimates of ephemeris data for all satellites which is computed and uplinked to be transmitted to the user. This data is generated using a curve fit which provides the control entity with a best estimate as to where the satellites are located at the time of uplink. Typically these errors are in the range of a few meters [45]. Computation of these ephemeris errors is done by projecting the error vector, the difference of broadcast orbit in contrast to the true orbit, onto the user-to-satellite Line of Sight (LOS) vector. These errors are smallest considered the radial direction, which means from satellite to center of earth, and much larger in the along-track, which is the travel direction of the satellite, and cross-track, which is vertical to along-track and radial direction. Fortunately larger along-track and cross-track ephemeris errors do not equal to larger measurement errors due to the fact that they do not influence the LOS factor significantly. All in all the resulting range error given ephemeris prediction errors is about 0.8m [44].

As expected these early stage measurement errors as a result of clock and ephemeris prediction errors, which have been given above, have decreased over time due to the fact that new satellites are brought into orbit which carry better performing atomic clocks as well as improvements made to the control segment. Several studies have shown general SISRE improvements from 4.5 meters to 2 meters from 1990 to 1997. Control segment improvements considering the ephemeris updates in 1997, called Ephemeris Enhanced Endeavour (EEE), reduced the error introduced through orbit offsets to about 1.1 meter. Additional introductions of NGA monitoring stations as part of the Legacy Accuracy Improvement Initiative (L-AII) of 2005 further reduced to orbit-only contribution to the measurement error from 0.45 to 0.25 meters. Combined with the other error components the total SISRE error was reduced to about 1 meter. More recent studies show an even greater improvement over time. A 3 year survey, starting at the turn of the half-year in 2005, show a SISRE value of 1.3 meters for Block IIA satellites and 0.63 meters for Block IIR or 0.77 meters for Block IIR-M satellites respectively. It is worth mentioning that Block IIA satellites are basically ancient technology, launched during the mid 1990s and at the time of this writing only two satellites of this series are in service [46]. During the period of 2008 till 2010 reported SISRE values for Block IIA, IIR and IIR-M satellites were 1.08, 0.42 and 0.53 meters respectively, with the latest reports showing a general space constellation SISRE average of 0.7 meters in the years 2012 and 2013. This incredibly improvement is in part credited to the replacement of the old Block IIA satellites by newer generations [47, 48, 49].

2.1.3.2 Relativistic Effects

Considering the fact that even little discrepancies can have huge effects on measurement errors, Einsteins' general and special theories of relativity have to be considered as relevant factors influencing pseudo-range and signal measurements. General Relativity (GR) comes into play any time the source of a signal and the respective receiver of that signal are located in different gravitational potentials. The satellites in high orbit above the earth experience less curvature of spacetime due to the planets mass than a receiver located on the surface. The prediction of GR states that clocks located closer to a massive object, like a planet or a black hole, run slower than a clock further away.

Applied to the situation with GNSS the clocks onboard appear to run faster than identical clocks on earth. Calculations using GR predict that the atomic clock aboard each GPS satellite will run faster by about 45 microseconds per day. Special Relativity (SR) must be considered every time the source of a signal or the respective receiver of that signal are in relative motion to one another. An observer on the surface sees the satellites of a GNSS in motion relative to him or her which according to SR results in a clock ticking more slowly than an identical clock on earth. This time dilation effect due to the relative motion delays the clocks aboard the satellites by about 7 microseconds per day. These two relative effects can now be combined to calculate the actual offset of the onboard clocks which means that each clock will run faster than an identical clock on the surface by about 38 microseconds per day [50, 51]. To compensate for both the GR and SR effect the frequency of the atomic clock onboard the satellite has to be adjusted at launch. The achieve the frequency used for the broadcast of GPS signals, which is 10.23 MHz, the clock frequency has to adjusted to exactly 10.22999999543 MHz [43]. To be precise only half of the relativistic corrections, namely the general relativistic correction, are taken care of with the setting of the clock frequency of each satellite. Special relativistic corrections require knowledge of the orbital parameters of the specific GPS satellite from which the signals are coming. This information is provided via the data transmitted from the specific satellite and the actual calculation is done by the individual receiver itself using relatively straightforward algorithms without the need for user interaction [52].

Another special relativistic effect that needs attention comes from the fact that the orbits of the satellites are slightly eccentric which results in a periodic change in their gravitational potential. Being at perigee the velocity of the satellite is higher and therefore the gravitational pull lower which results in an atomic clock that runs slower. On the other hand, being at apogee the velocity of the satellite is lower and therefore the gravitational pull higher which results in an atomic clock running faster [50, 51]. Leaving this uncorrected can lead to an maximum offset of about 70 nanoseconds which directly translates into a range error of about 21 meters [41].

The final relativistic error which has to be considered, called the Sagnac Effect, stems from the different reference frames in which the GPS satellite motion is defined and in which the final navigation solution is calculated as well as the constant rotation of the earth. GPS uses an Earth-Centered Inertial (ECI) frame called J2000, a frame defined at the epoch J2000. As the name suggests the ECI frame is a non-rotating, inert frame with its focal point located at the centre of the earth. The x-axis is aligned with the mean equinox, the y-axis is rotated 90 degrees towards east and the z-axis is aligned with the planets spin axis [53]. Reason for the ECI frame, besides the improved capability to characterize satellite motion, is that it is the most convenient to describe physical processes such as electromagnetic wave propagation. In contrast the frame used for the actual computation of PVT is an ECEF frame, which means that it co-rotates with the earth. A transformation from the ECI frame to the ECEF frame is therefore required. Important for this transformation and the general calculation of a navigation solution respectively, is to take earth's rotation into account. A stationary GPS receiver located on the equator will have traveled with about 465m/s [29] through the ECI frame during the time of signal transmission from satellite to receiver. If this effect is ignored an error of the magnitude of hundreds of nanoseconds is possible which directly translate to measurement error of tens of meters [50, 51]. There are different options to deal with the Sagnac Effect - a very common approach is to neutralize the effect completely, simply by working with an ECI frame for both environments, space segment as well as PVT calculations. During the pseudo-range measurements using the available satellites, a snapshot of the current status of the ECEF frame is made and used for further calculations. The Sagnac Effect does not arise using this frozen ECEF snapshot. A few additional calculations have to be done though, like the computation of the position of each satellite used at the time of transmission. This snapshot technique as well as a number of alternative rotation correction methods are explained exhaustive in [54].

2.1.3.3 Atmospheric effects

Atmospheric conditions and their concomitant inconsistencies affect the speed of GPS signals as they pass through the planets atmosphere. To provide corrections for these errors is not only mandatory to improve GPS accuracy but also provides a notable challenge due to these inherent fluctuations. Generally speaking, atmospheric effects become stronger the longer a satellite signal has to travel through the atmosphere, so satellites directly overhead of the receiver experience less influence than satellites near the horizon.

Ionospheric delay

The upper part of the planets atmosphere is called the ionosphere and ranges from about 60 to 2000km, with the densest point and therefore the highest amount of particles at around 300 to 400km. Extreme Ultra Violet (EUV) radiation coming from the sun ionizes the neutral gas in these layers considerably. Furthermore solar winds as well as general cosmic radiation contribute to the ionization. The result of this ionization is a production of free electrons and ions from interaction with atoms and molecules in the ionosphere. This resulting effect is called ionosphere refraction and it directly influences the propagation of electromagnetic waves including GPS signals broadcast by the space segment [55].

The concrete value of the ionospheric delay depends strongly on the frequency of the signal as well as the Total Electron Count (TEC), which is the electron density along the path from satellite to receiver. The TEC is defined as a function dependent of various factors like the time of day and current season, specific location of the receiver, elevation angle of the satellite, current magnetic sun spot activity and so on. Apex and nadir are hereby at mid-afternoon and midnight, respectively. There exist several methods to correct for this error. Due to the fact that the ionospheric delay is frequency dependent it can be effectively eliminated using a receiver capable of exploiting both frequency bands used by GPS. Pseudo-range is calculated using the L1 as well as L2 frequency to provide an estimate of the ionospheric delay. One drawback of this method is that measurement errors are magnified due to the combination. Ionospheric effects generally change slowly which helps with the smoothing of the error over time. This fact also enables a second method for the correction, usable also by receivers with only single frequency capability, which uses a calculated average value for the ionospheric delay in a general geographic region. These values are transmitted from secondary systems via radio or other links and allow for ionospheric corrections. Another method which is used frequently is the employment of models of the ionosphere to predict and correct for the ionospheric delay. An important example would be the Klobuchar Model, which is known to remove about 50 percent of the ionospheric effect by providing a set of coefficients in the GPS message [55].

As already mentioned the actual values for the delay are magnified not only by the TEC but also by the travel time of the signal through the ionosphere. A satellite broadcasting a signal at vertical or near vertical incidence angle experiences a delay of about 10ns at night and up to 50ns during the day, which in turn translates to an offset of 3 meters and 15 meters, respectively. Near the horizon with low viewing angles these values can go way up, reaching about 30ns, or 9 meters, at night and up to 150ns, or 45 meters, during the day [56].

Tropospheric delay

The lower part of the planets atmosphere is called the troposphere. Contrary to the ionosphere the propagation of electromagnetic waves in this layer is not frequency dependent but depends strongly on the tropospheric refraction index, which is a function influenced by local temperatures, pressure as well as humidity. These factors change more rapidly than ionospheric effects and appear more localized which makes the actual measurement and calculation more difficult. The refraction index is often calculated in 2 parts which consists of the dry or hydrostatic and wet or non-hydrostatic component. Given these 2 main components, 90% of the tropospheric delay stems from the hydrostatic factor which arises from dry air and is relatively easy to predict. What proves more problematic in terms of predictability are the remaining 10% which stem from the wet component and arise due to water vapor. Both of these components extend to different height levels in the troposphere with the hydrostatic layer reaching about 40km and the non-hydrostatic layer reaching about 11km [55].

Several different models to compute corrections for the tropospheric refraction exist in respective literature with differences in certain assumptions. Generally these models can be split into 2 general approaches. The first being geodetic-oriented which means the models are more accurate but also more complex and require concrete meteorological data. The other option is to use navigation-oriented models which are less accurate but less complex and without the need for meteorological input. If the tropospheric error is left uncorrected the actual delay varies again with the signal angle of arrival as well as the receivers height. A satellite broadcasting at vertical or near vertical position produces an offset of about 2 meters which can go up to about 25 meters with decline of the incidence angle [57].

2.1.3.4 Radio Frequency interference

Any Radio Frequency (RF) signal from an unwanted source which is picked up by an GNSS receiver is considered interference. Radio Frequency Interference (RFI) can be classified in many different ways, be it after wave characteristics, actual center frequency or power and time domain. Another possible way to classify RFI is by the source of the interference which can either be intentional or unintentional. GNSS systems like GPS, GLONASS or BeiDou were designed with a concrete military use as the ulterior motive, which holds still true to this day. Given this fact it is imperative to keep the possibility of intentional interference in mind - which can result in either the disruption of GNSS and therefore in a denial of service, also called jamming, or the intentional broadcast of fake/false GNSS signals to deceive the receiver, also known as spoofing. Even Galileo, which is primarily designed as a civil and research system, may be targeted with malicious intent - an important fact to consider given possible SAR operations. Nevertheless most of the interference found is still unintentional which can result from natural occurrences as well as other systems which use the same or a close neighbor frequency band to GNSS frequencies. Table 2.3 shows a number of sources which are unintentional interferers relevant to GNSS operations. Given these facts about RFI in GNSS several different effects can be identified and observed considering the output of GNSS receivers [6, 8]:

- **Loss of Signal**
  Given a strong enough RFI a GNSS receiver can lose track of all available satellite signals which results in a complete loss of the receivers functionality.
- **Repercussions on the Front End**
  The receiver front-end filters the incoming signal and prepares it for the Analog/Digital Converter (ADC). This includes one or more Adjustable Gain Control (AGC) stages which boost the signal from the space segment above the thermal noise level which is electronic noise produced by thermal agitation. Given enough interference these AGC stages boost the distorted signal to the maximum ADC levels which may cause the actual signal to get diminshed or even lost.
- **Repercussions on the Signal Aquisition**
  Aquistion describes the use of correlation of incoming signal with local signal to find a peak. Interference can cause an increase in the noise floor of the signal search space which in turn can mask the correct correlation peak. This can delay signal aquisition.
- **Repercussions on the Signal Tracking**
  Interference during the tracking increases the variance of the correlation outputs which in turn has direct influence on pseudo-range measurement errors.
- **Repercussions on the Signal-to-Noise Ratio (SNR)**
  The SNR is used to determine and evaluate the performance of the tracking as well as the acquisition stages in a GNSS receiver. Obviously this value is influenced by additional noise.

There are 3 main possibilities to deal with interference - threshold enhancements of receiver tracking with the help of an Inertial Measurement Unit (IMU), the elimination of certain frequencies and therefore the additional interference energy by the means of additional hardware filters or signal processing and antenna steering. The latter means a gain-steering toward the satellite and/or a null-steering toward RFI source. Furthermore LOS plays an important role in the effectiveness of RFI because it is necessary to exert the full effect [6, 8].

Origin	Frequency Range	Description
Self and/or other GNSS	complete GNSS frequency range	GNSS interfere with themselves and each other in general
Pseudolites	complete GNSS frequency range	Ground based “Pseudo-Satellite” which is used to boost performance of a GNSS
Distance Measuring Equipment, Tactical Air Navigation, Automatic Dependent Surveillance	960MHz to 1164MHz	pulsed signals, used for aircraft navigation
Link 16	960MHz to 1164MHz	pulsed signals, military communication system
RADAR	960MHz to 1164MHz 1215MHz to 1240MHz	pulsed signals
Amateur radio	1240MHz to 1300MHz	permitted by the International Telecommunication Union (ITU) as long as no harmful interference is caused
Mobile communications	1350MHz to 1400MHz	
Satellite communications	1535MHz to 1559MHz	Satellite Downlink
Satellite communications	1610MHz to 1626.5MHz	Satellite Uplink

Table 2.3: Overview of GNSS RFI interference origins (modeled after [6]).

2.1.3.5 Multipath and Shadowing

General improvements of GNSS over the last years have reduced many error sources to a minimum, leaving multipath and shadowing errors as a notable remaining contributor to overall measurement errors. Multipath is defined as the reception of reflected or even just diffracted replicas of the original signal coming from the space segment. Naturally the path traveled by the reflected signal is always longer than the signal traveling the direct path from satellite to receiver. In case of a large multipath delay - a delay of the magnitude of twice the spreading code period would qualify - the receiver is able to resolve the multipath easily as long as it tracks the direct signal path and the result on measurement performance is only minimal. In case of reflections from nearby sources and therefore shorter delays - in the order of nanoseconds - multipath signals can influence the correlation function between the received signal and the signal which is locally generated. Furthermore distortions in the carrier signal are also a possibility which will result in pseudo-range measurement errors [6, 8].

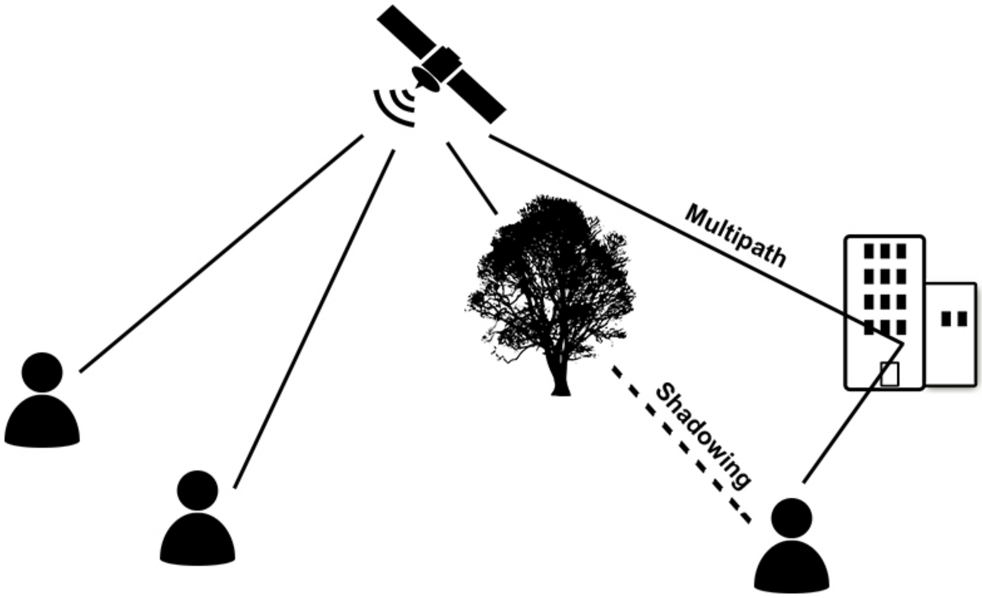

Figure 2.11: Situations in which Multipath and Shadowing effects can occur (modeled after [6]).

Shadowing describes the phenomenon of additional damping of the signal traveling the direct path from satellite to user. This dampening can have a multitude of sources but is usually introduced when the signal has to travel through structures or flora. Situations are possible where the received power level of the multipath signal is equal or even greater than the received power level of the shadowed, direct path signal. An example for such a situation is shown in figure 2.11. Shadowing of the direct path signal can even reach levels in which the receiver is only able to track the multipath signal. The introduced error does not only relate to the delay of the multipath signal but also to the power compared to the direct signal. Multipath signals with little received power in contrast to the power level of the direct signal introduce little distortion and therefore little measurement errors. Receiver capabilities which are most sensitive to multipath errors are the signal code and tracking accuracies [6, 8].

Signals from different satellites typically show different levels of multipath and shadowing influence on the resulting pseudo-range errors. Computer models in general provide accurate and even realistic scenarios yet provide no real insight into the core of the problem. On the other hand multipath models provide tremendous insight but leave much room in terms of realism which means that actual numerical results are often way off of real world scenarios but provide valuable diagnostic information. All in all multipath environments are a complicated and diverse topic which in turn makes it especially difficult to quantify multipath effects to make them valid in a general principle and very accurate at the same time. The fact that multipath and shadowing effects are such a dominant error source has sparked serious investigations into the development of mitigation techniques. An important group of mitigation techniques concerns itself with the reduction of the actual reception of multipath signals. These can be achieved through modification of the antenna in the form of absorptive coatings or the antenna angle and positioning [58, 59]. The removal of reflective structures around the antenna can yield good improvements on multipath signals. Another option to mitigate multipath effects is through receiver processing and new correlation kernels [60, 61]. If left uncorrected the effect of shadowing and multipath can be of the order of hundreds of meters - with the help of different correction configurations the error can be reduced to a range from a few centimeters to a few meters [62, 63]

2.2 LPS - Local Positioning Systems

Technologies based on Global Navigation Satellite System (GNSS), most notably Global Positioning System (GPS), have become the de-facto standard positioning method for Location Based Services (LBS). Navigation with the help of satellites has undergone a great transformation over the last 4 decades, starting from a simple experimental idea to multiple global networks which can pinpoint a users location down to a few centimeters - given the right equipment and access to proprietary signals. But even though the development of GNSS has come incredibly far, it is still not possible to calculate a universal applicable position solution with just this one technology. As already mentioned in the previous chapter, GNSS suffer from inherent drawbacks which become particularly evident in municipal or arboreous areas and indoor locations. GNSS signals coming from satellites, weakened by the tremendous distance and other effects, are simply not able to penetrate buildings or suffer from severe multipath effects. To serve as an aid, other radio signals and sensors are used to enhance and boost the positioning system and enable functionality in more complex situations [10].

2.2.1 Overview of Main Outdoor Techniques

Even though there has been a shift over the last few years concerning the usage of a lot of mobile devices, communication is still mostly the main function - typically with the help of Radio Frequency (RF) signals through wireless radio networks such as 2G, 3G, 4G, Wireless Local Area Network (WLAN) and Bluetooth. These so called "signals of opportunity" were not originally designed for location purposes but show a number of properties which are spatially correlated such as radio signal strength or direction of signal arrival. This fact makes them suitable for the adoption and use in positioning systems be it indoor or outdoor. Given the RF signals used by mobile devices provides us with a number of exploitable RF observables such as the radio signal coverage, the direction of signal arrival, the radio signal strength or the range using Time of Arrival (ToA) and Time Difference of Arrival (TDoA), respectively. Table 2.4 lists commonly used observables for mobile positioning.

In turn different location algorithms have been created using one or more of these observables - these algorithms provide positioning solutions based on [10]:

- Radio Signal Coverage Area
- Radio Signal Pattern
- Direction of Signal Arrival
- Range

The actual accuracy of these algorithms and therefore the position solution provided ranges from a few meters to a number of kilometers. Concrete values depend strongly on the used observable, the environment and the amount and density of the RF transmitters [10].

Observable	Used Sensor/Network
Range	GNSS receiver, Cellular Networks
Range Difference	GNSS receiver, Cellular Networks
Distance travelled	Accelerometer, Camera
Speed	GNSS receiver, Accelerometer, Camera
Acceleration	Accelerometer
Angles/Azimuth	Digital Compass, Cellular Network
Angle rates	Gyroscope
Signal Strength	WLAN, Bluetooth, RFID, Cellular Network
Cell-ID	MAC Address, Cellular Network
Image	Camera

Table 2.4: Mobile Positioning observables typically used to enhance or enable calculation of a position solution (modeled after [10]).

2.2.1.1 Radio Signal Coverage Area

One of the simplest positioning methods using RF signals is called the signal coverage area approach or Network Cell-ID (Cell-ID) method [64]. The basic idea behind this method is that when a mobile device establishes a connection with a RF transmitter, this device is guaranteed to be within the radio coverage area or effective range of said transmitter. This holds true for base stations of a cellular network as well as access points for WLANs and Bluetooth networks. Based on this, an easy way of assigning coordinates to the mobile device is to set them equal to the actual location of the, typically well known, transmitter as shown in Figure 2.12a - given the fact that the coverage area can range from a few meters, given a Bluetooth network or WLAN, up to a few kilometers, given a rural cellular network with only a few base stations, this basic approach leaves much to be desired.

To provide improved location accuracy and reduce the potential area the mobile device may be in, certain constraints can be applied to the position solution on condition that more information is available on the used RF signal. Generally used constraints thereby include the Direction of Arrival (DoA) and the range or a combination of the two. DoA can be estimated by using directional antennas or antenna arrays. Utilizing the DoA measurement provides a line between the transmitter and the estimated position of the mobile device. This approach is accompanied by a degree of uncertainty which is expressed as an angle which in turn translates to an angular section where the mobile device is located as seen in Figure 2.12b [10, 11].

There are several different ways to obtain the range observable - either through the derivation directly from sensors or receivers or indirectly via models [65] using direct observables like the received signal strength. Using models, which are basically functions of an observable like the aforementioned signal strength, to provide accurate range information can be an arduous task though. Uncertainties due to complex multipath

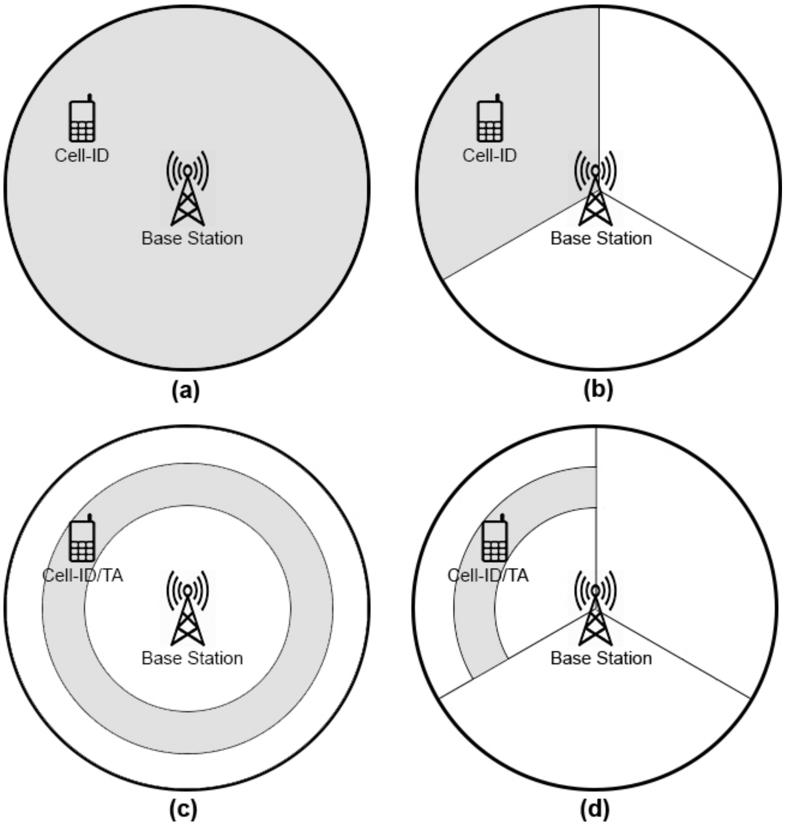

Figure 2.12: Basic Principles of Cell-ID approaches using a single cell and omni directional antenna (a), a three directional antenna with cell sectors (b), Enhanced Cell-ID using TA (c) and Enhanced Cell-ID using TA and a three directional antenna with cell sectors (d) (modeled after [11]).

issues causing fading effects make it very difficult to accurately model a radio signal. An easier and more common - if not most common - observable which is used to obtain the range is the ToA observable [66, 67]. ToA provides a value for the signal traveling time using [10, 11]:

$$ToA = t_r - t_t$$

where t_t is the time of signal transmission and t_r is the time of signal reception. Given these values and the fact that radio signals travel with the speed of light c, the range observable d can be estimated as follows:

$$d = ToA * c$$

This estimation also comes with a degree of uncertainty, expressed in an error called Δd. Given these 2 values the potential location of the mobile device can be reduced from the effective range of the RF transmitter to a ring. This ring has its center at the location of the RF transmitter, a radius of d and a width of $2 * \Delta d$ as seen in Figure 2.12c [10, 11].

The area in which the mobile device is potentially located can be even further reduced in case that both the range value as well as the DoA of the used RF signal is known. Given these 2 observables the area can be narrowed down to what is known as a annular sector as shown in Figure 2.12d - an intersection of the ring provided by the range observable and the angular sector provided by the DoA. The area provided by this advanced approach, also known as Enhanced Cell-ID, is significantly smaller which in turn means a higher location accuracy [10, 11].

2.2.1.2 Radio Signal Pattern

The previous approach using the radio signal coverage area or effective range describes the location of a mobile device using only one RF transmitter. Usually a mobile device receives RF signals not only from one transmitter but from several ones - the combination of those signals makes it possible to generate a so called radio signal pattern which can be used as another observable when locating the position of a mobile device [10, 11].

The most common approach using these radio signal patterns is called fingerprinting. The name stems from the way fingerprints are used to identify people, where in this case the radio signal patterns act as the fingerprints and specific locations act as the people to be identified with them. Fingerprinting is a technique used both indoors as well as outdoors given WLAN and cellular networks, respectively. Generally speaking the fingerprinting method consists of 2 phases [10, 11]:

1. **Training Phase**
   During this phase a set of reference RF signal patterns are collected at specific refernce locations inside a target area. The reference data is then stored in a reference database often called radio map or fingerprint database.

2. **Positioning Phase**
   During this phase an algorithm is used to estimate the most likeliest position of the user by comparing the currently observed radio signal pattern to a stored reference fingerprint, which in turn provides the user with a reference location.

Two distinct approaches concerning the algorithm used to find a match between the currently observed fingerprint and the reference fingerprint stored in the database have been established - the pattern recognition approach and the probabilistic approach. Pattern recognition uses the shortest Euclidian distance, also called the signal distance, between the 2 fingerprints, based on the signal strength of the observed and the reference value. During the training phase a multitude of radio signal measurements are taken, documenting the variance in the signal strength. Afterwards the average of the collected samples is taken to gain the reference radio signal pattern for the database. The probabilistic approach uses the maximum conditional probability that a user is located a a specific reference location given the observed radio signal pattern. To this end the reference radio signal patterns are not stored directly in a database as signal strength measurements but rather as vectors of probability distributions. A typical probability histogram, one of which is shown in Figure 2.13, consists thereby of six to eight histogram bins which is enough to represent a conclusive probability distribution - studies have shown that a differentiation in even more bins does not increase location accuracy in a significant way [68]. The algorithm in the positioning phase now tries to find the reference location with the highest probability value given the occurrence of the currently observed radio signal pattern [10, 11].

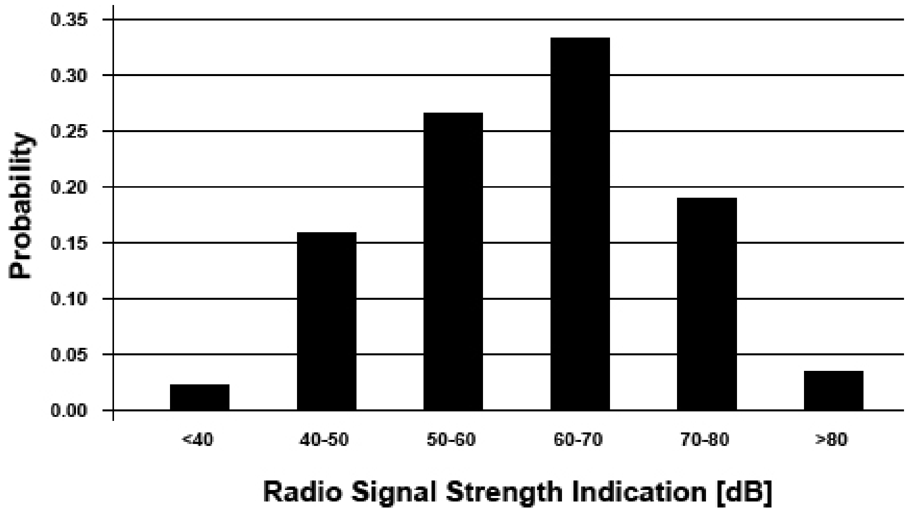

Figure 2.13: Histogram depicting the probability distribution of radio signal strength measurements (modeled after [10]).

2.2.1.3 Direction of Signal Arrival

As already mentioned during the signal coverage area approach, the direction of the arriving radio signal can be used as well to determine the location of a mobile device. The technique of measuring angles is actually quite old and well known - sailors have used this method for centuries to plot locations using specific landmarks known to them. The idea in wide-area telecommunication systems is basically the same, using base stations equipped with specialized antennas able to determine the absolute direction of arrival, also called the Angle of Arrival (AoA), of an incoming radio signal. Similar to the approach used in conjunction with the radio signal coverage area, a line is plotted from the base station to the mobile device using the AoA of the radio signal. A second base station, which picks up the same radio signal from the same mobile device, plots a second straight line, which intersects with the first at a certain point, providing the approximate location of the device in 2 dimensions as shown in Figure 2.14. Theoretically two base stations are sufficient to provide a position solution for a mobile device but more base stations may be able to provide better accuracy due to more angle measurements [9, 11].

This approach has its disadvantages, though. Assuming certain accuracies of angle measurements of the antennas or antenna arrays and effective ranges of the base stations, the total accuracy of a position solution can be of the order of a few hundred meters. It is easy to see that the accuracy further decreases the greater the distance from the mobile device to the base station becomes. Additionally to the accuracy issue the requirement for this method is an unobstructed Line of Sight (LOS) which can be difficult in metropolitan areas or indoor situations. However, the main disadvantage is the inherent complexity and therefore attached price tag which comes with the needed antennas or antenna arrays [9, 11].

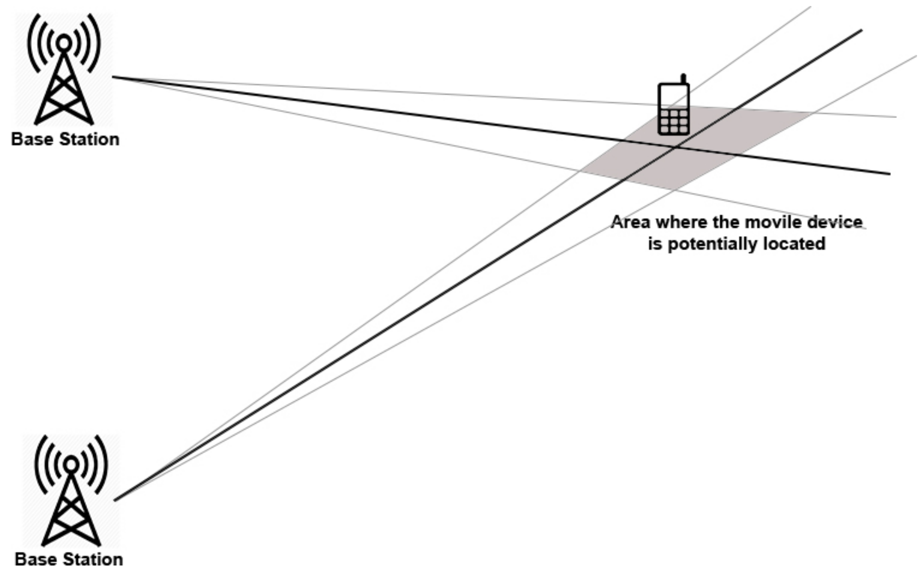

Figure 2.14: The basic principle of locating a mobile device using the angle of arrival (modeled after [11]).

2.2.1.4 Range

Another observable typically used when tasked with mobile device positioning in RF networks is the range. There are 2 common utilized methods to obtain a range measurement:

1. Measuring signal travel time and multiplying it by the speed of light
2. Using radio signal strength values and convert them to range values using path loss models

As already mentioned above, calculation on basis of a model is often a complex task with many uncertainties depending on the actual environment. More convenient is the consideration of position solutions involving the measurement of time. One such solution involves the measurement of the ToA of the radio signal [9, 11].

The basic idea is that the actual distance to the mobile device is determined by the delay of the radio signal between it and the base station for which the actual location has to be well known. Another approach using ToA is the measurement of the so called round-trip time, which means the amount of time it takes a radio signal to get from the base station to the mobile device and back. Using this method provides significant easement in complexity due to the fact that it eliminates the need for timing synchronization between the mobile device and the base station. All the necessary steps for a position solution are done at the base station and the final result can be sent back to the mobile device if desired. For reasons which are quite similar to these of a GNSS, an approach using ToA requires a high degree of synchronization within the base station network as well - which can be considered the main problem for a timing method. For obvious reasons the requirements for positioning services are not aligned with the requirements for basic telecommunication services. Considering a Global System for Mobile Communications (GSM) network a synchronization feature to define a common starting time for data transmission is typically done using a header data ahead of the actual transmission, which is simply not accurate enough. If no precise timing capabilities are present additional network hardware is needed which provide a method of synchronization between base stations. An example for such hardware add-ons would be a Location Measurement Unit (LMU). GSM (2G) networks are dependent on the use of LMUs whereas 3G networks like the Universal Mobile Telecommunications System (UMTS) already provide synchronized base stations. As for the mobile device itself little to no extra modification is necessary to be usable with this technique [9, 11].

Similar to the reasons for a GNSS based position solution it is necessary to provide at least 3 measurements using different base stations to be able to provide a two-dimensional position calculation. Generally speaking a mobile device can only be connected/registered to a single base station and have a single Cell-ID. Nevertheless the device will still send out signals to other base stations in the area, the reason being a smooth hand-over in case the mobile device leaves one cell and enters another. The aforementioned difficulties considering the timing become apparent when looking at accuracy which can be of the order of hundreds of meters. The culprit is basically the same as with GNSS, namely the fact that radio signals travel nearly with the speed of light and an offset of merely 10ns leads to a measurement error of 3 meters. Multipath makes the problem even worse and, as already mentioned in the previous chapter, occurs a lot in this medium [9, 11].

Another timing approach using TDoA mitigates this synchronization issues to a certain degree - instead of measuring the ToA, the differences of arrival times are considered. The difference in arrival times for the radio signal allows for the creation of a hyperbola of potential locations, using a technique which is called hyperbolic navigation. Important is the fact, that the absolute time at which the radio signal was sent is not relevant any more, only the time difference is essential. This method also works both ways which accommodates for certain use cases [9, 11].:

- **Surveillance:** 3 or more well known, synchronized base stations are able to locate a single transmitting mobile device.
- **Navigation:** A single receiving mobile device is able to locate itself using signals from 3 or more well known, synchronized base stations.

Studies have shown that the usefulness of both methods strongly depend on the environment - TDoA seems to perform better in situations where Non-Line-Of-Sight (NLOS) channels are dominant whereas ToA performed better with more LOS channels present [69].

2.2.2 Indoor Positioning - Of Complexity and a Wide Range of Possibilities

Many different techniques and methods have been described so far - starting from satellite based systems like GPS or Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) through to positioning using telecommunication networks. Though these systems provide very good results, they all suffer from the same handicap: providing a continued service and acceptable accuracy considering the application for indoor positioning. The topic of providing continued support and viable accuracy has become very important over the last few years. The advent of smartphones and the downright explosion of LBS which accompanied it, has led to many theoretical and experimental approaches using a range of different technologies and methods including the use of WLAN and bluetooth networks, pure GNSS techniques or the inclusion of other observables like pressure collected via a network of sensors [9, 12].

It seems only logical to consider a GNSS solution, widely seen as the "best" outdoor solution, as a first pick to try and transform it to an answer for indoor location purposes. To this end methods like Assisted GNSS (A-GNSS) and High Sensitivity GNSS (HS-GNSS) have been extensively utilized and tested. Another approach is the usage of a RF communications network, which is basically omnipresent in this day and age, namely WLAN. Much research effort is pooled into the topic of complementing the outdoor coverage provided by a GNSS with the indoor coverage of a RF network like WLAN including a smooth transition from one system to the other. A technique which has received much praise in this regard is called Ultra Wide Band (UWB) and is based on the same concept as radar technology [9, 12].

Complexity comes not only from a wide range of possibilities but also from specific inherent characteristics when thinking about indoor localization. Most notably among these are the often greatly reduced size and the increased diversity of situations. Different building materials like concrete, wood or metal contribute to the propagation of signals as well as different ways buildings are constructed - this does not only hold for various types of buildings like places where people live in contrast to places where people work but is also culturally diverse seen in different architectures around the world. Multipath issues prove to be a real challenge in these situations because the direct LOS path for signals is considered comparatively rare. Of course this also holds for positioning solutions outdoors, but the number of obstructions and reflective surfaces is considerably higher. A way to compensate for this new form of an already known obstacle is simulation to evaluate possible multipath problems. However, these kind of simulations require an exhaustive definition of the surroundings - information like the materials of different elements as well as position information for walls, ceilings, floors, windows and other furnishings. A task which is made only more complex due to uncertainties of the actual position of a receiver, which cannot be known for certain, given the inherent portability of a mobile device. Another issue comes with the often greatly reduced distances which have to be measured by an indoor location system. Considering time related measurements the requirements for accurate and spot on synchronization are very high [9, 12].

One final aspect which has to be considered when thinking about an indoor positioning system are specifications. Currently the available GNSS solutions like GPS or GLONASS provide very good coverage, accuracy and basically permanent availability for outdoors. The question is now, does an indoor positioning system require the same attributes? Is the need for accuracy and coverage the same or higher/lower? What about the need for constant availability? Is it essential that a user has access to real-time tracking? It should be obvious that, given a quite small number of requirements or needs, can lead to a huge number of different specifications considering diverse potential domains. To clarify, one may consider a simple navigation application in the field of Tourism. Given a use case like a guide through a museum one can comprehend accuracy constraints of about 1 meter and also the accurate tracking of the absolute orientation, to know when a user faces a certain exhibition piece. Another application in the field of tourism may simply guide a visitor in a mall from one point of interest to the next - a situation where the absolute orientation as well as an accuracy value of 1 meter may be of less importance. The real problem behind this is that these simple deviations lead to a large number of applications for which no global applicable solution, like a GNSS for outdoors, is available. A complex fact which can be seen as one of the reasons for the rather slow development of indoor location solutions [9, 12].

The following sections in this chapter give a conclusive overview over the techniques and methods mentioned above as well as additional options concerning indoor positioning. These approaches will be explored and explained as well as an assessment of their applicability will be given using the information provided in [9, 12, 13, 14, 15].

2.2.2.1 Positioning using a Sensor Network

Ultrasound

Contrary to a radio wave, a type of electromagnetic radiation, a sound wave is a mechanical wave of pressure and displacement in a specific medium like air or water. Ultrasound has no extra or different physical properties compared to normal sound except the frequency range starting at about 20kHz. Even though the actual physical form of radio waves and sound waves is essentially different, the propagation is very similar with one crucial difference which works quite beneficial - the velocity. As already mentioned, radio waves travel with the speed of light which is about 300.000.000m/s, sound waves on the other hand have a velocity of 300m/s. This fact makes accurate measurements much easier to attain when dealing with time related approaches like ToA and TDoA. To clarify the dimension of easement on time management, consider the deviation of 10ns - given radio waves this would mean an offset of about 3 meters. Using an ultrasound location system a deviation of 10ns would translate to an offset of only 3μm. Multipath issues have to be considered but due to the fact that the speed of the wave is considerably slower, stray signals can be easily discerned from direct path signals by travel time alone. Furthermore due to different physical forms sound waves do not interfere with other electromagnetic waves of other systems. Although the actual range of such a wave is relatively short, a solution can be achieved with comparatively cheap electronic parts. A model of such a system would be the so called Bat System, which has been developed at AT&T Cambridge. A short overview of technical details concerning ultrasound is provided in Table 2.5 [9, 12, 13, 14, 15].

Ultrasound	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor
Accuracy	Several centimeters
Range/Coverage	About 10 m^2

Table 2.5: Technical Overview of Ultrasound-based Positioning

Infrared Radiation

As is the case with RF communications, Infrared Radiation (IR) is a type of electromagnetic radiation which travels at the speed of light. Again, due to this fact, making measurements using timing based approaches like ToA or TDoA can be quite difficult. A central clock element has to be present to provide some sort of synchronization and the level of accuracy needed, makes this kind of method quite expensive. Therefore another kind of localization method has been deployed not based on giving absolute or relative position coordinates but rather on the concept of rooms. This means that the system uses several receivers which are able to cover a certain “spatial unit” - this unit can be of any order be it a room, corridor or hall. Given this fact it is obvious that the number of needed receivers for such a system is the number of actual “spatial units” which need coverage. An example of such a system has been developed at at AT&T Cambridge and is called the Active Badge System. These active badges worn by the user act as beacons which periodically emit a unique identifier every few seconds which is picked up by the IR sensors allocated all over a building. This information is collected at a central node which is then able to compare the unique identifiers detected at a location and determine the location of a specific user. A short overview of technical details concerning infrared is provided in Table 2.6 [9, 12, 13, 14, 15].

Infrared Radiation	
Localization	Pulse-based
Positioning	Absolute (no prior location needed)
Environment	Indoor
Accuracy	A “spatial unit”
Range/Coverage	Receiver/Beacon per “spatial unit”

Table 2.6: Technical Overview of Infrared-based Positioning

Pressure Sensors

In contrast to other indoor location methods which focus on the location considering a specific plane, a method involving pressure sensors or more specifically smartphones with built-in barometric sensors, focuses on the actual floor positioning in multi-storey buildings. This approach uses the well known fact that with increasing altitude the atmospheric pressure decreases. These atmospheric pressure values can be measured and conclusions can be drawn about the current floor location of the mobile device. Recent studies have shown that these algorithms can even determine the floor location without prior knowledge about the height of the floors. Furthermore a certain robustness considering factors like humidity and temperature which influence measurements can be trained. Accuracy of this kind of system can be further improved by deploying additional barometric sensors. A short overview of technical details concerning barometric sensors is provided in Table 2.7 [70, 71].

Barometric Sensors	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor
Accuracy	A floor
Range/Coverage	-

Table 2.7: Technical Overview of Positioning based on Barometric Sensors

Another approach using pressure is by providing floor tiles with pressure sensitive sensors. By simply observing the pressure value of a certain tile allows for conclusions to be drawn about the actual number of people on this specific floor tile. Of course using this approach only allows for the estimation if a person or multiple persons are present at a specific location. Exact identification of each person present would need additional effort. A short overview of technical details concerning pressure plates is provided in Table 2.8 [9].

Pressure Plates	
Localization	Continuous
Positioning	Relative to known location
Environment	Indoor
Accuracy	Several centimeters
Range/Coverage	Contingence

Table 2.8: Technical Overview of Positioning based on Pressure Plates

Radio Frequency Identification

Radio Frequency Identification (RFID) is an identification system using electromagnetic waves and consists of a reader element and a label element, the so called "RFID tag". In terms of power consumption readers are always active and RFID tags are mostly passive but can be active if needed. The RFID tag is associated with a certain object or location and stores specific information electronically. In case of passive RFID tags the magnetic field created by the reader provides the tag with power by electromagnetic induction and enables the information exchange. One advantage of this system is that no direct line of sight is needed, which enables the embedding of the RFID tag - clothing, valuables and even animals and people are possible tag targets due to the fact that a RFID tag can be the size of a grain of rice. The average ranges at which a reader is able to extract information go from 10 centimeters up to 2 meters. RFID tags production costs are very cheap so it is possible to cover a large area and provide continuous location support. The increased utilization of RFID tags and the potential for reading contained information without explicit consent has raised concerns regarding security and privacy. Several propositions have been made encouraging the use of RFID tag cryptography or digital signatures. Nowadays RFID technology can be found almost everywhere be it in access management, tracking of goods/animals or identification systems such as passports. A short overview of technical details concerning RFID is provided in Table 2.9 [9, 12, 13, 14, 15].

RFID	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor/Outdoor
Accuracy	10 centimeters to 2 meters
Range/Coverage	10 centimeters to 2 meters

Table 2.9: Technical Overview of RFID-based Positioning

2.2.2.2 Positioning using a Local Area Communication Systems

Given the fact that over the last few years local area communication systems like WLANs or Bluetooth networks have become virtually omnipresent, it can be considered as only natural to try and exploit these systems for localization purposes. A main requirement when thinking about positioning systems is continuity of service, which is currently not available to an extent which can be considered useful. Good outdoor solutions like the GNSS presented in previous chapters provide no real functionality indoors if anything with very poor accuracy - for the foreseeable future this fact provides a need for indoor location solutions.

The most popular approach when using positioning via a local area communication system is the Received Signal Strength (RSS) method. The basic idea is to use the attenuation of the radio signal to draw conclusions about the actual distance from base station to receiver. Possibilities include the utilization of a propagation model or the application of a fingerprinting algorithm. This technique has already been mentioned above during the discussion about the range observable and it has been stated that using other observables like the ToA or TDoA are preferred solutions. Considering outdoor positioning this is still true but in case of indoors the advantages of a RSS approach outweigh the costs. One crucial point is the significantly smaller area which has to be covered for the creation of a RSS map in contrast to outdoor positioning. The basic idea of such a RSS map, for which an example is shown in Figure 2.15, is to provide an overview of the measured signal strength at a given location. Furthermore the system can basically work out-of-the-box, due to the fact that there is no need for additional timing equipment which is very expensive. Nevertheless multipath and the general dynamics of the environment when dealing with indoor positioning is still a problem which has to be considered [9, 12, 13, 14, 15].

Bluetooth

Bluetooth was originally invented in 1994 by Ericsson, a Swedish multinational telecommunication vendor, to serve as an alternative for data transmission at terminals using a Wireless Personal Area Network (WPAN). Officially 3 classes of Bluetooth devices exist with maximum permitted power levels and typical ranges - Class 3 around 1 meter, Class 2 between 5 and 10 meters and Class 1 with up to 100 meters. Most devices found on

5	9	5	6	5	10.5	12
6	10	13	12	5	4	4.5
9	10	14	15.5	15	9	5
10	12	13	12	13	8.5	5
9	6	5.5	6	13.5	9	10
11	9.5	5	6	10.5	10	11

Figure 2.15: Example of a typical RSS map for a rectangular room indicating the power levels measured - usually in dB over a specific power value (modeled after [9]).

the market are either Class 1 or Class 2 - Class 3 devices are justifiably rather rare due to the very limited range. Technically there is no limit on the actual range of Bluetooth communication but values which exceed the ranges defined in the classes mentioned would also exceed allowed output power limitations in many countries. Advantages of Bluetooth are that the technology does not require LOS between devices, is very power efficient and the fact that Bluetooth-enabled devices are quite common in this day and age. Due to the fact that Bluetooth was designed to get rid of cables at terminals, the range is quite small which in turn can lead to a larger number of needed Bluetooth modules to cover a specific location. On the other hand a larger number of modules also means an increase in location accuracy. Another disadvantage is that Bluetooth operates at a radio frequency of 2.4 GHz, which is unlicensed and is therefore heavily utilized for communication purposes which can lead to additional Radio Frequency Interference (RFI). A short overview of technical details concerning Bluetooth is provided in Table 2.10 [9, 12, 13, 14, 15].

Bluetooth	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor
Accuracy	Depending on Class/Modules, Class 2 about 3 meters
Range/Coverage	Depending on Class, up to 100 meters

Table 2.10: Technical Overview of Bluetooth-based Positioning

WiFi

As already mentioned at the beginning of this section, the omnipresence of WLANs has made approaches using these kind of networks a primary target for research and development of indoor location applications. To be precise the term WLAN defines only properties of the used computer network, namely that the communication is wireless and that the range lies somewhere within 100 meters. WiFi, as defined by the Wi-Fi Alliance, is a trademark name used to brand electronic devices capable of communicating using Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards. Due to the fact that most modern WLANs are based on 802.11 standards, the terms Wifi and WLAN have since long become synonymous [9, 12, 13, 14, 15].

When looking at Wifi compared to Bluetooth, the technology and other properties like sensitivity or the ability to work without LOS are quite similar, with the range of an Access Point (AP) being the main difference. This is an important advantage when considering an installation of an indoor location system because the cost and therefore the actual number of APs is key. Additionally, the majority of devices nowadays are Wifi-enabled and the omnipresence of such networks makes it comparably easy to build a system upon an existing infrastructure. Given the fact of the range advantage of Wifi APs and the omnipresence of such networks the approach using a WLAN is preferred to Bluetooth. A short overview of technical details concerning Wifi is provided in Table 2.11 [9, 12, 13, 14, 15].

WiFi	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor (Outdoor possible)
Accuracy	Depending on APs, a few meters
Range/Coverage	Depending on APs

Table 2.11: Technical Overview of Wifi-based Positioning

Ultra Wide Band

UWB is a RF communication technique which has gained more and more interest over the last few years, especially after the opening of a 7.5 GHz frequency band by the Federal Communications Commission (FCC) in February 2002, ranging from 3.1 to 10.6 GHz. UWB works with very short pulses on a very broad bandwidth - usually the pulse duration is of the order of a nanosecond or less over a bandwidth of more than 500 MHz. The first use of UWB, originally named pulse radio, dates back to the 1970s for Radar applications like Ground Penetrating Radar (GPR). A positioning approach using UWB has several interesting properties [9, 12, 13, 14, 15].:

- The wide bandwidth makes it possible to get past certain obstacles. This is due to the fact that only a part of the signal is usually blocked or disturbed while the rest of the signal may pass relatively unhindered.

- The high bandwidth directly translates to an increased capacity for data transmittion as indicated by Shannon [72].
- Resistance to multipath effects due to the high time resolution and short pulse duration.
- Low power consumption which is in part due to FCC regulations. Additionally, due to the fact that the low power signal is spread over a large spectrum, it looks more like noise than an acutal data transmission. This can be directly translated to jam/eavesdropping resistance and less interference with other systems.

Disadvantages of an UWB approach include the relatively high cost of UWB equipment and the fact that metallic and/or liquid materials cause serious signal interference. Contrary to Bluetooth and WiFi, preferred position estimation techniques are ToA and/or TDoA instead of RSS mapping due to the increased resistance to multipath effects. Synchronization can be achieved either through specific algorithms using the short pulses or an additional UWB module which serves as an external clock. A short overview of technical details concerning UWB is provided in Table 2.12 [9, 12, 13, 14, 15].

Ultra Wide Band	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor
Accuracy	10 centimeters to 1 meter
Range/Coverage	several meters

Table 2.12: Technical Overview of UWB-based Positioning

2.2.2.3 Positioning using a Wide Area Communcation Systems

Given the fact that mobile devices like phones also get relatively good reception indoors, the consideration to use existing telecommunication networks like GSM and UMTS for indoor positioning purposes seems only logical. Considering such a Wireless Wide Area Network (WWAN), the possible position estimation techniques are pretty much the same as described during the discussion of main outdoor methods, namely measurements of RSS, ToA, TDoA and AoA. An advantage of the use of such networks is that they operate in regulated frequency bands, which means one can expect less RFI from other systems. Furthermore the coverage of the communication systems is quite good - most nations provide a telecommunication network which greatly outreach WLANs [9, 12, 13, 14, 15].

Indoor positioning using such a WWAN can be done but requires certain constraints which need to be fulfilled for a certain approach - and even then achieved accuracy levels can be quite daunting. The building needs to be covered by multiple base stations or one dominant one when using a RSS technique. Approaches depending on the AoA can be effectively eliminated due to the fact that the LOS requirement is rarely satisfied. Even if possible the accuracy would disqualify the observable once again. RSS methods are basically comparable to Cell-ID measurements for which the accuracy is depending on the cell size and can be up to a few kilometers. Enhancements as described during the main outdoor methods can be deployed to improve accuracy but it is overall not quite enough for indoor purposes. The last options are ToA and TDoA, timing based approaches, which suffer from the inherent drawback coming from the original purpose of a telecommunication network, namely the design for telecommunication and not for positioning. Base stations which are not synchronized or have poor timing accuracy take a heavy toll on location accuracy. Additionally the occurrence of multipath effects further deteriorate location estimations up to a few hundred meters. All in all indoor positioning using WWANs like GSM, UMTS or Long-Term Evolution (LTE) is possible but the overall location accuracy leaves much to be desired. A short overview of technical details concerning WWANs is provided in Table 2.13 [9, 12, 13, 14, 15].

Telecommunication Networks	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor/Outdoor
Accuracy	RSS/Cell-ID: depending on cell size up to a few kilometers
	ToA/TDoA: depending on network 20 to 100+ meters
Range	RSS/Cell-ID: depending on cell size up to a few kilometers
	ToA/TDoA: Network Range

Table 2.13: Technical Overview of Positioning based on Telecommunication Networks

2.2.2.4 Positioning using Inertial Systems

It is an interesting fact that a GNSS like GPS was not responsible for the first actual navigation of a car. Months before the official statement announcing the full functionality of GPS, inertial sensors made it already possible to follow the movements of a vehicle. Sensors like accelerometers and gyroscopes, which use inertial properties of any kind of motion, were used to determine the directional movement and provided data to plot the course taken from a known starting point. These kind of sensors are not only available for vehicular tracking but can also be embedded in mobile devices such as smartphones to keep track of movements like rotation, inclination or acceleration [9, 12, 13, 14, 15].

- **Accelerometers**
  Acceleration, per definition, is the change of velocity of an object over time - in case of a mobile device accelerometers are used to measure both, sudden accelerations like vibration and/or shock as well as the standard acceleration of the device body. The most common used accelerometer is the so called piezoelectric accelerometer

for which the name originates from the piezoelectric effect. Piezoelectricity is an electric charge which builds up in specific materials like crystalline solids due to mechanical stress. This charge can be measured and converted into an electric signal which is dependent on the applied force which can be directly translated into an acceleration value.

- **Gyroscopes**
  Gyroscopes enable the determination of the orientation of a mobile device by providing the change of the axis angle as output. The classical image of a gyroscope consists of a rather massive rotating disk, usually called rotor, which is suspended in 3 supporting rings. The basic principle is the conservation of angular momentum and the implication that angular momentum maintains magnitude as well as direction. If the gyroscope is tilted the rings will reorient to try to keep the rotor stable with reference to the spin axis. Several different types of gyroscopes exist, using different physical principles - an example for consumer electronics would be the vibrating structure gyroscope, also known as the Coriolis Vibratory Gyroscope (CVG), which is simpler and cheaper than its rotating brother. The basic idea behind the CVG is that vibrations or a vibrating object keeps the direction of the vibration even if the orientation changes.

- **Odometers**
  Odometers are used to determine the actual distance traveled, usually by counting the rotations of a wheel and multiplying this value by the circumference of said wheel. When thinking about vehicles like cars this may work reasonably well but considering indoor use, given a human being with a mobile device, the addition of wheels seems rather problematic. Luckily it is possible to circumvent this inconvenience by substituting the odometer for an accelerometer and simply double integrating the signal it provides.

- **Magnetometers**
  Previous sensors can all be considered as relative sensors which require a certain starting point for the measurements to make sense. Magnetometers are absolute sensors which are sensitive to Earth's magnetic field and can provide information about the absolute orientation of a mobile device - this means that the magnetometers provides the horizontal direction the mobile device is facing, just like a compass. This is particularly convenient due to the rather obvious fact that the magnetic field is available all around the globe.

Even though positioning using inertial system has the advantage that it basically works everywhere and is not dependent on a specific infrastructure, systems for pedestrian use are not very common. This stems from the fact that even though the accuracy of such systems is viable at first, the measurement error increases over time due to sensor bias. These introduced errors add up very quickly and make consistent and accurate positioning rather difficult. Additionally mobile devices wielded by pedestrians exhibit far more distinct situations which require more complex measurements compared to a vehicle like a car. A short overview of technical details concerning inertial sensors is provided in Table 2.14 [9, 12, 13, 14, 15].

Inertial Systems	
Localization	Continuous
Positioning	Relative (using Displacement)
Environment	Indoor/Outdoor
Accuracy	Time dependent, 1 to 5% of traveled distance or angle
Range/Coverage	Global

Table 2.14: Technical Overview of Positioning based on Inertial Systems

2.2.2.5 Positioning using a GNSS

Outdoor positioning without the use of a GNSS seems like a far fetched idea in this day and age. The unbelievable success of GPS has created a whole new branch of industry and even inspired the creation of other systems like Galileo or the restoration of neglected ones like GLONASS. This meteoric rise has also sparked a brisk interest to assess satellite based navigation for the use in indoor positioning scenarios. Alas for systems like GPS the signal strength is simply not high enough to penetrate most building materials like brick and concrete to remain useful for a standard GPS receiver. Nevertheless different approaches utilizing the existing GNSS networks have been proposed and deployed, some of which show interesting improvements [9].

HS-GNSS

As already mentioned during the discussion of GPS, each satellite uses a so called Pseudorandom Noise (PRN) sequence which works as a way of identification and also to diffuse the actual ranging signal. This PRN sequence is also known to the GPS receiver which can duplicate this code in order to overlap the two signals and extract the original signal from the noise - using a process which is known as correlation. This works very well if the actual signal is reasonably strong, but can decrease rapidly considering indoor locations. If the signal is too weak the needed correlation peak cannot be uniquely determined, which in turn can lead to false detections and the positioning accuracy will suffer. To combat this, high sensitivity receivers have been developed which are able to extract signals which have a power level of $1/1000$ of that of an outdoor signal. A typical HS-GNSS uses a long correlation period to find and extract the buried signal whilst filtering out false positives produced by noise, other satellites or RFI. Using HS-GNSS makes it possible to get a positioning solution even in difficult environments even though the accuracy is not perfect. Another disadvantage is the longer correlation time required to acquire the signal. A short overview of technical details concerning HS-GNSS is provided in Table 2.15 [9].

HS-GNSS	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor/Outdoor
Accuracy	several meters
Range/Coverage	Global

Table 2.15: Technical Overview of Positioning based on HS-GNSS

A-GNSS

To be able to calculate the actual position using a GNSS, the receiver needs to know the accurate position of the satellites in sight. This information is provided by the satellites themselves in form of the almanac and ephemeris data which are broadcast periodically. Considering a pure GPS receiver the completion of the data transfer takes 12.5 minutes for the almanac and 30 seconds for the ephemeris data - a period which can be considered as unacceptable for most modern use cases as the Time To First Fix (TTFF) would take at least 30 seconds. Furthermore if the data transmission is interrupted for whatever reason, the transfer starts again and already downloaded data is discarded. Luckily a system has been invented which “assists” a receiver in this matter, called A-GNSS. The basic principle is to use available telecommunication networks like GSM, UMTS or even existing WLANs to take care of the transfer of almanac and/or ephemeris. The network operator therefore deploys a so called A-GNSS server, which stores orbital information of each satellite in a database and provides mobile devices with access to download this data. Data rates over a mobile network or WiFi greatly outperform those of a satellite in orbit and therefore dramatically decrease the TTFF as well as providing a possibility to obtain a coarse location even in difficult situations like indoors. However given the actual use case for accurate indoor positioning, a system like A-GNSS is not able to provide a real answer like HS-GNSS. A short overview of technical details concerning A-GNSS is provided in Table 2.16 [9].

A-GNSS	
Localization	Continuous
Positioning	Absolute (no prior location needed)
Environment	Indoor/Outdoor
Accuracy	10 meters to 100+ meters
Range/Coverage	Global

Table 2.16: Technical Overview of Positioning based on A-GNSS

CHAPTER 3

Evaluation and Results

The information provided in the previous chapter gives a good overview of the inner workings of GPS. The literature analysis conducted shows the advantages and disadvantages, influencing factors as well as what to expect concerning accuracy values under certain circumstances. Given this information specific real-world scenarios have been created and are executed to provide an conclusive answer to the following research question:

- **Q3: How accurate are these techniques and methods?**

In particular two influences, which have come to attention during the literature analysis, should be interesting to observe during the test runs - the weather as well as multipath effects. To this end the created scenarios are executed under different conditions and environments to see the magnitude of influence of both factors.

3.1 Procedure

General Structure and Approach

The general idea of the scenarios is to provide plausible locations and situations where GPS might be used and determine if and when the localization runs into problems due to influences described during the chapter on GPS. To this end, locations were chosen which cover a range of possible influencing factors, from wide, open fields and a minimum of reflective surfaces like the Donauinsel to dense, urban areas with loads of foliage and/or high buildings like the Tuerkenschanzpark or the city center of Vienna.

The Ground Truth

In order to be able to determine the accuracy of a possible location provided by a mobile device, one of course needs some sort of reference point or ”ground truth“. The first idea was to use a special and highly accurate GPS device commonly used by surveyors. After an informative afternoon at the land surveying office of Vienna, it was clear that this was not an option. Other than the impossibility to loan such a pricey device for the purpose of this study, the idea of creating the needed reference points with another GPS device, although with greater precision, may run into the same inaccuracy problems as the mobile testing devices. Luckily the land surveying office of the city of Vienna, also called Stadtvermessungsamt or Magistratsabteilung (MA) 41, was able to help. They already provide an online service called "Geodatenviewer" [4] which provides accurate coordinates down to 25 centimeters for the city of Vienna. With this service it was relatively easy and straightforward to create the needed scenarios and reference points by simply placing pins at unique locations on the provided map and document the coordinates, which were conveniently already in World Geodetic System 1984 (WGS84) format.

The Mobile Devices

Three different devices have been used to provide a solid testing foundation and compensate for the possibility of flawed or defective parts. These devices include a Samsung Google Galaxy Nexus I9250 (Samsung Google Nexus 3), a HTC One SV and a Motorola Moto G2 for which exhaustive details can be found in Table 3.1. The phones were chosen for a number of reasons

1. Phones based on Googles operating system Android make up for a large market share of todays mobile devices. Additionally the devices were released 1 to 5 years ago and mimic a certain heterogenic user device range

2. The Motorola Moto G2 and the HTC One SV are capable of receiving GLONASS signals additional to GPS signals

3. Personal availability of the devices

The Application

The app which has been used to monitor all the relevant details like latitude, longitude or the actual accuracy is called "GPS Test Plus" [73] and is available for download from the Android PlayStore. This app has been chosen for its overwhelmingly good reviews and rating as well as the rich feature set including:

- Longitude and Latitude

- Accuracy of the measurements

- Information about the satellites which are in view compared to the ones which are actually used for a measurement

	Galaxy Nexus I9250	HTC One SV	Motorola Moto G2
Network	GSM/HSPA/LTE	GSM/HSPA/LTE	GSM/HSPA
Launch	November 2011	January 2013	September 2014
Platform	CyanogenMod 12.1 YOG7D (Rooted)	Android 4.2.2 with HTC Sense 5.0	Android 5.0.2
Chipset	TI OMAP 4460	Qualcomm MSM8960 Snapdragon S4 Plus	Qualcomm MSM8226 Snapdragon 400
CPU	Dual-core 1.2 GHz Cortex-A9	Dual-core 1.2 GHz Krait	Quad-core 1.2 GHz Cortex-A7
GPU	PowerVR SGX540	Adreno 305	Adreno 305
Memory	16 GB, 1 GB RAM	8 GB, 1 GB RAM	8 GB, 1 GB RAM
Comms	WLAN, Bluetooth, NFC, microUSB	WLAN, Bluetooth, Radio, NFC, microUSB	WLAN, Bluetooth, Radio, NFC, microUSB
Positioning	GPS	GPS/GLONASS	GPS/GLONASS
Sensors	Accelerometer, gyro, proximity, compass, barometer	Accelerometer, proximity, compass	Accelerometer, gyro, proximity, compass

Table 3.1: Overview of the mobile devices used during the testing scenarios.

- Information about the actual position of the satellites
- Information about GPS and GLONASS satellites
- Information about the signal quality
- The ability to store current location information in waypoints for later use
- Additional information like Heading, Altitude, Speed, Compass

The Weather and Time of Day

Another factor which had to be included into the scenarios was the actual weather. As described during the GPS chapter atmospheric effects have to be considered when dealing with satellite range measurements. To provide a certain coverage of this specific influence the testing was done during different conditions:

1. Saturday, 09.01.2016 and Sunday, 10.01.2016: Heavily clouded, heavy fog, light rain
2. Wednesday, 13.01.2016 and Thursday, 14.01.2016: Sunny, close to no clouds in the sky

The actual time of day should not be an issue due to the fact that the satellite systems used provide a round the clock coverage of the planet with 10+ satellites in view at all times and the fact that 4 are already enough for a fix in 3 dimensions.

3.2 Methods

The evaluation is based on the scenarios and general structure described extensively during this Chapter. Utilizing the GPS Test Plus app, available on Googles' Play Store, each of the three mobile devices has been used at the exact position determined by the Geodatenviewer. The different scenarios have been executed during both described weather conditions to determine the perceived latitude and longitude values, the accuracy as well as the satellites in view and in use at the time of the range measurements.

The actual distance between the asserted and the actual location is calculated using the haversine formula [74], a very important equation in the field of navigation. The actual haversine function is defined as follows:

$$haversin\ \theta = sin^2\frac{\theta}{2}$$

Using this function the distance d between two points p_1 and p_2 can be calculated by using the following formula:

$$d = 2r\ sin^{-1}\sqrt{haversin(\phi_2 - \phi_1) + cos(\phi_1)cos(\phi_2)haversin(\lambda_2 - \lambda_1)}$$

where:

ϕ is the latitude

λ is the longitude

r is the radius of the sphere, in this case 6371 kilometers, the radius of the Earth

With this formula it is possible to determine the shortest distance between 2 points factoring in the surface of a sphere - a crucial factor considering Euclidean geometry would draw the shortest line directly through the spheres interior and therefore result in wrong distances. Important to note is that the angles need to be in radians for this formula to work correctly.

Another interesting fact which has to be considered when comparing the accuracy value to the perceived position has to do with the inner workings of the Android Location Provider. According to the documentation the following holds for the accuracy value provided:

> "We define accuracy as the radius of 68% confidence. In other words, if you draw a circle centered at this location's latitude and longitude, and with a radius equal to the accuracy, then there is a 68% probability that the true location is inside the circle.

> In statistical terms, it is assumed that location errors are random with a normal distribution, so the 68% confidence circle represents one standard deviation. Note that in practice, location errors do not always follow such a simple distribution." [75]

This is striking considering 68% does not seem that much but as shall be seen during the next few sections, the experienced value is often even lower.

3.3 Testing Scenarios

3.3.1 Scenario 1 - Donauinsel

The first scenario was chosen to mimic a use case which should be known to many people living in Vienna. The wide rural area of the Donauinsel is perfect to escape the occasionally depressing concrete forest of the city and provides many people with some much needed tranquility and rest during a stroll. The reference points during this scenario, as shown in Figure 3.1, have been chosen to simulate such a walk - starting at the bridge, crossing over from Handelskai and finishing at the Schulschiff. The environment on the Donauinsel is mixed, from wide open fields with no reflective surfaces or shadowing elements like trees to denser parts with a low number of buildings or bridges.

Expectations

The general assumption concerning test results during this scenario are very accurate values for accuracy as well as a large number of visible and usable satellites. Furthermore the open nature of this scenario should provide good values during both weather conditions.

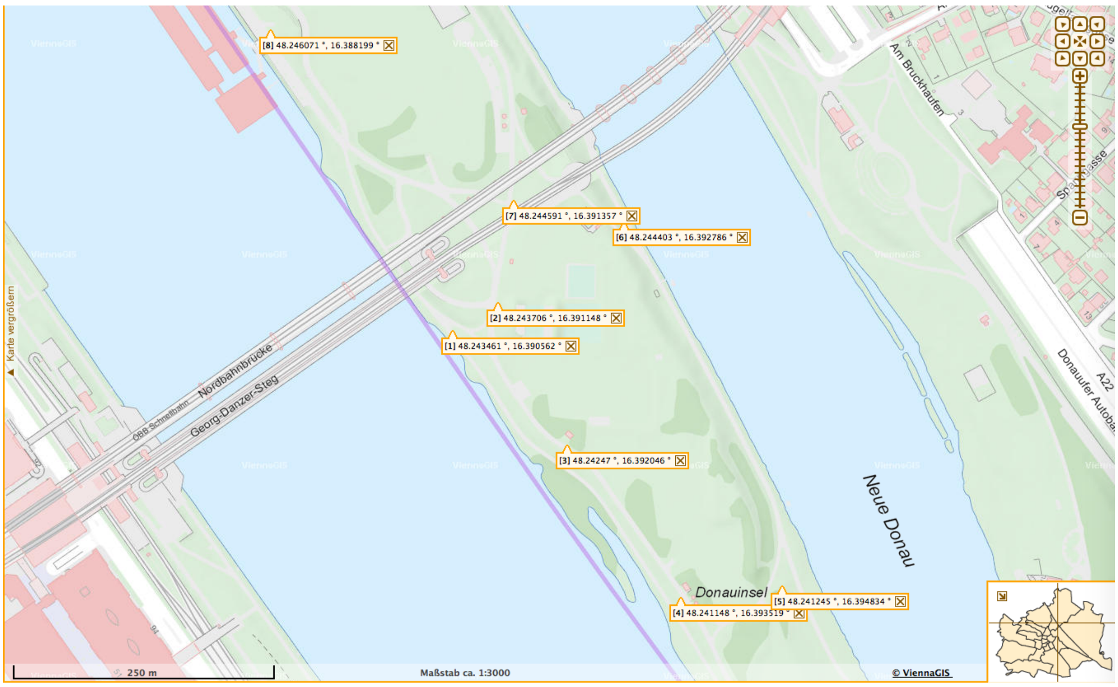

Figure 3.1: Scenario 1 - Donauinsel

3.3.2 Scenario 2 - Tuerkenschanzpark

The second scenario should mimic a use case along the lines of a "walk in the park". The park chosen for this purpose is the Tuerkenschanzpark, known for its medium to large size compared to other parks in Vienna as well as a personally convenient location. As with the Donauinsel before, the actual reference points were chosen to simulate such a stroll, starting from the north entrance at Peter-Jordan-Straße and finishing in the east at Linneplatz as shown in Figure 3.2. The general environment during this scenario can be considered as shadowed by trees with a few reflective surfaces such as buildings and ponds/lakes.

Expectations

The general assumption concerning test results during this scenario are very accurate values for accuracy as well as a large number of visible and usable satellites. Furthermore the relatively open nature of this scenario, despite a larger number of trees, should provide good values during both weather conditions. The increased number of shadowing trees should be compensated by the generally high number of satellites and therefore redundant range measurements.

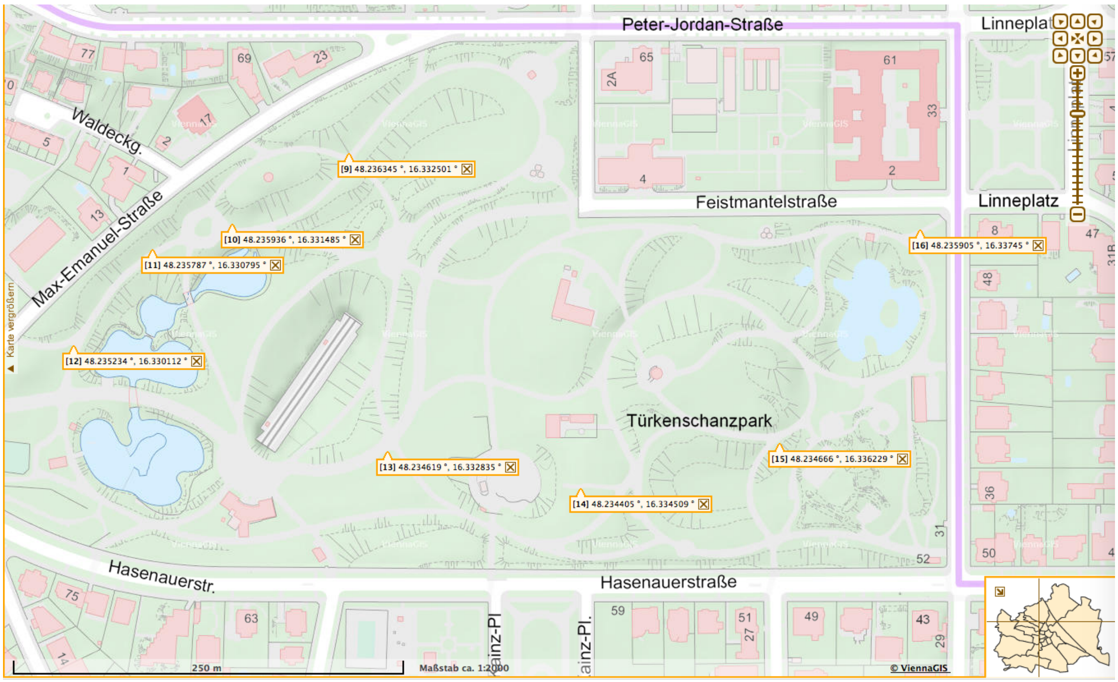

Figure 3.2: Scenario 2 - Tuerkenschanzpark

3.3.3 Scenario 3 - Innere Stadt

The third and final scenario should mimic a night out in the city center of Vienna. The actual reference points were chosen either at or at least near popular nightlife locations starting at the Ruprechtskirche near Schwedenplatz and finishing at Stephansplatz, right at the Stephansdom as shown in Figure 3.3. The general environment can be considered harsh when thinking about GPS accuracy - almost exclusively dense building structures with high buildings and small alleyways including lots of reflective surfaces.

Expectations

The general assumption concerning test results during this scenario are not very accurate values for accuracy as well as a fair number of visible and a low number of actually usable satellites. The dense way of construction of the inner city should cause severe multipath and shadowing problems which should directly translate to low accuracy values. It can be assumed that the weather conditions influencing the measurements are taking a backseat considering the much larger multipath/shadowing errors.

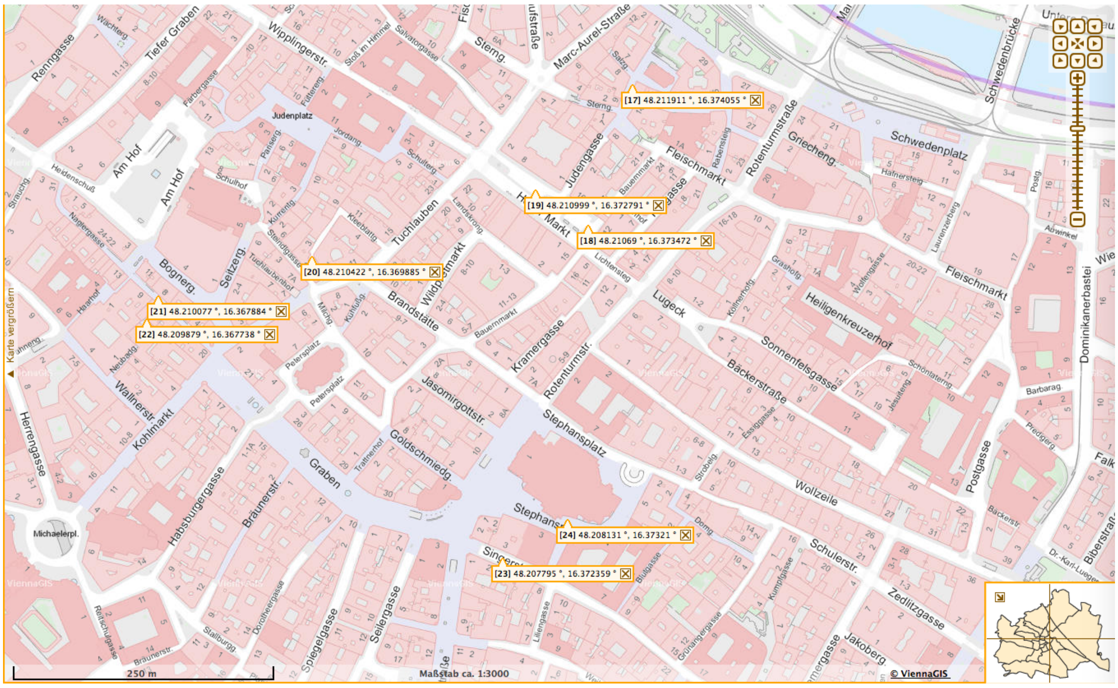

Figure 3.3: Scenario 3 - Innere Stadt

3.4 Results

3.4.1 Results for Scenario 1 - Donauinsel

As anticipated the results of the first scenario, which can be seen in Table 3.2, are quite good. Even though in some cases the offset between the perceived position and the actual position was of the order of 10-11 meters, the average value takes care of these outliers. With a total average of 3.85 meters on a clear day and 4.10 meters on a rainy day respectively, the experienced values live up to the expectations. Accuracy drops slightly due to weather conditions but to a degree which can be basically neglected. The haversine values can also be considered quite good with more often than not only a few meters discrepancy.

In case of the used satellites the results seem dead even considering the average satellites in view and only one more in average use. Interestingly enough at one occasion, reference point 5 to be exact, the HTC One SV saw the need to consult additional GLONASS satellites to provide the location manager with reasonable results. This seems noteworthy due to the fact that at any other time during the execution of the scenario the utilization of GPS satellites alone was deemed enough. Furthermore point 5 is also not especially shadowed or inaccessible in any way, as can be seen on the map or by just using the latitude/longitude values in the Geodatenviewer.

Considering the 68% circle the values were quite notably lower, with an overall score of 41.67% during rain and 54.16% during clear sky and sunshine.

Reference Point	Mobile Device	Accuracy (m)		Haversine (m)		Satellites in View		Satellites in Use		within 68% radius	
		Rainy	Sunny	Rainy	Sunny	Rainy	Sunny	Rainy	Sunny	Rainy	Sunny
P1	G2	3.96-4.88	3.96-4.88	1.346	4.32	10-11	12	8-10	11	✓	✓
	Nexus	4.88	4.88	7.299	6.863	9	11	7	11		
	One	4.88	3.05	1.186	2.263	10-11	12	10	11	✓	✓
P2	G2	3.05-3.96	3.05	11.289	3.217	11	12	7-9	11		
	Nexus	4.88	4.88	2.544	6.486	10	11	8	11	✓	
	One	3.05	3.05	7.615	4.329	11	12	9	11		
P3	G2	3.96-4.88	3.96-4.88	8.537	1.978	12	11-12	8-9	9-10		✓
	Nexus	4.88	4.88	10.929	6.346	10	11	8	10		
	One	3.05-3.96	3.05-3.96	4.27	2.338	11	12	8-9	11		✓
P4	G2	3.96	3.05	3.685	1.899	13	11	11-12	11	✓	✓
	Nexus	4.88	4.88	6.127	4.194	8	11	8	10		✓
	One	3.05	3.05	6.439	1.216	11	11	7-8	11		✓
P5	G2	4.88-6.1	3.05	8.063	5.24	12-13	12	9	9		
	Nexus	4.88	4.88	2.347	3.465	11	10	9	10	✓	✓
	One	3.05-3.96	3.05	4.603	3.829	21-22	11	14-15	10		
P6	G2	3.05	3.05	1.363	1.985	13	12	11	10	✓	✓
	Nexus	4.88	4.88	6.069	2.555	11	10	11	10		✓
	One	3.05	3.05	1.453	1.572	13	12	11	10	✓	✓
P7	G2	3.96-4.88	3.96-4.88	7.316	5.919	12	12-14	10-11	10-12		
	Nexus	4.88	4.88	11.483	11.784	11	12	11	10		
	One	3.05	3.05	4.419	4.751	12	13	10	10		
P8	G2	3.05	3.05	1.48	4.694	12	13	11	13	✓	
	Nexus	4.88	4.88	3.593	2.78	12	12	11	9	✓	✓
	One	3.05	3.05	0.63	1.648	12	13	11	13	✓	✓
⌀Average		4.10	3.85	5.17	3.99	12	12	10	11	41.67%	54.16%

Table 3.2: Overview of the test results gathered during the execution of Scenario 1.

3.4.2 Results for Scenario 2 - Tuerkenschanzpark

As is the case with scenario 1, the test results during this testing run live up to the expectations as well, as can be seen in Table 3.3. The general accuracy values can be considered quite good with 4.06 meters during rain and 4.19 meters during a clear day. The 2 average numbers are so close together that they can be considered even for the consumer grade quality of the used devices - as can be seen if the individual values at each reference point are compared side by side. They often match or at least provide a range which more often than not includes the other value.

Comparing the values for the average haversine distances of 6.75 meters during rain and 6.14 meters during a clear sky, one can also consider them relatively even with only 0.61 meters between the total averages. Shadowing effects and/or reflective surfaces seem to have a bigger impact during the measurements in the park than they did on the Donauinsel - even if not by much it is still detectable utilizing the 3 test devices.

Considering the satellites used during the execution of this scenario provides something interesting though. Again the HTC One SV chose to consult the GLONASS space segment to provide the location manager with reasonable results. Even more interesting is that this only happened during a clear sky and not during a heavily clouded and rainy day. One would assume this to be the other way around. Also worth noting is that the HTC One SV was the only mobile device which chose to do so, the Motorola Moto G2, which is also capable of using the GLONASS system, deemed the usage of only GPS as sufficient. The reason for this stems most likely from proprietary implementations of the underlying layers of the positioning system of the device which is done by the device manufacturer.

The values for the 68% circle were even lower during this testing scenario, with only about a third of the values actually lying within the given accuracy for both weather conditions.

Reference Point	Mobile Device	Accuracy (m)		Haversine (m)		Satellites in View		Satellites in Use		within 68% radius	
		Rainy	Sunny	Rainy	Sunny	Rainy	Sunny	Rainy	Sunny	Rainy	Sunny
P9	G2	3.05-3.96	3.96-4.88	10.103	3.217	13	12	10	9		✓
	Nexus	4.88	4.88	1.99	7.041	11	10	10	9	✓	
	One	3.05	3.05	7.543	6.983	12-13	21	9-10	15		
P10	G2	3.05-3.96	3.96-4.88	0.783	2.655	12-13	12	11	10	✓	✓
	Nexus	4.88	4.88	5.183	5.262	12	9	12	9		
	One	3.05	3.05	4.214	4.438	12	23	10	14		
P11	G2	3.96	3.96	12.09	12.04	12	12	10-11	10		
	Nexus	4.88	4.88	16.643	2.566	12	10	12	8		✓
	One	3.96-4.88	3.05	14.417	13.08	11-12	20	8-9	15		
P12	G2	3.05	3.96	4.188	2.665	11-12	13	11	11		✓
	Nexus	4.88	4.88	2.251	8.144	12	12	12	10	✓	
	One	3.05	4.88	3.483	9.834	12	12	10	9		
P13	G2	4.88	3.96	4.18	7	12	12-14	10-11	10-11	✓	
	Nexus	4.88	4.88	11.313	10.094	11	12	11	10		
	One	3.05	3.96-4.88	2.372	5.076	11-12	22	7-8	16	✓	
P14	G2	3.05-3.96	3.96	2.045	6.311	10-11	12	10-11	8-10	✓	
	Nexus	4.88	4.88	6.911	4.274	11	12	11	10		✓
	One	3.96-4.88	3.05	2.4	5.408	11	19	9	13	✓	
P15	G2	3.96-4.88	3.96	2.972	5.575	11	14	9	12	✓	
	Nexus	4.88	4.88	12.639	3.035	11	12	10	11		✓
	One	3.05	3.05-3.96	12.518	3.273	12	22	11	17		✓
P16	G2	3.96-4.88	4.88	4.487	2.676	11-12	11-13	9-10	9-11	✓	✓
	Nexus	4.88	4.88	5.159	10.643	10	11	10	10		
	One	3.05	3.05	12.181	6.014	11-12	20	10	15		
⌀Average		4.06	4.19	6.75	6.14	12	15	11	11	37.5%	33.3%

Table 3.3: Overview of the test results gathered during the execution of Scenario 2.

3.4.3 Results for Scenario 3 - Innere Stadt

The third and final scenario, which can also be considered the toughest environment for positioning using a GNSS like GPS or GLONASS, yielded some interesting results which can be seen in Table 3.4. The actual accuracy was much worse than during the first 2 scenarios but this was to be expected given the enormous increase of multipath and shadowing effects caused by the dense way of construction of the inner city. Values for the accuracy of the perceived position are often in the range of 10 to 20 meters and even reach 40 meters at reference point 22 during a rainy day. The interesting thing during this scenario was the impact of the weather on the actual test results. It was assumed that the weather, due to the predominant multipath and shadowing effects, would not be much of an issue and that the values for accuracy and haversine distance would be more or less the same for both testing conditions. This is, evidently, not the case. It is true that the other scenarios had cases too, in which the difference between two haversine distances were more than twice as big, but during this particular scenario the majority of the measurements are much worse during a rainy day. This is made more than obvious when considering the total average of the haversine values which is 18.76 meters during rain and 10.27 meters during a clear day.

Considering the satellites used during this scenario, the mobile devices capable of utilizing the GLONASS system, namely the Motorola Moto G2 and the HTC One SV, did so at every reference point. It is obvious that, given the difficult environment, there are simply not enough GPS satellites available which are in view and provide a good enough signal. A hypothesis which seems reasonable, when considering the values for the Galaxy Nexus which is not capable of doing so. More often than not, the number of satellites considered viable is around 6 or 7 - at one occasion, reference point 22 to be precise, the number of visible and used satellites even drops down to 3 - 4. Knowing that for an actual positioning fix in 3 dimensions, the number of satellites required is 4, the Galaxy Nexus was only able to provide a fix in 2 dimensions which basically means neglecting the altitude.

The increased accuracy values, which actually means a greater inaccuracy, does help the 68% circle though. Compared to the other 2 scenarios the values do get better, with 41.67% during rain and 58.33% during a clear sky, but can still be considered to low.

Reference Point	Mobile Device	Accuracy (m)		Haversine (m)		Satellites in View		Satellites in Use		within 68% radius	
		Rainy	Sunny	Rainy	Sunny	Rainy	Sunny	Rainy	Sunny	Rainy	Sunny
P17	G2	10.87	10.06-10.87	3.394	5.518	21	24	12	14	✓	✓
	Nexus	10.06	10.06-14.94	11.151	4.332	7	6	6	6		✓
	One	10.06	10.06-10.87	8.707	11.173	20	22	11	9	✓	
P18	G2	3.96	3.96	2.093	1.722	20	19	12	9	✓	✓
	Nexus	10.06	10.06	8.495	7.737	8	7	6	6	✓	✓
	One	3.05-3.96	3.05	4.99	3.537	20	20	8-9	9		
P19	G2	6.1-7.01	4.88	15.786	4.821	21	19	11	9		✓
	Nexus	10.06-14.94	4.88	13.657	6.116	9	7	5	7	✓	
	One	3.96-4.88	3.05-3.96	12.148	3.539	21	19	10	10		✓
P20	G2	11.89-14.02	11.89-14.02	12.578	19.589	21	19	7	9	✓	
	Nexus	20.12	20.12	34.812	5.406	4	6	4	4		✓
	One	11.89-13.11	10.87-13.11	18.611	38.845	20	19	6-7	8		
P21	G2	14.94-15.85	11.89-14.02	27.285	2.791	22	19	8	8		✓
	Nexus	10.06-14.94	14.94-20.12	11.428	14.442	8	6	4-5	6	✓	✓
	One	38.1-39.93	11.89-14.02	12.993	10.65	23	19	9	6	✓	✓
P22	G2	17.98-23.47	11.89-14.94	23.327	24.001	23	19	7	6-9	✓	
	Nexus	24.99-29.87	35.05	56.564	23.656	3-4	4	3-4	3-4		✓
	One	40.54	20.12	68.585	33.174	23	19	4-6	6		
P23	G2	4.88-6.1	3.05	20.592	3.271	21	22	12	9		
	Nexus	4.88	4.88	17.05	2.83	10	9	10	7		✓
	One	6.1-10.06	3.05	17.842	8.403	21	22	10-12	10		
P24	G2	7.01-10.06	3.96	3.672	3.623	22	21	11	10	✓	✓
	Nexus	10.06	4.88	12.077	2.001	10	7	9	7		✓
	One	10.06	3.96	32.39	5.41	22	21	10	8		
⌀Average		13.34	10.19	18.76	10.27	17	16	9	8	41.67%	58.33%

Table 3.4: Overview of the test results gathered during the execution of Scenario 3.

CHAPTER 4

Discussion

This chapter is devoted to the discussion of the major findings of the thesis. These findings range from theoretical results of the literature research to the empirical data collected with the help of the created scenarios. Goal of this section is to revise all the information gathered during this thesis, give a short but coherent summary on the topic and to provide a conclusive answer to the research questions proposed in Chapter 1.

4.1 State-of-the-Art Methods for the Collection of Location Data

One goal of this thesis was to provide a conclusive overview to the following questions:

- **Q1: Which techniques and methods for the collection of location data using mobile devices are state-of-the-art?**
- **Q2: Do these techniques and methods have specific advantages and/or disadvantages in certain cases or can be negatively influenced?**

Questions concerning the task of gathering location information, of how this is done right now, the current state-of-the-art techniques and methods. Based on these first two questions exhaustive literature research was conducted which has shown that the general topic of gathering location information using mobile devices can be divided into two major sections. The first section covers the generation of location data with the help of a Global Navigation Satellite System (GNSS) like the Global Positioning System (GPS) whereas the second section deals with an approach using a Local Positioning System (LPS) like cell towers. Another very interesting an controversial subtopic which has arisen during the research for the section on LPS is the domain of indoor positioning.

4.1.1 The Great Outdoors

Considering the great outdoors there is simply no better suited tool or system for obtaining accurate location data than an interconnected network of satellites. Even though the cost and effort, both in currency and actual labor, have been tremendous in order to get to the point in the development and deployment where we are now, the result speaks for itself. Given the right equipment the actual location of a device can be pinpoint down to less than a meter and - in some cases - even more accurate than that. Also with standard, consumer-grade quality equipment, which can be considered far from professional, the actual accuracy values using a GNSS can be considered quite impressive. Values from 2 to 5 meters are not only possible but are achieved on a regular and consistent basis. With more, newer and better optimized satellites these values will get even lower.

When thinking about global navigation, GPS is probably the first thing that comes to mind for most people but also other countries and communities like Russia, China and the European Union (EU) have started or are actively maintaining their own global satellite network. In an effort to bridge the gap between the countries and nations, joint ventures for the development have been used and some of these systems actively support each other. Furthermore it has become practically standard for receivers to be able to use not only one but more systems. This enables the device to combine the location data provided and get even better results concerning accuracy and availability. Speaking about availability, the continuity of service is also a big advantage when trying to get location data outside. Over the past few years the necessary ground equipment, like monitoring and control stations, as well as the space segment have been updated in a way that round the clock coverage is practically guaranteed.

But it’s not all roses - using a GNSS still has downsides and problems in certain situations. Getting location information underwater or inside buildings with dense building material basically cancels out any chance of seeing satellites or receiving their signals. Also different influencing factors like multipath, shadowing or atmospheric effects have to be considered when relying on a GNSS for location information. Different studies and also the scenarios conducted during this thesis show severe worsening of location accuracy under specific circumstances. Also one has to keep in mind that, though most of the systems mentioned are free to use by anyone with right equipment to receive the signals, the ”owner“ is still able to turn off the service at any time for any region.

4.1.2 Local Systems and Indoor Positioning

The limitations mentioned above, which are inherent for every solution based on a GNSS and the fact that it is still not possible to calculate a universal applicable position solution with just this one technology are responsible for the need of ”alternative“ location techniques. Considering the search for these alternatives one can deem it a lucky coincidence that with the advent of mobile communications mankind has inadvertently created the foundation for LPS. Communication networks like 2G, 3G, 4G, WLAN and

Bluetooth, so called “signals of opportunity”, were not originally designed for location purposes but show a number of properties which are spatially correlated such as radio signal strength or direction of signal arrival. These properties make them perfect for adoption and use in positioning systems be it indoor or outdoor. Discussed systems and approaches like the Radio Signal Coverage Area, Radio Signal Pattern, Direction of Signal Arrival or Range work perfectly fine and are used to supply location coverage on their own or provide assistance where a system like GPS may run into problems.

Still one has to discern between the requirement differences between providing location information indoors and outdoors - differences which should not be underestimated. Complexity comes not only from a wide range of possibilities, more specifically, which technology or communication network to use, but also from specific inherent characteristics. Most notably among these are the often greatly reduced size and the increased diversity of situations. Different building materials, different architectural styles, different habits of different cultures create a multitude of diverse and unique situations which need to be taken care of by the localization system. Problems like multipath issues, due to the rather rare availability of a direct Line of Sight (LOS) path for signals, or timing problems due to the greatly reduced distances which have to be measured, prove to be a real challenge.

Another aspect which has to be considered is specifications - what are the real needs of a particular use case and does the proposed system fulfill all necessary requirements or does one need a especially tailored solution? A real problem considering the uniqueness of indoor positioning which leads to a large number of solutions using technologies like RFID, UWB, ultrasound or infrared radiation. A problem for which no global applicable solution, like a GNSS for outdoors, is available yet.

4.2 Positioning Accuracy - Theory and Practice

The remaining question,...

- **Q3: How accurate are these techniques and methods?**

...the question for the accuracy has been answered using a two part approach. The literature research conducted for Chapter 2 has given tremendous insight into the inner workings of global systems as well as local systems and also provided a glimpse into the delicate world of indoor positioning. This research also provided detailed information about the actual accuracy values which one can expect from using such systems. As can be seen from the respective sections, these values range from below a meter using a global system like GPS, assuming one is in possession of the right receiver equipment, to a few kilometers using a local system like Cell-ID with a sparse cell tower coverage. As anticipated, even before concrete research was done, the accuracy is strongly dependent on the actual environment and circumstance. To get a better understanding, specific use case scenarios have been created and executed to experience what ”real-world“ values look like for a typical end user. As can be seen from Tables 3.2, 3.3 and 3.4, the results strongly correlate with the anticipation of environment dependent values. Very interesting to see was the magnitude of influence of certain factors like multipath or the weather. Empirical evidence gathered during Scenario 3 shows that accuracy decreases dramatically due to multipath effects - as shown by reference point 22 in Table 3.4. In this specific case, accuracy even drops down to 40 meters. Figure 4.1 show possible locations given the accuracy values gathered during Scenario 3. The inner and outer circle represent the best and the worst accuracy values, respectively. Also the actual latitude/longitude values, which were provided by the three test devices during the test run, are included.

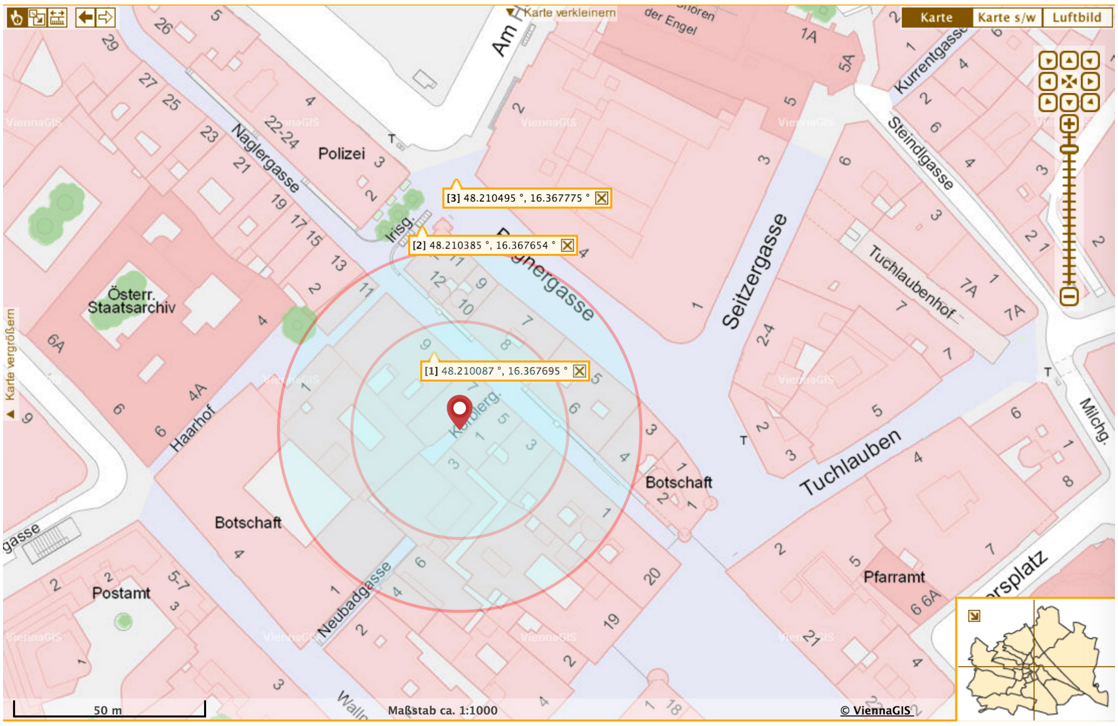

Figure 4.1: Potential location radius given the accuracy values gathered during Scenario 3. Also included are the concrete lattitude/longitude values provided by the three test devices during the test run.

Also weather effects, which thought to be of minor importance at first, showed noticeable impact during Scenario 3. Differences between accuracy values during a clear sky versus a rainy day went as high as 20 meters.

Of course, these values under these conditions represent something akin to a worst case scenario with lots of multipath and weather issues. The data gathered during Scenario 1 and 2 show that positioning, using a GNSS like GPS or GLONASS, more often than not provides the user with very good results but one has to keep in mind that positioning using mobile devices is strongly influenced by the environment.

CHAPTER 5

Conclusion and Future Work

5.1 Conclusion

As evidenced by the report [1], mentioned during the introduction, more and more people over the past few years are using and are dependent on LBS in their daily lives. Finding the closest service or just a route across the country are not use cases that will die out so easily. Therefore the demand for accurate positioning and location data when using mobile devices is a given and will likely only increase in the coming years.

One goal of this thesis was to provide a conclusive overview of how this is done right now, the current state-of-the-art techniques and methods, including strengths and weaknesses, for providing LBS with the much needed location data of the user. The obvious choice for the great outdoors is and, for the foreseeable future, probably will be a satellite based solution - a GNSS like GPS, GLONASS, which have provided a valuable service over the past years, or Galileo when it is finished in the near future. The literature research done during this thesis shows that navigation outdoors can be done by utilizing other means but the accuracy of these techniques leaves much to be desired. Also when thinking about global availability one can comprehend why a GNSS solution is preferable. This is also evidenced by the enormous amount of resources which have been poured into a satellite solution, financially as well as intellectually. Furthermore with the next batch of brand new GPS satellites, the GPS Block III, ready to launch in 2016, as well as other countries like Russia, Europe and China following closely behind, the future of outdoor navigation seems as bright as never before.

On the other hand lies the field of indoor navigation - a field of complexity and a wide range of possibilities. After extensive literature research the topic of providing a continued service and acceptable accuracy considering the application for indoor positioning still has no universally accepted answer. The greatly reduced size and the increased diversity of situations in combination with the ever changing requirements make up for a basically unique use case in every scenario. This alone makes a grand, prime solution, like a GNSS is considered to be for outdoors, virtually impossible. Maybe there is a solution for this kind of navigation in the future but as of right now, indoor positioning has to resort to a specifically tailored solution utilizing RFID tags or infrared systems.

The question for the accuracy of these methods has been answered in two parts - through extensive literature research as well as testing scenarios using three different mobile devices, designed with respective strengths and weaknesses in mind to provide accurate information at first hand. The results of these scenarios have shown that positioning utilizing GPS holds up to the expectations and theoretical accuracies in 2 out of 3 scenarios. During the third scenario the localization using GPS was severely affected by shadowing and multipath effects which lead to an offset of up to 70 meters. Even though these extreme values can be considered quite rare and often require a special kind of location, like particularly small alleyways, the possibility for such an extreme deviation has to be considered when using LBS. More often then not though, the perceived location is quite accurate and can be considered more than sufficient for the typical end user.

5.2 Future Work

During this work, the research, the design as well as the execution of the scenarios, several additional research questions worth pursuing emerged. Due to limited personal availability the testing devices for this thesis were all Android based which only makes up for a part of the device market - it is a large part, but a part nonetheless. Further research should include a more heterogeneous baseline considering the testing equipment as well as an increase in testing devices. Different manufacturers might implement the underlying layers of the location system differently and this could lead to noticeable differences when comparing operating systems like Android, iOS, Windows Phone and BlackBerry OS. Also the device hardware itself could be analyzed to reveal if a certain device manufacturer like HTC or Samsung uses superior or inferior equipment compared to others.

Another interesting topic is the world of indoor navigation itself. This thesis provides only an overview of the current techniques and methods which could be utilized when thinking about indoor navigation. Further research in the direction of UWB, an area which seems could gain more and more traction over the next few years, could be very promising.

Finally it is worth noting that the Defense Advanced Research Projects Agency (DARPA) has called for new ideas and methods [76] to circumvent some of the problems affiliated with GPS.

> “The military relies heavily on the Global Positioning System (GPS) for positioning, navigation, and timing (PNT), but GPS access is easily blocked by methods such as jamming. In addition, many environments in which our

> military operates (inside buildings, in urban canyons, under dense foliage, underwater, and underground) have limited or no GPS access. To solve this challenge, Adaptable Navigation Systems (ANS) seeks to provide GPS-quality PNT to military users regardless of the operational environment." [77]

No exact details are known to what this ANS will exactly look like, be it a whole new system and/or new algorithms. A solution is probably far from finished and will likely take several more years but it is definitely worth keeping an eye on.

APPENDIX A

Latitude/Longitude Data gathered during the Scenarios

Reference Point	Mobile Device	Rain		Sunny	
		Lattitude	Longitude	Lattitude	Longitude
P1	G2	48.2434692	16.3905754	48.2434235	16.3905468
	Nexus	48.2435188	16.3906087	48.2434349	16.3906460
	One	48.2434578	16.3905773	48.2434807	16.3905544
P2	G2	48.2436333	16.3912544	48.2437286	16.3911209
	Nexus	48.2437096	16.3911819	48.2437592	16.3911839
	One	48.2437530	16.3910732	48.2437401	16.3911762
P3	G2	48.2425461	16.3920612	48.2424698	16.3920193
	Nexus	48.2425461	16.3921394	48.2425041	16.3919773
	One	48.2424316	16.3920460	48.2424812	16.3920193
P4	G2	48.2411537	16.3935680	48.2411423	16.3935432
	Nexus	48.2411957	16.3935604	48.2411575	16.3935738
	One	48.2411041	16.3935757	48.2411575	16.3935108
P5	G2	48.2411880	16.3949013	48.2412186	16.3947754
	Nexus	48.2412643	16.3948212	48.2412605	16.3948746
	One	48.2412148	16.3948765	48.2412109	16.3948269
P6	G2	48.2443962	16.3928013	48.2443963	16.3928108
	Nexus	48.2444229	16.3928623	48.2444229	16.3928032
	One	48.2443924	16.3927746	48.2444050	16.3927650
P7	G2	48.2445602	16.3912697	48.2446442	16.3913593
	Nexus	48.2444992	16.3914280	48.2446938	16.3913956
	One	48.2446213	16.3913956	48.2446098	16.3914146
P8	G2	48.2460823	16.3881885	48.2460327	16.3882256
	Nexus	48.2460403	16.3882141	48.2460938	16.3881836
	One	48.2460670	16.3881931	48.2460632	16.3882179

Table A.1: Latitude/Longitude values measured during Scenario 1.

Reference Point	Mobile Device	Rain		Sunny	
		Lattitude	**Longitude**	**Lattitude**	**Longitude**
P9	G2	48.2363701	16.3326321	48.2363739	16.3325024
	Nexus	48.2363510	16.3324757	48.2362900	16.3325481
	One	48.2363091	16.3324146	48.2362823	16.3325062
P10	G2	48.2359428	16.3314819	48.2359123	16.3314896
	Nexus	48.2359085	16.3314285	48.2359810	16.3315070
	One	48.2359161	16.3315334	48.2359352	16.3315449
P11	G2	48.2357597	16.3306370	48.2357330	16.3306541
	Nexus	48.2356758	16.3306446	48.2357826	16.3307610
	One	48.2356949	16.3306580	48.2357178	16.3306522
P12	G2	48.2352715	16.3301067	48.2352104	16.3301182
	Nexus	48.2352180	16.3300934	48.2351608	16.3301086
	One	48.2352028	16.3301163	48.2351570	16.3301773
P13	G2	48.2346230	16.3327789	48.2346802	16.3328571
	Nexus	48.2346840	16.3329525	48.2346344	16.3327007
	One	48.2346344	16.3328571	48.2346497	16.3328857
P14	G2	48.2344170	16.3345299	48.2344551	16.3345490
	Nexus	48.2344551	16.3345642	48.2343903	16.3345623
	One	48.2343979	16.3344784	48.2344298	16.3345718
P15	G2	48.2346878	16.3362522	48.2346802	16.3361568
	Nexus	48.2347641	16.3363152	48.2346840	16.3362598
	One	48.2347570	16.3363285	48.2346954	16.3362274
P16	G2	48.2359314	16.3374958	48.2358818	16.3374596
	Nexus	48.2359467	16.3374805	48.2358093	16.3374519
	One	48.2360077	16.3375072	48.2358513	16.3374596

Table A.2: Latitude/Longitude values measured during Scenario 2.

Reference Point	**Mobile Device**	**Rain**		**Sunny**	
		Lattitude	**Longitude**	**Lattitude**	**Longitude**
P17	G2	48.2119331	16.3740234	48.2119560	16.3740864
	Nexus	48.2118149	16.3740120	48.2118721	16.3740520
	One	48.2119141	16.3739376	48.2119904	16.3741474
P18	G2	48.2107048	16.3734894	48.2106895	16.3734488
	Nexus	48.2107594	16.3735199	48.2107506	16.3734207
	One	48.2107277	16.3735085	48.2106582	16.3734730
P19	G2	48.2111397	16.3727627	48.2110405	16.3727722
	Nexus	48.2109337	16.3726349	48.2110519	16.3727684
	One	48.2108917	16.3728218	48.2110291	16.3728065
P20	G2	48.2105331	16.3699169	48.2103195	16.3701000
	Nexus	48.2101097	16.3698521	48.2104111	16.3698139
	One	48.2102547	16.3698921	48.2103906	16.3704071
P21	G2	48.2103004	16.3680363	48.2100945	16.3678570
	Nexus	48.2101097	16.3677378	48.2102051	16.3679161
	One	48.2099876	16.3677711	48.2101440	16.3679867
P22	G2	48.2100868	16.3676949	48.2100868	16.3678256
	Nexus	48.2103846	16.3676540	48.2099342	16.3674297
	One	48.2104953	16.3677750	48.2101402	16.3679543
P23	G2	48.2079773	16.3724079	48.2078124	16.3723946
	Nexus	48.2076492	16.3722878	48.2078193	16.3723703
	One	48.2076874	16.3725376	48.2078705	16.3723545
P24	G2	48.2081146	16.3731670	48.2080988	16.3732025
	Nexus	48.2080383	16.3731251	48.2081430	16.3731899
	One	48.2079468	16.3728714	48.2080994	16.3731545

Table A.3: Latitude/Longitude values measured during Scenario 3.

Reference Point	Lattitude	Longitude
P1	48.243461	16.390562
P2	48.243706	16.391148
P3	48.242470	16.392046
P4	48.241148	16.393519
P5	48.241245	16.394834
P6	48.244403	16.392786
P7	48.244591	16.391357
P8	48.246071	16.388199
P9	48.236345	16.332501
P10	48.235936	16.331485
P11	48.235787	16.330795
P12	48.235234	16.330112
P13	48.234619	16.332835
P14	48.234405	16.334509
P15	48.234666	16.336229
P16	48.235905	16.337450
P17	48.211911	16.374055
P18	48.210690	16.373472
P19	48.210999	16.372791
P20	48.210422	16.369885
P21	48.210077	16.367884
P22	48.209879	16.367738
P23	48.207795	16.372359
P24	48.208131	16.373210

Table A.4: Latitude/Longitude values of the Reference Points used during the Scenarios.

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Acronyms

Acronyms

A-GNSS Assisted GNSS. 51, 64, 65

ACM Association for Computing Machinery. 6

ADC Analog/Digital Converter. 40

AFSCN Air Force Satellite Control Network. 20

AGC Adjustable Gain Control. 40

AMCS Alternate Master Control Station. 20

ANS Adaptable Navigation Systems. 89

AoA Angle of Arrival. 49, 61

AP Access Point. 59

APL Applied Physics Laboratory. 8

AS Authorized Service. 31

BDC BeiDou Coordinate System. 32

BDT BeiDou System Time. 32

C/A Coarse/Acquisition. 12, 17, 23

CDMA Code Division Multiple Access. 30

Cell-ID Network Cell-ID. 45, 50, 61, 85

CGCS 2000 China Geodetic Coordinate System 2000. 32

CNSA China National Space Administration. 31

CS Control Segment. 20, 21

CVG Coriolis Vibratory Gyroscope. 62

DARPA Defense Advanced Research Projects Agency. 88

DNSS Defense Navigation Satellite System. 9

DoA Direction of Arrival. 45, 47

DoD Department of Defense. 7, 9

DOP Dilution of Precision. 33, 34

DoT Department of Transportation. 7

ECEF Earth-Centered, Earth-Fixed. 29, 37

ECI Earth-Centered Inertial. 37

EEE Ephemeris Enhanced Endeavour. 35

ESA European Space Agency. 30

EU European Union. 29, 30, 84

EUV Extreme Ultra Violet. 38

FCC Federal Communications Commission. 59, 60

FDMA Frequency Division Multiple Access. 30

FOC Full Operational Capability. 10, 29, 30, 32

GGSP Galileo Geodetic Service Provider. 31

GINS Global Indian Navigation System. 32

GLONASS Globalnaya Navigazionnaya Sputnikovaya Sistema. 29–31, 39, 51, 52, 63, 68, 69, 76, 78, 80, 86, 87

GNSS Global Navigation Satellite System. 2, 3, 16, 21, 22, 25, 29–34, 36, 39–41, 44, 50–52, 57, 61, 63, 64, 80, 83–88

GPR Ground Penetrating Radar. 60

GPS Global Positioning System. ix, xi, 2, 3, 5, 8–12, 16, 17, 19–34, 36–39, 44, 51, 52, 61, 63, 64, 67–69, 75, 76, 78, 80, 83–88

GR General Relativity. 36

GSM Global System for Mobile Communications. 50, 60, 61, 64

GST Galileo System Time. 31

GTRF Galileo Terrestrial Reference Frame. 31

HOW Hand Over Word. 24, 26

HS-GNSS High Sensitivity GNSS. 51, 63, 64

IEEE Institute of Electrical and Electronics Engineers. 6, 59

IERS International Earth Rotation and Reference Systems Service. 28

IGSO Inclined Geosynchronous Orbit. 32

IMU Inertial Measurement Unit. 40

IOC Initial Operational Capability. 29

IOV In-Orbit Validation. 30

IR Infrared Radiation. 54, 55

IRNSS Indian Regional Navigation Satellite System. 32

ISRO Indian Space Research Organisation. 32

ITRF International Terrestrial Reference Frame. 28, 31, 32

ITU International Telecommunication Union. 41

JPO Joint Program Office. 9

L-AII Legacy Accuracy Improvement Initiative. 35

LBS Location Based Services. ix, xi, 1, 3, 44, 51, 87, 88

LMU Location Measurement Unit. 50

LOS Line of Sight. 35, 40, 49, 51, 52, 58, 59, 61, 85

LPS Local Positioning System. xi, 3, 6, 83, 84

LTE Long-Term Evolution. 61

MA Magistratsabteilung. 68

MAD Mutually Assured Destruction. 12

MCS Master Control Station. 20, 32, 34

MEO Medium Earth Orbit. 31

NASA National Aeronautics and Space Administration. 7

NAVSEG Navigation Satellite Executive Group. 9

NAVSTAR Navigation System Using Timing and Ranging. 9

NGA National Geospatial-Intelligence Agency. 20, 35

NLOS Non-Line-Of-Sight. 51

NUDET Nuclear Detonation Detection System. 17, 22

OS Open Service. 31

PPS Precision Positioning Service. 10, 11, 23

PRN Pseudorandom Noise. 8, 9, 16, 17, 23, 30, 63

PVT Position - Velocity - Time. 17, 21, 25, 28, 31, 33, 34, 37

PZ90 Earth Parameter System 1990. 29

RF Radio Frequency. 39, 44, 45, 47, 49, 51, 52, 54, 59

RFI Radio Frequency Interference. 39–41, 58, 61, 64

RFID Radio Frequency Identification. 56, 57, 85, 88

RS Restricted Service. 32

RSS Received Signal Strength. 57, 58, 60, 61

SA Selective Availability. 11–14

SAR Search and Rescue. 30, 39

SECOR Sequential Correlation of Range. 9

SGS85 Soviet Geodetic System 1985. 29

SI International System of Units. 31, 32

SISRE Signal in Space User Range Error. 33, 35, 36

SNR Signal-to-Noise Ratio. 40

SoW Second of Week. 32

SPS Standard Positioning Service. 32

SPS Standard Positioning Service. 10

SR Special Relativity. 36

TA Timing Advance. 46

TAI Temps Atomique International. 31

TDoA Time Difference of Arrival. 44, 51, 54, 57, 60, 61

TEC Total Electron Count. 38

TLM Telemetry Word. 24, 26

ToA Time of Arrival. 44, 46, 50, 51, 54, 57, 60, 61

TTFF Time To First Fix. 64

UEE User Equipment Error. 33

UERE User Equivalent Range Error. 33

UMTS Universal Mobile Telecommunications System. 50, 60, 61, 64

UTC Coordinated Universal Time. 20, 28, 30, 32

UWB Ultra Wide Band. 52, 59, 60, 85, 88

WGS84 World Geodetic System 1984. 28, 29, 31, 68

WLAN Wireless Local Area Network. 44, 45, 47, 51, 52, 57–59, 61, 64, 84

WN Week Number. 32

WPAN Wireless Personal Area Network. 57

WWAN Wireless Wide Area Network. 60, 61

ZAOD Zero Age of Data. 35

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