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Planning a GNSS CORS Network for the Kurdistan Region of Iraq
“A study on how the baseline length and Galileo constellation influence the RTK positioning quality”

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ABSTRACT

Global Navigation Satellite System (GNSS) have become widely used in a variety of life applications by providing positioning, navigation, and timing data services (PNT). GNSS has become prosperous over the traditional surveying methods for positioning and navigation in many aspects, moreover, there have been high demands for better accuracy and precision obtainment. Through the last decades, many approaches have been followed to mitigate the inevitable errors such as using different observation techniques, multiple frequencies, multiple constellations, and network solutions.

Worldwide, many nations have adopted the so-called system of GNSS Continuously Operating Reference System (CORS) network for the geodetic, engineering, and other industrial applications. These networks, using real-time kinematic (RTK) technique, played vital roles in managing the engineering and industrial applications with high accuracy, precision, and efficiency. The number of CORS and their interstation distances are among the key principles for a high-quality positioning and service availability. On the other hand, the geodetic field status in the Kurdistan Region and the rest of Iraq highly necessitate evolvement. Currently, only three National Geodetic System CORS are operational which are insufficient for the coverage of the whole country and future developments (NGS). Besides, the system lacks supporting RTK and only capable of observing GPS and GLONASS constellations with dual-frequency.

This project is aimed to demonstrate plans and instructions for establishing a GNSS network and analysing the impact of the *length of baseline* and *Galileo Constellation* on the positioning quality. The study gives a clear insight into the needs to design an efficient network based on these major principles: *length of the baseline*, *large cities and settlements*, *important projects*, and *coverage*. Two scenarios have resulted from the planning efforts, Case-1 with a service range of 30 km and Case-2 with 50 km range. Furthermore, the examination is conducted based on empirical data provided by the Hungary E-GNSS Network. Twenty-seven baselines were chosen with varying lengths 13 km up to 348 km, post-processed as single-baseline solution technique, and analyses were carried out by means of python programming, statistical methods, visualisation, and a machine learning method.

This thesis proposes implementing a permanent GNSS network covering the Kurdistan Region with a 50-kilometre range of reliable data service. The network plan was decided based on the mentioned principles and analysis. The analysis results inferred the positioning quality is highly reliable up to 50 km. In addition, Galileo satellites contribution significantly improve the availability, accuracy, and reliability as well as the initialisation time and rate.

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CONTENTS

1. INTRODUCTION

1.1 Background

Over the last decades, the usability of GNSS has expanded exponentially and the requirements for higher quality measurements have been increasing. Various techniques were studied and proposed by researchers, agencies, and commercial firms. Such studies led to the use of the Continuously Operating Reference Station (CORS) firstly for geodetic purposes, then, enhanced to be used for monitoring applications (Bock – Shimada, 1990). Some geodetic, engineering, and industrial fields mandated on the fly corrections. Therefore, in the 1990s a new technique was invented known as real-time kinematic (RTK) (Rizos, 2008). For applications such as construction engineering surveying and machine guiding real-time positioning with high accuracy and precession was vital, hence, the RTK approach played a revolutionary role.

The key concept behind this technique was receiving corrections from a reference station in the vicinity. Along with the significant advantages, RTK users faced an additional constraint namely baseline length. The measurement errors emerged increasingly and proportionally with the interstation distance increment which was caused by the distance dependant sources of error: ephemeris, ionospheric, and tropospheric delays. In the early stages, this distance was limited to 10-20 km for a negligible atmospheric effect, followed by more findings that increased the usability of RTK over longer distances.

Moreover, the adjustments were transmitted from a base station which was either a permanent station or a temporary station operated over a control point deployed in advance. In these cases, a dense network of permanent GNSS stations is critical for an accurate and reliable RTK job, even though in the absence of a CORS a temporary station is needed which is an extra instrument and effort. For these reasons, the whole process was considered high-cost and inefficient in some cases.

Henceforth, a new approach was proposed, to overcome the above limitations, namely network solutions. Instead of taking advantage of one reference station, in this concept, the roving receiver performs corrections based on a net of reference stations. The benefits lie in the ‘24/7’ working network with strategic area coverage design broadcasting higher reliable and efficient correction models. With this approach, the distance restriction began to expand up to 50 km and more which was proposed by many influential researches (Odijk, 2000; Li et al. 2010; Tang et al. 2010; Silva, et al., 2020).

1.2 Statement of the Problem

Iraq and the Kurdistan Region are stepping toward development in all the aspects of civilisation. Yet, the circumstances in that territory and surrounding have been hindering the extensive efforts for the sake of stable growth. This had occurred and influenced all the sectors including the field of geodesy. The current geodetic status overview shows that the country lacks the availability of a GNSS network, only four NGS (National Geodetic Survey) single Contiguously Operating Reference Station (CORS) are operational across the whole of Iraq with the area of approximately 437,000 km^2 (NGS CORS). Besides these stations are incapable of real-time kinematic (RTK) service provision, with this small number of stations a huge shortage of coverage exists, and in many cases, the observations are based on extensive reference-rover separations. The only way to use these CORS is the static and post-processing kinematic (PPK) techniques followed by post-processing. To execute RTK surveys, prior static surveys must be performed, processed based on the nearest NGS GORS, and the new control point can be used as a reference. This approach has drawbacks of more time-consuming and costly, besides increasing the probability of errors and mistakes occurrence.

1.3 Purpose of the Thesis

This master’s thesis comprises of two major parts: (1) planning a CORS network and (2) investigations involving positioning quality. Based on various existing guidelines and principles, designs and plans for the establishment of a CORS network in the Kurdistan Region are proposed. The planning can be mainly classified into general and important considerations. The important considerations (principles) led to two major scenarios that are further classified into stages of improvement. The chosen main design principles were the *length of the baseline*, *large cities and settlements*, *important projects*, and *coverage*. Considering these principles and the range of a healthy RTK positioning, the two scenarios densified the network with stations of 30 km and 50 km service radii. The Case-1 (30 km) and Case-2 (50 km) scenarios were further subdivided into stages or plans (primary, secondary, and complimentary).

To further understand and improve the planned location of the CORS, the second part of the thesis studies the impact of the length of baseline and the involvement of Galileo constellation on the availability, accuracy, precision, and initialization time. For this aim, data was supplied by the Hungarian E-GNSS Network and processed in *single base solution* method with CHC Navigation Office 2 (CGO 2) software in two modes: *GPS-only* and *GPS+Galileo*. Python programming was used to extract data from processing reports, mathematical and statistical calculations, data visualisation, and modelling using a machine learning model.

Analysing the results were carried out in two major parts: long baseline and short baseline. The first part gives a solid understanding concerning how easting, northing, height, and time to first fix are influenced by interstation distance and Galileo contribution. The second part, on the other hand, focuses on the short baselines, examining the same elements, mainly up to approximately 50 km of range. This part has a vital role in the RTK applications requiring high-quality positioning.

For the Kurdistan Region, another important facet of the long baseline performance analysis is that it can simulate and give insight about the approximate positioning quality in case of static observation over a long distance and long duration. This is because only two CORS are serving the whole region with an area of approximately 40,000 km^2 and many cases require static observations based on over hundreds of kilometres.

1.4 Study Contribution

After careful planning, the implementation stage begins and both stages can reference to the general instructions and this study. Some scientific benefits of this project have been stated in the previous sections such as planning and analysing expected positioning quality. Moreover, the core purpose is the practical use of the results in the future. The effort aims to have the region well-covered with a network of CORS as the first step, and secondly provide a network RTK (N-RTK or NRTK) solution system for the future development of the dependent sectors. However, in the thesis, the methods of N-RTK will not be discussed in detail nor decided.

Wide variety of applications ranging in the fields of engineering, aviation, agriculture, transportation, machine guiding, and more, can take advantage of such a system of positioning. The current major needs for RTK and N-RTK concentrated in geomatics engineering, general engineering, and the oil industry. Also, in general, there are high demands for spatial information collection for the purpose of GIS, cartographical mapping, and cadastral mapping. The contribution of GNSS RTK is beneficial in both the direct way by using a roving receiver or indirectly using manned and unmanned aerial vehicles for remote sensing, aerial surveying, and photogrammetry.

1.5 Thesis Structure

The thesis begins with the introduction (Chapter 1) which addresses the background of GNSS, CORS, and RTK, problem statement, the purpose of the thesis, study contribution, and thesis structure. Chapter 2 provides a literature review of the evolvement of GNSS, guidelines, and relative conducted researches. Chapter 3 is specialised to planning the CORS network using principles and instructions. Chapter 4 (study and evaluation) consists of a detailed description of the network, data, software comparison, python library, methodology (procedure model), and statistical measures and models. Chapter 5 (results and analysis) reviews the results in forms of analysis using various statistics, visualisation, and modelling methods. Chapter 6 summarizes the findings of the thesis project and give future suggestions.

2. LITERATURE REVIEW

Since the second half of the 1980s, Global Positioning System (GPS) Continuously Operating Reference Station (CORS) applications have started to widen from geodetic control survey and precise orbit determination to monitoring investigations (Lichten – Border, 1987; Rizos, 2008). Networks of CORS have been employed for the provision of higher precision positioning applications. Practices such as crustal deformation monitoring, engineering structure monitoring, determination of ionospheric and tropospheric models, and other geoscience studies were implemented in California, Japan, the United States, and Canada (Bock – Shimada, 1990; Chen, 1994).

The scope of using CORS has further improved over the last two decades and many countries in the world started to own networks. With the growth of the demand for higher quality and real-time measurements, various efficient approaches were proposed. The mentioned projects were carried out by GPS static technique complemented with (followed by) a post-processing procedure. Albeit, some applications of engineering surveying, agriculture, and precise machine guidance required real-time correct positions rather than post-processed coordinates in case of static and post-processing kinematic (PPK). Thus, a new era of positioning and navigation has started with the advent of the real-time kinematic (RTK) technique in the early 1990s (Rizos, 2008).

Many governmental, scientific, and private sectors have proposed various methods to establish a CORS network. These manual instructions can be classified under scientific, instrumental, technical, construction, coverage area, standard and conventions, operation and monitoring, and more depending on the system. The majority of those parties adopted the NGS Guidelines for New and Existing Continuously Operating Reference Stations (NGS, 2020). Besides, proprietary guidelines and methods were suggested by researchers and countries.

Up to this point, corrections were transmitted from one reference station to the roving instrument which is referred to as RTK single baseline solution. Further developments emerged the RTK network solutions (N-RTK or RTN) taking correction based on a net of CORS. Wide Area Differential GPS (WADGPS) and the Wide Area Augmentation System (WAAS) were also network systems based on pseudo-range with metre level accuracy for long baselines. In comparison, RTK network is an integration of RTK and network system which is based on carrier phase measurements and upgrades to centimetre level accuracy with lower dependency on baseline length (Rizos, 2002).

Regarding the stations’ distribution structure, Chris Rizos (2008) proposed a hierarchy of CORS consisting of three tiers (classes): (1) Tier 1 defined as the highest international order such as IGS stations or equivalent, (2) Tier 2 defined as the highest national order with geodetic network specifications, and (3) Tier 3 defined as the secondary national order (state order). He has also classified Tier 3 networks to be compatible with the professional and industrial uses such as engineering and agriculture.

Additionally, the Guideline for Continuously Operating Reference Stations Special Publication 1(Intergovernmental Committee on Survey and Mapping [ICSM] – Permanent Committee on Geodesy [PCG], 2014) specified the distance between stations for each of the Tiers 1 to 3 as 500 to 1500, 80 to 500, and 20 to 80 kilometres respectively. However, the baseline lengths ought to be defined according to the country area and population distribution. Also, the same publication has addressed three key principles to design a GNSS CORS: (1) Length of the baselines, (2) Control stations’ linkage with the international and national reference frames, and (3) Studying the impact of a station service disruption.

Distance from the reference to the rover has a direct impact on the quality of positioning. To achieve centimetre and millimetre level accuracy, dense networks of Active Control Stations (ACS) are established. The baseline length is a dominant constraint in real-time kinematic both in single-base and network-based solutions. (Chen et al., 2001; Li et al., 2014) proposed this length to be limited to about 50 km or shorter in the mid-latitude regions which are under higher ionospheric effects.

The density of the station depends on the area of the country, for example, covering the whole of China or Australia with such density (50 km) would involve thousands of references stations that require a huge capital. Therefore, researchers have been working on developing new methods to increase the inter-station distance to about 100 km or more with preserving centimetric accuracy (Li et al. 2010; Tang et al. 2010; Silva et al., 2020).

These infer the determination of the number of stations and their location are critical aspects of the network design. The area of the country and the distribution of the population and strategical projects are the significant reasons to decide the density of the network. On the other hand, the evolution of GNSS can alleviate the baseline length constraint. Besides the valuable researches conducted to improve tropospheric models and ambiguity resolution (AR), GNSS development supports filling the gaps progressively. Receivers and antennas, nowadays, are manufactured with the capability of various satellite constellation reception: GPS, GLONASS, BDS, Galileo globally, and regional QZSS and IRNSS. Table 1 shows the GNSS constellation status on 11 May 2020 (Hein, 2020) and figure 1 shows the number of visible satellites at the sky of the Kurdistan Region capital city Erbil on the same date. Each of these satellites transmits observation and navigation data using triple-frequencies.

GNSS constellation Status 11.05.2020	**GPS**	**GLONASS**	**Galileo**	**BDS-2**	**BDS-3**
Total Satellites in constellation	32	27	24	15	34
Operational	31	24	22	15	28
Not included in the orbital constellation					5
Under maintenance	1				
Spares		2			
In the flight test phase		1	2		
IOV SV included in the operational constellation			3		

Table 1. GNSS constellation Status on the date 11 May 2020 (Hein, G. W., 2020)

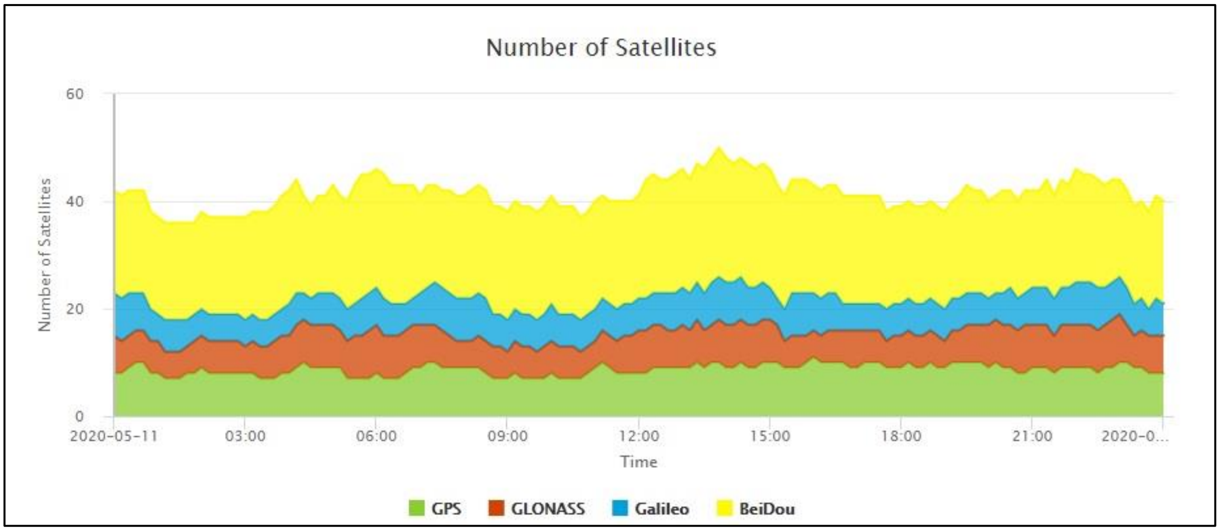

Figure 1. Stacked area chart showing the number of visible satellites at the Kurdistan Regional capital Erbil on the data 11 May 2020 (Trimble GNSS Planning Online).

There are some downsides of the redundant number of the available satellites and multiple frequencies, for example, compatibility and interoperability (Hein, 2020). On the other hand, empirical researches proved that adding more constellations parallel to GPS can improve the quality and reliability, including RTK PNT quality. These improvements are caused by the higher probability of availability and better ionospheric modelling and more immunity against interference and multipath as a result of using multi frequencies.

An excellent research under the title 'How Galileo Benefits High-Precision RTK' (Luo, 2017), investigated the role of using Galileo constellation. The practice consisted of four case studies: open sky, multipath, canopy, and Galileo only RTK. The study concluded that Galileo's contribution, with two to three satellites, had a significant impact on the improvement of availability, accuracy, reliability, and time to first fix (TTFF).

- In the open sky investigation, Galileo improved accuracy to centimetre-level over a long baseline of 116 km.
- In the multipath test, the root mean square error (true error) of the 3D coordinate was improved by 56.3%, TTFF was improved by 7.3%, and the median of the fixing time was lowered by 2 seconds (25% improvement).

- The canopy investigation showed that Galileo increased the probability of the fixed solutions by 12.2% and decimetre-level errors were highly improved.
- The fourth study case experimented with GPS only, GLONASS only, and Galileo only over a short baseline of 1 metre. To ensure the sufficient amount of satellite availability, specifically Galileo satellites, the cut of angle '0' was used. The result has shown that Galileo performed magnificent, with similar accuracy as GPS-only and approximately twice more accurate than GLONASS-only. Figure 2 shows the 3D error of fixed positions for each of the three constellations solely.

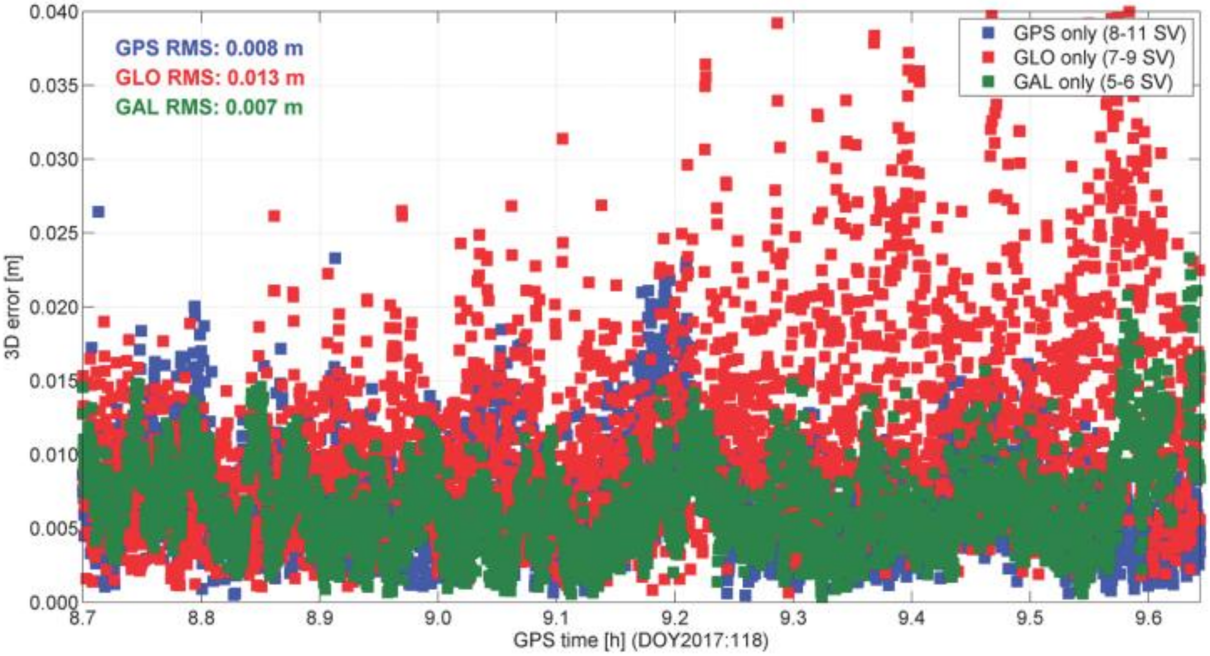

Figure 2. 3D true errors of fixed positions (DOY: day of the year, SV: Satellite Vehicle).

3. PLANNING THE CORS NETWORK

Planning of the CORS network establishment is very crucial in order to give a reliable, continuous, and accurate solution within the desired area. The principles of this design need to be negotiated and standardized to meet the national and international geodetic requirements. In general, the usage purposes, degree of stability, good coverage, and connection to the reference frames require diverse methods and design. To make it more rigorous, Chris Rizos (2008) introduced a CORS hierarchy which is classified under three orders (tiers) each with various requirements. However, this classification depends on the country's standards, prerequisites, and other aspects of plans rather than to be fixed.

The design of such a net of references directly influences the later quality of the service. A network with stable, reliable, and efficient spread stations as well as good system operation can assure a higher likelihood of success. This chapter introduces the main principles (parameters) to be considered during planning. Various resources and guidelines were used, to sum up with this instruction. More importantly, this project proposes two major scenarios each with their specific plans and pros and cons.

3.1 Parameters of the Design

The following three steps are the main parameters to design a permanent GNSS network proposed by the Guideline for Continuously Operating Reference Stations Special Publication 1(ICSM – PCG, 2014). These three points majorly lead to a coverage plan, more importantly in this thesis, the first and third parameters. It is also important to mention the additional directions (explained in later sections) which are vital for the installation of the system. The following are the key parameters:

1. Baseline length;
2. Linking to the global and/or national reference frame;
3. Effect of a station malfunction on the service.

3.1.1 Baseline length

Choosing the maximum distances between the stations is a crucial and complicated process as it is affected by many factors and it also leaves a great effect on the performance (this is further investigated in the following chapters). The base-rover separation is highly dependent on the orbital and atmospheric disturbances. This correlation is true in general but more crucial in case of real-time positioning. The reason is during RTK technique usually short observations are made, faster and more reliable phase ambiguity resolution (AR) are required, and broadcast ephemeris data is used. To warrant a fast fix solution (some seconds to few minutes) with a good validation and high accuracy, various methods are applied with the baseline length constraint cautious consideration amongst. The ICSM and PCG (2014) assigned the three mentioned tiers (orders) with three classes of separation between the stations:

- First-order 500 to 1500 kilometres;
- Second-order 80 to 500 kilometres;
- Third-order 20 km to 80 kilometres.

The highly important aspects of choosing the number of stations and their spread, need to be specified and prioritized to reach an effective design. This process can start with the development of some scenarios embracing strategical views. Each scenario may have its advantages and disadvantages, and the goal would be to select the best possible option that can help the post-establishment functioning and future development. The aspects and resulting scenarios accounted for are relative to the Kurdistan Region. The main aspects to be considered are:

- Large cities and important settlements
- Dams, oil fields and other strategic projects
- Best coverage plan
- Single CORS system or network of CORS

Starting with the best coverage plan, if the geometrical design is set to have the area fully covered the location of the stations will be mostly random. Consequently, the importance of the CORS for the large cities, which embrace most facilities in need for RTK network, for example, will be ignored. The same consequence is likely to happen in case of important projects such as dams, oil fields (figure 3), engineering, geological and so on. Unless an extra number of stations (redundant stations) are to be involved for the sake of 100% coverage and this way confronting an economic and strategic plan.

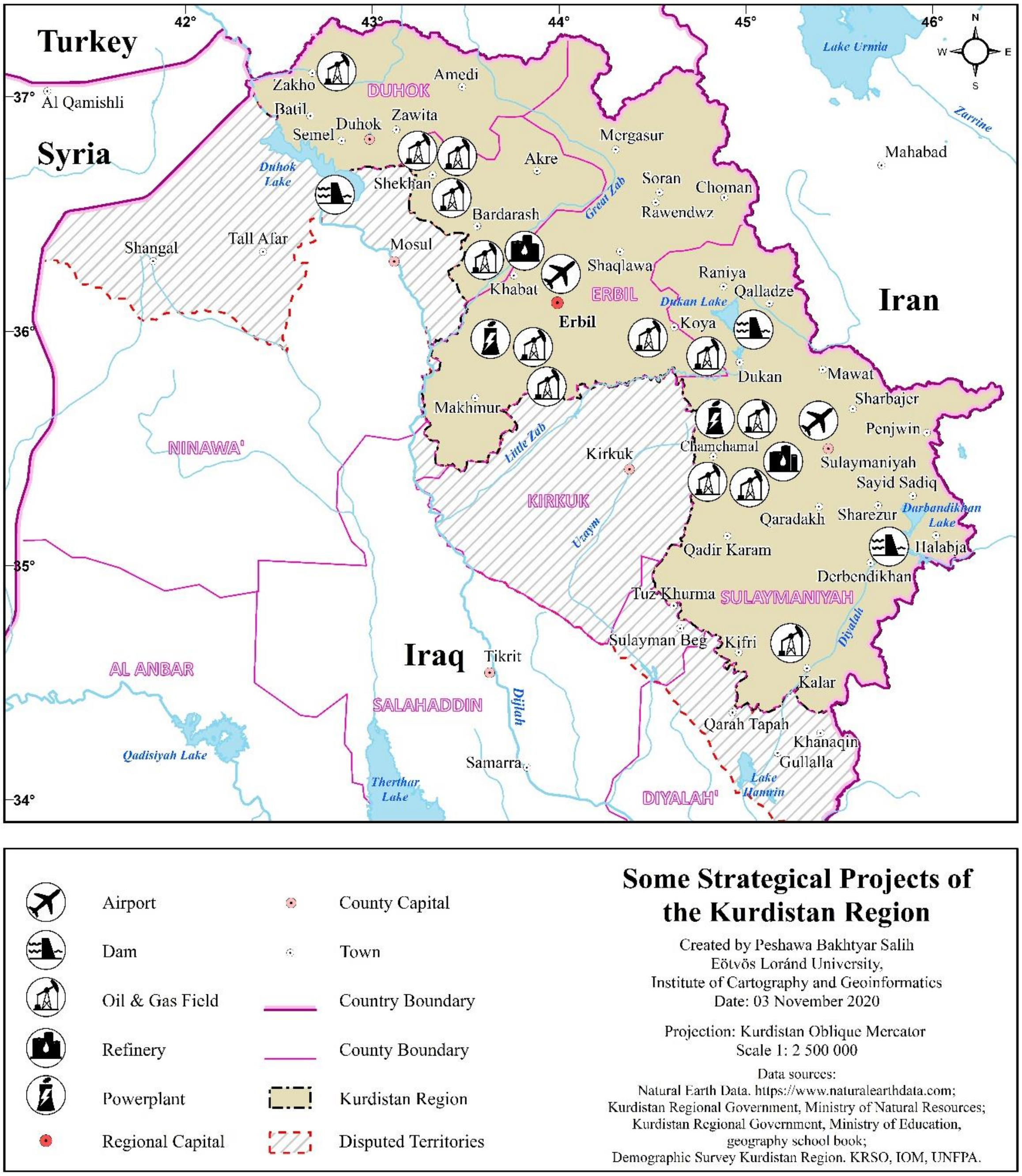

Figure 3. Map of the Kurdistan Region with some of the most important projects.

By taking into account the above four aspects, a design for a network system with the minimum number of stations can be reached. Here the key factor that is most influencing the aspects is the baseline length. The maximum allowed interstation distance and the importance of the stations are controlling the number of stations.

Different approaches can be used to generate scenarios such as manual and automated methods. The automated method is not recommended as it decreases the importance of some of the stations to the projects while it may help the area coverage. For the manual method, it is logical here to fix some of the aspects and alter the rest of them with considering the degree of importance. Two cases can be considered: 30 km range and 50 km range designs. Both can have positive and negative aspects, and each serves the system in different ways.

Case-1 scenario - 30 kilometres:

This case hypothesizes that each station would broadcast data with acceptable accuracy (centimetre-level) in the radius up to 30 km. To fill the region with this assumption, it would require more continuously operating stations. This will cause to increase the cost of establishment and management; however, it is very high-reliable in the respect of solution accuracy, faster time of fixing and station service outage.

The scenario fixes the stations at the large cities and the other most important locations, these fixed points can be classified as a primary plan. To cover the rest of the area, the secondary and the complementary plan is implemented in stages. The primary plan can be beneficiary for the large cities' development in the manner of airport services and projects such as transportation, engineering, dams, facilities, and some power plants and oil fields are included (figure 4). The mentioned services are crucial to fulfil remarkable developments of the country as a first stage. However, it is obvious that less than half of the area is covered with the primary. To reach the remain areas and include the remaining existing and upcoming projects, the secondary and third plan need to be accomplished.

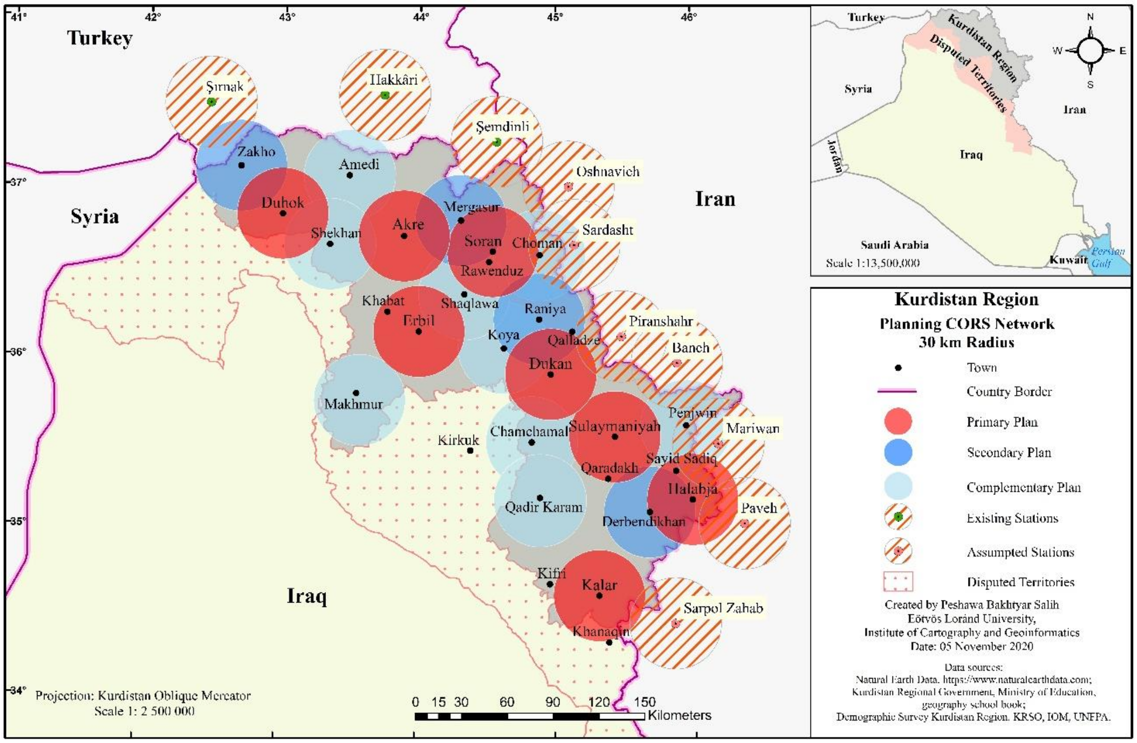

Figure 4. 30-kilometre range scenario with three sub-plans.

The complete design of 21 stations serves approximately 90% of the region which is the most important parts. The left areas are possibly filled with one of the network techniques such as FKP (area correction parameters), VRS (virtual reference station) and MAC (master – auxiliary concept). The unfilled regions receive corrections with possibly lower quality, however, with the N-RTK approach centimetre-level is reachable.

Case-2 scenario - 50 kilometres:

This case assumes that each station would broadcast data with acceptable accuracy (cm-level) in the range of 50 km. As a result, to fill the region it would require less continuously operating stations compared to the Case-1. This causes to decrease the cost of establishment and management; however, it can be less reliable in the respect of solution accuracy, time of fixing, and malfunction.

The scenario fixes the stations at the large cities and the other most important locations as a primary plan. To cover the rest of the area, the complementary plan is implemented. As mentioned in case-1 scenario, the primary plan can satisfy the essentials for the improvement of the cities and service provision for the critical projects (figure 5). However, the goal of establishing a reliable CORS network is unachievable with only the primary plan. By accomplishing the scenario there will be 9 CORS serving with the 50 kilometres radius plan. This will encompass all the required projects and services with the help of the network techniques. Nevertheless, the areas outside the network coverage will still receive service but with less probability of reliability, in another meaning, by increasing the design radius it means the reduction of quality and more time will be required to get a fixed solution.

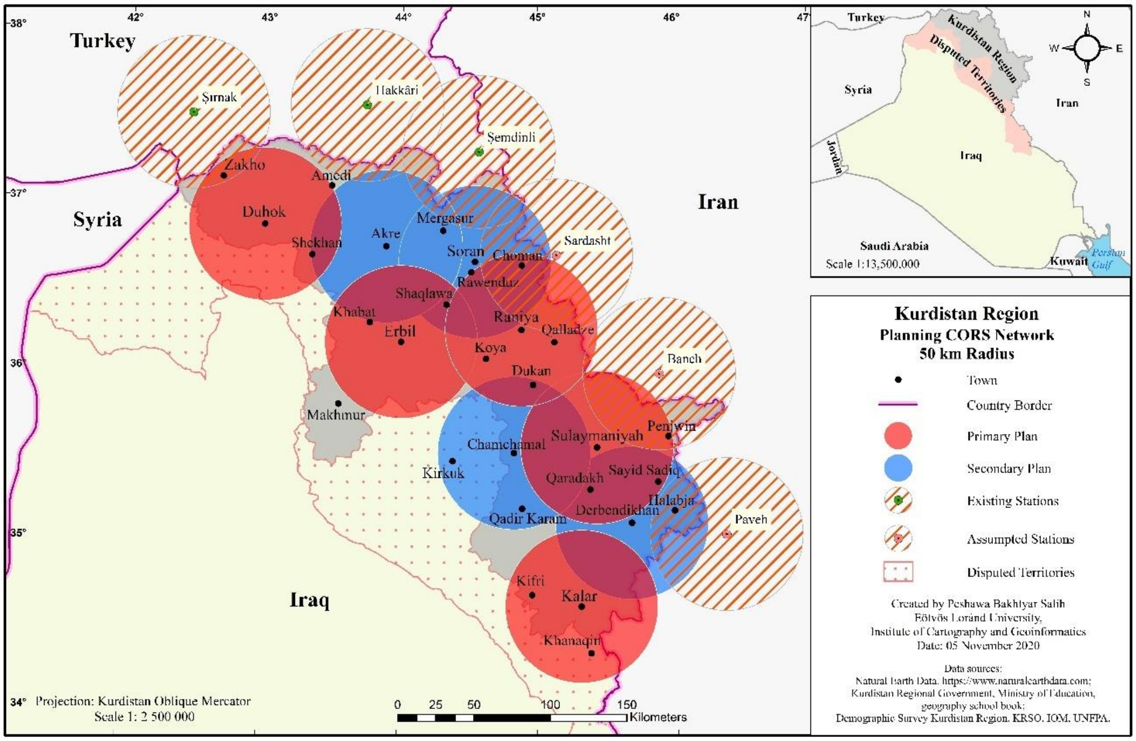

Figure 5. 50-kilometre range scenario with two sub-plans.

3.1.2 Reference Frames

Using and choosing between different frames depends on the country, purpose and availability of national frames. According to the EPSG Geodetic Parameter Dataset (*EPSG Iraq*), in Iraq Clarke 1880 (RGS), GRS 1980, and WGS 1984 ellipsoids are used to define the coordinate systems of the country. Based on those ellipsoids, many projected coordinate systems have been introduced and the most important are: Nahrwan 1934 reference to GRS 1980, Karbala 1979 reference to Clarke 1880 (RGS), Iraqi Geospatial Reference System (IGRS) reference to GRS 1980, and the Universal Transverse Mercator (UTM Zone 37) reference to all the three ellipsoids. Furthermore, transformation models have been developed between these projections. The purpose of this project is about GNSS network; therefore, the main scope is on the planning and investigation rather than dealing with reference frames and coordinates systems. It is recommended to use the WGS 84 with the UTM projection in the initial stage. On the second stage an optimised projection can be developed for the Kurdistan Region of Iraq, by studying the comparisons it can be decided which coordinate system be used.

3.1.3 Malfunction Effect

Testing the disorder of the network is highly required before the final launch of the system, this is mainly required in case of third order with RTK network system. It is substantial to test the disruption effect of a station on the bases of the territorial and the whole network. The test can be conveyed using simulation and manual investigations to predict the effect of the disruption. The results help in improving the weaknesses and reaching the higher reliable system. It will help to find out the probability of service stability using alternative stations, power supply, connection services, hardware and software. On the other hand, the generation or type of system plays a momentous role in compromising for the malfunction. Whether the system is single or network CORS, it leaves a unique effect on the solution during this situation.

The effect is also greatly influenced by the density and type of the system. Taking the mentioned scenarios as examples, the first case of design (30 km of radius) is significantly reliable due to the high number of surrounding stations. If we take Soran station as an example, a noticeable difference can be realized if the station is out of function when Case-1 or Case-2 are used. In the complete plan of the first case, the city is covered by the surrounding CORS with a significant probability. While in the complete plan of the second case the city lies on the edge of the surrounding station's coverage circle or even outlies. In addition to the importance of the number of the surrounding stations and overlapping of the circles, the closeness of these stations matters. It is obvious that in the first case aside from a large number of surrounding stations, the stations are much closer (the baselines are shorter) to the malfunctioned CORS.

3.2 CORS Establishment:

This section consists of all the needs to apply the design and establish the network. After choosing the approximate location in the planning section, the exact locations must be determined. The designated places must meet the minimum requirements of stability, satellite visibility, site security, power, communication, data standards and sharing, cost and management, topography and weather conditions, and many others. Most of the following instructions are adopted the NGS Guidelines for New and Existing Continuously Operating Reference Stations (NGS, 2020), the University NAVSTAR Consortium (UNAVCO), and the Guideline for Continuously Operating Reference Stations Special Publication 1(ICSM – PCG, 2014). This thesis briefly addresses those steps required for the establishment and the detail can be found in the mentioned guidelines.

3.2.1 Signal quality assessment

It is very important to test the received signal before constructing or mounting the antenna. The test compromises of controlling the sky visibility by means of elevation mask angle above the horizon, carefully choosing the location considering the multipath occurrence due to the surrounding natural and man-made objects, and signal interferences. Suspected objects such as solar powers, fences, other antennas and objects must carefully be situated with the distance of minimum 20 meters and below 5° elevation angle. Radiofrequency interferences (RFI) must be defined; RFI effect increases when it is harmonic to the GNSS signal frequency, even the GNSS radio link used to transmit data can be a source of interference itself. Other sources that interfering

GNSS signals are radio, television and mobile phone transmitters, microwave data links, power lines and power transformers.

To have a clear view, assure the required sky visibility and minimise the obstacles, in situ observations can be performed using sensors. The environment can be visualised by taking panoramic images (360 degrees) from cameras situated in place of the antenna. This way the elevation angle of the obstacles can be determined (figure 6). Furthermore, laser scanners can be used to determine the elevation angle and distance of the obstacles and features with respect to the antenna. To complete the signal quality valuation step, field observation data analysed with an assessment software such as TEQC. It is recommended to observe a minimum of two days (48 hours) with these settings: recording at 1 Hz, elevation mask 0°, and not smoothing the pseudo-range.

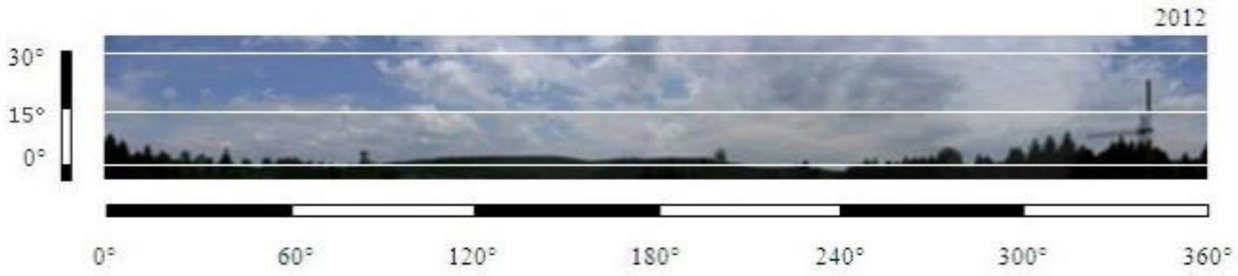

Figure 6. Camera 360° view showing the obstacles surrounding the CORS site with regards to the different elevation angles (from the Hungarian GNSSnet.hu).

3.2.2 Permission

Prior to the site investigation and construction, it is needed to get permission from the responsible owners that can comprise of private and governmental organisations or properties. For the construction of the monument geophysical sampling of the soil is taken and this needs to be done under the rules of the government. Besides, the environment and existing infrastructure must be taken into account.

3.2.3 Site access & security

The operation of the system consists not only the establishment; therefore, it is important to account for efficient sustainment of the system. Accessibility of the place of the station needs to be highly considered and easily reached by authorised persons, specifically, during adverse weathers. On the other hand, the site security must be maintained which includes protecting the CORS site and equipment from theft, destruction, weather, lightning, animals and insects. Reasons like future reliance of the stations for geodetic works and facilities and the cost of the establishment brings the site security necessity.

3.2.4 Site stability

For the structural stability of the antenna's foundation, the monument itself and the antenna mounting device are critical. The foundation depends on the order of the CORS. In an ideal situation, the first and second orders require extreme high stability with fixing it on bed deep rocks. The high stability required because it is important when data collected on tectonic plate motion, related tidal forces, and realisation of the national geodetic reference frame. Therefore, a site with exposed bedrock is preferred to ensure consistency and longevity. Where bedrock is more than 4 meters beneath the surface, a large concrete foundation may be used, for this reason, a geotechnical test of the soil is mandatory.

As for the third order, the antenna is fixed on existing concrete structures and it also gets benefit from the power, communication, and security of that place. It is recommended to use structures with a height less than ten meters (two-story building) because the effect of wind and thermal expansion increases with height. More precise information regarding this can be found in the NGS guidelines (NGS, 2020). Besides the advantages, it is recommended to use monuments and avoid existing structures because buildings are subjected to damage by earthquakes.

UNAVCO introduced the Braced Monuments with two main types, deep and shallow (drilled and non-drilled). The shallow braced monuments are designed as an equivalent class to the concrete pillar monuments with the braced monument having advantages. The shallow drilled braced monument comprises of 4 to 5 stainless steel legs with 1-inch diameter each and installed in the shape of a tripod. The drilled type must be deployed on deep bedrocks (or a surface with bedrocks under within 0.5 metre) up to about 5 to 6 feet. An ideal bedrock has no fracture or damage by the weather impacts. Such method is used at the PANGA, BARGEN, and PBO networks. The shallow non-drilled braced version of the monument uses the same type and dimensions of still legs as the drilled. This type is similar to the drilled monument except for that the legs are pounded into a loose ground or a hand boring is used to create holes. Table 2 and figure 7 demonstrates the comparison between some of the monumentation types and detailed information is provided by UNAVCO.

Type	**Stability**	**Cost**	**Install Time**	**Labor**	**Substrate**	**Site Impact**
Deep drilled braced (permanent)	⬆ high	🔴 $7,500-15,000	◔◔◔ 2-4 d	👤👤👤 3-4	BR, U	🔴 high
Shallow drilled braced (permanent)	⬆ high	🟠 $800+	◔◔ 1-3 d	👤👤 2-3	BR	🟠 med
Shallow braced (non-drilled) (permanent)	⬆ med-high	🟠 $800	◔ 1 d	👤👤 2-3	U	🟠 med
Concrete pillar (permanent)	⬆ med	🟠 $500-2,000	◔◔ 1-3 d	👤👤 2-3	BR, U	🟠 med
Building / other	⬆ med-high	🟡 $150-200	◔ <1 hr	👤 1	BR	🟡 low

Table 2. Comparison table of monumentation types by UNAVCO (Substrate: BR = bedrock, U = unconsolidated, R = rooftop).


Braced Monument
Concrete Pillar
Building Mounting

Figure 7. Three types of antenna mounting structures by UNAVCO.

The ICSM and PCG guidelines (2014) defines the characteristics of antenna monuments to include:

- short, medium, and long-term stability;
- minimal multipath;
- sufficient height to minimise obstructions;
- true verticality within 1 mm (Tiers 1 and 2) or 5 mm (Tier 3);
- simple design for ease of manufacture, installation and maintenance;
- low maintenance;
- corrosion, erosion, and subsidence resistant;
- capable of bearing the mass of antenna;
- Tamper-proof design

For concrete monuments, the design must be certified by engineers to meet the stability standards. To minimise the multipath effect, the top width or diameter of the monument must be less than the antenna diameter. Further, for both orders first and second the recommended height can be between 1.2 and 1.7 meters to minimise multipath, wind load, and expanding effects. For a third-order station, some specific stainless steel is used. If a structure with a metal roof or other reflective surface is used, avoid antenna heights that are multiples of GNSS carrier phase wavelengths (19 or 24 centimetres) (ICSM – PCG, 2014).

3.3 Time and cost management

The importance of time and capital can be considered alterable and complementary for each, meaning, good time management leads to an economic system and powerful finance can help shorten the time of execution. Similar to the engineering projects, it is required to implement a good management plan during the establishment of a CORS network. Starting with the cost, all the necessary equipment and services that are used in the system must be considered. In order to obtain a good insight, a rigorous consideration must be followed that include all the sources of expenditure. Costs for one station establishment can be determined from the estimation of the minimum available known costs, however, all the costs are subjected to change through time. The elements per station can be generalised into the costs of hardware and software, services, labours, fuel, maintenance, maintaining, management, and security, construction, and other costs.

Time, as a critical parameter, leave impacts on the finance, availability, and reliability of the system. If the system is required to be ready and complete in time, that means the process demands more members of the workforce, more equipment and other needs, thus, higher expense. Moreover, a more reliable system requires extreme time management, fast maintenance and customer service.

The UNAVCO, which is a non-profit university-governed association working with geoscience research and education using Geodesy, provides useful information regarding GNSS such as the permanent GNSS/GPS Stations – Budgets which is used as a source in this project. The below table (Table 3) is a short form of the original table showing the total equipment and establishment cost of one station (the detailed budget report is available at UNAVCO).

Sample Project Budget		
Statement of Work: This budget includes the estimated costs associated with the installation of a standard DC-powered GNSS/GPS station installed in the western United States. The assumed data telemetry consists of both phone and radio modems.		
	Number of Units	**Total Cost**
GPS Receiver with Choke Ring Antenna	**1**	**10,475.00**
Radio and Ancillary Hardware	**1**	**1,875.00**
Monumentation- Drilled Braced Monument	**1**	**1,750.00**
Relay Hardware	**1**	**2,225.00**
Solar Systems / Enclosures	**1**	**6,015.00**
Computer System	**1**	**2,330.00**
Total Equipment	**1**	**24,670.00**

Table 3. UNAVCO report of the Permeant GNSS budget (permanent GNSS/GPS stations budgets).

It should be noted that the report was updated in June 2020, however, the type of the GNSS/GPS is not precisely specified. The prices, as mentioned in the table description, are based on the Western United States. The total cost of the equipment, regardless of the total purchase service and travel, calculated as 24,670.00 US Dollars. The prices are due to change based on many factors, nonetheless, it can provide a good insight into the approximate prices and required units.

3.4 Maintaining control and management

After the system establishment, another stage of the system's availability to the users and management emerges. Such management includes regular field checking, site security, and remote control. Regularly checking the system by field visits is essential to keep the network performance smooth and reliable. It has to be inspected whether the GNSS instrument, power, communication, and weather measuring devices are working well and how the surrounding environment has changed. Based on these visit bases, it can be decided when an equipment needs replacement and how to maintain the site by decreasing the multipath and RFI effects. Site security can be governed in various ways such as using a secure site or building for the GNSS instrument, using fences (carefully made to avoid multipath), fire security, power security, and limiting accessibility.

The remote control is a very important part of the process. This is usually done through the central monitoring station (Master Station) through an internet connection, telecommunication, computers, website and software. This can provide powerful remote monitoring through surveillance and robust dynamic analysis dashboard using computers. Another importance of distant monitoring is decreasing the number of field check and cost of the management in that regard. Further, an interactive, smart, and user-friendly website makes available numerous data analysis through tables, charts, plots, and maps to the customers.

3.5 Data standards and sharing

The GNSS instrument and its working mechanism prove that the system is collaborative rather than an individual. A GNSS instrument is always connected to several satellites in case of stand-alone and additionally connected to other instruments in the territory during RTK technique, therefore, data are shared as there are different links. On the other hand, interoperability is another important subject since there is a connection between various instrument manufacturers and further between neighbouring countries. For these reasons, standards are required for the data formats, sharing methods and protocols, and communication link. The current globally used data standards are: RINEX (Receiver Independent Exchange Format), NMEA (National Marine Electronics Association), RTCM (Radio Technical Commission for Maritime Services), and NTRIP (Networked Transport of RTCM via Internet Protocol) (Heo, 2009).

The CORS networks which were established in the early 2000s, for example, the Swiss AGNES (founded in 1998-2001), or even earlier have shifted from propriety to standard data format and upgraded through time. In order to plan the CORS network for Kurdistan Region, it is ought to follow the standards and use the latest version of them. It is also extremely recommended to follow the standard conventions of data transmission protocols such as TCP/IP or UDP/IP and communication links via the internet such as GSM, GPRS, and others.

The master station or the main control station, which is in continues communication with the auxiliary stations, requires a system to manage the network. The system can use specially designed software to maintain a smooth data transmission and provide the solution alongside with the website designed for the network. Nonetheless, to provide more efficient performance flow it is advisable to use software designed by professional firms such as Leica GNSS Spider Software.

3.6 Other Important Aspects

3.6.1 Topography and Environmental Considerations

The terrain type and the geographical location of the area leave effects on the accuracy of GNSS single baseline and/or network measurements. The interstation variation of height causes the alternation of the tropospheric layer; accordingly, the generated tropospheric error would be varied. On the other hand, the topography and the location can also affect environmental measures. The most important are temperature, barometric pressure and humidity. For the mentioned reasons, it is required to study the area in terms of geography, creating cartographical maps and to install environmental gauges to monitor the changes. Further, the large variation of height in the Kurdistan Region causes the telecommunication coverage problem and data transmission challenging. This requires an extensive study to ensure reliable communication and alternatives in case of shortage.

The topographical maps depict Iraq, the Kurdistan Region, and disputed areas (figures 8 and 9). Large variations in Elevation exist across the country and the Kurdistan Region specifically. The most populated places of Iraq are located on the lowlands with elevation less than 100 metres. On the other hand, in the Kurdistan Region, there are large variations in the terrain relief (400 to 3600 metres above mean sea level) in correlation with smaller variation of horizontal distance. Due this fact, extensive study of geography, climate, and telecommunication service testing are required to ensure a healthy system.

To demonstrate the effect of the relief on the troposphere, tropospheric delays can be calculated using one of the models. The below table (Table 4) uses Hopfield model to calculate tropospheric delay values from elevations (Dach et al., 2015). The elevation range is chosen to be between the actual elevation range of the Kurdistan Region of Iraq and the increment does not reflect the actual elevation of the CORS sites but rather to depict the effect of relief on tropospheric delay.

It should be emphasized that another scientific application of tropospheric modelling using GNSS measurements is significant for weather forecasting (Mile et al., 2019).

Elevation (m)	**Temperature (°C)**	**Air pressure (millibar)**	**Humidity (%)**	**Partial water vapour pressure (millibar)**	**Dry tropospheric delay (m)**	**Wet tropospheric delay (m)**	**Total Tropospheric Delay in Zenith (m)**
500	14.8	954.84	36.3	5.4	2.180	0.053	2.232
750	13.1	926.67	30.9	4.2	2.115	0.041	2.157
1000	11.5	899.18	26.4	3.2	2.053	0.032	2.085
1250	9.9	872.35	22.5	2.5	1.991	0.025	2.017
1500	8.3	846.17	19.2	1.9	1.931	0.020	1.951
1750	6.6	820.63	16.3	1.5	1.873	0.016	1.888
2000	5.0	795.72	13.9	1.2	1.816	0.012	1.828
2500	1.8	747.73	10.1	0.7	1.706	0.007	1.714
3000	-1.5	702.10	7.3	0.4	1.602	0.004	1.606
3500	-4.8	658.76	5.3	0.2	1.503	0.003	1.505

Table 4. Calculating tropospheric delay from elevation using Hopfield model.

The cartographical maps in this chapter are generated by the ArcGIS ArcMap and the data sources are indicated on the maps and captions. All the maps relative to the Kurdistan Region uses a projection which I defined for that region namely Kurdistan Oblique Mercator. The projection is the first version rather than optimised one which uses two standard parallels and smallest scale factor of 0.9996.

The spot elevations were determined from a set of SRTM digital elevation models (DEMs) of 1 arcsecond with the raw data size of about 1.7 Gigabytes. In brief, the steps to generate the maps were data collection, shapefiles and layers creation, SRTM DEM masking, combining individual raster files, generating hillshades, define colour scheme, and layout the map.

Figure 8. Topographical map of Iraq.

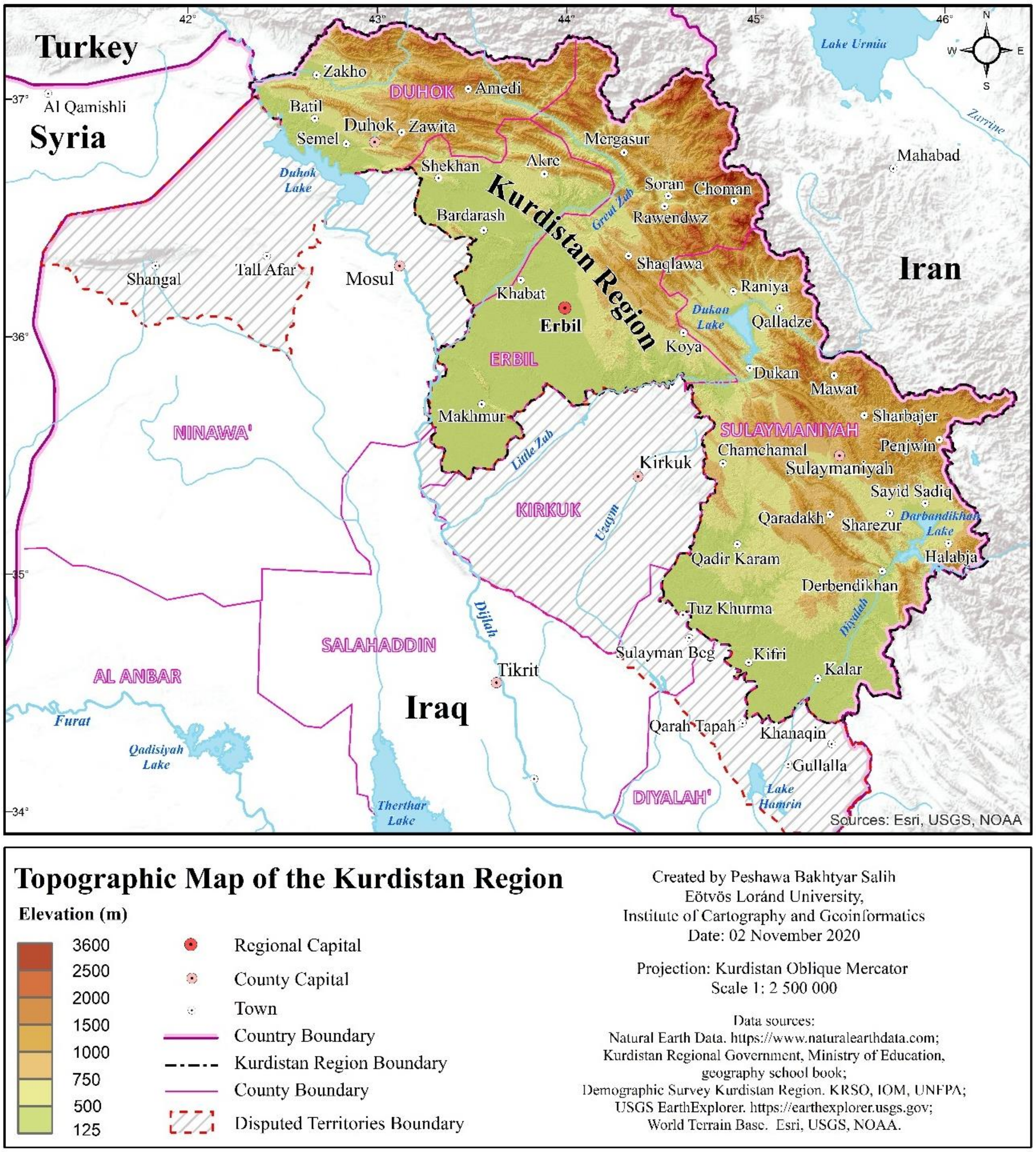

Figure 9. Topographical map of the Kurdistan Region.

3.6.2 Current Status of GNSS Network in Iraq

Studying the available network services in the country and the neighbouring countries will assist an effective and precise plan of the network. Currently, Iraq does not own a national CORS network and there is only one International GNSS Service (IGS) station in Baghdad according to IGS (IGS, ISBA00IRQ Station Information - Site Page). According to the National Oceanic and Atmospheric Administration (NOAA), there are 13 National Geodetic Survey (NGS) CORS situated in Iraq and the Kurdistan Region, however, only 3 of them are operational and one of them is located in Kurdistan Region in the capital city of Erbil (see figure 10 and table 5).

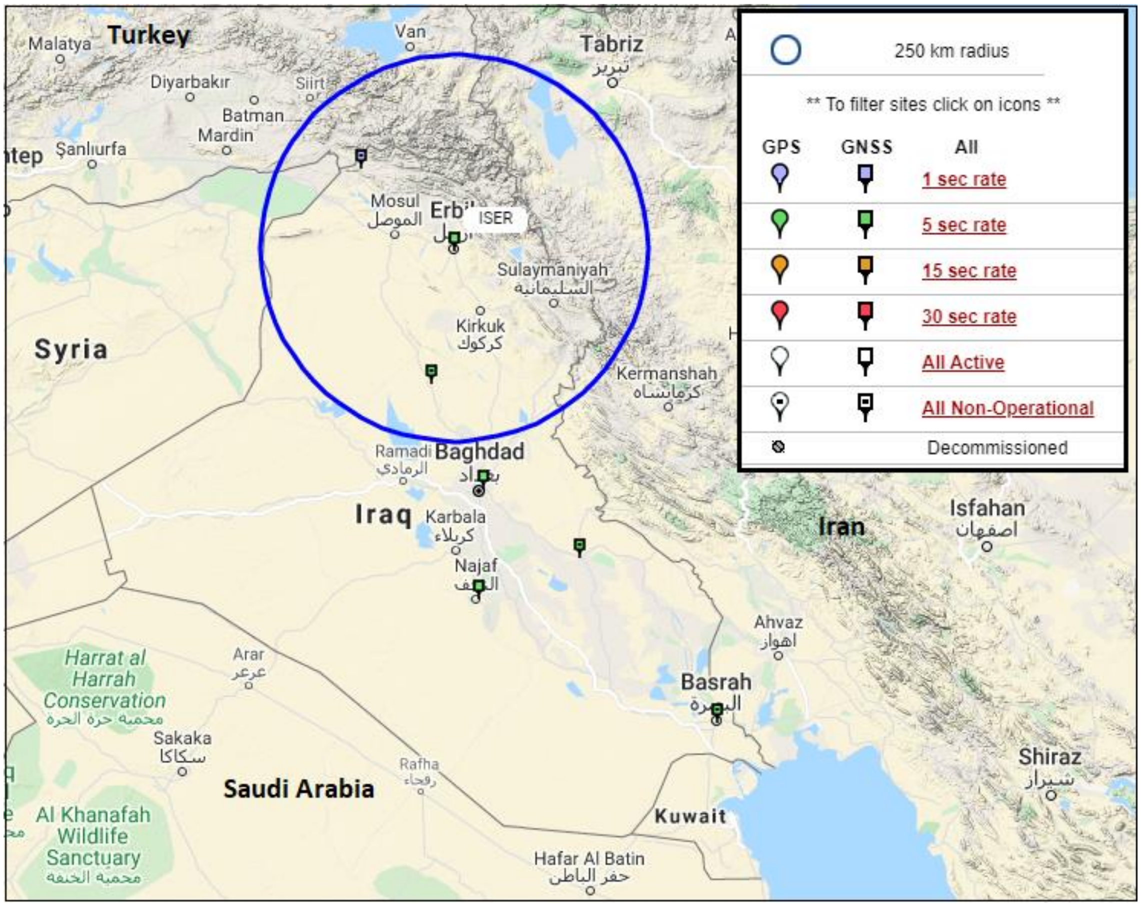

Figure 10. CORS map of Iraq of the date: 30 October 2020 (NGS, CORS Map).

Site Name	**ID**	**Rate**	**Frequency**	**Agency**	**Status**
IRAQ_SURY_BAGHDAD	ISBA	5	60	IRAGDS	Operational
IRAQ_SURVY_BASRAH	ISBS	5	60	IRAGDS	Non-Operational
IRAQ_SURVY_ERBIL	ISER	5	60	IRAGDS	Operational
IRAQ_SURVEY_KUT	ISKU	5	60	IRAGDS	Non-Operational
IRAQ_SURVEY_NAJAF	ISNA	5	60	IRAGDS	Operational
IRAQ_SRVEY_TIKRIT	ISSD	5	60	IRAGDS	Non-Operational
AL_ASAD_IRAQ	IZAD	1	60	320ENG	Decommissioned
BASRAH_IRAQ	IZBA	1	60	320ENG	Decommissioned
BAGHDAD_IRAQ	IZBD	1	60	320ENG	Decommissioned
BALAD_IRAQ	IZBL	1	60	320ENG	Decommissioned
AL_QAYYARAH_IRAQ	IZQW	1	60	320ENG	Decommissioned
TALLIL_IRAQ	IZTL	1	60	320ENG	Decommissioned
UNI_ZAKHO	ZAXO	1	60	IRAGDS	Non-Operational

Table 5. IGS and NGS stations in IRAQ and the Kurdistan Region on the date: 30 October 2020 (NGS, CORS sites).

The neighbouring countries of the Kurdistan Region are Iran and Turkey. Iran has no national CORS network but only two IGS stations. However, Turkey currently has 6 IGS stations and two permeant GPS/GNSS networks namely Turkish National Permanent GPS Network (TNPGN) consisting of 21 stations (figure 11) and Continuously Operating Reference Stations (CORS-TR) consisting of 146 stations (figure 12) (Kurt et al., 2018). Three of these CORS are close to the border of the Kurdistan Region which are located in Shirnak, Hakkari, and Semdinli. These three stations are used in the planning scenarios and since Iran has no CORS network and no station close to the border some stations were proposed in the planning.

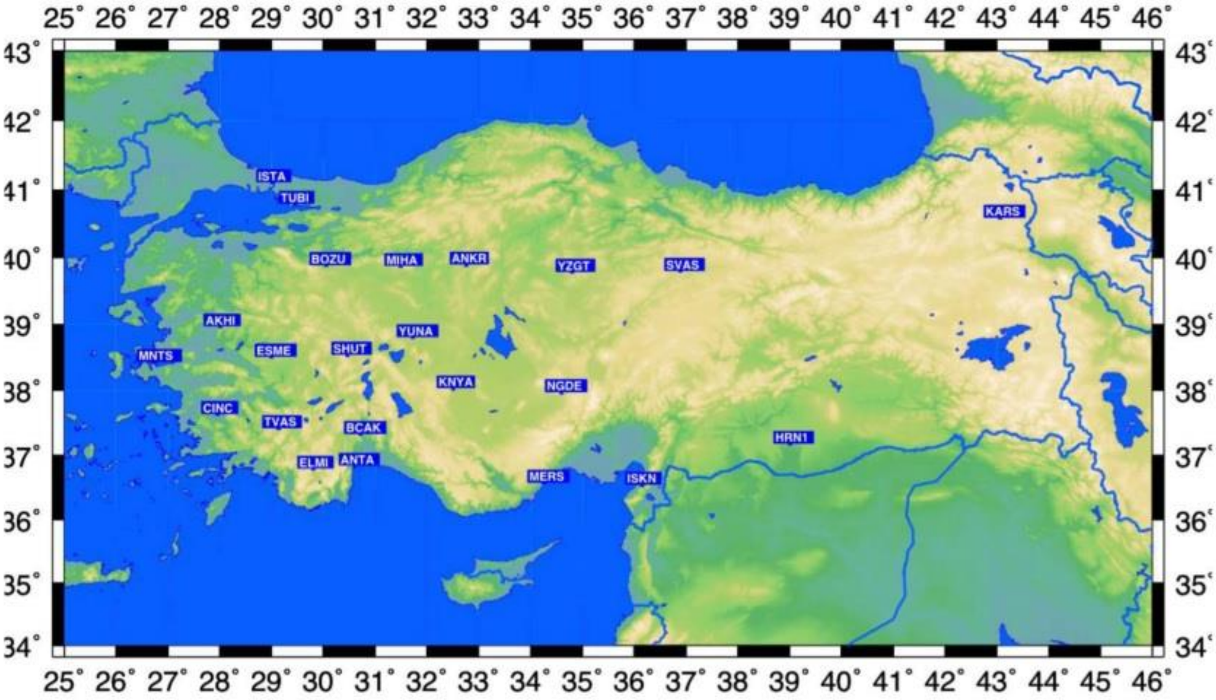

Figure 11. Distribution of Turkish National Permanent GPS Network (TNPGN) sites.

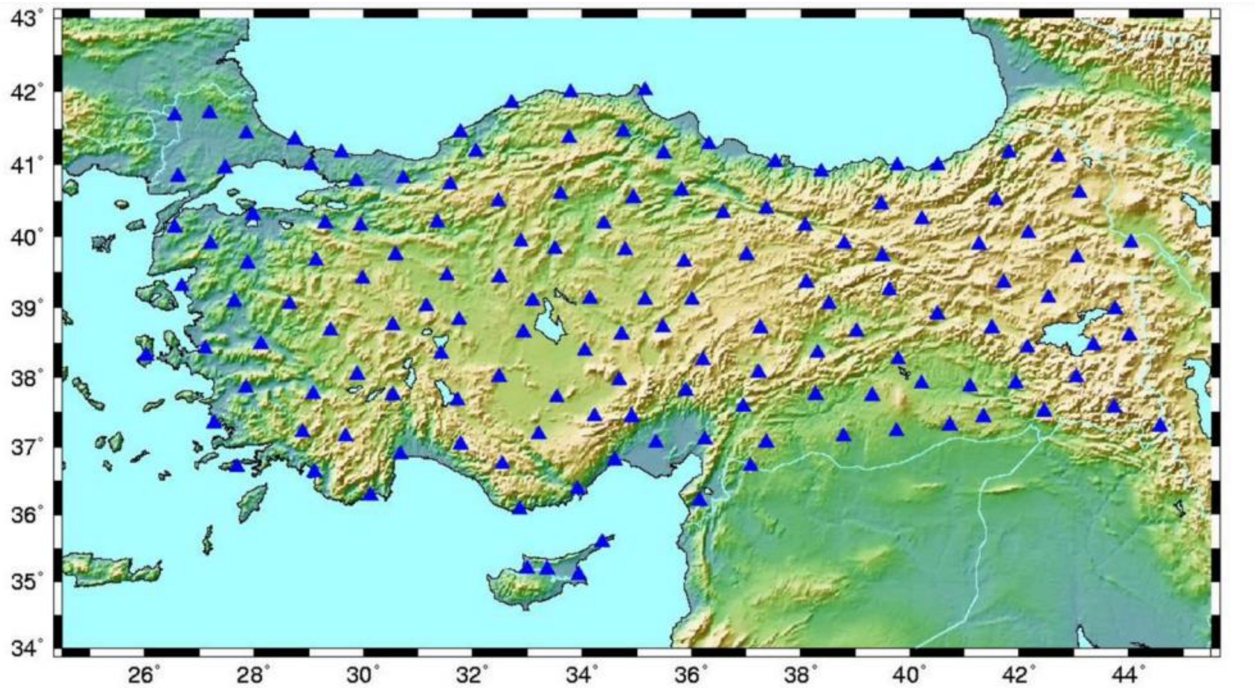

Figure 12. Distribution of the Continuously Operating Reference Stations (CORS-TR) sites.

4. STUDY AND EVALUATIONS

This chapter explains the necessary materials, models, and procedures of performing the empirical study. Since the Kurdistan Region of Iraq does not own a GNSS CORS network, the study was conducted on an available network in Hungary named “Hungarian E-GNSS Network”. The used design of the network and the quality of positioning are significant considerations for deciding an effective CORS network for the Kurdistan Region and future establishment. A large data from E-GNSS and the European EUREF Permanent GNSS Network (EPN) was processed for varying purposes. The processing stages were carried out using different software and coding methods. Finally, the results are used to generate plots and models depicting the status of actual accuracies and the time required for the first fix both according to the base-rover separations (the results are discussed in the next chapter).

4.1 The network

The Hungarian E-GNSS Network is established and maintained in cooperation of the Budapest University of Technology and Economics (BME), HungaroControl and PildoLabs. The network has been deployed for the purpose of PBN4HU (Implementation of PBN procedures in Hungary) project for the framework of the aviation (Bence et al., 2020). Performance-based Navigation (PBN) is a satellite-based landing system that takes advantage from area navigation (RNAV) which provides navigation aids for the aircraft operations. The main benefits of PBN are safety improvement, improves operation efficiency, decrease environmental impact, increases airspace capacity, and reduce infrastructure (*Performance-based Navigation (PBN) Frequently Asked Questions (FAQ)*). The network consists of 11 stations, all the stations located at the airports except for the three stations Ságvár, Bugac, and Sajóhídvég. The minimum and maximum possible baseline lengths formed by these sites were between 12.7 km and 370.8 km. The most important property of the network for this study is that all the stations have the capability of *observing GPS and Galileo constellations* with *triple frequency*. These are significant for the investigation since these two qualities are recent and essential worldwide, especially for Iraq and the Kurdistan Region.

Among the 11 stations, hundreds of possible baselines can be formed by making connections between the CORS stations. However, only *twenty-seven* baselines were preferred for this study with the minimum length of 12.7 km and the maximum length 347.7 km. Except for the BUTE station at BME which uses Leica antenna type “LEIAR25.R4”, the rest of the stations are equipped with Septentrio antennas of the type “AERAT1675_382 NONE”. The data for each station are stored hourly, meaning, each day is divided into 24 sessions and these sessions are designated by the English Alphabet letters from “a” to “x” following the global convention (NGS, 2020). To make the reading and representation easier, from now on the station names will be replaced with codes (table 6).

Name	ID	Location	Network
BUTE	200	University	EPN
Budapest (Liszt Ferenc Airport)	205	Airport	Hungarian E-GNSS
Nyíregyháza	206	Airport	Hungarian E-GNSS
Sármellék	207	Airport	Hungarian E-GNSS
Szeged	208	Airport	Hungarian E-GNSS
Győr- Pér	209	Airport	Hungarian E-GNSS
Ságvár	210	HC premises	Hungarian E-GNSS
Békéscsaba	211	Airport	Hungarian E-GNSS
Debrecen	212	Airport	Hungarian E-GNSS
Pécs-Pogány	213	Airport	Hungarian E-GNSS
Bugac	214	HC premises	Hungarian E-GNSS
Sajóhídvég	215	HC premises	Hungarian E-GNSS

Table 6. Station names, study defined identification codes, airport locationalities, and their parent network.

4.2 Data

Apart from the data used for mapping (chapter 3), the used GNSS data belonged to two different networks of GNSS and various days of two years. The most important data sets to be mentioned were a whole day data of 1st of December 2019 and 7th of August 2020 from the E-GNSS and one-week data from 2nd to 8th of August 2020 from the E-GNSS and EPN networks. The data size of one day was about 2.6 Gigabytes, making the whole data more than 20 Gigabytes. The data formats were varying from Septentrio raw data format to RINEX v.2 and v.3 in the compact RINEX or RINEX formats.

4.3 Data processing methodology

The processing of the raw data followed many steps and tests that evolved into a reliable processing model. The data processing was mainly carried out by using two different software: RTKLIB and CHC Geomatics Office 2 (CGO 2). The generation of the model procedure began with manual processing with RTKLIB between two baselines of one session (session k) of the day number 014 of the year 2020 and each with two modes (GPS and GPS+Galileo). The two baselines were 200-205 with the length of 12.7 km and 200-215 with the length of 155.8 km. This test was performed in a completely manual approach which was comprised of the raw data file conversion to observation and navigation data files, post-processing the baselines, and plotting using RTKLIB RTKPLOT feature. The purpose was to test the software and compare the results of the two baselines.

The next test processed all the sessions (a to x) of the same two baselines (200-205 and 200-215) automatized with python codes and the commands provided by the RTKLIB. After comparing the two modes, some of the results were sceptical because the Galileo system contribution dropped the expected results. This result necessitated the use of the second software CGO 2 to process and cross-check the RTKLIB accuracy.

The outcome from the CGO 2 depicted improvement with the Galileo system in most of the cases, proving erroneous processes made by the RTKLIB. At this stage, the RTKLIB configuration of the processing parameters was expected to be incorrect or unsuitable for this type of process and needed improvement. The differences of the results between the two software, especially from the mid-long baselines, led to the decision of using CGO as part of the model procedure knowing that RTKLIB can only fix ambiguity as single frequency which is clarified in the comparison section.

4.3.1 The comparison between RTKLIB & CGO 2

RTKLIB is an open-source free software with various tools and features providing a very high degree to control the parameters. Example of such tools: data conversion, post-processing, RTK, NTRIP, plotting, and more useful tools. The importance of the software, besides the simple GUI, is that command lines with coding can be used to control the software and automatize data processing. This property greatly facilitates the atomization and bulk data processing very fast.

CHC Geomatics Office 2 (CGO 2) is a software created by CHC Navigation Company that provides innovative GNSS navigation and positioning solutions. CGO important tools are GNSS, RTK, Roads, UAV, and Tools. The most frequently used tools for this project were GNSS for post-processing and Tools' coordinate system manager and antenna manager. The software GUI is more sophisticated, simple and user friendly. However, all the processes need to be carried out manually, thus, it is not recommended for bulk data processing of various sessions and days.

To comprehend the quality of the position solutions' performance, processed baseline 210-211 session "v" with the length of 233.7 km was chosen with both of the software. The main difference between CGO2 and RTKLIB is that when Galileo constellation satellites are involved, CGO gives more accurate PPK solution (figure 13). It has been tested that RTKLIB generates better results when only GPS is used rather than GPS+Galileo. Further investigations concluded that the RTKLIB is not suitable for this project despite of its positive traits. It has been proven that the RTKLIB is a single frequency dependant, in another meaning, the ionosphere disturbance is not cancelled using the multi-frequency techniques (*rtklibexplorer, a first look at rtklib with dual frequency receivers*). Thus, causing in erroneous fixed coordinates when the amount of error increases with the increase in baseline's length. In the following figure, the left plot shows CGO 2 processing with much higher accuracy and reliability than the right plot resulted from RTKLIB process.

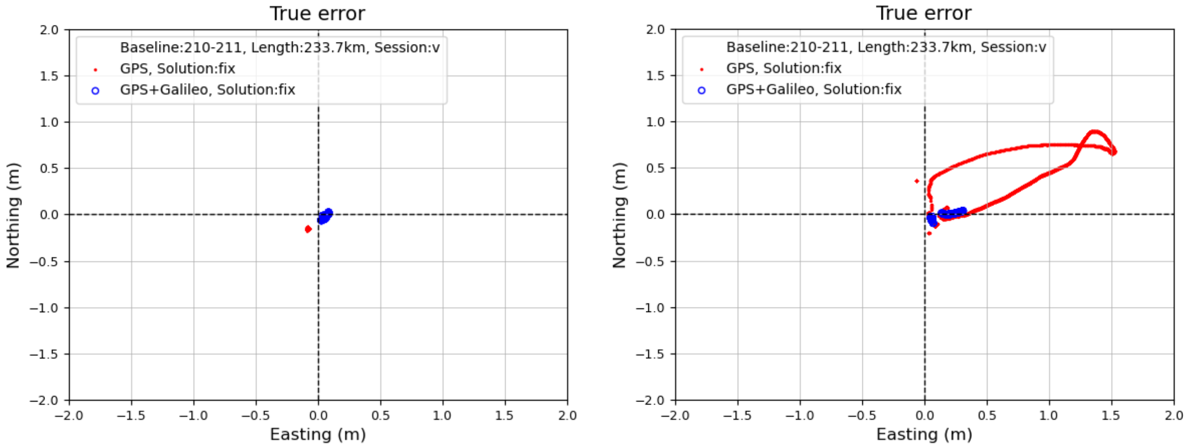

Figure 13. Scatter plots showing the differences between CGO 2 (left side plot) and RTKLIB (right side plot).

4.3.2 Python coding

Python is a high-level and general-purpose programming created by the Python Software Foundation which is free to use and distribute. Python supports various programming paradigms such as structured, object-oriented, and functional programming. It is easy and fast with very rich libraries making the language very fast-growing with a very high rank.

For the purpose of atomization of the whole process, Python coding with PyCharm IDE (Integrated Development Environment) has been used. Executing the written code can perform data conversion, data post-process, data extraction, mathematical and statistical calculations, graphs, models and report generation, and even more functions. Along with planning the model procedure, Python coding played a key role in the improvement. Testing different methods and codes led to an effective special-purpose python library. It is special-purpose since the library needs more improvement and generalization to give it the capability of accepting various data file formats from different software and conditions. The library comprised of many classes, modules, and functions, the most important are:

- baseline_process.py
  This module was used to import and run the modules and functions. Instances of the following modules, new functions were introduced to convert, process, generate plots and reports, and testing. This method makes it more flexible, controllable and organized, especially, with the raw

data conversion and post-processing. In this manner, various functions can be developed for a test process, special process, and actual process.

- rawfile_process.py

  This module comprised of two classes which are only used in case of RTKLIB data processing. The first one developed to convert the raw data from the Septentrio equipped stations to RINEX format and the second class to perform post-process of the baselines. The classes' methods involved both python codes and commands specific to the RTKLIB. CONVBIN and RNX2RTKP commands have been implemented for the conversion and post-processing respectively.

```
≫ convbin –y S “output path” “raw file path” –r sbf –v 3.03
≫ rnx2rtkp –k “configuration file path” -o “output path” “rover observation file path” “base navigation file path” “base observation file path”
```

- txt_to_csv.py

  This module comprised of functions to convert text reports to the comma-separated values (CSV) format file. Position file (.pos) which is also considered as a text file from RTKLIB and text files (.txt) from CGO process outputs were converted using these functions. Text files are not straightforward formats to control and extract data, for this reason, they need to be converted into CSV file. The functions are similar and simply consisted of three important steps. The first step was to read the text file, the second step was iterating through the text lines and make replacements, and the third step was to write the lines into a CSV format file.

- parameter.py

  This module consists of a class which initializes and defines the static, dynamic and global variables and parameters, file paths to read and write processed data, and codes to generate lists of the file paths. This class have instances in other modules and this way the modules' codes will be well-organized.

- plotting_posfile.py

  This module contains tens of useful and smart functions to handle data extraction, calculations, and generate reports and plots. The module first imports the necessary libraries and modules such as CSV, math, statistics, matplotlib, pyplot, pandas, and other libraries. Further, the pre-created modules and classes are also imported such as parameter and txt_to_csv. This module is specified to CSV file generated from the position file of RTKLIB.

- plotting_cgofile.py

  This module is similar to plotting_posfile.py, except for that it is written especially for CGO CSV reports with some special functions and methods.

- model.py

  This module consists of statistical and modelling functions. The most important functions were used to generate histograms, accuracy bands, correlations, outliers, pie charts, and machine learning model (Linear Regression Model).

4.3.3 Processing procedure model

The previously mentioned stages of planning, coding, and processing promoted the final *Processing Procedure Model*. The model is a robust version of the performed trials which is reliable, fast, and giving accurate results. The idea of processing a vast amount of data, statistical and mathematical calculations, and graph and model generations required faster coding techniques.

The first step began with enhancing the Python codes. As a private module, instead of using various functions to each calculate a single type and amount of data, all of the functions have been combined into fewer major functions working statically and functionally rather than automatically.

The major function generates two information files and two sets of three files (each for one processing mode) containing data about processed coordinates for latitude, longitude and height. Another important function imports the former generated eight files, calculates the mean true errors from these files, and writes the values to other files. For clarification, a calculated mean true error is a statistical average calculated from the true errors of all the fixed solutions in one session of a baseline. Each type of files is generated for both modes and all of them are written in CSV format. The advantage of this method is that the mentioned part of data extraction and calculations are static, unchanged for the same dataset, therefore, it is logical to be discluded in the dynamic part of the process. The generated files have further been used to extract data, generate statistical summaries, graphs, and models. This technique is highly efficient and capable of speed up the processing time from days and hours to a few minutes and seconds.

Secondly, the up to date coordinates of the stations were used which were generated with the Bernese GNSS Software. On the other hand, one-week data (week number: 2117) has been processed using CGO 2 with the static mode to find the true coordinates of the E-GNSS stations. For this purpose, seven EPN stations were also used. Four of the stations are located in Hungary and the remaining in the neighbouring countries Austria, Croatia, and Ukraine (Table 7). The number of possible baselines formed from the EPN to the E-GNSS stations was 98 baselines for each of the days.

Station Name	**Country**	**X (m)**	**Y (m)**	**Z (m)**
BUTE	Hungary	4081881.8001	1410011.6161	4678199.7372
OROS	Hungary	4110946.6151	1551048.9035	4608010.1686
PENC	Hungary	4052449.2212	1417681.3693	4701407.2427
SPRN	Hungary	4123047.7260	1227806.6317	4693474.3556
CAKO	Croatia	4227250.2256	1247281.1103	4595193.6823
GRAZ	Austria	4194423.5767	1162702.9433	4647245.5582
MKRS	Ukraine	3915408.8758	1638600.4674	4745087.2187

Table 7. EPN sites by their names, located countries, and coordinates.

The baselines were chosen to be only forward from EPN to E-GNSS stations (i.e. baselines between the Hungarian stations and from these stations to the EPN are not considered) (figure 14). It must be noted that the majority of the baselines were processed using only GPS satellites. This is due to the fact that some of the EPN stations are only capable to observe GPS and GLONASS, whereas, the E-GNSS only observes GPS and Galileo, meaning, the intersection is GPS in most cases. During the process the following specifications were used:

- One-week daily data (days: 215-221) data were processed with EPN reference stations,
- Precise Ephemeris data were used which were downloaded from IGS,
- Elevation mask: 15°,
- Frequencies: Triple frequency,
- Tropospheric model: Saastamoinen Model,
- Phase ambiguity resolution model: LAMBDA,
- Sample Interval: 30 seconds,
- Constellations: GPS or GPS and Galileo (minority of the cases)
- Processing mode: Static

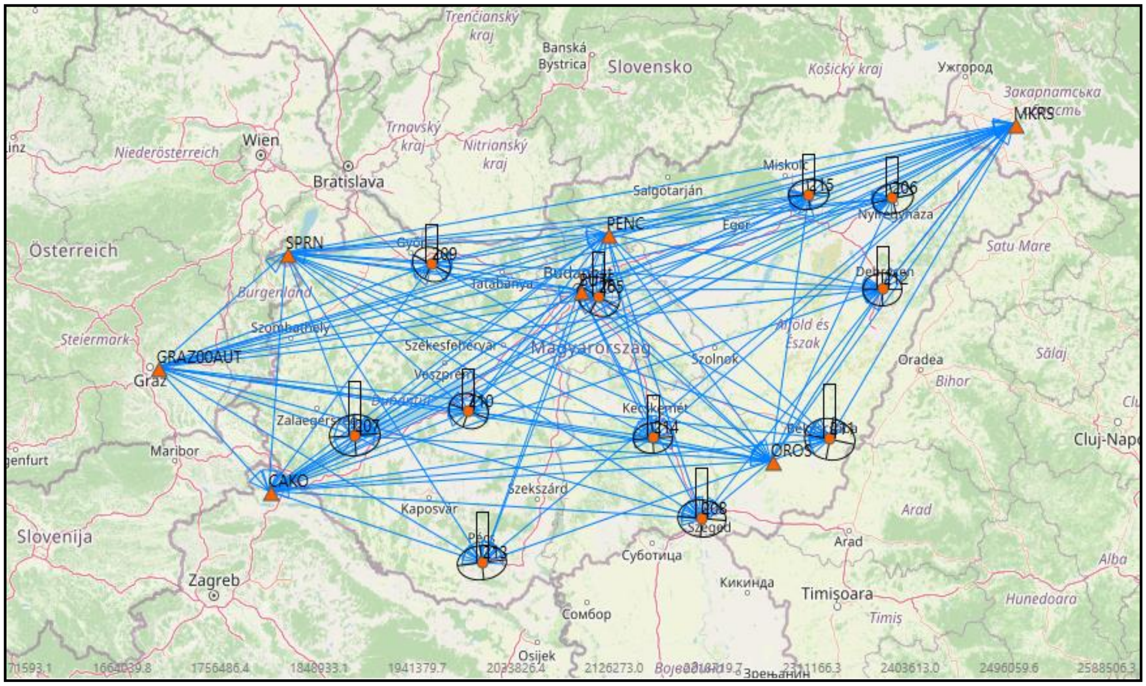

Figure 14. Map of the E-GNSS stations and surrounding EPN stations in Hungary which is generated by CGO 2 software (triangle: fixed stations; circles: processed stations; blue line: baseline; pointer: direction of the process).

This way 541 triangle loops were formed and later an automatic network adjustment was performed (Table 8). The adjusted coordinates of the stations were averaged for the seven days to obtain the final result. These coordinates were compared to the reference coordinates calculated from the Bernese GNSS Software for the quality assessment (table 9). Though the differences were mainly in millimetres, it was decided to use the Bernese generated coordinates for better data processing.

Station Name	ID	Avg. Major Axis(mm)	Avg. Short Axis(mm)	Avg. Azimuth (°)
Liszt Ferenc Airport	205	8	6	19
Nyiregyháza	206	7	6	8
Sármellek	207	10	7	17
Szeged	208	8	6	18
Győr-Per	209	7	5	19
Ságvár	210	9	6	20
Békéscsaba	211	9	7	14
Debrecen	212	8	6	172
Pécs-Pogány	213	8	6	163
Bugac	214	7	5	52
Sajóhídvég	215	8	5	173

Table 8. Average error ellipse of the E-GNSS stations' coordinates over seven days postprocessing. Generated by the CGO2 network adjustment.

Station Name	ID	Avg. latitude CGO	Latitude Error (mm)	Avg. longitude CGO	Longitude Error (mm)	Avg. height CGO	Height Error (mm)
Liszt Ferenc Airport	205	46.68658931	-3.7	19.68229655	-2.1	161.712	-1.8
Nyiregyháza	206	47.44703581	0.1	19.21675894	2.3	196.332	-7.7
Sármellek	207	47.97963450	0.2	21.68988123	8.1	152.372	-36.2
Szeged	208	46.69664988	-3.6	17.16009411	-5.4	175.665	22.9
Győr-Per	209	46.24004372	-1.0	20.08920364	5.0	127.205	-15.0
Ságvár	210	47.62329444	1.4	17.80459130	0.6	180.580	-6.3
Békéscsaba	211	46.82976535	-0.8	18.11724700	-0.5	192.190	14.9
Debrecen	212	46.67682677	4.0	21.16136780	7.9	140.779	-27.1
Pécs-Pogány	213	47.49245064	n.a.	21.61183803	n.a.	158.859	n.a.
Bugac	214	45.99523112	-2.1	18.23322081	1.1	254.108	9.0
Sajóhídvég	215	47.99717787	3.4	20.98758195	5.4	147.929	-16.7

Table 9. Average WGS84 coordinates of Hungarian E-GNSS stations with their residuals calculated from the fixed coordinates obtained by Bernese.

Thirdly, CGO 2 has been designated for the GNSS data PPK processing (figure 15). The first-hand plan was to process the data from one or two month(s) and ten baselines per session with the RTKLIB automated code-supported method. However, after careful review, the RTKLIB realized to be incompatible with multi-frequency. For this reason, the plan has to be reconsidered to process one-day data and 27 baselines per session with CGO 2 (table 10).

	Baseline	**Baseline length (km)**		**Baseline**	**Baseline length (km)**		**Baseline**	**Baseline length (km)**
1	200-205	12.7	**10**	206-211	150.9	**19**	206-214	210.8
2	206-215	52.5	**11**	200-215	155.3	**20**	206-208	230.1
3	206-212	54.7	**12**	200-208	159.8	**21**	207-208	231.8
4	207-210	74.6	**13**	207-205	176.4	**22**	206-209	294.9
5	200-209	95.5	**14**	200-213	177.7	**23**	206-210	301.5
6	200-214	100.8	**15**	200-211	184.5	**24**	207-211	306.4
7	200-210	102.1	**16**	200-212	192.7	**25**	207-215	320.6
8	207-209	114.2	**17**	207-214	193.1	**26**	207-212	347.2
9	207-213	114.2	**18**	206-205	195.9	**27**	206-213	347.7

Table 10. The formed 27 baselines by the E-GNSS stations and their lengths.

The process followed these configuration setting:

- Data: two days data (335 and 220) of the years 2019 and 2020 were processed,
- Ephemeris: broadcast,
- Elevation mask: 10,
- Frequencies: Triple frequency,
- Tropospheric model: Saastamoinen Model,
- Phase ambiguity resolution model: LAMBDA,
- Sample Interval: 1 second,
- Constellations: GPS and Galileo,
- Processing mode: PPK

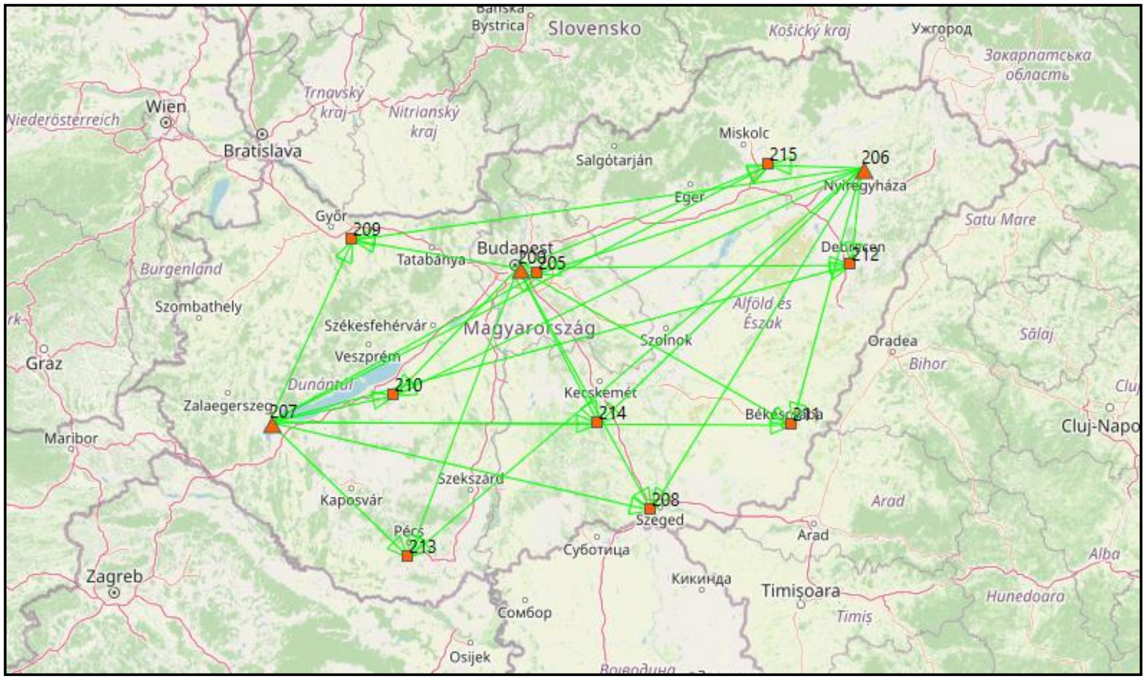

Figure 15. Map of the E-GNSS stations in Hungary which is generated by CGO 2 software (triangle: fixed stations; circles: processed stations; blue line: baseline; pointer: direction of the process).

4.4 Statistics and Models

Statistics as the science of dealing with data, comes considerably important, specifically, when the amount of the data is large and complicated. In such cases of working with numerical data, the mathematical calculations are followed by statistical calculations. These calculations can lead to statistical summaries, models, and data analysis and visualisation. The main calculations were true error, geographical to cartesian coordinate transformation, data correlation, skewness, kurtosis, accuracy classification, model generation, and others.

Data visualisation methods play an important role to complete the data comprehension and analysis process. Unlike data descriptions, statistical summaries, and tables, graphs are a unique way to give tangible and faster communication to the data. Along with all these useful traits mentioned, statistics and data visualisation methods can be sensitive to use. Choosing between the mean and median, for example, and setting limits are decided very carefully here.

As stated earlier, the goal is to compare the quality between the two modes. Python has been used to extract the desired data from the PPK reports. Using well-structured codes calculation, filtering, and smoothing has been performed to generate secondary reports. Taking practical thinking into consideration, only the fixed solutions are extracted and used in most cases. The comparison was divided into two major parts, first involved all the 27 baselines (13km to 350km) and the second comprised of baselines shorter than 100km.

The first part assessment provides a strong overview of how the two important measures of RTK are changing relative to some factors. This is advantageous generally and specifically as it associates with the current system used in Iraq and the Kurdistan Region (the CORSs only provides RINEX data for post-processing). From the results of this study, one can estimate the accuracy based on the rover distance from the CORS and the duration of observation.

The second part, on the other hand, is more specific to RTK solutions. The detail investigations deeply clarify how accuracy and TTFF would be expected. This is an effective valuation for the networks planned for the Kurdistan Region (30 km and 50 km ranges scenarios) that gives effective vision about the RTK ranges of accuracy when a single baseline solution is used. Of course, enhancing the study and design to a network RTK will vastly increase the reliability and quality.

5. RESULTS AND ANALYSIS

This chapter thoroughly interprets and examines the results using rich statistical and visualisation approaches. The chapter is mainly divided into three sections: long baseline analysis, short baseline analysis, and CORS plan decision. The conclusions of the long and short baseline analysis will be used to decide a strategic plan for the permeant GNSS network.

5.1 Part one – long baseline analysis

5.1.1 Accuracy

The initial step of working with such large data is to understand the population distribution. Various methods can be used for this purpose, for instance, using histogram, kurtosis, and skewness. The results can effectively depict how the data is distributed around the mean value and gives an insight into outliers. The preferred shape of the data and its values are relevant to the type of data and investigation. While the population distribution of a sample of people's height is normally distributed, the true error or accuracy population or sample possess a different shape of distribution.

A normal distribution (bell shape) has excess kurtosis (i.e. normalised kurtosis which equals kurtosis - 3) and skewness both at 0 value. On the other hand, an accuracy data favours a spread of high positive excess kurtosis (leptokurtic) and skewness to be 0. Zero skewed population means symmetrical spread around the true value and greater positive excess kurtosis means a high rate of the data is accumulated on the true value rather than spreading to further sides.

The following graphs (figure 16) combine the results with the histogram to present a faster visualisation. The positive values of excess kurtosis are good signs of data accumulation around their true value (i.e. higher accuracy). The distribution is skewed between values -0.52 and 0.88 and this depicts some minor values of low accuracy with the error more than 0.5 meter, specifically, in case of height (i.e. lower precision). The excess kurtosis values are noticeably higher in case of including Galileo satellites. This different caused by two facts, firstly, that Galileo usage improved the accuracy generally, positional accuracy specifically. The other reason was that GPS+Galileo has more data to be drawn since more sessions were fixed than GPS only (higher rates of resolved ambiguity with Galileo).

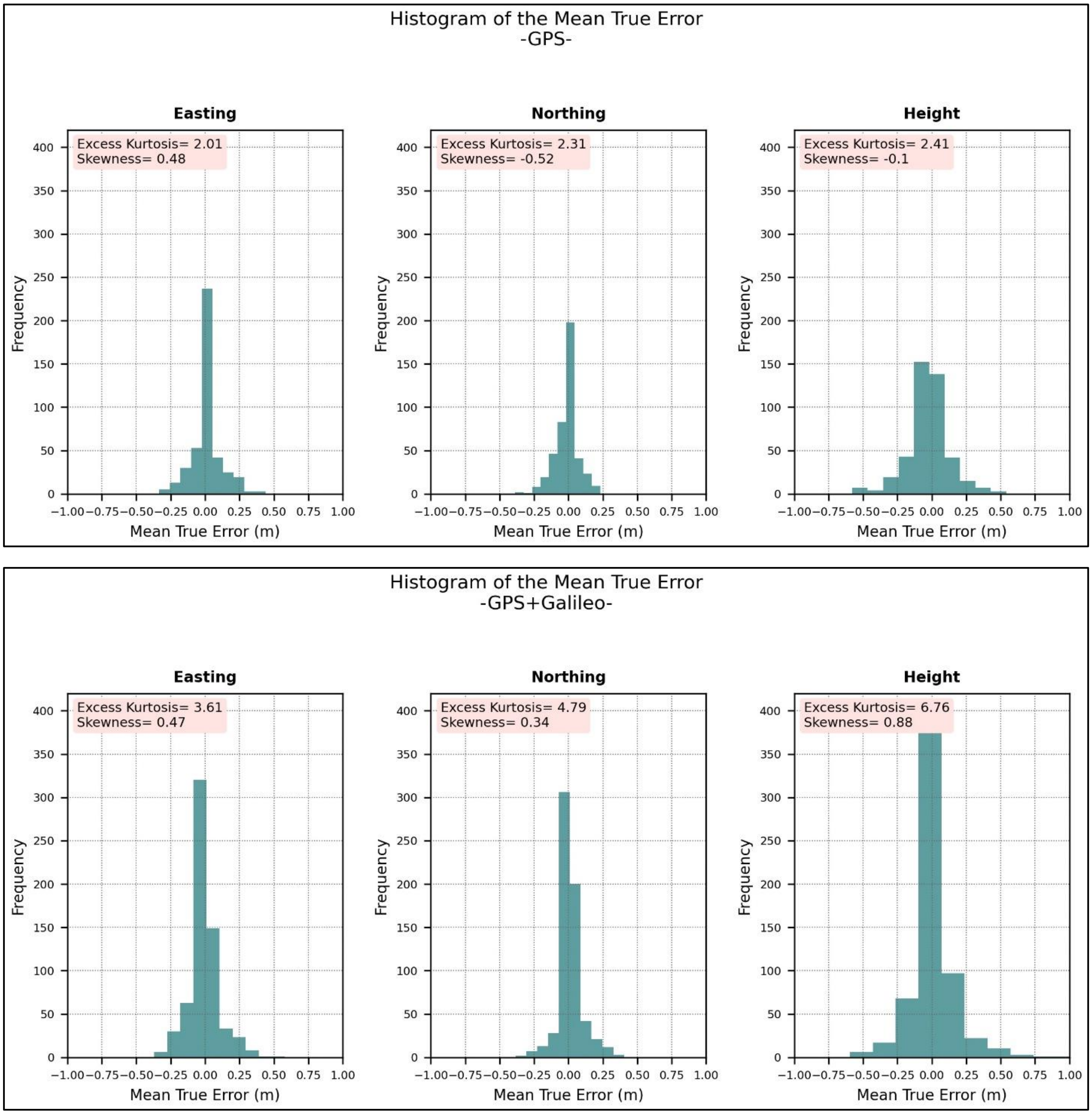

Figure 16. Histogram of the mean true error with the Excess Kurtosis and Skewness measures.

Each type of statistical and visualization methods has its drawbacks, including histograms. The method can show the general shape of the data; however, it lacks showing the rate of the distribution. To complete the comprehension of the mean true error, a unique approach of visualizing accuracy percentage distribution bands was used. For this purpose, ten baselines were chosen, and four graphs were made to represent the horizontal and vertical accuracies for each of the modes. To keep the simplicity, only five bands of accuracy were used: smaller than 1.0 cm (millimetric level), 1.0 to 5.0 cm, 5.0 to 10.0 cm, 10.0 to 20.0 cm, and greater than 20.0 cm. For each band a colour has been used that formed a scheme from higher to lower accuracy: green, lime green, light yellow, light orange, and red (figures 17, 18, 19, and 20).

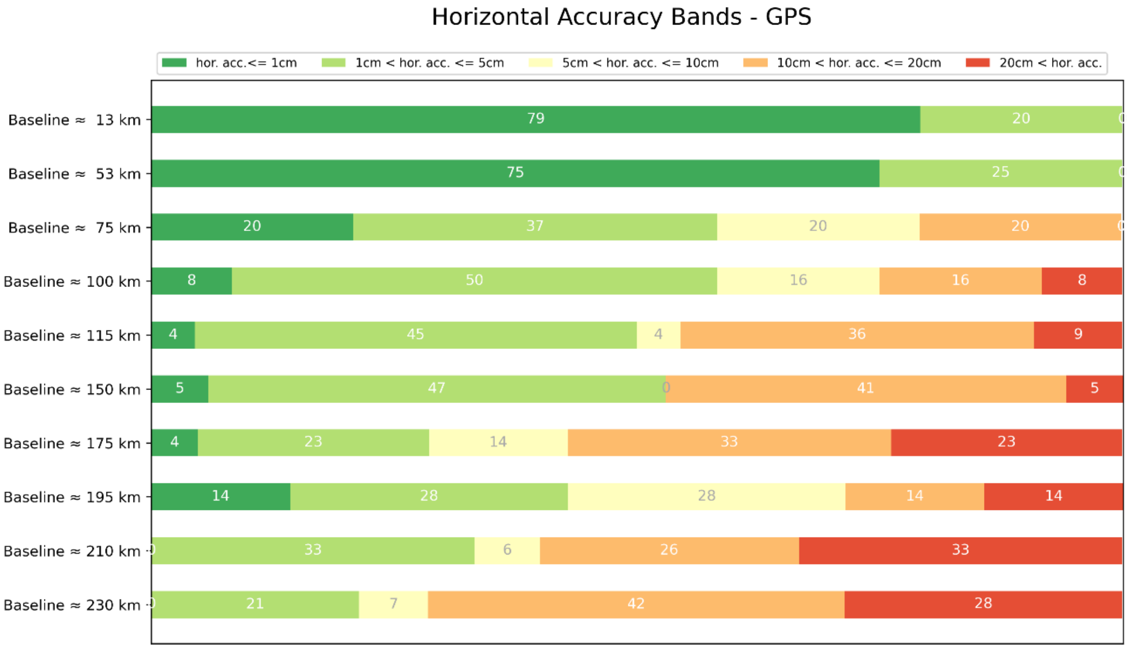

Figure 17. A plot visualising the GPS horizontal accuracy divided into five bands by percentage (below 1.0 cm, 1.0 to 5.0 cm, 5.0 to 10.0 cm, 10.0 to 20.0 cm, and greater than 20.0 cm).

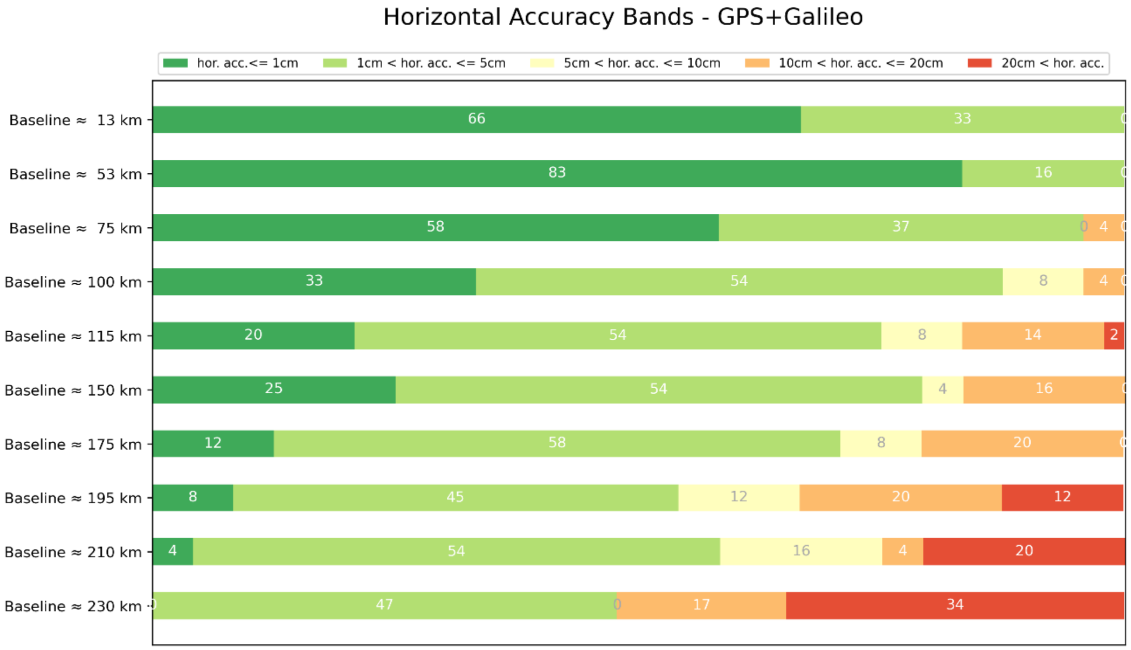

Figure 18. A plot visualising the GPS+Galileo horizontal accuracy divided into five bands by percentage (below 1.0 cm, 1.0 to 5.0 cm, 5.0 to 10.0 cm, 10.0 to 20.0 cm, and greater than 20.0 cm).

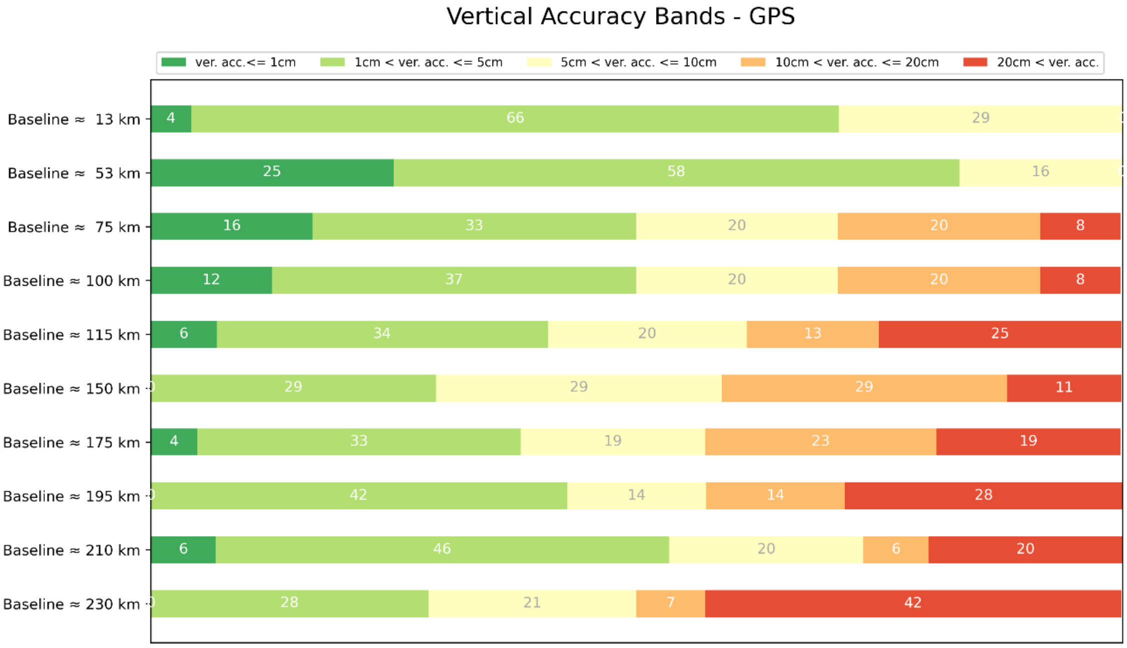

Figure 19. A plot visualising the GPS vertical accuracy divided into five bands by percentage (below 1.0 cm, 1.0 to 5.0 cm, 5.0 to 10.0 cm, 10.0 to 20.0 cm, and greater than 20.0 cm).

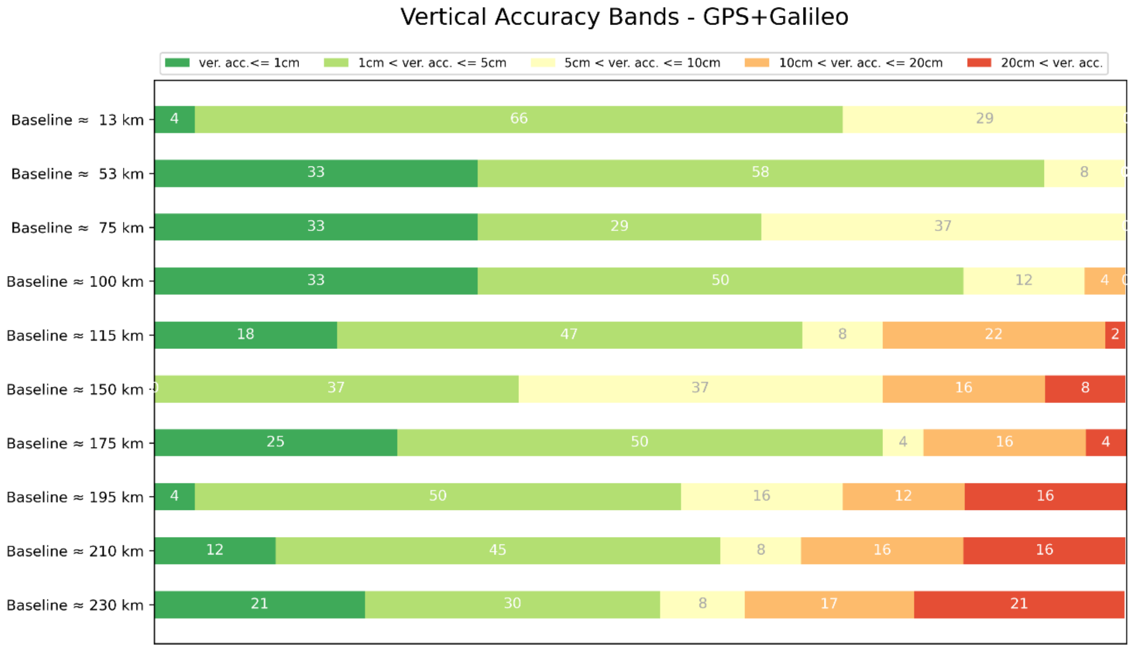

Figure 20. A plot visualising the GPS+Galileo vertical accuracy divided into five bands by percentage (below 1.0 cm, 1.0 to 5.0 cm, 5.0 to 10.0 cm, 10.0 to 20.0 cm, and greater than 20.0 cm).

The figures depict that the horizontal accuracy is highly improved when Galileo constellation satellites were observed. On the other hand, the vertical accuracy gives the impression of more complexity. Even with short separations, the majority of the values appear to be between 5.0 to 20.0 cm accuracy which is poorer than the horizontal accuracy. Nevertheless, while comparing both modes one can observe improvement when Galileo is involved.

Furthermore, there are some facts about this visualization approach that must be considered. Firstly, it is noticeable that some of the longer baselines appear to be more accurate, but the factual comparison is made between the baselines with the same length of the two modes. Secondly, the utilized limits of accuracy to classify the mean true error values highly affect the formation of these figures. In another mean, alteration of the limits can generate varying results.

The previous analyses of the accuracy majorly show independency, meaning, no clear relationships to certain factors were aimed. The next phase comprises of studying the correlation of each of the accuracy elements (easting, northing, and height) with the length of baseline. Although the accuracy bands visualization method can show the relationship with length, more sophisticated models can be used for better insight.

To fulfil this aim, *Linear Regression Models* were generated with python scikit-learn machine learning library. During the coding, 80% of the data was used to solve the line equation and the remaining 20% of the data was used to draw the line. In the case of GPS, the fixed mean true error counts were 430 values and 634 values in the GPS+Galileo mode. For an accurate linear model, absolute values of the mean true errors were used instead of the original values with positive and negative sings. The models show how the accuracies change with respect to the length increment and which mode performed better.

The outcomes portray that there is a positive correlation in all cases, though, the correlation is low (figure 21 and 22). In contrary to some phenomena, low correlation is more valued in such a study. Based on this, there is the probability that the effect of distance between the base and rover stations is not significant on positional accuracy, regardless of other factors. The vertical accuracy, on the other hand, is more affected by this factor, thus, shows a higher correlation (figure 23). Besides, the linear models show that Galileo usage improves the positional and height accuracies.

Due to the fact of existing various factors and sources of errors, these representations of accuracy are not abstract. For the same reason, these generated simple linear regression models are inadequate for predicting accuracies of different conditions. In reality, the nature and quantity of the errors are varying non-linearly, for example, ionospheric errors. Therefore, it is more precise to generate separate dynamical models for each of the error sources. These models can be regarded as private to this study and they efficiently proved the effect of baseline length and the comparison intuition.

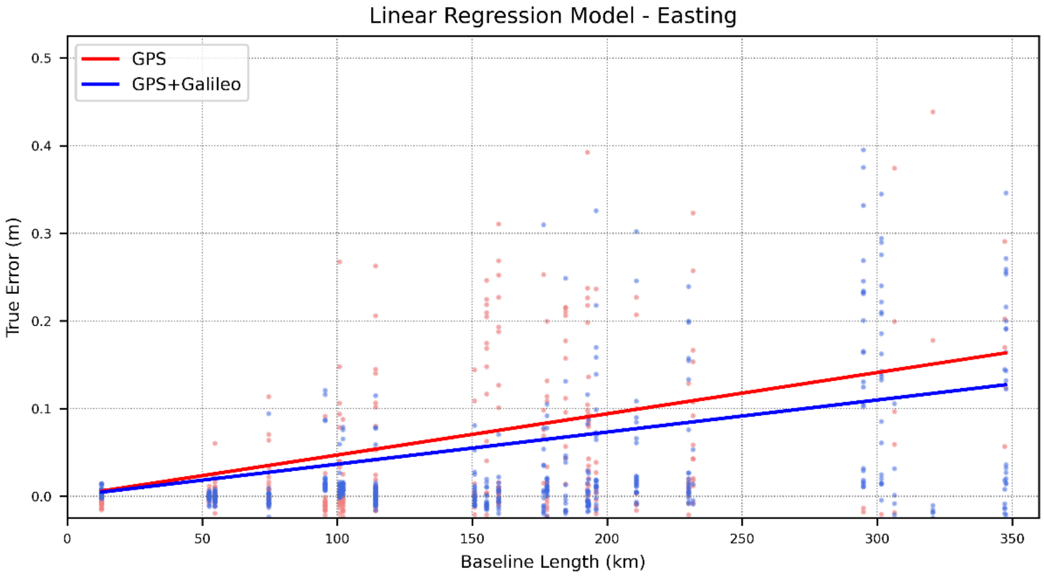

Figure 21. Linear regression model showing the correlation between easting accuracy and baseline length and comparing GPS and GPS+Galileo performances.

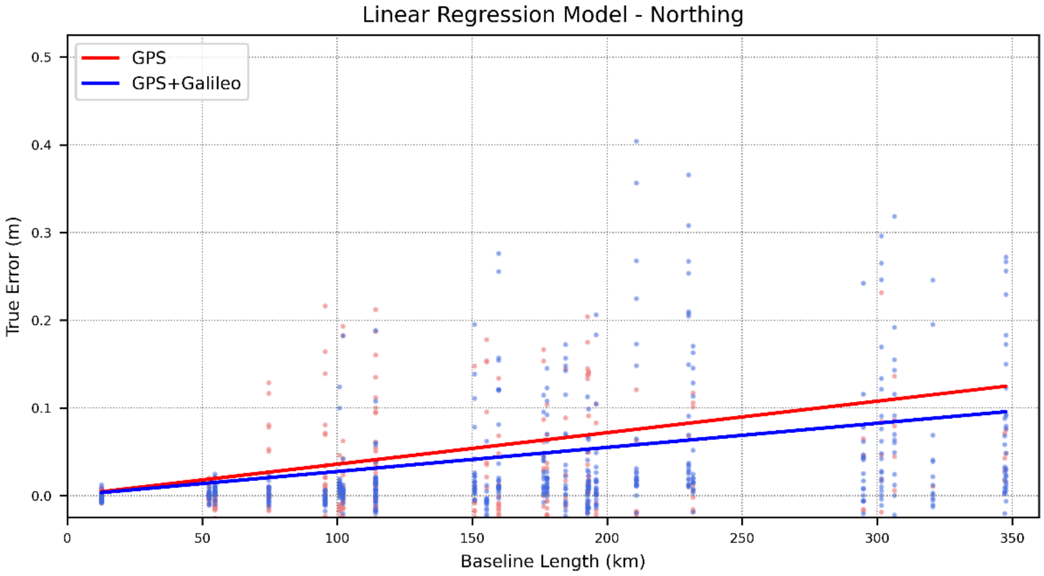

Figure 22. Linear regression model showing the correlation between northing accuracy and baseline length and comparing GPS and GPS+Galileo performances.

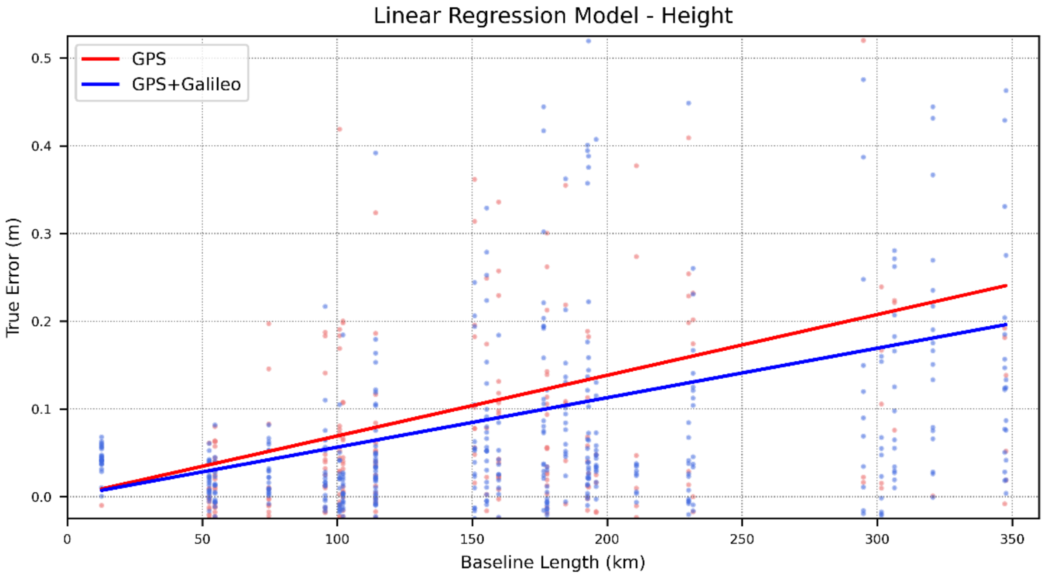

Figure 23. Linear regression model showing the correlation between height accuracy and baseline length and comparing GPS and GPS+Galileo performances.

5.1.2 Time to First Fix

Ambiguity resolution is a critical task in RTK technique due to its reliance on carrier phase measurements. In order to obtain reliable position coordinates, the ambiguous range needs to be figured out. Methods have been found for solving ambiguity and validation and the most widely used solution approach is LAMBDA. The so-called fixed position is more stable and accurate, thus, GNSS RTK applications require fixed positions. Since the ambiguous positions take a period to resolve, the concept of time to first fix has been a vital research topic. The time to first fix or shortly TTFF is considered a very important measure, for example, in surveying engineering. The shorter the TTFF means the faster the surveyor can start to work which leaves effects on the time-cost and reliability.

Assessing the TTFF is another key investigation of the current project. Improving this measure is analogous with the accuracy improvement and as important. The assessment is performed by the rate of fix solutions and correlation of first fix time to the distance between the reference and rover stations (figure 24). The python code was written in a manner to filter out the float solutions, thus, only the fixed solutions are included in the study. Moreover, the proportion of fixed values indicates the reliability of the system.

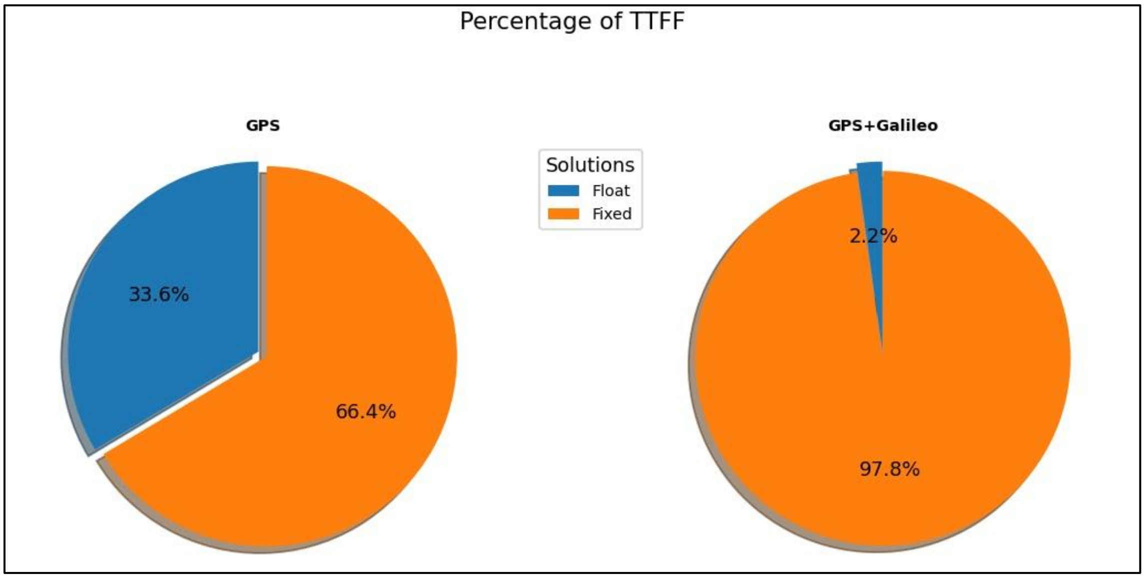

Figure 24. Pie plots showing the rate of float and fixed position by modes (GPS and GPS+Galileo).

For each mode, there were 648 solution values (27 baselines times 24 sessions) resulted. GPS observation-based could yield 430 fixed values which are 66.4% and GPS+Galileo could yield 634 fixed values which are 97.8%. of the whole solutions. This can depict how Galileo improves the probability of getting the positions fixed, though, the speediness of fixing and quality is absent in this approach.

More importantly, the speed of obtaining the first fix better pictures the differences between both modes. Linear regression used here to model the correlation of the TTFF with the baseline length (figure 25). Based on the result, GPS forms a higher correlation which means more significantly affected by the increasing distance. In spite of the higher percentage of fixed solutions, Galileo increases the speed and reliability of fixing with a high probability. As a result, on average for all the baselines, Galileo improved the ambiguity resolution by 31.4% and the TTFF by 18.8%.

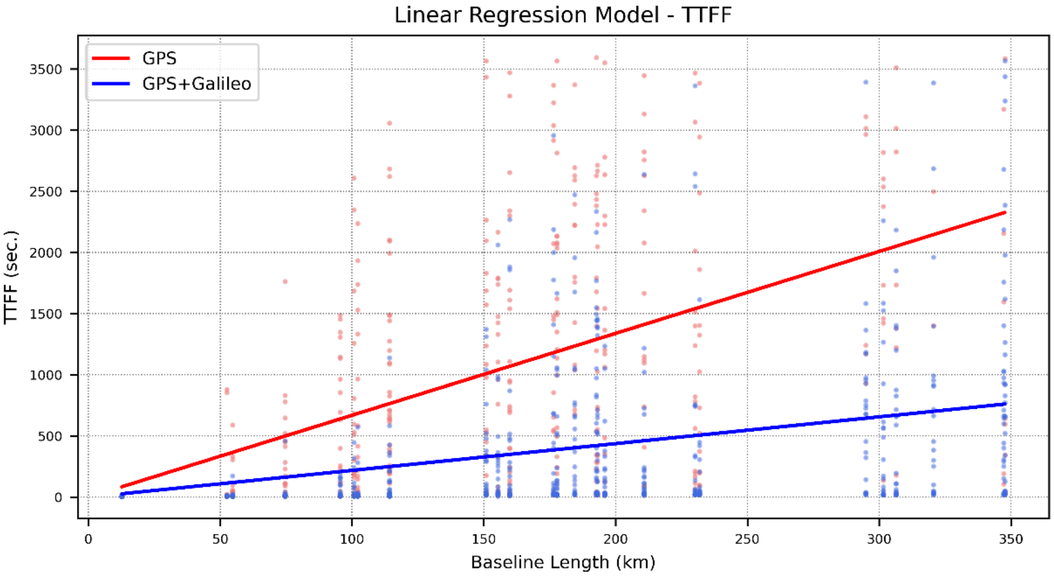

Figure 25. Linear regression model showing the correlation between TTFF and baseline length and comparing GPS and GPS+Galileo performances.

5.2 Part two – short baseline analysis

Working with GNSS RTK technique both in single and network solution takes advantage from short baselines, mainly shorter than 50 km and up to approximately 75 km in case of a network system. Keeping the inter-station separation shorter ensures the probability of a higher positioning quality and reliability due to the distance related errors such as ionospheric disturbance. Therefore, this part meticulously examines the accuracy and initialisation time focusing on the RTK requirements. Different methods have been used to visualise the processing results and conduct the examination using only the fixed solutions.

5.2.1 Accuracy

RTK technique is originally designed to provide positions in real-time. The universal demand stays high on more accurate and reliable positioning and navigation. Accordingly, considering these requirements are critical principles of designing a network of CORS. Taking into account the separation between base and rover, four baselines were chosen for this analysis with approximate lengths: 13 km, 55 km, 75 km, and 95 km. The first two are in the range of the planning, additionally, the last two baselines are an extended study showing the rate of change of accuracy and precision. Line graphs are used here to visualize the change of fixed positions' accuracy over time. Firstly, one session 'a' was chosen to be plotted and the percentage of the fixed solution indicated for each. For more clarification and reality simulation, only one hour of observation has been plotted. The graphs depict how much time needed for the TTFF (fix%), how much the expected errors are, and how stable the observations are.

The 13 km long baseline session 'a' shows that only a few seconds for both of the modes were required for the positions in order to get fixed (figure 26). The percentage of fixed positions were 99.86% and 99.89% for GPS and GPS+Galileo. The horizontal position standard deviations were 8.2 mm and 2.0 mm in case of GPS and +Galileo respectively. Conversely, the vertical position standard deviation is more precise in case of GPS, which is 0.8 mm, but when Galileo constellation was observed standard deviation was 6.6 mm (table 11). This concludes that the horizontal positioning was four times better and vertical positioning which is eight times worse when Galileo was used.

The vertical positioning quality showed unexpected results compared to the general impression of Galileo contribution due to some reasons. The statistics were derived from one session (a) and this is specific to the baseline 13 km. Despite lower precision, the results are in millimetre which is very promising. Further, it is important to clarify that the outcome varies from sessions, days, and baseline length which is explained elaborately later.

True Error Statistical Summary – Baseline Length 13 km						
Easting			Northing		Height	
	GPS	GPS+Galileo	GPS	GPS+Galileo	GPS	GPS+Galileo
Statistical measures	Values (mm)	Values (mm)	Values (mm)	Values (mm)	Values (mm)	Values (mm)
mean	+4.2	+1.9	-1.1	-0.5	-3.7	-41.8
std	+4.4	+4.1	+6.9	+6.6	+0.8	+6.6
min	-6.8	-9.9	-11.5	-10.0	-5.8	-61.8
25%	+1.1	-0.7	-7.5	-6.3	-4.2	-46.6
50%	+3.7	+1.8	-2.0	-2.9	-3.7	-41.9
75%	+7.1	+5.2	+5.4	+7.0	-3.2	-36.7
max	+15.6	+11.7	+15.3	+12.8	-1.4	-26.7

Table 11. Statistical summary of the true error values of baseline 13 km.

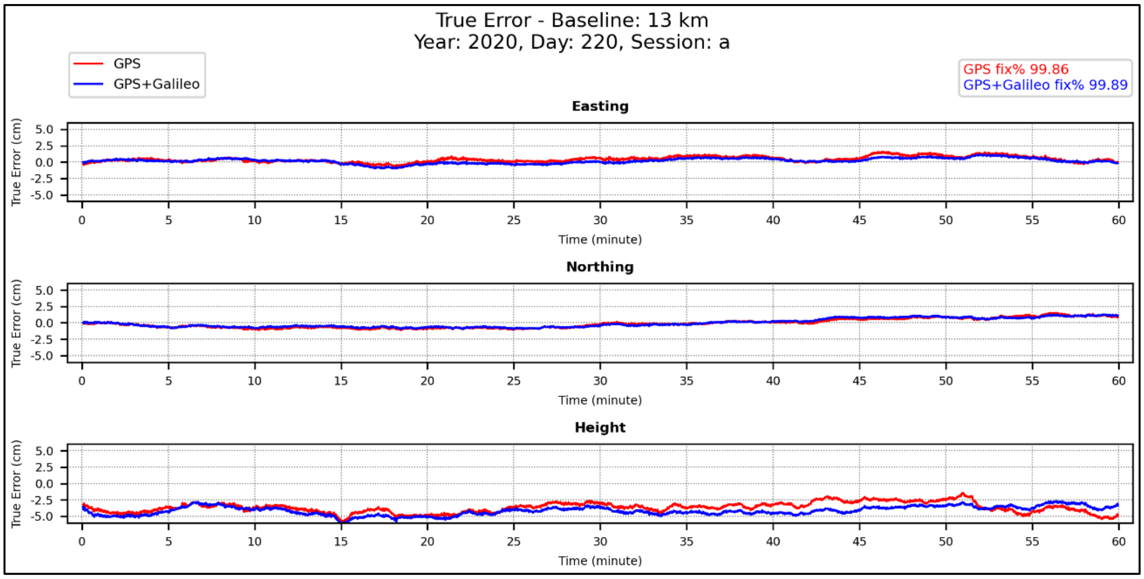

Figure 26. Line plot of true error values with the indication of the percentage of fixed positions (baseline length: 13 km, year: 2020, day: 220, session: a).

On the contrary, 55 km baseline decreases the TTFF for GPS, though, when Galileo was involved the TTFF remains as fast. The percentages of fixed positions were 90.78% and 99.83% for GPS and +Galileo (figure 27). The horizontal and vertical standard deviations were [7.0 mm, 2.0 mm] and [5.0 mm, 21.0] for GPS and +Galileo respectively (table 12). Similar conclusions can be seen from the 55 km baseline and this in fact requires thorough investigation in the causes of errors which is a different focus than this study.

True Error Statistical Summary – Baseline Length 55 km						
Easting			Northing		Height	
	GPS	GPS+Galileo	GPS	GPS+Galileo	GPS	GPS+Galileo
Statistical measures	Values (mm)	Values (mm)	Values (mm)	Values (mm)	Values (mm)	Values (mm)
mean	+1.0	-1.4	-2.1	-2.9	-2.8	-4.6
std	+4.6	+3.8	+4.9	+3.8	+1.7	+21.2
min	-12.4	-10.5	-15.0	-15.4	-9.2	-51.7
25%	-1.9	-3.9	-5.4	-5.5	-3.3	-18.3
50%	+1.0	-2.2	-1.8	-3.6	-2.7	-8.6
75%	+4.2	+0.2	+1.0	-0.5	-1.9	+0.5
max	+12.5	+11.2	+13.0	+8.6	+2.0	+69.5

Table 12. Statistical summary of the true error values of baseline 55 km.

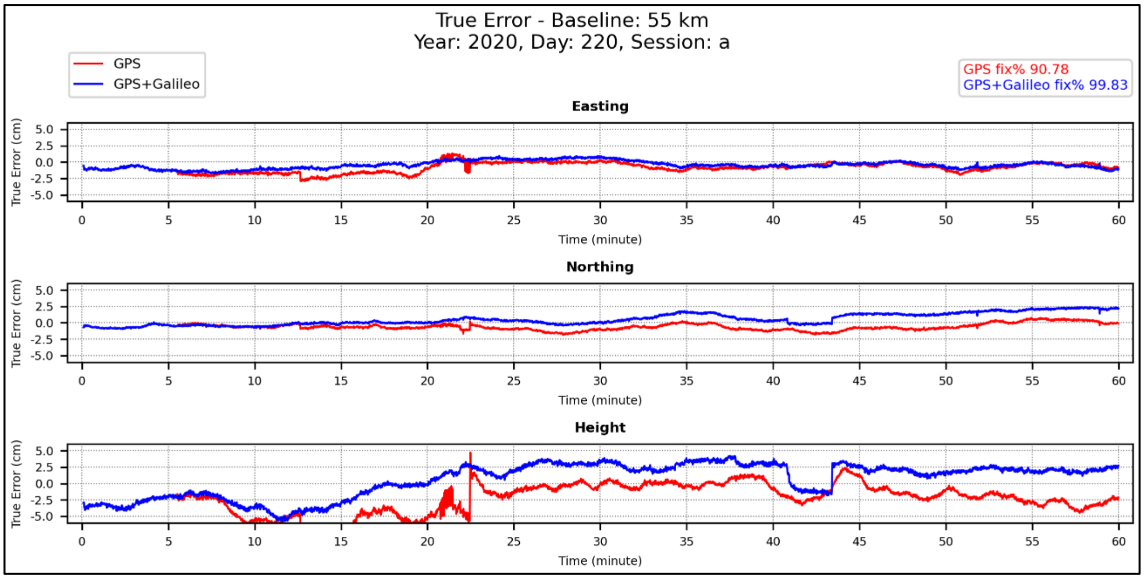

Figure 27. Line plot of true error values with the indication of the percentage of fixed positions (baseline length: 55 km, year: 2020, day: 220, session: a).

To better understand the effect of Galileo and baseline's length, 24 hours of the day 220 were plotted. It must be noted that for the following plots the processings were performed hourly then the results were combined. During field observations, this would be similar to reinitialise the roving instrument after one hour of observation. Only four baselines were chosen for this analysis with approximate lengths: 13 km, 55 km, 75 km, and 95 km (figures 28, 29, 30, and 31).

Noticeably, positioning is highly stable and accurate for the shortest baseline (13 km). Except for the smaller deviations of the red line (GPS) in very few occasions and the accuracy degradation at the beginning of the 22nd hour by the blue line (GPS+Galileo), the results are significantly dependable. During the 55 km distance, two major differences are noticed. Generally, both of the lines appear to be more undulating (less precision) compared to the shorter baseline. Further, more deviation with higher amplitude can be seen with the red line.

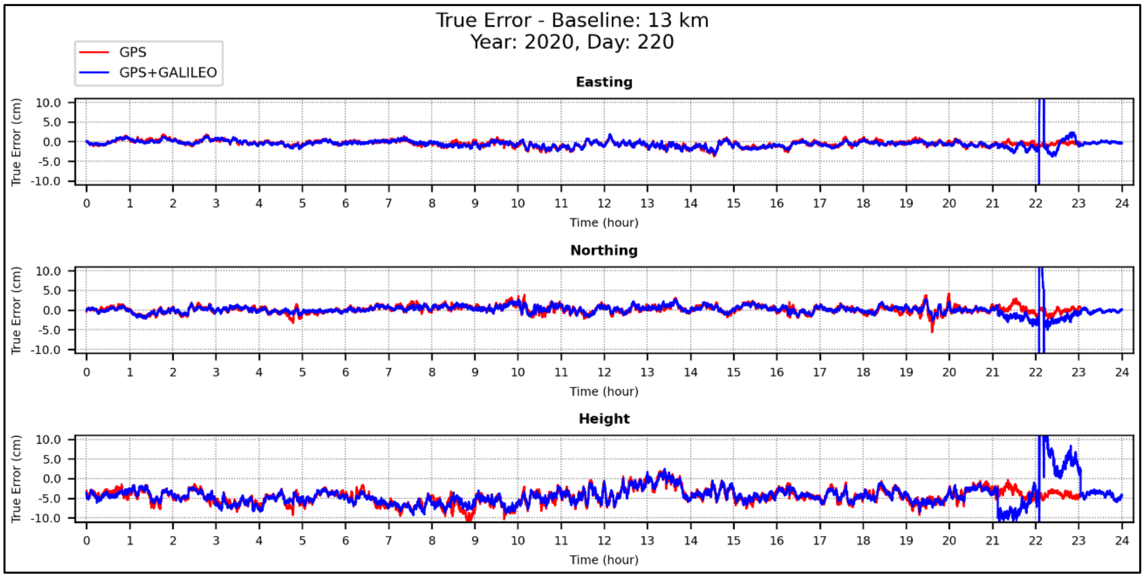

Figure 28. Line plot of true error values (baseline length: 13 km, year: 2020, day: 220, session: 24 hours).

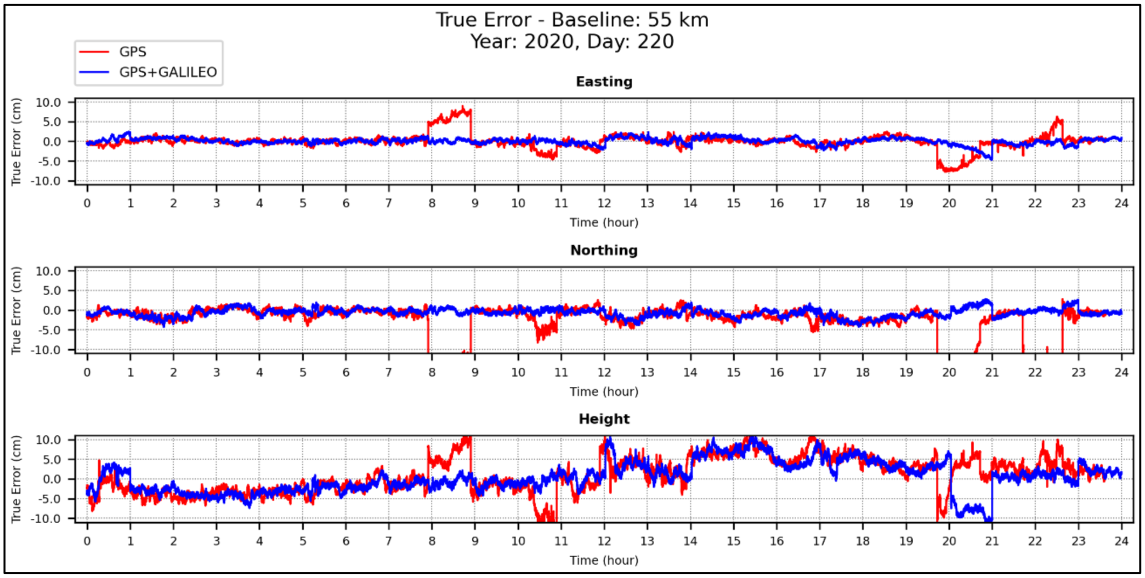

Figure 29. Line plot of true error values (baseline length: 55 km, year: 2020, day: 220, session: 24 hours).

In the case of longer baselines (75 km and 95 km), higher undulations and diverse deviations have occurred. The deviations plotted are more frequent with greater values, moreover, Galileo involvement partially prevented the occurrence of these effects but not completely (e.g. 20th hour in 75 km, and 17th hour in 95 km). These results prove the impacts of the distance between the two stations on the positioning quality.

These outcomes concluded in a strong interpretation of the studied factors impacting the positioning accuracy, precision, and the TTFF. By expanding the range between the two stations the quality of measurements (both accuracy and precision) can be vastly degraded. It has been verified that the contribution of Galileo can drop theses effects, though, the length of the baseline conquers this effort during single baseline solutions.

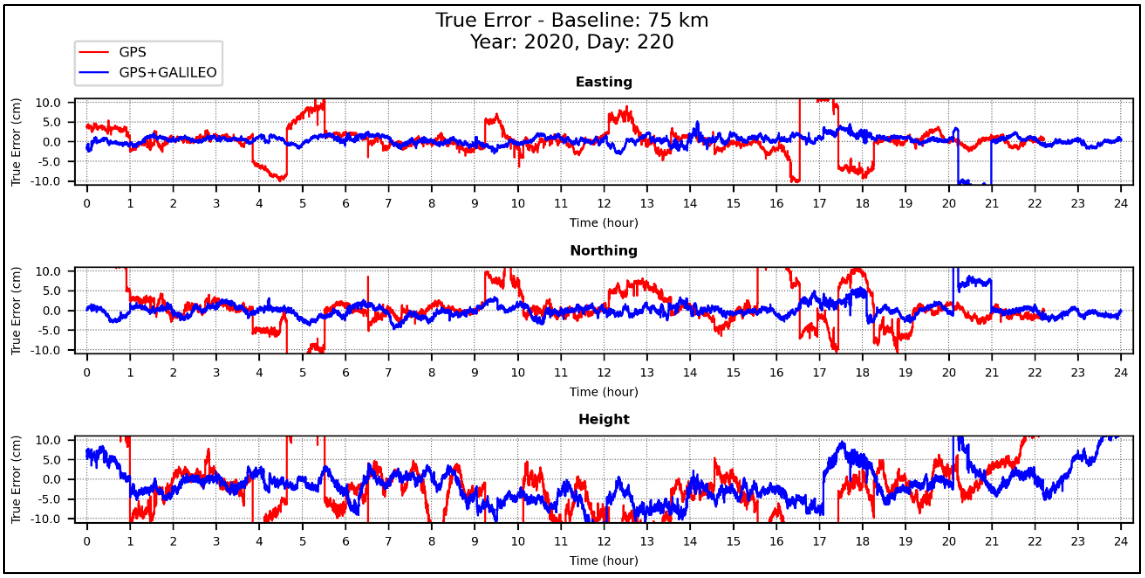

Figure 30. Line plot of true error values (baseline length: 75 km, year: 2020, day: 220, session: 24 hours).

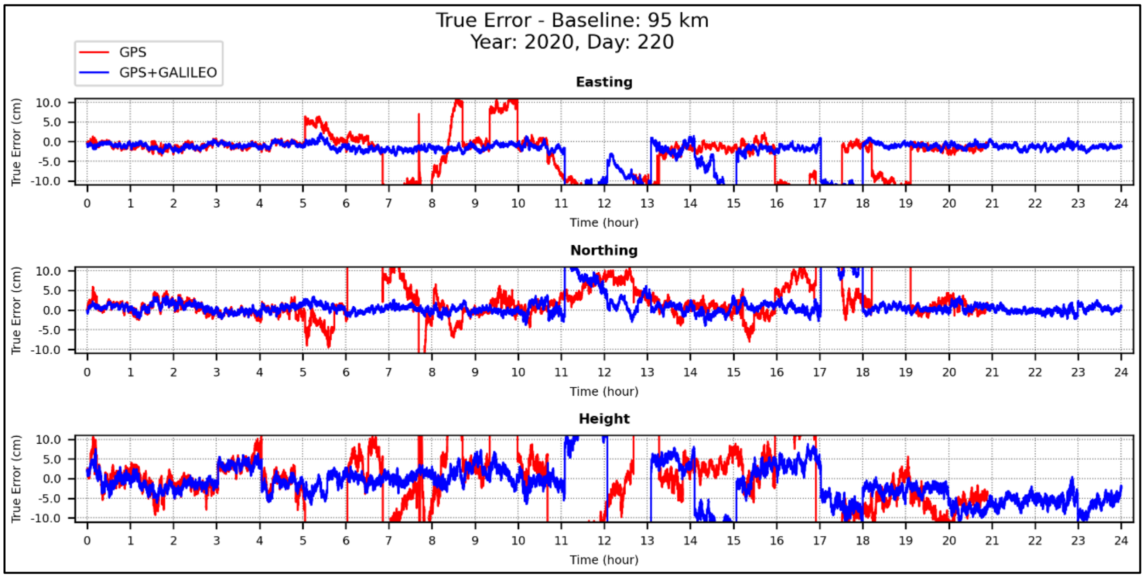

Figure 31. Line plot of true error values (baseline length: 95 km, year: 2020, day: 220, session: 24 hours).

In order to deeper understand the amount and dispersion nature of the true errors, special scatter plots of the fixed positions have been generated. Line graphs and tables are deficient in providing a complete demonstration of data quality. Thus, two-dimensional individual scatter plots were created using python with the characteristics of illustrating accuracy, precision, and covariance ellipse with three standard deviations. Due to the large number of baselines and sessions, few samples are to be displayed here that are distances 13, 55, and 75 km with the sessions a and d (figures 32, 33, and 34).

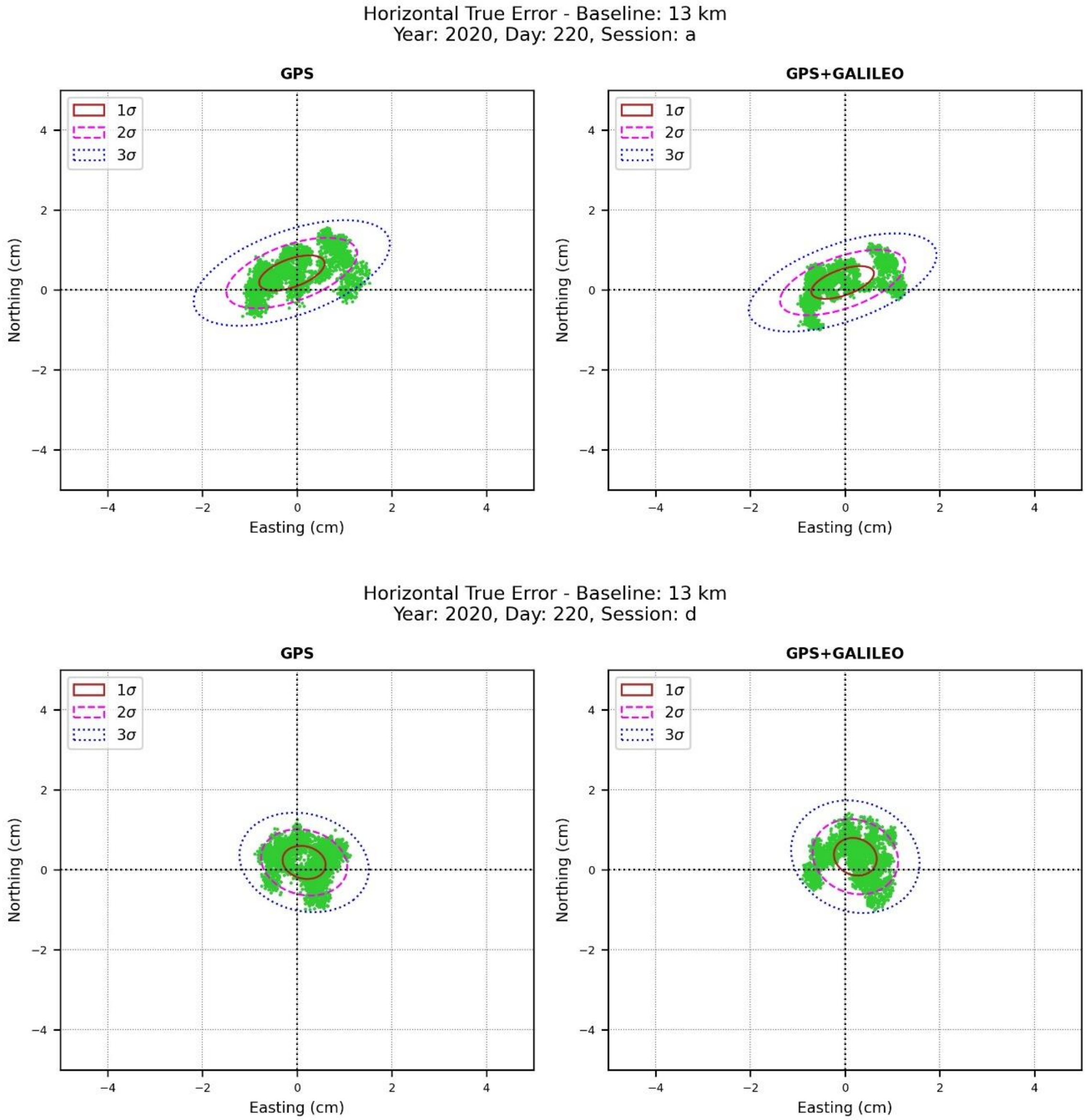

Figure 32. Scatter plots with covariance ellipse (baseline length: 13 km, year: 2020, day: 220, session: a and d).

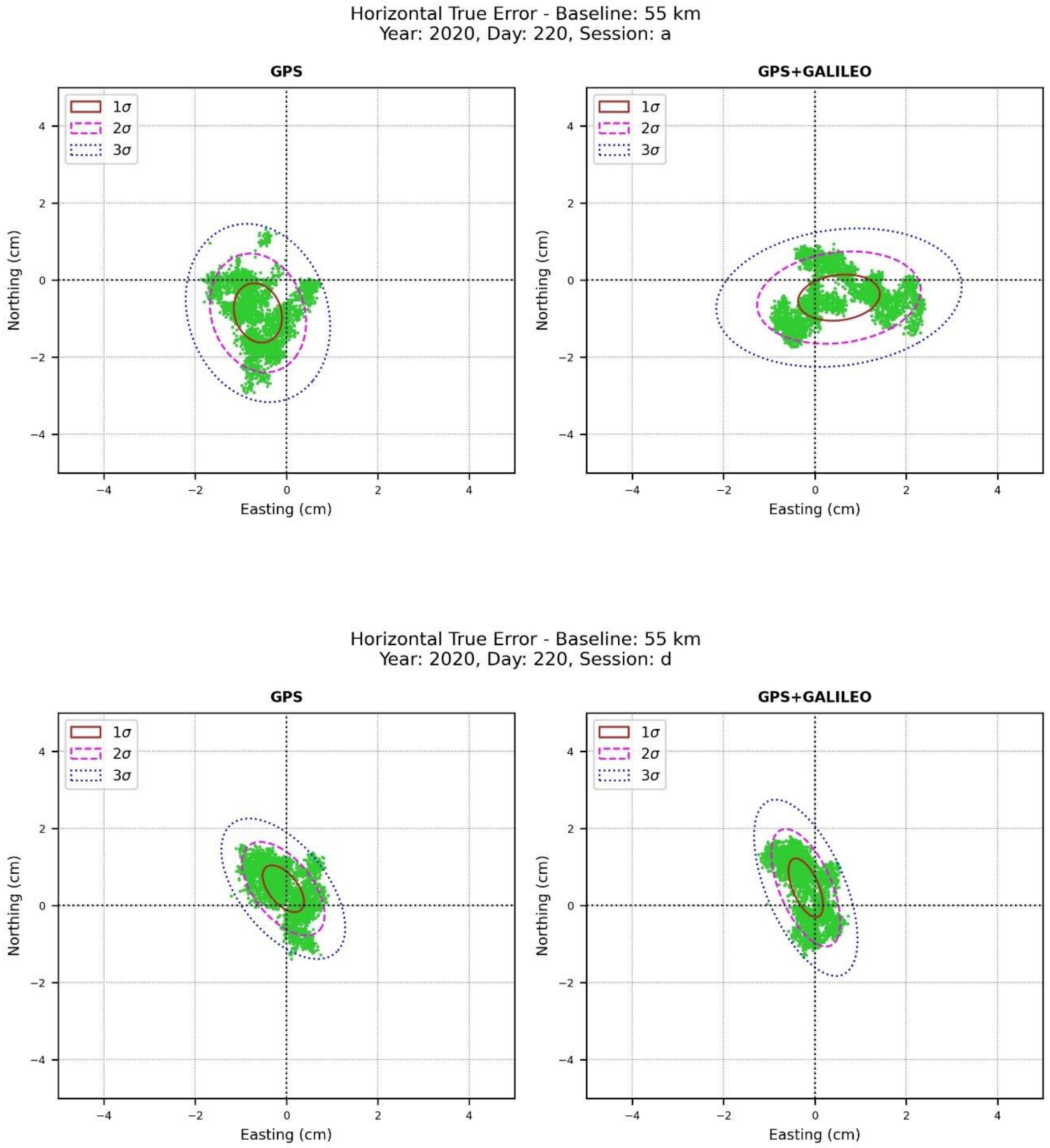

Figure 33. Scatter plots with covariance ellipse (baseline length: 55 km, year: 2020, day: 220, session: a and d).

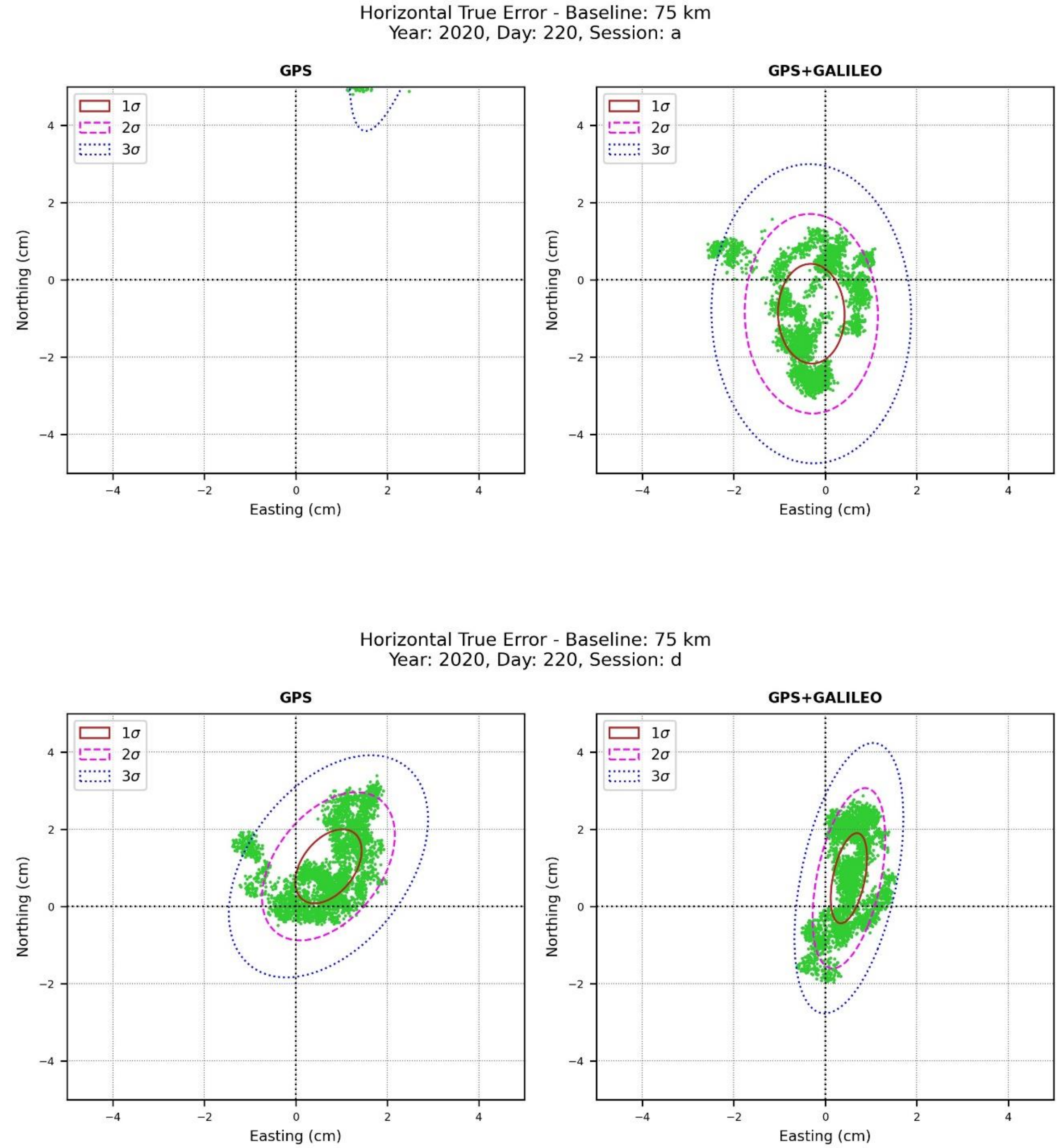

Figure 34. Scatter plots with covariance ellipse (baseline length: 75 km, year: 2020, day: 220, session: a and d).

5.2.2 Time to First Fix

The importance of the fixed positions and the time to first fix have been explained for long measurements. However, the RTK method's applications impose better and faster quality of measurements in real-time. Hence, the shorter distances were chosen for the assessment of the results. Simple node plot was used to illustrate the TTFF, its change with respect to the baseline length, and improvement with the contribution of Galileo constellation (figure 35).

The linear model showed the correlation of the TTFF and length and how Galileo improved that measure, additionally, more clarification used in the following graph. The length increment delays the fixing time, on the other hand, Galileo can drop and stabilize that effect significantly. Despite of that, the first fix achieved very fast and stably in case of 13 km baseline in the way that all the nodes are overlapped around the zero second time axis. The result here plays a vital role in the decision of network design and establishment.

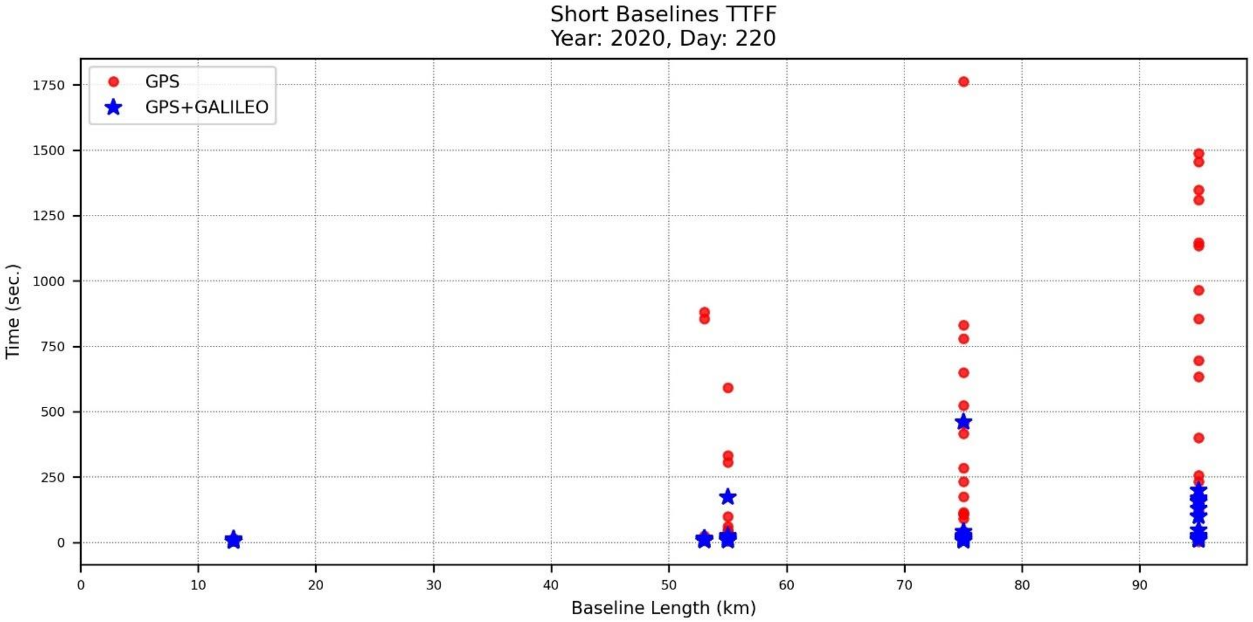

Figure 35. Node plot showing the TTFF comparing both modes (GPS and GPS+Galileo).

5.3 Deciding the CORS network plan

This section summarises the analysis chapter into a decision supported by obtained outcomes. The network design must fulfil the major principles: good area coverage and distribution, reliable quality and operation, economical and manageable, and usability for geoscience researches. These requirements are intersecting, meaning good distribution with reliable quality make the system viable for researches and future developments such as national reference frame definition. Furthermore, a successful plan embraces alternatives and flexibility with future evolvements.

The preceding results such as the accuracy bands (by using mean true errors of the fixed solutions) and line plots (by using the true error of the fixed positions) showed that the accuracy is highly reliable up to the range of approximately 50 kilometres. Talking about the horizontal accuracy, on average in both modes 75% of the results were sub-centimetric level (millimetre-level) accuracy and the remaining 25% were centimetric level accuracy (1.0 to 5.0 cm). The accuracy bands showed that Galileo contribution could raise the quality of horizontal positioning significantly over 75 km baseline, resulting into 58% millimetric, 37% centimetric (1.0 to 5.0), and very few of them (4%) with decametric level accuracy. The following table (table 13) demonstrates the average improvement in the percentage of expected accuracy in the result of the Galileo involvement (averaged over all the baselines).

Accuracy	mm-level	1.0 to 5.0 cm	< 5.0 cm	5.0 to 10.0 cm	dm-level
Horizontal	+10.0%	+12.3%	+22.3%	-4.0%	-18.3%
Vertical	+11.0%	+5.5%	+16.5%	-4.0%	-12.5%

Table 13. Percentage of average quality improvements by using Galileo constellation. Calculated from the accuracy bands data ('+' sign means improving; '-' sign means decreasing).

As for the vertical positioning quality, the statistics and figures can depict this quality was approximately twofold in case of short baselines and more complicated in case of longer baselines. The vertical accuracy bands generated the same result for both of the modes over 13 km baseline. The baseline 53 km resulted in better height quality than 13 km which is an odd outcome. However, as mentioned earlier, statistical methods (using average values) and the limiting accuracy bands can leave impacts with varying probability. On average, using GPS+Galileo the vertical accuracy percentages over a range up to 75 km were: 24% millimetre-level, 51% centimetric (1.0 to 5.0), and 25% centimetric-level (5.0 to 10.0).

This study was conducted as a single base solution and using only GPS and Galileo with their current constellation state. The minimum and the maximum number of satellites for GPS were [6, 11] and for Galileo were [5, 9] on the data 07 August 2020 (see figure 36).

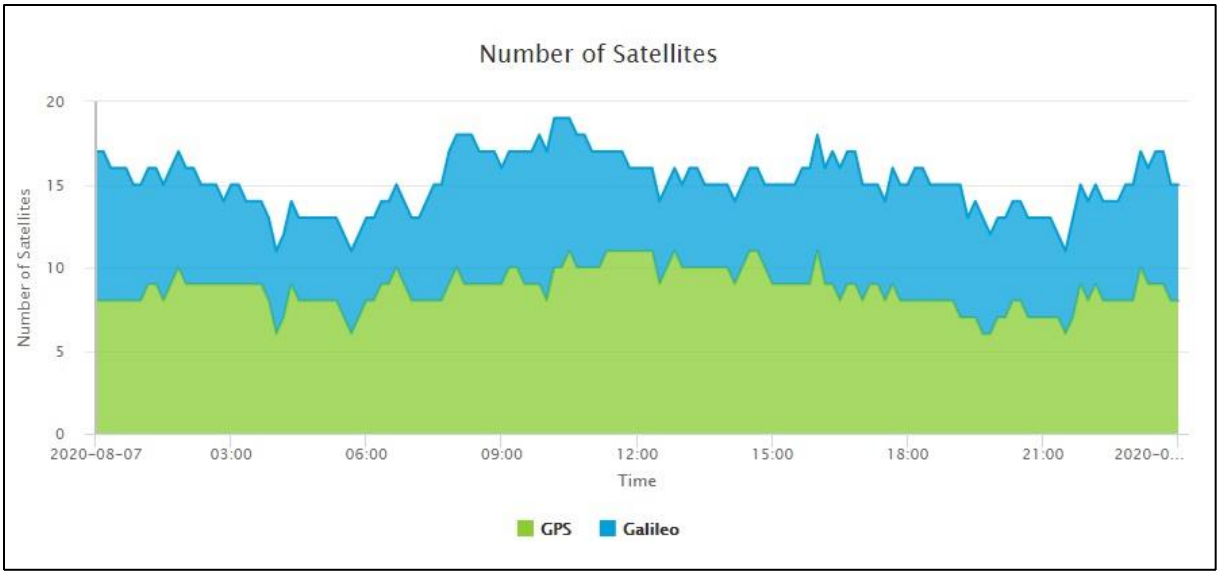

Figure 36. Stacked area chart showing the number of visible satellites of GPS and Galileo constellations at Budapest on the data 07 August 2020 (Trimble GNSS Planning Online).

Whereas, for a new CORS network system establishment, GNSS instruments can be used with the multi-system capability (GPS, GLONASS, BeiDou, and Galileo). Using all the global constellations for GNSS observation, the minimum and the maximum number of the total satellites can reach up to [30, 40] (figure 37). Furthermore, it is planned more satellites will be launched in the following years, specifically by the BeiDou and Galileo systems.

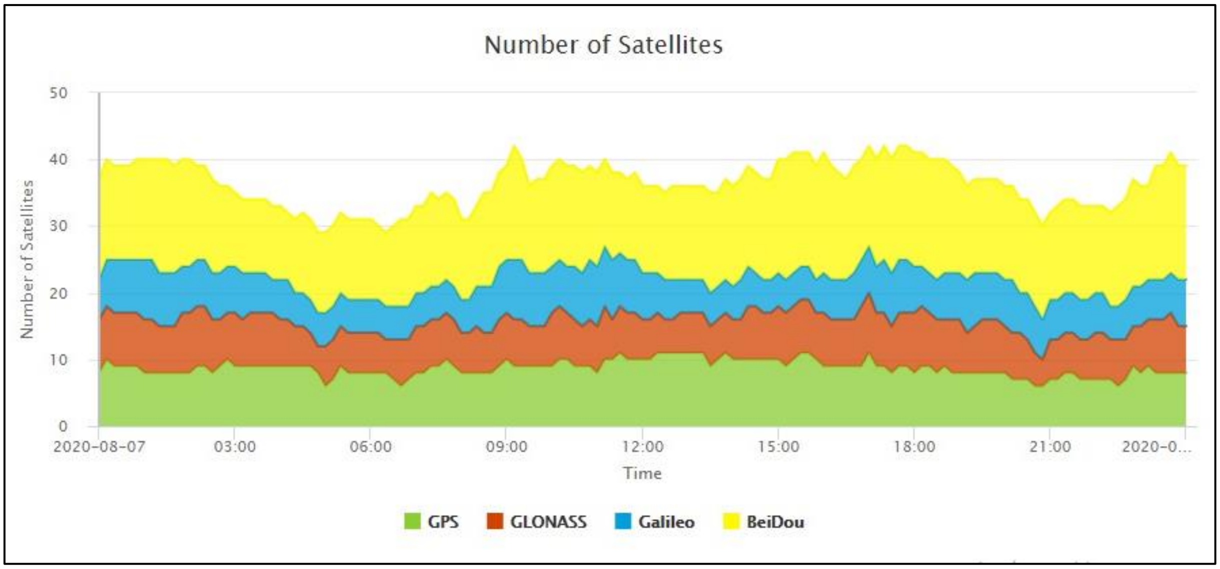

Figure 37. Stacked area chart showing the number of visible satellites at Budapest on the data 07 August 2020 (Trimble GNSS Planning Online).

In light of this study, the network plan of 50 kilometres can be adopted. Additionally, with using a network solution the probability of better quality is higher with an extended range of 75 km. The following figure (figure 38) maps the separation between the stations of the primary plan for the purpose of having an intuition about the limitations and service quality. To cover the remaining parts of the region, most of these areas can be covered under 75 km range service. Further, the dams and other strategical projects can be served with specific permeant and/or temporary GNSS stations installed in situ for monitoring purposes.

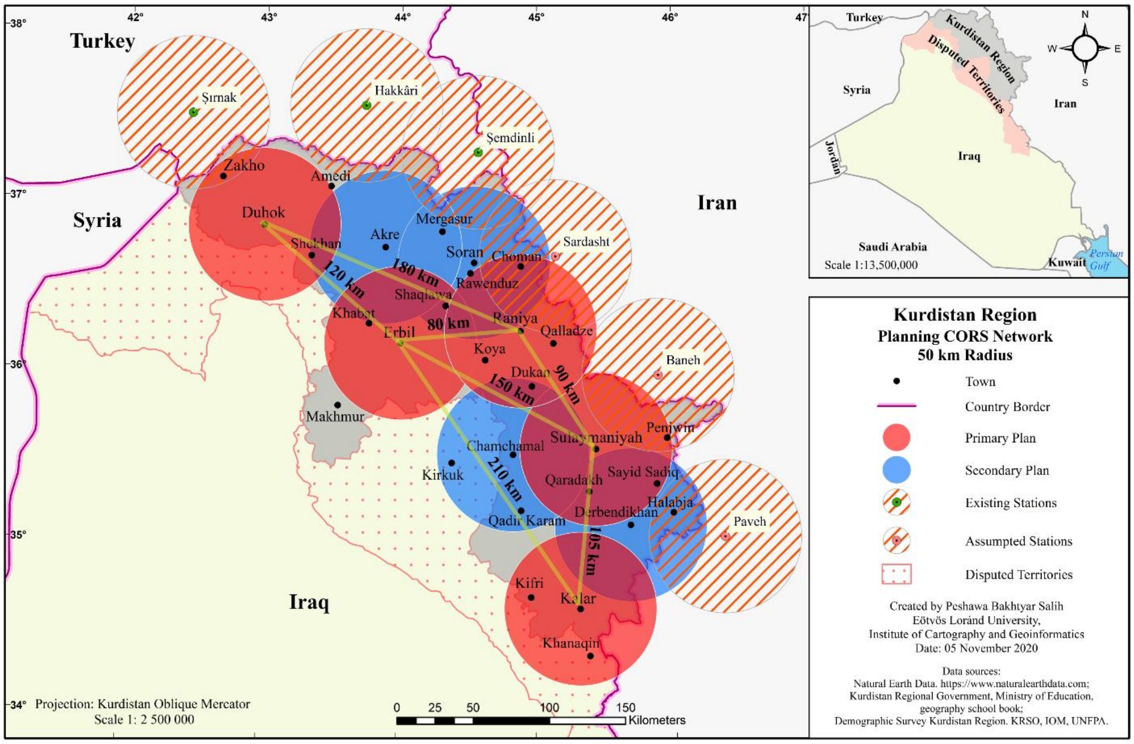

Figure 38. Map showing 50 km scenario with the distance between primary plan stations.

After selecting the structure plan category, further investigation and refinement can be made in support of a more successful system. One of the major parts of the design, which is the distribution of the stations and the investigation of quality assessment, was discussed thoroughly in this project. Meanwhile, many other important aspects are left open and that brings the necessity of more inspection and tests.

6. CONCLUSION

Throughout this thesis, instructions and planning principles were introduced for the purpose of establishment of a permanent GNSS network. The principles were used to propose some scenarios for the reference station's distribution in the Kurdistan Region. To support the design and have a correct perception about the current state, an investigation was performed to find out how the positioning quality changes based upon reference-rover separation and Galileo constellation's participation.

A sustainable CORS network in Iraq and the Kurdistan Region is highly needed for many applications ranging from scientific to commercial. The existing structure of the NGS CORS is very sparse in Iraq, partly functional, and intended for post-processing techniques only. Therefore, a real-time survey requires two main steps: 1) deployment of a new control point via static observation with long durations; and 2) using the new control point as a reference for the RTK job. This method has drawbacks and it is impractical since it increases the time and cost and decreases accuracy and reliability.

The first important contribution of this study lies in the collecting and summarising guidelines on CORS network establishment and propose planning approaches. The planning resulted in two scenarios each with different defined RTK covering range: 30 and 50 kilometres. The service from each station is considered to be accurate and reliable, in the determined circle, proportionally with the distance growing.

The second importance is the analysis performed on the real-time observation excellence. This was derived by studying the effect of the interstation distance and Galileo constellation on the RTK positioning quality. For this aim, stages of data collection, inspection, processing, extraction, calculation, modelling, visualisation, and mapping were applied in order to come up with an efficient processing procedure model. 24-hours data (year 2020; day 220) from the Hungarian E-GNSS Network was processed using CGO 2 software. Also, python programming was used to create a private purpose library that generated plots and models. The following can be inferred from the analysis outcomes:

- According to the linear regression model all the elements, easting, northing, height, and TTFF, are in positive correlation with baseline length.
- Positioning quality was highly reliable up to approximately 50-kilometre baseline. The average probabilities of millimetre-level accuracies were 76% and 16.5% for horizontal and vertical respectively. The remaining 3D accuracy probabilities were between 1.0 to 5.0 centimetre.
- Galileo satellites improved the average expected accuracies by [10.0%, 11.0%] millimetric and [26.3%, 20.5%] centimetric for horizontal and vertical respectively.
- Galileo's contribution made significant improvement in the rate of phase ambiguity resolution by 31.4% and the faster initialisation time averagely by 18.8%.

These results were vital for selecting the CORS network density. The 50-kilometre range scenario was adopted as an efficient solution for the Kurdistan Region considering the aspects of expected accuracy, reliability, and availability. Further, this design covers the important areas with nine stations, and it is superior to the 30 km range plan economically. In this investigation, the data processing was performed as the single base solution approach, however, a network solution can produce higher quality service. Also, deploying GNSS instruments with the multi-constellation and multi-frequency capability further increase the 3D accuracy and reliability.

In light of these findings, this thesis concludes that some major stages of a CORS network design have been discussed in the planning and investigation chapters. Such a network will play a key role in the development of geodesy, cartography, engineering, oil industry, irrigation, transportation and other industrial applications. To complete the network design and establishment, the below are recommended for the future study and work:

- Conducting a study and analysis for the adoption of a network RTK approach for the CORS network.
- Fieldwork survey embracing accurate statistics and data collection for the network plan improvement.
- An extensive study is required to write a complete mandate taking into consideration the scientific, technical, investment and economical, standards and sharing, interoperability, licensing, and other necessary aspects for the establishment and operating a permeant GNSS network.

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DECLARATION

I, undersigned *Peshawa Bakhtyar Salih* (ZTIWRA), declare that the present master's thesis is my original intellectual product in full and that I have not submitted any part or the whole of this work to any other institution. Permissions related to the use of copyrighted sources in this work are attached.

I AGREE to the publication of the accepted master's thesis in pdf form on the website of the Institute of Cartography and Geoinformatics.

Budapest, *01 December 2020*

Peshawa B. S

(signature of the student)