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# Contribution of Using Multiple GNSS Constellations in Precise Point Positioning Applied to Monitoring

## *Contribution of the use of multiple GNSS constellations in precise point positioning applied to monitoring*

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**Abstract:** With the evolution of GNSS constellations and positioning algorithms, Precise Point Positioning (PPP) has established itself as a viable alternative for the geodetic monitoring of structures in urban environments. This study investigates the performance of the PPP method using different combinations of GNSS constellations – GPS, GLONASS, Galileo, and BeiDou – in a controlled setting, with simulated horizontal displacements and statistical analysis of the results. The methodology involved GNSS data collection at points with predefined displacements, followed by processing with RTKLIB software and application of the Student's t-test to assess significant differences. The results showed that although the use of MULTI-GNSS increased the robustness of the solutions, the GPS + Galileo combination delivered statistically comparable performance, especially under more stable tracking conditions. However, it was found that both configurations still present limitations in the precise detection of millimetric displacements when less rigid supports were used. The altitude data also showed significant variability, indicating the need for refinement in vertical correction models. This demonstrates that PPP using multiple constellations or GPS + Galileo can be effective for urban monitoring, provided that the operational and structural constraints of the application environment are respected.

**Keywords:** PPP 1; RTKLIB 2; Multi-constellation 3.

**Resumo:** Com a evolução das constelações GNSS e dos algoritmos de posicionamento, o Posicionamento por Ponto Preciso (PPP) tem se consolidado como uma alternativa viável para o monitoramento geodésico de estruturas em ambientes urbanos. Este trabalho investiga o desempenho do método PPP utilizando diferentes combinações de constelações GNSS – GPS, GLONASS, Galileo e BeiDou – em ambiente controlado, com simulação de deslocamentos horizontais e análise estatística dos resultados. A metodologia consistiu na coleta de dados com receptor GNSS em pontos com deslocamentos previamente definidos, seguidos de processamento com o software RTKLIB e aplicação do teste t de Student para verificação de diferenças significativas. Os resultados demonstraram que, embora o uso do MULTI-GNSS tenha ampliado a robustez das soluções, a combinação GPS + Galileo apresentou desempenho estatisticamente comparável, sobretudo em condições mais estáveis de rastreio. Constatou-se, no entanto, que ambas as configurações ainda apresentaram limitações para a detecção precisa de deslocamentos milimétricos quando utilizados suportes menos rígidos. Os dados altimétricos também indicaram variabilidade significativa, apontando para a necessidade de refinamento dos modelos de correção vertical. Demonstrando que o PPP com múltiplas constelações e com GPS + Galileo pode ser eficaz no monitoramento urbano, desde que respeitados os limites operacionais e estruturais do ambiente de aplicação.

**Palavras-chave:** PPP 1; RTKLIB 2; Multi-constelações 3.

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## 1. Introduction

Satellite positioning through Global Navigation Satellite Systems (GNSS) technology is important in engineering projects, aimed at determining the coordinates of points on the features of interest. In recent years, with the evolution of electronics and the era of artificial satellites, GNSS has been used more frequently, since greater numbers of satellites and constellations are available, allowing GNSS positioning algorithms to obtain more accurate coordinates for the end user. Among the available GNSS constellations are the Global Positioning System (GPS), the Global'naya Navigatsionnaya Sputnikovaya System (GLONASS), the Galileo and the BeiDou Satellite System (BDS) (TEUNISSEN; MONTENBRUCK, 2017).

Among the main GNSS positioning methods, the following subdivision can be assumed: absolute positioning methods and relative (differential) positioning methods. There are also other methods resulting from combinations of the two strands (absolute and relative), and especially for real-time applications, methods based on network-based positioning solutions are strongly highlighted (OLIVEIRA JR, 2017; WÜBBENA; SCHMITZ; BAGGE, 2005). In general, for the user, in absolute methods, using only one GNSS receiver, it is possible to determine the position of the receiver's antenna. On the other hand, in relative methods, there is a need for at least 2 or more GNSS receivers collecting information simultaneously to establish the position of the user's receiver antenna (MONICO, 2008).

One of the applications of GNSS positioning is the monitoring of natural and artificial structures, especially for the purpose of preventing disasters that may cause financial, environmental and human losses. In this case, GNSS positioning is used to determine movement parameters that allow characterizing the displacements of a network of points, many of which are located in the structure to be monitored. Thus, quality precision better than the centimetric level is usually aimed at (CHAVES; SEGANTINE, 2014; CALDAS; CHAVES, 2014; OLIVEIRA JR, 2015).

In general, relative positioning is more applied in monitoring work, however one of the absolute positioning methods, the so-called Precise Point Positioning (PPP), allows the collections carried out with only one GNSS receiver to obtain good results (accuracy at the centimeter level) after post-processing the data obtained (IBGE, 2021). Many of the structures that are intended to be monitored are located in large urban centers, where the presence of skyscrapers can significantly affect the availability of data. This is due to the strong obstruction and reflection of electromagnetic signals in these places, caused by the multipath effects on the GNSS signals.

Recent studies seek to highlight the gains obtained when using MULTI-GNSS positioning, that is, the use of several constellations in a combined way. In this sense, Lin et al. (2021) applied MULTI-GNSS positioning for the monitoring of landslides using the PPP method. The authors concluded that the use of multiple satellite navigation systems (MULTI-GNSS) allows the PPP solution to achieve centimeter accuracy in about 30 minutes of occupation of the tracked point. In the same work, the authors conclude that the PPP method with MULTI-GNSS can meet the criteria for monitoring rapid landslides.

Song and Zhao (2021) demonstrate the potential of daily and hourly solutions by the PPP method with the use of multiple frequencies in the European region. In this work, the authors focus their efforts on evaluating the Galileo constellation and point out that some of the challenges that can degrade the quality of positioning are clock errors and combinations of Galileo observables (E1/E5a and E1/E5b). Even so, the authors conclude that it is possible to produce daily solutions of millimetric quality and hourly solutions of centimeter quality.

In Brazil, several studies have sought alternatives for the use of PPP, such as Collischonn and Matsuoka (2016) who present a methodology for network development using GNSS data processed by the PPP method. In this study, stations belonging to the Brazilian Network of Continuous Monitoring (RBMC) were used, presenting as an advantage the possibility of applying quality control based on the results of the adjustment. In addition, other studies aimed at comparing the results of PPP and relative positioning for monitoring purposes indicate that both methods present accuracy results at the centimeter level for the identification of displacements (ZANETTI; VALENTINE; OLIVEIRA JÚNIOR, 2020).

Observing the studies mentioned above, in national and international literature, it was possible to identify the need for more research that evidences the limits of the PPP method for the purpose of monitoring structures, bringing greater safety to its application. Such studies are even more important if we consider the increasingly frequent modernizations in GNSS technology, with the incorporation of new constellations and new signals. Therefore, this scientific article aims to analyze the performance of GNSS positioning with the PPP method in a controlled urban environment in the monitoring of structures, using different compositions of the GNSS constellations, as well as the use of multiple constellations simultaneously (MULTI-GNSS).

## 2. Methodology

The activities developed in this work are illustrated in Figure 1, below, by means of a detailed flowchart. Where all phases of the experiment, from the construction of the physical reference model to the statistical analysis of the processed data are presented. This scheme allows for a clear view of the procedures adopted for the collection, processing and validation of GNSS data, in addition to highlighting the statistical analysis tool for the evaluation of the challenges and effectiveness of positioning in an urban environment.

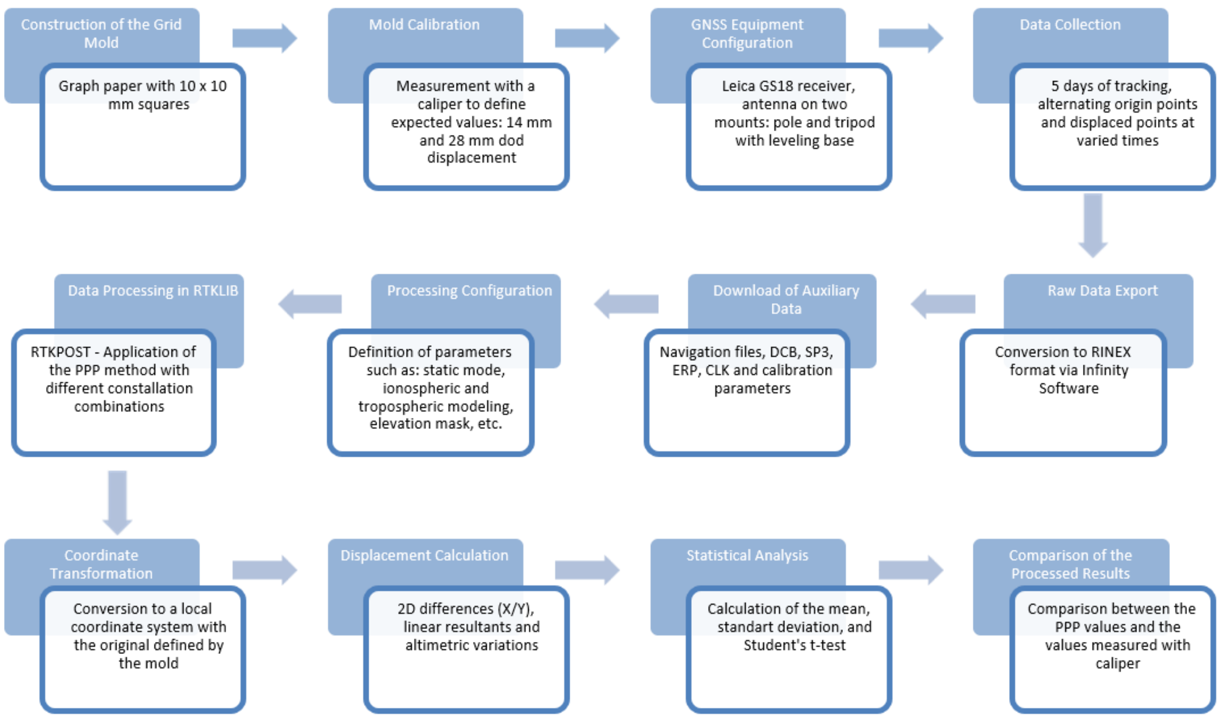


*Figure 1 – Flowchart of the activities developed.*
*Source: The authors (2024).*

In order to build conditions that would allow the evaluation of the potential for detecting coordinate displacements by positioning with GNSS technology, the tests were carried out in a controlled environment. The procedure for motion control involved the creation of a grid mold, which was plotted, simulating a millimeter surface spaced by squares of 10 mm by 10 mm. This mold was fixed to the ground where the screenings were carried out.

The points to be measured were defined in relation to the origin of the mold in results from movements of 10x10 mm and 20x20 mm, that is, the crossing of the lines of the central axis is the departure (origin) for the variation of the measured points (displacements).

The value of the results found by calculating the square roots of the squared differences was 14 mm and 28 mm, for the movements mentioned, 10 and 20 mm, respectively. To control possible distortions in the prints, the model was measured three times in each position with a caliper as standard in the measurement of the grid and the means of these measurements corresponded to the values of the calculated results, as shown in Figure 2.

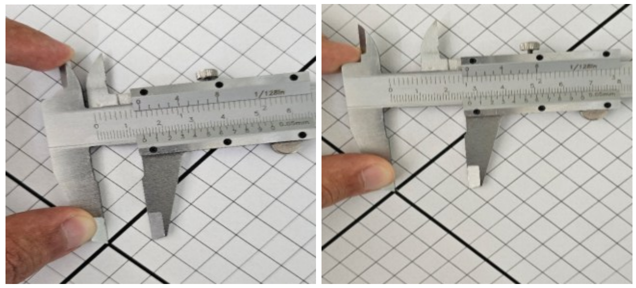

*Figure 2 – Point offset 14 and 28 mm from the origin.*
*Source: The authors (2024).*

The GNSS point tracking was carried out in the Manfra building, today the headquarters of the Leica Geosystems do Brasil Company, in the city of Curitiba. Figure 3 below shows the location map.

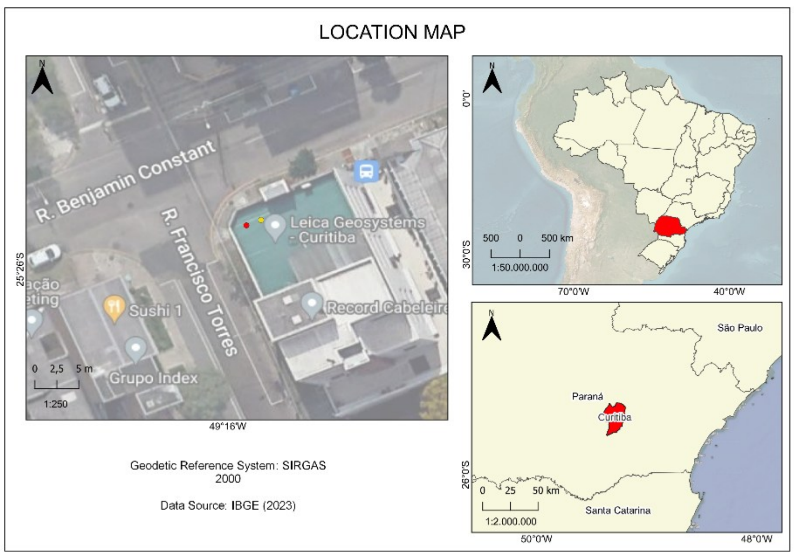


*Figure 3 – Location map.*
*Source: The authors (2024).*

The GNSS receiver used was the GS18 model from Leica Geosystems, with the following technical characteristics: nominal accuracy (static mode) of up to 3 millimeters + 0.1 ppm (parts per million), in the horizontal component, and up to 3.5 millimeters + 0.4 ppm in the vertical component; ability to combine the use of GPS, GLONASS, Galileo and BeiDou/BDS constellations; and recording of observables at multiple frequencies.

In all, 05 (five) days of collection were carried out between the 79th and 83rd of the year 2023, when the screenings lasted an average of 2 hours each, starting around 9 am and ending between 3 pm and 5 pm. On each of the five working days, two to three pairs of dots were tracked, namely the dots at the origin of the system (central point of the graph paper produced) and dots with predefined displacement (dots with resulting displacements in the graph paper produced). In total, 24 points were collected in the screening experiment.

For the installation of GNSS antennas at the points, a stick supported by a bipod and a tripod with a leveling base were used. Where the antenna attached to the stick was used to track the point with a defined offset of 14 mm from the origin of the model (Figure 4). While the tracked point with the antenna attached to the leveling base and the tripod had a displacement of 28 mm in relation to the origin of the model.

*Figure 4 – Point displaced 10 mm from the origin.*
*Source: The authors (2024).*

In order to obtain screenings under similar conditions for all points surveyed, the origin point and displaced point screenings were alternated over the days. That is, on the first day, the point of origin was tracked in the morning, and the shifted point was tracked in the afternoon. On the second day, the procedure was reversed, with the displaced point being tracked in the morning and the point of origin in the afternoon.

This method of systematic tracking of the points by GNSS, alternating between the origin and the displaced point, allowed the obtaining of data at different times of the day, making the comparisons consistent for the performance of subsequent geodetic analyses. The GS18 antennas used were provided free of charge by Leica Geosystems Brasil for the experiment of this work. The receiver was configured to collect the GPS, GLONASS, Galileo and Beidou constellations, as well as the L1, L2 and L5 frequencies.

In the context of GNSS data processing, the conversion of raw data to the RINEX format plays an important role. The conversion process was initiated by importing the raw data into the commercial software Infinity, version 3.8, also made available for this research free of charge by Leica Geosystems. In Infinty 3.8, the export of raw data to the RENEX format was configured, specifically in the RINEX 3.04 version. The choice of this version is because it is the last one available on the software and supports the export of multi-constellation observations in a single file.

In the process of obtaining accurate data for processing, several files are needed to improve the accuracy and quality of the results. Initially, navigation data from the nearest RBMC Station, the Federal University of Paraná (UFPR) Station, were obtained by downloading the RINEX 3 1-second files available on the website of the Brazilian Institute of Geography and Statistics (IBGE). These files, which are provided by the hour and every 15 minutes, were always downloaded that the screenings occurred during the survey days.

In addition to the navigation data, other products were downloaded from the National Aeronautics and Space Administration's (NASA) Crustal Dynamics Data Information System (CDDIS) website. Differential Code Bias (DCB) files were obtained, which provide information on the differential biases of the satellite codes, improving the accuracy of positioning.

Also downloaded were the Satellite Precise Ephemeris (SP3) files, containing precise ephemeris of the GNSS satellites, essential for calculating the positions of the satellites at the time of the observations. Earth Rotation Parameters (ERP) files were obtained to provide information on the parameters for correcting the Earth's rotation during positioning. Finally, the Clock (CLK) files were downloaded to correct the clock errors of the GNSS satellites and improve the temporal accuracy of positioning.

In addition to these files, the file containing the antenna calibration parameters (GS18), referenced to the last ITRF, was also downloaded from the National Geodetic Survey (NGS) website. This file contains information about satellite antennas and GNSS receivers. Included is information related to radiation patterns (PCO and PCV), calibration factor, and offset, and is necessary to correct antenna characteristics during data processing.

Obtaining this accurate data is critical to ensuring reliable GNSS positioning results by integrating navigational information, ephemeris, differential biases, Earth rotation parameters, and clock errors. This data, together with the antenna file, is essential for successful processing and obtaining more accurate results.

For the processing of the raw data itself, the software used was RTKLIB, specifically using the RTKPOST module, which is a project to process and analyze the data collected by GNSS receivers in a post-processed way. Table 1 summarizes the main PPP processing configurations described in this section.

*Table 1 – Description of the table.*

| **RTKLIB Settings** | |
|---|---|
| Positioning Mode | Static DPI (Static PPP) |
| Orbits and clocks | CODE orbit and clock products |
| Ionosphere | Ionospheric-free |
| Zenith Tropospheric delay | Estimate ZTD (Modeled Hydrostatic Component and Estimated Residual Wet Component) |
| Elevations mask | 15° |
| Sampling data | 1 second |
| Filter Type | Combined (Forward + Backward) |
| Software | RTKlib 2.4.2 |

*Source: The authors (2024).*

The resulting solution from the processing for both methods is provided in the X/Y/Z-ECEF format, which represents the three-dimensional coordinates in the Earth-Centered, Earth-Fixed coordinate system (ECEF).

The default values proposed by the RTKLIB were used, in relation to the statistics and information on the accuracies of the observables for the construction of the matrix of weights as well as other aspects related to the stochastic model. This means that standard software statistics are generated to assess the quality and accuracy of the positioning solution obtained, providing insight into the errors and reliability of the solution (RTKLIB, 2021).

It is important to note that the data processing by the PPP method was carried out in several ways, with respect to the use of GNSS constellations. It was carried out including MULTI-GNSS, which involves the use of the four main GNSS constellations available (GPS, Glonass, Galileo and Beidou). In addition, specific processing was carried out with pairs of constellations (GPS + Glonass and GPS + Galileo) and individual processing with each constellation (GPS, Glonass, Galileo and Beidou).

Armed with the results of the processing, the transformation of the coordinates was carried out to allow a more precise analysis of the differences resulting from the controlled movement. By using a local geodetic system, data can be evaluated against a specific reference, making it easier to interpret the results and providing relevant information about the movement of the point of interest.

In order to facilitate the analysis of the data, the geodesic orthogonal Cartesian coordinates of the origin of the system were defined as being equal to the coordinates of the origin of each mold. In other words, the local coordinate generated by the transformation is equal to the difference in the coordinates in their components.

With the set of linear differences of the transformed coordinates, the arithmetic mean estimator of the resultant and the standard deviation of the sample were calculated for the set of points measured with the stick and those measured with the Tripod. These statistical data were also calculated with the altitude data, since it is not part of the linear distance of the points, but is a calculated coordinate belonging to them.

These results supported the calculations for the practice of the paired Student's Test, performed in an Excel spreadsheet. This test was chosen because it is ideal for small samples and efficient for performing quantitative information analysis of paired data. That is, through it it will be verified whether there are statistically significant differences between the results obtained by calculating the coordinates of the multi-constellation GNSS surveys and the result value measured with the caliper in the grid model.

## 3. Results and discussion

Since in the calculation of the transformations the geodesic Cartesian coordinates of the origin of the system were defined as being equal to the coordinates of the origin of each grid mold, the difference values are the results of the transformations, that is, the value of the origins will always be zero and the coordinates obtained at the point of displacement will already be the values of controlled movements.

From these calculations it was observed that the surveys carried out on day 3 formed 2 pairs of points for each type of support using the antenna supported with tripod and leveling base. And for day 5, the data tracked with tripod had to be excluded from the observations, due to the unfeasibility of their results for the differences expected in this research.

Therefore, from the other values of the differences in each horizontal component of the coordinates of the points, it was possible to calculate the values of the linear resultant (2D) for each measured point.

The results from these calculations for the determination of the linear results are shown in Table 2 for each day, for each constellation used and divided by support instruments for collection (stick or tripod with leveling base).

*Table 2 – Stored data of the resulting 2D calculated in mm.*

| | MULTI-GNSS | GPS | GPS+GLONASS | GPS+GALIEO | Support instrument + expected value of movement |
|---|---|---|---|---|---|
| Day 1 | 39 | 29 | 13 | 24 | Stick 14 mm |
| Day 2 | 50 | 142 | 165 | 24 | |
| Day 3 | 28 | 41 | 16 | 18 | |
| Day 4 | 11 | 102 | 4 | 41 | |
| Day 5 | 26 | 17 | 28 | 26 | |
| Day 1 | 56 | 43 | 52 | 59 | Tripod 28mm |
| Day 2 | 29 | 30 | 41 | 27 | |
| Day 3 | 40 | 21 | 68 | 32 | |
| Day 4 | 22 | 102 | 22 | 19 | |

*Source: The authors (2024).*

For the validation of the results, the averages of the results were calculated from the set of data obtained previously, below is shown in Figure 5, the averages of the results for each combination of GNSS constellations.

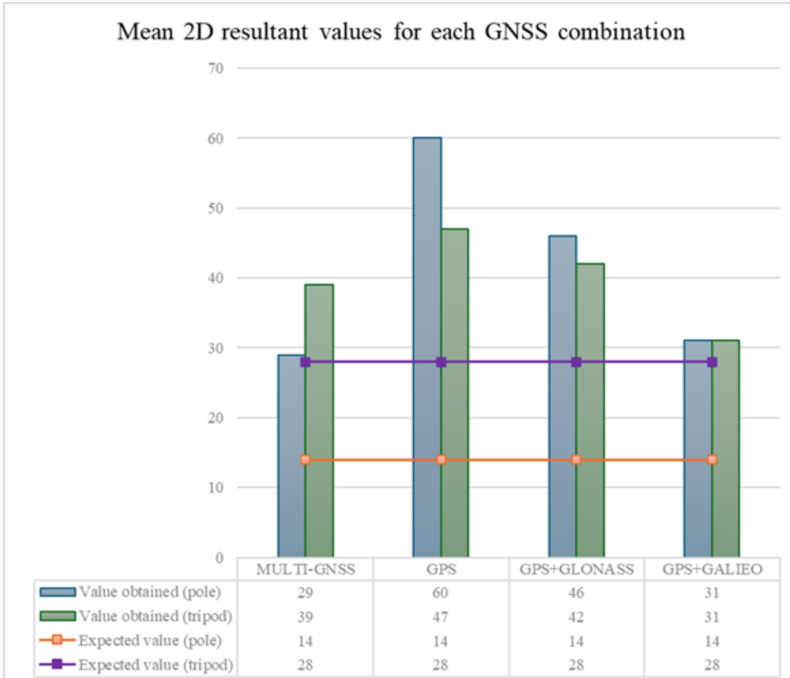


*Figure 5 – Averages of the resulting 2D for each GNSS combination.*
*Source: The authors (2024).*

As can be seen in the graph and based on these values, only the means of lower magnitude, i.e., those that were closest to the expected movement values, were selected for the use of the t-test. Specifically, the combination MULTI-GNSS (GPS + GLONASS + GALILEO + BEIDOU) and GPS + GALILEO were chosen for the application of this test, where an expected average of 14 mm was assumed, a significance level of 95% and having 5 degrees of freedom. Table 3 presents the results found for the set of points measured with the stick.

*Table 3 – Dataset of the resulting 2D measured with a stick.*

| Measured Set | Average (mm) | Standard Deviation (mm) | TABLED | CALCULATED |
|---|---|---|---|---|
| MULTI-GNSS | 29 | 14 | 2,571 | 2,642 |
| GPS+GALILEO | 31 | 14 | 2,571 | 2,642 |

*Source: The authors (2024).*

Performing the pertinent analyses of these tests, it was possible to observe that the calculated T values are higher than those of tabulated T, so the null hypothesis for both sets of points is rejected. In other words, it was found that there were statistically significant differences between the results obtained by calculating the coordinates of the GNSS MULTI-GNSS surveys and the GPS+GALILEO combination, compared to the value of the result measured in the stick grid model. Table 4 below presents the results found for the set of points measured with the tripod.

*Table 4 – Dataset of the resulting 2D measured with a tripod.*

| Measured Set | Average (mm) | Standard Deviation (mm) | TABLED | CALCULATED |
|---|---|---|---|---|
| MULTI-GNSS | 39 | 14 | 2,776 | 1,822 |
| GPS+GALILEO | 31 | 17 | 2,776 | 0,402 |

*Source: The authors (2024).*

In this case, it was possible to observe that the calculated T values are lower than those of$_{\text{tabulated T}}$, so the null hypothesis is accepted. In other words, it was found that there were no statistically significant differences between the results obtained by calculating the coordinates of the GNSS MULTI-GNSS surveys and the GPS+GALILEO combination, compared to the result measured in the grid model with the tripod.

The values of the differences in altitudes, on the other hand, also did not necessarily need to be calculated, because the transformation of the coordinates already has its differences. These values of the differences in the levels of the points on each day, for each constellation used and divided by support instruments for collection (stick or tripod with leveling base) are shown in Table 5 below:

*Table 5 – Stored data of altitude differences (H) in mm.*

| | MULTI-GNSS | GPS | GPS+GLONASS | GPS+GALIEO | Support instrument + expected value of movement |
|---|---|---|---|---|---|
| Day 1 | 8 | 48 | 49 | 15 | Stick<br>0 mm |
| Day 2 | 16 | 72 | 40 | 29 | |
| Day 3 | 4 | 55 | 74 | 48 | |
| Day 4 | 17 | 63 | 9 | 9 | |
| Day 5 | 54 | 121 | 55 | 81 | |
| Day 1 | 49 | 8 | 58 | 35 | Tripod<br>0mm |
| Day 2 | 65 | 85 | 37 | 52 | |
| Day 3 | 41 | 60 | 80 | 65 | |
| Day 4 | 16 | 27 | 46 | 53 | |

*Source: The authors (2024).*

The statistical test was also applied with the altitude data, since it is not part of the linear distance of the points, but is a calculated coordinate belonging to them. Table 6 below shows the averages of the level differences for each combination of GNSS constellations.

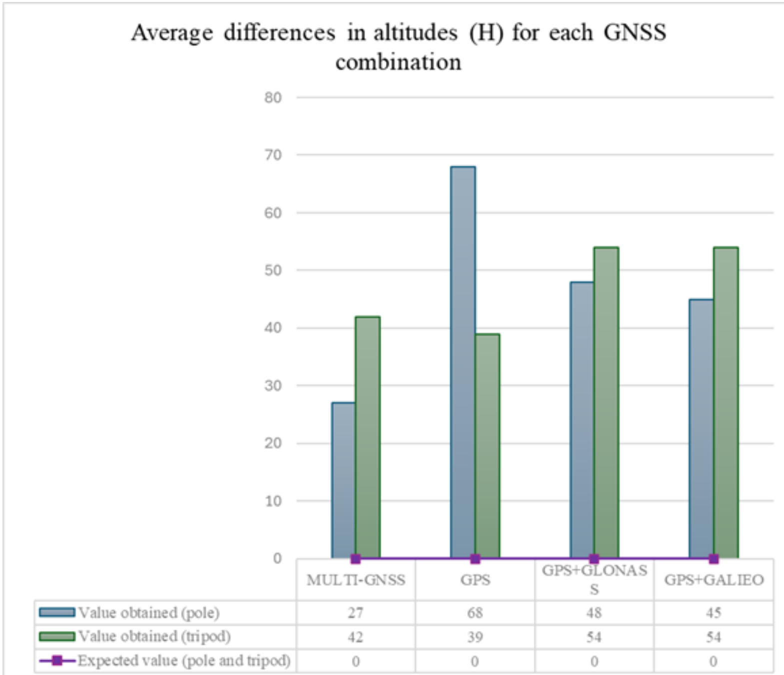


*Figure 6 – Average differences in altitudes (H) for each GNSS combination.*
*Source: The authors (2024).*

Also based on the mean values, only the lowest magnitude was selected for the use of the t-test. That is, specifically the MULTI-GNSS combination. Assuming 0 mm of the expected mean and adopting a significance level of 95%, with 5 degrees of freedom, the test was performed and its results are presented in Table 6 below.

*Table 6 – Dataset of the altitude differences of the MULTI-GNSS combination.*

| Instrument | Average (mm) | Standard Deviation (mm) | TABLED | CALCULATED |
|---|---|---|---|---|
| Stick | 27 | 23 | 2,571 | 2,858 |
| Tripod | 42 | 16 | 2,571 | 6,050 |

*Source: The authors (2024).*

Therefore, it can be seen with this result that the null hypothesis is rejected for the 2 types of screening (stick and tripod), that is, for the altimetric data of the sample there are statistically significant differences in their measurements obtained in the GNSS data processing.

## 4. Final considerations

From the experimental analysis conducted in a controlled urban environment, it becomes evident that Precise Point Positioning (PPP), when combined with the use of multiple GNSS constellations, represents a viable and promising path for geodetic monitoring of structures. Although the results obtained still have limitations in relation to the expected precision — especially when compared to the relative methods — the statistical tests performed indicate that, in certain configurations, the differences between the measured and the expected values are not statistically significant. This finding validates the applicability of the PPP method with multiple constellations as an efficient and simplified alternative, especially in scenarios where the implementation of reference infrastructures is not feasible.

The results obtained in this study show that when comparing the results of the MULTI-GNSS combination with those obtained through the GPS + Galileo combination, it is observed that the latter presented statistically similar performances, and, in some cases, comparable in terms of the expected horizontal precision.

The statistical analysis showed that, for the set of data collected with the tripod, there were no significant differences between the expected and observed results, both in the MULTI-GNSS scenario and in the GPS + Galileo combination. This suggests that, under certain conditions and with the use of stable support, the GPS + Galileo combination can offer results compatible with more complex and dense solutions, such as those obtained via MULTI-GNSS.

On the other hand, in the tests performed with a stick, both configurations presented significant discrepancies in relation to the expected displacement values, pointing to the influence of the type of support and the stability of the station on the accuracy of the method. In addition, the variations detected in the vertical components (altitudes) indicate that, regardless of the constellation configuration employed, improvements in the correction models and calibration parameters are still needed for the PPP to achieve a more reliable altimetric performance.

Thus, it is concluded that both the MULTI-GNSS approach and the GPS + Galileo combination have potential for application in the monitoring of urban structures, and the choice between them depends on the operational context, the available infrastructure and the established accuracy objectives. Thus, the importance of continuing research aimed at optimizing the PPP is reinforced, with a focus on the intelligent integration of constellations, the refinement of error models and the development of practical solutions for applied engineering.

## Thanks

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