

ANALYZING RINEX DATA FILES USING THE PYTHON PROGRAMMING LANGUAGE

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ABSTRACT:

The techniques and tools developed for geodetic determinations have made it possible, over the past half century, to carry out measurements using global navigation satellite systems. As the accuracy and precision of positioning solutions, such as Fast Static and RTK, improve through technological advances, more applications will become available that can provide users with positioning information over time, autonomously verify the integrity of transmitted data, and ensure sufficient accuracy for their intended purposes. In our study for the interpretation, analysis, and visualization of raw and/or processed RINEX GNSS data recorded over time at a geodetic point using the information available from the Fast Static technique, we used the GeoRinex library from the Python programming language. This library converts data to xarray.data set, for easy use in processing parameter sets, from Rinex files: of ROMPOS reference stations and of the new B10 point resulting from measurements using the Fast Static technique: pseudorange (C1, C2, P1, P2,...), carrier phase (L1, L2,...), doppler (D1, D2,...) and signal strength (S1, S2,...). All this information will help us to analyse and interpret the degradation of the parameters associated with Rinex version 2.11 epoch positioning files 12.02.2023, time interval 12:00-14:00 (fast static) and to understand their accuracy and behavior in different environments. Based on this study, our aim was to evaluate the error in determining the positioning accuracy of the B10 point located in a crowded and heavily trafficked area, which allows sufficient coverage of the GNSS satellites.

1. INTRODUCTION

For the past few decades, the Global Positioning System (GPS) has been the number one positioning tool in a few geodetic and geophysical applications. Emerging regional and global navigation satellite systems (RNSS/GNSS) can enhance positioning and non-positioning applications (Odolinski, Teunissen, and Zhang 2020).

Today, we have four operational global constellations of positioning satellites: GPS (USA), GLONASS (Russia), Galileo (Europe), and BDS (China), with the word GNSS attached to them, and two regional augmented constellations: QZSS (Japan) and NavIC (India), generally known as Regional Navigation Satellite System (RNSS) ((Li et al. 2023). The successful completion of the work of the International Committee for Global Navigation Systems (ICG), in establishing interoperability between global systems, has enabled GNSS users to use a single instrument to receive signals from multiple satellite systems. This has provided additional data, especially in urban and mountain regions, and greater accuracy in time or position measurements ("GNSS," n.d.).

The purpose of developing these satellite systems is to determine the position of a point in the three-dimensional coordinate system with high accuracy, either relative to each other or relative to a reference system.

The quality of this positioning information is normally demonstrated by seven key parameters: accuracy, integrity, continuity, availability, time to first fix, robustness, and authentication, which are defined as follows: system accuracy is the degree of overlap between the estimated, measured position and the actual position at a given time.

The performance of GNSS systems (Figure 1) is assessed using four indicators (Mora et al. 2022):

- ✓ Accuracy: the difference between the actual position, speed or time and the position measured by a receiver.
- ✓ Integrity: the ability of a system to provide a confidence threshold and, in the event of an anomaly in positioning data, an alarm.
- ✓ Continuity: the ability of a system to operate without interruption.
- ✓ Availability: the percentage of time a signal meets the criteria of accuracy, integrity, and continuity.

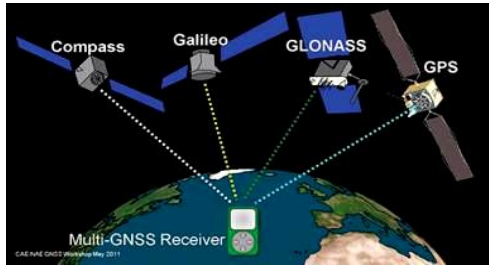


Figure 1. Global Navigation Satellite Systems (copyright Inside GNSS Magazine, Digital Edition, "The International GNSS Monitoring and Assessment Service", 2016, accessed 20.01.2023)

Below are some relevant research studies in the field that examine the accuracy of determining a point through GNSS positioning techniques. National Continuously Operating Reference Station (CORS) networks, operating on the Real Time Kinematic (RTK) principle, are multifunctional geodetic networks and provide services to a large part of society, including all public institutions and other organizations, military and civilian users, and scientific researchers (Tusat 2018). These networks are used in real-time positioning applications, using the Network Real-Time Kinematic (NRTK) method, as well as in static applications, using Receiver Independent EXchange (RINEX) format data from reference stations. Based on these remarks, the authors performed static and virtual reference station (VRS) GNSS measurements based on a continuous operating reference station-Turkey (CORS-TR) network in a test network established in Turkey (Tusat 2018). As a result of the measurements, the repeatability obtained by the VRS method was examined. Based on the accuracy obtained of better than 5 cm for planimetric accuracy and better than 10 cm for ellipsoidal height accuracy, it was found that NRTK techniques in real-time GNSS networks can be used to produce spatial data and create topographic maps (Tusat 2018).

The effects of Non-Line-Of-Sight (NLOS) measurement error on relative GNSS positioning for a short base, both theoretically and through field tests, are demonstrated by (Ye et al. 2020). The results show that the effects of NLOS signal, both in pseudo-distance and carrier phase, make ambiguity unresolvable successfully. In addition, the authors found that after removing the labelled NLOS observations, positioning accuracy can be significantly improved (Ye et al. 2020). The larger the number of available LOS satellites, the higher the robustness of the resolution of the ambiguity for NLOS satellites.

The accuracy of planimetric precision at the centimetre level is examined and solutions at three test sites in United States (Mora et al. 2022). The solutions were characterized to examine the dispersion of vertical measurements in the context of different environments. The results of this study suggest that both methods have advantages and disadvantages; in particular, the data showed that the distribution and network density of the reference stations, the coverage of the cellular network, and environmental dynamics have a significant impact on the vertical accuracy, where it was observed to be 2-4 times lower compared to the measurements of RTK (Mora et al. 2022). Estimating the quality of the accuracy performance in the research gives us the possibility to interpret the data resulting from the two tested methods, without indicating which is the most accurate, proposing the introduction of the most reliable

and accurate methods for positioning and navigation applications.

2. BACKGROUND

The development of measurement technology and point positioning on the earth is rapidly evolving as satellite systems are available around the world. The application of measuring instruments has become easier and faster, and the dream has become a reality (Nordin, Mustapa, and Abdul Satar 2021).

There are two basic approaches to GNSS measurements: absolute and relative. In geodesy, for accurate determination of the receiver position, relative methods are most often used, as they provide a level of accuracy down to a few centimetres (Ltd. 2022). The main feature of these methods is that there must be at least two receivers, one of which is located on a point with known and predefined coordinates and the other on a new point. Relative GNSS methods are RTK and Static with the common characteristics summarized in Table 1:

Positioning techniques	Static	Real Time Kinematic (RTK)
Number of GNSS receivers	At least 4 receivers: 3 base + 1 rover	At least 1 base + 1 rover
Real-time transmission	Not necessary	4G/Radio
Measuring time	≥ 40 min	1 – 10s per point
Processing time	Processing measurements	Real-time processing
Distance between base and rover	≥ 50 km	10 – 20 km
Positioning frequency	Until 50 Hz	1 – 2 Hz
Positioning accuracy	2.5 mm + 1 ppm Horizontal 5 mm + 1 ppm Vertical	8mm +1 ppm Horizontal 15mm+1ppm Vertical
Applications	Control points	Topographic surveys, stake-out survey, etc.

Table 1. The difference between Static and RTK (copyright Geo Matching Magazine, Digital Edition, "Which is Better Among Static Survey, RTK or PPK?", 2022, accessed 20.01.2023)

✓ **RTK (real-time kinematic)** measurement system generally consists of three parts: GNSS receivers, data transmission system, and dynamic measurement software system. The RTK measurement technique (Figure 2) is based on carrier phase observations and features differential carrier phase measurement technology with fast and high accuracy positioning functions. It can obtain real-time three-dimensional station positioning results in the specified coordinate system and has centimeter-level positioning accuracy.

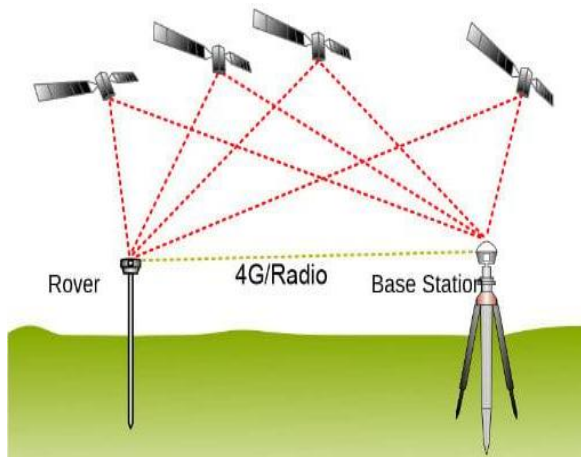


Figure 2. Real Time Kinematic Measurement Principle (copyright Geo Matching Magazine, Digital Edition, "Which is Better Among Static Survey, RTK or PPK?", 2022, accessed 20.01.2023)

- ✓ **Static** measurement principle (figure 3): Based on the carrier phase observations measured by several GNSS receivers tracking GNSS satellite signals, using the differential method, the coordinate difference between the observing stations, i.e. the baseline vector, is obtained. Then, depending on the coordinates of the known points and the baseline vector, the coordinates of the other stations are obtained. Relative positioning can eliminate or greatly reduce errors (such as satellite clock errors, ionospheric delays, and process delays, etc.) so that a highly accurate relative position can be obtained, which is widely used in control measurements.

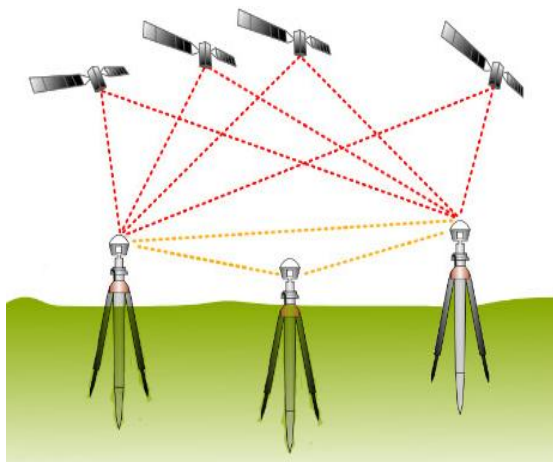


Figure 3. Static Measurement Principle (copyright Geo Matching Magazine, Digital Edition, "Which is Better Among Static Survey, RTK or PPK?", 2022, accessed 20.01.2023)

From these references described above, Ian Lauer presents in his article the advantages and disadvantages of two techniques, RTK and Rapid Static (Lauer, 2018). The data is described in Table 2.

Positioning techniques	Advantages	Disadvantages
Real Time Kinematic (RTK)	Real-time corrected positions in a known grid of fixed coordinates	Significant increase in equipment cost (higher number of channels) and logistics. Must have a radio connection between base and rover.
Rapid Static	Reduced equipment costs compared to RTK	Requires a longer standing time of up to 2 hours or more. Lower accuracy than RTK, because data formats from base stations are needed for processing

Table 2. Advantages and disadvantages of GNSS positioning techniques (copyright Ian Lauer, "Static GPS/GNSS Survey Methods Manual", Version January 19, 2018)

The purpose of these GNSS systems is to determine the position of a point in the three-dimensional coordinate system with high accuracy, either relative to each other or to a reference system. These reference systems can provide high accuracy of positioning a point. In Romania, users of GNSS technology benefit from the national reference station system: Romanian Position Determination System (ROMPOS), which consists of 98 stations, 81 of which are operational (Figure 4).

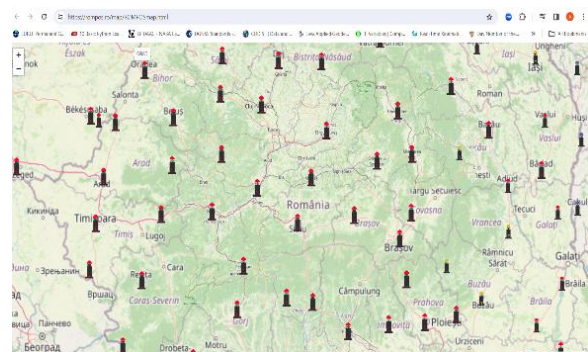


Figure 4. ROMPOS network of GNSS reference stations (Source: Rompos)

With advancements in technology enhancing the accuracy and precision of positioning solutions like Fast Static and RTK, an array of applications will emerge to harness the information generated by these methods and systems. Using the GeoRinex library for the Python programming language (Michael Hirsch 2019), we analysed and interpreted the degradation of parameters (pseudorange (C1, C2, P1, P2,...), carrier phase (L1, L2...), Doppler (D1, D2,...) and signal strength (S1, S2,...)) associated with Rinex data formats (technique Fast Static) and to understand their accuracy and behaviour in different environments.

All this information will help us to evaluate the error in determining the positioning accuracy of points located in dense and heavily trafficked urban areas, allowing sufficient coverage of GNSS satellites using the two GNSS measurement techniques.

3. MATERIALS AND METHODS

For our research, we chose a geodetic point in Timisoara municipality (latitude: 45.7445892, longitude: 21.23011121) materialized on Victor Babeş street (Figure 5), located in a dense area with heavy traffic, which allows sufficient coverage of GNSS satellites. Fast static and RTK measurements were carried out at this point on 12.02.2023, during the time interval 12⁰⁰-14⁰⁰.

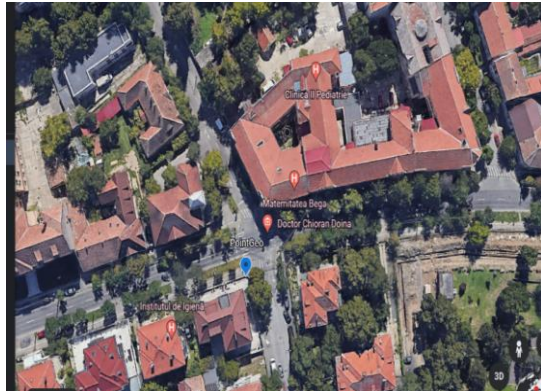


Figure 5. Geodetic point location on the Google Maps

Before performing the GNSS measurements in the 12.02.2023 12⁰⁰-14⁰⁰, positioning epoch, the quality of the reference stations in the ROMPOS network was analysed online to obtain centimetre accuracy in RTK measurement (Figure 6).

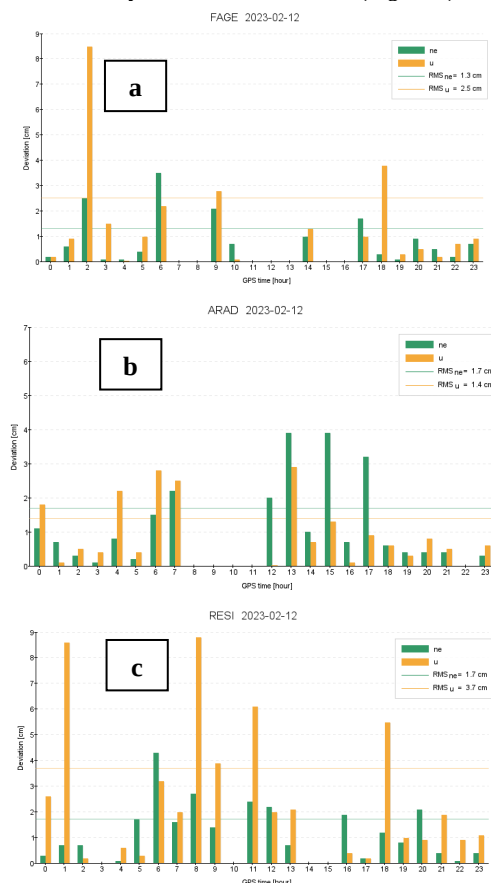


Figure 6. Determination accuracy as a function of the ROMPOS reference station in the positioning epoch: (a) FAGE, (b) ARAD and (c) RESI (copyright <http://monitoringepus.gku.sk/>)

The GNSS equipment used to perform the 12.02.2023 positioning epoch phase (RTK and Fast Static measurements) and data recording is a Trimble R10 dual-frequency (L1, L2) 492-band GNSS receiver (Table 3). The data was converted to Rinex 2.1 version (Pestana 2015). Following the conversion of a Rinex 2.1 file at geodetic point B10 with the Convert to Rinex programme, we wanted to have the same type of Rinex files from the three ROMPOS reference stations (ARAD, FAGE, and RESI) to use the same parameters (C1, C2, L1, L2, P1, P2, S1, S2) for post-processing (Table 3).

Item no.	Point name	Parameters	File type	Type receiver	Type antenna
1	ARAD - ROMPOS	G, R: C1L1L2 P1P2S1S2	Rinex 2.11	TPS NETG3	TPSCR .G3
2	FAGE- ROMPOS	G, R: C1C2L1L2 P2S1S2	Rinex 2.11	LEICA GRX12 00+GNSS	LEIAR 25
3	RESI - ROMPOS	G, R: C1L1L2 P1P2S1S2	Rinex 2.11	TPS NETG3	TPSCR .G3
4	Geodetic Point-B10	G și R: C1C2L1L2 P2	Rinex 2.11 –Fast Static file	TRIMBLE R10	R10 internal

Table 3. Information from Rinex files 12.02.2023

The Stereographic Projection System 1970 is used as a reference system in Romania and Trimble Business Center (TBC) gives us the possibility to set this reference system before post-processing the GNSS data (Figure 7).

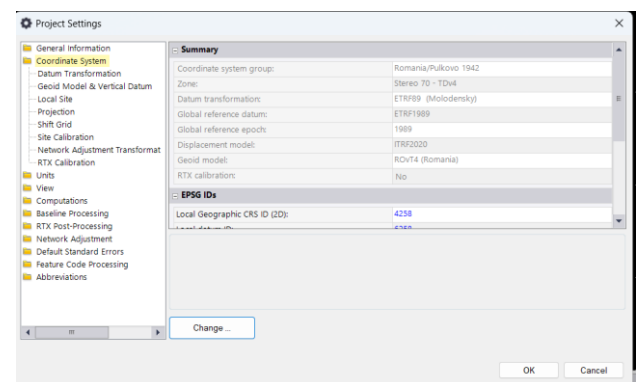


Figure 7. Coordinate System Setting using Trimble Business Center

Trimble Business Center (TBC) software enables surveyors to analyse and compensate for metadata, such as vector quality, then enhance raw observations with least squares or GNSS post-processing (Figure 8).

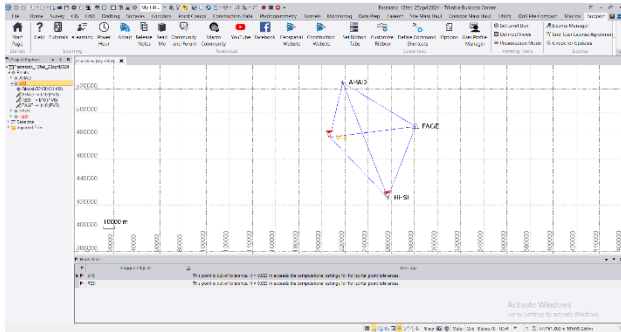


Figure 8. GNSS data processing from 12.02.2023 using Trimble Business Center

Most geodetic processing software for GNSS data use a well-defined set of observables (Pestana 2015):

- ✓ **The carrier-phase** measurement at one or both carriers (being a measurement on the beat frequency between the received carrier of the satellite signal and a receiver-generated reference frequency).
- ✓ **The pseudorange** (code) measurement is equivalent to the difference between the time of reception (expressed in the time frame of the receiver) and the time of transmission (expressed in the time frame of the satellite) of a distinct satellite signal.
- ✓ **The observation time** being the reading of the receiver clock at the instant of validity of the carrier phase and/or the code measurements.

Usually, the software assumes that the observation time is valid for both the phase and code measurements, and for all observed satellites. Consequently, all these programmes do not need most of the information that is usually stored by the receivers. They need phase, code, and time in the above-mentioned definitions, and some station-related information like station name, antenna height, etc.

It is necessary to select the most representative group of stations, providing GNSS observations of the best quality, that is, considering factors, such as the number of observations and the measured signal-to-noise ratio (Galdyn, Zajdel, and Sońnica 2023).

To use the GeoRinex library in Python, GNSS data files containing actual measurements. These data are raw Rinex file formats (Table 3 and Tabel 4) from registered reference stations and satellites common to the geodetic point (Table 3 and Tabel 4) from the positioning epoch 12.02.2023 as time interval 12⁰⁰-14⁰⁰.

Item no.	Point name	Visible satellites
1	ARAD - ROMPOS	G06, G11, G12, G24, G25, G29, G32, R01, R11, R21
2	FAGE- ROMPOS	G06, G11, G12, G24, G25, G29, G32, R01, R11, R21
3	RESI - ROMPOS	G06, G11, G12, G24, G25, G29, G32, R01, R11, R21
4	Geodetic point-B10	G06, G11, G12, G24, G25, G29, G32, R01, R11, R21

Table 4. Information common satellites visible from Rinex files 12.02.2023

To run the experiment and manipulate the GNSS data volumes, the Python programming language version 3.10.11 with the GeoRinex 1.16.1 library was used to interpret, analyse, and visualize the parameters in the RINEX data files.

The RINEX data files format allows efficient and unambiguous archiving of GNSS data and associated metadata in one place (in a human-readable form), while also facilitating the easy transfer and distribution of such data, independent of the equipment used to collect it and the engine employed for data processing (“Coordinates: A Resource on Positioning, Navigation and beyond» Blog Archive» Understanding the RINEX Format for GNSS Data Transfer and Storage,” n.d.).

4. RESULTS AND DISCUSSION

The post-processing of the GNSS data from the positioning epoch 12.02.2023 time interval 12⁰⁰-14⁰⁰ resulted in the following three-dimensional coordinates of point B10 obtained using the two techniques Fast Static and RTK (Table 5).

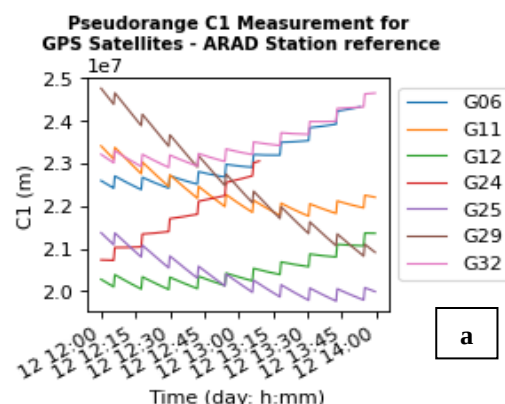
Test	X (m)	Y (m)	Z (m)
Fast Static	478571.094	206866.223	87.718
RTK	478570.917	206866.596	87.650

Table 5. Three-dimensional coordinates of geodetic point B10 on 12.02.2023

After post-processing, it can be seen from Figure 8 that we have a horizontal deviation of 0.023m on the B10-Resi vector. To understand what happened to the parameters in the Rinex files during the fast static measurement, we will run the algorithm using the GeoRinex library, the following steps:

- installing the GeoRinex library for Python 3 <https://pypi.org/project/georinex/>
- Collection of data from Rinex files according to positioning epochs from 12.02.2023 in the interval 12:00-14:00 (Table 3 and Table 4). These data should include the time ("time"), parameters C1, C2, L1, L2, P1, P2, S1, S2 for each of the common satellites.
- Visualizing all the parameters (C1, C2, L1, L2, P1, P2, S1, S2) from Rinex data for each reference station in the ROMPOS network (ARAD, FAGE, and RESI) and geodetic point B10 using the common satellites for each satellite system GPS and GLONASS as follows:

- ✓ **GPS satellite system:** G06, G11, G12, G24, G25, G29; G32 (figure 9 and figure 10) parameters Pseudorange C1, C2, P1, P2



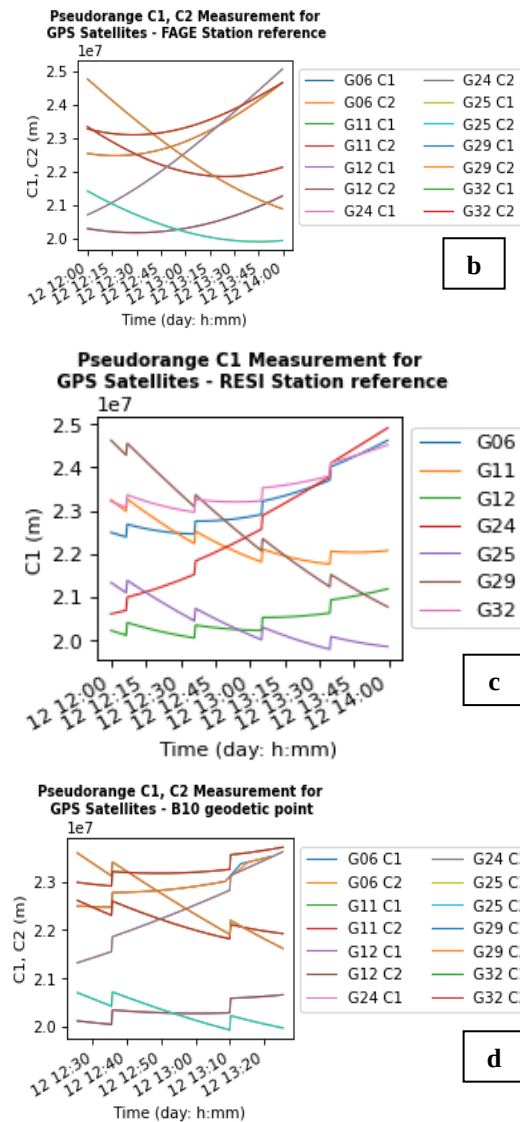


Figure 9. View parameters pseudorange C1, C2 for GPS satellite system from the Rinex file of: (a) ARAD station reference; (b) FAGE station reference, (c) RESI station reference and (d) geodetic point B10

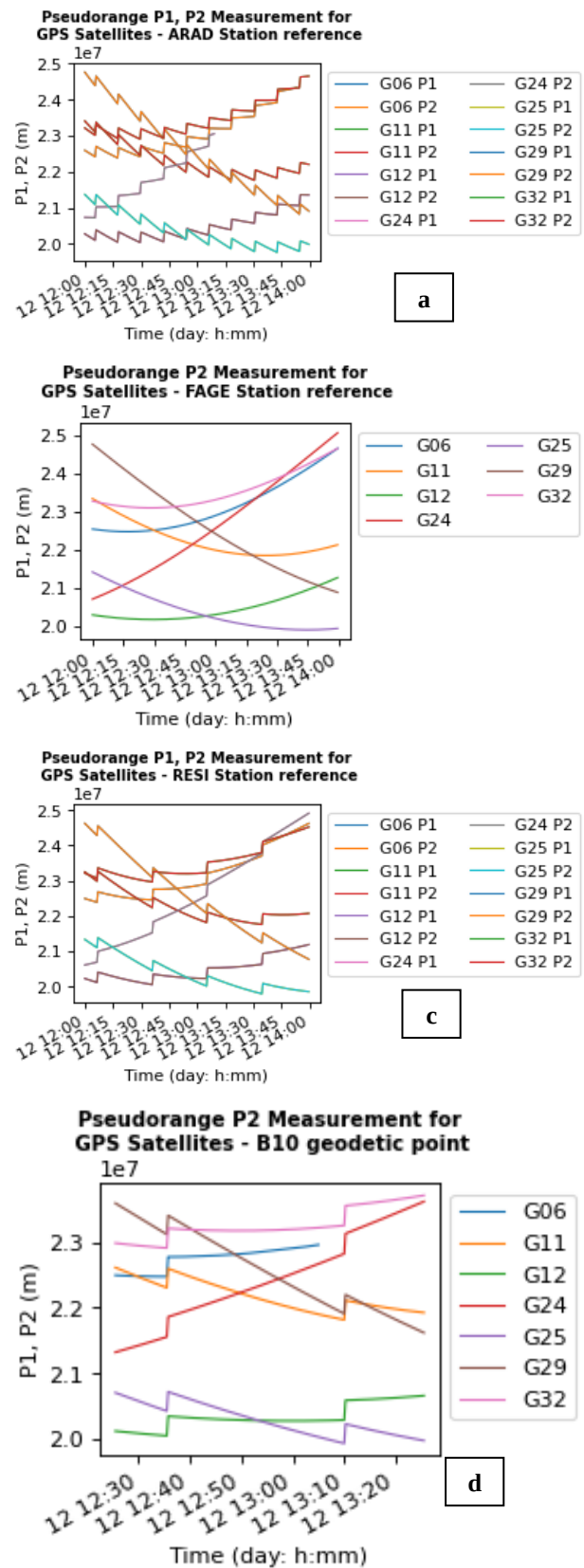


Figure 10. View parameters pseudorange P1, P2 for GPS satellite system from the Rinex file of: (a) ARAD station reference; (b) FAGE station reference, (c) RESI station reference and (d) geodetic point B10

- ✓ **GPS satellite system:** G06, G11, G12, G24, G25, G29; G32 (Figure 11) parameters Carrier Phase L1, L2

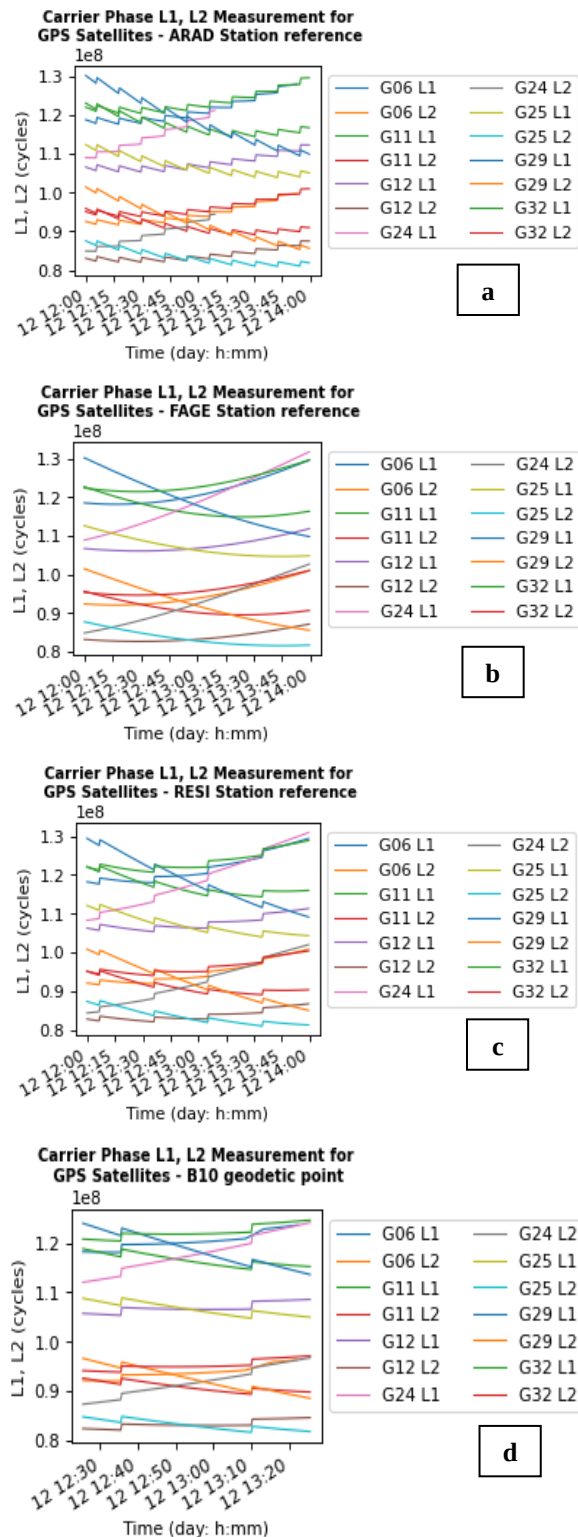


Figure 11. View parameters carrier phase L1, L2 for GPS satellite system from the Rinex file of: (a) ARAD station reference; (b) FAGE station reference, (c) RESI station reference and (d) geodetic point B10

- ✓ **GPS satellite system:** G06, G11, G12, G24, G25, G29; G32 (Figure 12) parameters Signal Strength S1, S2

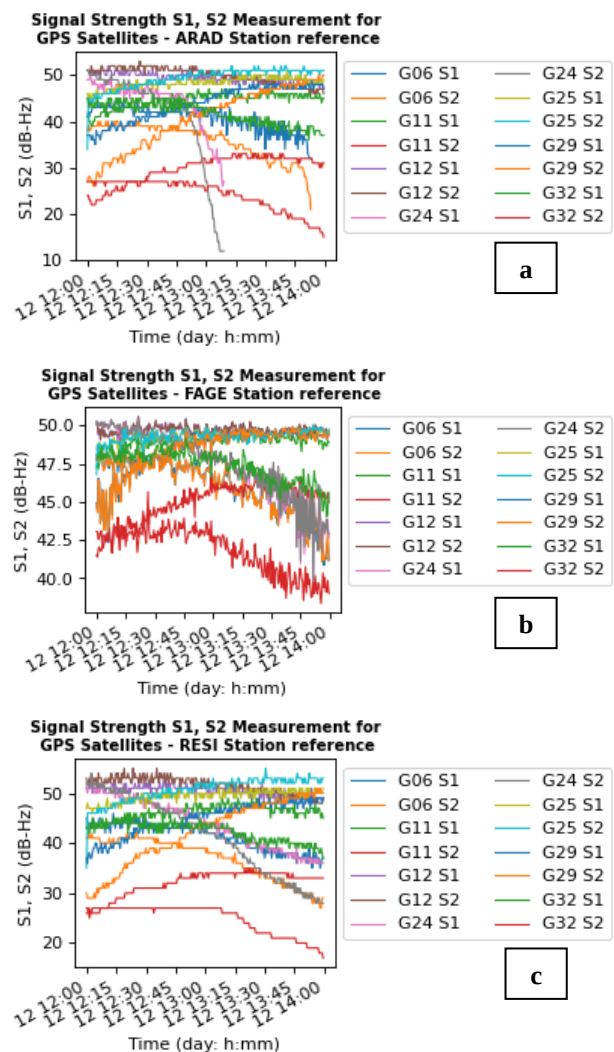


Figure 12. View parameters signal strength S1, S2 for GPS satellite system from the Rinex file of: (a) ARAD station reference; (b) FAGE station reference and (c) RESI station reference

- ✓ **GLONASS satellite system:** R01, R11, R21 (Figure 13 and Figure 14) Pseudorange C1, C2, P1, P2

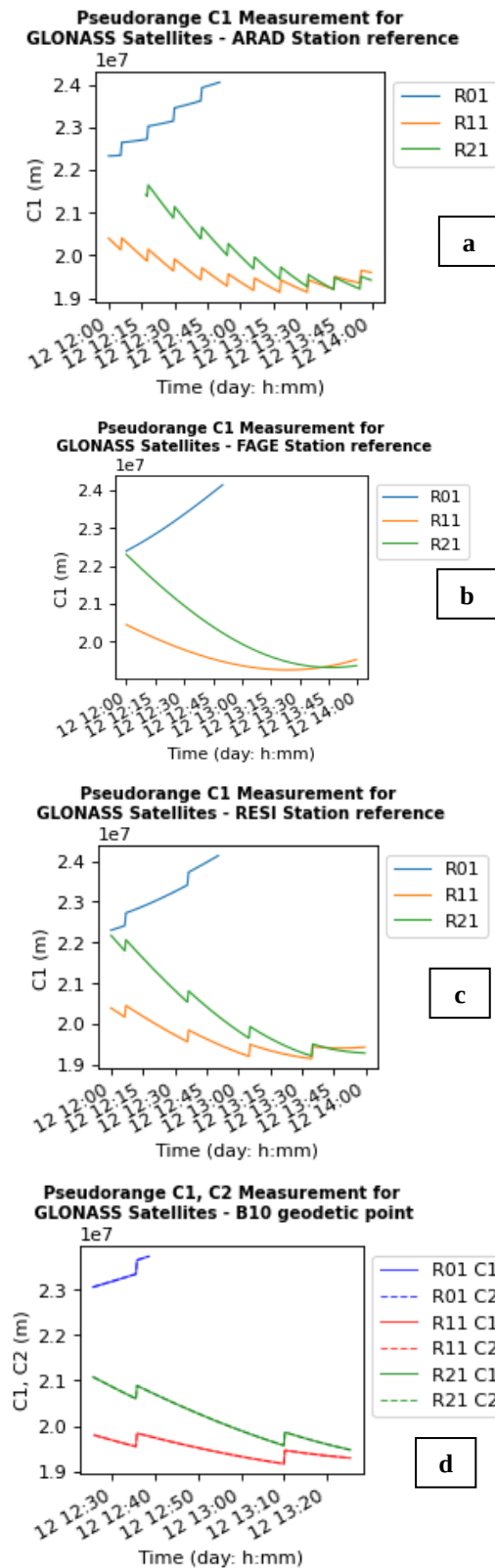


Figure 13. View parameters pseudorange C1, C2 for the GLONASS satellite system from Rinex file of: (a) ARAD station reference; (b) FAGE station reference; (c) RESI station reference and (d) geodetic point B10

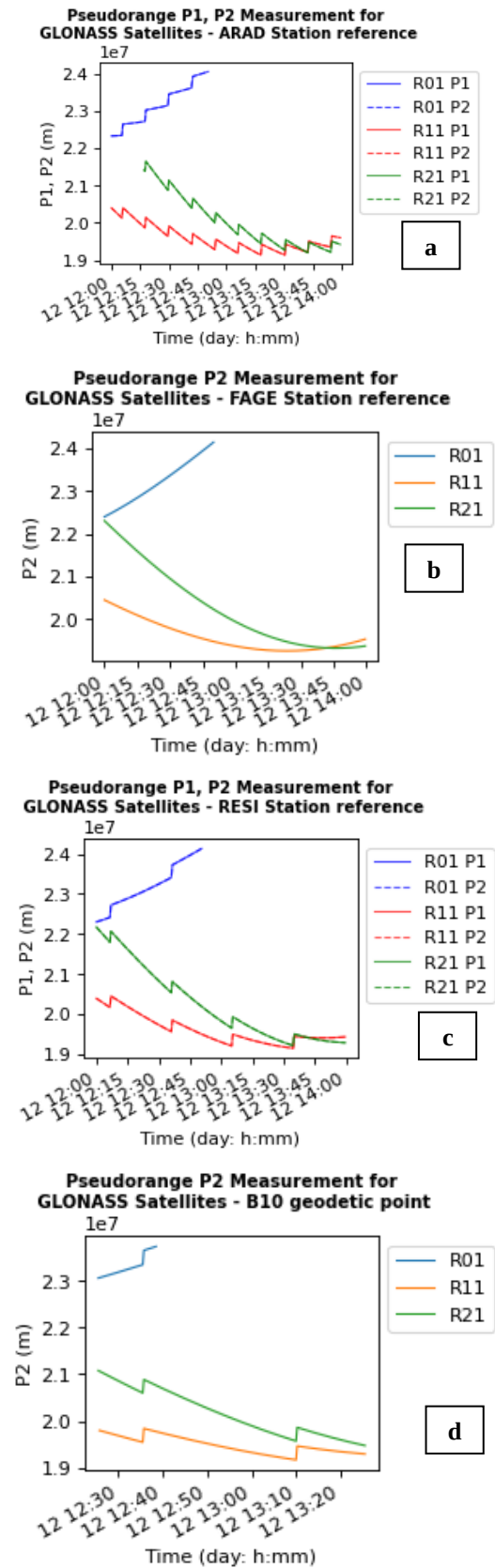


Figure 14. View parameters pseudorange P1 P2 for the GLONASS satellite system from Rinex file of: (a) ARAD station reference; (b) FAGE station reference; (c) RESI station reference and (d) geodetic point B10

- ✓ **GLONASS satellite system:** R01, R11, R21 (Figure 15) parameters Carrier phase L1, L2

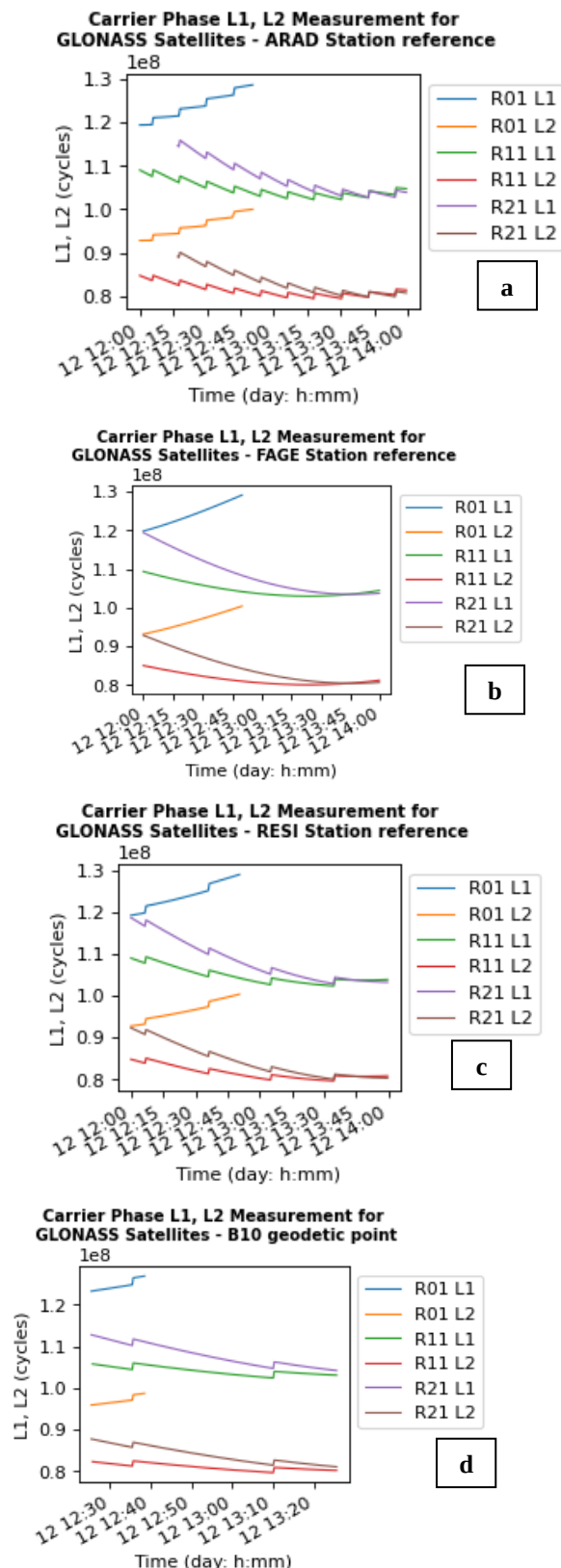


Figure 15. View parameters carrier phase L1, L2 for the GLONASS satellite system from Rinex file of: (a) ARAD station reference; (b) FAGE station reference; (c) RESI station reference and (d) geodetic point B10

- ✓ **GLONASS satellite system:** G06, G11, G12, G24, G25, G29; G32 (Figure 16) parameters Signal Strength S1, S2

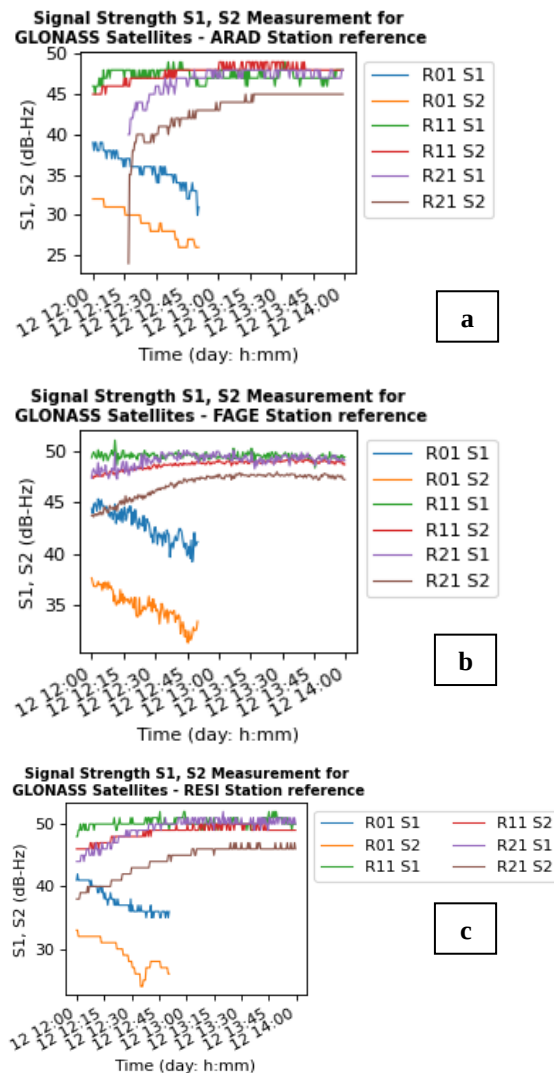


Figure 16. View parameters signal strenght S1, S2 for GLONASS satellite system from Rinex file of: (a) ARAD station reference; (b) FAGE station reference and (c) RESI station reference

The techniques and tools developed for geodetic determinations have enabled measurements over the last half century to be made using systems consisting of one or more satellite constellations, which allow position, velocity, and time information to be received.

GNSS surveying technology can provide an efficient and effective option for measuring points even in dense urban areas. To determine such points, there are several conditions: satellite geometry, a larger number of visible satellites, satellite cut-off angle, signal blockage, data latency, signal interference, distance between base and rover, location of the rover within reference station networks, and number of channels of this rover to record data from multiple satellite systems (Figure 17). For Fast Static measurement dual-frequency receivers can be used for faster acquisition of correct ambiguities that provide centimetre-level positioning accuracy.



Figure 17. Satellite geometry and PDOP value on 12.02.2023

Our research explored the accuracy of GNSS Fast Static measurement for a set of measurements at geodetic points located in dense, high-traffic urban areas. Our main objective was to better interpret their behaviour in different environments. Therefore, we analysed and interpreted the degradation of the information obtained from fast static measurements using the GeoRinex library in Python, paying attention to the known parameters in the Rinex files: pseudorange, carrier phase, and signal strength.

5. CONCLUSIONS

The input data features in the RINEX files were selected based on the knowledge gained from years of work in the field of GNSS measurements; however, the selection was limited to a set of indicators that can be measured using GNSS reference station systems and technology in the field.

Based on research from the results obtained using the GeoRinex library in the Python programming language to evaluate the error in determining the positioning accuracy of geodetic point B10 located in a crowded and heavily trafficked area using the Fast Static technique, which allows sufficient coverage of GNSS satellites, is due to the inconsistency of parameters in the Rinex version 2 files.

Therefore, attention was paid to the variations of parameters C1, C2, L1, L2, P1, P2, S1, and S2 in the Rinex files from the ROMPOS reference stations and the geodetic point B10. The following differences can be observed according to the resulting graphs (Figure 8, Figure 9, Figure 10, Figure 11, Figure 12, Figure 13, Figure 14, and Figure 15) using the GeoRinex library in the Python programming language:

- The ARAD and RESI reference stations lack the C2 pseudorange parameter for both GPS and GLONASS satellite systems.
- Contrary to the two previous stations mentioned above, the FAGE reference station lacks the pseudorange parameter P1 (both GPS and GLONASS satellite systems) and C2 for the GLONASS satellite system.
- At geodetic point B10 the parameters: pseudorange P1 and signal strength S1, S2 for both GPS and GLONASS satellite systems are missing.
- Also the fact that from the GLONASS satellite system we have only three satellites (R01, R11, R21) that have been taken into account according to the Rinex

files in determining the position of point B10, it can be observed that in the positioning epoch 12.02.2023, 12⁰⁰-14⁰⁰, the satellite R01 has a short period of parameter transmission (45 minutes according to figure 12, figure 13, figure 14 and figure 15).

- It can be observed that pseudorange parameters: C1, C2, and P1, P2 determined from the three GLONASS satellites: R01, R11, R21 in RESI reference stations coincide in the measurement epoch.

Therefore, the accuracy of position determination is influenced by these parameters of the raw RINEX datasets. The observed results can be used to understand the accuracy of the Fast Static technique (as can be seen in Figure 8) and to better interpret their behavior in different environments.

For future work one direction is to investigate the effectiveness of using machine learning algorithms to improve the quality of positioning information (RINEX files) of geodetic points in dense urban areas provided by Global Navigation Satellite Systems (GNSS) receivers.

The multipath propagation mitigation method based on these machine learning algorithms is efficient, easy to use, and can be easily extended by adding auxiliary input features, such as signal-to-noise ratio, during model training (Pan, Möller, and Soja 2023).

In conclusion, when characterising the accuracy performance of Fast Static measurements, the results showed that the method requires careful analysis of the types of data used to ensure that we benefit from the reliability, availability, and accuracy of each system without having to invest in additional solutions to determine the accuracy of a point located in dense urban areas.

Authors' Contributions

The authors made the following contribution to this paper: Conceptualization (ACB); Data curation and formal analysis (ACB, BCD, FMB); Methodology (ACB, FMB); GeoRinex work (BCD, ACB); Writing - original draft (ACB); Writing - review and editing (ACB, BCD, FMB). In addition, the authors thank National Cartography Center for helping with collection Rinex data from ROMPOS network. All authors read and approved the final manuscript.

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