UNIVERSITÀ DEGLI STUDI DI PADOVA
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Department Of Civil, Environmental and Architectural Engineering

Corso di Laurea Magistrale in Environmental Engineering

TESI DI LAUREA

ANALYSIS OF REAL-TIME GNSS POSITIONING USING RTK NETWORKS: VENETO REGION CASE STUDY

Relatore:
Chiar.mo PROF. MASSIMO FABRIS

Laureando: ABHA ARANI ISLAM
2012974

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Abstract

In this project, we aim to understand the accuracy of GNSS positioning given by different RTK networks, namely the Veneto GPS network, the Leica network (HxGN SmartNet), the Marussi network (Friuli-Venezia Giulia), and the TPOS (Trentino) network. For this purpose, the real-time differential corrections for elevations and geographic coordinates obtained utilizing these four networks are compared among themselves and also with the coordinates achieved using the relative positioning technique, which provides positioning with a very high level of precision. Among the four different networks, the Leica network is a national network and the other three networks are regional and all of them are the networks of continuous GNSS stations. The field surveys were carried out in two different test sites located in Padua and Longarone due to distances from regional networks and the positioning was performed at two observation points in each site. The differential corrections were achieved from the four networks using two antennas connected with two receivers and the corrections from each network were acquired within just five minutes, while the relative positioning performed using two receivers required a three-hour session in each site. These elevations and coordinates were determined using different spatial reference systems and UTM zones for comparison and finding the most accurate result. Furthermore, the results obtained using differential and relative positioning techniques were also compared with positioning obtained using classical topographic methods, which are: geometric leveling from the middle and total station survey, to observe whether the GNSS positioning determined using these different methods is comparable. The classical topographic method yields positioning results with the highest precision and thus they were considered to be the correct value. The difference in elevations between each of the two points and the 2D distance from the difference in the coordinates were calculated for implementing the comparison. It was found that the static or relative positioning method provided the most accurate results, which are very close to the positioning obtained through the classical topographic survey, while the differential positioning computed by different RTK networks also provided positioning with high level of precision, in the order of mm, and varied depending on their distance from the test site and other relevant factors.

Acknowledgement

First and foremost, I would like to express my gratitude to the Almighty for giving me the strength to complete the study successfully. I would like to thank my family for their constant support. This research paper is made possible through the help and support of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of the study.

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Abha Arani Islam

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Chapter 1
Introduction

From the very beginning of the scientific revolution, mankind is interested in the field of positioning system, trying to develop a technology for determining its exact location on earth. At present, many technologies are being utilized in this process. For example, satellites, stations, and specific devices are employed to improve the accuracy of the location.

It is possible to describe how the positioning is performed by a satellite by considering an example of a lighthouse and a ship, which are assumed to be the satellite and the receiver, respectively. The ship, whose position has to be determined, receives signals transmitted by the satellite. The distance between the lighthouse and the ship is obtained by multiplying the time that the signal takes to travel from the lighthouse to the ship by the speed of the signal. Using this distance, a circular domain containing the possible location of the ship can be created, which can be further improved by creating another circle using an additional lighthouse as shown in Figure 1.1 [2].

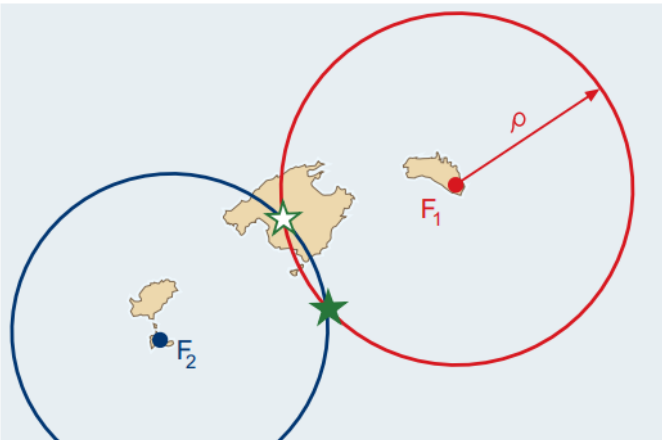

Figure 1.1: Radius for positioning purposes [2]

In an attempt to develop a robust navigation system, the U.S. department of defense launched the first experimental Navstar-GPS system in 1978, which originally used 24 satellites to perform positioning calculations. This system was made available for civilian use from 1980. Further developments of the system took place in the following years to eliminate the errors that occurred in the GPS calculated positions.

These kinds of errors are still present in the modern positioning systems and different correction methods are utilized for minimizing these errors. A significant reduction of these errors can be achieved by using the differential positioning techniques such as real-time, network RTK and post-processing techniques.

The differential technique uses two receivers and the correction is performed using pseudorange errors, at a known point provided by a secondary station located within the same geographic area.

In the real-time technique or RTK (Real-Time Kinematics), the phase measurements of the signal's carrier wave obtained from the rover given by the different satellites are corrected at the moment with a base station solution. This technique provides a high-level accuracy while using the positioning services.

When a network of base stations is used to perform corrections instead of a single base station, it is referred to as network RTK. Compared with traditional RTK, this technique offers greater accuracy, since it can reduce spatially correlated errors.

The post-processing technique involves the correction of the data collected at a later time. This process needs the differential corrections from a base station, that allows to perform the study. These base station data could be freely downloaded depending on the project's proximity to a permanent GPS network eliminating the need of establishing one's own base station.

The relative positioning technique uses two GPS receivers, one of which is used as a reference and is placed at a point with known coordinates, while the other receiver is placed at a point whose coordinates are unknown. The objective is to determine the unknown coordinate which can be achieved by employing the two receivers simultaneously that track the same satellites and allows the real-time or post-processing of the baseline connecting the two points.

1.1 GNSS Architecture

GNSS is made up of satellite navigation systems like GPS, Glonass, Galileo, and Beidou that provide continuous positioning. GNSS can be divided into three categories, the space segment, which includes the satellites; the control segment, which includes all the data treatment operations; and the user segment, which involves all the devices that participate in data reception. Positioning information is provided by the carrier frequencies, which are distinct for each GNSS signal.

1.1.1 GNSS Segments

As already mentioned, GNSS is composed of three segments (Figure 1.2). The space segment is responsible for the generation and transmission of code and carrier phase signals. High precision atomic clocks are used to calculate the difference between the signal sent out and the one received; these clocks are onboard the satellites.

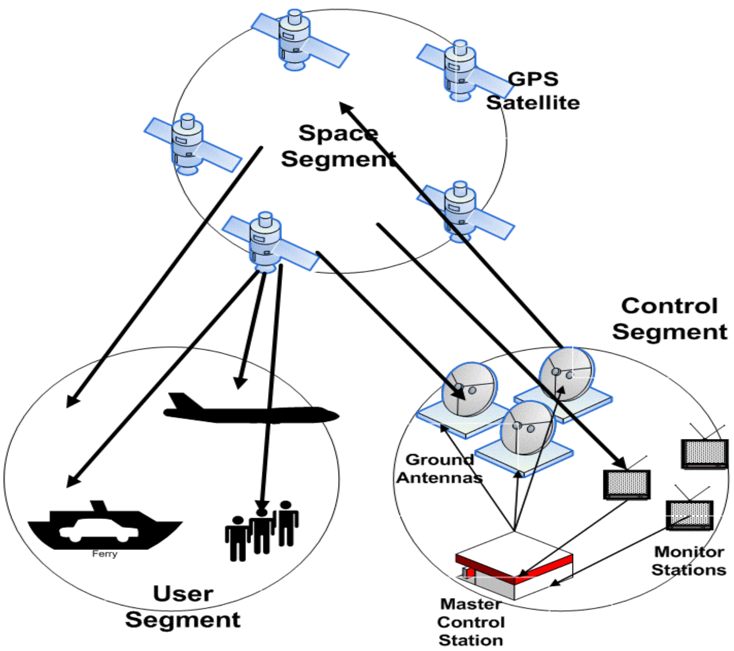

Figure 1.2: The GNSS segments [3]

This segment is composed of all the satellite fleet, ensuring a good number of them to achieve good generation, transmission and receiving of code. Also is important, that the rover, detects a high number of satellites (with a minimum number of 4) to be successful in the process.

The control or ground segment is responsible for the management of the status and configuration of the satellites and keeping track of ephemeris and clock performance. In addition, it maintains the proper GNSS timescales and keeps up to date on the navigation files that are received by satellites. The base stations for the correction of data are included in this field.

Finally, the user segment is comprised of all the GNSS receivers or rovers, where the signals are analysed, the pseudoranges are calculated and the navigation equation is solved to determine the location and a highly precise time. A GNSS receiver is basically composed of an antenna, a controller with a microprocessor, a power system, some memory for data recording, and an interface with the user.

All these fields, involve the different GNSS signals which will be talked about in the following section, analysing how they are integrated into the system.

1.2 GNSS Signals

The satellites transmit information in frequency bands, each band corresponds to different signals, these are: GPS, GLONASS, Galileo and Beidou. With this signal, the positioning calculation is possible thanks to the travel time that can be computed by the user. The signals are composed by:

Carrier: Depending on the frequency in which the signal is focused, a sinusoidal wave will be given.

Ranging Code**:** The main tool for calculating the time it takes for a signal to travel from the satellite to the receiver, is a binary sequence.

Navigation Data: Ephemeris (from the different signals), clock parameters, and status of the satellites are provided in these data.

The frequency in which the data are sent, depends on the signal and the capability of the rover/receiver to acquire one of them. In many cases, some devices are only capable to access some signals, obviously, if the receiver is able to reach more satellite signals better for the position accuracy.

1.2.1 GPS Signals

The radio frequency in which the GPS (United States) signals are transmitted are named L1, L2, and L5 (L band), whose frequencies are represented in Table 1.1 [2]. GPS provides two services: Standard Positioning Services (SPS), centered in L1, and Precise Positioning Service (PPS) which uses L1 and L2. The codes and messages that are modulated are namely the *C/A* code (Coarse/acquisition or Clear/Access), Precision code *P(t)*, and navigation message *D(t)*

Table 1.1: Frequencies of GPS Signal Components

Components	Frequencies (MHz)
L1	1575.42
L2	1227.60
L5	1176.45
P code	10.23
C/A code	1.023
Navigation message D(t)	50 Hz

Satellites receive information from the antennas on earth, and then, they send information back to the rovers, this information is named navigation message. These data contain all the requirements that the user needs to compute the position. Clock data, ephemeris, ionospheric model parameters, and the almanac are given in the message. The most recent messages are named CNAV, CNAV-2, MNAV and L5-CNAV, being the last one modulated using the L5I signal.

1.2.2 Glonass Signals

For this signal (Russian Space Forces) the radio frequencies are also in the L band and have the names L1, L2, and L3 with their respective values in Table 1.2 [2].

Also, can be differentiated between two services, SPS, which transmits in L1 and recently it uses L2, and PPS, which allows two bands, L1 and L2.

Table 1.2: Frequencies of Glonass Signal Components

Signals	Frequencies (MHz)
L1	1598.0625– 1609.3125
L2	1242.9375– 1251.6875
L3	1202.025

Also, the navigation message is present in Glonass, being a bit different with respect to GPS, but containing the necessary information for positioning processing.

1.2.3 BeiDou Signals

BeiDou (China) works also in the L-band, using the frequencies named B1, B2, and B3 [2] and using only an Open Service and an Authorized Service.

Table 1.3: Frequencies of BeiDou Signal Components

Signals	Frequencies (MHz)
B1	1561.098
B2	1207.140
B3	1268.520

The values correspond to BeiDou Phase II, which provided a regional service, using a reduced constellation of 10 satellites.

1.2.4 Galileo Signals

Galileo GNSS system (European Union) uses the frequencies E1, E5a, E5b, AltBOC and E6 and the services offered are different with respect to the two previous signals, these are: OS (Open Service), PRS (Public Regulated Service), CS (Commercial Service), SAR (Search and Rescue) and SoL (Safety-of-Life). Each frequency support one of the services mentioned and the values of them are shown in Table 1.4 [2].

Table 1.4: Frequencies of Galileo Signal Components

Signals	Frequencies (MHz)
E1	1575.42
E5a	1176.45
E5b	1207.14
AltBOC	1191.79
E6	1278.75

1.3 Classical Topographic Methods

1.3.1 Geometric Levelling (From the middle)

Geometric levelling provides a means of accurately measuring height differences between points some tens of meters apart. This method is very precise and has an accuracy of the order of mm.

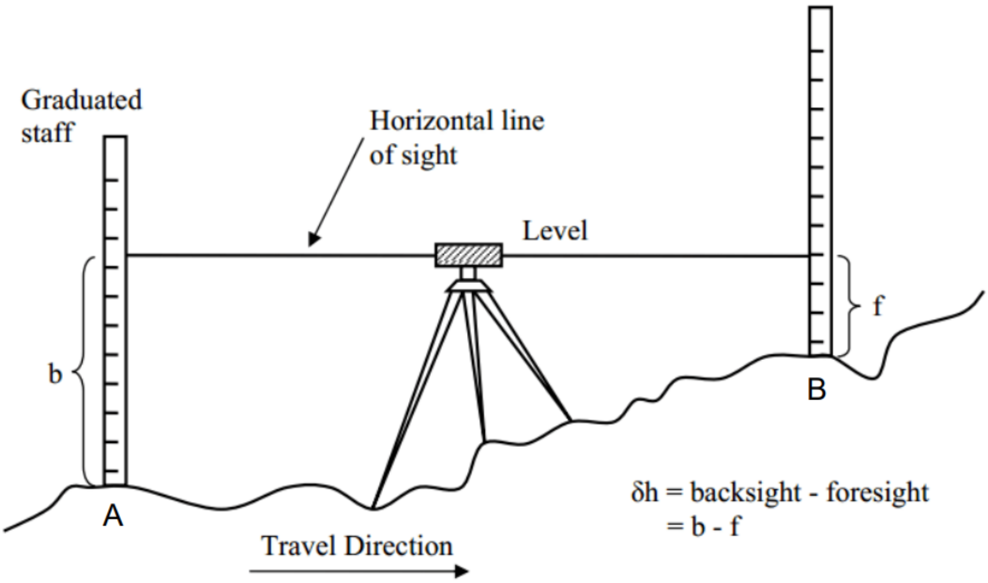

Figure 1.3: Geometric levelling from the middle [4]

A level is set up on a tripod and levelled so that the line of sight is horizontal (Figure 1.3). A graduated staff is held vertically over the first point A and a reading made of the intersection of the cross-hair with the image of the staff (backsight - b). The same (or an identical) staff is then held vertically over the second point B and a further reading is made (foresight - f). The difference between the two readings is the difference in height between the two points A and B.

This process of geometric levelling from the middle can be applied repeatedly in case of long distances between two points. To do this, the level is moved beyond the second point and the height difference between the second and a third point is measured in the same way. Consequently, by accumulating the height difference between the intermediate points one obtains the height difference between the widely separated points.

1.3.2 Total Station

A total station is an optical surveying instrument that uses electronics to measure simultaneously angles (Azimuthal and Zenithal), distances (inclined and horizontal) and differences in elevation. It combines the functions of a theodolite with that of a transit level and electronic distance meter. It also has an integrated microprocessor, electronic data collector, and storage system that allows measurements to be stored on the device (which can be uploaded to a computer for further processing).

Total stations measure distance by using a modulated infrared carrier signal, which is generated by a small solid-state emitter inside the instrument's optical path. This beam is reflected off a prism or an object that the user wants to survey, while the modulated pattern of the returning signal is read and interpreted by a computer inside the instrument.

Most total stations can measure angles with a precision varying from 0.5" to 1.0" and distances with an accuracy of about 1.5 millimeters plus two parts per million over distances up to 1,500 meters. This is much more accurate than a GPS or any type of base station.

Chapter 2

Networks of Continuous GNSS Stations

2.1 HxGN SmartNet

HxGN SmartNet (Leica network) is the world’s largest Global Navigation Satellite System (GNSS) correction service provider. HxGN SmartNet allows GNSS users to increase productivity and solve common problems, such as limited availability and communication issues, through local Real-Time Kinematic (RTK) networks [5]. This network supports four constellations: GPS, GLONASS, Galileo and BeiDou. Figure 2.1 shows the 194 continuous GNSS stations of Leica network, which are active 24/7. The green dots represent the online stations, the red dots represent temporarily offline stations, and the orange dots are representative of stations with problems.

Figure 2.1: Continuous GNSS stations of Leica network

Here is a description of how this network works:

- GNSS satellites broadcast signals, sending data to reference stations and GNSS devices around the globe.
- Reference stations stream the GNSS data to HxGN SmartNet servers, which also receive approximate positions of GNSS devices.
- This data is then processed, and HxGN SmartNet sends RTK corrections back to GNSS devices over the mobile internet.
- The corrected position is accurate down to the centimetre, providing HxGN SmartNet users with reliable precision.

HxGN SmartNet has perfected the need for accuracy and availability. Users receive high-precision correction data in an open standard format (RTCM) simply by connecting any GNSS-enabled devices over the mobile internet. This correction data is used on the GNSS device to enhance its autonomous position even down to a centimeter. This precise position can be used afterward in the application of devices, assets and machines. On the device or even in the cloud, the value of the application is enhanced.

HxGN SmartNet delivers the maximum precision out of any RTK-enabled device where the GNSS devices has service coverage. The network also supports the open RTCM standard. The advantages clearly outperform the old and complicated process of reference station setup and maintenance.

2.2 Veneto GPS network

The GPS Veneto Network constitutes an essential geodetic infrastructure to support topographic and cadastral survey operations on the regional territory [6].

The network operates on the territory with 29 permanent stations active 24 hours a day 7 days a week (Figure 2.1). The services offered free of charge include the availability of RINEX files for post-processing differential correction and the real-time positioning service distributed via the internet using NTrip protocol.

Figure 2.2: GPS stations of Veneto Region Network [6]

The permanent stations of the GPS Veneto Network are provided by Institutional Bodies and Private Entities and the observation data is freely accessible through this portal after registration.

The Network makes use of the scientific support of the University of Padua. Furthermore, it is part of the National Dynamic Network RDN of the IGMI and the EPN Permanent European Network of the EUREF.

The Veneto Region, through the University of Padua and in agreement with the Territory Agency, is committed to activating and operating a Regional Positioning Network based on the satellites of the Global Navigation Satellite System (GNSS). This system currently includes the American GPS satellites and the Russian GLONASS satellites, with the prospect of enlargement to the European satellites of the Galileo constellation. The objective is to guarantee the trigonometric coverage of the regional territory with a service of precision, reliability and quality standards in line with European ones.

2.3 The Marussi Network

The "Antonio Marussi" GNSS network is an essential geodetic infrastructure for performing professional topographic measurements in the territory of the region of Friuli Venezia Giulia [8]. The network is composed of ten permanent stations which are active 24/7 (Figure 2.2). The network allows the GPS, GLONASS and

GALILEO constellations to be traced. Because of the availability of the files of the individual stations in RINEX format, it is possible to access the services both

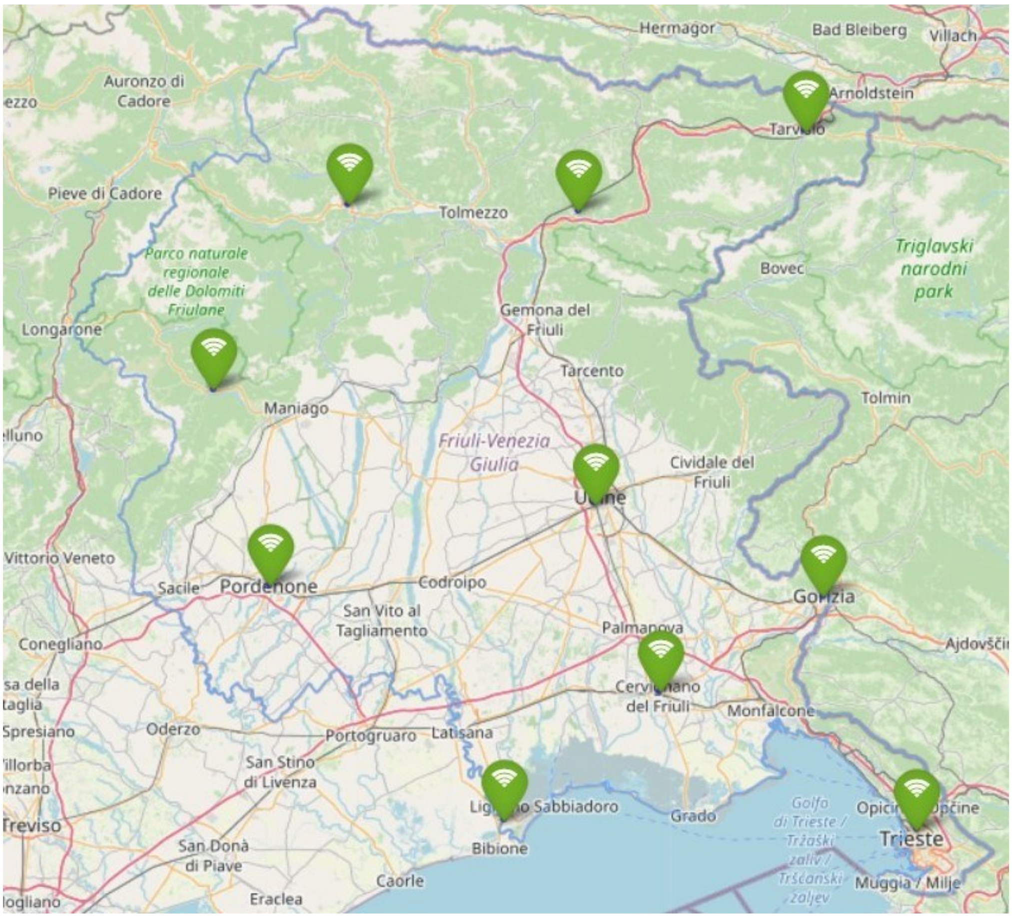

Figure 2.3: Stations of Marussi GNSS Network [8]

for differential correction in post processing and real-time positioning free of charge. The service distributes corrections in real-time, via the internet using Ntrip, according to the systems of Single Base (DGPS and RTK), Nearest, VRS and MAC.

2.4 Trentino Positioning Service (TPOS)

The TPOS network consists of 24 permanent GNSS stations which allows precise positioning information to be collected (Figure 2.3). The network is created and run by *Servizio Catasto della Provincia Autonoma di Trento*.

TPOS replaces the utilisation of base-stations located in fiducial points and offers benefits of convenience, savings and accuracy [7]. This system currently makes use of the GPS and GLONASS satellites. The network was created primarily for professionals and public body technicians, but now it is available to all.

Figure 2.4: Permanent stations of Trentino Positioning Service (TPOS) network [7]

Chapter 3
Objectives

Nowadays GNSS is used for very wide ranges of applications. These applications require suitable measurements and positioning techniques in order to have highly accurate and reliable positions. Two common positioning techniques are relative positioning and differential positioning. This project applies an RTK positioning technique with the usage of RTK carrier-phase differential GNSS receiver systems and correction services for obtaining centimeter level positions instantaneously. Recently network-based approaches by delivering RTK carrier-phase differential GNSS services have become more important as they are essential tools for high accuracy real-time positioning for applications such as geodesy, surveying, machine control, attitude determination and precision agriculture.

The main purpose of this project is to understand the accuracy of positioning given by different networks. The different networks related to different regions continuously collect satellite observations and send them to a central processing facility, at which the station observations are processed in a common network adjustment and observation errors and their corrections are computed. The observation corrections obtained from the network are then sent to the user, operating within the coverage area of the network. The order of magnitude of precision of these corrections is then compared.

The main points of this project can be established as follows:

- Performance assessment of the networks HxGN Smartnet and Veneto GPS network for relative positioning. Obtaining the order of magnitude of the final precision of positioning in Padova.
- Post-processing methods to apply corrections to relative positioning.
- Obtaining differential positioning from four networks, namely: HxGN Smartnet, Veneto GPS network, The Marussi network and TPOS network.

- Comparison among relative and differential measurements.
- Performing field survey using classical topographic methods. A survey using geometric levelling and total station is performed. These methods give very high precision positioning.
- To find out whether the difference in elevation obtained by geometric levelling is comparable with maximum precision obtained from relative and differential GPS measurements.
- To determine whether the planimetric positioning given by the total station is comparable with GPS measurements obtained by relative and differential techniques.
- To understand the accuracy of RTK measurements versus the relative method due to the long time and high costs of the relative positioning, which makes it less flexible than RTK positioning technique.
- To find out if we can replace relative positioning tehcnique with RTK positioning. In other words, to understand whether the RTK (or differential) positioning have the same accuracy as relative positioning.

Chapter 4
Technical background

GPS (Global positioning system) has received considerable attention in navigation application due its several advantages such as, simplicity of use, successful implementation and global availability. The Veneto GPS network, Leica geosystems and other networks integrates GPS with other functioning satellite-based positioning system such as GLONASS to improve the positioning performance.

4.1 GPS Measurements

4.1.1 Pseudo-range

The GPS receiver estimates the distances to the tracked satellites, and this is defined as a pseudo-range, which is the range to the satellite and the receiver's clock offset assuming a non-perfect synchronization between these two clocks. These pseudo-ranges are based on GPS observable that is achieved by using the C/A and/or P-codes. Based on the pseudo-range measurements, the position calculations are performed as the following:

$$\rho_i = c.\Delta t = \sqrt{(X_i - X_u)^2 + (Y_i - Y_u)^2 + (Z_i - Z_u)^2} + ct_u \tag{4.1}$$

where, (X_u, Y_u, Z_u) are the unknown coordinates of user receiver position, (X_i, Y_i, Z_i) are the known satellite ephemerides, t_u is the offset of receiver clock from the system time, and c is light speed in the space.

A system of at least four pseudo-range equations in four unknowns is required to solve the problem. Thus, we need the observation of at least four satellites to compute the unknown receiver's position solution.

4.1.2 Carrier-phase based ranging

This technique is based on the assumption that the GNSS receiver clock and the transmitter clock at the satellite are synchronous, so the phase of the carrier will be the same for both. In this case, the time taken by the signal to travel among both devices is computed by the lag that the signal presents, and this is due to the linear variation behaviour of the signal with time (Figure 4.1).

It is necessary to differentiate between the transmission time (t_1) and the current time (t_2), measured by the current phase that arrive to the receiver at the current moment. The phase difference between these two is the parameter from which the propagation time can be obtained.

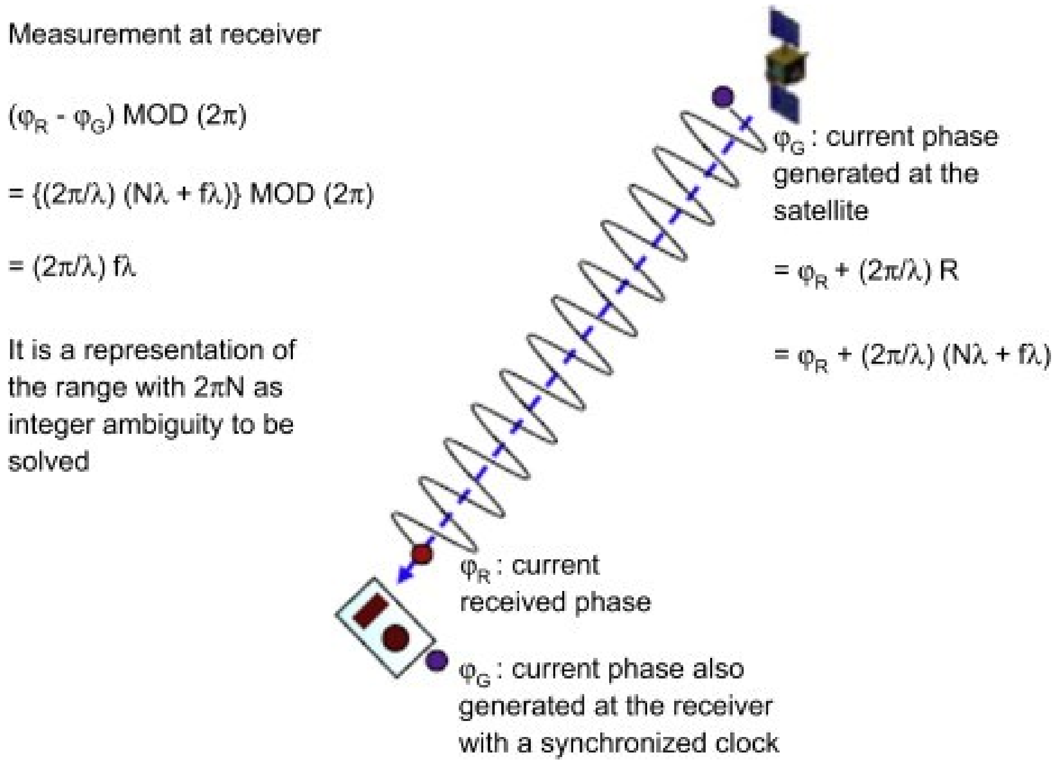

Figure 4.1: Carrier-phase based ranging [10]

It is possible to compute the transmission time and the received time, Tt and Tr respectively by *Equation 4.2* and *Equation 4.3*.

$$Tt = k(n_1 2\pi + \alpha_t) \tag{4.2}$$

$$Tr = k(n_2 2\pi + \alpha_r) \quad (4.3)$$

where, ($n_1 2\pi + \alpha_t$) is the transmission carrier phase, ($n_2 2\pi + \alpha_r$) is the received carrier phase, n_1 and n_2 are the number of complete 2 pi radians executed by the phases, and k is the factor conversion from phase to time.

By taking the difference between the transmission time and the received time, the propagation time is easily computed as follows:

$$Tr - Tt = k((n_2 - n_1)2\pi + (\alpha_r - \alpha_t)) \quad (4.4)$$

$$\delta T = kN2\pi + k\delta\rho(t) \quad (4.5)$$

4.2 Differential GPS system

The differential GPS (DGPS) is based on the concept of correcting the GPS position solution. A DGPS system is composed of three elements which include firstly, an antenna or GPS receiver at a point with known coordinates, secondly, another GPS receiver at an unknown point and finally a communication medium is present between these two receivers. A reference station (Master) is present in known coordinates and by comparing these known locations, a correction vector could be generated with the calculated measurements at the reference station and these signals are sent to the second receiver (rover) for the correction of the errors, that are similar between the stations (Figure 4.2). DGPS is applied in the code pseudo-rangers after estimating the corrections which are in the carrier phase. This process is known as real-time kinematics in which the communication of these corrections requires a radio modem connection or telephonic connection.

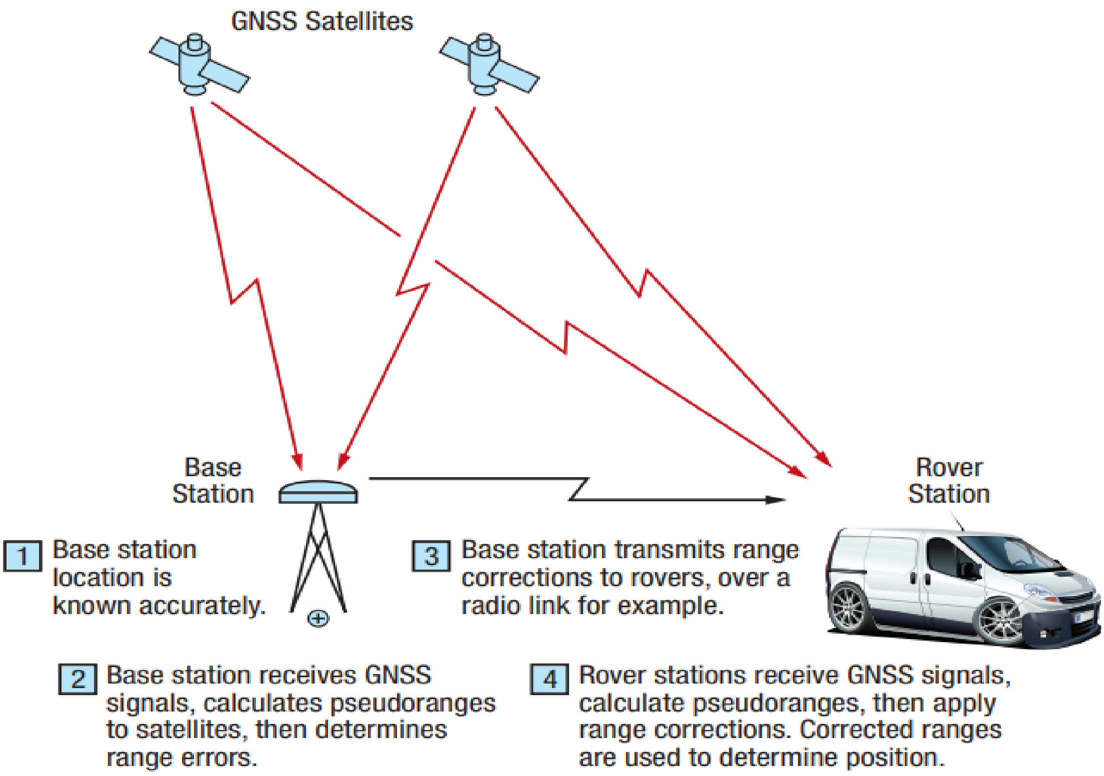

Figure 4.2: Differential Technique [1]

Differential GPS can use a network of fixed, ground-based reference stations which sends the difference between the position transmitted by the GPS satellites and the known fixed positions. In this project, four networks are used which receives these differences, processes the data and subsequently sends the RTK corrections to the GNSS devices over the internet connection within five minutes. Access to this correction information makes differential GPS receivers much more accurate than other receivers. With these errors removed, a GPS receiver can achieve accuracies down to centimetres.

4.3 Relative positioning

In relative positioning, two receivers are employed. One of these two receivers is placed in a known position, which is the base. The goal of the survey is to determine the position of the rover which is placed on an unknown point relative to the base. The vector that connects the base and the rover is known as the "baseline" (Figure 4.3). Both the receivers observe the same constellation of satellite at the same time and there is an extensive correlation between observations at the base and the rover as the baseline is so short compared to the altitude of the GPS satellites. This method allows maximum accuracy by eliminating many errors in the system. When the two receivers remain stationary during the entire observation session in a survey of a single baseline vector between points A and B, it is known as a static relative positioning.

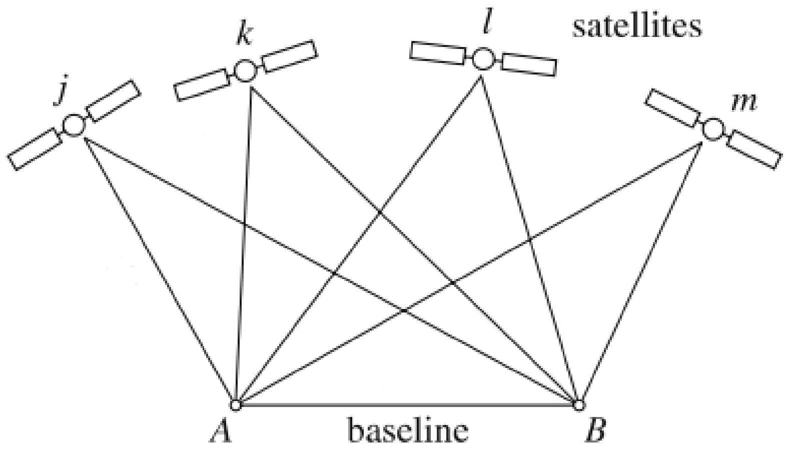

Figure 4.3: Relative Positioning [11]

In this project, the relative positioning solutions are post-processed using the corrections which are received from HxGN SmarNet and Veneto GPS network within a period of 15-20 days.

4.4 Real Time Kinematic (RTK)

RTK positioning is a system that uses carrier-based ranging and allows centimeter level accuracy positioning in real-time. This technique efficiently reduces and removes errors from sources such as satellite clocks and ephemerides, and ionospheric and tropospheric delays, which are common to a pair of base and rover. A conventional RTK positioning system typically comprises a single base station that transmits formatted information such as code and carrier phase observations to one or more rover units in the field, as shown in Figure 4.4. The reference station data is combined with local measurements collected at the rover using proprietary differential processing techniques to yield precise relative coordinate estimates.

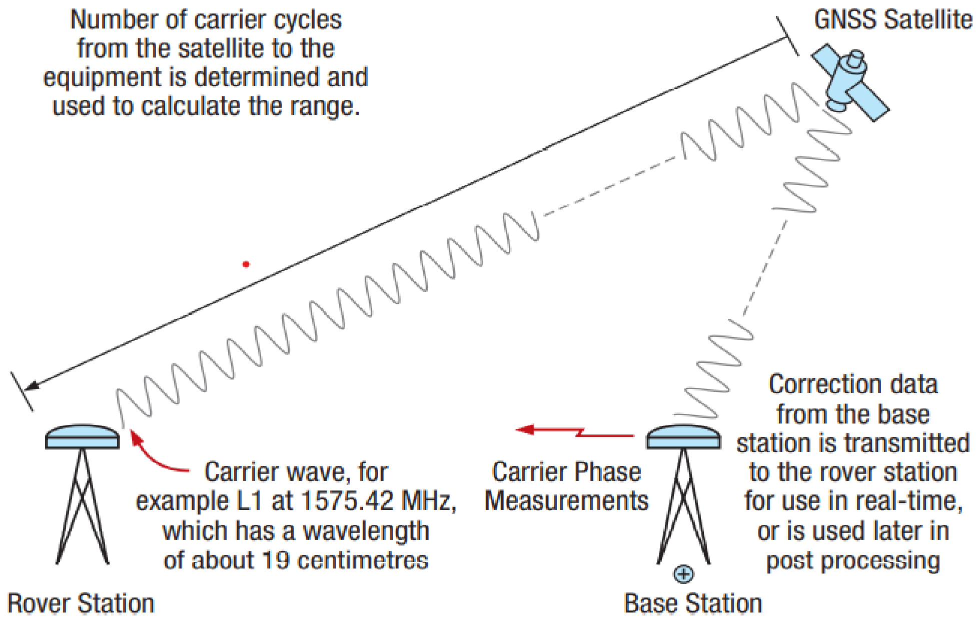

Figure 4.4: Real-time kinematic system [1]

4.5 Network Real-Time kinematic (NRTK)

The network RTK system is currently a dual system combination of GPS and GLONASS positioning system which increases the positioning accuracy by minimizing the distance dependant errors on the computed position of a rover within the bounds of the network. It is possible to achieve the redundancy of reference stations in the solution through NRTK. When observations from one reference station are unavailable, a solution can still be obtained through the gathering and processing of observations in a common network adjustment [9].

The typical network RTK comprises three or more permanent reference stations connected to a central processing facility that generates corrections for the distance dependant errors for the network area. The information from the network helps to reduce the distance-dependent errors viewed at the rover, resulting in more homogenous position accuracy within the region surrounded by the reference stations. The NRTK performance is dependent, to some extent, on the number of available satellites.

4.6 Post processing method

This process involves the treatment of data when the GNSS satellite measurements are already collected and is performed when the GNSS positions are not required in real-time. Here, the base correction data was collected from the Veneto GPS network, HxGN SmartNet, the Marussi network and the TPOS network over the internet, which was then used to post-process the previously stored raw GPS base data in the Receiver Independent Exchange (RINEX) format. RINEX is a data format used to archive GPS navigation and observation data for post-processing purposes, which is stored inside the GPS receiver.

In this project the precise ephemerides of satellites were downloaded from the NASA website and by incorporating these data with the RINEX data, the pseudo-range was measured and the correct position in the ground was obtained. For performing the post-processing of these GNSS data the Leica Infinity Survey Software was utilized.

The accuracy of this method depends on the capabilities of the rover receiver and type of post-processing software used. A requirement for post processing the data is that, the roving receiver and the base receiver must be collecting the GPS data at the same time and must have at least four satellites in common. It is possible to achieve high precision positioning through the post processing method, which is generally more accurate than the real-time positioning.

4.7 Common errors in the GNSS positioning

A GNSS receiver calculates the position of a point on the earth's surface based on the data collected from the satellites. However, many errors influence the accuracy of the positioning that needs to be corrected in order to have a precise positioning. These errors are drastically reduced in the differential and the relative positioning.

4.7.1 Satellite clocks errors

This error is mainly due to a bad synchronization between the satellite and the receiver clock. A small error in the satellite clock can result in a significant error in the positioning calculated by the receiver. It is advantageous to use a differential GNSS or RTK receiver configuration in order to correct this kind of inaccuracy.

4.7.2 Errors of satellite orbits

The GNSS ground control system monitors satellite locations at all times, calculates orbit eccentricities and whenever the satellite orbit changes, it sends and compiles these deviations in documents called ephemerides. GNSS receivers are able to process ephemerides and compensate for some orbital errors. However, small errors can still be present in the orbit which can result in a significant error in positioning.

4.7.3 Ionospheric delays

When a GNSS signal passes through the ionosphere (upper atmosphere), which is located 50-1000 km above the earth's surface, the signals get delayed and distorted due to the electron density of the terrestrial atmospheric layers. The ionospheric delays depend on how close the satellite is to the horizontal plane. It also varies with the solar interactions and the frequency of the signal passing through the ionosphere. It is possible to eliminate the errors by modelling ionospheric characteristics so that the GNSS monitoring stations can calculate and send the correction to the satellite and then to the receivers.

4.7.4 Tropospheric delays

The troposphere is the closest to the earth's surface and extends to an altitude of about 50 km. This dense lower atmosphere delays the GNSS signals and limits the precision in the GPS measurements due to the effects of changing humidity, temperature and atmospheric pressure. The closer the satellites are to the horizon, the more delayed the signals are, since they pass through the most atmosphere. GNSS receivers can use the tropospheric mathematical models for the correction of the tropospheric delays but the problem is still open.

4.7.5 Multipath errors

When the GNSS signals travelling from the satellites are reflected from reflective surfaces such as buildings or trees, instead of coming directly to the GNSS receiver, the signal gets delayed and introduces noise in data causing the receiver to calculate an incorrect position (Figure 4.5). Therefore, the GNSS receiver must

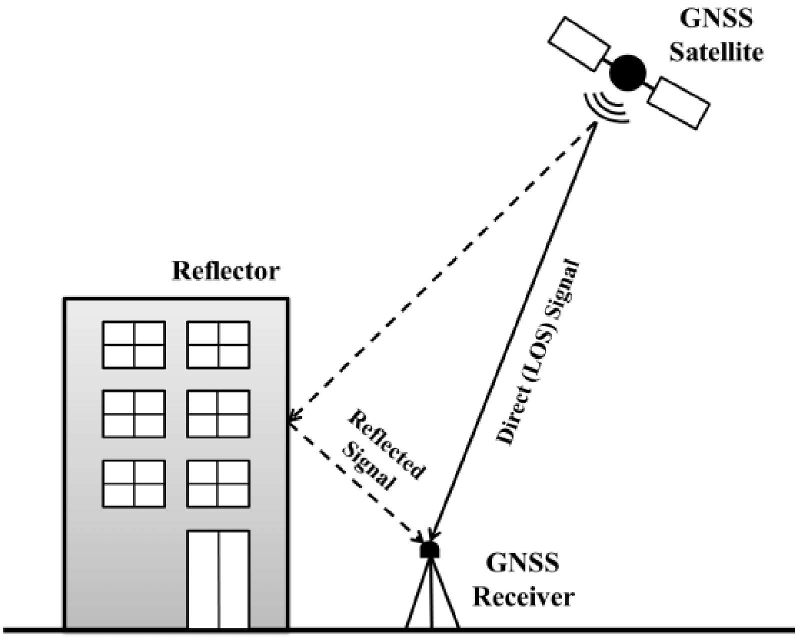

Figure 4.5: Multipath Error [12]

distinguish between these two signals for minimizing the multipath errors and this can be achieved by designing high end GNSS receivers and antennas and placing the GNSS antenna in a location that is far away from a reflective surface.

Chapter 5
Instruments

It is important to set the devices that are going to be used and the functionality of each one for carrying out the survey and further data processing.

Two different types of survey were performed in this project, which are the classical topographic survey and relative and differential positioning using the GPS networks. Each of this positioning system makes use of distinct instruments which is going to be described in this section.

5.1 Instruments for classical topographic survey

The classical topographic instruments can be divided into three categories;

- Theodolite: is used for measuring the azimuthal (horizontal) and zenithal (vertical) angles.

- Levels: measures the difference in level between two points, i.e. the difference in height between two points on the earth's surface.

- Electronic distance-meter: is used for measuring inclined and horizontal distances.

- Total station: is used for simultaneous measurement of angles, distances (inclined and horizontal) and differences in elevation. It integrates an electronic transit theodolite with an electronic distance meter.

5.1.1 Digital Level

For performing the geometrical levelling from the middle this Leica digital level DNA03 was utilised, which precisely measures the height and the distance to the staff by pressing a button, then calculates the height of the point and saves it in the internal memory (Figure 5.1). This instrument performs by comparing the internal reference barcode with the bar code reported on the staff rod, which is placed vertically on a point to be measured. Leica digital levels can make single measurements, calculate the average or median of multiple measurements with a defined standard deviation, and repeat single measurements. According to the instrument specification, the standard deviation for the height measurement is 0.30 mm for a 1 km double levelling [14]. This device allows for a simple, highly precise and quick measurement.

Figure 5.1: Digital level Leica DNA03

5.1.2 Total Station

The total station employed in this study is a "Leica TCR 1201+R400" which is a very high-precision total station from Leica Geosystems (Figure 5.2). Thanks to its high flexibility, it has proven its effectiveness on many occasions during the experiment. This instrument eliminates the need for an assistant staff member as the operator holds the retroreflector and controls the total station from the observation point. According to the manufacturer specifications, the TCR 1201+R400 allows a precision of up to 0.30 milligon (1") for angle measurements and 1 mm +/- 1.5 ppm for distance measurement.

Figure 5.2: Total Station Leica

A 360-degree survey prism is also used, which reflects the electronic distance measurement beam (EDM) from a total station (Figure 5.3). This prism reflects the EDM beam back to its source with both a wide angle of incidence and high precision. By reducing the scatter of the beam as it is reflected back to the total station, prisms allow for a more accurate measurement as well as a longer range of measurement.

Figure 5.3: Leica 360-degree survey prism

5.2 GPS survey equipment

The differential and relative positioning is performed with the assistance of two GPS receivers, one of which serves as a reference station located in a known coordinate and the other serves as a rover operating in an unknown position that collects data from the reference station and combines it with local measurements. The GPS receiver used for this survey is composed of the following components:

- GPS smart antenna
- GPS controller with microprocessor
- Data recording system
- Power system (Battery)

5.2.1 GPS smart antenna

The smart antenna utilized in this project is a "Leica Viva GS16" which is a self-learning and high accuracy GPS antenna (Figure 5.4). This device receives and amplifies the radio signals from GNSS satellites which are transmitted on specific frequencies and converts them for use by a GPS receiver. A GPS antenna output is fed into a receiver that determines position.

Figure 5.4: Leica smart antenna [13]

The measurement performance and accuracy of this device according to the positioning technique utilized, is reported below in Table 5.1.

Table 5.1: Measurement performance and accuracy of Leica smart antenna [13]

Positioning Technique	Correction method	Horizontal precision	Vertical precision
Real-Time kinematic	Single baseline	8 mm + 1 ppm	15 mm + 1 ppm
	Network RTK	8 mm + 0.5 ppm	15 mm + 0.5 ppm
Post-processing	Static phase with long observations	3 mm + 0.1 ppm	3.5 mm + 0.4 ppm
	Static and rapid static phase	3 mm + 0.5 ppm	5 mm + 0.5 ppm
Code differential	DGPS	25 cm	50 cm

5.2.2 GPS controller

A “Leica Viva CS15” field controller was used that collects the positioning solution from the different regional networks over the internet connection, in conjunction with the GPS antenna (Figure 5.5). This controller is an effective wireless field controller which has an easy-to-understand software and a built in 3.5G internet modem.

Figure 5.5: GPS controller

Chapter 6
GNSS Survey

6.1 Test Site

Two different test sites were chosen for performing the survey and comparing the positioning results. These test sites are located in Veneto, which is a region in the North-eastern part of Italy (Figure 6.1). Veneto region is bordered by Friuli-Venezia Giulia region on the east side and by Trentino-Alto Adige region on the north side.

Figure 6.1: Map of Italy with the subdivisions into regions [17]

One of the test sites was selected at Padova which is located at the centre of Veneto region and the other one was selected at Longarone which is located near the border of Veneto region with Friuli-Venezia Giulia (Fig 6.2).

Figure 6.2: Map of Veneto Region with the borders of Trentino and Friuli Venezia Giulia Regions, with the locations of the test sites [18]

The second site was selected at this border so as to study whether the Marussi network which is located in Friuli-Venezia Giulia provides better results in this test site as a result of being close to the network.

6.1.1 Test site 1

We set up the first test site in Padua, which is a city in Northern Italy's Veneto region. Two observation points A (1000) and B (2000) were selected for performing the survey, with these two points being located at unknown coordinates (Figure 6.3). These selected points were within the visibility range of each other and the distance between them is about 76 m. We selected two points instead of using only one point because we cannot directly compare the coordinates of the same point acquired from different networks as the differences could be due to the different reference system used by the networks. But if we consider two points, the differences in elevation and in East and North coordinates from different networks must be the same, independently of the reference system.

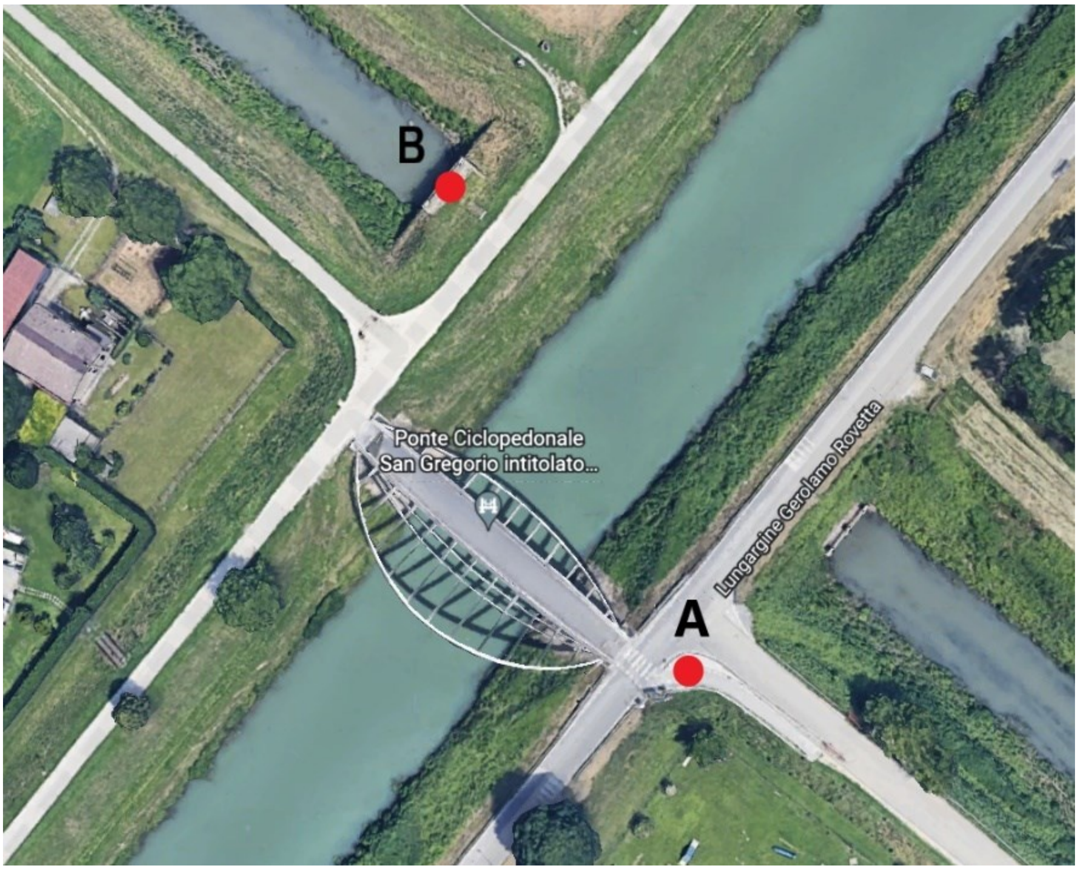

Figure 6.3: Map of project site 1

6.1.2 Test site 2

The selected site for the performing the 2nd test is located in Longarone, which is a town on the banks of the Piave in the province of Belluno, in Northeast Italy (Figure 6.4). The town is close to theborders of Veneto region with Friuli-Venezia Giulia. The survey was conducted by selecting two observation points with the IDs 3000 and 4000 at this site in the same manner as it was performed at test site 1.

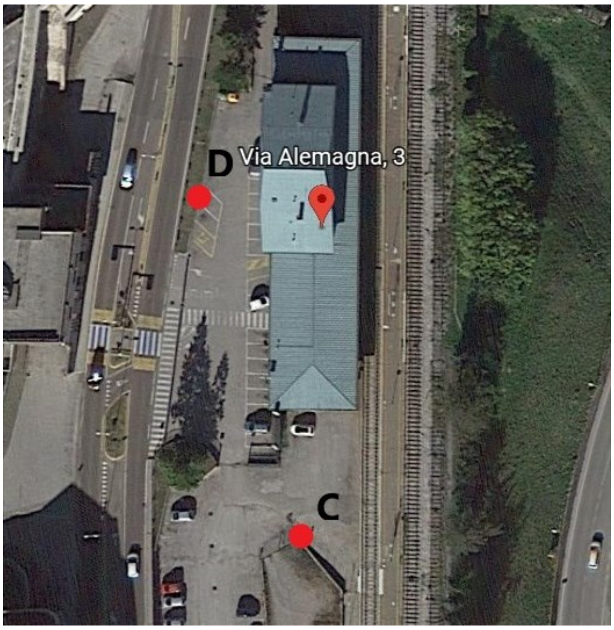

Figure 6.4: Map of project site 2

6.2 Geometric Levelling (from the middle)

In order to perform geometric levelling from the middle, a Leica digital level was used with a graduated staff that was placed vertically on the point to be measured (Figure 6.5). The levelling was performed repeatedly starting from point A up to point B to determine the difference in elevation between these two points. This method is highly accurate and a precision of 0.06 mm was achieved.

Figure 6.5: Geometric levelling setup

6.3 Total Station Survey

Total station surveys using a Leica TCR 1201+ instrument and Leica 360° prism target were performed to provide local precision and accuracy. The instrument was mounted on a pole with tripod legs 1.5 m above the ground. As a first step, the total station was setup at point A and observations were made by setting up the prism target at point B as shown in Figure 6.6. Subsequently, the position of the total station and the prism were altered and observations were made at point A. At one setup per total station, direct and reverse measurements were taken to ensure agreement. The total station was set to average two measurements per observation, resulting in an average of four observations on each point.

Figure 6.6: Total station and prism target setup

6.4 RTK GNSS Survey

The RTK survey was performed utilizing two setups of GPS receivers as rovers, each consisting of a Leica Viva GS16 smart antenna and a Leica Viva CS15 GPS controller. Each setup was mounted on a 1.1 m fixed height pole with tripod legs (Figure 6.7).

Figure 6.7: RTK GNSS setup

One of the rovers was located at point A and the other rover was located at point B. Each receiver was connected to four GPS networks (HxGN SmartNet, Veneto GPS network, The Marussi network and The TPOS network) via the internet. Differential corrections in real-time from each network were received within five minutes. A precision of the order of cm was obtained using this technique.

6.5 Static GNSS Survey

The static GNSS survey consisted of a session of 3 hours on two observation points at each study site. These two points were selected ensuring that one point was visible from the other point. Static GNSS observations were collected using two Leica Viva GS16 combined antenna/receivers mounted on 1 m fixed height tripods. The fixed-height tripod level bubbles were checked for calibration prior to use. The static observations were collected from the Veneto GPS network, the HxGN SmartNet, the Marussi network and TPOS network which uses the constellation combinations of GPS+GLO, GPS+GLO+GAL+BDS, GPS+GLO+GAL and

GPS+GLO respectively. These observations were received within approximately 20 days from these four networks and were post-processed afterwards. This method allowed for a maximum precision positioning, which was very close to the precision acquired by applying classical topographic method.

Chapter 7

Result Analysis and Discussion

7.1 Altimetric survey results

This section describes the results obtained from the altimetric survey conducted in Padua and Longarone on the observation points A, B, C, and D which have been assigned the IDs 1000, 2000, 3000, and 4000 respectively. In the altimetric survey, the geoid is taken as the reference surface. The measurements had been performed by using the level DNA03, the total station TCR 1201, and the GPS receiver Leica Viva GS16. The elevations of the observation points A (1000) and C (3000) are unknown and hence their elevations have been assigned as 0.0 m.

The elevations were obtained using three different reference systems, which are as follows: 1) Ellipsoidal elevations in the ETRS89 and other RTK elevations in the ETRF2000 reference system; 2) Ellipsoidal elevations in the ETRF2000 reference systems for all techniques; and 3) Orthometric elevations obtained using the IGMI grids from ellipsoidal elevations ETRF2000.

Table 7.1: Ellipsoidal elevations in the ETRS89 and other RTK elevations in the ETRF2000 reference system. Test DGNSS networks: first test in PADUA-TERRANEGRA (02 MAY 2022).

ID	DNA03 (Level)	TCR1201 (Total Station)	Relative positioning	RTK LEICA	RTK VENETO	RTK TPOS TRENTINO	RTK Marussi FRIULI VENEZIA
1000	0.000	0.000	58.111	58.271	58.249	58.272	58.300
2000	-0.641	-0.641	57.472	57.621	57.608	57.583	57.663
Difference in elevation (m)	-0.641	-0.641	-0.639	-0.651	-0.641	-0.689	-0.636

At first, the ellipsoidal elevations obtained using the classical topographic survey, performed with the help of level and total station have been adjusted considering the European Terrestrial Reference System 1989 (ETRS89), while the other RTK elevations have been determined using the European Terrestrial Reference Frame 2000 (ETRF2000) as datum (Table 7.1). Considering the same reference system, the elevation data were also obtained for the test performed at the test site located in Longarone in a similar manner (Table 7.2).

Table 7.2: Ellipsoidal elevations in the ETRS89 and other RTK elevations in the ETRF2000 reference system. Test DGNSS networks: second test in LONGARONE (20 MAY 2022).

ID	DNA03 (Level)	TCR1201 (Total Station)	Relative positioning	RTK LEICA	RTK VENETO	RTK TPOS TRENTINO	RTK Marussi FRIULI VENEZIA
3000	0.000	0.000	513.374	513.391	513.405	513.347	513.378
4000	0.728	0.729	514.105	514.106	514.122	514.071	514.127
Difference in elevation (m)	0.728	0.729	0.731	0.715	0.716	0.724	0.749

Using different reference systems, different results are obtained, and it is not possible to compare the individual elevation of each point obtained using different positioning methods. Therefore, the difference in elevations between the two observation points determined using each method has been analysed and compared, as this difference in elevations has to be the same.

The classical topographic method is highly precise and the differences in elevations obtained using these two instruments have been found to be the same.

The relative positioning method utilized the permanent GPS station of Padova and the baseline between the station and observation point A (1000) together with the baseline between the station and observation point B (2000) formed a triangle, which was then measured. The value of the difference in elevation utilizing the relative positioning technique was found to be -0.639 and this value has a difference of 2 mm from the value obtained by using the classical topographic survey which was -0.641. Since this difference is very small, the relative positioning technique was considered to be highly accurate.

Table 7.3: Ellipsoidal elevation in the ETRF2000 reference systems for all techniques. Test DGNSS networks: first test in PADUA-TERRANEGRA (02 MAY 2022).

ID	DNA03 (Level)	TCR1201 (Total Station)	Relative positioning	RTK LEICA	RTK VENETO	RTK TPOS TRENTINO	RTK Marussi FRIULI VENEZIA
1000	0.000	0.000	58.147	58.271	58.249	58.272	58.300
2000	-0.641	-0.641	57.508	57.621	57.608	57.583	57.663
Difference in elevation (m)	-0.641	-0.641	-0.639	-0.651	-0.641	-0.689	-0.636

Table 7.4: Ellipsoidal elevation in the ETRF2000 reference systems for all techniques. Test DGNSS networks: second test in LONGARONE (20 MAY 2022).

ID	DNA03 (Level)	TCR1201 (Total Station)	Relative positioning	RTK LEICA	RTK VENETO	RTK TPOS TRENTINO	RTK Marussi FRIULI VENEZIA
3000	0.000	0.000	513.502	513.391	513.405	513.347	513.378
4000	0.728	0.729	514.234	514.106	514.122	514.071	514.127
Difference in elevation (m)	0.728	0.729	0.732	0.715	0.716	0.724	0.749

In the second case, the ellipsoidal elevations were determined by utilizing the ETRF2000 reference system for all the positioning methods (Tables 7.3 and 7.4). The differences in elevations obtained by applying different positioning techniques considering this reference system are similar to those obtained using the combination of ETRS89 and ETRF2000 reference systems. The results obtained using ETRF2000 were considered to be the best as they were determined using this same reference system for all the positioning techniques.

Table 7.5: Orthometric elevations obtained using the IGMI grids from ellipsoidal elevations ETRF2000. Test DGNSS networks: first test in PADUA-TERRANEGRA (02 MAY 2022).

ID	DNA03 (Level)	TCR1201 (Total Station)	Relative positioning	RTK LEICA	RTK VENETO	RTK TPOS TRENTINO	RTK Marussi FRIULI VENEZIA
1000	0.000	0.000	14.056	14.180	14.158	14.181	14.209
2000	-0.641	-0.641	13.414	13.527	13.514	13.489	13.569
Difference in elevation (m)	-0.641	-0.641	-0.642	-0.653	-0.644	-0.692	-0.640

Table 7.6: Orthometric elevations obtained using the IGMI grids from ellipsoidal elevations ETRF2000. Test DGNSS networks: second test in LONGARONE (20 MAY 2022).

ID	DNA03 (Level)	TCR1201 (Total Station)	Relative positioning	RTK LEICA	RTK VENETO	RTK TPOS TRENTINO	RTK Marussi FRIULI VENEZIA
3000	0.000	463.946	463.948	463.837	463.851	463.793	463.824
4000	0.728	464.675	464.675	464.547	464.563	464.513	464.568
Difference in elevation (m)	0.728	0.729	0.727	0.710	0.712	0.720	0.744

In the third case, the ellipsoidal elevations of ETRF2000 were transformed into orthometric elevations, where the heights of the points refer to the mean sea level (Tables 7.5 and 7.6). This transformation was done incorporating the undulation of geoid N which is a deviation between the ellipsoidal height h and orthometric height H and it was considered to be 5 cm, which was not so precise. For this reason, we considered the results obtained using the ellipsoidal elevation h to be the most accurate.

For comparing the results obtained in Padua and Longarone using different positioning techniques, the deviation of each value of the difference in elevation from the correct value was calculated (Table 7.7). In this case, the correct value was considered to be the differences between elevations measured utilizing the digital level DNA03. Analysing the result, it was clear that the relative positioning technique yielded a highly accurate value of elevation since its deviation was just 2 mm and 4 mm from the correct value for Padua and Longarone respectively.

Table 7.7: Differences with respect to the correct value (Elevation) considering ellipsoidal elevation in the ETRF2000 reference system

	TCR 1201 (Total Station)	Relative Positioning	RTK LEICA	RTK VENETO	RTK MARUSSI	RTK TPOS
Δ Elevation (Padua) (mm)	0.00	2.06	10.00	0.00	4.86	48.00
Δ Elevation (Longarone) (mm)	1.00	4.00	13.00	12.00	21.00	4.00

For the RTK technique utilized in Padua, among the four different networks, the Veneto GPS network provided the most precise positioning value as it demonstrated a deviation of 0.0 mm from the correct value. This is due to the fact that the network is located very close to the test site. The Marussi network also worked remarkably well as it allowed for a positioning value that deviated just 4.86 mm from the correct value despite being quite far from the place of survey. The third best elevation results were obtained from the HxGN SmartNet (LEICA) network which has a difference of 10 mm with respect to the correct value. It was also evident that the TPOS network does not work very well as it yielded a large deviation of 48.00 mm from the correct value.

In Longarone, however, the most accurate result was provided by the TPOS RTK network, which provided a deviation of 4.00 mm from the correct value. The RTK networks of Leica and Veneto demonstrated almost similar results with deviations of 13 and 12 mm respectively. The most unexpected performance was demonstrated by the Marussi network as it provided the least accurate result with a difference of 21 mm from the correct value despite being close to the test site.

7.2 Planimetric positioning results

In the same manner, as described in the previous section, the planimetric survey was performed on the four points A, B, C, and D. This kind of survey utilizes the ellipsoid as the reference surface. Here, the measurements were performed using the Total station TCR 1201 and the GPS receiver Leica Viva GS16.

This test was performed considering two different UTM reference systems which are: 1) UTM 32 and 2) UTM 12 zone. In this case, the east and the north coordinates were determined for each survey point and the difference between the east coordinates of the two points and the difference between the north coordinates of the two points were calculated for each test site. Subsequently, the 2D distance between these two observation points was determined from the difference between the east and north coordinates for different positioning methods.

In the first case, the planimetric coordinates UTM32 were obtained using the IGMI grids from the geographic coordinates ETRF2000 (Table 7.8). Since the total station works in ellipsoid and not in the cartographic plane, deformations are introduced due to the cartographic plane of UTM 32. For this reason, the value of 2D distances obtained using the relative positioning technique represented a variation of 1.9 cm with respect to the results provided by the total station. This deviation also arises due to the fact that the north of UTM 32 zone is relatively far from Padua. Similarly, these data were also obtained for the test site in Longarone (Table 7.9). Also, in this case, a variation of 2.3 cm was observed between the 2D distances provided by the relative positioning technique and the total station.

Table 7.8: Planimetric coordinates using UTM32 and 2D distances. Test DGNSS networks: first test in PADUA-TERRANEGRA (02 MAY 2022).

ID	TCR1201 (Total Station)		Relative positioning		RTK LEICA		RTK VENETO		RTK TPOS (TRENTINO)		RTK Marussi (FRIULI VENEZIA GIULIA)	
	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH
1000	728370.360	5031632.974	728370.360	5031632.974	728370.383	5031632.884	728370.375	5031632.926	728370.391	5031632.904	728370.375	5031632.882
2000	728334.467	5031700.018	728334.458	5031700.034	728334.482	5031699.951	728334.472	5031699.981	728334.489	5031699.958	728334.476	5031699.945
Diff.	-35.893	67.044	-35.902	67.060	-35.901	67.067	-35.903	67.055	-35.902	67.054	-35.899	67.063
D2D	76.047		76.066		76.071		76.062		76.060		76.067	

Table 7.9: Planimetric coordinates using UTM32 and 2D distances. Test DGNSS networks: second test in LONGARONE (20 MAY 2022).

ID	TCR1201 (Total Station)		Relative positioning		RTK LEICA		RTK VENETO		RTK TPOS (TRENTINO)		RTK Marussi (FRIULI VENEZIA GIULIA)	
	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH
3000	754419.150	5129013.724	754421.202	5129014.174	754421.197	5129014.127	754421.190	5129014.160	754421.206	5129014.145	754421.197	5129014.144
4000	754407.709	5129068.030	754407.709	5129068.030	754407.699	5129067.981	754407.694	5129068.010	754407.718	5129067.976	754407.704	5129067.982
Diff.	-11.441	54.306	-13.493	53.856	-13.498	53.854	-13.496	53.850	-13.488	53.831	-13.493	53.838
D2D	55.498		55.521		55.520		55.515		55.495		55.503	

Table 7.10: Planimetric coordinates using UTM 12 zone and 2D distances. Test DGNSS networks: first test in PADUA-TERRANEGRA (02 MAY 2022).

ID	TCR1201 (Total Station)		Relative positioning		RTK LEICA		RTK VENETO		RTK TPOS (TRENTINO)		RTK Marussi (FRIULI VENEZIA GIULIA)	
	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH
1000	728370.360	5031632.974	2993577.971	5029505.579	2993577.991	5029505.488	2993577.985	5029505.530	2993578.000	5029505.508	2993577.983	5029505.487
2000	728334.467	5031700.018	2993544.603	5029573.914	2993544.624	5029573.831	2993544.615	5029573.861	2993544.631	5029573.837	2993544.618	5029573.825
Diff.	-35.893	67.044	-33.368	68.335	-33.367	68.343	-33.370	68.331	-33.369	68.329	-33.365	68.338
D2D	76.047		76.047		76.053		76.044		76.042		76.048	

Table 7.11: Planimetric coordinates using UTM 12 zone and 2D distances. Test DGNSS networks: second test in LONGARONE (20 MAY 2022).

ID	TCR1201 (Total Station)		Relative positioning		RTK LEICA		RTK VENETO		RTK TPOS (TRENTINO)		RTK Marussi (FRIULI VENEZIA GIULIA)	
	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH	EAST	NORTH
3000	3023259.543	5125808.966	3023259.543	5125808.966	3023259.536	5125808.919	3023259.530	5125808.951	3023259.546	5125808.936	3023259.536	5125808.936
4000	3023248.102	5125863.272	3023248.102	5125863.272	3023248.091	5125863.223	3023248.086	5125863.253	3023248.109	5125863.218	3023248.095	5125863.225
Diff.	-11.441	54.306	-11.441	54.306	-11.445	54.304	-11.444	54.302	-11.437	54.282	-11.441	54.289
D2D	55.498		55.498		55.497		55.495		55.474		55.481	

The results achieved utilizing the UTM 12 zone were considered to be the most accurate as this zone is coincident with the Greenwich prime meridian and this meridian passes for Padova (Table 7.10). This is why deformations are not introduced when the coordinates are acquired considering this reference system. In this case, both the measurements performed utilizing the total station and relative positioning technique yielded the same value of 2D distance. Likewise, the planimetric coordinates and 2D distances data obtained for Longarone considering the same UTM zone is shown in Table 7.11.

Considering the 2D distance obtained by employing the total station as the correct value, the deviation of estimates of 2D distance determined by the relative and differential positioning were determined and compared (Table 7.12). Similarly, to the case of altimetric positioning results, also, in this case, the relative positioning technique yielded the most accurate value for both the test sites.

Table 7.12: Differences with respect to the correct value (Distance)

	Relative Positioning	RTK LEICA	RTK VENETO	RTK MARUSSI	RTK TPOS
Δ Distance (D2D) - Padua (mm)	0	6	3	1	5
Δ Distance (D2D) – Longarone (mm)	0	1	3	17	24

For Padua, the most accurate RTK solution was remarkably provided by the Marussi network which had a deviation of only 1 mm from the correct value despite being relatively far from Padua. The difference in the 2D distance provided by the Veneto GPS network and TPOS network from the correct value was found to be 3 mm and 5 mm respectively. The data obtained from the Leica network (HxGN SmartNet) displayed a comparatively large deviation of 6 mm from the correct value.

However, the Leica network appeared to provide the most accurate value for the test performed in Longarone with a variation of just 1 mm with respect to the value obtained from the total station. The second most accurate result was provided by the Veneto network. The performances of the Marussi and the TPOS network were comparatively less satisfactory in this case as they represented quite large differences of 17 and 24 mm respectively.

Hence, these results shown in table 7.12 highlights the unexpected performance of Marussi network, due to the fact that it should have provided better results in Longarone than in Padua, since Longarone is closer to Friuli than Padua. But instead, it surprisingly provided the best results in Padua.

Finally, the 3D distances between the two observation points in Padua, A (1000) and B (2000), and between the two points in Longarone, C (3000) and D (4000) were calculated using the 2D distances and difference in elevations between each of these two points for each of the positioning methods (Table 7.13).

Table 7.13: 3D Distance between the two observation points at each of the test sites

	TCR 1201 (Total Station)	Relative positioning	RTK LEICA	RTK VENETO	RTK MARUSSI	RTK TPOS
3D Distance (Padua) (m)	76.0497	76.0497	76.0558	76.0467	76.0507	76.0451
3D Distance (Longarone) (m)	55.5028	55.5028	55.5016	55.4996	55.4861	55.4787

Chapter 8
Conclusions

In this study, we evaluate the survey productivity and real-time positioning accuracy of four RTK GNSS networks using different constellation combinations and different reference systems at two test sites in Northern Italy. The four RTK networks are: (1) Veneto GPS network, (2) Leica network (HxGN SmartNet), (3) Marussi network (Friuli Venezia Giulia) and (4) TPOS network (Trentino). The fidelity of the solutions provided by these four networks was verified by comparing them with the results derived using classical topographic methods, namely (1) Geometric leveling from the middle and (2) Total station survey. The classical topographic survey provides positioning solutions with very high precision and this is why they are considered to be perfect.

Elevations and reference coordinates for two observation points in each of the two test sites were computed through the digital level and total station survey. Subsequently, they were also computed by employing static and real-time positioning technique through the four RTK GNSS networks. The total station survey achieved an average of two observations for each point. The relative positioning survey consisted of a 3-hour session for each test site and the real-time kinematics positioning consisted of a 5-minute session for receiving solutions from each RTK network.

Three different spatial reference systems for altimetric positioning and two different UTM zones for planimetric positioning were utilized for obtaining the elevations and geographic coordinates of the observation points respectively, in order to compare the accuracy of the data in each reference system and to achieve the most accurate solution. The reference systems were employed in three different ways to compute elevations: (1) Ellipsoidal elevations in the ETRS89 and other RTK elevations in the ETRF2000 reference system, (2) Ellipsoidal elevations in the ETRF2000 reference systems for all techniques and (3) Orthometric elevations obtained using the IGMI grids from ellipsoidal elevations ETRF2000. The UTM zones utilized are: (1) UTM 32 and (2) UTM 12 zone. The most accurate elevations were the ellipsoidal ones achieved using the ETRF2000 reference systems and the most accurate geographic coordinates are those determined using UTM 12 zone.

In the case of altimetric positioning performed in Padua, the most accurate real-time kinematic positioning solution was yielded by the Veneto GPS network with no variation from the correct value, thanks to the closeness of this network to the test site. The second and third best results were provided by the Marussi network and Leica network respectively. The TPOS network presented the least accurate result which may be attributable to the fact that it is quite far from the test site in Padua. However, in Longarone the most precise elevations were given by the TPOS RTK network with a deviation of only 4 mm from the correct value of Δ elevation; since this network is the closest to the test site in Longarone. The second-best result was shown by the Veneto GPS network, followed by the Leica network and Marussi network respectively.

For the planimetric positioning carried out in Padua, the most precise RTK solution was provided by the Marussi network, with a difference of only 1 mm with respect to the correct 2D distance value. The Veneto GPS network also worked quite well with an RTK solution that resulted in a deviation of just 3 mm from the correct value of 2D distance. For the test site in Longarone, the Leica network (HxGN SmartNet) yielded the most accurate value of 2D distance with a variation of only 1 mm from the correct value. The second most accurate result was obtained utilizing the Veneto RTK network which represented a variation of 3 mm from the correct value provided by the total station.

In both the cases of altimetric and planimetric survey, the most precise solution was achieved through the employment of relative positioning technique. This method yielded an elevation variation of 2 mm and 4 mm respectively, for the tests carried out in Padua and Longarone in the case of the altimetric survey, while it provided a 2D distance value that absolutely matches the correct value given by the classical topographic method.

The results from the experiments have shown and thus confirmed that all the four RTK networks have provided similar positioning solutions with the expected accuracy and that this accuracy level varied with the distance of the different test sites to the RTK GNSS network stations. Remarkably excellent performance was demonstrated by the Marussi network in Padua. Also, good agreement was observed between the relative positioning and RTK positioning results provided by the Veneto and Leica networks both in Padova and in Longarone (both for the planimetric and altimetric survey). However, further investigations are needed for checking the accuracy level of these results.

8.1 Future Developments

The results of this experiment are in fact related to only one measure in Padova and one measure in Longarone. But if we take more measurements, for instance, on different days and at different times of the day, the results might vary and might not be the same. Therefore, the repeatability of the measurements will be checked in the next work. In fact, the results provided by the Marussi network, which demonstrated better results for Padova than Longarone, could be a chance effect.

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