TESTING OF LOW-COST GNSS RECEIVERS FOR LOCAL MONITORING IN DIFFERENT OPERATIONAL CONDITIONS

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Academic Year 2017/2018
Abstract

The development of low-cost, single frequency GNSS receivers, capable to provide carrier phase data to the user, has been studied over the years. In this thesis, low-cost GNSS receivers are tested for a purpose of local monitoring in different conditions.

In particular, different series (LEA-4T, NEO-7P and LEA-M8T) of the u-blox low-cost GNSS receivers are tested, through different experiments. Moreover, the utility of the Virtual Reference Station (VRS), as a replacement for a physical one, is tested with respect to the u-blox receiver.

The evaluation is carried out by processing three different sets of data, collected in the following tests: Milano Test, Como Test and Lomazzo Test. While collecting data, different geodetic receivers were used together with u-blox receivers. Once the acquisition was completed, data were processed with two software packages, Leica Geo Office (a commercial package) and RTKLIB (a Free Open Source Software). After the baseline processing and the coordinate estimation on hourly basis, results are compared and accuracy and utility of them is examined. Experiments prove that survey results achieved an accuracy classification of 1-2 centimeters, or even below, in 95% of sessions.

The layout of the thesis is the following:

- Chapter 1 contains an introduction to the subject of the thesis together with motivation and objectives.
• Chapter 2 provides an introduction to the Global Navigation Satellite Systems (GNSS) with brief explanation of the GPS and basic informations about other GNSSs (e.g. Glonass, Galileo, etc.)

• Chapter 3 provides a brief explanation of the GPS positioning principles. It contains fundamentals of the GPS positioning, analitical explanation of code and phase observations, including error sources, and differencing positioning techniques.

• Chapter 4 introduces GNSS receivers that are available today on the market with emphasis on receivers used in experiments for thesis. Besides, in this chapter, the concept of Virtual Reference station is introduced and challenges are presented.

• Chapter 5 states research approach through instrumentation and sofware explanation. Experiment set up is discussed in this section of thesis.

• Chapter 6 presents data preprocessing, data processing and results discussion of experiments with emphasis on achieved accuracy and reliability.

• Chapter 7 states out the key aspects of the thesis and recommendations for future work.
Acknowledgements

This thesis was carried out at Politecnico di Milano, School of Civil, Environmental and Land Management Engineering, the Department of Environmental and Geomatic Engineering.

The completion of this thesis would not have been possible without the support and encouragement of several special people. Hence, I would like to take this opportunity to show my gratitude to those who have assisted me.

I would like to express my very great appreciation to my thesis advisor Professor Ludovico Biagi for his valuable and constructive suggestions during the planning and development of this research work. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

I would also like to acknowledge my friends, thank you for listening, offering me advice, and supporting me through this entire process.

Finally, I must express my very profound gratitude to my parents and my brother, for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis.

The last word goes for my mother, thank you for being my best friend, biggest supporter and mother.
To my mother

with love and eternal appreciation
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# Table of Acronyms

ARP Antenna Reference Point
ASCII American Standard Code for Information Interchange
BDS BeiDou
C/A Coarse Acquisition
CDMA Code Division Multiple Access
CEP Circular Error Probable
CODE Centre for Orbit Determination in Europe
CORS Continuously Operating Reference Station
CS Commercial Service
DD Double Differences
DDC Display Data Channel
DGPS Differential GPS
DGNSS Differential GNSS
DoD Department of Defense
EBIRBS Emergency Position Indicating Radio Beacon
EGNOS European Geostationary Navigation Overlay Service
ELTS Emergency Locator Transmitter
FDMA Frequency Division Multiple Access
FOSS Free and Open Source Software
FTP File Transfer Protocol
GIS Geographic Information System
GLONASS Global Navigation Satellite System
GNSS Global Navigation Satellite Systems
GPS Global Positioning System
IERS International Earth Rotation Service
IGS International GPS Service
IGSO Inclined Geosynchronous Satellite Orbit
ITRF International Terrestrial Reference Frame
ITRS International Terrestrial Reference System
LAMBDA Least-Squares Ambiguity Decorrelation Adjustment
LGO Leica Geo Office
MEO Medium Earth Orbit
MIL-STD Military Standard
NAVSTAR Navigation Satellite Timing and Ranging
NMEA National Marine Electronics Association
NTRIP Networked Transport of RTCM via Internet Protocol
OS Open Service
OCS Operational Control Segment
PCC Phase Centre Corrections
PCO Phase Centre Offset
PCV Phase Centre Variations
PDOP Position Dilution of Precision
PDA Personal Digital Assistant
PPP Precise Point Positioning
PPS Pulse-Per-Second signal
TAI International Atomic Time
TRU TruSense
QZSS Quasi Zenith Satellite System
RINEX Receiver Independent Exchange Format
RTK Real Time Kinematic
SBAS Satellite Based Augmentation Systems
SNR Signal to Noise Ratio
SPS Standard Positioning Service
TEC Total Electron Content
UTC Coordinate Universal Time
UTM Universal Transverse Mercator
WAAS Wide Area Augmentation System
WAD Wide Area Differential
1. INTRODUCTION

1.1. Motivation

Global Navigation Satellite Systems (GNSS) were initially developed in the early seventies to improve global positioning and navigation from space. The Global Positioning System (GPS) was the first system to launch an operational prototype satellite in February of 1978. Shortly after, the number of GPS satellites in orbit increased to four but this was the absolute minimum to obtain a “fix”. More satellites would be needed if continuous global coverage was expected. GNSS constellations are constantly being expanded and upgraded but many of the initial designs and integrated systems on the original satellite are still found on newer satellites in the current GPS constellation. (Dr. Neil D. Weston, Dr. Volker Schwieger, 2010)

The first commercial GPS receivers were on the market in 1982. The receivers were large and bulky and could only track four satellites simultaneously. The satellites to track had to be selected manually on the receiver. Moreover, national geodetic agencies, research institutions and universities spent up to 250,000 € for a single receiver. Today, modern receivers are much more sophisticated and can track GPS and GLONASS satellites simultaneously on more than 50 channels, together with SBAS, Galileo, Beidou and QZSS satellites. Everything from satellite tracking to coordinate determination are computed automatically in real time. At the same time costs of new receivers continue to decrease. A high-end geodetic quality GNSS receiver costs around 15,000 €. If a user is restricted to single-frequency, geodetic quality receivers, one would still have to spend 5,000 € to 12,000 €. In general, this does not pose a problem in developed countries, but it may be a drawback in developing countries or for tasks where the surveyor needs a lot of receivers for specialized tasks such as monitoring.
Normal geodetic GNSS surveys are based on high-quality GNSS receivers and antennas. Frequently, the surveying community uses dual-frequency receivers to solve the ambiguities faster and more reliably. In the last few years, single-frequency receivers have proved to work very reliably if baseline lengths are below 10 km to 15 km. This opens up the market for receivers that are used for navigation since these receivers generally have a single frequency.

In general, navigation type receivers do not use the phase data. This problem is overcome by some manufactures where they provide access to the code and phase measurements from the raw via a serial or a USB interface. Some of manufacturers (e.g. u-blox) are officially documenting their format while others (e.g. Garmin) do not provide official format information or guarantee that the format will exist in the future. Finally, some manufacturers (e.g. Sirf) document their phase data format but do not provide access to the data for the users. With respect to geodetic quality receivers, a real time solution cannot be provided. Currently the raw carrier phase and code data are transformed into RINEX data and stored before it can be used efficiently. For the u-blox receivers (Lea-4T, Lea-6T), the conversion from raw data to RINEX may be carried out using different software techniques (e.g. RTKLIB). These advantages lead to the fact that most of the currently running research and solutions are driven by u-blox products.

For geodetic applications, highly precise antennas such as the micro-strip and choke rings are commonly used. They are constructed to reduce multipath effects and phase centre variations as well as type specific variations regarding the antenna phase centre offset. These choke ring antennas may cost up to 10,000 €. One disadvantage of the choke rings designed for dual frequency receivers is there compromise regarding the construction with respect to the two frequencies. For low-cost receivers the construction can be optimized for one frequency thus obtaining an increased
multipath reduction. Sometimes the GNSS receiver and antenna are integrated as one unit. In contrast, many navigation type receivers integrate low-priced, simple antennas directly into their receiver box, while some receivers simply connect to an external antenna via a cable. In the latter case, the antenna may be fixed such as on the roof of a car using a magnet on the antenna casing. Portable antennas usually range in price but start at several €s or $s. In general, however, an antenna and a receiver are sold as a package. The quality of the performance of navigation type receivers can be improved if precise geodetic antennas are used. In this case, the cost-effectiveness is clearly reduced, so in this report concentrates on the combination of navigation type receiver and navigation type antenna.

1.2. Research objectives

In this paper, different u-blox (LEA-4T, LEA-M8T and NEO-7P), low-cost single-frequency GPS receivers, which fulfills accuracy requirements for all static surveying applications are used to collect GPS data.

Objective 1: The main objective of the paper is to evaluate the performance of such a single frequency receiver in a different operational conditions.

To evaluate this performance, three different experiments, on three different sites, have been set. In each experiment different u-blox receiver has been used and baseline is estimated between u-blox receiver and a referent station. A challenge is to have a robust GNSS equipment which can provide results with an accuracy of about 1 - 2 cm or even in sub centimeter level for the purpose of local monitoring.

Objective 2: Processing collected data with two different softwares, Leica Geo Office, a commercial one and RTKLIB, a Free and Open Source Software and comparing estimated results.
Aim is to process data with different softwares and compare them. A challenge is to use a low cost GNSS receiver, process data with RTKLIB and see if FOSS programs can give results close enough to commercial software and which processing parameters should be used to improve processing.

Objective 3: Experimentally study the capability of Virtual Reference Station as a replacement to the geodetic receiver.

Virtual Reference Station (VRS) is used in the one of experiments. Processed baseline with VRS is compared to the one processed with geodetic receiver. In both processing, same u-blox is used as a rover. Challenge was to see the accuracy which can be obtained by using VRS instead of geodetic receiver.
2. GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

Satellite navigation systems has become integral part of all applications where mobility plays an important role (Heinrichs G., 2005). GNSS development has an interesting aspect due to its sensitive nature. Considerable events or developments are always subject to a couple of differentiators: technological developments and political decisions.

In this chapter main characteristics and technologies related to Global Navigation Satellite System (GNSS) will be presented.

The first systems were developed in the 20th century, mainly to help military personnel find their way, but location awareness soon found many civilian applications. GNSS is used to describe the collection of satellite positioning systems that are now operating or planned.

The meaning of GNSS is the technical interoperability and compatibility between various satellite navigation systems such as modernized GPS, Galileo, reconstructed GLONASS to be used by civilian users without considering the nationalities of each system in order to promote the safety and convenience of life (Galileo, 2003). The main application of GNSS is focused on the potential of to determine the position in the Global reference system anywhere and anytime on the Globe in a simple, fast and cost-effective manner. The GNSS consist of three main satellite technologies: GPS, Glonass, Galileo. Each of them consists mainly of three segments: (a) space segment, (b) control segment and (c) user segment. These segments are almost similar in the three satellite technologies, which are all together make up the GNSS (Kornhauser, 2017).
Nowadays, new technologies are developing corresponding to different countries, like BeiDou (China), IRNSS (India) and QZSS (Japan).

GNSS applications in all fields will play a key role, moving its use from the transportation domain to multimodal use, outdoors and indoors. It is expected that GNSS will increase significantly the precision in position domain (Lachapelle, 2002).

The overall of mentioned signals (Modernized GPS, Galileo and Glonass signals), make up the GNSS signals as shown on Figure 2-2: GNSS Signals. Each satellite system has specific signal characteristics, but each system attempts to be compatible with the others in order to prevent the interferences and attenuation between the signals (Kornhauser, 2017).
Figure 2-2: GNSS Signals (http://www.novatel.com)

Figure 2-3: Future GNSS/RNSS common frequencies, showing the potential of E5a/L5 and E1/L1 combination* (http://www.novatel.com)

* ARNS = Arenautical Radio Navigation Service: Frequency bands allocated worldwide to GNSS on a primary basis, granting a better protection against interference
2.1. Global Positioning System (GPS)

GPS was the first GNSS system (Figure 2-4: GPS IIRM Satellite. The United States Department of Defense (DoD) has developed the Navstar GPS, which is an all-weather, space based navigation system to meet the needs of the USA military forces and accurately determine their position, velocity, and time in a common reference system, anywhere on or near the Earth on a continuous basis (W.H., 1985). Originally developed for the U.S. military, the U.S. Government decided to make it available also for civilian purpose, when it was yet in the experimental phase, after the incident that involved the Korean Air Lines Flight 007 in 1983. (S. Pace, 1995)

GPS has made a considerable impact on almost all positioning, navigation, timing and monitoring applications. It provides particularly coded satellite signals that can be processed in a GPS receiver, allowing the receiver to estimate position, velocity and time (Hofmann-Wellenhof B., 2001). GPS was launched in the late 1970s by the United States Department of Defense (DoD). It uses a constellation of 27 satellites, and provides global coverage. (Jeffrey, 2010).

Figure 2-4: GPS IIRM Satellite (Jeffrey, 2010)
Now, GPS is used in cellular phones, outdoor recreation, emergency services, navigation and map making. It is also used a lot in scientific research. For example, meteorologists use GPS to forecast the weather and geologists use it to measure earthquake movement.

There are four GPS satellite signals that are used to compute positions in three dimensions and the time offset in the receiver clock.

**2.1.1. GPS Segments**

GPS consists of three segments i.e. Space, Control, and User (see on Figure 2-5).

![GPS Segments](image)

*Figure 2-5: GPS Segments (Aerospace Corporation, 2003)*

**2.1.1.1. Space Segment**

The first GPS satellite was launched by the U.S. Air Force in early 1978. There are now at least 24 MEO satellites orbiting the earth at an altitude of about 20 200 km (Figure 2-6: GPS Constellation). The high altitude insures that the satellite orbits are stable, precise and predictable, and that the satellites' motion through space is not affected by atmospheric drag. These 24 satellites make up a
full GPS constellation; however, today there are more than 30 satellites in orbit. From August 25, 2017, there are a total of 31 operational satellites in the GPS constellation, not including the decommissioned, on-orbit spares.

The GPS space segment consists of a constellation of satellites transmitting radio signals to users. The GPS space segment is summarized in Table 2-1. The orbit of each satellite is approximately 12 hours, so this provides a GPS receiver with at least six satellites in view from any point on Earth, under open-sky conditions. Power by solar cells, the satellites continuously orient themselves to point their solar panels toward the sun and their antenna toward the Earth. Orbital planes are centered on the Earth. Each plane has about 55° tilt relative to Earth’s equator in order to cover the polar regions (Figure 2-7: GPS Satellite Orbit

*Table 2-1. GPS Satellite Constellation*

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellites</td>
<td>21 plus 3 spares</td>
</tr>
<tr>
<td>Orbital planes</td>
<td>6</td>
</tr>
<tr>
<td>Orbit inclination</td>
<td>55 degrees</td>
</tr>
<tr>
<td>Orbit radius</td>
<td>26,560 km</td>
</tr>
</tbody>
</table>

*Figure 2-6: GPS Constellation* (https://www.nasa.gov)
2.1.1.2. Control segment

The GPS control segment (CS) consists of a global network of ground facilities that track the GPS satellites, monitor their transmissions, perform analyses, and send commands and data to the constellation. Functionally, the CS monitors the downlink L-band navigation signals, updates the navigation messages, and resolves satellite anomalies (Elliott D. Kaplan, Christopher J. Hegarty, 2005).

Additionally, the CS monitors each satellite’s state of health, manages tasks associated with satellite station keeping maneuvers and battery recharging and commands the satellite payloads, as required (Elliott D. Kaplan, Christopher J. Hegarty, 2005).

The current Operational Control Segment (OCS) includes a master control station, an alternate master control station, 11 command and control antennas, and 16 monitoring sites. The locations of these facilities are shown on Figure 2-8.
Control segment elements (GPS.GOV, 2017):

1. Monitor Stations
   - Track GPS satellites as they pass overhead.
   - Collect navigation signals, range/carrier measurements, and atmospheric data.
   - Feed observations to the master control station.
   - Utilize sophisticated GPS receivers.
   - Provide global coverage via 15 sites: 6 from the Air Force plus 10 from NGA.

2. Master Control Station
   - Provides command and control of the GPS constellation.
   - Uses global monitor station data to compute the precise locations of the satellites.
   - Generates navigation messages for upload to the satellites.
   - Monitors satellite broadcasts and system integrity to ensure constellation health and accuracy.
• Performs satellite maintenance and anomaly resolution, including repositioning satellites to maintain optimal constellation.

• Currently uses separate systems (AEP & LADO) to control operational and non-operational satellites.

• Backed up by a fully operational alternate master control station.

3. Ground Antennas

• Send commands, navigation data uploads, and processor program loads to the satellites.

• Collect telemetry.

• Communicate via S-band and perform S-band ranging to provide anomaly resolution and early orbit support.

• Consist of 4 dedicated GPS ground antennas plus 7 Air Force Satellite Control Network (AFSCN) remote tracking stations.

2.1.1.3. User segment

GPS boosts productivity across a wide swath of the economy, to include farming, construction, mining, surveying, package delivery, and logistical supply chain management. Major communications networks, banking systems, financial markets, and power grids depend heavily on GPS for precise time synchronization. Some wireless services cannot operate without it. GPS also advances scientific aims such as weather forecasting, earthquake monitoring, and environmental protection. Most civilian uses of GPS, using GPS receivers, however, fall into one of four categories: navigation, surveying, mapping and timing (Figure 2-9).

Finally, GPS remains critical to U.S. national security, and its applications are integrated into virtually every facet of U.S. military operations. Nearly all new military assets - from vehicles to munitions - come equipped with GPS (GPS.GOV, 2017).
2.1.2. GPS Signal structure

Satellites have highly precise oscillators with a fundamental frequency of 10.23 MHz. Satellite signals basically consists of 3 components (NPTEL, Module 2: Global Positioning System, 2017):

a) Two micro wave L-band (also called Carrier) waves:
   - L1 carrier: 1575.42 MHz
   - L2 carrier: 1227.60 MHz

b) Ranging codes modulated on the carrier waves:
   - C/A code, the clear/access or coarse/acquisition code modulated at 1.023 MHz, degraded code for civilian users, modulated on L1 only.
   - P (Y) code, the private, protected, or precise code modulated at 10.23 MHz It is modulated on both L1 and L2 carrier waves, for authorized military users.

c) Navigation message
   - Modulated on both L1 and L2 and contains satellite positions and constants.

The structure of GPS carrier signals, codes and their combinations is quite complex. Since the carriers are pure sinusoids, they cannot be used easily for instantaneous positioning purposes and
therefore two codes are modulated onto them: The C/A (coarse acquisition) code and P (precise) code. The codes (P and C/A) are nothing but binary sequence of information generated by a complicated algorithm.

2.1.2.1. GPS Carrier waves

The two carrier waves L1 and L2 are pure right handed circularly polarized sinusoidal waves. Two frequencies are useful to eliminate ionospheric effects. Figure 2-10 provides a schematic diagram for carriers and codes for GPS signal. (NPTEL, Module 2: Global Positioning System, 2017).

Figure 2-10: Structure of various types of GPS signals (NPTEL, Module 2: Global Positioning System, 2017)
2.1.2.2. GPS code

a) C/A Code

- It is a binary sequence of information. It is also called pseudo random noise (PRN) code (states of 0 and 1) consisting of 1,023 elements, or chips or bits, that repeats itself every millisecond giving rise to a chipping rate (the rate at which each chip is modulated onto the carrier) of 1.023 Mbps (megabits per second). The term pseudo random indicates that the code is apparently random although it has been generated by means of a known process, providing the repeatability.
- PRN codes allow range measurements, accesses to underlying carrier signals, satellite message, and time markers.
- The chip length (distance corresponding to one chip or bit) corresponds to 293 m in length.
- Due to the code length, the ambiguity in measurement with C/A code is approximately 293 km - i.e. the complete C/A code pattern repeats itself every 293 km between the receiver and the satellite.

b) P code

- Very long sequence (about $10^{14}$) of pseudo random binary biphase modulations on the GPS carrier at a chip rate of 10.23 MHz which repeats itself every 266 days. Each one-week segment of the P-code is unique to one GPS satellite and is reset each week.
- The chip length (distance corresponding to one chip or bit) corresponds to 29.3 m in length.
- C/A and P codes are rotated by $90^\circ$ (called phase quadrature) to each other.
2.1.3. GPS Principles

At least four (4) satellites are required to solve four (4) unknown parameters: Latitude, Longitude, Height and Receiver time offset (difference between the receiver clock's indicated time and a well-defined time scale reference such as UTC (Coordinated Universal Time), TAI (International Atomic Time) or GPST (GPS Time)). The following 5 basic steps are required to obtain these coordinates (NPTEL, Module 2: Global Positioning System, 2017):

- All GPS satellites have synchronized atomic clocks as time keepers.
- The coordinates of all satellites, acting as moving control stations, are known precisely with the help of system control.
- Satellite coordinates and time signals are transmitted to ground receiver.
- These signals reach the ground delayed by distance traveled.
- Making use of simple resection principle and the range information to each satellites, the receiver computes its coordinates.

During GPS based positioning, the following steps are followed (Pratap Misra, Per Enge, 2006):

4. Basic navigation point position can be calculated like a resection in which satellites are the orbiting control stations.

5. Range vectors are measured to each of the satellites using a time dependent code based on the times of transmission and receipt of the signals.

6. Since these times are biased by a common amount due to offset between the satellite and receiver clocks; they are called pseudoranges.

7. Pseudorange measurements from four satellites are needed to estimate the user position and the corresponding receiver clock bias.
The above principle is explained in Figure 2-11, where 4 known GPS satellite coordinates are shown as (Xi, Yi, Zi). The unknown coordinates of GPS receiver u = (Ux, Uy, Uz) are calculated by solving 4 range (or pseudorange P) equations. A minimum of four equations are needed to solve for four unknowns—three unknown position coordinates (Ux, Uy, Uz) and to account for the fact that atomic clocks onboard GPS satellites and quartz clocks in GPS receivers are not synchronized. This unknown time variable is called receiver time offset or bias (dTu). This part will be briefly explained in the next chapter.

\[
P_{u}^{i} = dT_{u} \times c
\]

*Equation 2-1*

Where:

\[P_{u}^{i} = \text{Pseudorange from receiver } u \text{ to satellite } i\]

\[c = \text{velocity of light}\]

\[dT_{u} = \text{Satellite-receiver clock bias} \quad (\text{Sickle, 2015})\]
2.1.4. Modernized GPS

Due to the vast civil applications of GPS technology during the past decade or so and due to the new technologies used in the satellite and receivers, the U.S government has decided to extend the capabilities of GPS to give more benefits to the civil community. In addition to the existing GPS signals, new signals will be transmitted by GPS satellite.

Three additional signals were anticipated to be broadcast by GPS satellites by 2006. As illustrated in Figure 2-12, these include two new civil signals, an L2 civil (L2C) signal and a signal at 1,176.45 MHz (115 \( f_0 \)) referred to as L5. A new military signal, M code, will also be added at L1 and L2 (Elliott D. Kaplan, Christopher J. Hegarty, 2005).

![Figure 2-12: Legacy (top) and modernized GPS signals (bottom) (NPTEL, Module 2: Global Positioning System, 2017)](image)

a) The L2C code is the new civilian code modulated on top of the L2 carrier wave. This code was introduced with the help of the Block IIR satellites, lunched with beginning of 2003. To satisfy aviation user requirements, a third civil signal called L5 was introduced with the help of first Block IIF satellites, launched in 2005.

b) The L5 is composed of (Elliott D. Kaplan, Christopher J. Hegarty, 2005):
• The carrier waves at $f = 1176.45$ MHz and wavelength $\lambda = 26$ cm.

• A new military code called M-code, designed with the purpose of replacing the P(Y) code in the future. This code offers better jamming resistance than the P(Y) signal and more robust signal acquisition than is achieved today.

• The navigation message, which will contain more or less the same data as the L1 and L2 channels, has an entirely different, more efficient, structure.

c) The M code signal has been designed for autonomous acquisition, so that a receiver will be able to acquire the M code signal without access to C/A code or Y code signals.

• The M-code signal data message structure was designed to meet the following set of criteria:
  - provide flexibility of format, control and content
  - improve the performance of all key parameters (e.g., better error rates and reduced data collection times)
  - improve the system’s data security and integrity
  - enable enhancements to the system’s security, architecture and key management infrastructure
  - enable future adaptations to the GPS data message as military applications, technology and mission requirements evolve (Barker, 2006)

Different frequencies are used to eliminate errors introduced by ionospheric refraction (Figure 2-13).
2.1.5. Satellite or navigation message

Navigation message includes information on (NPTEL, Module 2: Global Positioning System, 2017):

- Satellite time of transmission
- Precise satellite position
  (ephemerides)
- Satellite health
- Satellite clock correction
- Propagation delay effects (due to signal propagation in ionosphere and troposphere)
- Time transfer to UTC (Coordinated Universal Time)
- GPS satellite Constellation status

Figure 2-13: GPS frequencies (NPTEL, Satellite or navigational message, 2010)
Length of navigation message is 1500 bits which is modulated onto both L1 and L2 carriers. Message takes about 30 seconds, each second contains 50 bits.

Data is modulated at a much slower rate of 50 bps and thus it takes 12.5 minutes to transmit all of the information. In order to reduce the time, it takes to obtain an initial position, the ephemerides and clock data is repeated every 30 seconds.

Each satellite sends (Parkinson and Spilker, 1996):

- A full and precise description of its own orbit and clock data (within the ephemerides information) and an approximate guide to the orbits of other satellites (almanac information).
- Parameters representing the delay caused by signal propagation through the ionosphere (called the ionospheric propagation delay parameters).

Accuracy of some aspects included in navigation message deteriorate with time which are updated by certain renewal mechanisms from the ground monitoring stations.

*Figure 2-14: Frame and sub frames in Navigational message (NPTEL, Satellite or navigational message, 2010)*
2.1.6. Generation of GPS signals

The structure of GPS carrier signals and codes is quite complex in order to satisfy the several requirements as given below:

1. Multi-user system:
   - GPS is used for one-way measurements (a listen-only system)

2. Real-time positioning:
   - Since there are simultaneous measurements to many satellites, there is a need to identify different signals
   - Unambiguous range measurements - need to determine signal delay
   - Satellite positions needed hence one needs broadcast ephemerides

3. High accuracy positioning:
   - Microwave carrier frequency - 1.2 to 1.6 GHz; use of dual-frequency to minimize ionospheric delay
   - High frequency modulation
   - Anti-jamming requirement: GPS uses a special technique called the Spread spectrum technique for this purpose

4. Military and civilian users:
   - GPS needs two different codes and restriction on dual-frequency use in order to provide differential access to civilian and military/authorized users

2.1.6.1. GPS Services

Two types of services are available:

1. SPS (Standard Positioning Service)
Positioning accuracy that is provided by GPS measurements based on the single L1 frequency C/A code.

2. PPS (Precise Positioning Service)

Highest level of dynamic positioning accuracy that is provided by GPS measurements based on the dual frequency P-code and M-code in the future.

2.2. Other global navigation systems

It is already mentioned at the beginning of this chapter that there are other GNSS beside GPS. They are described in following part of this chapter.

2.2.1. GLONASS

GLONASS was developed by the Soviet Union as an experimental military communications system during the 1970s. When the Cold War ended, the Soviet Union recognized that GLONASS had commercial applications, through the system’s ability to transmit weather broadcasts, communications, navigation and reconnaissance data. The first GLONASS satellite was launched in 1982 and the system was declared fully operational in 1993. After a period where GLONASS performance declined, Russia committed to bringing the system up to the required minimum of 18 active satellites. Currently, GLONASS has a full deployment of 24 satellites in the constellation. GLONASS satellites have evolved since the first ones were launched. The latest generation, GLONASS-M, is shown in Figure 2-15 being readied for launch (Jeffrey, 2010).
2.2.1.1. GLONASS System Design

The GLONASS constellation provides visibility to a variable number of satellites, depending on your location. A minimum of four satellites in view allows a GLONASS receiver to compute its position in three dimensions and to synchronize with system time.

2.2.1.2. GLONASS Segments (Jeffrey, 2010)

a) GLONASS Space Segment

The GLONASS space segment is summarized in a Table 2-2. The GLONASS space segment consists of 24 satellites, in three orbital planes, with eight satellites per plane. The GLONASS constellation geometry repeats about once every eight days. The orbit period of each satellite is approximately 8/17 of a sidereal1 day so that, after eight sidereal days, the GLONASS satellites have completed exactly 17 orbital revolutions.
Table 2-2: GLONASS Satellite Constellation (Jeffrey, 2010)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellites</td>
<td>24 plus 3 spares</td>
</tr>
<tr>
<td>Orbital Planes</td>
<td>3</td>
</tr>
<tr>
<td>Orbital Inclination</td>
<td>64.8 degrees</td>
</tr>
<tr>
<td>Orbit Radius</td>
<td>19,140 km</td>
</tr>
</tbody>
</table>

The satellites are placed into nominally circular orbits with target inclinations of 64.8 degrees and an orbital radius of 19,140 km, about 1,060 km lower than GPS satellites.

The GLONASS satellite signal identifies the satellite and includes:

- Positioning, velocity and acceleration information for computing satellite locations.
- Satellite health information.
- Offset of GLONASS time from UTC (SU) [Coordinated Universal Time Russia].
- Almanac of all other GLONASS satellites.

b) GLONASS Control Segment

The GLONASS control segment consists of the system control center and a network of command tracking stations across Russia. The GLONASS control segment, similar to that of GPS, monitors the satellites health, determines the ephemerides corrections, as well as the satellite clock offsets with respect to GLONASS time and UTC (Coordinated Universal Time). Twice a day, it uploads corrections to the satellites.

**2.2.1.3. GLONASS Signals**

Each GLONASS satellite transmits on a slightly different L1 and L2 frequency (Table 2-3), with the P-code (HP code) on both L1 and L2, and the C/A code (SP code), on L1 (all satellites) and L2 (most satellites). The nominal carrier frequencies for the L1 and L2 signals may be written as shown below (Leick, 2003):
\[ f_1^R = 1602 + 0.5625 \cdot n MHz \]  \hspace{1cm} \text{Equation 2-2}

\[ f_2^R = 1246 + 0.4375 \cdot n MHz \]  \hspace{1cm} \text{Equation 2-3}

, with

\[ \frac{f_1^R}{f_2^R} = \frac{9}{7} \]  \hspace{1cm} \text{Equation 2-4}

where \( n \) is the frequency channel number \( 1 \leq n \leq 24 \), covering a frequency range in L1 from 1602.5625 MHz to 1615.5 MHz. On the contrary to GPS, where the broadcast ephemerides are defined by modified Keplerian elements, the broadcast ephemerides of GLONASS satellites are defined by positions and velocities referred to an Earth-centered and Earth-fixed systems (PZ 90). The broadcast ephemerides of the Glonass satellites are updated every 30 minutes.

GLONASS satellites transmit the same code at different frequencies, a technique known as FDMA, for frequency division multiple access.

\textit{Table 2-3: GLONASS Signal Characteristics}

<table>
<thead>
<tr>
<th>DESIGNATION</th>
<th>FREQUENCY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>1598.0625–1609.3125 MHz</td>
<td>L1 is modulated by the HP (High Precision) and the SP (Standard Precision) signals.</td>
</tr>
<tr>
<td>L2</td>
<td>1242.9375–1251.6875 MHz</td>
<td>L2 is modulated by the HP and SP signals. The SP code is identical to that transmitted on L1.</td>
</tr>
</tbody>
</table>

As the current GLONASS-M satellites reach the end of their service life, they will be replaced with next generation GLONASS-K satellites. The new satellites will provide the GLONASS system with new GNSS signals: (Jeffrey, 2010)

a) L3

The first block of GLONASS-K satellites (GLONASS-K1) will broadcast the new civil signal,
designated L3, centered at 1202.025 MHz. Unlike the existing GLONASS signals, L3 is based on CDMA which will ease interoperability with GPS and Galileo. The first GLONASS-K1 satellite was launched in February 2011.

b) L1 and L2 CDMA

The second block of GLONASS-K satellites (GLONASS-K2) adds two more CDMA based signals broadcast at the L1 and L2 frequencies. The exiting FDMA L1 and L2 signals will continue to be broadcast as well to support legacy receivers. Due to delays with the development of the GLONASS-K2, Roskosmos had to order a total of nine GLONASS-K satellites for a routine replacement of the GLONASS-M spacecraft. In July 2016, ISS Reshetnev announced that the company had begun testing the GLONASS-K2 satellite in the thermal and vacuum chamber, however the planned launch date for the satellite was not confirmed at the time.

c) L5

The third block of GLONASS-K satellites (GLONASS-KM) will add an L5 signal to the GLONASS system.

*Table 2-4: GLONASS constellation status, 15.10.2017 (Information and analysis center, 2017)*

<table>
<thead>
<tr>
<th>GLONASS Constellation Status, 15.10.2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total satellites in constellation</td>
</tr>
<tr>
<td>Operational</td>
</tr>
<tr>
<td>In commissioning phase</td>
</tr>
<tr>
<td>In maintenance</td>
</tr>
<tr>
<td>Under check by the Satellite Prime Contractor</td>
</tr>
<tr>
<td>Spares</td>
</tr>
<tr>
<td>In flight tests phase</td>
</tr>
</tbody>
</table>
2.2.2. BeiDou

China has started the implementation of a GNSS system known as BeiDou Navigation Satellite System (BDS). The system is being implemented in two phases: the initial phase provides regional coverage, while the second phase will provide global coverage.

The initial phase of the BeiDou system officially became operational in December 2012, providing coverage for the Asia Pacific region. The regional BeiDou space segment has five Geostationary Earth Orbit (GEO) satellites, five Inclined Geosynchronous Orbit (IGSO) satellites and four Medium Earth Orbit (MEO) satellites (summarized in Table 2-5).

*Table 2-5: Regional BeiDou Satellite Constellation (Jeffrey, 2010)*

<table>
<thead>
<tr>
<th>Satellites</th>
<th>5 GEO</th>
<th>5 IGSO</th>
<th>4 MEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Inclination</td>
<td>–</td>
<td>55 degrees</td>
<td>55 degrees</td>
</tr>
<tr>
<td>Orbit Radius</td>
<td>35,787 km</td>
<td>35,787 km</td>
<td>21,528 km</td>
</tr>
</tbody>
</table>

The second phase of the BeiDou system is planned to be completed by the end of 2020 and will provide global coverage with enhanced regional coverage. The space segment will consist of a constellation of 5 GEO, 3 IGSO and 27 MEO satellites, as shown in Table 2-6.

*Table 2-6: Planned Global BeiDou Satellite Constellation (Jeffrey, 2010)*

<table>
<thead>
<tr>
<th>Satellites</th>
<th>5 GEO</th>
<th>3 IGSO</th>
<th>27 MEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Planes</td>
<td>–</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>Orbital Inclination</td>
<td>–</td>
<td>55 degrees</td>
<td>55 degrees</td>
</tr>
<tr>
<td>Orbit Radius</td>
<td>35,787 km</td>
<td>35,787 km</td>
<td>21,528 km</td>
</tr>
</tbody>
</table>
2.2.2.1. BeiDou Signals

The BeiDou signals, based on CDMA technology, are summarized in Table 2-9. Three levels of service will be provided:

- Public service for civilian use and free to users. The public service provides position accuracy of 10 meters, velocity accuracy within 0.2 meters per second and timing accuracy of 10 nanoseconds.
- Licensed service is available only to users who have obtained a subscription. The licensed service improves position accuracy to 2 meters. This service also provides bidirectional short messaging (120 Chinese characters) and provides information about the system status.
- Restricted military service, more accurate than the public service, also provides system status information and military communications capability. (Jeffrey, 2010)

Table 2-7: BeiDou Signal Characteristics

<table>
<thead>
<tr>
<th>DESIGNATION</th>
<th>FREQUENCY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1561.098 MHz</td>
<td>B1 provides both public service signals and restricted service signals.</td>
</tr>
<tr>
<td>B2</td>
<td>1207.140 MHz</td>
<td>B2 provides both public service signals and restricted service signals.</td>
</tr>
<tr>
<td>B3</td>
<td>1268.520 MHz</td>
<td>B3 provides restricted service signals only.</td>
</tr>
</tbody>
</table>

2.2.3. GALILEO

Satellite navigation, positioning, and timing have already found widespread applications in a large variety of fields. Recognizing the strategic importance of its applications, a European approach was developed in the early 1990s. It started with the European contribution to the first generation

The Galileo, Europe’s planned global navigation satellite system is being designed to meet a variety of user needs, out of which a number of representative services has been identified to form the basis of the design and to allow the definition of the main features of Galileo (see on Figure 2-16). The Galileo will provide a highly accurate and guaranteed global positioning service under civilian control. The United States and European Union have been cooperating since 2004 to ensure that GPS and Galileo are compatible and interoperable at the user level (Kornhauser, 2017).

![GALILEO Satellite in Orbit](Jeffrey, 2010)

**2.2.3.1. GALILEO System Design**

Galileo navigation signals will provide coverage at all latitudes. The complete Galileo constellation will consist of 27 satellites plus 3 spares. With the satellites taking about 14 hours to orbit Earth at altitudes of 23 222 km, there will always be at least four satellites visible anywhere in the world (Table 2-8). The 30 satellites will be in three orbital planes at an angle of 56 degrees
to the equator, which will provide coverage right up to the polar regions. The large number of satellites, together with the optimization of the constellation and the availability of the three active spare satellites, will ensure that the loss of one satellite has no discernible effect on the user segment.

Table 2-8: GALILEO Satellite Constellation

<table>
<thead>
<tr>
<th>Satellites</th>
<th>27 operational and three active spares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital planes</td>
<td>3</td>
</tr>
<tr>
<td>Orbital inclination</td>
<td>56 degrees</td>
</tr>
<tr>
<td>Orbit radius</td>
<td>23,222 km</td>
</tr>
</tbody>
</table>

Two Galileo Control Centres (GCCs) have been implemented on European ground to provide for the control of the satellites and to perform the navigation mission management. The data provided by a global network of Galileo Sensor Stations (GSSs) are sent to the Galileo Control Centres through a redundant communications network. The GCCs use the data from the Sensor Stations to compute the integrity information and to synchronize the time signal of all satellites with the ground station clocks. The exchange of the data between the Control Centres and the satellites is performed through up-link stations (ESA, Galileo navigation, 2017).

2.2.3.2. GALILEO Segments

Galileo segments are almost similar to GPS, but with some modification. The main extension of Galileo compared to GPS is the implementation of a global/regional segment for integrity monitoring. The objective is to assist the safety critical aircraft navigation and locate and guide railway trains (ESA, Galileo navigation, 2017).

2.2.3.3. GALILEO Signals

Table 2-9 provides further information about Galileo signals.
The Galileo frequency should respect the radio-regulations as they are discussed and agreed on at the International Telecommunications Union (ITU) forums such as the World Radio-Communication Conference (WRC). There were different studies that were conducted before the determination of the Galileo signal allocations in order to avoid interference with GPS and Glonass systems, which operate in the same portion of the RF spectrum. The Galileo constellation offers the capability of broadcasting globally a set of six signals supporting the open, commercial, safety-of-life and public regulated services.

On 8th of June 2017 two further satellites have formally become part of Europe’s Galileo system, broadcasting timing and navigation signals worldwide while also picking up distress calls across the planet. These are the 15th and 16th satellites to join the network, two of the four Galileo’s

---

**Table 2-9: Galileo Signal Characteristics (Jeffrey, 2010)**

<table>
<thead>
<tr>
<th>DESIGNATION</th>
<th>FREQUENCY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 A</td>
<td>1575.42 MHz</td>
<td>Public regulated service signal.</td>
</tr>
<tr>
<td>E1 B</td>
<td></td>
<td>Safety-of-Life and open service signal (data).</td>
</tr>
<tr>
<td>E1 C</td>
<td></td>
<td>Safety-of-Life and open service signal (dataless).</td>
</tr>
<tr>
<td>E5a I</td>
<td>1178.45 MHz</td>
<td>Open service signal (data).</td>
</tr>
<tr>
<td>E5a Q</td>
<td></td>
<td>Open service signal (dataless).</td>
</tr>
<tr>
<td>E5b I</td>
<td>1207.14 MHz</td>
<td>Safety-of-Life and open service signal (data).</td>
</tr>
<tr>
<td>E5b Q</td>
<td></td>
<td>Safety-of-Life and open service signal (dataless).</td>
</tr>
<tr>
<td>AltBOC</td>
<td>1191.795 MHz</td>
<td>Combined E5a/E5b signal.</td>
</tr>
<tr>
<td>E6 A</td>
<td></td>
<td>Public regulated service signal.</td>
</tr>
<tr>
<td>E6 B</td>
<td>1278.75 MHz</td>
<td>Commercial service signal (data).</td>
</tr>
<tr>
<td>E6 C</td>
<td></td>
<td>Commercial service signal (dataless).</td>
</tr>
</tbody>
</table>
satellites that were launched together by Ariane 5\(^1\) on 17th of November, and the first additions to the working constellation since the start of Galileo Initial Services on 15th of December (ESA, Launching Galileo, 2017).

### 2.2.3.1. Galileo Search and Rescue Service

The Galileo Support to Search and Rescue Service (SAR), represents the contribution of Europe to the international COSPAS-SARSAT\(^2\) co-operative effort on humanitarian Search and Rescue activities. Search and Rescue (SAR) operations involve locating and helping people in distress. Galileo takes an important part of the Medium Earth Orbit Search and Rescue system (MEOSAR). Galileo satellites will be able to pick up signals from emergency beacons (a transmitters) carried on ships, planes or persons and ultimately send these back to the national rescue centres. From this, a rescue centre can know the precise location of an accident. At least one Galileo satellite will be in a view of any point on the Earth so near real-time distress alert is possible. In some cases, feedback could be sent back to the emergency beacon, something which is only made possible by Galileo (see on Figure 2-17). The service will be available at sea, in the mountains, across the desert and in the air inside the Galileo/SAR Service Coverage area, this essential Galileo service helps operators respond to a distress signal faster and more efficiently. The Galileo/SAR Service will allow for important improvements of the existing COSPAS-SARSAT system:

\[\text{_______________}\]

---

\(^1\) Ariane 5 is a European heavy-lift launch vehicle that is part of the Ariane rocket family, an expendable launch system used to deliver payloads into geostationary transfer orbit (GTO) or low Earth orbit (LEO).

\(^2\) The International COSPAS-SARSAT Programme provides accurate, timely, and reliable distress alert and location data to help search and rescue authorities assist persons in distress. The objective of the Cospas-Sarsat system is to reduce, as far as possible, delays in the provision of distress alerts to Search and Rescue (SAR) services, and the time required to locate a distress and provide assistance, which have a direct impact on the probability of survival of the person in distress at sea or on land.
• near real-time reception of distress messages transmitted from anywhere on Earth (the average waiting time is currently one hour);

• precise location of alerts (a few meters for EPIRBs and ELTs equipped with Galileo receivers, while the current specification for location accuracy is 5 km)

• multiple satellite detection to avoid terrain blockage in severe conditions

• increased availability of the space segment (27 Medium Earth Orbit satellites on top of the four Low Earth Orbit satellites and the three Geostationary satellites in the current system)

In addition, Galileo/SAR Service will introduce a new SAR function, namely the return link from the SAR operator to the distress emitting beacon, thereby facilitating the rescue operations and helping to identify and reject the false alerts (ESA, 2017).

The Search and Rescue Transponder on Galileo satellites detects the distress alert from any COSPAS-SARSAT beacon emitting an alert in the 406 – 406.1 MHz band, and broadcasts this information to dedicated ground stations in the “L6” band. COSPAS-SARSAT Mission Control Centres (MCC) carry out the position determination of the distress alert emitting beacons, once they have been detected by the dedicated ground segment.

Figure 2-17: GALILEO/SAR architecture (ESA, Galileo navigation, 2017)
Table 2-10: Service performances requirements for the Galileo Search and Rescue Service (ESA, 2017)

<table>
<thead>
<tr>
<th>Galileo support to Search and Rescue Service (SAR/Galileo)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
</tr>
<tr>
<td>Each satellite shall relay signals from up to 150 simultaneous active beacons</td>
</tr>
<tr>
<td><strong>Forward System Latency Time</strong></td>
</tr>
<tr>
<td>The communication from beacons to SAR ground stations shall allow for the detection and location of a distress transmission in less than 10 min. The latency time goes from beacon first activation to distress location determination.</td>
</tr>
<tr>
<td><strong>Quality of Service</strong></td>
</tr>
<tr>
<td>Bit Error Rate &lt; 10e-5 for communication link: beacon to SAR ground station.</td>
</tr>
<tr>
<td><strong>Acknowledgment Data Rate</strong></td>
</tr>
<tr>
<td>6 messages of 100 bits each, per minute.</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
</tr>
<tr>
<td>&gt; 99.8%</td>
</tr>
</tbody>
</table>

2.2.4. IRNSS (INDIAN REGIONAL NAVIGATION SATELLITE SYSTEM)

India is in the process of launching its own regional navigation satellite system to provide coverage for India and the surrounding regions. The IRNSS system will consist of seven satellites, three of them in geostationary orbits and four in inclined geosynchronous orbits. The system will provide a position accuracy of better than 10 meters throughout India and better than 20 meters for the area surrounding India by 1500 km. IRNSS will provide two services. A Standard Positioning Service (SPS) available to all users and a Restricted Service (RS) available to authorized users only.

Table 12 summarizes the IRNSS signals. The first IRNSS satellite was launched in July of 2013 and the second satellite was launched in April 2014. The full constellation of seven satellites is planned to be completed by 2015. (Jeffrey, 2010)

2.2.5. QZSS (QUASI-ZENITH SATELLITE SYSTEM), JAPAN

QZSS is a four satellite system that will provide regional communication services and positioning information for the mobile environment. One of the four satellites was launched in 2010. The focus of this system is for the Japan region, but it will provide service to the Asia-Oceania region. QZSS will provide limited accuracy in standalone mode, so it is viewed as a GPS augmentation service. The QZSS satellites use the same frequencies as GPS and have clocks that are synchronized with GPS time. This allows the QZSS satellites to be used as if they were additional GPS satellites.
QZSS satellites also broadcast an SBAS compatible signal and a high-precision signal at E6. Three of the QZSS satellites will be placed in a periodic Quasi-Zenith Orbit (QSO). These orbits will allow the satellites to “dwell” over Japan for more than 12 hours a day, at an elevation above 70° (meaning they appear almost overhead most of the time). In the future, Japan intends to expand the QZSS system to a seven satellite system (Jeffrey, 2010).
3. GPS POSITIONING PRINCIPLES

The operating principle is similar to all GNSS systems mentioned in the previous section however the most used and widely studied is the GPS system, this system will be used as a reference in the descriptions that follow, although the principles described are generally applicable to all GNSS system.

### 3.1. Fundamentals of GPS positioning

A GPS receiver calculates its position by a technique called satellite ranging, which involves the measure of the distance between the GPS receiver and GPS satellites in the view. The range (the range a receiver calculates is actually a pseudorange, or an estimate of the range rather than a true range) or distance, is measured as an elapsed travel time. The position of each satellite is known, and the satellites transmit their positions as a part of the "messages" they send via radio waves. The GPS receiver on the ground is the unknown point, and can compute its position based on the information it receives from the satellites.

GPS positioning is based on trilateration, which is the method of determining position by measuring distances to points at a known coordinate. Trilateration requires minimum 3 ranges to 3 known points. If the distance from one point on the earth to three satellites is known, the coordinate of the point can be determined by resection.

#### 3.1.1. Code (Pseudorange) Observation Model

The first step in measuring the distance between the receiver and one satellite requires measuring the time it takes for the signal to travel from the satellite to the receiver. Once the receiver knows how much time has elapsed, it multiplies the travel time of the signal with the speed of light (because the satellite signals travel at the speed of light, approximately 300 000 kilometers per
second) to compute the distance. Distance measurements to four satellites are required to compute a 3-dimensional (latitude, longitude and altitude) position.

\[ P_R^S(t) = \Delta t_R^S * c \]  \hspace{1cm} \text{Equation 3-1}

where

\[ P_R^S(t): \text{ pseudorange between satellite and receiver} \]

\[ \Delta t_R^S: \text{ travel time between receiver and satellite} \]

\[ c: \text{ speed of light, 300 000 km/s} \]

Equation 3-1 is true when the satellites clocks are perfectly synchronized with GPS time, which is practically impossible, or to know the offset of each clock with respect to GPS time.

The satellite is identified by its own C/A code. After the identification, the receiver performs a correlation between its internally generated C/A code and the one received from the satellite (see on Figure 3-3). These observations can be done with both, C/A and P(Y) codes. The delay between the received signal and the internal one is electronically measured. There are two epochs related to the satellite clock (starting epoch) and the receiver clock (receiving epoch). These epochs are related to the local time of the clocks. Therefore, they are affected by the two clock offsets.

Observation equation will be given by:

\[ \Delta t_R^S(t) = t_R(t) - t^S(t - \tau_R^S) \]  \hspace{1cm} \text{Equation 3-2}

where

\[ \Delta t_R^S(t): \text{ a delay observed between the receiver and the satellite signal} \]

\[ t_R(t): \text{ a receiving epoch recorded by the receiving clock} \]

\[ t^S(t - \tau_R^S): \text{ a starting epoch recorded by the satellite clock} \]

\[ \tau_R^S: \text{ the signal traveling time from the satellite to the receiver} \]

\[ t: \text{ an observation epoch} \]

The satellite is not synchronized with the receiver GPS time, so we have:
\[ t^S(t - \tau^S_R) = t - \tau^S_R + dt^S(t - \tau^S_R) \]

Equation 3-3

, where \( dt^S(t - \tau^S_R) \) represents clock offset of the satellite and \( dt_R(t) \) is a clock offset of the receiver.

After replacing Equation 3-3 in Equation 3-2, observation equation is given by:

\[ \Delta t^S_R(t) = t_R + dt_R(t) - (t^S - \tau^S_R + dt^S(t - \tau^S_R)) \]

Equation 3-4

after some basic calculation in Equation 3-4 observation equation is written as:

\[ \Delta t^S_R(t) = \tau^S_R + dt_R(t) - dt^S(t) \]

Equation 3-5

After replacement of Equation 3-5 in Equation 3-1, code (pseudorange) observation equation is following:

\[ P^S_R(t) = c\tau^S_R + c(dt_R(t) - dt^S(t)) \]

Equation 3-6

Figure 3-1: A schematic diagram showing how the GPS code (pseudorange) observation

is related to the satellite and receiver clocks (Blewitt, 1997)

In order to measure the travel time of the satellite signal, the receiver has to know when the signal left the satellite and when the signal reached the receiver. Knowing when the signal reaches the receiver is easy, the GPS receiver just "checks" its internal clock when the signal arrives to see
what time it is. To know when the signal leaves the satellite all GPS receivers are synchronized with the satellites so they generate the same digital code at the same time. When the GPS receiver receives a code from a satellite, it can look back in its memory bank and remember when it emitted the same code. This little trick allows the GPS receiver to determine when the signal left the satellite.

Once the receiver has the distance measurements, it is basically a problem of geometry. At least four satellites are necessary to determine the four unknowns: X, Y, Z and $dt_R$. If the receiver knows where the four satellites are, and how far it is from each satellite, it can compute the location of its antenna through 3D multi-trilateration. Here is an illustration of how it works (see Figure 3-2: Three satellites in view (red, green and purple clock): location of the GPS receiver is at the point of intersection of the three spheres.

If the receiver picks up another satellite, another sphere is formed, and there are only two points where the three spheres intersect. Usually the receiver can discard one of the last two points because it is nowhere near the earth. So, we are left with one point which is the location of the GPS receiver. At this moment three of the initial unknowns are solved: X, Y, Z coordinates of the antenna. In practice, a fourth measurement is needed to correct for clock error, $dt_R$.

Figure 3-2: Three satellites in view (red, green and purple clock): location of the GPS receiver is at the point of intersection of the three spheres (Cătălin, 2015)
3.1.2. Carrier Phase Observation Model

3.1.2.1. Basic concept of carrier waves (signals)

Before deriving the phase observation model an analytically introduction into signals must be provided. Phase is simply angle of rotation, which is conventionally in units of cycles for GPS analysis. Consider a point moving anti-clockwise around the edge of a circle, and draw a line from the centre of the circle to the point. As illustrated in Figure 3-3, the phase \( \phi(t) \) at any given time \( t \) can be defined as the angle through which this line has rotated.

Therefore, GPS carrier phase (signal) is an oscillating phenomenon, which repeats itself cyclically in time, is described by following equation:

\[
A(t) = A_0 \sin(\omega t + \varphi_0)
\]

Equation 3-7

where

\( A(t) \): signal at epoch \( t \)

\( \varphi_0 = \) initial phase at epoch \( t \), where \( \varphi_0 = \varphi(0) \)

\( A_0 \): is a signal amplitude

\( \omega \): is angular velocity

In GPS terminology instead of \( \varphi(t) \) it is used \( \Phi(t) = \frac{\varphi(t)}{2\pi} \) and given in [cycles]. [cycle] = \([\text{rad}]\), \(\frac{1}{2\pi}\).

The frequency is expressed in units of cycles per second, is the number of times the line completes a full 360 degrees’ rotation in one second (which of course, is generally a fractional number).

\[
f = \frac{1}{T} = \frac{\omega}{2\pi} = \frac{1}{[\text{sec}]} = [\text{Hz}]
\]

Equation 3-8

where

\( T \): is period of the signal and the time needed to complete one full revolution given in [sec];
One can better define frequency instantaneously as the first derivative of phase with respect to time; that is, the angular speed (Blewitt, 1997).

\[ f = \frac{d\phi(t)}{dt} \]  
\textit{Equation 3-9}

**THE CARRIER PHASE FOR AN IDEAL OSCILLATOR:**

Constant frequency is the basis of an ideal clock. If the frequency can be written as a constant, \( f_0 \), then we can write the phase of an ideal clock as:

\[ \phi_i(t) = f_0 t + f_0 dt_i(t) + \phi_0 \]  
\textit{Equation 3-10}

\[ t_i(t) = t + dt_i(t) \]  
\textit{Equation 3-11}

, where \( i \): represents an oscillator.

**3.1.2.2. Carrier phase observation equation**

The satellite carrier signal is mixed with reference signal generated by receiver’s clock. The result, after high pass filtering, is a ‘beating’ signal. The phase of this beating signal equals the reference phase minus the incoming GPS carrier phase from a satellite; however, it is ambiguous by an integer number of cycles. By ‘carrier beat phase’ it is simply meant the ‘carrier phase’ but not the phase of the incoming signal.
The observation equation at epoch $t$ is given by:

$$\Delta \Phi^S_R(t) = \Phi_R(t) - \Phi^S(t - \tau) \quad \text{Equation 3-12}$$

where,

$\Delta \Phi^S_R(t)$: is phase difference observation at epoch $t$

$\Phi_R(t)$: receiver internally generated phase at epoch $t$

$\Phi^S(t - \tau)$: phase of satellite signal generated at the emission period $(t - \tau)$

After substituting $\Phi_R(t)$ and $\Phi^S(t - \tau)$ from Equation 3-10 with Equation 3-8 observation equation is following:

$$\Delta \Phi^S_R(t) = f_0 \tau^S_R + f_0 (dt_R(t) - dt^S(t)) + \phi^S_0 R - \phi^S_0 S \quad \text{Equation 3-13}$$

, where

$\phi^S_0 R$: is the initial phase of the receiver;

$\phi^S_0 S$: is the initial phase of the satellite

The range between satellite and receiver is expressed in units of cycles of the carrier frequency but in the model an integer number of cycles $N$ is missing. To deal with this, the following assumption holds true. Suppose we only record the fractional phase of the first measurement. There is no way of knowing which integer $N$ has to be added to this recorded phase so that it really provides the difference in phase between the replica signal and the GPS signal. This is fundamentally because we have no direct measure of the total phase of the incoming GPS signal. We can express this as follows:

$$\Delta \Phi^S_R(t) = f_0 \tau^S_R + f_0 (dt_R(t) - dt^S(t)) + \phi^S_0 R - \phi^S_0 S + N_R - N^S \quad \text{Equation 3-14}$$

We can interpret $N$ as equal to the number of carrier wavelengths between the receiver (at the time it makes the first observation), and the satellite (at the time it transmitted the signal). If the receiver
loses count of the oscillations (e.g., because the signal is obstructed), then a new integer parameter must be introduced to the model, starting at that time. This integer discontinuity in phase data is called a cycle slip.

It is convenient to convert the carrier phase model into units of range. This simplifies concepts, models, and software. In the range formulation, we multiply the carrier phase equation by the nominal wavelength, $\chi_0$.

$$ L^S_R(t) = \chi_0 \phi^S_R(t) \quad \text{Equation 3-15} $$

after substitution Equation 3-14 in to Equation 3-15 and some calculations, phase equation is:

$$ L^S_R(t) = c t^S_R(t) + c(d_t^R(t) - d^S(t)) + B^S_R \quad \text{Equation 3-16} $$

, where $B^S_R = \chi(N^S_R(t) + \phi_{0R} - \phi^S_0)$ and is carrier phase bias.

Where we still retain the name carrier phase for $L^S_R(t)$ which is in units of meters. We see immediately that this equation is identical to that for the pseudorange, with the exception of the carrier phase bias.

### 3.1.3. Error Sources

Orbit errors, satellite and receiver clock biases, atmospheric delays, antenna phase centre offsets and variations, multipath and measurement noise are discussed in the following sections. (Geomatics, 2018)

#### 3.1.3.1. Orbit Errors

Errors in the estimates of the satellite coordinates will propagate directly to the estimation of the parameters. For this reason, orbit errors have to be minimized, primarily by accurately modelling the satellite orbits. The International GNSS Service collects, archives and distributes GPS and GLONASS observation data sets from a global GNSS reference station network that are used for the combination and analysis of the IGS orbit products at the IGS Analysis Centres. These products
with their respective accuracy and latency specifications are summarized. The high accuracies of the IGS orbit products benefit many GPS applications, and specifically scientific and engineering applications such as deformation of structures and geophysical investigations.

Table 3-1: Accuracy of IGS orbit products

<table>
<thead>
<tr>
<th>GPS Satellite Ephemerides</th>
<th>Accuracy(cm)</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast</td>
<td>100</td>
<td>Real time</td>
</tr>
<tr>
<td>Ultra Rapid (predicted half)</td>
<td>5</td>
<td>Real time</td>
</tr>
<tr>
<td>Ultra Rapid (observed half)</td>
<td>3</td>
<td>3-9 hrs</td>
</tr>
<tr>
<td>Rapid</td>
<td>2</td>
<td>17-41 hrs</td>
</tr>
<tr>
<td>Final</td>
<td>2</td>
<td>12-18 days</td>
</tr>
</tbody>
</table>

3.1.3.2. Satellite and receiver clock Errors

The role of the receiver and satellite clocks is very important in precise GPS surveying. As shown in Equations 3-5 and 3-6, the receiver and satellite clock error components are multiplied by the speed of light c. Hence, because of the factor c, a small clock error can cause a very large code and phase error. For example, a clock error of 1 ns translates to 0.3 m in range error, whereas 1 μs in 300 m.

In relative positioning, between satellites differencing eliminates the receiver clock error term. In Network RTK, where double difference is adopted as the main observable, receiver and satellite clocks are completely eliminated through differencing.

3.1.3.3. Tropospheric delay

The tropospheric delay is caused by the refractions of a GPS signal in the lower atmosphere (the layer from the earth surface to approximately 60 km). The magnitude of this error is influenced by a number of parameters such as the temperature, humidity, pressure, and the type of the terrain below the signal path. A number of studies have been performed to create tropospheric models (Hopfield, 1969, Saastamoinen, 1973, Black, 1978). A thorough analysis of these models can be found in (Hoffmann et al., 1992).
Approximately 80-90% of the delay is due to the wet portion of the troposphere which is contained within the first 10 km. However, this is the most difficult portion to model due to the variability in the atmospheric conditions. The wet tropospheric delay is affected by factors such as temperature, pressure, humidity, and satellite elevation. The other part of the tropospheric delay is the dry delay, which is primarily due to oxygen and nitrogen in the atmosphere. At the zenith, the dry delay is 2.3 m, while the wet delay is 1-80 cm. The total error increases more than 10 times as the satellite gets closer to the horizon (Seeber, 2003). In differential positioning with short inter-receiver distances, the tropospheric delay is significantly reduced. Unfortunately, in single point or differential positioning with a long inter-receiver distance the troposphere can lead to increases in the position errors. Since the troposphere is not dispersive at GPS frequencies, a model must be used to estimate the tropospheric effect. Some of these models include: The Hopfield model (Hopfield, 1969), the modified Hopfield model (Goad C.C., 1974), and the Saastamoinen model (Saastamoinen, 1973). Goad and Goodman (1974) showed that the modified Hopfield model gives the best results for low elevation satellites. Each of these models gives similar results for satellites above 20 degrees. The dry part of the tropospheric delay can be estimated to a few millimeters using a model, while the estimation of the wet portion is much less accurate. The models are only accurate to 10-20% for the wet part of the tropospheric delay.

3.1.3.4. Ionospheric delay

The ionosphere is the zone of the terrestrial atmosphere that extends itself from about 60 km until more than 2,000 km in high. As it name says, it contains a partially ionized medium, as result of the X and UV rays of Solar Radiation and the incidence of charged particles. The propagation speed of the GNSS electromagnetic signals in the ionosphere depends on its electron density (see below), which is typically driven by two main processes: during the day, sun
radiation causes ionization of neutral atoms producing free electrons and ions. During the night, the recombination process prevails, where free electrons are recombined with ions to produce neutral particles, which leads to a reduction in the electron density.

In a good approximation the ionospheric range error is related to the total electron content by:

\[ I = \frac{40.3}{f^2} \times TEC \]  \hspace{1cm} \text{Equation 3-17}

where

- \( I \): is a ionospheric range error at frequency \( f \) [m];
- \( TEC \): is the number of electrons per unit area along the path of propagation;

The ionospheric error is not equal on L1 and L2, the following relation holds true:

\[ I_2 = \frac{f_1^2}{f_2^2} I_1 \]  \hspace{1cm} \text{Equation 3-18}

Moreover, L1 and L2 carrier phases can be combined together that will reduce ionospheric effect to zero. A new equation L3 is obtained

\[ L3(t) = \frac{f_1^2}{f_1^2 - f_2^2} L1(t) - \frac{f_2^2}{f_1^2 - f_2^2} L2(t) \]  \hspace{1cm} \text{Equation 3-19}

Substituting L1 and L2 with the observation equation for carrier phase and rearranging the terms, ionospheric effect vanishes at the end.

\[ \frac{f_1^2}{f_1^2 - f_2^2} L1(t) - \frac{f_2^2}{f_1^2 - f_2^2} f_1^2 l_1(t) = 0 \]  \hspace{1cm} \text{Equation 3-20}

One option to correct the ionospheric range error in GPS applications is the use of models such as the Klobuchar (Klobuchar, 1987) model for GPS (GPS Interface Control Document [ICD] 200C). Another option is to take advantage of an additional augmentation service such as EGNOS in Europe (or WAAS in US).
3.1.3.5. *Antenna phase centre offset*

For any given GPS antenna, the electrical phase centre is not stable but changing with the changing direction of the signal from the satellite. Antenna instantaneous phase centre errors depend mainly on the elevation of the satellite (Wubenna et al, 1997). However, azimuthal effects introduced by the local environment around each individual site need also to be considered.

The point in the antenna that is used to determine the offset in relation to the geodetic point above which the antenna is installed, is selected by the user. For example, the antenna reference point (ARP), is defined for each antenna type, usually as the intersection of the rotation axis of the antenna and the bottom of pre amplifier or the top of pole. The use of different antenna types in differential positioning is a typical phenomenon, thus makes the application of an antenna phase centre offset and PCV correction essential.

3.1.3.6. *Multipath*

Multipath is the error that is caused by reflections near the receiver and results in the GPS signal arriving at the receiver via more than one path. Multipath is highly dependent on the environment surrounding the receiver, the type of antenna that is used and the tracking loop algorithms of the receiver, making it thus a difficult error to remove. It affects both code and phase measurements. Carrier phase multipath is a fraction of the wavelength, whereas code multipath is limited by the chipping rate.

It is important to avoid multipath error in carrier phase and pseudorange measurements, because it will propagate to the estimated receiver positions. To mitigate the multipath bias in the solution, radio frequency absorbing material near the antenna, carefully designed antennas, such as choke ring design and use of ground planes, in combination with a careful selection of antenna location can be employed.
3.1.3.7. Measurement Noise

Measurement noise is the sum of all the unmodelled errors and second order effects. It is any noise that is generated by the receiver itself in the process of taking code or phase measurements. For the phase observations the noise is at the millimeter level and consequently the effect on the Network RTK processing minimal.

3.1.3.8. The observation geometry effect

The precision of positioning depends on the individual pseudorange measurement and the geometric configuration of the satellites. This configuration is expressed in terms of a scalar value, which is called DOP (Dilution of Precision). The DOP value describes the quality of constellation distribution. If the DOP valued is high, the anticipated imprecision is higher. There are a variety of DOP terms used:

- GDOP (Geometric-DOP): Describes the influence of satellite geometry on the position in 3D space and time measurement.
- PDOP (Positional-DOP): Describes the influence of satellite geometry on the position in 3D space.
- HDOP (Horizontal-DOP): Describes the influence of satellite geometry on the position along upon a plane (2D).
- VDOP (Vertical-DOP): Describes the influence of satellite geometry on height (1D).
- TDOP (Time-DOP): Describes the influence of satellite geometry on time measurement.

The best way of minimizing the DOP is to observe as many satellites as possible. Generally, the accuracy is better when DOP value is low.
The precision, accuracy and reliability of the position obtained from GPS depends upon the accuracy of the range measurements (UERE)\textsuperscript{3} and the geometric effect of the spatial relationship of the satellites relative to the user (GDOP)\textsuperscript{4}. The measurements differ from the true range in that they incorporate a number of errors. These errors appear in Equation 3-21 and Equation 3-22 for the carrier phase and pseudorange observation equation respectively.

Final model for pseudorange (code) observations:

\[ P_R^S = \rho_R^S(t_R, t^S) + c(d t_R (t) - d t^S(t)) + T_R^S + I_R^S \]  \hspace{1cm} \text{Equation 3-21}

Final model for phase observations:

\[ L_R^S = \rho_R^S(t_R, t^S) + c(d t_R (t) - d t^S(t)) + T_R^S + I_R^S + B_R^S \]  \hspace{1cm} \text{Equation 3-22}

\textsuperscript{3} UERE - User Equivalent Range Error
\textsuperscript{4} GDOP - Geometric Dilution of Precision
3.2. Differencing positioning technique

Differential or relative positioning requires at least two receivers set up at two stations (usually one is known) to collect satellite data simultaneously in order to determine coordinate differences. This method will position the two stations relative to each other (hence the term “relative positioning”) and can provide the accuracies required for basic land surveying and hydrographic surveying. Differential GPS (DGPS) positioning can be performed in either a static or kinematic mode. Differential GPS positioning in static mode is used while doing experiments for this work.

The relative positioning allows to improve the accuracy. This improvement depends on:

- kind of receivers and from observations that can be acquired
- distance between the reference station and the rover
- kind of survey done, time of unknown point occupation
- kind of data processing (real-time, post-processing)

Accuracy can be from 1-2 meters with code observations in real time, to the centimeter (also sub-centimeter) with static survey with dual-frequency receivers (Biagi, 2009.)

Assuming such simultaneous observations from receivers a and b to satellites 1 and 2, linear combinations can be formed leading to single, double or triple differences. Differencing can be accomplished between receivers, between satellites and between time (Geomatics, 2018).

3.2.1. Single differencing

In single differencing method (SD) two receivers (Figure 3-5), R1 and R2, acquired data from one satellite S at the same epoch. The single difference is the difference between the observations of the two receivers and can be considered itself an observation (Biagi, 2009.).
The SD code observation can be written as:

\[ P_{R1,R2}^S(t) = P_{R1}^S(t) - P_{R2}^S(t) \]  \hspace{1cm} \textit{Equation 3-23}

\[ = \rho_{R1}^S(t) - \rho_{R2}^S(t) + c(dt_{R1}^S(t) - dt_{R2}^S(t)) - c(dt^S(t) - dt^S(t)) + I_{R1}^S - I_{R2}^S + T_{R1}^S(t) - T_{R2}^S(t) \]

The SD phase observation can be written as:

\[ L_{R1,R2}^S(t) = L_{R1}^S(t) - L_{R2}^S(t) \]  \hspace{1cm} \textit{Equation 3-24}

\[ = \rho_{R1}^S(t) - \rho_{R2}^S(t) + c(dt_{R1}^S(t) - dt_{R2}^S(t)) - c(dt^S(t) - dt^S(t)) - I_{R1}^S + I_{R1}^S + T_{R1}^S(t) - T_{R2}^S(t) + \lambda(N_{R1}^S(t) - N_{R2}^S(t) - \phi_{R1} - \phi_{R2}) \]

The single differencing method erased from the observation equation in the terms of:

- offset of satellite clock and
- satellite initial phase.

Due to the differentiation following errors are reduced:

- ionospheric effect \( \rightarrow I_{R1,R2} = I_{R2}^S - I_{R1}^S \)
- tropospheric effect \( \rightarrow T_{R1,R2} = T_{R1}^S - T_{R2}^S \)
- satellite ephemerides \( \rightarrow \rho_{R1,R2} = \rho_{R1}^S(t) - \rho_{R2}^S(t) \)

### 3.2.2. Double differencing

The double differencing method (DD) is the differences of two simultaneous single differences between two receivers, R1 and R2 and two satellites, S1 and S2 (Figure 3-6).

![Figure 3-6: Double differences (Biagi, 2009.)](image)

Regarding code observations the double difference can be written: (Biagi, 2009.)

\[
\begin{align*}
P_{R1,R2}^S(t) &= P_{R1,R2}^{S1}(t) - P_{R1,R2}^{S2}(t) \\
&= \rho_{R1}^{S1}(t) - \rho_{R2}^{S1}(t) - \rho_{R1}^{S2}(t) + \rho_{R2}^{S2}(t) + c(dt_{R1}(t) - dt_{R2}(t)) - \\
&- c(dt_{R1}(t) - dt_{R2}(t)) + I_{R1}^{S1}(t) - I_{R2}^{S1}(t) + T_{R1}^{S1}(t) - T_{R2}^{S1}(t) - (I_{R1}^{S2}(t) - \\
&- I_{R2}^{S2}(t) + T_{R1}^{S2}(t) - T_{R2}^{S2}(t)) = \\
&= \rho_{R1}^{S1}(t) - \rho_{R2}^{S1}(t) - \rho_{R1}^{S2}(t) + \rho_{R2}^{S2}(t) + T_{R1}^{S1}(t) - T_{R2}^{S1}(t) - T_{R1}^{S2}(t) - T_{R2}^{S2}(t) \\
&+ I_{R1}^{S1}(t) - I_{R2}^{S1}(t) - I_{R1}^{S2}(t) + I_{R2}^{S2}(t)
\end{align*}
\]
If phase observation is considered the double differences will be written in following form:

\[
L_{R1,R2}^S(t) = L_{R1,R2}^{S1}(t) - L_{R1,R2}^{S2}(t)
\]

\[
= \rho_{R1}^{S1}(t) - \rho_{R2}^{S1}(t) - \rho_{R1}^{S2}(t) + \rho_{R2}^{S2}(t) + c(dt_{R1}(t) - dt_{R2}(t)) - c(dt_{R1}(t) - \\
- dt_{R2}(t)) + T_{R1}^{S1}(t) - T_{R2}^{S1}(t) - T_{R1}^{S2}(t) + T_{R2}^{S2}(t) - I_{R1}^{S1}(t) + I_{R2}^{S1}(t) + I_{R1}^{S2}(t) - \\
- I_{R2}^{S2}(t) + \lambda(N_{R1}^{S1}(t) - N_{R2}^{S1}(t) - N_{R1}^{S2}(t) - N_{R2}^{S2}(t) + \phi_{R1} - \phi_{R2} - \phi_{R1} + \phi_{R2})
\]

DD contain only geometric and integer ambiguities parameters plus reduced atmospheric effects.

Double differencing positioning is used to reduce satellite clock and orbit errors, to localize atmospheric errors and receiver clock errors. Usually adopted by the final carrier phase GPS solution.
4. GNSS RECEIVERS

GNSS receivers are part of the GNSSs ground segment. GNSS receivers are a suboptimal implementation of a maximum likelihood estimator of the signal propagation time. In order to ensure tracking of the signals in each processing channel, receivers are continuously estimating and correcting two parameters:

1) The code delay, which quantifies the misalignment between the incoming signal and the local PRN code replica.

2) The carrier phase, or its instantaneous value, the Doppler frequency, which reflects the relative motion between user and satellites (Linty, 2015).

After synchronization with the incoming signals and demodulation of the navigation message, the receiver is able to determine pseudo-ranges to each satellite, and to compute a navigation solution.

Back in the 1970s, receivers were large analog hardware equipment, targeting military applications. Around 1980 the first commercially available GPS receiver, the STI-5010, built by Stanford Telecommunications, Inc. has been introduced in the market. It was a dual-frequency, C/A and P-code, slow-sequencing receiver. Cycling through four satellites took about five minutes, and the receiver unit alone required about 30 centimetres of rack space. By 1990, a number of manufacturers were offering receivers for positioning, navigation, and timing applications. Already, the first handheld receiver was on the market, the Magellan NAV 1000. Its single sequencing channel could track four satellites.

Nowadays, consumer-grade GNSS receivers have been widely expanded to miniaturized platforms, chipsets, microprocessors, integrated circuits, Digital Signal Processors (DSP), Field Programmable Gate Arrays (FPGA), handheld devices, including integration in most mobile phones (Linty, 2015).
Typically, commercial GNSS receivers vary according to their receiving capabilities. There are different types such as single-frequency code receivers, single-frequency carrier-smoothed code receivers, single-frequency code and carrier receivers, dual-frequency receivers, and triple-frequency receivers.

At this moment the following classification of GNSS sensors can be done:

- **Chipsets in smartphones.** Generally, these units are single-frequency (L1 band) and capable not only for code measurements and positions, but also smartphones are capable to release a raw data as an output at user interface.

- **Evaluation kits.** The main difference with the previous category consists in the possibility to store raw data. The classification of Evaluation kits can be taken one step further: they started as single-frequency receivers capable of providing only C/A code solution, then evolved to single frequency carrier-smoothed code receiver (phase observations are used to smooth the code, which will smooth the noise) and in the end improved by adding phase observations to the already available C/A code observations. The low-cost sensor tested, the u-blox NEO 7P, is falling in this last category.

- **Geographic Information System (GIS)/cartographic handheld receivers.** They are again L1 receivers but typically have better components (antenna). A GIS data collector is

---

*Figure 4-1: Standard GNSS receiver structure (Linty, 2015)*
composed by a special graphic computer, GIS software and GPS module for real-time land use.

- Geodetic receivers. This type is the most complete one, it comes in pair with geodetic antenna, which are more resistant to interference and multipath (Cătălin, 2015).

Table 4-1. lists receiver classes, typical applications and accuracy levels. The distinction between geodata acquisition and geodetic receivers is not clear in any case. Sometimes one frequency geodetic receivers are used for geodata acquisition.

If we compare these accuracies to the possible GPS measurement techniques, it is obvious that we need phase measurements to reach the accuracy required for geodetic applications. Besides the large difference in accuracy level the purchasing costs for the different receiver classes show large differences too (Volker Schwieger, Andreas Gläser, Cairo, April 18th, 2005).

*Table 4-1: Receiver classes, applications and accuracy levels of static positioning*

<table>
<thead>
<tr>
<th>RECEIVER CLASS</th>
<th>USED SIGNAL</th>
<th>APPLICATIONS</th>
<th>ACCURACY</th>
<th>APPR. COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW COST</td>
<td>code or phase-smoothed code, 1 frequency</td>
<td>car navigation, location based services, sailing, mass market</td>
<td>1 to 10 m</td>
<td>100 – 500 €</td>
</tr>
<tr>
<td>GEODATA ACQUISITION</td>
<td>phase-smoothed code, 1 frequency</td>
<td>infrastructure planning, architecture, GIS applications</td>
<td>0,5 to 3 m</td>
<td>5 000 – 10 000 €</td>
</tr>
<tr>
<td>GEODETIC</td>
<td>code and phase, in general 2 frequencies</td>
<td>surveying, geodynamics</td>
<td>0,001 to 0,1 m</td>
<td>10 000 € - 15 000 €</td>
</tr>
</tbody>
</table>

Currently the most advanced approach for increased spatial separation of permanent stations and error modeling is the so-called virtual reference station (VRS) network concept. The concept was firstly introduced in a part of the German reference station network SAPOS (Landau, March 13-17). The name of this approach results from the fact that observations for a “virtual” non-existing
station are created from the real observation of a multiple reference station network. This approach will be briefly explained in last section of this chapter.

4.1. Geodetic receivers

The accuracy requirements of geodetic receivers are usually about 1-5 cm (or even better). It requires the full ranges of code and phase measurements and the application of relative data processing technique to benefit the high accuracy of phase measurements. The raw data can be stored for post-processing. Such a receiver can be integrated in geodetic total stations (originally designed for digital angle and distance measurements) to determine the positions for geodetic mapping purposes. In the case of total station, the graphic representations and digital mapping is the trend of the new developments.

The outline of present developments is clear: the weight of the systems decreases along with the required number of cables, and Bluetooth finds its applications. Some systems are prepared to receive and process correction data like WAAS, EGNOS and MSAS, although this is not yet bringing centimeter accuracy (International, 2017).

Leica Geosystems is one of the industry leaders in measurement and information technologies. Leica’s, Topcon’s and Trimble’s GNSS receivers are used in experiments for different reference sites and will be explained in text below.

1) Leica GRX1200
2) Topcon Net-G5
3) Trimble BD930

4.1.1. The Leica GRX1200

The Leica GRX1200 Series is designed and can be used both as rover and as a reference. The measurement engine supports GPS, GLONASS, Galileo and BeiDou. Regarding data management,
removable and robust CompactFlash cards up to 1 GB are used for logging data. According to Leica, 1 GB is sufficient for about 7 weeks of 1Hz L1+L2 GPS data. There is no need for power-consum ing external memory storage, which typically cannot fulfil in the tough environment conditions to which reference stations are exposed. Files can be logged in raw data and/or RINEX format (Cătălin, 2015).

Main characteristics and benefits: (Geosystems, Leica GRX1200+ Series, 2017)

- Acquisition within seconds
- Excellent signal strength
- Reliable tracking to low elevations
- Phase and code multipath suppression
- High precision code and phase measurements up to 20 Hz
- High reliability and robustness
- Low power consumption

GPS and GLONASS are continually improving and the European Galileo and Chinese Compass systems are emerging to provide additional benefits for world-wide users. With the GRX1200 receivers all new GNSS systems are supported. To use and work with receiver of this type different types of antenna should be connected. Usually, AX1202GG antenna is used. Using this type of antenna Leica GRX1200 provides high quality observations for single stations and networks. Latest generation of geodetic antenna from Leica includes sub-millimeter phase centre accuracy, high quality measurements even from low elevation satellites and have built-in ground plane for multipath suppression.
Measurement precision and accuracy in position and in height are dependent upon various factors including number of satellites, geometry, observation time, ephemerides accuracy, ionospheric conditions, multipath etc. Figures quoted assume normal to favorable conditions. Times can also not be quoted exactly. Times required are dependent upon various factors including number of satellites, geometry, ionospheric conditions, multipath etc.
Table 4-2: Technical data for GRX1200 (courtesy Leica Geosystems)

<table>
<thead>
<tr>
<th>Leica GRX1200</th>
<th>Nominal value of frequency in L1 sub-band, in MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS technology</td>
<td>SmartTrack+</td>
</tr>
<tr>
<td>Measurement precision</td>
<td>L1: rms = 0.2 mm; L2: rms = 0.2 mm</td>
</tr>
<tr>
<td>- carrier phase</td>
<td>L1: rms = 20 mm; L2: rms = 20 mm</td>
</tr>
<tr>
<td>- code</td>
<td></td>
</tr>
<tr>
<td>Web &amp; FTP services</td>
<td>yes</td>
</tr>
<tr>
<td>Optional control software</td>
<td>Leica GPS Spider software</td>
</tr>
<tr>
<td>Weight</td>
<td>1.2 kg</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-40°C to +65°C</td>
</tr>
<tr>
<td>Waterproof</td>
<td>MIL-STD-810F Temporary submersion to 1 m</td>
</tr>
<tr>
<td>Shock/drop on hard surface</td>
<td>Withstand 1.0 m drop</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>Nominal 12V DC</td>
</tr>
<tr>
<td>Raw data logging</td>
<td>MDB (Leica proprietary format) and RINEX</td>
</tr>
<tr>
<td>Data streaming</td>
<td>RTCM v2.1/2.2/2.3/3.0</td>
</tr>
<tr>
<td></td>
<td>NMEA 0183</td>
</tr>
<tr>
<td></td>
<td>Leica LB2 raw data</td>
</tr>
<tr>
<td>NTRIP</td>
<td>Integrated NTRIP server</td>
</tr>
</tbody>
</table>

4.1.2. Topcon NET-G5 (Topcon, 2015)

The Net-G5 is a multi-frequency, GNSS receiver built to be the most advanced and convenient network reference receiver. The integrated receiver design includes a GNSS receiver board based on Vanguard™ technology, industry leading Fence Antenna™, internal long life batteries, memory storage and optional cellular wireless communication technology. The Net-G5 delivers world class positioning and navigation capability to your application by tracking signals from multi-constellation satellite systems, including GPS, GLONASS, SBAS, BeiDou and Galileo.
The Net-G5 can receive and process multiple signal types (including the latest GPS L2C, L5, GLONASS C/A L2 and Galileo signals) improving accuracy and reliability of the solution, especially under difficult job-site conditions.

Receiver features:

- 448 universal tracking channels
- Multipath reduction
- USB storage device
- Removable memory
- Backup battery system
- Satellite Based Augmentation Systems (WAAS, EGNOS, etc.)
- Dual- or multi-frequency modes, including static, kinematic, real time kinematic (RTK) and differential (DGPS) survey modes

CONFIGURING THE RECEIVER:

The Net-G5 is generally configured as a static Reference Station that collects GNSS measurements information and logs the data to a removable SD card, streams the data to a central computer and possibly connects directly to one or more radios. The Topcon Receiver Utility (TRU) and TopNET + software is used to manage and configure the various functions of the receiver.

Once connection between the receiver and the computer is established, one is able to:

- configure the receiver and its components
- send commands to the receiver
- download files from the receiver’s memory
- load different configuration files to the receiver
Table 4-3: Technical specifications - GNSS

<table>
<thead>
<tr>
<th>GNSS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Channels 1:</td>
<td>Channel Vanguard Technology</td>
</tr>
<tr>
<td>Number of Channels 2:</td>
<td>with Universal Tracking Channels</td>
</tr>
<tr>
<td>Signals Tracked 1:</td>
<td>L-Band and BeiDou (BDS)</td>
</tr>
<tr>
<td>Signals Tracked 2:</td>
<td>L-Band and BeiDou (BDS)</td>
</tr>
<tr>
<td>Antenna Type 1:</td>
<td>External – Geodetic full wave CR-G5</td>
</tr>
<tr>
<td>Antenna Type 2</td>
<td>or PN-A5 antenna</td>
</tr>
</tbody>
</table>

Table 4-4: Technical specifications - ACCURACY

<table>
<thead>
<tr>
<th>ACCURACY</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RTK</td>
<td>H: 10 mm+1 ppm; V: 15 mm+1 ppm</td>
</tr>
<tr>
<td>Post processed Static</td>
<td>H: 3.0 mm+0.1 ppm; V: 3.5 mm+0.4 ppm</td>
</tr>
</tbody>
</table>

Table 4-5: Technical specifications - ENVIRONMENTAL

<table>
<thead>
<tr>
<th>ENVIRONMENTAL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature 1</td>
<td>-40°C to 80°C with external power</td>
</tr>
<tr>
<td>Operating Temperature 2</td>
<td>-30°C to 65°C with integrated batteries</td>
</tr>
<tr>
<td>Humidity</td>
<td>100% condensing</td>
</tr>
<tr>
<td>Drop 1</td>
<td>2 meter drop to concrete surface</td>
</tr>
<tr>
<td>Drop 2</td>
<td>IEC 60068-2-29, IEC 60068-2-27</td>
</tr>
<tr>
<td>Vibration 1</td>
<td>Compliance with MIL-STD 810G,</td>
</tr>
<tr>
<td>Vibration 2</td>
<td>Method 514.6, Category 4</td>
</tr>
<tr>
<td>Shock</td>
<td>Method 516.6 (40 g RMS)</td>
</tr>
</tbody>
</table>
4.1.3. Trimble BD930 receiver

The Trimble BD930 GNSS receiver supports both triple frequency from the GPS and GLONASS constellations plus dual frequency from BeiDou and Galileo. As the numbers of satellites in the constellations grow the BD930 is ready to take advantage of the additional signals. This delivers the quickest and most reliable RTK initializations for 1–2 centimeter positioning. For applications that do not require centimeter accuracy the BD930 contains an advanced Kalman filter PVT engine that delivers high accuracy GNSS, DGNSS positions in the most challenging environments such as urban canyons. Different configurations of the module are available. These include everything from an autonomous GPS L1 unit all the way to a four constellation triple frequency RTK unit (Trimble, 2015).

With the latest Trimble-precise Maxwell™ 6 technology, the BD930 provides assurance of long-term future-proofing and trouble-free operation. Moving the industry forward, the Trimble BD930 redefines high-performance positioning:
• On-board multipath mitigation

• Proven low-elevation tracking technology

The receiver can be configured as an autonomous reference station (sometimes called a reference station) or as a rover receiver (sometimes called a mobile receiver). Streamed outputs from the receiver provide detailed information, including the time, position, heading, quality assurance (figure of merit) numbers, and the number of tracked satellites. The receiver also outputs a one pulse-per-second (1 PPS) strobe signal which lets remote devices precisely synchronize time. Designed for reliable operation in all environments, the receiver provides a positioning interface to an office computer, external processing device, or control system.

![Image of Trimble BD930 receiver and Trimble Zephyr antenna]

*Figure 4-4: Trimble BD930 receiver (left) with Trimble Zephyr antenna (right) (Trimble, 2015)*

The receiver has the following features:

• Position antenna based on a 220-channel Trimble Maxwell™ 6 chip:
  - GPS: L1 C/A, L2E, L2C, L5
  - BeiDou: B1, B2 I GLONASS: L1 and L2 C/A, L3 CDMA
  - Galileo: E1, E5A, E5B, E5AltBOC
  - QZSS: L1 C/A, L1 SAIF, L2C, L5
• SBAS: L1 C/A, L5

• Advanced Trimble Maxwell 6 Custom Survey GNSS Technology

• High precision multiple correlator for GNSS pseudorange measurements

• Unfiltered, unsmoothed pseudorange measurement data for low noise, low multipath error, low time domain correlation and high dynamic response

• Very low noise GNSS carrier phase measurements with < 1 mm precision in a 1 Hz bandwidth

• Proven Trimble low elevation tracking technology

*Table 4-6: Technical specifications—positioning and environmental*

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initialization time</td>
<td>Typically &lt; 10 seconds</td>
</tr>
<tr>
<td>Initialization accuracy</td>
<td>&gt;99.9%</td>
</tr>
<tr>
<td>Temperature</td>
<td>Operating: -40°C to 80°C (-40°F to 176°F)</td>
</tr>
<tr>
<td></td>
<td>Storage: -55°C to 85°C (-67°F to 185°F)</td>
</tr>
<tr>
<td>Vibration</td>
<td>MIL810F, tailored</td>
</tr>
<tr>
<td></td>
<td>Random 6.2 gRMS operating</td>
</tr>
<tr>
<td></td>
<td>Random 8 gRMS survival</td>
</tr>
<tr>
<td>Mechanical shock</td>
<td>MIL810D</td>
</tr>
<tr>
<td></td>
<td>+/- 40 g operating</td>
</tr>
<tr>
<td></td>
<td>+/- 75 g survival</td>
</tr>
<tr>
<td>Operating humidity</td>
<td>5% to 95% R.H. non-condensing, at +60°C (140°F)</td>
</tr>
</tbody>
</table>
### Table 4-7: Positioning specifications

<table>
<thead>
<tr>
<th>Mode</th>
<th>Accuracy</th>
<th>Latency (at max. output rate)</th>
<th>Maximum Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Baseline RTK (&lt;30 km)</td>
<td>0.008 m + 1 ppm horizontal 0.015 m + 1 ppm vertical</td>
<td>&lt;30 ms</td>
<td>20 Hz</td>
</tr>
<tr>
<td>DGSP</td>
<td>0.25 m + 1 ppm horizontal 0.5 m + 1 ppm vertical</td>
<td>&lt;20 ms</td>
<td>20 Hz</td>
</tr>
<tr>
<td>SBAS</td>
<td>0.5 m horizontal 0.85 m vertical</td>
<td>&lt;20 ms</td>
<td>20 Hz</td>
</tr>
</tbody>
</table>

### 4.2. Low cost GNSS receivers

Technology of low-cost single-frequency RTK (real time kinematic) is booming in popular GNSS application, however, the poor data quality and hardware performance of low-cost receivers bring about great challenges to its positioning algorithm.

Thanks to the small size, low price and easy-embedding, the low-cost GNSS receivers have great application markets. They can easily be embedded into mobile phones, smart vehicles or other portable positioning advices to provide PNT service. Moreover, low-cost RTK could also be applied in some traditional areas, such as geodetic monitoring, intelligent transport, precise farming and related location based service. Compared to the traditional survey-grade receivers, the low-cost receivers have obvious cost advantage. However, data of low-cost receivers usually have unsatisfactory quality owning to their poor hardware performance, for instance, frequent loss of lock, unpredictable data gap, less observations and low signal-to-noise ratio. Besides, most low-cost GNSS receivers only output single-frequency signals, which make it infeasible to eliminate the systematic errors and detect the cycle slips with combination of different frequencies. For low-cost GNSS receivers, above-mentioned limitations bring in great difficulties in high-precise positioning (Tianxia Liu, Bofeng Li, 2017).

Single-frequency receivers access the L1 frequency only. The single-frequency code receiver, is the cheapest and the least accurate type of receivers, also called low cost GNSS receiver.
measures the pseudoranges with the C/A code only. Single-frequency code and carrier receivers output the raw C/A-code pseudoranges, the L1 carrier phase measurements in addition to the navigation message. This is a major setback especially for removing ionosphere delays: since Iono free combination cannot be used, models or IGS products have to be considered. Moreover, multipath is another source of errors and its behavior is site dependent, therefore very difficult to deal with.

In this work different types of u-blox single-frequency receiver are used and that will be briefly explained in the next section of this chapter.

4.2.1. U-blox

U-blox is a Swiss company that creates wireless semiconductors and modules for consumer, automotive and industrial markets. They operate as a fabless IC and design house. Their wireless solutions connect machines, vehicles and people to locate their exact positions and communicate via short range (WI-FI, Bluetooth) or cellular networks. Using their portfolio of chips, modules or software solutions it’s possible to create subsystems and products to fulfill needs for the Internet of Things (IoT), M2M or Car2Car (or Vehicle to Vehicle) solutions quick and cost-effectively.

U-blox develops and sells chips and modules that support global satellite navigation systems (GNSS), including receivers for GPS, GLONASS, Galileo, BeiDou and QZSS. One of their products is described in following paragraph.

4.2.1.1. U-blox LEA-4T - receiver

The u-blox LEA-4T receiver supports precision GPS timing and raw measurement data for demanding positioning applications. It features a Time Mode function whereby the GPS receiver assumes a stationary 3D position, whether programmed manually or determined by an initial self-survey. Stationary operation enables GPS timing with only one visible satellite and eliminates
timing errors which otherwise result from positioning errors. The accuracy of the time pulse is as good as 50 ns, synchronized to GPS or UTC time. An accuracy of 15 ns is achievable by using the quantization error information to compensate the granularity of the time pulse. The built-in 2-channel time mark and counter unit provides precise time measurement of external interrupt signals. The u-blox LEA-4T receiver also supports raw measurement data (carrier phase with half-cycle ambiguity resolved, code phase and Doppler measurements), which can be used in external applications that offer precision positioning, real-time kinematics (RTK) and attitude sensing.

Main features:

- 16-channel ANTARIS®4 positioning engine
- Stationary mode for GPS timing operation
- 15 ns timing accuracy (error compensated)
- Single Satellite GPS timing
- 10 Hz raw measurement data output
- Supports SBAS: WAAS, EGNOS, MSAS

### 4.2.1.2. u-blox EVK NEO – 7P receiver

U-blox 7 receivers are designed to receive and track the L1C/A signals provided at 1575.42 MHz by the Global Positioning System (GPS). NEO-7P delivers the benefits of PPP carrier-phase tracking with GPS signals.

NEO-7P (Figure 4-5) is one of u-blox’ NEO-7 series of standalone GNSS modules benefiting from the exceptional performance of the u-blox 7 GNSS (GPS, GLONASS, QZSS and SBAS) engine. NEO-7P brings Precise Point Positioning (PPP) technology using GPS signal carrier-phase to maintain the precision of every individual fix without restricting user dynamics. NEO-7P is ideal
for portable, survey, agricultural, machine control, sports and leisure applications where clear-sky visibility enables continuous carrier-phase tracking.

The NEO-7 series provides maximum sensitivity while maintaining low system power. The NEO form factor allows easy migration from previous NEO generations. Sophisticated RF-architecture and interference suppression ensure maximum performance even in GNSS-hostile environments.

U-blox 7 receivers are designed to receive and track the L1C/A signals provided at 1575.42 MHz by the Global Positioning System (GPS). NEO-7P delivers the benefits of PPP carrier-phase tracking with GPS signals (u-blox 7 Precise Point Positioning GNSS module, 2017).

Figure 4-5: U-blox EVK NEO – 7P receiver and antenna (U-blox 7 Precise Point Positioning GNSS module, 2017)

Kit includes:

- Compact 105 x 64 x 26 mm EVK-7 unit
- USB cable
- Active GPS/GLONASS antenna with 3 m cable
- Quick Start reference card

Benefits of the U-blox EVK NEO – 7P receiver:
- High precision GNSS < 1 m
- DGPS by SBAS or RTCM
- Combines low power consumption and high sensitivity
- Simple integration with u-blox cellular modules
- Backward compatible with NEO-6 and NEO-5 families
- Raw measurement data (GPS).

U-blox EVK NEO – 7P supports raw data output at an update rate of 5 Hz and includes carrier phase, code phase and Doppler measurements. The receiver can be used with a PDA, smartphone, tablet or a notebook PC. It supports differential GPS operation, assisted-GNSS services and GLONASS data acquisition. The nominal accuracy quoted by the manufacturer is 2.5 m circular error probability (CEP) using GPS and 4 m CEP using GLONASS (U-blox 7 Precise Point Positioning GNSS module, 2017).

4.2.1.3. U-blox LEA-M8T – receiver

The NEO-M8T and LEA-M8T standalone concurrent GNSS modules are built on the experience of the u-blox M8 GNSS (GPS, GLONASS, BeiDou, QZSS, SBAS and Galileo-ready1) engine in the industry proven NEO and LEA form factors. The u-blox M8 series of modules offers high sensitivity and rapid acquisition in applications requiring low system power. The LEA-M8T module meets the requirements for GNSS timing applications (including fixed location, survey-in and RAIM). The module delivers multi-GNSS, raw measurement data (code and carrier phase, Doppler) and multi-GNSS, QZSS L1S and IMES message data. The LEA-M8T module offers easy
design migration from previous generations adding BeiDou and concurrent multi-GNSS capability to existing products. Sophisticated RF-architecture and interference suppression ensure maximum performance even in GNSS-hostile environments. The LEA-M8T includes a SAW filter and antenna power supervision and is perfect for use with active antennas or antenna signal distribution systems. Module include Flash memory for field upgrade if required. UART, SPI and DDC (I2 C compatible) interfaces provide connectivity and enable synergies with most u-blox cellular modules. U-blox M8 modules use GNSS chips qualified according to AEC-Q100, are manufactured in ISO/TS 16949 certified sites, and fully tested on a system level. Qualification tests are performed as stipulated in the ISO16750 standard: “Road vehicles – Environmental conditions and testing for electrical and electronic equipment”. u-blox’ AssistNow Assistance services supply aiding information, such as ephemerides, almanac and time, reducing the time to first fix significantly and improving acquisition sensitivity. The u-blox M8 generation extends validities of AssistNow Offline data (up to 35 days) and AssistNow Autonomous data (up to 6 days), providing the benefits of faster acquisition for longer durations since last use (LLC, 2018).

4.2.1.4. Potential of the u-blox receivers

U-blox M8 acquires and tracks two GNSS systems concurrently – default is GPS and GLONASS. Concurrent reception of GPS and BeiDou or even concurrent GLONASS and BeiDou reception can be selected on-the-fly. Optimized signal reception circuitry in combination with software algorithms and advanced tracking and search engines capitalize on the quality, and not only the quantity, of satellites used, providing optimal solutions in GNSS hostile environments. With market leading -167 dBm dynamic sensitivity, 1 second TTFF and 2-meter positioning accuracy, u-blox M8 is the perfect solution for performance critical applications like car navigation, drive
recorder or emergency call systems. For such applications, high performance is key. By utilizing
the new u-blox Multi GNSS AssistNow service and local satellite augmentation services (SBAS,
QZSS), u-blox M8 provides even more accurate position information within seconds - virtually
anywhere. u-blox M8 is the first mass produced stand-alone receiver to include BeiDou reception.
With the concurrent reception of GPS and BeiDou, a sensitivity of -165 dBm has been achieved,
making u-blox M8 the best performing GPS/BeiDou receiver on the market. All in all, u-blox M8
is the perfect choice for high performance positioning applications, bringing the increased
performance of concurrent GNSS reception to practical application. By applying an external SQI
flash, u-blox M8 is also future-proof, as firmware updates easily can be made, for example adding
Galileo when it becomes fully operational.
In case of less critical applications requirements where the important key parameters are low power
and low cost, u-blox 7 is the perfect answer. U-blox 7 is optimized for low-cost, low-power
applications where single GNSS reception is sufficient. U-blox 7 is one of the lowest power multi-
GNSS receiver platform on the market, particularly attractive for small battery powered devices
like asset and vehicle tracking boxes. In case of rural or suburban areas, the u-blox 7 single GNSS
reception is more than sufficient to provide accurate and reliable positioning information. u-blox
7 supports single reception of either GPS or GLONASS, selectable on start-up by command. (Nigg,
2014). Moreover, this receiver supports the output format NMEA, the standard for navigation
applications and the Radio Technical Commission for Maritime Services (RTCM) 2.3 standard.
This last protocol is a unidirectional protocol (input to the receiver) that is used to supply the GPS
receiver with real-time differential correction data (DGPS). The RTCM protocol specification is
4 messages are supported: type 1, 2, 3 and 9; if either message 1 or 9 is received, then the receiver will use the corrections delivered to provide a position estimate using the available satellites for which corrections are available.

*Table 4-8: Supported RTCM 2.3 messages types*

<table>
<thead>
<tr>
<th>Message type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Differential GPS corrections</td>
</tr>
<tr>
<td>2</td>
<td>Delta Differential GPS corrections</td>
</tr>
<tr>
<td>3</td>
<td>GPS Reference Station Parameters</td>
</tr>
<tr>
<td>9</td>
<td>GPS Partial Corrections Set</td>
</tr>
</tbody>
</table>

The DGPS feature does not need any configuration to work properly. When an RTCM stream is input on any of the communication interfaces, the data will be parsed and applied if possible, which will put the receiver into DGPS mode.

The following restrictions apply to DGPS mode:

- The DGPS solution will only include measurements from satellites for which DGPS corrections were provided. This is because the navigation algorithms cannot mix corrected with uncorrected measurements.
- SBAS corrections will not be applied when using RTCM correction data.
- Precise Point Positioning will be deactivated when using RTCM correction data.
- RTCM correction data cannot be applied when using Assist Now Offline or Assist Now Autonomous (Cătălin, 2015).

*4.2.1.5. Challenges of the u-blox receiver*

As high sensitivity type of the receivers, u-blox is capable of tracking signals close to -160 dBm which means that even the attenuated and reflected signals (multipath) are used and proper mitigation techniques become critical. In addition, being a single frequency receiver u-blox performance can be greatly influenced by ionosphere delays.
First challenge is related to the multipath (explained in Chapter 3). U-blox 7P platform was used in one of the experiments. This cannot track at the same time two or more satellite systems. Therefore, multipath errors will be more significant than in the case of concurrent GPS and GLONASS acquisition. However, the latest model from u-blox, the eight generation positioning platform 8M, used in other experiment, allow the user to enable in the tracking configuration 2 satellite systems: GPS and GLONASS or BeiDou or GLONASS and BeiDou. Although having more satellites in view is of great help in the processing mode, concurrent tracking of more systems is not enough. There are few methods that can be applied in the field for reducing the influence of multipath on the data. Some of this spatial mitigation techniques required the use of a special antennas (such as the choke-ring type), multi-antennas arrays, antenna location strategy and ground plane.

Second challenge is due to ionosphere delays (see Chapter 3). U-blox receivers, as all the other low cost devices, are single frequency and only L1 raw measurements are available hence the iono-free combination of L1 and L2 carrier is not possible. However, as aforesaid there are options for reducing the influence of the ionosphere: most processing software have ionospheric models implemented, Klobuchar is the most popular one by far, or they read and apply in processing IONEX grids from the International GPS Service for Geodynamics (IGS) or products from the Center for Orbit Determination in Europe (CODE) that illustrates the geographic variation of TEC. Both IGS and CODE offer to user ionosphere maps on daily basis and free of cost. However, u-blox EVK-7P offers another way of modelling more accurate the ionosphere: this receiver is capable of tracking 3 SBAS satellites and therefore can take advantage of the ionospheric corrections sent by this augmentation system (Cătălin, 2015).
4.3. Virtual reference station (VRS)

Recent developments in differential GPS (DGPS) services have concentrated mainly on the reduction of the number of permanent reference stations required to cover a certain area and the extension of the possible ranges between reference and rover stations. Starting from networked DGPS stations where all stations are linked to a central control station for data correction and modeling, the most advanced technique nowadays is based on the virtual reference station (VRS) network concept. In this case, observation data for a non-existing “virtual” station are generated at the control center and transmitted to the rover (Retscher, 2002).

To reach a centimeter level – or even better – accuracy of positioning typically requires use of precise dual frequency carrier phase observations. Furthermore, these observations are usually processed using differential GNSS (DGNSS) algorithm. However, implicit in the process is an assumption that the quality of the reference station data is consistent with the desired level of positioning accuracy.

4.3.1. Virtual reference station network concept (Kislig, 2011)

The virtual reference station (VRS) concept can help to satisfy this requirement using a network of reference stations. As a quick review, a typical DGNSS setup consists of a single reference station from which the raw data (or corrections) are sent to the rover receiver (i.e., user). The user then forms the carrier phase differences (or corrects their raw data) and performs the data processing using the differential corrections.

In contrast, GNSS network architectures often make use of multiple reference stations. This approach allows a more precise modeling of distance-dependent systematic errors, principally caused by ionospheric and tropospheric refractions and satellite orbit errors. More specifically, a
GNSS network decreases the dependence of the error budget on the distance of nearest antenna. The general concept of network based processing (example of AGNES) is shown in Figure 4-6.

![Figure 4-6: GNSS network concept concluding VRS (Kislig, 2011)](image)

The network of receivers is linked to a computation center, and each station contributes its raw data to help create network-wide models of the distance-dependent errors. The computation of error based on the full network's carrier phase measurement involves, first of all, the resolution of carrier phase ambiguities and requires knowledge of the reference station positions.

At the same time the rover calculates its approximate position and transmits this information to the computation server, for example, via GSM or GPRS using a standard National Marine Electronics Association (NMEA) format. The computation center generates in real time a virtual reference station at or near the initial rover position. This is done by geometrically translating the pseudorange and carrier phase data to the virtual location and the adding the interpolated errors from the network error models.
This generated VRS data is then sent to the user through a wireless connection, often using the Networked Transport of RTCM via Internet Protocol (NTRIP). Finally, just as if the VRS data had come from a physical reference station, the rover receiver uses standard single-baseline algorithms to determine the coordinates of the user's receiver, in near-real-time kinematic or post processed modes.

The main purpose of a VRS station is to reduce the baseline distance between the rover and the reference station in order to efficiently remove spatially correlated errors using differential processing and to incorporate error corrections obtained from the reference stations network. To this end, the position of the VRS plays a critical role. In particular, because the user receiver cannot, by design, distinguish a real reference station and a VRS, the distance of the VRS from the user must be commensurate with the level of errors present in the VRS data. This is what allows the receiver to use its standard data processing algorithms, which vary as a function of the baseline length (i.e., distance) to the reference station.

Example: Assume the user receiver performs L1-only processing for baselines up to 8 km and wide-lane dual-frequency (L1/L2) combinations for longer baselines. If the errors in the VRS data were similar to a 20-kilometer baseline, but the VRS position was situated only 2 kilometers from the user. In this case, the user's receiver would attempt to use L1-only processing, but the level of errors in the data would almost certainly not allow reliable results using this approach. From this example, it can be seen that the VRS concept basically needs the resource of a physical GNSS network surrounding the measurement area of the rover, with a minimum of three reference stations to enable the modelling of errors. However, the estimation accuracy increases as more physical reference stations are added to the network, especially as the number of stations exceeds five at which point the increased redundancy and improved network geometry provide more
accurate error modeling. To conduct a survey employing a VRS network, the physical stations themselves must be installed over stable sites, preferably distributed homogenously over the operational area. If possible, the antennas must be fixed in bedrock to ensure long term stability of the receiver's position.

As an example, Figure 4-7 shows and Automated GNSS Network for region of Piedmont and Lombardy in Italy (SPIN GNSS). GNSS Lombardy is established in 2005 (convention between the Lombardy Region, IREALP and Politecnico di Milano) and was the first Public GNSS network in Italy. Piedmont GNSS was launched in 2011 (project by Region of Piedmont, CSI Piedmont and Politecnico di Torino).

![GNSS Network Map](https://www.spingnss.it)

*Figure 4-7: The GNSS Network of the Lombardy and the Piedmont region ([https://www.spingnss.it](https://www.spingnss.it))*

There are 30 GNSS permanent stations with dual-frequency GPS/GLONASS receivers covering the 49,263 km² surface area with free access to all the services. SPIN GNSS generate VRS solution for whole Lombardy and Piedmont.
To create the virtual reference station data for a certain GPS rover station, the user receiver’s approximate location accurate to about 100 m is transmitted to the network control center (Figure 4-9). As a result, a bi-directional communication link between the user and the control center is required.

Figure 4-9: Estimation of Virtual Reference Station (https://water.usgs.gov)
4.3.2. Challenges of the VRS

Although the VRS approach generally provides an overall improvement relative to single reference station systems, it poses some challenges.

First is dependence of the VRS service on a communication system, such as the mobile phone network. Moreover, this technique requires a bi-directional communicational link between the receiver and the computation center, because the rover has to send information about its current position and has to receive the VRS data. This telecommunication link must provide high bandwidth communication between all the elements of system: the reference station, the master control center and the user receiver.

A second challenge is that errors can be generated by different tropospheric and stratospheric models applied between the computation center and the rover. The initial position provided by the rover to generate the VRS data is not usually precise, especially in height, the troposphere error computed by the network will not be perfect, with every 10 meters of initial height error yielding up to 0.2 mm of error from the troposphere model. Fortunately, obtaining a 10-meter height error is quite reasonable in most application involving carrier phase data, meaning the resulting troposphere modeling errors will usually be small.
5. RESEARCH APPROACH

To assess the feasibility of the low-cost GPS receivers for the monitoring applications, their accuracy and limitations need to be identified. This work extensively investigates the performance of the low-cost single-frequency GPS receivers (see in Chapter 4) for static conditions.

This chapter describes used instrumentation and the experiment setup to evaluate the positioning accuracy using low cost GNSS receivers and to compare the processed data using two different software packages.

Three static tests, Milano Test, Como Test and Lomazzo Test have been set and processed data have been used to see the possible application of using low-cost single-frequency receivers for local monitoring in different operational conditions. Relative static processing is typically used in monitoring activities through evaluating positioning accuracy using different low cost GNSS receivers.

5.1. Instrumentation

The main instrumentation used in the experiments includes:

- 1 geodetic Topcon receiver with Antenna type: TPSCR3_GGD CONE (Milano Test)
- 1 geodetic Topcon receiver (see Chapter 4) - EUREF Permanent Station – COMO, with Antenna type: TPSCR3_GGD CONE (Como Test)
- 1 geodetic Leica receiver (see Chapter 4) with Antenna type: Leica AX1202GG (Como Test)
- 1 geodetic Trimble BD930 receiver (see Chapter 4) with Antenna type: Trimble Zephyr (Lomazzo Test)
• 3 u-blox modules of different generation (LEA-4T with default antenna for Milano Test, NEO-7P with default antenna for Como Test and LEA-M8T with Tallysman TW3470 antenna for Lomazzo test)

• Virtual Reference Station (see Chapter 4, Lomazzo test)

5.2. Software packages

In this work data are processed using different software packages. Author had aim to compare a commercial integrated Office Software - Leica Geo Office with an open source program package for standard and precise positioning with GNSS – RTKLIB. Main goal of this work is to determine accuracy of using low cost GNSS receivers for local monitoring purpose under different operational conditions, but also to check data accuracy, when data are being processed with an open source program as RTKLIB.

5.2.1. Leica Geo Office

Leica Geo Office (LGO) is a software produced by Leica Geosystems, a Switzerland enterprise that produces instruments for surveying and measurement and the relative software to process the data acquired. LGO is dedicated to process data from GNSS survey and is able to handle many different processing scenarios: static, rapid static, stop-and-go, kinematic. It can process data from multi constellations, GPS, Glonass and Galileo and can process both single frequency and dual frequency data. Many tools to import data from different formats (for example raw data, cad and GIS data), to export data and create report are available (Negretti, 2013/2016). In this thesis the version 8.3 was used to process data from GNSS receivers, both single and double frequency, using the double differences observations. The first step is data organization, i.e., project creation. LGO differs a lot from other software packages in the means of data organization, visual interpretation, and the logic of data processing
itself. After the program start, the user creates the project and gives it a name. After that, a new window is opened, where the user sets the parameters related to the project itself. It is possible to edit the parameters later, during the GPS data processing.

The next step is import and set of the project files. The LGO working desktop is divided into a number of tabs. The most important tabs for GPS measurements processing are: View/Edit, GPS-Proc, Adjustment, Points, Antennas, and Results. View/Edit is dedicated to graphical display of the data. To process the vector, the user has to switch to GPS-Proc tab, where all vectors within their sessions are present (see Figure 5-1).

Table 5-1: Interface of the GPS Processing tab with all vectors presented within their sessions

A new drop-down list GPS Process occurs, offering the options such as Processing Mode and Processing Parameters. Processing Mode offers automatically vector processing, as well as, interactive processing, where the user chooses a reference station and a rover. After processing the baselines, the user enters the necessary parameters within the option Processing Mode. This option
opens a window consisting of several tabs. After the baseline processing is completed, the program displays the dialog Results, with the data of all processed vectors. Selecting all or a subset of the baselines, a new dialog Store appears, allowing the user to save the processed data.

5.2.2. RTKLIB

RTKLIB is an open source program package for standard and precise positioning with GNSS (global navigation satellite system). It is developed by Mr. Tomoji Takasu of the Tokyo University of Marine Science and Technology.

RTKLIB consists of a portable program library and several APs (application programs) utilizing the library.

The features of RTKLIB are (T.Takasu, 2018):

- It supports standard and precise positioning algorithms with: GPS, GLONASS, Galileo, QZSS, BeiDou and SBAS
- It supports various positioning modes with GNSS for both real-time and post-processing: single, DGPS/DGNSS, Kinematic, Static, Moving-Baseline, Fixed, PPP-Kinematic, PPP-Static and PPP-Fixed
- It supports many standard formats and protocols for GNSS: RINEX 2.10, 2.11, 2.12 OBS/NAV/GNAV/HNAV/LNAV/QNAV, RINEX 3.00, 3.01, 3.02 OBS/NAV, RINEX 3.02 CLK, RTCM ver.2.3, RTCM ver.3.1 (with amendment 1-5), ver.3.2, BINEX, NTRIP 1.0, RTCA/DO-229C, NMEA 0183, SP3-c, ANTEX 1.4, IONEX 1.0, NGS PCV and EMS 2.0 (refer the Manual for details)
- It supports several GNSS receivers' proprietary messages: NovAtel: OEM4/V/6, OEM3, OEMStar, Superstar II, Hemisphere: Eclipse, Crescent, u-blox: LEA-4T/5T/6T,
SkyTraq: S1315F, JAVAD: GRIL/GREIS, Furuno: GW-10 II/III and NVS NV08C

- It supports external communication via: Serial, TCP/IP, NTRIP, local log file (record and playback) and FTP/HTTP (automatic download)

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**Figure 5-1: RTKLIB Applications (http://www.rtklib.com)**

In this work author used RTKPOST application for data processing.

### 5.2.2.1. RTKPOST

RTKPOST is a post-processing application that computes positioning solutions by various modes including single-point, DGNSS, kinematic, static and PPP.

- Static Post-Processing (RTKPOST)

The static positioning mode processes a baseline between a known reference point (base) and a static antenna (rover). It requires:

- Reference station data with known coordinates
- Precise satellite orbits
• Antenna information

Figure 5-2: Static Post Processing (function of the RTKLIB software)

5.3. Experiment set up

To test the performance of the low-cost single-frequency GPS receivers for local monitoring, different operational conditions were set. In total, three experiments were performed in three different locations, Milano, Como and Lomazzo. Experiments are used to estimate accuracies provided by different GPS units by recording data over an extended period of time. A time window of 15 - 60 minutes should be correct for applications of local monitoring, for example landslides, and it was decided to work with hourly sessions, because this length of the sessions allowed a high number of available observations under any conditions.

Problems due to the use of low cost antennas are expected, in particular regarding a more sensibility to multipath and there is no availability of information about the Phase Center Variation (PCV). To perform experiments and test the reliability, utility and accuracy of results, for the purpose of low cost monitoring, different u-blox receivers were used with respect to different
referent stations. All experiments were held under static conditions. Static GPS survey procedures allow various systematic errors to be resolved when high accuracy positioning is required. The field procedure of relative static survey is performed by placing a receiver on a known point and the second receiver on an unknown point. Data are collected simultaneously from at least four satellites. Experiments were carried out to assess the variation in the static measurements over the certain time and the possibility of using DGPS concept with a low-cost single-frequency receiver for application of monitoring, with cm level of accuracy. In the next sections of this chapter each experiment will be explained.

5.3.1. Milano test

The test has been set in Milano in period from 9-Feb 2014 to 18-Feb 2014 (from GPS day 040 to GPS day 049) on the roof of the Department of Architecture building (Politecnico di Milano) in via Edoardo Bonardi 9 (see Figure 5-3).

First task of this experiment is a general assessment of the processing of a geodetic-low cost baseline. The comparison of the two GNSS processing packages was a secondary task. The chosen software programs were Leica Geo Office Version 8.3 and RTKLIB. More about processing data will be explained in the next chapter.

Surveyor used two different GNSS receivers to make this experiment: Geodetic receiver (Topcon) – Milano Permanent Station and u-blox receiver (LEA-4T).

Estimated baseline (approximately 64 m length), formed with a geodetic receiver (Milano Permanent station) as a reference station and the u-blox receiver LEA-4T as a rover, is represented on a Figure 5-3 (black line).
5.3.2. Como Test

Experiment site is set in Como Campus, Politecnico di Milano. First task of this experiment is to compare two similar baselines, one geodetic – geodetic and the other geodetic – u-blox. Second task is based on processing collected data using two different softwares (already mentioned in Milano Test) and comparing obtained results.

Since Como is surrounded with mountains, instruments are set on the roof of two buildings (Valleggio building and Castelnuovo building Figure 5-5), to avoid problems of visibility of low elevation satellites. Considering the multipath effect, quality of signal is better if it is placed at a higher position. Different GNSS receivers were used to perform this experiment: EUREF Permanent Station – COMO EPS (COMO) (see Figure 5-4), one u-blox receiver and one geodetic receiver (described in Chapter 4 and can be seen on Figure 4-2 and Figure 4-5 ).
Figure 5-4: TOPCON CR.G3 antenna with TPSH dome

EUREF Permanent Station and the u-blox receiver were set on the roof of the Valleggio building and Geodetic receiver with antenna were set on the roof of the Castelnuovo building. Together, they simulate a local geodetic network (see Figure 5-5).

Relative static positioning is done in period from 26-Jan 2016 to 19-Feb 2016 (from GPS day 026 to GPS day 049) with COMO as a reference station and the u-blox receiver as a rover. Measurements between COMO as a reference station and Como geodetic receiver as a rover (geodetic - geodetic measurements) and Como geodetic receiver as a reference station and u-blox receiver as a rover (geodetic - u-blox measurements) are both done in the period from 28-Jan 2016 to 19-Feb 2016 (in period from GPS day 28 and GPS day 49), for one week of data acquisition (check in Table 5-2)

Table 5-2: Table of available days for data acquisition

| AVAILABLE DAYS | 28.1. | 29.1. | 8.2. | 9.2. | 10.2. | 18.2. | 19.2. |
Figure 5-5: Location of experiment site (Como Test) and estimated baselines (black lines)

Tracking configuration on u-blox side was following:

- static mode,
- used only GPS satellites,
- elevation mask 15°,
- sampling rate of 1 Hz

Tracking configuration was slightly different for geodetic receivers since they can track more signals and not only GPS satellite constellations. The GNSS receivers are dual-frequency with the sampling rate of up to 10 Hz respectively 50 Hz. They are capable of tracking in the same time more than one satellite constellations, provided an appropriate license is installed. Geodetic receivers are capable of acting as reference stations: they can send corrections to users using the well-known standards RTCM and NMEA (for real time positioning) or their raw data can be used in post-processing for baselines estimation. For short baselines an accuracy of few millimeters can be obtained with GNSS receivers (Leica GRX1200).
However, in processing part only L1 code and phase of GPS constellation will be used in order to make more realistic comparison with the u-blox receiver, which is a single-frequency receiver. A geodetic antenna Leica AX1202GG, set on the roof of the Castelnuovo building, was used to reduce multipath error, which is one of the main error sources for the GNSS stations. Last step, the PC, which acts as the main power source and server for u-blox receiver, was placed and locked inside the rack to protect it against the elements and other unpleasant situations. (Figure 5-6).

![Logical scheme of instrumentation set-up: the u-blox receiver and its antenna (upper left corner), Leica GRX1200 (bottom right corner), the PC server and the special cage that protects the server.](image)

The obtained data set is relevant to the three baselines, one short baseline (approximately 7 m between COMO and u-blox receiver, see Figure 5-5), and two longer baselines (approximately 130 m between Como geodetic receiver and u-blox receiver and approximately 120 m between COMO and Como geodetic receiver, see Figure 5-5).
5.3.3. Lomazzo Test

The last test is set in Lomazzo in period from 12-Aug 2017 to 21-Aug 2017 (from GPS day 224 to GPS day 233) on the roof of the Como NEXT building, Via Cavour. Main task of this experiment was to see the difference in accuracy of estimating same baseline with two different reference stations, VRS and geodetic receiver. Second task is the same as in previous tests, processing with two different softwares and its comparison.

Surveyor used two different GNSS receivers to make this experiment: Geodetic receiver (Trimble BD930) and u-blox receiver (LEA-M8T).

![Location of site and estimated baseline (black line)](image)

Estimated baseline (short baseline, approximately 1.5 m) formed with a geodetic receiver – as a reference station and an u-blox receiver as a rover, is presented on Figure 5-7 (black line). As already mentioned at the beginning of this chapter, Virtual Reference Station (VRS) is used as a reference station to estimate baseline where same u-blox receiver is used as a rover.
6. DATA PROCESSING AND RESULTS DISCUSSION

This chapter will be divided in three sections corresponding to the experiments already mentioned in Chapter 5. First experiment (Milano Test), presented in the first section, is based on the estimation of the baseline between u-blox receiver and the geodetic receiver. Data is processed and results are obtained using two software packages. Next section contains results collected in Como Test, performance of the low cost GNSS receiver is tested through different measurements. Data is processed for the baselines between Como EUREF Permanent Station (COMO) and u-blox receiver, Como EUREF Permanent Station and geodetic receiver and geodetic receiver and u-blox receiver. In the last part of this chapter, Lomazzo Test is presented where data are collected between geodetic receiver and u-blox receiver and in the second part of this experiment, Virtual Reference Station is used instead of geodetic receiver to estimate the baseline with respect to the u-blox receiver.

While processing raw data, collected with GNSS relative static measurements, two types of software programs are used. One of them is Leica Geo Office, commercial software and other one is RTKLIB, so called FOSS\textsuperscript{5} software. Author made comparison among them using results obtained with baseline processing.

6.1. Milano Test

The first data set, set up on the roof of the Department of Architecture building (Politecnico di Milano), was collected in a period from 9-Feb 2014 to 18-Feb 2014 (from GPS day 040 to GPS day 049) using two receivers: Milano Permanent Station - geodetic receiver (Topcon) and u-blox

\textsuperscript{5} FOSS - Free and open-source software
receiver (LEA-4T) at a sampling interval of 1 second. The overall procedure will be presented in the next part of this section.

**Figure 6-1: Flow diagram of the overall procedure applied in Milano Test**

### 6.1.1. Data preprocessing – Milano Test

In this section data are 'cleaned' through certain procedure called preprocessing. In the preprocessing phase different actions can be done, due to:

- GPS observation files, site database, Earth rotation data, satellite ephemerides, surface meteorological data, water vapor radiometer data
- formatting
- tools (satellite removal, data windowing, concatenation, etc.)
- editing (detecting and removing outliers and cycle slips)
• thinning (data decimation, data smoothing)

• data transformation (double differencing, ionosphere-free combination, etc.)

• ambiguity initialization (and possible resolution) (Springer-Verlag, 1998).

In this test author has been concerned to convert u-blox raw data stored in .ubx format to RINEX format. RINEX (Receiver Independent Exchange Format) is a data interchange format for raw satellite navigation system data which allows user to post-process the received data in different softwares. To make this conversion, author used RTKCONV, function of the RTKLIB software (see on Figure 6-2). The raw observation data acquired by u-blox is continuous and it can be divided into hourly sessions data by using RTKCONV function. Author is free to choose what to show in so called RINEX header (see Figure 6-3) such as receiver type, antenna type, approximate position, which observations should be written: only GPS or mixed file, which of the signals (L1, L2, L5 and so on) and for each signal the observation type (code with/without phase). Even though u-blox receiver is a single frequency receiver (see Chapter 4), code and phase observation are stored in the output file.

![Figure 6-2: Interface of the RTKCONV function of the RTKLIB software](image)
After data being converted, next step is the estimation of the coordinate of u-blox receiver which will be explained in the next section. The GPS processing technique for this research is the relative static positioning. The principle of this technique is based on the determination of baseline between the reference point and the receiver. Relative static positioning by double differencing the carrier phase observations is mostly used as it can achieve accuracy at sub-centimeter level.

### 6.1.2. Data processing – Milano Test

In data processing, Milano Permanent Station (MPN) is used as reference, with the known coordinates downloaded from the GNSS positioning service portal of Piedmont Region and Lombardy Region (see Figure 6-4).
The data were first processed using LGO software and then using RTKLIB software.

### 6.1.2.1. Data processing and results with Leica Geo Office 8.3

After data conversion into RINEX file, data processing with LGO is fast and automatic. First step is to create a project where data will be assigned (see Figure 6-5: User interface of LGO software).
After data being imported, there are parameters to be chosen.

Figure 6-6: Processing parameters of LGO, Relative Static positioning
After data assignment, setting parameters and setting reference station (MPN), next step is estimation of the coordinates of the u-blox receiver. The daily RINEX files were decimated into hourly files and the 3-D coordinates of the u-blox were computed for each of these hourly files. In total, 240 hourly sessions have been obtained. After processing 240 sessions, there were two suspicious sessions. Those results were detected as outliers. Therefore, the meaning of outlier must be defined. It is called outlier a data point that is different from the rest of data set. To detect and confirm an outlier, statistic tests are performed. In this thesis, author decided to consider a threshold of 2 cm for the outlier detection, based on expected accuracy of low-cost GNSS sensors, on accuracy required by local monitoring and lack of antenna calibration procedure. In case when outliers cannot be fixed, they are eliminated from data set. Moreover, the meaning of fixing outliers must be defined. Fixing of outliers presents finding an approach to correct data points which are detected as outliers. After outliers are fixed (corrected) they can be part of further analysis of data set. In other case, outliers should be removed (eliminated) from data set.
Author focused on the satellite visibility, while trying to fix outliers. Since satellites have problems at low elevations, for correction of outliers two different approaches were tested:

1) Excluding one of satellites (detected as a suspicious in LGO report file)
2) Changing a cut-off angle

First approach, excluding one of suspicious satellites for marked sessions, gives a good result with a high percentage of the ambiguity fixing (see on Figure 6-8). For this reason, first approach is used for fixing detected outliers.

Table 6-1: Detected sessions and its influence in the final 3-D position

<table>
<thead>
<tr>
<th>SESSION</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>-0.44</td>
<td>4.82</td>
<td>-39.78</td>
</tr>
<tr>
<td>60</td>
<td>-5.94</td>
<td>5.62</td>
<td>-31.68</td>
</tr>
</tbody>
</table>

*Figure 6-8: Removing outliers by removing one of suspicious satellites (left), ambiguity statistics (right)*

By using second approach, increasing cut-off angle (from 15° to 20°), solutions were good (in term of coordinates), but with a few ambiguity fixing (see on Figure 6-9, right photo).
Next table shows sessions where outliers are detected together with suspicious satellites, that were removed in processing.

Table 6-2: Sessions with outliers and suspicious satellites

<table>
<thead>
<tr>
<th>SESSION</th>
<th>SATELLITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>G01</td>
</tr>
<tr>
<td>60</td>
<td>G21</td>
</tr>
</tbody>
</table>

Difference in coordinates (given in UTM) between detected outliers and corrected ones in cm is shown in Table 6-3.

Table 6-3: Fixing outliers with respect to removing suspicious satellites (see Table 6-1)

<table>
<thead>
<tr>
<th>SESSION</th>
<th>detected outliers (do)</th>
<th>corrected outliers (co)</th>
<th>difference (do-co)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N [m]</td>
<td>E [m]</td>
<td>h [m]</td>
</tr>
<tr>
<td>36</td>
<td>5036253.311</td>
<td>517879.848</td>
<td>193.410</td>
</tr>
<tr>
<td>60</td>
<td>5036253.302</td>
<td>517879.846</td>
<td>193.409</td>
</tr>
</tbody>
</table>

After this corrections, the reference value of the baseline is estimated and the coordinates of the u-blox receiver are calculated. Average value of the u-blox coordinates from all sessions is used to calculate residuals and verify the accuracy of the results. Results are presented in following tables.
Table 6-4: Estimated coordinates of the u-blox receiver and coordinates of Milano Permanent Station obtained from https://www.spingnss.it/spiderweb/frmIndex.aspx

<table>
<thead>
<tr>
<th>STATION</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILANO PERMANENT STATION</td>
<td>4421849.890</td>
<td>718507.406</td>
<td>4525043.324</td>
<td>5036298.545</td>
<td>517924.013</td>
<td>187.266</td>
</tr>
<tr>
<td>U-BLOX RECEIVER</td>
<td>4421893.008</td>
<td>718469.522</td>
<td>4525016.029</td>
<td>5036253.290</td>
<td>517879.835</td>
<td>193.385</td>
</tr>
</tbody>
</table>

Table 6-5: Statistics of estimated coordinates of the u-blox receiver in term of residuals (LGO)

<table>
<thead>
<tr>
<th>Basic statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>MAX</td>
<td>0.6</td>
<td>0.5</td>
<td>2.2</td>
</tr>
<tr>
<td>MIN</td>
<td>-0.9</td>
<td>-1.0</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

It can be seen from Table 6-5, that STDEV in all components is below 1 cm. Results obtained by LGO processing have achieved accuracy at sub-centimeter level, therefore they are reliable for purpose of local monitoring.

**LGO PROCESSING RESULT ANALYSIS:**

Graphical representations of the residuals for each 3-D coordinate of the u-blox receiver will be shown in graphs below.
Figure 6-10: Residuals in the North direction, 1 hourly sessions, static method

Figure 6-11: Residuals in the East direction, 1 hourly sessions, static method
6.1.2.2. Data processing and results with RTKLIB

Before processing data using RTKPOST, as a function of RTKLIB software, some parameters should be set according to the positioning technique. It can be seen on Figure 6-13. Using RTKPOST function of RTKLIB software, author realized that RTKPOST function does not take into account phase center of geodetic receiver antenna and u–blox antenna in processing height. Author had to add those values manually, reading from the RINEX files.
After processing data using RTKPOST function, 9 outliers are detected. Outliers in a form of residuals are listed in a table below.

Table 6-6: Outliers detected using RTKPOST processing

<table>
<thead>
<tr>
<th>Session</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>-0.3</td>
<td>-15.7</td>
<td>4.5</td>
</tr>
<tr>
<td>49</td>
<td>11.1</td>
<td>-6.4</td>
<td>-29.2</td>
</tr>
<tr>
<td>73</td>
<td>-1.8</td>
<td>-12.6</td>
<td>-7.1</td>
</tr>
<tr>
<td>97</td>
<td>3.7</td>
<td>-17.2</td>
<td>-21.0</td>
</tr>
<tr>
<td>121</td>
<td>1.1</td>
<td>0.7</td>
<td>-13.7</td>
</tr>
<tr>
<td>145</td>
<td>-3.7</td>
<td>6.1</td>
<td>-22.8</td>
</tr>
<tr>
<td>169</td>
<td>-19.1</td>
<td>26.3</td>
<td>10.9</td>
</tr>
<tr>
<td>193</td>
<td>-6.6</td>
<td>23.8</td>
<td>-22.2</td>
</tr>
<tr>
<td>217</td>
<td>-17.0</td>
<td>-2.2</td>
<td>-2.4</td>
</tr>
</tbody>
</table>

Author was not able to fix outliers as in LGO software, since in RTKLIB it is not possible to remove some of satellites as in LGO and with increasing of cut-off angle, ambiguities were not fixed. Hence, in next part of this section results and graphs will be presented without outliers.
Table 6-7: Statistics of estimated coordinates of the u-blox receiver in terms of residuals (RTKLIB)

<table>
<thead>
<tr>
<th>Basic statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>MAX</td>
<td>-0.1</td>
<td>-0.6</td>
<td>-0.4</td>
</tr>
<tr>
<td>MIN</td>
<td>0.6</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Residuals are calculated with respect to reference coordinates obtained by the LGO average. In the Table 6-7 it is shown that without outliers and after fixing height (taking into account correction for the phase center of the u-blox antenna in all sessions), results are below 1 cm.

RTKLIB PROCESSING RESULT ANALYSIS:

Graphical representations of the residuals for each 3-D coordinate will be shown in graphs below.

![Residuals in the NORTH direction [mm] for u-blox receiver](RTKLIB)

Figure 6-14: Residuals in the North direction, 1 hourly sessions, static method
Figure 6-15: Residuals in the East direction, 1 hourly sessions, static method

Figure 6-16: Residuals in the Height, 1 hourly sessions, static method
Objective of this experiment is also to compare processing baseline, geodetic – u-blox, with two different softwares. Baseline is estimated with respect to both softwares (see results in Table 6-8).

*Table 6-8: Estimated baseline (MPN - u-blox receiver) with LGO and RTKLIB*

<table>
<thead>
<tr>
<th>SOFTWARE</th>
<th>BASELINE [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGO</td>
<td>63.556</td>
</tr>
<tr>
<td>RTK</td>
<td>63.556</td>
</tr>
</tbody>
</table>

| difference in [mm] | -0.229 |

Difference in the baseline estimation using different softwares is in mm range.

Next table shows difference between coordinates, calculated as an average value of coordinates from all sessions, of the u-blox using LGO and RTKLIB.

*Table 6-9: Coordinates of the u-blox receiver (LGO and RTKLIB)*

<table>
<thead>
<tr>
<th>SOFTWARE</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGO</td>
<td>5036253.283</td>
<td>517879.853</td>
<td>193.382</td>
</tr>
<tr>
<td>RTK</td>
<td>5036253.282</td>
<td>517879.853</td>
<td>193.284</td>
</tr>
</tbody>
</table>

| difference in [mm] | 1.0  | 0.2  | 7.0  |

Coordinates are estimated with both softwares and their difference is in mm level. Even though outliers could not be fixed, RTKLIB is shown as successful in data processing, since less than 5% (9 outliers within 240 sessions) of data were outliers.

To conclude the work of this experiment, a comparison had to be made between the results obtained with both software packages. In the following pictures with graphs a comparison with respect to North, East and Height component is presented:
Figure 6-17: Residuals in the North direction, 1 hourly sessions, static method (LGO and RTKLIB)

Figure 6-18: Residuals in the East direction, 1 hourly sessions, static method (LGO and RTKLIB)
From graphs above it can be seen that LGO was able to fix detected outliers, while RTKLIB had problems with fixing it (outliers are just excluded from further processing). Therefore, after outlier removal, residuals from LGO are higher compared to the residuals obtained by RTKLIB processing (it is seen on Figure 6-17, Figure 6-18 and Figure 6-19), but still at the sub-centimeter level of accuracy.

6.2. Como Test

Como Test is set up on the roof of two buildings, Valleggio and Castelnuovo building in the Como Campus, Politecnico di Milano. Data acquisition is performed in a period from 26-Jan 2016 to 19-Feb 2016. Processing is done by the hourly and daily sessions. In the following part overall procedure for Como Test is presented (see Figure 6-20). Data acquisition has already been explained in the Chapter 5.
6.2.1. Data preprocessing – Como Test

Procedure is the same as for the Milano Test. In the first step, data in .ubx format are converted into RINEX format. To obtain this conversion, RTKCONV, as a function of RTKLIB software, is used (see Figure 6-2 in Milano Test). After data being converted, second step is estimation of the coordinates of the u-blox receiver by the processing of the baseline between geodetic and u-blox receivers.
6.2.2. Data processing – Como Test

In data processing, Como EUREF Permanent Station is used as reference, with known coordinates downloaded from EUREF Permanent GNSS Network (Figure 6-21).

\[ \text{Current station configuration: como_20170207.log (current) \ View} \]

COM000ITA is operated by DICA and Integrated in the EPN since 11-04-2004.
RECEIVER: TPS NET-GS
ANTENNA: TPS/RG, G3 TPSH
SET TO TRACK: GPS+GLO
INDIVIDUAL CALIBRATION: YES (show calibrations)
Data routinely analysed by ASI, BEK, IGN, UPA.

Data Provided

RINEX Data Quality

Position, Velocity & Time Series

\[ \text{COM000ITA (Class A station)} \]

Last position valid from 04/2017 to 31/2017
expressed at epoch 001/2019

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>4398306.557 m</td>
<td>704149.609 m</td>
<td>4550154.455 m</td>
</tr>
</tbody>
</table>

\[ \text{ESRIN (ETRF2000) position & velocity} \]

Figure 6-21: Como EUREF Permanent Station (downloaded from: http://www.epncb.oma.be/_networkdata

In the next section processed data will be presented in both the software packages, Leica Geo Office (LGO) and RTKLIB.

6.2.2.1. Data processing and results with Leica Geo Office 8.3

Since the area where experiment is set and the range of baseline length is similar to the Milano Test, processing parameters are also the same as for Milano Test (see Figure 6-6).

After data being converted, next step is to estimate a position of the u-blox receiver. In the first part of Como Test, baseline is estimated using relative static positioning between Como EUREF Permanent Station (COMO) and the u-blox receiver set on the roof of the Valleggio building. By
processing baseline with a known position of COMO, coordinates of the u-blox receiver are estimated on hourly basis. Results, collected during available days (20 days, 194 sessions) and stated in a Table 6-10: Available days used to estimate the u-blox coordinates, are presented in the following Table 6-11.

Table 6-10: Available days used to estimate the u-blox coordinates (baseline: COMO-u-blox)

<table>
<thead>
<tr>
<th>AVAILABLE DAYS</th>
<th>26.1</th>
<th>27.1</th>
<th>28.1</th>
<th>29.1</th>
<th>1.2</th>
<th>2.2</th>
<th>3.2</th>
<th>4.2</th>
<th>5.2</th>
<th>8.2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.2</td>
<td>10.2</td>
<td>11.2</td>
<td>12.2</td>
<td>13.2</td>
<td>15.2</td>
<td>16.2</td>
<td>17.2</td>
<td>18.2</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Table 6-11: Coordinates of COMO obtained from http://www.epncb.oma.be/ and estimated coordinates of the u-blox receiver

<table>
<thead>
<tr>
<th>STATION</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMO EUREF P.S</td>
<td>4398306.113</td>
<td>704150.034</td>
<td>4550154.809</td>
<td>5072071.495</td>
<td>507430.809</td>
<td>292.291</td>
</tr>
<tr>
<td>U-BLOX RECEIVER</td>
<td>4398303.593</td>
<td>704156.094</td>
<td>4550157.224</td>
<td>5072074.284</td>
<td>507437.180</td>
<td>292.955</td>
</tr>
</tbody>
</table>

Como test will be divided in four parts. In the first part of processing there are 194 sessions. Estimated baseline (between COMO - u-blox receiver) is very short, around 7 m. All results are below 1.5 cm of difference with respect to the average value of the estimated u-blox coordinates. There are no detected outliers. Statistics in term of residuals are presented in the following Table 6-12.

Table 6-12: Statistics of estimated coordinates of the u-blox receiver in term of residuals, where baseline is processed with respect to COMO as a reference (LGO)

<table>
<thead>
<tr>
<th>Basic statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.5</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>MAX</td>
<td>1.2</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>MIN</td>
<td>-1.2</td>
<td>-1.2</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

It can be seen from the Table 6-12, that standard deviation in all positions, North, East and Height, is below 1 cm. It can be seen that standard deviation is in the same range as in Milano Test.
Difference is in detection of outliers. In Milano Test, there were few outliers, while in Como Test outliers were not detected. Therefore, this difference is related to the type of the u-blox receiver used in Como Test (u-blox EVK NEO - 7P) which is a newer version in compare to u-blox used for Milano Test (u-blox LEA 4T). For the purpose of local monitoring, obtained accuracy is acceptable and this part of experiment can be concluded as a successful.

Second part of Como Test contains estimation of the reference position of geodetic receiver placed on the roof of the Castelnuovo building with respect to the COMO. Processing is done on daily basis, taking into account days that are overlapping in both data sets. Available days are listed in the following Table 6-13.

Table 6-13: Available days for processing with LGO

<table>
<thead>
<tr>
<th>AVAILABLE DAYS</th>
<th>28.1.</th>
<th>29.1.</th>
<th>8.2.</th>
<th>9.2.</th>
<th>10.2.</th>
<th>18.2.</th>
<th>19.2.</th>
</tr>
</thead>
</table>

Coordinates are estimated using known position of COMO, by averaging all processed sessions, and processed baseline values are listed in Table 6-14. Estimated baseline is around 122 m.

Table 6-14: Estimated coordinates (averaged values) of the Leica geodetic receiver (LGO)

<table>
<thead>
<tr>
<th>STATION</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leica geodetic receiver</td>
<td>4398265.326</td>
<td>704035.179</td>
<td>4550193.53</td>
<td>5072140.224</td>
<td>507323.807</td>
<td>279.320</td>
</tr>
</tbody>
</table>

Table 6-15: Statistics in term of residuals, where baseline is processed between COMO and Leica geodetic receiver (LGO)

<table>
<thead>
<tr>
<th>Basic statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>MAX</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>MIN</td>
<td>-0.2</td>
<td>-0.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

It can be seen from Table 6-15 that STDEV is below 0.5 cm which is the expected accuracy for a data set obtained with geodetic receivers.
In the next part of this experiment author was testing the baseline between the geodetic in Castelnuovo and the u-blox in Valleggio, by fixing the estimated position of the geodetic receiver. In this processing there were 69 sessions processed and estimated baseline is around 132 m. Obtained statistics are shown in a table below.

Table 6-16: Statistics of estimated coordinates of the u-blox receiver in term of residuals, where baseline is processed with respect to geodetic receiver as a reference (LGO)

<table>
<thead>
<tr>
<th>Basic statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.5</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>MAX</td>
<td>1.3</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>MIN</td>
<td>-1.0</td>
<td>-1.3</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

There are no outliers detected while processing data. It can be seen from Table 6-16 that STDEV is below 1 cm, which is acceptable accuracy for this kind of experiment. Since the reference position of the u-blox receiver was estimated by processing two baselines (one short baseline with length of 7 m and other baseline with 132 m length), differences in the final coordinates, calculated as an average value of processed coordinates of u-blox receiver in all sessions, are shown in a Table 6-17. Sessions which are overlapping (see Table 6-13) in both experiments are taken into account while making differences between coordinates.

Table 6-17: Estimated position of the u-blox receiver with processing two different baselines (LGO)

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>coordinates of the u-blox receiver - ROVER</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N [m]</td>
<td>E [m]</td>
<td>h [m]</td>
</tr>
<tr>
<td>Geodetic receiver</td>
<td>5072074.281</td>
<td>507437.182</td>
<td>292.946</td>
</tr>
<tr>
<td>Como EUREF P.S.</td>
<td>5072074.283</td>
<td>507437.178</td>
<td>292.955</td>
</tr>
<tr>
<td>difference in [mm]</td>
<td>-2.4</td>
<td>3.7</td>
<td>-9.7</td>
</tr>
</tbody>
</table>

Differences in the final coordinates of the u-blox receiver estimated with respect to the two baselines are in the range of mm in the north and east component, while in the height this value is almost 1 cm. This difference in height is significant, since coordinates of geodetic receiver are estimated with respect to the COMO reference station.

LGO PROCESSING RESULT ANALYSIS:
Graphical representations of the residuals for each 3-D coordinate will be shown in graphs below.

Figure 6-22: Residuals in the North direction, 1 hourly sessions, static method, COMO – u-blox, LGO
In previous graphs, graphical representations of the residuals for each 3-D coordinate is presented with respect to COMO as a reference station for baseline processing and coordinate estimation. It can be seen from graphs that there is a certain continuity in residuals, expect 90th session where discontinuity is presented, but still residuals are in expected range of accuracy.

In the next graphs, representation will be with respect to the geodetic receiver placed on the roof of the Castelnuovo building.
Figure 6-25: Residuals in the North direction, 1 hourly sessions, static method, GEO. R.- u-blox, LGO

Figure 6-26: Residuals in the East direction, 1 hourly sessions, static method, GEO. R.- u-blox, LGO
To conclude this part of experiment a comparison had to be made between the results obtained with both processed baselines (COMO - u-blox and GEO.R – u-blox). In the following figures with graphs a comparison with respect to North, East and Height component is presented:
Figure 6-28: Time series of residuals for North direction, static method, 1 hour session, where baseline is estimated between u-blox and COMO and u-blox and Leica geodetic receiver (GEO.R.), LGO.

Figure 6-29: Time series of residuals for East direction, static method, 1 hour session, where baseline is estimated between u-blox and COMO and u-blox and Leica geodetic receiver (GEO.R.), LGO.
Figure 6-30: Time series of residuals for North direction, static method, 1 hour session, where baseline is estimated between u-blox and COMO and u-blox and Leica geodetic receiver (GEO.R.), LGO.

It can be seen from the graphs on figures above, by comparing two different baselines, that in both baselines, the residuals are in range of 1.5 cm. LGO in this experiment provides accurate and reliable results which approve utility of u-blox for monitoring application.

Aim of this experiment (Como Test) is to compare two similar baselines, one geodetic – geodetic (COMO and Leica geodetic receiver) and the other geodetic – u-blox (Leica geodetic receiver and u-blox). Differences between residuals (when processing is done on daily basis, 7 days measurements) are shown in the following. It can be seen that results obtained by processing baselines between two geodetic receivers are with higher accuracy than results obtained by processing baseline between geodetic receiver - u-blox, still both results are in acceptable range (with difference not more than 1.5 cm).
Table 6-18: Statistics in the terms of residuals of two similar baselines (LGO)

<table>
<thead>
<tr>
<th>BASELINE</th>
<th>COMO – GEO.R.</th>
<th>GEO.R. – u-blox</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dN [cm]</td>
<td>dE [cm]</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>MAX</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>MIN</td>
<td>-0.2</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>-1.0</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

As already presented in, processing of baseline is with higher accuracy when it is measured between two geodetic receivers, where STDEV is below 2 mm. On the other hand, processing baseline with u-blox receiver, where STDEV is below 1 cm, is in the range of expected accuracy and acceptable for purpose of local monitoring.

6.2.2.2. Data processing and results with RTKLIB

In this experiment, function called RTKPOST has been used for the data processing. RINEX data have been imported and processed (see Figure 6-31). Also with these data, author had to correct antennas heights manually.

![Figure 6-31: Importing data in RTKPOST function of RTKLIB software](image)

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Processing baselines is divided as in LGO processing. Before processing, basic parameters and coordinates of the reference station should be inserted in the software (see Figure 6-13, Milano Test). As already mentioned, data processing has three parts. In the first part baseline between COMO and u–blox receiver is processed and coordinates of the u–blox receiver are estimated. For the aim of comparison of the baselines using different receivers, author is processing, on hourly basis, days that are overlapping in both part of experiment. Statistics in the form of residuals are presented in following Table 6-19.

*Table 6-19: Basic statistics of estimated coordinates of the u-blox receiver in term of residuals, where baseline is processed with respect to COMO as a reference (RTKLIB)*

<table>
<thead>
<tr>
<th>Basic statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.7</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>MAX</td>
<td>-1.9</td>
<td>-0.9</td>
<td>-2.1</td>
</tr>
<tr>
<td>MIN</td>
<td>2.0</td>
<td>1.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

It can be seen that STDEV is below 1 cm in all directions. Residuals are slightly bigger with respect to LGO, which is due to the software algorithms. Taking in to account that RTKLIB is a FOSS software results below 2.5 cm are good and acceptable. There are no outliers, therefore all sessions are acceptable and used for estimation of the baseline.

Then, the position of the u-blox receiver on Valleggio, is estimated using geodetic receiver in Castelnuovo as reference: the geodetic coordinates are fixed to the values obtained by LGO processing. In this part, two outliers have been detected in sessions 45 and 69. In the session 45 value of outlier was 4 cm difference from reference solution and in the session 69 value of outlier was 6 cm of difference from reference solution. For these outliers, ambiguities have not been fixed and results of residuals without outliers are presented in a Table 6-20.
Table 6-20: Statistics of estimated coordinates of the u-blox receiver in term of residuals, where baseline is processed with respect to geodetic receiver as a reference (RTKLIB)

<table>
<thead>
<tr>
<th>Basic statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.6</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>MAX</td>
<td>1.7</td>
<td>1.1</td>
<td>2.5</td>
</tr>
<tr>
<td>MIN</td>
<td>-1.3</td>
<td>-0.7</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

Results are below 2.5 cm, except two detected and removed outliers, which is in range of expected accuracy for this kind of experiment.

Table 6-21 represents coordinates of u – blox receiver with respect to different baselines and differences between them, calculated by averaging coordinates in processed sessions.

Table 6-21: Estimated position of u-blox receiver with respect to processing two different baselines (RTKLIB software)

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Como EUREF P.S.</td>
<td>5072074.284</td>
<td>507437.180</td>
<td>292.955</td>
</tr>
<tr>
<td>Geodetic receiver</td>
<td>5072074.281</td>
<td>507437.182</td>
<td>292.934</td>
</tr>
<tr>
<td>difference in [mm]</td>
<td>2.7</td>
<td>-2.1</td>
<td>20.83</td>
</tr>
</tbody>
</table>

Differences are in mm range except height, where difference is around 2 cm. As expected the difference height value is bigger than the difference for East and North, mostly because of the satellite geometry (it is impossible to track satellites below the horizon) and because of lack of antenna corrections (typically the PCO vertical component is the highest one).

Table 6-22: Statistics in the terms of residuals between two similar baselines (RTKLIB)

<table>
<thead>
<tr>
<th>BASELINE</th>
<th>COMO – GEO.R.</th>
<th>GEO.R.– u-blox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic statistics</td>
<td>dN [cm]</td>
<td>dE [cm]</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>MAX</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>MIN</td>
<td>-0.2</td>
<td>-0.3</td>
</tr>
</tbody>
</table>
From the Table 6-22 it can be seen that residuals, calculated with respect to the average value of coordinates within all sessions, are in range of mm. Results are better in case of baseline processed between geodetic receivers (COMO - GEO.R.), as expected.

**RTKLIB PROCESSING RESULT ANALYSIS:**

Graphical representations of the residuals for each 3-D coordinate will be shown in graphs below.

In the graphs below, where baseline between COMO and u-blox receiver is processed, it can be seen continuity in residuals in all sessions. All residuals are in a range of expected accuracy and two outliers are eliminated from data set.

![Residuals in the North direction, 1 hourly sessions, static method COMO – u-blox, RTKLIB](image)

*Figure 6-32: Residuals in the North direction, 1 hourly sessions, static method COMO – u-blox, RTKLIB*
In the next graphs residuals will be presented for the baseline between the geodetic receiver (GEO. R.) and u-blox.
Figure 6-35: Residuals in the North direction, 1 hourly sessions, static method, GEO. R – u-blox, RTKLIB

Figure 6-36: Residuals in the East direction, 1 hourly sessions, static method, GEO. R – u-blox, RTKLIB
Presented graphs on figures above show that baseline between Leica geodetic receiver and u-blox is in range of few centimeters, which is acceptable considering processing with RTKLIB software. Next graph will show comparison between two processed baseline in term of residuals.

Figure 6-37: Residuals in the Height, 1 hourly sessions, static method, GEO. R – u-blox, RTKLIB

Figure 6-38: Time series of residuals for North direction, static method, 1 hour session, where baseline is estimated between u-blox and COMO and u-blox and Leica geodetic receiver (GEO.R.), RTKLIB
It can be seen from the graphs that results are not as good as with LGO, but still acceptable and below 2.5 cm. Two outliers have been detected and removed from statistics and graphics.
representation. Since, RTKLIB is a FOSS software and data are collected with u-blox low cost receiver, processed results are in range of expected accuracy for monitoring.

Comparison between used software programs will be shown in following tables and graphs. After data processing, coordinates of u-blox are estimated by hourly session between COMO as a reference and u-blox as a rover. To calculate baseline length, average value of u-blox coordinates from all sessions is estimated and used for calculation.

**Table 6-23: Estimated baseline (COMO - u-blox receiver) with LGO and RTKLIB**

<table>
<thead>
<tr>
<th>SOFTWARE</th>
<th>BASELINE [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGO</td>
<td>6.9889</td>
</tr>
<tr>
<td>RTK</td>
<td>6.9857</td>
</tr>
<tr>
<td>difference in [mm]</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Coordinates of the u-blox receiver are calculated by averaging hourly processed sessions and presented in a table below.

**Table 6-24: Coordinates of the u-blox receiver (COMO - u-blox receiver) with LGO and RTKLIB**

<table>
<thead>
<tr>
<th>SOFTWARE</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGO</td>
<td>5072074.283</td>
<td>507437.178</td>
<td>292.955</td>
</tr>
<tr>
<td>RTK</td>
<td>5072074.28</td>
<td>507437.180</td>
<td>292.954</td>
</tr>
<tr>
<td>difference in [mm]</td>
<td>-0.2</td>
<td>-1.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Same procedure is done for baseline processing between Leica geodetic receiver and u-blox.

**Table 6-25: Estimated baseline (Leica geodetic r. - u-blox receiver) with LGO and RTKLIB**

<table>
<thead>
<tr>
<th>SOFTWARE</th>
<th>BASELINE [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGO</td>
<td>131.9212</td>
</tr>
<tr>
<td>RTK</td>
<td>131.9197</td>
</tr>
<tr>
<td>difference in [mm]</td>
<td>1.6</td>
</tr>
</tbody>
</table>

**Table 6-26: Coordinates of the u-blox receiver (Leica geodetic r. - u-blox receiver) with LGO and RTKLIB**

<table>
<thead>
<tr>
<th>SOFTWARE</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGO</td>
<td>5072074.281</td>
<td>507437.18</td>
<td>292.945</td>
</tr>
<tr>
<td>RTK</td>
<td>5072074.28</td>
<td>507437.18</td>
<td>292.93</td>
</tr>
<tr>
<td>difference in [mm]</td>
<td>0.0</td>
<td>0.0</td>
<td>11.8</td>
</tr>
</tbody>
</table>
Figure 6-41: Comparison of processing baseline in the North direction (COMO – u-blox), LGO and RTKLIB.

Figure 6-42: Comparison of processing baseline in the East direction (COMO – u-blox), LGO and RTKLIB.
From the graph on Figure 6-41, it is visible that results obtained with LGO are better than those obtained with RTKLIB. On the another hand, accuracy is acceptable in both cases, since the greatest value of residual is around 2 cm.

On the second graph on Figure 6-44, results obtained by LGO processing are similar to those obtained by RTKLIB processing, since in RTKLIB processing outliers are excluded from calculations of residuals.
Figure 6-44: Comparison of processing baseline in the North direction (Leica geodetic r. – u-blox), LGO and RTKLIB

Figure 6-45: Comparison of processing baseline in the East direction (Leica geodetic r. – u-blox), LGO and RTKLIB
Figure 6-46: Comparison of processing baseline in the Height (Leica geodetic r. – u-blox), LGO and RTKLIB

From the graphs presented above it can be concluded that Como Test is shown as a successful experiment. Results obtained processing different baselines, comparing similar ones and using different software programs with u-blox receiver in static processing, are reliable and in the expected range of accuracy.

6.3. Lomazzo Test

Data set for this test has been collected in Lomazzo in the period from 12-Aug 2017 to 21-Aug 2017 (from GPS day 224 to the GPS day 233) on the roof of the Como NEXT building, Via Cavour. Dataset was collected by the following hardware:

- Trimble BD930 receiver, with a Trimble Zephyr antenna
- GeoGuard monitoring unit (GMU), that embeds a u-blox LEA-M8T receiver, with a Tallysman TW3470 antenna.
In this test two receivers have been used. Besides geodetic receiver used as reference, Virtual Reference Station (VRS) has been used in this test and one more experiment with VRS as a base has been done and processed. Author processed data in RINEX format with LGO software. Complete procedure will be presented in the next part of this section.

**Figure 6-47**: Flow diagram of the overall procedure applied for Lomazzo test

### 6.3.3. Data preprocessing – Lomazzo Test

Procedure is similar as in the previous experiments. In the first step data are converted in RINEX format. Second step is related to the VRS. Data for VRS has been downloaded from the portal of GNSS positioning service of Regione Piemonte and Regione Lombardia by using Virtual RINEX Service (see ).
To download Virtual RINEX data, date, local start time and duration, latitude, longitude and height should be inserted (see \ref{fig:6-48}). Aim of this experiment is to compare the accuracy obtained by the baseline processing and coordinate estimation of the u-blox receiver using both geodetic receiver and VRS as references. Therefore, the coordinates of Lomazzo geodetic receiver are used to generate the Virtual Station. Note that the VRS is generated by using the physical data acquired by Como, Milano, Lecco, Novara, Vigevano, Corno, Gozzano and Pavia permanent stations (see \ref{fig:6-48}).
Figure 6-49: RINEX file – VRS

Figure 6-50: Map of available stations for VRS estimation

(https://www.spingnss.it/spiderweb/frmIndex.aspx)
6.3.4. Data processing – Lomazzo Test

After data conversion and downloading data set for VRS, next step is baseline processing and estimation of the coordinates of u-blox receiver. Also in this case, processing was planned with both LGO and RTKLIB. However, with this dataset, we had significant problems with RTKLIB, on which we are still working; therefore, in the thesis only LGO results are presented.

6.3.4.1. Data processing and results with Leica Geo Office 8.3

Processing parameters are as same as in Como and Milano Tests (see Figure 6-5 and Figure 6-6). In the first part of this experiment, baseline is processed between geodetic and u-blox, whose coordinates are estimated by averaging hourly sessions. In total, there are 240 sessions. Outliers are detected in sessions 143 and 239, with more than 5 cm difference from reference solution. For this outliers, ambiguities have not been resolved and errors' magnitude is of about 16 cm for the East component of session 143 and of about 10 cm for the East component of session 239. Basic statistics in term of residuals and estimated coordinates of the u-blox receiver are presented in following tables without detected outliers.

Table 6-28: Basic statistics in term of residuals, where baseline is processed between geodetic receiver and u-blox (LGO)

<table>
<thead>
<tr>
<th>Basic statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>MAX</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>MIN</td>
<td>-3.5</td>
<td>-0.6</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

Table 6-29: Estimated coordinates of the u-blox receiver (baseline: GEO R. – u-blox, LGO)

<table>
<thead>
<tr>
<th>STATION</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-BLOCK RECEIVER</td>
<td>4407345.955</td>
<td>700838.738</td>
<td>4542057.277</td>
<td>5060401.884</td>
<td>502748.190</td>
<td>357.142</td>
</tr>
</tbody>
</table>
It can be seen from , that STDEV is below 0.5 cm in all directions. This was expected because the baseline is very short and, in this case, u-blox is equipped with a good external antenna. In the second part of this experiment VRS is used as reference station. In total, again 240 sessions are processed. In this case, 10 outliers are detected (that is less than 5% of all data). To fix them, same approach is used as in Milano Test, by increasing cut off angle and/or removing suspicious satellite from processing. It is presented in Table 6-30 that some sessions are corrected by increasing cut off angle and others are corrected by removing suspicious satellites. After this fixing approach, almost all outliers were fixed and processed with other data. At the end, 3 outliers are left without ambiguity fixing and they are excluded from statistic calculations. Fixed and not fixed (eliminated) outliers are stated in following tables.

Table 6-30: Sessions with outliers and fixing approach

<table>
<thead>
<tr>
<th>Session</th>
<th>cut off (standard 15°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>20°</td>
</tr>
<tr>
<td>46</td>
<td>20°</td>
</tr>
<tr>
<td>62</td>
<td>20°</td>
</tr>
<tr>
<td>120</td>
<td>20°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Session</th>
<th>removed satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>G01</td>
</tr>
<tr>
<td>239</td>
<td>G07</td>
</tr>
<tr>
<td>240</td>
<td>G05</td>
</tr>
</tbody>
</table>

Table 6-31: Sessions with not fixed outliers and its influence on the final 3D position of receiver

<table>
<thead>
<tr>
<th>Session</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>7.0</td>
<td>19.0</td>
<td>10.0</td>
</tr>
<tr>
<td>147</td>
<td>5.0</td>
<td>18.0</td>
<td>12.0</td>
</tr>
<tr>
<td>173</td>
<td>12.0</td>
<td>19.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

After ambiguity fixing and excluding not fixed outliers, statistic in term of residuals is calculated and results are shown in .
Statistics in term of residuals, where baseline is VRS - u-blox (LGO)

<table>
<thead>
<tr>
<th>Statistics</th>
<th>dN [cm]</th>
<th>dE [cm]</th>
<th>dh [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.5</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>MAX</td>
<td>-1.8</td>
<td>-1.6</td>
<td>-1.3</td>
</tr>
<tr>
<td>MIN</td>
<td>1.3</td>
<td>1.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Standard deviation is in cm range and it shows reliability and utility of this experiment for a purpose of local monitoring. After calculation of statistics and checking data quality, coordinates of u-blox receiver are estimated by averaging hourly sessions and presented in following table.

Estimated coordinates of the u-blox receiver (baseline: VRS – u-blox, LGO)

<table>
<thead>
<tr>
<th>STATION</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
<th>N [m]</th>
<th>E [m]</th>
<th>h [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-BLOX RECEIVER</td>
<td>4407345.979</td>
<td>700838.740</td>
<td>4542057.304</td>
<td>5060401.886</td>
<td>502748.189</td>
<td>357.178</td>
</tr>
</tbody>
</table>

The purpose of this experiment is to check the quality of results obtained with VRS by processing baseline VRS – u-blox and comparing them to the results obtained by processing baseline, geodetic receiver – u-blox. In the next table, difference between estimated coordinates of the u-blox receiver, calculated by averaging of all sessions, with respect to different reference station is presented.

Estimated position of the u-blox receiver with processing two baselines (LGO)

<table>
<thead>
<tr>
<th>BASE</th>
<th>coordinates of the u - blox receiver - ROVER</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N [m]</td>
<td>E [m]</td>
<td>h [m]</td>
<td></td>
</tr>
<tr>
<td>Geodetic receiver</td>
<td>5060401.884</td>
<td>502748.190</td>
<td>357.142</td>
<td></td>
</tr>
<tr>
<td>VRS</td>
<td>5060401.886</td>
<td>502748.189</td>
<td>357.178</td>
<td></td>
</tr>
<tr>
<td>difference in [mm]</td>
<td>-1.9</td>
<td>1.6</td>
<td>-36.2</td>
<td></td>
</tr>
</tbody>
</table>

It can be seen that for North and East results differ in mm range, but in Height difference is around 3.5 cm. This can be caused by a mismodeling of atmospheric effects in the generation of the VRS and is still under investigation.

Baseline is estimated using Cartesian coordinates of reference station and averaged coordinates of u-blox receiver within all sessions. Results are presented in the following table.
Table 6-35: Estimated baselines (LGO)

<table>
<thead>
<tr>
<th>BASELINE [m]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO R - u-blox</td>
<td>1.325</td>
</tr>
<tr>
<td>VRS - u-blox</td>
<td>1.318</td>
</tr>
<tr>
<td>diff in mm</td>
<td>9.1</td>
</tr>
</tbody>
</table>

LGO PROCESSING RESULT ANALYSIS:

Graphical representations of the residuals for each 3-D coordinate of the u-blox receiver with respect to both receivers, geodetic receiver and VRS, will be shown in graphs below.

Figure 6-51: Time series of residuals for North direction, static method, 1 hour session, where baseline is estimated between u-blox and geodetic receiver and u-blox and VRS, LGO
Figure 6-52: Time series of residuals for East direction, static method, 1 hour session, where baseline is estimated between u-blox and geodetic receiver and u-blox and VRS, LGO.
Figure 6-53: Time series of residuals for Height, static method, 1 hour session, where baseline is estimated between u-blox and geodetic receiver and u-blox and VRS, LGO

The graphical representation of residuals helps visual interpretation of results. They prove that u-blox receivers are suitable for applications with cm-level accuracy when paired with an appropriate processing software: for the 2D position the errors are around 2 cm in most of the cases and for height, as expected, the residuals are slightly higher but still below 5 cm-level accuracy (in case of VRS – u-blox baseline processing).
7. CONCLUSION AND RECOMMENDATION

According to the aim of thesis research, main remarks of processed results are presented:

- Quality of obtained results depend on the baseline length and on the base station type (i.e., geodetic versus low-cost, physical versus virtual).
- The results of this research show that it is possible to reach sub-centimeter or even millimeter accuracy with the single-frequency mass-market GNSS receivers, under appropriate operative conditions. This level of accuracy can allow to realize the monitoring of movements and deformations.
- Processing baseline between u-blox receiver and VRS and obtained results are in range of expected accuracy and reliable for a purpose of monitoring.
- The precision level, ranging from 1 mm to 1 cm in standard deviation in all experiments is influenced by the distance of the base station and its observation quality and in range of expected accuracy for the purpose of local monitoring.
- This indicates to hat the particular type of receiver (e.g. LEA-4T, NEO-7P and LEA-M8T in this work) can provide positioning results for general purpose of local monitoring and that are comparable to using geodetic receivers and with a significantly lower cost.
- The performed experiment shows that, as expected, shorter baselines provide more accurate solutions, physical stations perform slightly better than virtual ones, and geodetic-grade bases better than low-cost ones.
- LGO software is suitable for processing GNSS data with high accuracy. s. One of reasons are the faster data capture as well as the shorter time and safer means of data processing.
• RTKLIB as a Free Open Source Software is able to achieve similar results to the LGO. Main issue with this software is that RTKPOST function does not take into account phase center of u–blox antenna in processing height. Author had to add those values manually, reading from the RINEX files.

7.1. **Recommendations for Future Research**

• It is possible, in principle, to achieve centimeter-level accuracy with low-cost solutions, needing to have on monitored points just smart devices with their own embedded receivers and antennas.

• In any case, in order to achieve high-precision results it is necessary to know the exact positions of phase centers: a relative antenna calibration to estimate the phase center variations (PCVs) is needed to improve the results in future.

• The use of Virtual Reference Station allows to eliminate the need of a local geodetic reference.

• The performances of geodetic receivers and low cost receivers prove to be similar for sessions of 1 hour and shorter than 1 km. In Milano and Como Test good results are obtained with both software packages, LGO and RTKLIB. In Lomazzo Test, LGO succeed to provide good results and RTKLIB had problems with processing Virtual RINEX data, which is still under investigation.

• The experiments were done in a simulated environment, with simplified and ideal conditions. However, a real landslide condition is more complex, for example for the presence of trees: a validation in real cases is needed. Therefore, next experiments will be done to test the monitoring of real landslide site. If the technique will be validated on an actual landslide site, it can be generalizing to more fields.
8. Bibliography


ESA. (2017, 10 14). Retrieved from Launching Galileo: http://www.esa.int


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Jeffrey, C. (2010). An Introduction to GNSS. Published by NovAtel Inc.


