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CIRCLE FITTING FOR IMPROVED GNSS POSITIONING VIA SMARTPHONES FOR ENGINEERING PURPOSES

Ajustamento de circunferência como melhora do posicionamento GNSS via smartphones para fins de engenharia

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Abstract:

With access to the raw data collected by certain Android smartphones, it is possible to perform post-processing of the data. Thus, it is possible to employ certain satellite positioning methods that were previously restricted to geodetic receivers. Thanks to this and other innovations, such as the emergence of smartphones with modern GNSS sensors, a promising scenario is seen when employing these devices in engineering applications. Generally, in certain applications that require high accuracy, centimeter and millimeter order, geodetic receivers are used. However, these devices are expensive when compared to smartphones. In this research, the coordinates of a point were determined via a smartphone with a modern GNSS sensor, whose data were post-processed by the IBGE-PPP service, using the combination GPS+GLONASS and L1 frequency. Thus, using circle adjustment techniques based on least squares, it was possible to obtain horizontal accuracy of approximately 12 cm and 25 cm with a set of about 128-hour and 24-hour sessions respectively. The results obtained in this research suggest that the applied methodology can be used in certain applications in engineering, such as land surveying of rural properties.

Keywords: Smartphone; GNSS; IBGE-PPP; Adjustment; Least Squares

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1. Introduction

Several mobile and wearable electronic devices, such as smartphones, tablets and smartwatches, use position information from Global Navigation Satellite Systems (GNSS). Technological advances have made some of these objects essential items in the daily life of modern society, which drive an increasing diversification of Location-Based Services (LBS).

Currently, every modern smartphone has an embedded GNSS sensor. According to GSA (2019), among the 1.6 billion GNSS receiver shipments in mass market devices in 2019, 90% were inserted in smartphones and wearables. However, the professional segment represented less than 3% of the total GNSS receivers shipments in the same year, with around 1.5 million units.

Smartphone is a mobile phone with an operating system capable of downloading and running a software application (app) (Ericsson, 2018). According to GSA (2019), in 2020 smartphones will be the most used electronic devices in the world. Under good visibility conditions, positioning via smartphones can result in accuracy better than 10 m (Banville and Diggelen, 2016), between 1 to 2 m (Kaleev and Saburova, 2018), and between 2 to 3 m (Pesyna et al., 2014). However, in adverse conditions, when there are obstructions, the accuracy can be worse than 10 m. This level of accuracy, however, may be sufficient for certain LBS's, such as navigation, vehicle tracking, social networks, deliveries, among others (Banville and Diggelen, 2016).

This research seeks to refine the GNSS solutions obtained with a smartphone by adjusting the coordinates obtained in different positions to estimate a central position. This is a pioneering study regarding the positioning at the centimeter level considering three aspects: GNSS data via a smartphone with a modern GNSS sensor; post-processing of data via the free service most used in Brazil (IBGE-PPP); and methods of adjusting observations based on Least Squares.

This article is structured as follows: Session 2 presents the theoretical fundamentals. Session 3 presents the characteristics related to the data collection campaigns, the equipment, positioning method and data adjustment. Session 4 presents the mathematical models adopted for the analysis of the results shown in Session 5. Final considerations are presented in Session 6.

2. Theoretical fundamentals

In certain engineering applications, it is necessary to use conventional geodetic receivers that, depending on the method and technique adopted, can provide position coordinates at the centimeter level (even millimeter) (LEICK et al., 2015). In the current Brazilian scenario, these applications include the land surveying of rural properties, ground control points for photogrammetry, monitoring of structures and masses, paving, sanitation, precision agriculture, bathymetric surveys, among others.

On the other hand, when aiming to obtain geodetic coordinates with high accuracy, the user must consider several characteristics in their decision-making, including the cost benefit. In general, these characteristics include factors such as study area, satellite positioning method, execution time, receiver model, and software.

There are several positioning methods that make it possible to obtain highly accurate geodetic coordinates. The Precise Point Positioning (PPP) method is one of the most viable options in terms of cost-benefit. The Brazilian Institute of Geography and Statistics (IBGE) manages a free online service for processing GNSS data, called IBGE-PPP. In addition, with IBGE-PPP, the user can obtain geodetic coordinates referenced to the Brazil geodetic reference system, the Geocentric Reference System for the Americas (SIRGAS2000) (IBGE, 2017). Another advantage when adopting the PPP method is the possibility of using only one receiver during the survey, making this method independent of the baseline length (LEICK et al., 2015).

Despite their potential, geodetic receivers have high cost and their price can reach hundreds of thousands of dollars in the Brazilian market. Thus, in applications where a higher risk of damage and loss of the receiver is expected, the user may be discouraged from using such equipment.

With the increasing use of GNSS sensors in mobile devices and the expansion of LBS, the global market has been directing several technologies and tools seeking to increase the quality and robustness of the positioning via these electronics. In August 2016, Google made possible for the first time to access raw GNSS data collected by smartphones and tablets compatible with the Android Nougat operating system and greater versions (Malkos, 2016). Among the main information, navigation messages, carrier phase information, Doppler measurements, and information that make up the pseudorange are now available. Later, in 2018 Xiaomi launched the first smartphone with dual frequency GNSS sensor (Technology, 2018).

Due to the restriction on raw GNSS data, several authors consider mobile devices “black boxes”, since only the final solutions are available to app developers (Banville and Diggelen, 2016; Redelkiewicz et al., 2018). Accessing raw GNSS data, more robust multi-GNSS apps (multiple constellations and frequencies) can be developed, such as the Geo++ app, which enables the collection and storage of raw GNSS data in the universal Receiver Independent Exchange Format (RINEX) (Geo++, 2017).

In previous research, several authors sought to analyze the positional quality of tablets and smartphones. Gill et al. (2017) and Zhang et al. (2018), incorporated carrier phase observations in the static positioning solution using the Nexus 9 tablet, with which the authors achieved RMS error less than 37 and 60 cm in the horizontal and vertical direction, respectively. Håkansson (2019) achieved decimeter to meter level accuracy via the same tablet and identified a high sensitivity of accuracy under different multi-path conditions.

Pirazzi et al. (2017) evaluated the performance of a smartphone under different scenarios and obtained decimetric accuracy via the PPP method in static mode. Lu et al. (2018) compared the performance of different smartphone models in open sky scenario, and obtained meter level horizontal RMS error via the Single Point Positioning (SPP) method. On the other hand, Dabove et al. (2020) achieved decimeter level planimetric accuracy via the relative method in static mode, using smartphones Huawei P10 + and Samsung Galaxy S8 +.

After processing the raw data and obtaining the geodetic coordinates, the user can employ technical methods for adjusting observations in order to increase the robustness of their solutions. Among the various adjustment methods, the Gauss-Helmert (GH) and Gauss-Markov (GM) methods are most common (LEICK et al., 2015).

3. Material and Methods

3.1 Experimental setup

The scenario chosen to carry out data collection is free of obstructions, since there are no buildings or trees above the horizon within 50 meters distance. The geodetic mark consists of a rigid concrete pillar of approximately 1.5 m height installed on the roof of a single-story building. It is located next to the Laboratory of Spatial Geodesy and Hydrography (LAGEH), at the Polytechnic Center Campus of the Federal University of Paraná (UFPR) in Curitiba, Paraná, Brazil (Approximate geodetic coordinates: 25° 26′ 54.89″ latitude, -49° 13′ 52.26″ longitude).

There is a forced centering device (a standard screw) on the pillar that makes it possible to position a geodetic antenna on it. In addition, three auxiliary points around the center were considered, at a fixed distance of 20 cm from the central point (on the left of Figure 1). The fixed distance was possible by means of a special support (Figure 1).

The smartphone selected was the Xiaomi Mi 8, whose dual-frequency GNSS sensor (BCM47755) is compatible with multiple GNSS: GPS (L1 and L5), GLONASS (L1), Galileo (E1 and E5) and BeiDou (B1). The second frequency (L5) data was not utilized in this study. Nevertheless, there is no information regarding the exact position of the antenna and its phase center calibration parameters (Skorupa, 2020). Thus, in all data collected, the smartphone was horizontally positioned on the support, as shown on the right of Figure 1. Therefore, due to the dimensions of the smartphone body (74.8 mm X 154.9 mm X 7.6 mm), it is observed that there is a maximum uncertainty equal to 15.5 cm.

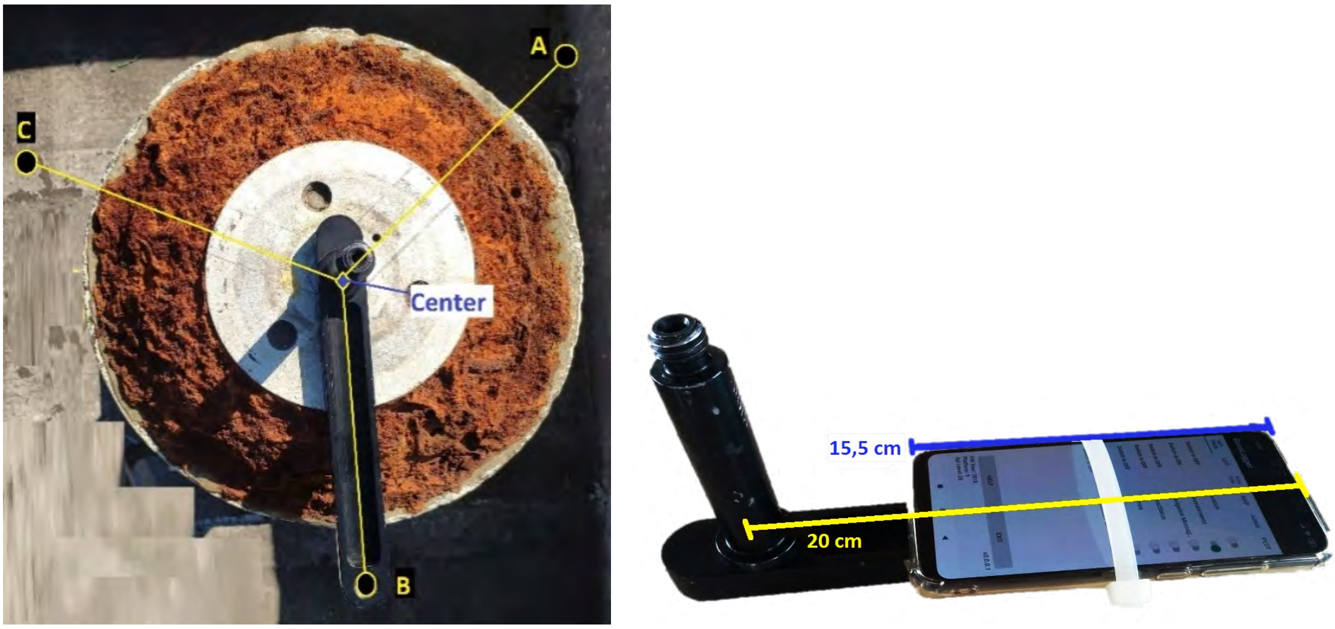

Figure 1: On the left, the figure shows the position of the support on the pillar oriented in relation to the point B. On the right, the figure shows the position of the smartphone to the support and its dimensions.

The reference coordinates of the points were determined by the relative positioning method (LEICK et al., 2015), using the Topcon HiPer SR dual frequency geodetic receiver with built-in antenna, which provided positional accuracy at the millimeter level. Therefore, in this research, these coordinates will be called “true” or “reference” coordinates. The base station is located at a distance of approximately 25 m, configuring an extremely short baseline. This base station belongs to the Brazilian Network for Continuous Monitoring of the GNSS Systems (RBMC), called RBMC-UFPR (IBGE, n.d.). This station uses a Trimble NetR9 receiver with Zephyr 3 geodetic antenna. The reference coordinates were obtained with data collection of approximately 4 hours.

3.2 Data collection and Post-processing

The Mi 8 smartphone allows access to raw data, thus, the Geo++ Rinex Logger app (version 2.0.1) was used, which converts the collected data and stores it in the universal RINEX format. The app was configured to track all possible frequencies with a data recording interval of 1 s.

Each field campaign had an average duration of approximately 4 hours. However, each campaign was also processed using only the first initial hour. The general characteristics of the campaigns are shown in Table 1.

Table 1: Static data collection campaigns conducted with Mi 8.

Campaign	Auxiliary point	Identification	Date (yyyy-mm-dd)	Duration (hh:mm)
1	A	1A	2019-02-04	4:50 and 1:00
2	C	2C	2019-02-04	4:00 and 1:00
3	B	3B	2019-02-05	4:50 and 1:00
4	B	4B	2019-02-05	4:10 and 1:00
5	A	5A	2019-02-06	4:50 and 1:00
6	C	6C	2019-02-06	5:10 and 1:00
7	A	7A	2019-02-07	4:00 and 1:00
8	C	8C	2019-02-07	4:00 and 1:00
9	B	9B	2019-02-12	4:15 and 1:00
10	B	10B	2019-02-12	4:00 and 1:00
11	B	11B	2019-02-12	4:10 and 1:00
12	C	12C	2019-02-13	4:00 and 1:00
13	C	13C	2019-02-13	4:00 and 1:00
14	C	14C	2019-02-13	4:00 and 1:00
15	C	15C	2019-02-13	4:00 and 1:00
16	C	16C	2019-02-14	3:30 and 1:00
17	A	17A	2019-02-14	5:40 and 1:00

The IBGE-PPP uses the CSRS-PPP (GPS Precise Point Positioning) program developed by the Geodetic Survey Division of Natural Resources of Canada (NRCan) (IBGE, 2017). All campaigns carried out with Mi 8 were post-processed by the online service IBGE-PPP, with the following characteristics: data recording interval equal to 1 s; GPS and GLONASS constellations; elevation mask equal to 10 degrees (default); final precise ephemeris. Although the Mi 8 has a dual frequency GNSS sensor, the IBGE-PPP service is not compatible with modern frequencies (L5 and E5), and with the Galileo and BeiDou constellations.

The campaigns carried out with the geodetic receiver were post-processed using the commercial software Leica Infinity. To facilitate understanding, the Universal Transverse of Mercator (UTM) system was adopted, whose plane coordinates are expressed in metric units.

4 Circle Adjustment models adopted

To determine the horizontal coordinates (2D) of the central position of the column (forced centering device), the Gauss-Helmert (GH) or mixed model was adopted, demonstrated in detail in Leick et al. (2015).

In the GH model, the observations that make up the observation vector are the UTM coordinates ("east" – E and "north" – N), as demonstrated in equation 1. The unknown parameters are the center coordinates (E_0, N_0) and the distance (radius - r_0) between the center of the column and the vertices (A, B and C). The partial derivative expressions can be found in detail in Gemael et al. (2015).

$$(E_i - E_0)^2 + (N_i - N_0)^2 - r_0^2 = 0 \quad (1)$$

To verify the quality of the adjustment, statistical tests were carried out according to the following hypotheses:

Null hypothesis: H_0: $\hat{\sigma}^2 \leq \sigma_0^2$ against Alternative hypothesis: H_1: $\hat{\sigma}^2 > \sigma_0^2$

Where: σ_0^2 and $\hat{\sigma}_0^2$ are the a-priori and a-posteriori variance factors, respectively.

The basic hypothesis is not rejected, at the level of significance α (5%), if:

$$v^T P v \leq \chi^2_{n-u,\alpha} \tag{2}$$

Where $v^T P v$ is the weighted sum of the squared residuals, P is the weight matrix and $\chi^2_{n-u,\alpha}$ is the critical value in Chi-square distribution with n-u degrees of freedom and significance level of α.

Two adjustments were performed (Table 2). By analyzing the residuals generated in the first solution, those that were higher than the smallest standard deviation were removed from the new adjustments. The variance input in the circle adjustment was taken from the PPP output, ignoring covariances. The general characteristics adopted in each adjustment are shown in Table 2.

Table 2: General characteristics of the six circle adjustments.

Solutions	Weight	Number of Observations	Number of Equations	Session Duration (hh:mm)	Total survey duration
GH1	$\frac{1}{\sigma^2 E}$; $\frac{1}{\sigma^2 N}$	34	17	4:00	136h
GH2	$\frac{1}{\sigma^2 E}$; $\frac{1}{\sigma^2 N}$	32	16	4:00	128h
GH3	$\frac{1}{\sigma^2 E}$; $\frac{1}{\sigma^2 N}$	34	17	1:00	34h
GH4	$\frac{1}{\sigma^2 E}$; $\frac{1}{\sigma^2 N}$	28	14	1:00	28h
GH5*	$\frac{1}{\sigma^2 E}$; $\frac{1}{\sigma^2 N}$	24	12	4:00	96h
GH6*	$\frac{1}{\sigma^2 E}$; $\frac{1}{\sigma^2 N}$	24	12	1:00	24h

* The same number of campaigns in each point (A=4, B=4 and C=4).

4.1 Discrepancies and Accuracy

Two analysis strategies were adopted. The first consists of making an average of post-processed observations (without circle adjustment). This approach was defined in order to verify the effectiveness of the adopted adjustment technique, that is, to verify if the circle adjusted observations actually generated better results. Thus, two computations were performed: using the average of the observations obtained by the PPP method (via Mi 8), and the adjusted observations.

Thus, the calculation of bias (Δ) with respect to the reference coordinates is given by equation 3:

$$\Delta N = N_R - N \quad and \quad \Delta E = E_R - E \tag{3}$$

Where: N_R and E_R are the reference coordinates.

The East, North and the horizontal accuracy (2D), were obtained using the bias (Δ) and the standard deviation (σ), obtained from the circle adjustment a posteriori variance-covariance matrix, as follows:

$$Accuracy_{N,E} = \sqrt{\Delta_{N,E}^2 + \sigma_{N,E}^2}$$
$$\text{2D Accuracy} = \sqrt{\text{Accuracy N}^2 + \text{Accuracy E}^2} \quad (4)$$

5. Results

5.1 Adjustment results and Accuracy

All adjustments made were accepted in the hypothesis test at a significance level of 5%. The general results of each solution are shown in Table 3.

Table 3: General results of adjustments.

Solutions	East (m)	σ_E (cm)	North (m)	σ_N (cm)
Average	677856.019	55.7	7184200.417	54.2
Weighted Average	677856.126	55.7	7184200.414	54.2
GH1	677855.950	12.3	7184200.308	10.7
GH2	677856.051	8.8	7184200.364	7.1
Average*	677855.949	61.6	7184200.417	108.0
Weighted Average*	677856.012	61.6	7184200.344	108.0
GH3*	677856.071	18.7	7184200.404	12.6
GH4*	677856.044	17.4	7184200.508	11.4
GH5	677855.520	17.4	7184200.552	14.2
GH6*	677856.031	18.9	7184200.365	15.0

* Used the set of campaigns lasting only 1 hour.

As expected, the adjustments that used observations with sets having session duration equal to 1 hour (GH3*, GH4* and GH6*), resulted in the worst precision.

Notably, better precision were obtained when the outliers are eliminated (GH2 and GH4*). Table 4 contains the discrepancies calculated between the reference coordinates of the pillar center, determined by static relative positioning method. The solution “Average” in the table corresponds to the arithmetic average performed in each set of campaigns (without circle adjustment).

Table 4: Discrepancies and the solutions accuracies.

Solutions	Discrepancy East (cm)	Discrepancy North (cm)	Accuracy East (cm)	Accuracy North (cm)	2D Accuracy (cm)
Average	8.1	5.0	56.3	55.9	79.4
Weighted Average	2.6	4.7	55.8	55.9	79.0
GH1	15.0	5.9	19.3	12.2	22.9
GH2	4.9	0.3	10.1	7.1	12.3
Average*	15.1	2.3	63.5	61.7	88.5
Weighted Average*	8.9	2.3	63.3	61.7	87.7
GH3*	2.9	3.7	19.0	13.1	23.1
GH4*	5.6	14.1	18.2	18.1	25.7
GH5	58.0	18.4	60.5	23.3	64.8
GH6*	6.9	0.3	20.1	15.0	25.1

* Used the set of campaigns lasting only 1 hour.

It is observed that there were no significant differences between the Averages and the Weighted Averages. Analyzing the Average and GH1 solution (both with sets of 4 hours), there was an improvement in the accuracy with the circle adjustment of about 66%, 78% and 71% for the East, North and 2D accuracy, respectively. Through the sets of campaigns carried out with 1 hour, the circle adjustment provided gains of about 70%, 79% and 74%, for the East, North and 2D accuracy, respectively.

With the exception of the set with 1 hour, removing the outliers (GH4*) improved results. The gain percentage was approximately 48%, 42% and 46%, for the East, North and 2D accuracy, respectively.

It was expected that the solutions that use the set of campaigns with the longest duration (about 4 hours), would present the best results. This occurred only when the outliers were removed (GH2). However, this did not occur in the GH1 and GH5 solutions, when we carried out the circle adjustment using the same number of campaigns on the three points (A = 4, B = 4 and C = 4).

It is important to note that there was no consideration of the uncertainty associated with the position of the antenna. This uncertainty is at most 15.5 cm, which is superior to the accuracy value obtained by the GH2 solution.

In general, all the results obtained via the circle adjustments are in accordance with the precision established by the literature for the PPP method, albeit using geodetic equipment and shorter total session duration.

6. Conclusion

One of the factors considered most important in this research concerns the potential of the tracked data. The Mi 8 smartphone allowed the collection of data from the four global constellations and with different frequencies. However, the IBGE-PPP service was compatible with the L1 frequency and observations from the GPS and GLONASS constellation. Thus, it should be made clear that the total potential of the measurements made was limited to the processing service adopted. Therefore, further tests should be carried out in the future to include data from the other constellations.

In addition, information related to the position of the GNSS antenna on the smartphone is unknown. Thus, in the future an improvement in results is expected due to the possibility of performing the linear combination (L1 +

L5) and the use of the antenna calibration parameters.

Using circle adjustment techniques it is possible to determine the coordinates of the pillar with decimetric accuracy, approximately 12 cm. However, all the accuracy obtained by the adjustments, meets certain engineering applications, such as the land surveying of rural properties (MDA, 2013). Despite this, we emphasize that there were sets of campaigns being used instead of just single campaigns.

Unfortunately, we were unable to achieve 2D centimeter accuracy. However, we noticed that the 2D Error reduces when outliers are removed. In addition, we observed that when adopting the same number of campaigns on the three points (A=4, B=4 and C=4), the 2D accuracy obtained by campaigns with a shorter duration (1 hour), presented better results than those with 4 hours. This is an important indicator and an aspect to be investigated.

In future works, it is suggested to carry out campaigns adopting a radius greater than that adopted in this research (20 cm).

Therefore, in the not too distant future, there may be a decrease in the distance between exclusive applications of conventional geodetic receivers and smartphones, increasing the freedom of choice and competitiveness in the geoscience market.

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AUTHOR´S CONTRIBUTION

Author 1 was responsible for the research design, method proposition, data preparation, analysis and wrote the manuscript. Author 2 contributed to the revision, method proposition and text review. Author 3 contributed to the supervision.

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