Testing of low-cost GNSS receivers for landslide monitoring

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Abstract

Landslides are dangerous natural hazards, responsible for considerable loss of property and lives worldwide. Key indicator for stability assessment of sliding slopes is usually displacements at the surface, which must be determined with accuracy in the centimeter range. Geodetic GNSS (Global Navigation Satellite System) receivers are traditionally used in these applications because of a high level of accuracy. Due to the price of geodetic receivers are high, the unstable slopes may collapsed and destroy the receivers, slopes are monitored sporadically only. Early warning of landslides monitoring requires a permanently operable measuring system on site. Thus low-cost GNSS receivers can be used for such demanding challenges. Over the last twenty years, positioning with low-cost GNSS sensors have rapidly developed around the world at both commercial and academic research level.

The aim of this thesis is to test the actual performance of low-cost GNSS receivers, with the purpose of verifying if they can be used for landslides monitoring. To achieve the target, both geodetic and low-cost receivers are used in the experiment: Leica GX1230 GG and single frequency u-blox EVK-7P receivers. To simulate the displacement of landslides, a sliding device built by Laboratory of Topography of the Politecnico di Torino was used. The antenna of low-cost receiver was placed on the sliding device, which can be moved on both vertical and horizontal direction.

The experiment was planned and performed in Como, the antenna of u-blox EVK-7P receiver was moved by 5mm increments alternating the horizontal and vertical direction every two hours. In total, the antenna has been moved 10 cm both in the horizontal and vertical direction. Then the data was processed by LGO (Leica Geo Office) and RTKLIB. The experiment proved that u-blox EVK-7P receiver is capable in detecting displacements at centimeter level, even sub-centimeter level for the horizontal direction.
The first three chapters introduce relevant background material to this thesis, the research approach, results, conclusion and recommendations are presented in the last three chapters.

- Chapter 1 is the introduction of the research including motivation and objective.

- GNSS systems, including the history, the constellation, signal spectrum and latest update of satellites are discussed in Chapter 2.

- Chapter 3 describes the fundamental of GPS positioning, including the pseudorange observation, carrier phase observation, error sources and principle of differential GPS.

- Chapter 4 introduces the approach used in this investigation. The details on how, where, and when the experiment was setup and data acquisition are given in this chapter. The software used for data processing is also introduced in this chapter.

- Chapter 5 presents the results processed by commercial software LGO and open source software RTKLIB, the displacements detected by the low-cost receiver comparing with the theoretical movements are discussed in this chapter.

- Chapter 6 gives some conclusions of this research, and recommendation for future work. Low-cost GNSS receiver u-blox EVK-7P can be trusted for applications that require centimeter level accuracies.
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Contents

Chapter 1. The introduction of the research ................................................................. 1

1.1 Motivation ................................................................................................................. 1

1.2 Thesis Objective ....................................................................................................... 7

Chapter 2. Review of GNSS ........................................................................................... 9

2.1 GPS ............................................................................................................................ 9

2.1.1 GPS Segment ...................................................................................................... 11

2.1.2 Current and planned signals ............................................................................... 14

2.1.3 GPS modernization ............................................................................................ 18

2.2 GLONASS .................................................................................................................. 22

2.2.1 GLONASS Segment ............................................................................................ 22

2.2.2 Current and planned signals ............................................................................... 24

2.3 Beidou ......................................................................................................................... 25

2.3.1 Beidou Segment .................................................................................................. 26

2.3.2 Current and planned signals ............................................................................... 28

2.4 Galileo ........................................................................................................................ 29

2.4.1 Galileo Segment .................................................................................................. 30

2.4.2 Current and planned signals ............................................................................... 31

2.4.3 Projected Galileo services .................................................................................. 33

2.5 Satellite based augmentation systems, SBAS (WAAS, EGNOS) ..................... 35

Chapter 3. Fundamental of GPS positioning ............................................................... 39
3.1 GPS positioning ..........................................................39
3.2 Differential GPS ..........................................................48
  3.2.1 Single differencing ....................................................49
  3.2.2 Double Differencing ..................................................50
Chapter 4. Experimental approach .........................................53
  4.1 Experiment introduction ................................................53
  4.2 Instrumentation ..........................................................54
    4.2.1 GNSS receivers .....................................................55
    4.2.2 Software introduction ..............................................62
  4.3 Experiment setup .......................................................65
Chapter 5. Data processing and discussion ................................72
  5.1 Pre-processing ..........................................................72
  5.2 Data processing of Simu-slide ........................................80
    5.2.1 Baseline EUREF permanent station and u-blox rover ........82
    5.2.2 Baseline u-blox reference and u-blox rover ....................86
Chapter 6. Conclusion and recommendation ............................90
Bibliography ...........................................................................93
List of Figures

Figure 1.1: Landslides map of Italy ................................................................. 2

Figure 1.2: Landslides map of the world ......................................................... 3

Figure 2.1: WGS 84 coordinate system ............................................................ 10

Figure 2.2: GPS system segment (http://www.gps.gov/systems/gps/space/) .............. 11

Figure 2.3: GPS constellation ........................................................................ 12

Figure 2.4: GPS ground control segment worldwide ......................................... 13

Figure 2.5: Measuring signal travel time ......................................................... 14

Figure 2.6: Data structure of GPS Signal .......................................................... 15

Figure 2.7: Structure of the entire navigation message ...................................... 17

Figure 2.8: GPS modernization program ......................................................... 18

Figure 2.9: Block IIR-M satellite (http://www.gps.gov/systems/gps/modernization/) ... 19

Figure 2.10: Modernized GPS signals .............................................................. 19

Figure 2.11: Available and modernized GPS signals .......................................... 20

Figure 2.12: launch of GPS IIF-12 satellite

Figure 2.13: GLONASS orbital constellation ................................................... 23

Figure 2.14: GLONASS-K satellite ................................................................. 23

Figure 2.15: GLONASS signals ..................................................................... 24

Figure 2.16: A Soyuz-2-1b rocket lifts off with GLONASS-M No. 51 satellite on Feb. 7, 2016................................................................. 25
Figure 2.17: China launched latest satellite to support its global navigation and positioning
(english.gov.cn/news/top_news/2016/03/30/content_281475317487645.htm) ...... 29

Figure 2.18: Galileo system Constellation ................................................................. 30
Figure 2.19: Galileo system architecture (http://www.esa.int) .................................... 30
Figure 2.20: Frequency ranges of the Galileo signals ................................................ 32
Figure 2.21: Galileo 11 and 12 lifted off ...................................................................... 35
Figure 2.22: Principle of all Satellite Based Augmentation Systems SBAS ............... 36
Figure 2.23: WAAS area of coverage .......................................................................... 37
Figure 2.24: Position and coverage of WAAS, EGNOS, GAGAN and MSA ............. 38
Figure 3.1: Trilateration positioning ........................................................................... 39
Figure 3.2: Basic idea of satellite positioning ............................................................... 40
Figure 3.3: Pseudorange positioning .......................................................................... 40
Figure 3.4: GPS pseudorange observation .................................................................. 41
Figure 3.5: The meaning of phase ............................................................................... 42
Figure 3.6: Principle of the phase measurement ............................................................ 42
Figure 3.7: Choke-Ring Antenna ................................................................................ 46
Figure 3.8: The flatter the angle with which the circles with ranges R1 and R2 intersect,
the higher the DOP value ......................................................................................... 48
Figure 3.9: The observation geometry effect ............................................................... 48
Figure 3.10: Single differencing geometry .................................................................. 49
Figure 3.11: Double differencing geometry ................................................................ 51
Figure 4.1: Location of experiment site ...................................................................... 54
Figure 4.2: Leica GX1230 GG ................................................................................... 57
Figure 4.3: u-blox EVK-7P evaluation kit ................................................................. 59
Figure 4.4: Micrometric slide ......................................................................................... 61
Figure 4.5: Micrometric slide setup ................................................................................. 61
Figure 4.6: Functions of RTKLIB .................................................................................. 62
Figure 4.7: Como EUREF Permanent station ................................................................. 67
Figure 4.8: Power supply cabinet .................................................................................... 67
Figure 4.9: Setup of sliding device and receivers ............................................................. 68
Figure 4.10: Fixing the north direction of sliding device ................................................ 68
Figure 5.1: Interface of RTKCONV .............................................................................. 73
Figure 5.2: Option of RTKCONV .................................................................................. 73
Figure 5.3: Flowchart of u-blox reference station coordinate estimation ...................... 74
Figure 5.4: Interface of LGO ......................................................................................... 75
Figure 5.5: Processing parameters of LGO ................................................................. 75
Figure 5.6: Processing parameters input panel .............................................................. 77
Figure 5.7: Option of RTKLIB ...................................................................................... 77
Figure 5.8: Time series of residuals for North, static method, 1 hour session (LGO) ....... 79
Figure 5.9: Time series of residuals for East, static method, 1 hour session (LGO) ...... 80
Figure 5.10: Time series of residuals for Height, static method, 1 hour session (LGO) .. 80
Figure 5.11: Flowchart of Simu-slide coordinate estimation ........................................ 81
Figure 5.12: Processing parameter of LGO .................................................................. 82
Figure 5.13: Point properties setting of LGO ............................................................... 83
Figure 5.14: Horizontal difference between theoretical and estimated displacement ...... 83
Figure 5.15: Vertical difference between theoretical and estimated displacement ......... 84
Figure 5.16: Horizontal errors (Baseline EUREF permanent station and u-blox rover) .. 84
Figure 5.17: Vertical errors (Baseline EUREF permanent station and u-blox rover) ...... 85
Figure 5.18: Horizontal difference between theoretical and estimated displacement ...... 87
Figure 5.19: Vertical difference between theoretical and estimated displacement .......... 87
Figure 5.20: Horizontal errors (Baseline u-blox reference and u-blox rover) ............... 88
Figure 5.21: Vertical errors (Baseline u-blox reference and u-blox rover) .................. 88
List of Tables

Table 1.1: Landslides classification scheme (Adapt from Cruden and Carnes, 1996) .................................. 2
Table 1.2: Methods and techniques for measuring landslides (Gili et al., 2000) ................................... 5
Table 1.3: Rate of movement scale for landslides .................................................................................. 5
Table 1.4: Typical accuracy in baseline estimation ............................................................................... 6
Table 2.1: Parameters of WGS-84 Reference Ellipsoids .................................................................. 11
Table 2.2: GPS signal characteristics .................................................................................................. 15
Table 2.3: Characteristics of the GPS signals in L5 ........................................................................... 21
Table 2.4: Existing signal characteristics ............................................................................................. 24
Table 2.5: The orbit parameters of non-geostationary satellites ....................................................... 27
Table 2.6: Existing BeiDou Signals ...................................................................................................... 28
Table 2.7: Frequency plan of Galileo .................................................................................................. 31
Table 4.1: Summary of Leica GX 1230 GG ...................................................................................... 58
Table 4.2: Code and phase measurement precision of Leica GX1230 GG ........................................ 58
Table 4.3: Accuracy (RMS) with post processing ................................................................................. 59
Table 4.4: ITRF2008-WGS84 coordinate of EUREF Permanent station ............................................. 67
Table 4.5: Time table of displacements ................................................................................................. 71
Table 5.1: Processing parameters of LGO ........................................................................................... 74
Table 5.2: The coordinates of u-blox reference station (Processed by LGO) ...................................... 76
Table 5.3: Processing parameters of RTKLIB .................................................................................... 76
Table 5.4: The coordinates of u-blox reference station (Processed by RTKLIB) .............................. 78
Table 5.5: Result comparison of LGO and RTKLIB .............................................................................. 78
Table 5.6: Coordinates comparison of u-blox reference initial and ending position ...... 79
Table 5.7: LGO processing parameters ................................................................. 82
Table 5.8: Statistics analysis of errors (Baseline EUREF permanent station and u-blox rover) .................................................................................................................. 85
Table 5.9: Number of residuals for different residual classes (Baseline EUREF permanent station and u-blox rover) .................................................................................................................. 86
Table 5.10: Horizontal and vertical difference between theoretical and estimated displacement (Baseline u-blox reference and u-blox rover) ................................................. 89
Table 5.11: Number of residuals for different residual classes (Baseline u-blox reference and u-blox rover) .................................................................................................................. 89
Table of Acronyms

ARP Antenna Reference Point
ASCII American Standard Code for Information Interchange
ATX Antenna Exchange Format
BDS BeiDou Navigation Satellite System
C/A Coarse Acquisition
CDMA Code Division Multiple Access
CGCS200 China Geodetic Coordinate System 2000
CS Commercial Service
DD Double differences
DGPS Differential GPS
DOP Dilution of Precision
DTM Digital Terrain Model
ESSP European Satellite Services Provider
EU European Union
FAA Federal Aviation Administration
PCVs Phase Center Variations
FOSS Free and Open Source Software
GEO Geostationary Earth Orbit
GIS Geographic Information System
GNSS Global Navigation Satellite Systems
GPS Global Positioning System
IERS International Earth Rotation Service
IGS International GPS Service
ITRF International Terrestrial Reference Frame
ITRS International Terrestrial Reference System
LGO Leica Geo Office
MEO Medium Earth Orbit
MCS Master Control Station
MS Monitor Stations
OS Open Service
PDOP Three-dimensional Dilution of Precision
PPP Precise Point Positioning
PRN Pseudorandom noise
QZSS Quasi Zenith Satellite System
RINEX Receiver Independent Exchange Format
RMS Root Mean Square
RTCM Radio Technical Commission for Maritime Services
RTK Real Time Kinematic
SA Selective Availability
SBAS Satellite Based Augmentation Systems
SNR Signal to Noise Ratio
SoL Safety of Life Service
SPS Standard Positioning Service
TEC Total Electron Content
TPS Total Station
USB Universal Serial Bus
UTC Coordinate Universal Time
UTM Universal Transverse Mercator
WAAS Wide Area Augmentation System
WAD Wide Area Differential
Chapter 1. The introduction of the research

1.1 Motivation

Landslide is defined as “the movement of a mass of rock, debris, or earth down a slope” (Cruden, 1991), it is a dangerous natural hazard, responsible for considerable loss of property and lives worldwide. The attention given to landslide is not as focused as other hazards, such as earthquakes, volcanoes and hurricanes, however the loss of lives and property due to landslides are more than earthquakes, flood and windstorms. Most landslides occur at steep slopes, which can be triggered by natural environmental changes or by human activities. Earthquakes, volcanic activity, heavy rainfall and changes of ground water level are typical natural triggering mechanisms for landslides (P. D. Savvaïdis, 2003). Due to the specific amount of landslides is difficult to determine, their impacts always be underestimated.

Data from the Centre for Research on the Epidemiology of Disasters (CCRED) suggests that landslides were responsible for over 10,000 deaths and left 2.5 million people homeless over the past decade (CED, 2011). However, the true loss of life and incidence of injury may be much larger, due to the under-reporting of small events in many parts of the world. Although most common in mountainous areas, landslides are not restricted to them. Landslides may also occur in incised valleys in area of otherwise low relief and are common in many lakes, in fjords, and on the seafloor at the edges of continental shelves. Irrespective of relief, water, and discontinuities in earth materials are critical determinants of slope stability.

Geo-scientists distinguish landslides that occur in rock from those occur in fine and coarse textured unconsolidated sediments. They further categorize landslides according to the failure mechanism, water content and speed.
<table>
<thead>
<tr>
<th>Fall</th>
<th>Rockfall</th>
<th>Debris fall</th>
<th>Earth fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topple</td>
<td>Rock topple</td>
<td>Debris topple</td>
<td>Earth topple</td>
</tr>
<tr>
<td>Slide</td>
<td>Rockslide</td>
<td>Debris slide</td>
<td>Earth slide</td>
</tr>
<tr>
<td>Spread</td>
<td>Rock spread</td>
<td>Debris spread</td>
<td>Earth spread</td>
</tr>
<tr>
<td>Flow</td>
<td>Solifluxion flow</td>
<td>Debris flow</td>
<td>Earth flow</td>
</tr>
<tr>
<td>Complex</td>
<td>e.g. Rock avalanche</td>
<td>e.g. Debris slide-debris blow</td>
<td>e.g. Earth slide-earth flow</td>
</tr>
</tbody>
</table>

Table 1.1: Landslides classification scheme (Adapt from Cruden and Carnes, 1996)

In Italy, 5813 people died in a total of 1882 landslides events, corresponding to a frequency of 18.4 landslides events every year between 1900 and 2002. The large density of landslides casualties in northern Italy is due to the meteorological, morphological, and geological settings.

Figure 1.1: Landslides map of Italy
The map shows that the location of 2533 sites affected by landslides events in previous years. In the upper-right corner, the density of landslides sites per square kilometer, it is divided in five classes. Moreover, in the central part of the graph that shows number of landslides events at each site (y-axis) against rank (x-axis), in logarithmic coordinates.

China also suffers from various geological problems. With the boom of economy and a great deal of ongoing engineering projects such as transportation, water conservancy and resource development as well as the influence of environmental changes, damages caused by landslides are sharply increasing. In recent years, rock falls, landslides and debris flow have caused an economic loss of about 10 billion RMB and over 1000 lives per year. More than 10,000 hazardous landslides occurred in 2014, which caused a total number of 618 deaths and injuries, and a direct economic loss of 5.41 billion CNY (Irasema Alcántara Ayala et al., 2015). About 700 counties have suffered from geologic hazards, tens of millions of residents living in these area face threaten of serious geological hazards. This causes serious social problems. Therefore, it is particularly important to develop cost-effective reliable landslides monitoring systems and technologies.

Figure 1.2: Landslides map of the world

(http://www.livescience.com/22410-landslide-deaths-underestimated.html)
Monitoring landslides is important because the risk of humans, engineering structures and environment. The timely monitoring of landslides can save lives, avert financial loss and can avoid environmental damage. By monitoring the surface displacement of a slope, the information of dynamics of landslides can be provided. If the displacement can be detected early enough, the warning system is able to give early warning message to people live in influent areas, the loss of landslides can be avoid.

Several methods and techniques have been used for landslides deformation monitoring during the last decades. The examples are given in Table 1.2, which is adopted and updated from (Gili et al., 2000). By measuring changes in distances, height differences, angles or relative coordinates of the stations, landslides deformation can be monitored.

<table>
<thead>
<tr>
<th>Method</th>
<th>Results</th>
<th>Typical range</th>
<th>Typical precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision tape</td>
<td>Δdistance</td>
<td>&lt;30 m</td>
<td>0.5 mm/30 m</td>
</tr>
<tr>
<td>Fixed wire extensometer</td>
<td>Δdistance</td>
<td>&lt;10-80 m</td>
<td>0.3 mm/30 m</td>
</tr>
<tr>
<td>Rod for crack opening</td>
<td>Δdistance</td>
<td>&lt;5 m</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Offsets from baseline</td>
<td>ΔH, ΔV</td>
<td>&lt;100 m</td>
<td>0.5-3 mm</td>
</tr>
<tr>
<td>Surveying triangulation</td>
<td>ΔX, ΔY, ΔZ</td>
<td>&lt;300-1000m</td>
<td>5-10 mm</td>
</tr>
<tr>
<td>Surveying traverses</td>
<td>ΔX, ΔY, ΔZ</td>
<td>Variable</td>
<td>5-10 mm</td>
</tr>
<tr>
<td>Geometrical levelling</td>
<td>ΔZ</td>
<td>Variable</td>
<td>2-5mm/km</td>
</tr>
<tr>
<td>Precise geometrical levelling</td>
<td>ΔZ</td>
<td>Variable</td>
<td>0.2-1mm/km</td>
</tr>
<tr>
<td>Electronic distance measurement (EDM)</td>
<td>Δdistance</td>
<td>Variable (usual 1-14km)</td>
<td>1-5mm+1-5ppm</td>
</tr>
<tr>
<td>Terrestrial photogrammetry</td>
<td>ΔX, ΔY, ΔZ</td>
<td>Ideally&lt;100m</td>
<td>20mm from 100m</td>
</tr>
<tr>
<td>Aerial photogrammetry</td>
<td>ΔX, ΔY, ΔZ</td>
<td>H_{flight}&lt;500m</td>
<td>10cm</td>
</tr>
<tr>
<td></td>
<td>(\Delta x)</td>
<td>(\pm 10^\circ)</td>
<td>0.01-0.1°</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------</td>
<td>------------------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Clinometer</strong></td>
<td>(\Delta x), (\Delta y), (\Delta z)</td>
<td>Variable (usual &lt; 20 km)</td>
<td>5-10 mm + 1-2 ppm</td>
</tr>
<tr>
<td><strong>GPS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2: Methods and techniques for measuring landslides (Gili et al., 2000).

The scale of landslides varies from few meters to few kilometers. For different scale of landslides monitoring, different approaches are used to achieve the need. Generally the accuracy required for measurement of landslides displacements are typically at the order of centimeters.

<table>
<thead>
<tr>
<th>Rate of movement</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 meters per second</td>
<td>Extremely rapid</td>
</tr>
<tr>
<td>0.3 meters per minute</td>
<td>Very rapid</td>
</tr>
<tr>
<td>1.5 meters per day</td>
<td>Rapid</td>
</tr>
<tr>
<td>1.5 meters per month</td>
<td>Moderate</td>
</tr>
<tr>
<td>1.5 meters per year</td>
<td>Slow</td>
</tr>
<tr>
<td>0.06 meters per year</td>
<td>Very slow</td>
</tr>
</tbody>
</table>

Table 1.3: Rate of movement scale for landslides

GPS is a passive, all-weather satellite-based navigation and positioning system, which is designed to provide precise three dimensional position and velocity, as well as time information on a continuous worldwide basis (Hofmann-Wellenhof, et al., 1994). GPS has revolutionized our ability to measure surface ground motions associated with earthquakes, plate movements, fault motions, volcanoes, subsidence, and landslides. In the last two decades, GPS has been frequently applied to landslides studies worldwide, both as a complement and as an alternative to conventional landslide surveying methods. GPS could provide a relatively wide spectrum of positioning accuracy, from millimeter level (mm level) to meter level. Compared with conventional surveying techniques, GPS techniques generally increase survey accuracy, monitoring capability, meanwhile reducing cost (Guoquan Wang, 2015).
<table>
<thead>
<tr>
<th>Time</th>
<th>1 km</th>
<th>10 km</th>
<th>50 km</th>
<th>1000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic</td>
<td>2.5 cm</td>
<td>4.0 cm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10 minutes</td>
<td>1.5 cm</td>
<td>2.5 cm</td>
<td>5 cm</td>
<td>-</td>
</tr>
<tr>
<td>1 hour</td>
<td>1.0 cm</td>
<td>1.5 cm</td>
<td>2 cm</td>
<td>-</td>
</tr>
<tr>
<td>24 hour</td>
<td>0.3 cm</td>
<td>0.5 cm</td>
<td>&lt;1 cm</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>1 week</td>
<td>0.1 cm</td>
<td>0.1 cm</td>
<td>0.3 cm</td>
<td>&lt;1 cm</td>
</tr>
</tbody>
</table>

Table 1.4: Typical accuracy in baseline estimation.

For high level of precision monitoring of deformations, the dual frequency GNSS receivers are usually employed. However the price of geodetic-grade receivers are expensive, ranging from 10,000 to 30,000 euro. The challenge in GNSS monitoring is how to reduce the cost of the monitoring scheme.

The cost of monitoring includes:

- The costs of GPS receivers
- The cost of power supply
- The cost of communication system
- The cost of logistics
- The cost of personnel

Single-frequency GNSS receivers are potentially suitable for landslide monitoring because of their small size, low cost, and less power consumption. The shortcoming of this approach is lack of possibility to correct the data for ionospheric delay. Research on the development of low-cost GNSS deformation monitoring systems for landslides monitoring application are ongoing, with positive results. A low-cost GNSS receiver is able to satisfy the needs of some specific monitoring applications by determining the properties of the landslides.
1.2 Thesis Objective

A complete landslides monitoring system is a complex system, which consists of various hardware pieces and software. This thesis will only focus on evaluating the performance of low-cost GNSS receivers.

*Objective 1: Compare the accuracy performance of low-cost GNSS receiver with geodetic receiver and discover if detected displacements agree with the controlled displacements.*

To verify the capability of the receiver to detect a deformation, a sliding device was used in order to conduct a dedicated test. The device was able to move both in horizontal and vertical directions with high precision. The sliding device was used in this experiment in the following way: the antenna of low-cost receiver was fixed on the sliding device and then shifted 5 mm every two hours in horizontal or vertical direction. The data were processed after acquisition to get the real time coordinates for each session, then with these coordinates it was possible to compute the displacements between two time intervals. The theoretical and estimated movements were compared in order to assess the performance of u-blox receiver.

*Objective 2: Experimentally study the capability of low-cost receiver can detect movements, with the purpose of verifying if such type of sensors can be used for landslides monitoring.*

The accuracy of GNSS receiver is important for landslide monitoring, however very high accuracy level is difficult to achieve. The target of the experiment is to investigate the accuracy level that the low-cost GNSS receiver can reach, the centimeter level is sufficient for landslide monitoring. If the low-cost receiver can achieve centimeter level accuracy, it can be used for specific landslide monitoring. According to the previous research, this kind of accuracy can be obtained by evaluation of carrier phase measurement over a time interval of 15-60 min. The displacement of each interval is 5 mm every two hours.

*Objective 3: Compare the performance of different GPS software: RTKLIB open source software and LGO commercial software.*
On the market, there are many different kinds of available software, including open resource software and commercial software. Different software gives results with slight difference even when same method and processing parameters are being used. The commercial software is pricey, more robust, and supports more data formats. Usually, a commercial software does not publish the mathematical models used for baseline processing, network adjustment and coordinate transformations. On the other hand, a FOSS allows users more flexibility in terms of handling the processing parameters, and the algorithms. In the experiment, the performance assessment is done by comparing the results between open source software RTKLIB and commercial software LGO.
Chapter 2. Review of GNSS

This chapter introduces different GNSS systems, including the history, the constellation, signal spectrum and latest updates of satellites. GNSS (Global Navigation Satellite System) is the generic term used for all the satellite navigation systems that have a global coverage (Lekkerkerk, 2014). Four main GNSS systems are in operation or construction: GPS, GLONASS, Galileo and Beidou. GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System) are well developed GNSS and already in full operation. Meanwhile, European Union’s Galileo program and China Beidou system are in construction, both are planned to give a global coverage. Japan and India are also developing regional systems, Japanese Quasi-Zenith Satellite System (QZSS) and Indian Regional Navigation Satellite System (IRNSS) are developed by Japan and India respectively. Currently there are 31 operational GPS satellites, GLONASS has 24 operational satellites, Galileo has 6 operational satellites, and Beidou has 22 operational satellites (G. W. Roberts et al., 2015).

2.1 GPS

The Global Positioning System (GPS) is a U.S. owned utility that provides users with positioning, navigation, and timing services. This system is developed, maintained and operated by U.S. Air Force. GPS system consists of three segments: the space segment, the control segment and the user segment.

WGS84 is the reference system for GPS. This is compatible with the International Terrestrial Reference System (ITRS). The current realization of WGS84 (G1674) follows the criteria outlined in the International Earth Rotation Service (IERS) Technical Note 21 (TN21). The responsible organization is the National Geospatial-Intelligence Agency (NGA).
Figure 2.1: WGS 84 coordinate system

- **Origin**: Earth’s center of mass being defined for the whole Earth including oceans and atmosphere.

- **X-Axis**: Intersection of the IERS Reference Meridian (IRM) and the plane passing through the origin and normal to the Z-axis. The IRM is coincident with the BIH Zero Meridian (epoch 1984.0) with an uncertainty of 0.005".

- **Y-Axis**: Completes a right-handed, Earth-Centered Earth-Fixed (ECEF) orthogonal coordinate system.

- **Z-Axis**: The direction of the IERS Reference Pole (IRP). This direction corresponds to the direction of the BIH Conventional Terrestrial Pole (CTP) (epoch 1984.0) with an uncertainty of 0.005".

- **Orientation**: Orientation is given by the Bureau International de l’Heure (BIH) orientation of 1984.0.

- **Time Evolution**: Its time evolution in orientation will create no residual global rotation with regards to the crust.
<table>
<thead>
<tr>
<th>Semi major axis a (m)</th>
<th>Semi minor axis b (m)</th>
<th>Flattening</th>
</tr>
</thead>
<tbody>
<tr>
<td>6,378,137.00</td>
<td>6,356,752.31</td>
<td>298,257223563</td>
</tr>
</tbody>
</table>

Table 2.1: Parameters of WGS-84 Reference Ellipsoids

(https://confluence.qps.nl/pages/viewpage.action?pageId=29855173)

### 2.1.1 GPS Segment

GPS is comprised of three segments: satellite constellation, ground control network and user receiving equipment. The satellite constellation is a set of satellites in orbit that provide signals and data messages to user equipment. The control segment tracks, maintains the satellites and updates the satellite ephemerides. The user receiver equipment performs navigation, timing or surveying.

![GPS system segment](http://www.gps.gov/systems/gps/space/)

Figure 2.2: GPS system segment

- **Space segment**

GPS space segment consists of a constellation of satellites transmitting radio signals to users. The United States is committed to maintaining the availability of at least 24 operational GPS satellites for 95% of the time. The extra satellites may increase GPS performance but are not
considered part of the core constellation. The Air Force has been flying 31 operational GPS satellites for the past few years.

![GPS constellation](image)

Figure 2.3: GPS constellation

The satellites in the GPS constellation are arranged into six equally spaced orbital planes surrounding the Earth. Each plane contains four slots occupied by baseline satellites. They orbit at a height of 20,180km above the Earth’s surface and are inclined at 55° to the equator. Any one satellite completes its orbit in around 12 hours. Due to the rotation of the Earth, a satellite will be at its initial starting position above the earth’s surface after 23 hours 56 minutes.. The recent GPS constellation is a mix of old and new satellites including current and future generations of GPS satellites, including Block IIA (2nd generation, "Advanced"), Block IIR ("Replenishment"), Block IIR (M) ("Modernized"), Block IIF ("Follow-on"), and GPS III.

- **Ground segment**

The GPS control segment consists of four subsystems: a master control station, an alternate master control station, a network of four ground antennas and a network of globally distributed monitor stations.

- **Master control station**
The master control station is located at Schriever Air Force Base, in Colorado, United States, and is the central control node for the GPS constellation.

The master control station is responsible for all aspects of constellation command and control, including the following:

- Routine satellite bus and payload status monitoring
- Satellite maintenance and anomaly resolution
- Navigation message data upload operations as required to sustain performance in accordance with accuracy and integrity performance standards
- Management of signal-in-space performance in support of the GPS standard positioning service and precise positioning service performance standards
- Detecting and responding to GPS signal-in-space failures

**Ground segment of the GPS**

There are 38 wide-area reference stations throughout North America (in Canada, Mexico and the United States, including Alaska and Hawaii) and Puerto Rico.

![Figure 2.4: GPS ground control segment worldwide](image)
The user segment includes military and civilian users. The user can receive GPS signal using a GPS receiver connected with a GPS antenna. The user can determine its position anywhere in the world without charge. The radio signal transmitted by GPS satellites take about 67 milliseconds to reach a receiver on Earth with the speed of light. To compute the distance between a satellite and receiver the user has to know the travel time of signal with very good precision. This travel time is the main observable and it is obtained by synchronizing the replica signals generated in the receiver with that sent by the satellite. Usually, this time shifts is noted with $\Delta t$ is multiplied by speed of light to compute the pseudorange.

**Figure 2.5: Measuring signal travel time**

### 2.1.2 Current and planned signals

The satellite generates signals on board with fundamental frequency $f_0=10.23$MHZ, which is controlled by atomic clock and has stability in the range of $10^{-13}$ per day. Two carrier signals in the L-band, denoted L1 and L2, are generated by integer multiplications of $f_0$. The L1 carrier is generated at 1575.42MHZ, while the L2 carrier is generated at 1227.6 MHZ.

The carriers L1 and L2 are biphasic modulated by codes to provide satellite clock and transmit the orbital parameters. The codes are a sequence with the states +1 or -1, the biphasic modulation is performed by a 180° shift in the carrier phase when the code state changes.
GPS provides two levels of service based on different codes:

- Standard positioning service, which uses the C/A code on the L1 frequency, the standard positioning service is available to all users worldwide on a continuous basis and without any direct user charge.

- Precise positioning uses the C/A code on the L1 frequency and the P(Y) code on both the L1 and L2 frequencies. The precise positioning service is restricted to the United States Armed Forces, federal agencies and selected allied armed forces and governments.

<table>
<thead>
<tr>
<th></th>
<th>C/A</th>
<th>P(Y)</th>
<th>Navigation data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1.023 MHZ</td>
<td>10.23 MHZ</td>
<td>50 HZ</td>
</tr>
<tr>
<td>Length per chip</td>
<td>293 m</td>
<td>29.4 m</td>
<td>5950 km</td>
</tr>
<tr>
<td>Repetition</td>
<td>1 ms</td>
<td>1 week</td>
<td>N/A</td>
</tr>
<tr>
<td>Code type</td>
<td>Gold</td>
<td>Pseudo random</td>
<td>N/A</td>
</tr>
<tr>
<td>Carried on</td>
<td>L1</td>
<td>L1, L2</td>
<td>L1, L2</td>
</tr>
</tbody>
</table>

Table 2.2: GPS signal characteristics
The specific capabilities provided by the GPS open service are published in the GPS Standard Positioning Service Performance Standards. The United States Department of Defense, as the operator of GPS, will continue enabling codeless/semi-codeless GPS access until 31 December 2020, by which time the L2C and L5 signals will be available on at least 24 modernized GPS satellites.

The GPS message

The GPS message is a continuous stream of data transmitted at 50 bits per second. Each satellite relays the following information to Earth:

- System time and clock correction values
- Its own highly accurate orbital data (ephemeris)
- Approximate orbital data for all other satellites (almanac)
- System health, etc.

Structure of the navigation message

The navigation message is needed to calculate the current position of the satellites and to determine signal travel times. Data is transmitted in logically grouped units known as frames or pages. Each frame is 1500 bits long and takes 30 seconds to transmit. Each subframe is 300 bits long and takes 6 seconds to transmit. In order to transmit a complete almanac, 25 different frames are required. Transmission time for the entire almanac is 12.5 minutes. The structure of the navigation message is illustrated in a diagram in Fig. 2.7.
A frame is divided into five subframes, each subframe transmitting different information.

- **Subframe 1** contains the time values of the transmitting satellite, including the parameters for correcting signal transit delay and onboard clock time, as well as information on satellite health and an estimate of the positional accuracy of the satellite. Subframe 1 also transmits the so-called 10-bit week number. GPS time began on Sunday, 6th January 1980 at 00:00:00 hours. Every 1024 weeks the week number restarts at 0. This event is called a “week rollover”.

- **Subframes 2 and 3** contain the ephemeris data of the transmitting satellite. This data provides extremely accurate information on the satellite’s orbit.

- **Subframe 4** contains the almanac data on satellite numbers 25 to 32, the difference between GPS and UTC time and information regarding any measurement errors caused by the ionosphere.
Subframe 5 contains the almanac data on satellite numbers 1 to 24 (N.B. each subframe can transmit data from one satellite only). All 25 pages are transmitted together with information on the health of satellite numbers 1 to 24.

2.1.3 GPS modernization

In January 1999, the U.S. government announced a new GPS modernization initiative that called for the addition of civil signals to be added to new GPS satellites. The GPS modernization program involves a series of consecutive satellite acquisitions, including GPS IIR (M), GPS IIF, and GPS III, which also involves improvements to the GPS control segment, including the Architecture Evolution Plan (AEP) and the Next Generation Operational Control System (OCX). The GPS ground stations will also be renewed. The entire system overhaul should be complete and operational by 2021. The new signals will then be fully available to users.

Figure 2.8: GPS modernization program
Due to the vast civil applications of GPS technology during the past decade and the new technologies used in the satellite and receivers, the U.S government 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. Moreover, this will increase the robustness in the signals and improve the resistance to signal interference.

The government is in the process of fielding three new signals designed for civilian use: L2C, L5, and L1C. The legacy civil signal, called L1 C/A, will continue broadcasting in the future, for a total of four civil GPS signals. Users must upgrade their equipment to benefit from the new signals. The new civil signals are phasing in incrementally as the Air Force launches new GPS satellites to replace older ones. Most of the new signals will be of limited use until they are broadcast from 18 to 24 satellites.

Figure 2.9: Block IIR-M satellite (http://www.gps.gov/systems/gps/modernization/)

Figure 2.10: Modernized GPS signals
The schedule for GPS modernization is shown below:

L2C civil signal

- Available since 2005 without data message
- Phased roll-out of civil navigation message starting in 2009
- 24 satellites by 2016

L5 civil signal

- First launch in 2009
- 24 satellites by 2018

L1C civil signal

- Launches with GPS III in 2014
- 24 satellites by 2021

Ground segment

- Ongoing upgrades synchronized with satellite modernization

Figure 2.11: Available and modernized GPS signals

The GPS L5 (1176.45 MHz) signal will be transmitted for the first time on board IIF satellites. The GPS carriers of the L5 band are modulated by two bit trains in phase quadrature: the L5
data channel and the L5 pilot channel. Moreover, two PRN ranging codes are transmitted on L5: the in-phase code (denoted as the I5-code) and the quadrature phase code (denoted as the Q5-code).

The technical characteristics of the GPS signals in L5 can be summarized as follows:

<table>
<thead>
<tr>
<th>Service Name</th>
<th>L5I</th>
<th>L5Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre Frequency</td>
<td>1176.45MHz</td>
<td>1176.45MHz</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>L5</td>
<td>L5</td>
</tr>
<tr>
<td>Access Technique</td>
<td>CDMA</td>
<td>CDMA</td>
</tr>
<tr>
<td>Spreading modulation</td>
<td>BPSK(10)</td>
<td>BPSK(10)</td>
</tr>
<tr>
<td>Code Frequency</td>
<td>10.23 MHz</td>
<td>10.23 MHz</td>
</tr>
</tbody>
</table>

Table 2.3: Characteristics of the GPS signals in L5

**Latest Launch**

The U.S. Air Force and its mission partners successfully launched the 12th Boeing-built Global Positioning System GPS IIF satellite aboard a United Launch Alliance Atlas V Evolved Expendable Launch Vehicle from Space Launch Complex 41, Cape Canaveral Air Force Station, Fla. at 8:38 a.m. EST (5:38 a.m. PST) on Feb 5, 2016. All 12 satellites in the GPS IIF series have now been completed and launched into orbit.
2.2.1 GLONASS Segment

- **Space segment**

The main constellation of GLONASS comprises 24 GLONASS-M satellites that are uniformly deployed in three roughly circular orbital planes at an inclination of 64.8° to the equator on the orbit attitude 19,100 km. The orbit period of each satellite is 11 hours, 15 minutes, 45 seconds. The orbital planes are separated by 120° right ascension of the ascending node. Eight satellites are equally spaced in each plane with 45° argument of latitude. The orbital planes have an argument of latitude displacement of 15° relative to each other.
The GLONASS ground segment consists of a system control center; a network of five telemetry, tracking and command centers, the central clock, three upload stations, two satellite laser ranging stations, and a network of four monitoring and measuring stations, distributed over the territory of the Russian Federation. Six additional monitoring and measurement stations are to
start operating on the territory of the Russian Federation and the Commonwealth of Independent States in the near future (United Nations office for outer space affairs, 2010).

2.2.2 Current and planned signals

Every GLONASS satellite transmits two codes (C/A and P-Code) on L1 and L2 frequencies, with P code on both L1 and L2, and with C/A code only on L1 at present. Every satellite transmits the same code, but at different frequencies in the vicinity of 1602MHz (L1 Band) and 1246 MHz (L2 Band).

![GLONASS signals](image)

**Figure 2.15: GLONASS signals**

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 carrier frequencies</td>
<td>1,598.06–1,604.40 MHz</td>
</tr>
<tr>
<td>L2 carrier frequencies</td>
<td>1,242.94–1,248.63 MHz</td>
</tr>
<tr>
<td>Superframe volume</td>
<td>7,500 bit</td>
</tr>
<tr>
<td>Superframe duration</td>
<td>2.5 minutes</td>
</tr>
<tr>
<td>Data rate</td>
<td>50 bps</td>
</tr>
<tr>
<td>Time marker iteration period</td>
<td>2 seconds</td>
</tr>
</tbody>
</table>

Table 2.4: Existing signal characteristics

**Latest Launch**
Russian military successfully launched a navigation satellite to replace its failed predecessor in the nation's GLONASS navigation network. The Soyuz-2-1b rocket lifted off as scheduled from Pad 4 at Site 43 in Plesetsk on February 7, 2016 at 03:21 Moscow Time (7:21 p.m. EST on February 6), carrying the GLONASS-M-51 satellite.

Figure 2.16: A Soyuz-2-1b rocket lifts off with GLONASS-M No. 51 satellite on Feb. 7, 2016

2.3 Beidou

BeiDou Navigation Satellite System (BDS) is constructed and operated by China independently, which is the third Global Navigation Satellite System by following the GPS and GLONASS. The final BDS system will be consisted of 5 GEO, 3 IGSO, and 27 MEO satellites. Coordinate System BDS adopts the China Geodetic Coordinate System 2000 (CGCS200). BDS began to provide regional service from December 27, 2012. The system is designed to provide global coverage around 2020.

- The origin is located at the mass center of the Earth.
- The Z-axis is in the direction of the IERS (International Earth Rotation and Reference System Service) Reference Pole (IRP).
• The X-axis is directed to the intersection of IERS Reference Meridian (IRM) and the plane passing the origin and normal to the Z-axis.

• The Y-axis, together with Z-axis and X-axis, constitutes a right handed orthogonal coordinate system.

• The origin of the CGCS2000 is also the geometric center of the CGCS2000 ellipsoid, and the Z-axis is the rotation axis of the CGCS2000 ellipsoid.

The parameters of the CGCS2000 ellipsoid are as follows:

Semi-major axis: \( a = 6378137.0 \text{ m} \)

Geocentric gravitational constant: \( \mu = 3.986004418 \times 10^{14} \text{ m}^3/\text{s}^2 \)

Flattening: \( f = 1/298.257222101 \)

Rate of earth rotation: \( 7.2921150 \times 10^{-5} \text{ rad/s} \)

The time reference for the BDS uses the BeiDou navigation satellite system Time (BDT). BDT adopts international system of units (SI) seconds, rather than leap seconds, as the basic unit for continuous accumulation. The start epoch of BDT was 00:00:00 on January 1, 2006 of Coordinated Universal Time (UTC). BDT is counted with week and seconds of week (SOW). BDT is related to the UTC through UTC (NTSC). BDT offset with respect to UTC is controlled within 100 nanoseconds. The leap seconds are broadcast in navigation message.

2.3.1 Beidou Segment

• Space Segment
The planned space constellation of Beidou consists of five Geostationary Earth Orbit (GEO) satellites, twenty seven Medium Earth Orbit (MEO) satellites and three Inclined Geosynchronous satellite Orbit (IGSO) satellites.

- The GEO satellite orbit is at the altitude of 35,786 kilometers, which positioned at 8.75°E, 80°E, 110.5°E, 140°E and 160°E respectively.

- The MEO satellite orbit is at an altitude of 21,528 kilometers and an inclination of 55° to the equatorial plane.

- The IGSO satellites are operating in orbit at an altitude of 35,786 kilometers and an inclination of 55° to the equatorial plane.

<table>
<thead>
<tr>
<th></th>
<th>Medium-Earth orbit</th>
<th>Inclined geosynchronous orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of satellites</td>
<td>27</td>
<td>3</td>
</tr>
<tr>
<td>Number of orbit planes</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Orbit altitude (km)</td>
<td>21500</td>
<td>36000</td>
</tr>
<tr>
<td>Orbit inclination (degree)</td>
<td>55</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 2.5: The orbit parameters of non-geostationary satellites

- **Ground Segment**

The ground control segment consists of a Master Control Station (MCS), Time Synchronization/Upload Stations (TS/US) and Monitor Stations (MS).

The Master Control Station (MCS) collects observing data from Monitor Stations, process data, generate and upload navigation messages, monitor satellite payload to perform mission planning and conduct system control. Time Synchronization/Upload Stations (TS/US) upload navigation messages, exchange data with Master Control Station and accomplish time synchronization and measurement under the general coordination of Master Control Station.
The main tasks of MCS are to collect observing data from each MS, to process data, to generate satellite navigation messages, to upload navigation messages, to monitor satellite payload, to perform mission planning and scheduling, and to conduct system operation and control. The main tasks of TS/US are to upload navigation messages, to exchange data with MCS, to accomplish time synchronization and measurement, under the general coordination of MCS. The main tasks of MS are to continuously track and monitor navigation satellites, to receive navigation signals and provide observing data to the MCS for generating navigation messages (China Satellite Navigation Office, 2013).

2.3.2 Current and planned signals

The BeiDou system is currently broadcasting signals on three bands: B1 (centered at 1561.098MHz in E2), B2 (centered at 1207.14MHz in E5b), and B3 (centered at 1268.52MHz in E6). The frequency bands of the BeiDou Navigation Satellite System include:

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency</th>
<th>Chip Rate (cps)</th>
<th>Bandwidth (MHz)</th>
<th>Modulation Type</th>
<th>Service Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1(I)</td>
<td>1561.098</td>
<td>2.046</td>
<td>4.092</td>
<td>QPSK</td>
<td>OS</td>
</tr>
<tr>
<td>B1(Q)</td>
<td>1561.098</td>
<td>2.046</td>
<td>4.092</td>
<td>QPSK</td>
<td>AS</td>
</tr>
<tr>
<td>B2(I)</td>
<td>1207.14</td>
<td>2.046</td>
<td>24</td>
<td>QPSK</td>
<td>OS</td>
</tr>
<tr>
<td>B2(Q)</td>
<td>1207.14</td>
<td>10.23</td>
<td>24</td>
<td>QPSK</td>
<td>AS</td>
</tr>
<tr>
<td>B3</td>
<td>1268.52</td>
<td>10.23</td>
<td>24</td>
<td>QPSK</td>
<td>AS</td>
</tr>
</tbody>
</table>

Table 2.6: Existing BeiDou Signals
Latest Launch

China launched a satellite to support its global navigation and positioning network at 4:11 a.m., March 30, 2016. The satellite launched from the Xichang Satellite Launch Center in the southwestern province of Sichuan, was taken into orbit by a Long March-3A carrier rocket. It is the 22nd satellite in the BeiDou Navigation Satellite System (BDS).

Figure 2.17: China launched latest satellite to support its global navigation and positioning
(english.gov.cn/news/top_news/2016/03/30/content_281475317487645.htm)

2.4 Galileo

Galileo is Europe’s own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. On 21 October, 2011 came the first two of four operational satellites designed to validate the Galileo concept in both space and on Earth. Two more followed on 12 October, 2012. This 'In-Orbit Validation' (IOV) phase has been followed by additional 'Full Operational Capability' (FOC) satellite launches. Four pairs of FOC satellites have so far been launched by Soyuz from French Guiana, on 22 August, 2014, 27 March 2015, 11 September, 2015 and 17 December, 2015.
2.4.1 Galileo Segment

The fully deployed Galileo system will consist of 24 operational satellites plus six in-orbit spares, positioned in three circular Medium Earth Orbit (MEO) planes at 23,222 km altitude above the Earth, and at an inclination of the orbital planes of 56 degrees to the equator. The Galileo satellites have a mass of 700 kg and dimensions of 2.7m*1.2m*1.1m, which is designed to have an operational lifespan of 15 years. The power supply is a solar panel with 1500W.

Figure 2.18: Galileo system Constellation

Figure 2.19: Galileo system architecture (http://www.esa.int)
The Ground Control Segment monitors and controls the satellite platforms, the Galileo Control Centre is in Oberpfaffenhofen near Munich in Germany, and linked to telemetry, tracking and command stations in Kiruna, Sweden, and Kourou, French Guiana.

The Ground Mission Segment, located in the other Galileo Control Centre in Fucino, central Italy, ensures cutting-edge navigation performance from Galileo by continuously checking on each satellite and producing a correction message to compensate for any slight timing or orbital drift. This correction message is uplinked to the satellite for rebroadcast to users embedded in the navigation signal every 100 minutes or less. In the future Oberpfaffenhofen and Fucino will host equivalent facilities, working together as ‘hot backups’ with real time data synchronization to increase the system’s overall robustness.

2.4.2 Current and planned signals

Galileo will provide 10 navigation signals in Right Hand Circular Polarization (RHCP) in the frequency ranges 1164-1215 MHz (E5a and E5b), 1215-1300 MHz (E6) and 1559-1592 MHz (E2-L1-E11), which are part of the Radio Navigation Satellite Service (RNSS) allocation.

<table>
<thead>
<tr>
<th>Band: Frequency (MHz)</th>
<th>Signal Name</th>
<th>Frequency of Maxima (MHz)</th>
<th>Data Rate (Bit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5: 1191.795</td>
<td>E5a (l5)</td>
<td>1176.45</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>E5b</td>
<td>1207.14</td>
<td>250</td>
</tr>
<tr>
<td>E6: 1278.75</td>
<td>E6b</td>
<td>1278.75</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>E6a</td>
<td>1268.52 &amp; 1288.98</td>
<td>-</td>
</tr>
<tr>
<td>L1: 1575.42</td>
<td>L1 (L1 OS)</td>
<td>1574.661 &amp; 1576.178</td>
<td>250</td>
</tr>
<tr>
<td>E1, E2: 1575.42</td>
<td>E2 &amp; E1</td>
<td>1560.075 &amp; 1590.765</td>
<td>-</td>
</tr>
<tr>
<td>L6: 1544.5</td>
<td>L6</td>
<td>1544.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.7: Frequency plan of Galileo
The radio-frequency air interface between the space and user segments is composed of three independent CDMA signals, named E5, E6 and E1-L1, and they are permanently transmitted by all Galileo satellites. The E5 signal is further sub-divided into two signals denoted as E5a and E5b.

Figure 2.20: Frequency ranges of the Galileo signals

All the Galileo satellites will share the same nominal frequency, making use of Code Division Multiple Access (CDMA) compatible with the GPS approach. Six signals, including three data-less channels, so-called pilot tones (ranging codes not modulated by data), are accessible to all Galileo Users on the E5a, E5b and L1 carrier frequencies for Open Services (OS) and Safety-of-life Services (SoL). Two signals on E6 with encrypted ranging codes, including one data-less channel are accessible only to some dedicated users that gain access through a given Commercial Service (CS) provider. Finally, two signals (one in E6 band and one in E2-L1-E1 band) with encrypted ranging codes and data are accessible to authorized users of the Public Regulated Service (PRS).

**Galileo E1**

The Galileo E1 band is centered at 1575.42 MHZ. It comprises two signals that can be used alone or in combination with signals in other frequency bands, depending on the performance demanded by the application. The signals are provided for the open service and the public regulated service, both of which include a navigation message. Moreover, an integrity message
for the safety-of-life service is included in the open service signal. The E1 carrier is modulated with a CBOC (6, 1, 1/11) (following the MBOC spectrum) code for the open source and a BOCcos (15, 2, 5) code for the public regulated service.

- **Galileo E6**

  The Galileo E6 signal is transmitted on a centre frequency of 1278.75 MHz and comprises commercial service and public regulated service signals, which are modulated with a binary phase shift keying (BPSK)(5) and BOCcos(10,5) code, respectively. Both signals include a navigation message and encrypted ranging codes.

- **Galileo E5**

  The wideband Galileo E5 signal is centered on a frequency of 1191.795 MHz and is generated with an AltBOC modulation of side-band sub-carrier rate of 15.345 MHZ. This scheme provides two side lobes. The lower side lobe of E5 is called the Galileo E5a signal, which is centered on a frequency of 1176.45 MHz and provides a second signal (dual frequency reception) for the open service and safety-of-life services, both of which include navigation data messages. The upper side lobe of E5 is called the Galileo E5b.

2.4.3 Projected Galileo services

For certain critical applications Galileo will provide information about the system integrity in order to assure the accuracy of positioning. Integrity is understood to be the reliability of information and data provided. Users will quickly receive a warning when the system accuracy falls below the given minima. The Galileo operators are of the opinion that these warnings are provided soon enough even for critical applications. Each service provides different demands on function, accuracy, availability, integrity and other parameters.

- Open Service (OS) is foreseen for mass-market applications. It provides free signals for the determination of position and time. Applications with lower demands for accuracy will
use cheaper single-frequency receivers. Because the transmitted frequencies from GALILEO and GPS (L1) are the same for this application, navigation receivers will be able to combine the signals. Due to the increase in the number of satellite signals received there will be an improvement in the reception properties even in suboptimal conditions (e.g. in urban environments). OS will not be provided with System Integrity Information and the Galileo operators make no guarantees of availability and accept no liability.

- The Commercial Service (CS) is envisaged for market applications with higher performance demands than the OS. CS is designed to provide a variety of beneficial services to its customers on a fee for usage basis. Typical examples of these applications would be services providing high-speed data transmission, guarantees of availability, exact-time related services, as well as local correction signals for maximal positioning accuracy.

- The Safety of Life Service (SoL) is envisaged primarily for transportation applications for which an impairment of the navigation system without adequate warning could result in a life-threatening situation. The primary difference to OS is the worldwide high level of information integrity provided to such crucial applications as maritime navigation, aviation and rail traffic. This service is only accessible by using a certified double-frequency receiver. To achieve the necessary signal protection, SoL will be deployed using the aviation communication channels (L1 and E5).

- The Public Regulated Service (PRS) will be available to police and fire departments and border patrols. Access to this service is restricted and controlled by a civilian agency. The PRS must be available continually and under all conditions, especially during crisis situations where other services can be disrupted. The PRS will be independent of the other services and will be characterized by a high level of signal stability. PRS will also be protected against electronic interference and deception.
The SAR service will be used by humanitarian search and rescue services. Emergency transmitters and satellites enable the location of individual persons, crafts and vehicles in aviation, land and maritime emergencies. At the end of the 1970s, the USA, Canada, the USSR and France developed a satellite system for the location of activated distress beacons. The system is referred to as SARSAT (Search And Rescue Satellite-Aided Tracking). The Russian name for the system is “COSPAS”. The COSPAS-SARSAT system employs six LEO (Low Earth Orbit) and five GEO (geostationary) satellites.

**Latest Launch**

Galileo 11 and 12 lifted off together at 11:51 GMT (12:51 CET, 08:51 local time) on 17 December 2015 atop a Soyuz rocket from French Guiana. All Soyuz stages performed as planned, culminating in the Fregat upper stage deploying the twin satellites into orbit close to 23,500 km altitude, around 3 hours and 48 minutes after liftoff.

![Figure 2.21: Galileo 11 and 12 lifted off](image)

**2.5 Satellite based augmentation systems, SBAS (WAAS, EGNOS)**

Satellite Based Augmentation System (SBAS) are used to enhance the GPS, GLONASS functions. Correction and integrity data for GPS or GLONASS is broadcast from geostationary satellite over the GNSS frequency. SBAS is able to increase positioning accuracy using
correction data. SBAS provides differential correction data with which the GNSS position accuracy is improved.

**Figure 2.22: Principle of all Satellite Based Augmentation Systems SBAS**

**SBAS system:**

- **Reference Station:**

  In the SBAS area there are several reference base stations, which are networked to each other. Each station receive the GNSS signals and determine the deviation between the actual and calculated position. The data is transmitted to a control center.

- **Control center:**

  The control center carry out the evaluation of the correction data from the reference base stations, determine the accuracy of all GNSS signal received by each base station, detect inaccuracies, possibly caused by turbulence in the ionosphere and monitoring the integrity of the GNSS system.
• Satellite Ground Station:

These stations broadcast signals to the different geostationary satellites.

• Geo satellites:

The SBAS GEO satellites receive the signals from the satellite ground stations and broadcast them to the GNSS user. The GEO satellite do not have onboard signal generators but equipped with transponders. The signal are transmitted to earth on the GNSS L1 frequency (1575.42MHZ). The SBAS signals are received and processed by GNSS receivers.

**North America (WAAS, Wide Area Augmentation System):**

The US Federal Aviation Administration (FAA) is leading the development of the Wide Area Augmentation System, which covers the US, Canada and Mexico.

![WAAS area of coverage](image)
Other existing and planned systems:

- Europe (EGNOS, European Geostationary Overlay Service) is operated by the European group of three comprising ESA, the European Union, and EUROCONTROL is developing EGNOS.

- Japan (MSAS, Multifunctional Satellite Based Augmentation System and QZSS, Quazi Zenith Satellite System)

- India (GAGAN, GPS and GEO Augmented Navigation)

- Russia (SDCM, System for Differential Correction and Monitoring)

Figure 2.24: Position and coverage of WAAS, EGNOS, GAGAN and MSA
Chapter 3. Fundamental of GPS positioning

3.1 GPS positioning

GPS positioning is based on trilateration, which is the method of determining position by measuring distances to points at known coordinates. 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.

![Trilateration positioning](image)

Figure 3.1: Trilateration positioning

The satellites continuously transmit microwave radio signal composed of carriers, codes and navigation message. The signal is encoded with navigation message. The navigation message includes orbit parameters from which the receiver can compute satellite coordinates. When the receiver is on, it will pick up the signal through the antenna. The receiver can process the signal by built-in software.
Pseudorange observation

The time of signal is transmitted form the satellite is encoded on the signal which is generated by an atomic clock onboard the satellite. Time of signal reception is recorded by receiver using an atomic clock. A receiver measures difference in these times.

\[ \text{Pseudorange} = (\text{time difference}) \times (\text{speed of light}) \]  

3.1

Figure 3.2: Basic idea of satellite positioning

Figure 3.3: Pseudorange positioning
The pseudorange is almost like range, except that it includes clock errors because the receiver clocks are far from perfect. Satellite clock error is given in Navigation Message, in the form of a polynomial. The unknown receiver clock error can be estimated by the user along with unknown station coordinates. There are 4 unknowns, hence we need a minimum of 4 pseudorange measurements.

**Point positioning by code observation**

The time of signal transmitted from the satellite is encoded on the signal which is generated by an atomic clock onboard the satellite. Time of signal reception is recorded by receiver using an atomic clock. A receiver measures difference in these times. Point positioning is performed by least squares adjustment of all the available code observations from one receiver to all the in view satellites at one epoch.

\[
P^s = (T - T^s)c
\]

3.2

*P* is the receiver clock time when signal is received, *T* is the satellite clock when the signal was transmitted, *c* is the speed of light.

![GPS pseudorange observation](image)

Figure 3.4: GPS pseudorange observation

The observation can be developed by setting the clock time *T* equal to the true receiver time *t* plus the clock bias, for both the receiver and satellite clocks:
The carrier phase observation

The carrier phase observation is used for high precision applications. “Phase” is “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.

![Diagram of phase measurement](image1.png)

Figure 3.5: The meaning of phase

The phase at any given time can be defined as the angle through which this line has rotated. The frequency expressed in units of cycles per second is the number of times the line completes a full 360° rotation in one second.

![Diagram of phase measurement](image2.png)

Figure 3.6: Principle of the phase measurement
GPS receivers which record carrier phase, measure the fraction of one wavelength (i.e. fraction of 19 cm for the L1 carrier) when the receiver first locks onto a satellite and continuously measure the carrier phase from that time. The number of cycles between the satellite and receiver at initial startup (referred to as the ambiguity) and the measured carrier phase together represent the satellite-receiver range (i.e. the distance between a satellite and a receiver).

\[
\text{Measured carrier phase} = \text{range} + (\text{ambiguity} \times \text{wavelength}) + \text{error} \quad 3.4
\]

\[
\Phi = \rho + N\lambda + \text{error} \quad 3.5
\]

Where \( F \) is the measured carrier phase in meters, \( r \) is the satellite-receiver range in meters, \( N \) is the ambiguity (i.e. number of cycles) and \( \lambda \) is the carrier wavelength in meters (Geoffrey Blewitt, 1997).

**Error sources**

- **Ephemerides data:**
  
  For the Global Positioning System (GPS), real-time satellite orbits and clock biases are derived from predicted ephemeris and clock parameters in broadcast navigation messages. The performance of broadcast ephemerides is critical to billions of GPS users in terms of position accuracy and integrity.

- **Satellite clocks:**
  
  Although each satellite includes four atomic clocks, the time base contains offsets. A time error of 10ns is reached at an oscillator stability of approx. \( 10^{-13} \) per day. A time error of 10ns immediately results in a distance error of about 3m. As with the orbits, the satellite clock error can be determined by using parameters from the navigation message. Due to the differences in velocity and gravitational potential of the satellite and antenna there is an apparent frequency shift in the satellite oscillator. This leads to an error of up to 70 ns for the satellite clock.

- **Ionosphere error:**
The ionosphere is a region of ionized gases in the atmosphere which affects GPS signals. The ionosphere situates between 60 and 1000 km above the Earth’s surface. The gas molecules in the ionosphere are heavily ionized. This effect is different on the L1 and L2 frequencies, so the magnitude of the error can be computed. A typical ionospheric error is 5 meters (Skone, 1998), it varies due to factors such as the elevation angle and the time of day. The magnitude of the ionospheric error is proportional to the total electron content (TEC), which varies during the solar cycle.

The level of ionization varies depending on time and location, and is strongest during the day and at the equator. If the ionization strength is known, this effect can be compensated with geophysical correction models. The GPS broadcast message includes the parameters of a predicted ionospheric model (Klobuchar 1996; Leick 1995). Using the model parameters, the ionospheric effects can be computed and corrected.

Daily TEC variations are essentially caused by changes in the structure of the ionosphere which occur between night and day. In particular, the trend of electronic density is influenced by solar radiation and by the recombination time. Therefore, as regards daily TEC values, a maximum value is frequently produced one hour after solar noon, generally between 1:00 p.m. and 3:00 p.m. local time; occasionally, another peak can be recorded during the hours after sunset (Hernández-Pajares et al., 2006). TEC values also have seasonal variations based upon the months of the year. In the Northern hemisphere, minimum values are recorded during summer and maximum values during both the equinoxes and winter. The entity of TEC may be two to three times greater in winter as opposed to summer. TEC values also vary according to solar activity and is characterised by an average periodicity of eleven-years (Nicola Crocetto et al., 2008).

- **Troposphere error:**
The troposphere is the atmospheric layer located between 0-15 km above the Earth’s surface. The cause of the error here is the varying density of the gas molecules and the air humidity. The density decreases as the height increases. The increase in density or humidity retards the speed of the satellite signals.

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 (Qui, 1993). 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 (Spilker, 1996b). The total error increases more than 10 times as the satellite gets closer to the horizon (Seeber, 1993).

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 and Goodman, 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.

- **Multipath:**

  Multipath is the phenomenon whereby a signal is reflected or diffracted from various objects and arrives at the receiver via multiple paths (Braasch and Van Graas, 1991). GPS
signals can be reflected from buildings, trees, mountains. Multipath propagation affects both pseudorange and carrier phase measurements. For both static and kinematic position, it is an error source need to be consider. Multipath is a localized effect, which is depend on the local environment surrounding the antenna. Thus the effect of multipath can be partially compensated by the selection of the measuring location, a good antenna and measuring time.

![Geometry of multipath effects](image1.png)

Fig. 3.9: Geometry of multipath effects

Multipath can be reduced by use of special GPS antenna that incorporates a ground plane, which is basically circular, metallic disk about 50cm in diameter to prevent low elevation signals reaching the antenna. For higher accuracy, the preferred solution is the use of a choke ring antenna. A choke ring antenna has 4 or 5 concentric rings around the antenna that trap any indirect signals.

![Choke-Ring Antenna](image2.png)

Figure 3.7: Choke-Ring Antenna
- **Receiver noise:**

  Receiver noise is any noise that is generated by the receiver itself while taking measurements. This noise is considered to be white noise in GPS receivers for a typical sampling interval. The noise is not correlated between the GPS code and carrier phase measurements since each uses a different tracking loop. The noise is principally caused by tracking loop jitter (Raquet, 1998).

- **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.
Figure 3.8: The flatter the angle with which the circles with ranges R1 and R2 intersect, the higher the DOP value.

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.

Figure 3.9: The observation geometry effect

A “good geometry” therefore gives low DOP values. A “poor geometry” can give very high DOP values. As a general rule, PDOP values larger than 5 are considered poor.

3.2 Differential GPS

Differential GPS is a method to improve the positioning or timing performance of GPS using one or more reference stations at known locations, each equipped with at least one GPS receiver.
The differential GPS technique uses minimum two GPS receivers simultaneously. The Reference receiver antenna is mounted on a previously measured point with known coordinates. The receiver that is set at this point is known as the reference receiver or base station. The reference receiver can estimate very precisely what the ranges to the various satellites. The reference receiver can work out the difference between the computed and measured range values, these differences are corrections. There are two type of positioning errors, correctable and non-correctable. Correctable error is the error that is essentially same for two GPS receiver in same area. Non correctable errors cannot be corrected between two receivers in same area. The reference receiver is usually attached to a radio data link which is used to broadcast these corrections, the rover receiver is on the other end of these corrections. The rover receiver has a radio data link attached to it that enables it to receive the range corrections broadcast by the reference receiver and calculates ranges to the satellites. It then applies the range corrections received from the reference. This lets it calculate a much more accurate position than would be possible if the uncorrected range measurements were used. Using this technique, all of the error sources are minimized. The carrier phase is used because it provide more accurate measurement than use P code and C/A code. The L1 carrier wavelength is 19.4cm. Once the number of wavelength is measured, the range can be calculated with high accuracy.

3.2.1 Single differencing

![Single differencing geometry](image)

Figure 3.10: Single differencing geometry
Single differencing is used to eliminate satellite clock bias. Assume the observation equations for two receivers, A and B observing same satellite j:

The observation equation is:

\[ L_A^j = \rho_A^j + c\tau_A^j - c\tau_j^j + Z_A^j - I_A^j + B_A^j \]  

\[ L_B^j = \rho_B^j + c\tau_B^j - c\tau_j^j + Z_B^j - I_B^j + B_B^j \]  

The single difference phase is defined as the difference between two receivers:

\[ \Delta L_{AB}^j = L_A^j - L_B^j \]

\[ = (\rho_A^j + c\tau_A^j - c\tau_j^j + Z_A^j - I_A^j + B_A^j) - (\rho_B^j + c\tau_B^j - c\tau_j^j + Z_B^j - I_B^j + B_B^j) \]

\[ = (\rho_A^j - \rho_B^j) + (c\tau_A^j - c\tau_B^j) - (c\tau_j^j - c\tau_j^j) + (Z_A^j - Z_B^j) - (I_A^j - I_B^j) - (B_A^j - B_B^j) \]

\[ = \Delta \rho_{AB}^j + c\Delta \tau_{AB}^j + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j \]

The atmospheric delay is reduced, and vanish when two receivers are near. The differential troposphere can usually be ignored for horizontal separations less than approximately 30 km. The differential ionosphere can usually be ignored if the distance between the points of the baseline is between 1 and 30 km, depending on ionospheric conditions.

The single difference has the advantage that many error sources are eliminated or reduced, the disadvantage is that only relative position can be estimated, the receiver clock bias is still unknown. Thus double differencing is needed.

**3.2.2 Double Differencing**

The majority of the error incurred when making an autonomous position comes from imperfections in the receiver and satellite clocks. One way of passing this error is to use a
technique known as Double Differencing. If two GPS receivers make a measurement to two
different satellites, the clock offsets in the receivers and satellites cancel out, removing any
source of errors that they may contribute to the equation.

Consider the single difference observation equations for two receivers A and B observing
satellites j and k.

Figure 3.11: Double differencing geometry

The purpose of double differencing is to eliminate receiver clock bias. Consider the single
differenced observation equations for two receivers A and B observing satellites j and k:

$$\Delta L_{AB}^j = \Delta \rho_{AB}^j + c \Delta \tau_{AB}^j + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j$$  \hspace{1cm} 3.9

$$\Delta L_{AB}^k = \Delta \rho_{AB}^k + c \Delta \tau_{AB}^k + \Delta Z_{AB}^k - \Delta I_{AB}^k + \Delta B_{AB}^k$$  \hspace{1cm} 3.10

The double difference phase is defined as the difference between these two:

$$\Delta L_{AB}^{jk} = (\Delta \rho_{AB}^j + c \Delta \tau_{AB}^j + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j) - (\Delta \rho_{AB}^k + c \Delta \tau_{AB}^k + \Delta Z_{AB}^k - \Delta I_{AB}^k + \Delta B_{AB}^k)$$

$$= \Delta \rho_{AB}^{jk} + \Delta \tau_{AB}^{jk} - \Delta I_{AB}^{jk} + \Delta B_{AB}^{jk}$$  \hspace{1cm} 3.11
Any systematic effects due to unmodelled atmospheric errors are generally increased slightly by approximately 40% by double differencing as compared to single differencing. Similarly, random errors due to measurement noise and multipath are increased. Overall, random errors are effectively doubled as compared with the undifferenced observation equation. On the other hand, the motivation for double differencing is to remove clock bias, which would create much larger errors.
Chapter 4. Experimental approach

4.1 Experiment introduction

The accuracy of landslides monitoring should be in the centimeter level. GNSS allows positioning with the accuracy ranging from meters to millimeters, which depends on the GNSS equipment, positioning technique and surrounding environment. Geodetic GNSS receivers are usually deployed to conduct landslides monitoring, which is proved to be able to achieve high accuracy, but they are costly due to the high price and the loss because of unstable slope. The possible consequences are to restrict the number of receivers employed in the field, thus another cheaper but with less performance monitoring technique is needed. In recent years, precise positioning using low-cost receivers is becoming possible with the developing of technology. Several studies have been done to investigate the potential of low-cost GNSS receivers in recent years, the reported result is positive.

To simulate the displacement of landslide, a sliding device built by Laboratory of Topography of the Politecnico di Torino was used. The antenna of low-cost receiver was placed on the sliding device, which can be moved on both vertical and horizontal direction. The low-cost receiver used in the experiment is u-blox EVK-7P, which support raw data output. 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 the unknown point, data are collected simultaneously data from at least four satellites (Magged, K.M.A., 2014). Two reference stations were used for differential GPS, one is Geodetic GNSS receiver, and another is low-cost receiver u-blox EVK-7P.

The experiment site is located in Como Campus, Politecnico di Milano. Como is surrounded by mountains, which may block low elevation satellites. Considering the multipath effect, the
quality of signal is better if it is placed higher position. Two buildings are available in the campus: one of the receivers was placed on the roof of Castelnuovo building and the reference station was installed on the roof of Valleggio building in Como campus, Politecnico di Milano.

Three GNSS receivers were used in this experiment: EUREF Permanent station, u-blox reference station and one u-blox rover. The sliding device, together with u-blox rover antenna was placed on the roof of the Castelnuovo building. The sliding device was fixed on the roof to avoid unpredictable movements. The orientation towards north direction was done with the help of a total station.

![Figure 4.1: Location of experiment site](image)

**4.2 Instrumentation**

The instrumentation used in experiment is as follow:

- 2 u-blox evaluate kit EVK-7P and default antennas
- Como EUREF Permanent station
- A Geodetic Leica GX1230 GG receiver
- A Laptop with u-center software
- A Sliding device
- A Power supply
- A Sokkia Total station

4.2.1 GNSS receivers

The use of GNSS positioning is common with the developing of GNSS technology, ranging from geodetic receiver using triple frequency and multi-constellation to mass-market instruments that typically use only GPS constellation and pseudorange measurements on a single frequency. The accuracy is different for these two different type of receivers. Geodetic receivers can reach centimeter accuracy in real-time positioning and a sub-centimeter accuracy in post-processing while low-cost receivers are less accurate. Regarding post-processing, accuracy at centimeter level can be achieved even with a low-cost receiver. Nowadays, the use of low-cost receivers is widespread due to low cost but also because of the acceptable performance achieved in certain applications.

GNSS receivers can be divided into various groups according to different criteria. One classification of GPS receivers is based on acquisition of data types.

- C/A code receiver
- C/A code + L1 Carrier phase
- C/A code + L1 Carrier phase + L2 Carrier phase
- C/A code + P code + L1, L2 Carrier phase

55
• L1 Carrier phase

• L1, L2 Carrier phase

Based on technical realization of channel, the GPS receivers can be classified as:

• Sequential receiver: A GPS receiver in which the number of satellite signals to be tracked exceeds the number of available hardware channels. Sequential receivers periodically reassign hardware channels to particular satellite signals in a predetermined sequence.

• Multiplexing receiver: Multiplexing channel is one for which the sequencing time for all satellites assigned to channel is 20 milliseconds

• Multi-channel receiver: Most receivers are multi-channel, they are able to lock on to more than one satellite at a time

GPS receivers can also be classified based on the purpose as:

• Military receiver

• Civilian receiver

• Navigation receiver

• Timing receiver

• Geodetic receiver

For geodetic application it is essential to use the carrier phase data as observable. Use of L1 and L2 frequency is also essential for applications that requires sub centimeter accuracies.
Leica GX1230 GG

Leica GX1230 GG receivers were selected as reference station. It is able to provide the flexibility, power and performance needed for every type of GNSS application. It can be used as a reference or rover in any mode from static to RTK. The receiver is small, light, and supporting all formats and communication devices, which can be used on a pole, on a tripod, or on a construction machine, survey boat or aircraft.

![Leica GX1230 GG receiver](image)

Figure 4.2: Leica GX1230 GG

The SmartTrack+ measurement engine used in the receiver utilizes two global navigation satellite systems increasing the number of tracked satellites. Time needed to acquire all satellites after GNSS switching on is typically about 50 seconds. Measurement re-acquisition of satellites after loss of lock technology typically within 1 second. The receiver is able to acquire more than 99% of all possible observations above 10 degrees elevation.
<table>
<thead>
<tr>
<th>Receiver type</th>
<th>Dual-frequency, GNSS, geodetic, real-time RTK receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary of measuring, modes and applications</td>
<td>Static, rapid static, kinematic, on the fly L1+L2, code, phase, Real-time RTK, post processing, DGPS/RTCM standard survey, Geodetic and real-time RTK applications</td>
</tr>
<tr>
<td>Receiver technology</td>
<td>SmartTrack+ is built on SmartTrack technology and enhanced for GNSS signals.</td>
</tr>
<tr>
<td>No. of channels</td>
<td>72 channels</td>
</tr>
<tr>
<td></td>
<td>14 L1 + 14 L2 GPS</td>
</tr>
<tr>
<td></td>
<td>2 SBAS 12 L1 + 12 L2</td>
</tr>
<tr>
<td></td>
<td>GLONASS</td>
</tr>
<tr>
<td>Ports</td>
<td>4 RS232 port</td>
</tr>
<tr>
<td></td>
<td>1 Power only port</td>
</tr>
<tr>
<td></td>
<td>1 TNC port for antenna</td>
</tr>
<tr>
<td></td>
<td>1 PPS, 2 Event port optional</td>
</tr>
<tr>
<td>Dimensions</td>
<td>0.212m x 0.166m x 0.079m</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>Nominal 12V DC</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Range 10.5-28V DC</td>
</tr>
<tr>
<td></td>
<td>Typically 3.2W, 270mA</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of Leica GX 1230 GG

Leica GX1230 GG can reach very high accuracy when it is used for both carrier phase and code observation.

<table>
<thead>
<tr>
<th>Carrier phase on L1</th>
<th>0.2mm RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier phase on L2</td>
<td>0.2mm RMS</td>
</tr>
<tr>
<td>Code (pseudorange) on L1</td>
<td>2cm RMS</td>
</tr>
<tr>
<td>Code (pseudorange) on L2</td>
<td>2cm RMS</td>
</tr>
</tbody>
</table>

Table 4.2: Code and phase measurement precision of Leica GX1230 GG
<table>
<thead>
<tr>
<th>Static (phase), long lines, long observations, choke ring antenna</th>
<th>Horizontal: 3mm + 0.5ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vertical: 6mm + 0.5ppm</td>
</tr>
<tr>
<td>Static and rapid static (phase) with standard antenna</td>
<td>Horizontal: 5mm + 0.5ppm</td>
</tr>
<tr>
<td></td>
<td>Vertical: 10mm + 0.5ppm</td>
</tr>
<tr>
<td>Kinematic (phase), in moving mode after initialization</td>
<td>Horizontal: 10mm + 1ppm</td>
</tr>
<tr>
<td></td>
<td>Vertical: 20mm + 1ppm</td>
</tr>
<tr>
<td>Code only</td>
<td>Typically 25cm</td>
</tr>
</tbody>
</table>

Table 4.3: Accuracy (RMS) with post processing

**u-blox EVK-7P**

The u-blox EVK-7P receiver was developed by u-blox, which is a leading provider of wireless and positioning sensors and modules for the automotive, industrial and consumer markets. EVK 7P is a consumer-grade GNSS receiver equipped with the u-blox GPS platform NEO-7P and a high performance active GNSS antenna. EVK-7P GNSS module support both PPP and RTCM D-GPS in standard point-positioning mode for survey use.

![u-blox EVK-7P evaluation kit](image)

Figure 4.3: u-blox EVK-7P evaluation kit

EVK-7P evaluation kit includes:

- Compact 105*64*26mm EVK unit
- Antenna with 3m cable
- Extra battery RENATA CR2450
- Quick start reference card

The receiver has the following advantage:

- Easy to use, extensive visualization and evaluation features
- Support u-blox AssistNow GNSS Online, Offline and Autonomous
- All ports accessible outside
- USB(V2.2 compatible) available for power supply and data transfer

To configure and use a u-blox receiver a user must install on a PC the u-center evaluation software. This software can provide a powerful platform for product evaluation, configuration, testing and real time performance visualization of u-blox GNSS receiver products. U-center provides a convenient means to configure the GNSS receiver, to save customized configuration settings in the GNSS receiver flash memory and to restore factory settings if needed.

The u-center can perform structured and graphical data visualization in real time:

- Satellite summary view
- Navigation summary view
- Compass, speedometer, clock, altimeter
- Chart view of any two parameters of choice
- Data recording and playback functionality
Micrometric Slide (Sliding device)

The micrometric slide was built by the Laboratory of Topography at Politecnico di Torino. It is composed of a hardened steel bar with a special support which allows to forced centering on a known point. A hand-wheel controls the horizontal and vertical movement on the rail. The controls demonstrated that the precision of slide movement is better than 1mm, therefore it can satisfy the experiment needs. The movement in the horizontal direction is up to 1.3m and in the vertical direction is up to 30cm. For this experiment, it was decided to move the antenna by 5mm increments alternating the horizontal and vertical direction after every two hours. In total, at the end of the experiment the antenna has been moved 10 cm both in the horizontal and vertical direction.

![Micrometric slide](image1)

**Figure 4.4: Micrometric slide**

![Micrometric slide setup](image2)

**Figure 4.5: Micrometric slide setup**
4.2.2 Software introduction

There are a lot of GNSS manufacturers, and they use different GNSS processing software packages. Each of them is unique when it comes to data processing algorithms. Thus, processing same data in different software will lead to results which are slightly different. Usually commercial software do not publish the mathematical models used for baseline processing, network adjustment and coordinate transformations.

A GNSS software generally consists of three basic components: a functional library, a data platform and a data processing core. The functional library provides all possibly needed physical models, algorithms and tools. The data platform prepared all possibly needed data for use and performing the preparation in a time loop. The data processing core forms the observation equations, accumulates them within the time loop and solves the problem.

- **RTKLIB**

RTKLIB is an open source program package for standard and precise positioning. It consists of a portable program library and several APs (application programs) utilizing the library.

![Figure 4.6: Functions of RTKLIB](image)

The features of RTKLIB:

- 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 BINR.

• It supports external communication via: Serial, TCP/IP, NTRIP, local log file and FTP/HTTP.

• It provides many library functions and APIs for GNSS data processing: satellite and navigation system functions, matrix and vector functions, time and string functions, coordinates transformation, input and output functions, debug trace functions, platform dependent functions, positioning models, atmosphere models, antenna models, earth tides models, geoid models, datum transformation, RINEX functions, ephemerides and clock
functions, precise ephemerides and clock functions, receiver raw data functions, RTCM functions, solution functions, Google Earth KML converter, SBAS functions, options functions, stream data input and output functions, integer ambiguity resolution, standard positioning, precise positioning, post-processing positioning, stream server functions, RTK server functions, download functions.

- **Leica Geo Office**

Leica Geo Office is an easy, fast and comprehensive, automated suite of programs for TPS, GPS and level data developed by Leica Geosystem. It is able to process independently or combine data, including post processing and support of real-time GPS measurements. The software functions include project management, data transfer, import/export, processing, viewing data, editing data, adjustment, coordinate systems, transformations, codetests, reporting etc.

Leica Geo office has a complete range of libraries and tools for defining coordinate systems and transforming coordinates from one system to another. The software allows different management like projects, coordinate systems, GPS antennas and report templates. The software has libraries of ellipsoids, projections, geoidal models and six different transformation methods. The conversion between WGS84 and local coordinates is possible with the Leica Geo office coordinate management.

**Software components**

- **Data and Project Management:**

  Data and project management is able to manage all points and measurements within projects. According to well-defined rules to ensure data integrity is always maintained. Projects, coordinate systems, antennas, report templates and code lists all have their own management. Numerous transformations, ellipsoids and projections, as well as user-
defined geoid models and country specific coordinate systems which are based on a grid of correction values are supported.

- Import & Export:

  Import & Export allows to import data from compact-flash cards, directly from receivers, total stations and digital levels, or from reference stations and other sources via the Internet. Import of real-time (RTK), DGPS coordinates is also available.

- ASCII Import & Export:

  ASCII Import & Export allows to import coordinate lists as user-defined ASCII files using the import wizard. Export results in any format to any software can be done by ASCII export function. Transfer point, line, area, coordinate, code and attribute data to GIS, CAD and mapping systems is also available.

- View & Edit:

  The various graphical displays form the basis for visualizing data and giving an instant overview of the data contained within a project. Point, line and area information may be viewed in View/Edit together with coding and attribute information. Editing functionality is embedded allowing to query and clean up the data before processing or exporting it further.

Two main modules are used for data processing in this experiment, which are coordinate transformations and GNSS post-processing. The GNSS post-processing module can process most type of GNSS raw data including the data from Leica and u-blox receivers.

### 4.3 Experiment setup

The experiment was performed between 19 Jan, 2016 and 19 Feb, 2016, from GPS day 28 to GPS day 50. The short baseline EUREF Permanent station and u-blox reference is used to
estimate the coordinates of u-blox reference station based on the data acquire from 19 Jan to 28 Jan. The Simu-slide experiment started on 28 Jan, 2016 and ended on 11 Feb, 2016. Because data for several days had a low quality, to be accurate, some displacements were repeated during 11 Feb, 2016 to 19 Feb, 2016 in the end of the experiment.

**Step 1. Instrumentation setup**

The first step of setup is to install all the instrumentation. Three GNSS receivers and the sliding device were installed on different sites. Next, we worked on the orientation and leveling of sliding device with the help of a total station we oriented the device along the North-East direction.

The receivers are installed in different site:

- Valleggio u-blox:
  
  u-blox EVK-7P was placed on Valleggio building. This receiver was used as reference station.

- Geodetic reference:
  
  Leica GRX-1230 GG was placed on the Castelnuovo building.

- Castelnuovo slide:
  
  U-blox EVK-7P antenna was fixed on sliding device on the roof of the Castelnuovo building.

- EUREF Permanent station:
  
  Topcon geodetic receiver was on the Valleggio building.
The u-blox reference and the EUREF permanent station was already installed on the roof of Valleggio building, which do not need any installment.

Figure 4.7: Como EUREF Permanent station

The coordinates of the EUREF Permanent Station are known. The X, Y, Z coordinates in ITRF2008-WGS84 are as follow:

<table>
<thead>
<tr>
<th></th>
<th>X(m)</th>
<th>Y(m)</th>
<th>Z(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUREF Permanent station</td>
<td>4398306.009</td>
<td>704150.056</td>
<td>4550154.799</td>
</tr>
</tbody>
</table>

Table 4.4: ITRF2008-WGS84 coordinate of EUREF Permanent station

Figure 4.8: Power supply cabinet
The u-blox receiver rover was placed in a plastic box to prevent rain getting to it. To configure the receiver a connection via a USB cable to a laptop was used. The antenna was fixed on the sliding device on a special support that allows centering and fixing. The laptop and geodetic receiver Leica GX 1200 GG was placed in the rack in the cabinet to ensure safety and prevent any damage caused by rain.

Figure 4.9: Setup of sliding device and receivers

Figure 4.10: Fixing the north direction of sliding device
Step 2. SIMU-SLIDE

The second part of the experiment is the simulation of a landslide, this work is the core part of the thesis. The simulation is done by using the sliding device. The sliding device can be shifted on both vertical and horizontal directions, which allowed us to reproduce the typical movements of landslides. In the experiment, the horizontal and vertical total displacements amounted to 10 cm and it was achieved by 5 mm increments. Each observation day had 4 sessions, two hours long each and consisted in alternating between horizontal and vertical induced displacements. The working scheme for the displacements is as follows: first movement took place between 8am to 9am local time, the second movement took place between 11 and 12am local time, the third displacement took place between 2pm and 3pm local time, and the last movement of the antenna was done between 5pm and 6pm local time. The session length is 2 hours, which is long enough to fix the ambiguity as integer and be able to achieve sub-centimeter accuracy.

The tracking configuration used during the experiment is presented below:

- GPS satellites
- Static mode
- Elevation mask 15°
- No SNR mask
- Sampling rate of 1 Hz

The displacement schedule is as follow:

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Horizontal(cm)</th>
<th>Vertical(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28/01/2016</td>
<td>08:00 – 09:00</td>
<td>50.00</td>
<td>30.00</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>50.50</td>
<td>30.00</td>
</tr>
<tr>
<td>Date</td>
<td>Time</td>
<td>Price</td>
<td>Commission</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------</td>
<td>-------</td>
<td>------------</td>
</tr>
<tr>
<td>29/01/2016</td>
<td>08:00 – 09:00</td>
<td>51.00</td>
<td>29.00</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>51.50</td>
<td>28.50</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>51.50</td>
<td>28.00</td>
</tr>
<tr>
<td></td>
<td>17:00 – 18:00</td>
<td>52.00</td>
<td>28.50</td>
</tr>
<tr>
<td>01/02/2016</td>
<td>08:00 – 09:00</td>
<td>52.00</td>
<td>28.00</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>52.50</td>
<td>28.00</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>52.50</td>
<td>27.50</td>
</tr>
<tr>
<td></td>
<td>17:00 – 18:00</td>
<td>53.00</td>
<td>27.50</td>
</tr>
<tr>
<td>02/02/2016</td>
<td>08:00 – 09:00</td>
<td>53.00</td>
<td>27.00</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>53.50</td>
<td>27.00</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>53.50</td>
<td>26.50</td>
</tr>
<tr>
<td></td>
<td>17:00 – 18:00</td>
<td>54.00</td>
<td>26.50</td>
</tr>
<tr>
<td>03/02/2016</td>
<td>08:00 – 09:00</td>
<td>54.00</td>
<td>26.00</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>54.50</td>
<td>26.00</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>54.50</td>
<td>25.50</td>
</tr>
<tr>
<td></td>
<td>17:00 – 18:00</td>
<td>55.00</td>
<td>25.50</td>
</tr>
<tr>
<td>04/02/2016</td>
<td>08:00 – 09:00</td>
<td>55.00</td>
<td>25.00</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>55.50</td>
<td>25.00</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>55.50</td>
<td>24.50</td>
</tr>
<tr>
<td></td>
<td>17:00 – 18:00</td>
<td>56.00</td>
<td>24.50</td>
</tr>
<tr>
<td>05/02/2016</td>
<td>08:00 – 09:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>56.00</td>
<td>24.00</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>56.50</td>
<td>24.00</td>
</tr>
<tr>
<td></td>
<td>17:00 – 18:00</td>
<td>56.50</td>
<td>23.50</td>
</tr>
<tr>
<td>08/02/2016</td>
<td>08:00 – 09:00</td>
<td>57.00</td>
<td>23.50</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>57.00</td>
<td>23.00</td>
</tr>
<tr>
<td>Date</td>
<td>Time</td>
<td>Value 1</td>
<td>Value 2</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>09/02/2016</td>
<td>08:00 – 09:00</td>
<td>58.00</td>
<td>22.50</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>58.00</td>
<td>22.00</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>58.50</td>
<td>22.00</td>
</tr>
<tr>
<td></td>
<td>17:00 – 18:00</td>
<td>58.50</td>
<td>21.50</td>
</tr>
<tr>
<td>10/02/2016</td>
<td>08:00 – 09:00</td>
<td>59.00</td>
<td>21.50</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>59.00</td>
<td>21.00</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>59.50</td>
<td>21.00</td>
</tr>
<tr>
<td></td>
<td>17:00 – 18:00</td>
<td>59.50</td>
<td>20.50</td>
</tr>
<tr>
<td>11/02/2016</td>
<td>08:00 – 09:00</td>
<td>60.00</td>
<td>20.50</td>
</tr>
<tr>
<td></td>
<td>11:00 – 12:00</td>
<td>60.00</td>
<td>20.00</td>
</tr>
<tr>
<td></td>
<td>14:00 – 15:00</td>
<td>60.00</td>
<td>20.00</td>
</tr>
</tbody>
</table>

Table 4.5: Time table of displacements
Chapter 5. Data processing and discussion

This chapter includes three sections. First section is the data processing of the short baseline between Como EUREF Permanent station and u-blox reference station on the Valleggio roof to estimate the coordinate of u-blox reference station. The second part is the data processing of baseline between Como EUREF Permanent station and the rover u-blox on the sliding device. The last section of the chapter presents the results obtained after processing the data for the baseline between the u-blox used as reference station and the u-blox used as rover.

Raw data acquired in a GNSS static survey can be post-processed with scientific, commercial and FOSS software. For our purpose we decided it is enough to use two software: one commercial and one FOSS. Some FOSS allow users to control in a deep the processing strategy, which is useful especially for very experienced users. However, the drawback is that these type of software are less stable.

5.1 Pre-processing

The pre-processing includes two steps: first step is to convert u-blox raw data to RINEX format and second step, to estimate the coordinates of the u-blox reference station.

Raw data logged by u-blox receiver is stored in .ubx format, which need to be convert to RINEX format. RINEX (Receiver Independent Exchange Format) is a data interchange format which allows the user to post-process the received data in different software. RTKCONV function of the RTKLIB software was used for converting the .ubx format data to RINEX format.

The raw observation data acquired by u-blox reference station is continuous, it also can be divided into hourly interval data by using RTKCONV function.
The approximate position of the reference station need to be typed in the software before data converting.

After converting the data format, the second step is to estimate the coordinates of u-blox reference station. The GPS processing technique for this research is relative static positioning. Relative positioning exploits data from two or more GPS receivers, simultaneously tracking the same satellites. The principle of this technique is based on determining baseline between the
reference site and the rover. Static relative positioning by double differencing the carrier phase observations is the most frequently used as it can achieve accuracy at sub-centimeter level.

The first baseline is between Como EUREF Permanent station and the u-blox on the Valleggio roof. By processing this baseline, the coordinates of u-blox reference station is estimated. The data set acquisition is from 19 Jan, 2016 to 28 Jan, 2016.

![Figure 5.3: Flowchart of u-blox reference station coordinate estimation](image)

- **Data processing using LGO**

LGO is a commercial software developed by Leica Geosystem, which is widely used for GPS data processing. As to the processing parameters, broadcast ephemeris, GPS L1 data, the Saastamoinen tropospheric model and ionospheric model Klobuchar were adopted.

The processing parameters are as follows:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix Ambiguities up to</td>
<td>Yes</td>
</tr>
<tr>
<td>Cutoff angle</td>
<td>15 degree</td>
</tr>
<tr>
<td>Ionospheric model</td>
<td>Klobuchar</td>
</tr>
<tr>
<td>Tropospheric Model</td>
<td>Saastamoinen</td>
</tr>
<tr>
<td>Ephemerides</td>
<td>Broadcast</td>
</tr>
</tbody>
</table>

Table 5.1: Processing parameters of LGO
After RINEX conversion, the data collection is imported into a processing software LGO using the function “import”, the data were processed hour by hour.

The ITRF2008-WGS84 coordinates of reference point were input to the software before data processing:

Figure 5.4: Interface of LGO

Figure 5.5: Processing parameters of LGO
**Result:**

Table 5.2 shows the basic statistics computed based on the results of 169 hourly sessions. The RMS is less than 1cm in by of the 3 components (East, North and Height), which illustrates the result is reliable.

<table>
<thead>
<tr>
<th></th>
<th>East(m)</th>
<th>North(m)</th>
<th>Height(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>507437.1924</td>
<td>5072074.2737</td>
<td>292.9479</td>
</tr>
<tr>
<td>RMS</td>
<td>0.0022</td>
<td>0.0029</td>
<td>0.0050</td>
</tr>
<tr>
<td>Minimum</td>
<td>507437.1875</td>
<td>5072074.2669</td>
<td>292.9377</td>
</tr>
<tr>
<td>Maximum</td>
<td>507437.1987</td>
<td>5072074.2808</td>
<td>292.9613</td>
</tr>
</tbody>
</table>

Table 5.2: The coordinates of u-blox reference station (Processed by LGO)

- **Data processing using RTKLIB**

RTKLIB is also used to process the GPS data. RTKLIB support various positioning modes real-time and post-processing: Single, DGPS/DGNSS, Kinematic, Static, Moving-Baseline, Fixed, PPP-Kinematic, PPP-Static, PPP-Fixed.

<table>
<thead>
<tr>
<th>Positioning Mode</th>
<th>Static</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>L1</td>
</tr>
<tr>
<td>Fix Ambiguities up to</td>
<td>Yes</td>
</tr>
<tr>
<td>Cutoff angle</td>
<td>15 degree</td>
</tr>
<tr>
<td>Ionospheric model</td>
<td>Klobuchar</td>
</tr>
<tr>
<td>Tropospheric Model</td>
<td>Saastamoinen</td>
</tr>
<tr>
<td>Ephemerides</td>
<td>Broadcast</td>
</tr>
</tbody>
</table>

Table 5.3: Processing parameters of RTKLIB
These parameters were set in the “option” panel of RTKLIB software:

![Processing parameters input panel](image)

Figure 5.6: Processing parameters input panel

The reference station coordinates also need to be typed into the software in the “position” panel:

![Option of RTKLIB](image)

Figure 5.7: Option of RTKLIB
Result:
The result analysis is performed in Table 5.4, the RMS of 3 components (East, North and Height) are all greater than the result processed by LGO, which is due to the two software using different algorithm, the overall RMS is still less than 1cm.

<table>
<thead>
<tr>
<th></th>
<th>East(m)</th>
<th>North(m)</th>
<th>Height(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>507437.1921</td>
<td>5072074.2727</td>
<td>292.8835</td>
</tr>
<tr>
<td>RMS</td>
<td>0.0038</td>
<td>0.0058</td>
<td>0.0094</td>
</tr>
<tr>
<td>Minimum</td>
<td>507437.1828</td>
<td>5072074.2592</td>
<td>292.8637</td>
</tr>
<tr>
<td>Maximum</td>
<td>507437.2028</td>
<td>5072074.2844</td>
<td>292.9133</td>
</tr>
</tbody>
</table>

Table 5.4: The coordinates of u-blox reference station (Processed by RTKLIB)

- **Result comparison between LGO and RTKLIB:**

<table>
<thead>
<tr>
<th></th>
<th>East(m)</th>
<th>North(m)</th>
<th>Height(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTKLIB</td>
<td>507437.1921</td>
<td>5072074.2727</td>
<td>292.8835</td>
</tr>
<tr>
<td>LGO</td>
<td>507437.1924</td>
<td>5072074.2737</td>
<td>292.9479</td>
</tr>
<tr>
<td>Difference</td>
<td>0.0003</td>
<td>0.0010</td>
<td>0.0644</td>
</tr>
</tbody>
</table>

Table 5.5: Result comparison of LGO and RTKLIB

The horizontal coordinates given by LGO and RTKLIB are slightly different (see Table 5.5). For east and north differences are 3mm and 1 mm respectively. These values are within the error limitation, and are caused by the different processing algorithms used by the software. However, the difference for vertical direction reaches 6.44 mm, which exceeds the error range. After investigation, the error is due to the RTKLIB cannot estimate the phase center of the u-blox antenna. Based on the comparison outcome it was decided to use only LGO for the next phase of the testing campaign.

After processing all data, it was discovered that the initial position at the beginning and at the end of the experiment are different. After more in depth checking it was noticed a shift in the
position of u-blox receiver used as reference station. This problem occurred on February the 3rd between 22:00-23:00. Most probably this issue was caused by adverse weather conditions. On that particular day heavy rain with powerful wind occurred. At this point it was necessary to identify the magnitude of the shift and then removed it from all sessions starting with 23:00, 3rd of February 2016. Table 5.6 shows that the shift on east is 6.4 mm, north is 5.4 mm and height is 0.4 mm. The overall shift is less than 1cm but still too big to be neglected. Thus the final position of u-blox reference station was re-estimated from 23:00, 3rd of February 2016 to the end, the new coordinates of the u-blox reference station is used for the data processing.

<table>
<thead>
<tr>
<th></th>
<th>East(m)</th>
<th>North(m)</th>
<th>Height(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial position</td>
<td>507437.1924</td>
<td>5072074.2737</td>
<td>292.9479</td>
</tr>
<tr>
<td>Ending position</td>
<td>507437.1988</td>
<td>5072074.2683</td>
<td>292.9483</td>
</tr>
<tr>
<td>Displacement</td>
<td>0.0064</td>
<td>-0.0054</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

Table 5.6: Coordinates comparison of u-blox reference initial and ending position

**LGO processing result analysis:**

Fig. 5.8-Fig. 5.10 illustrate that for horizontal direction all residuals are less than 1 cm, while for height the situation is slightly worse but still satisfactory. In the vertical direction the largest residual did not reach 1.5 cm.

![Figure 5.8: Time series of residuals for North, static method, 1 hour session (LGO)](image-url)
5.2 Data processing of Simu-slide

The main goal of Simu-slide experiment is to determine whether the low-cost receiver can detect the sub-centimeter displacement. A controlled displacement of 5 mm was induced after every two hours, alternating between horizontal and vertical movements. The position of the antenna is estimated after each displacement and then compared with the known theoretical displacement. It is known that vertical accuracy is worse compared to horizontal accuracy. In
order to check this statement the basic statistics indexes computed for horizontal and vertical residuals were compared.

The data acquisition was from 28 Jan, 2016 to 11 Feb, 2016. The data was processed by the commercial software Leica Geo Office developed by Leica Geosystems, which is based on the double differences approach. In the next picture it can be seen the flowchart that summarizes the overall working procedure adopted in this project.

Two baselines were processed, EUREF Permanent station with u-blox rover and u-blox reference with u-blox rover, the result and comparison was performed.

![Flowchart of Simu-slide coordinate estimation](image)

Figure 5.11: Flowchart of Simu-slide coordinate estimation

The frequency was set as L1 because the low-cost receiver u-blox EVK-7P is only able to receive the L1 signal. The cut-off angle is set as 15 degrees because the low altitude satellite signal quality is not good due to the effect of the mountains around the receiver.

Processing parameters of LGO:
Table 5.7: LGO processing parameters

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix Ambiguities up to</td>
<td>yes</td>
</tr>
<tr>
<td>Cut-off</td>
<td>15 degrees</td>
</tr>
<tr>
<td>Ionospheric model</td>
<td>Klobuchar</td>
</tr>
<tr>
<td>Tropospheric model</td>
<td>Saastamoinen</td>
</tr>
<tr>
<td>Ephemerides</td>
<td>Broadcast</td>
</tr>
</tbody>
</table>

5.2.1 Baseline EUREF permanent station and u-blox rover

For the first part of the experiment we used a geodetic receiver as reference station, while the low-cost receiver was placed on the sliding device, and used as rover. This pair of observation is used as reference due to the EUREF permanent station use a geodetic receiver, which is stable and precise.
Result and discussion:

The orange line is the estimated displacement. The displacement is computed by using the coordinate of each position. The blue line is the theoretical displacement, which is 5mm between each session.

Figure 5.14: Horizontal difference between theoretical and estimated displacement

(Baseline EUREF permanent station and u-blox rover)
The Fig. 5.14 and 5.15 illustrate that the receiver is able to detect the displacement trend for both horizontal and vertical direction. For each session, there are some errors, the typical errors are millimeter level in horizontal and centimeter level in vertical direction.

The statistic analysis of errors is as follow:

Figure 5.15: Vertical difference between theoretical and estimated displacement

(Baseline EUREF permanent station and u-blox rover)

Figure 5.16: Horizontal errors (Baseline EUREF permanent station and u-blox rover)
The maximum horizontal error between estimated and theoretical displacement is 1.04 mm, the average error is -0.1 mm, the maximum vertical error is 3.05 mm, the average vertical error is 2.8 mm. The overall accuracy of detected displacement achieves centimeter level, see Table 5.8.

<table>
<thead>
<tr>
<th></th>
<th>Horizontal(m)</th>
<th>Vertical(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>-0.0001</td>
<td>0.0028</td>
</tr>
<tr>
<td>RMS</td>
<td>0.0042</td>
<td>0.0137</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.0104</td>
<td>0.0305</td>
</tr>
<tr>
<td>Minimum</td>
<td>-0.0001</td>
<td>-0.0001</td>
</tr>
</tbody>
</table>

Table 5.8: Statistics analysis of errors (Baseline EUREF permanent station and u-blox rover)

Table 5.9 illustrates the statistic analysis of the residuals in different residual classes. In 54 out of 78 cases, the residuals are less than 5 mm for the North, and 68 out of 78 cases for the East, no residual is greater than 20mm for the horizontal direction. The height results are slightly worse with 12 sessions having residuals greater than 20 mm, 66 sessions are less than 20mm, and the result shows that even for the geodetic receiver, the height accuracy is less accurate than horizontal.
<table>
<thead>
<tr>
<th>Error class</th>
<th>East</th>
<th>North</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5mm</td>
<td>68</td>
<td>54</td>
<td>18</td>
</tr>
<tr>
<td>5-10mm</td>
<td>7</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>10-15mm</td>
<td>3</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>15-20mm</td>
<td>0</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>&gt;20mm</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 5.9: Number of residuals for different residual classes (Baseline EUREF permanent station and u-blox rover).

5.2.2 Baseline u-blox reference and u-blox rover

For the second baseline it was decided to use as reference station a low cost receiver. In this way a fully low-cost configuration could be tested. The advantage is that the cost of the monitoring system is significantly lower when compared to the first case (geodetic receiver used as reference station). The drawback is that u-blox itself is less stable than a geodetic receiver, and the antenna is the weak link of the chain. If the final result is positive, the target of using only low-cost receivers for landslides monitoring can be reached.

Two analysis were performed: first, a comparison between theoretical and estimated displacement, and secondly, the comparison between the results of the two baselines of the experiment.
Based on the summary presented in Figures 5.18 and 5.19, it can be stated that the performance of the low-cost receiver is encouraging. These figures illustrate that even though there are errors between theoretical and estimated displacements when single sessions are individually analyzed, the trend of the theoretical displacement is closely detected by the system. The best results were obtained for horizontal displacements: they follow very closely the theoretical displacements, except one session. Both the trend line in Fig. 5.14 and Fig. 5.18 fit the
theoretical displacement well, the slight difference is that first figure fits better, the geodetic receive is still more stable than low-cost receiver.

The residuals were computed by subtracting the estimated displacements from the theoretical displacements. These residuals are presented in Figure 5.20 for horizontal direction and in Figure 5.21 for vertical direction.

![Figure 5.20: Horizontal errors (Baseline u-blox reference and u-blox rover)](image)

![Figure 5.21: Vertical errors (Baseline u-blox reference and u-blox rover)](image)

The horizontal residuals are less than 1 cm except one session (Fig. 5.20), while the vertical residuals present worse statistics but still the errors are well under 5 cm except two sessions (Fig. 5.21).
Table 5.10: Horizontal and vertical difference between theoretical and estimated displacement (Baseline u-blox reference and u-blox rover)

<table>
<thead>
<tr>
<th></th>
<th>Horizontal(m)</th>
<th>Vertical(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>-0.0014</td>
<td>0.0120</td>
</tr>
<tr>
<td>RMS</td>
<td>0.0064</td>
<td>0.0181</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.0236</td>
<td>0.0812</td>
</tr>
<tr>
<td>Minimum</td>
<td>-0.0001</td>
<td>-0.0001</td>
</tr>
</tbody>
</table>

Table 5.11 is the statistic analysis of the residuals in different residual classes. In 56 out of 78 cases, the residuals are less than 5 mm for the North, and in 67 cases out of 78 cases for the East. However, height results are slightly worse with 20 session residuals greater than 20 mm.

<table>
<thead>
<tr>
<th>Error class</th>
<th>East</th>
<th>North</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5mm</td>
<td>67</td>
<td>54</td>
<td>12</td>
</tr>
<tr>
<td>5-10mm</td>
<td>6</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>10-15mm</td>
<td>2</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>15-20mm</td>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>&gt;20mm</td>
<td>2</td>
<td>2</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 5.11: Number of residuals for different residual classes (Baseline u-blox reference and u-blox rover)

By comparing the Table 5.9 and Table 5.11, results from two different baselines, the performance of the first baseline is more reliable due to the geodetic receiver is more stable. Both the results are satisfying with most of the residues are less than 5mm.
Chapter 6. Conclusion and recommendation

This thesis has presented an experimental study on feasibility of low-cost GNSS receivers for landslides monitoring. This last chapter summarizes conclusion of the experiment had done in last few months and the recommendation for the future research.

6.1 Conclusion

Landslide is one of the most damaging and deadly of natural hazards which responsible for considerable loss of property and lives worldwide. Monitoring landslide is important because the risk for human, engineering structures and environment. The timely monitoring of landslide deformation can save lives, avert financial loss can avoid environmental damage.

By monitoring the surface displacement of a slope, the information of dynamics of a landslide can be provided. GPS has been frequently applied to landslide studies worldwide, both as a complement and as an alternative to conventional landslide surveying methods. It is particularly important to develop cost-effective reliable landslide monitoring systems and technologies. Single-frequency GPS receivers are potentially suitable for landslide monitoring because of their small size, low cost and less power consumption. The performance of low-cost receiver is accessed in the thesis.

The development of low-cost GNSS receivers is very fast, and new technologies evolve continuously. In this contribution, the author decided to analysis the feasibility of low-cost GNSS receiver for landslide monitoring. The low-cost GNSS receiver tested in the experiment is u-blox EVK-7P.

Regarding the main topic of this research, SIMU-SLIDE, the main conclusions of the results obtained are summarized below:
• LGO software is able to process all kinds of GNSS data with high accuracy. By using different strategy, LGO is able to give satisfying result, it also can handle local networks for deformation monitoring.

• RTKLIB is able to achieve similar results comparing with LGO, the results are only slightly different. The problem of RTKLIB is that the software do not support all the antenna types.

• u-blox can be trusted for applications that require centimeter level accuracies. In the experiment, the low-cost GNSS receiver u-blox EVK-7P can detect the 5mm displacement in horizontal, and centimeter level accuracy in vertical direction. The performance is more reliable in horizontal direction than vertical direction.

• Either geodetic receiver or low-cost receiver can be used as reference station, both the methods can achieve sufficient accuracy. Using geodetic receiver as reference station, the performance is more stable in each session comparing with using the low-cost receiver as reference station. In real landslide monitoring, different receivers can be used according to different demands.

6.2 Recommendations for future research

• During the experiment, almost all the data recorded under bad weather conditions (heavy rain) have low SNR values and many cycle slips. Clearly, this is a main problem because in the landslide monitoring, the receiver should be able to work in all-weather conditions. Thus, investigating the effect of rain on the low-cost antenna becomes an important issue. New low-cost receivers needed to be tested in future.

• In order to achieve high-precision GPS results it is necessary to know the exact position of the phase, a relative antenna calibration to estimate the phase center variations (PCVs) is needed to improve the results in future.
• The length of each session should be decreased, a shorter time interval of 15 min can be considered for having a higher sampling rate of the landslide area.

• The experiment was done in simulation way, which is a simplified and ideal condition. However, the real landslide condition is more complex. Even if the technique is proved in experimental condition, the validation in real case is needed. Once all the experimental work is done with satisfying results, we can start to perform a monitoring of real landslide site. If the technique is proved in both experiment and actual landslide site, it can be generalize to more fields.
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