Positioning Evaluation of Single and Dual-Frequency Low-Cost GNSS Receivers Signals Using PPP and Static Relative Methods in Urban Areas

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Abstract: A positional accuracy obtained by the Precise Point Positioning and static relative methods was compared and analyzed. Test data was collected using low-cost GNSS receivers of single- and dual-frequency in urban areas. The data was analyzed for quality using the TEQC program to determine the degree of affection of the signal in the urban area. Low-cost GNSS receivers were found to be sensitive to the multipath effect, which impacts positioning. The horizontal and vertical accuracy was evaluated with respect to Mexican regulations for the GNSS establishment criteria. Probable Error Circle (CEP) and Vertical Positioning Accuracy (EPV) were performed on low cost GNSS receiver observation data. The results show that low-cost dual-frequency GNSS receivers can be used in urban areas. The precision was obtained in the order of 0.013 m in the static relative method. The results obtained are comparable to a geodetic receiver in a geodetic baseline of <20 km. The study does not recommend using single and dual frequencies low cost GNSS receivers based on results obtained by the Precise Point Positioning (PPP) method in urban areas. The inclusion of the GGM10 model reduces the vertical precision obtained by using low cost GNSS receivers in both methods, conforming to the regulations only in the horizontal component.

Keywords: Precise Point Positioning; static relative; urban areas; GNSS; low-cost receivers

1. Introduction

Researchers have conducted several studies utilizing Global Navigation Satellite Systems (GNSS) signals with geodesy and satellite technology advancement. These studies have focused on the accuracy of the location on the earth’s surface and how the satellite signal is affected by the surrounding environment of the receiving antenna [1]. Apart from location accuracy, topics such as crustal deformation, analysis of the ionosphere variability as a seismic precursor, and meteorology have been widely studied using GNSS signals [2–8]. GNSS observation processing platforms commonly use the static relative method to obtain high precision positioning deploying signals from two or more receivers at the same observation time [9]. The static relative method for obtaining precise positioning has the disadvantages of observation time and the dependence on a reference station with known coordinates [10]. Despite this, the static relative method is commonly used in urban areas for topographic-geodetic work, as it is possible to minimize the source of errors derived from the location of the antenna. On the other hand, the Precise Point Positioning (PPP) method is gaining popularity because of its effectiveness for GNSS data processing through precise satellite orbits, clock corrections, bias products, and a single receiver to obtain high accuracy [11,12]. The PPP method is ideal for applications such as monitoring structures [13,14] and precise positioning through low-cost GNSS receivers signals [15,16].
In addition, the PPP method has been tested in urban environments considering online scientific GNSS processing software [17,18], studies of the atmosphere [19], geodetic control establishments [20], and real-time applications [21] on smartphones [22]. The standard PPP method also uses antenna phase center correction, phase shift corrections (phase advance and delay) due to the relative rotation between the satellite and receiver antennas (phase windup correction), solid-earth tides, and ocean tide loading despite having a long observation time, since it takes at least 30 min to achieve the first solution of the fixed ambiguity and to counter the effects caused by the noise of the pseudo range and the slowly changing spatial geometry satellites [23–28]. On the other hand, the new approach to integer ambiguity resolution has helped decrease convergence times and increase the precision of solutions [29]. The number of visible GNSS satellites is affected by the environment, such as urban areas, mountains, tree coverage, high voltage power lines, buildings, bodies of water, etc., which block, degrade, or scatter the signal, affecting accuracy [17]. The static relative method is commonly applied in urban areas because it offers high precision in less observation time.

Moreover, the new generations of low-cost GNSS equipment make it possible to test explicit methodologies for geodetic receivers that allow innovation in applications where low-cost equipment may be used. Commonly, the cost of the low-cost GNSS receivers of a new generation is ~200 €. The low-cost GNSS receivers were evaluated to study their performance in short and long baselines, real-time feasibility, the environment around receiving antenna, and positioning performance with single-frequency receivers by constraining the baseline distance among many studies [29–35]. Comparison studies of PPP with low-cost receivers on different platforms to test the possibility of using low-cost dual-frequency receivers for geodetic monitoring and inertial navigation system (INS) measurements have been attempted by many researchers [31–35].

This study focuses on the statistical analysis of the observations generated by PPP and static relative methods in urban areas using low-cost single and dual-frequency GNSS receivers. In both the cases, the resulting coordinates referred to the official reference frame in Mexico (i.e., ITRF08 at 2010.0 epoch). The quality control analysis was performed over the data as per IGS standard [36]. The prime objective of the present study is to verify the accuracy of the single and dual-frequency low cost receiver in urban areas. The research seeks to determine if the low-cost GNSS receiver can be used in urban areas for geodetic and topographic applications. The present study improves understanding and provides results on accuracy and positioning estimates for different low-cost GNSS receivers. The study recommends performing many tests in different environmental conditions and locations worldwide to evaluate equipment for various applications.

2. Materials and Methods
2.1. General Characteristics of the Receivers Used in the Experiment

The present study used two geodetic and two low-cost receivers (Tables 1 and 2 and Figures 1A and 2A). For low-cost receivers, the ZED-F9P (Figure 2B) and NV08C-CSM (Figure 2A) models were used, with dual and single frequency, respectively (Table 1), in conjunction with an ANN-MB antenna (Figure 1A) for the dual-frequency receiver and a Tallysman (Figure 1B) for the single-frequency. Additionally, we used GC10 single-frequency and ZENITH25 (to obtain the reference values) dual-frequency geodetic receivers. CULC reference station from INEGI was considered for the static relative method.
Table 1. Characteristics of the low-cost receivers.

| Station Name | Receiver Type | Convergence Time | Sensitivity | Supported Signal | Antenna |
|--------------|---------------|------------------|-------------|------------------|---------|
| LCDF         | ZED-F9P       | RTK < 10 s cold start (24 s), reaction (2 s) | Track & Nav 167 dBm, Cold Start −148 dBm, Hot Start −157 dBm, Reaction 160 dBm | GLONASS, GALILEO, GPS, BEIDOU, QZSS | ANN-MB: GPS + GLONASS + GALILEO + BEIDOU |
| LCSF         | NV08C-CSM     | Reaction time < 1 s, hot start < 3 s, cold start 30 s | Tracking and acquisition −160 dBm, cold start −143 dBm | GPS, GLONASS, GALILEO, BEIDOU, SBAS | Tallysman TW4721: GPS + GLONASS + GALILEO + BEIDOU |

Table 2. Characteristics of the geodetic receivers.

| Station Name | Receiver Type | Convergence Time | Sensitivity | Supported Signal | Antenna |
|--------------|---------------|------------------|-------------|------------------|---------|
| EST1-6       | GEOMAX ZENTIH | RTK < 8 s cold start (30 s), reaction (8 s) | Track Acquisitions −140 to −150 dBm, Tracking Nav −150 a 165 dBm | GPS L1, L2, L2GLONASS L1, L2 BeiDou B1, B2 | Internal GSM antenna quad band and penta band UMTS 800/850/900/1900/2100 MHz |
| ISL1-3       | LEICA GC10    | Acquisition of cold start (45 s), reaction (10 s) | Track Acquisitions −140 to −150 dBm, Tracking Nav −150 a 165 dBm | GPS L1 | Internal GSM antenna monoband |

Figure 1. (A) ANN-MB multiband antenna; (B) Tallysman TW4721 antenna.

Figure 2. (A) NV08C-CSM low-cost single-frequency receiver; (B) ZED-F9P low-cost dual-frequency receiver.

2.2. GNSS Data Collections, Pre-Processing, and Quality Check

The methodology adopted is outlined in Figure 3. GNSS Data was collected through a campaign survey at 11 locations (Figure 4 and Table 3) located in an urban growth area. The survey was carried out in different environments that degrade the GNSS signal, i.e.,
dense tree cover, buildings, ravines, etc., in the City of Culiacán Sinaloa, Mexico. The main characteristics of the observations are presented in Table 3. Only the GPS constellation is considered because the GC10 geodetic receiver only captures GPS signal. The static relative method needs at least 30/20 min of occupation time for data collections. As a thumb rule, for first 20 km of distance from the continuously operating reference station, 20 min of occupation is required followed by 2 min of additional occupancy for each km. In our analysis, we considered 2 h observations for low cost GNSS receiver and 30 min plus 3 min/km in case of single frequency receivers.

![Flowchart depicting Methodology adopted.](image)

**Figure 3.** Flowchart depicting Methodology adopted.

![Example of 3D location of the low cost GNSS Antenna.](image)

**Figure 4. (a,b)** Example of 3D location of the low cost GNSS Antenna. (c) Location GNSS stations occupied in the observation campaigns, located in Culiacán Sinaloa, Mexico.
Table 3. Characteristics of the GNSS observations.

| Receiver | Name | Sample Rate (s) | Elevation Mask (°) | Constellation | Observation Time (h) | Date of Observation |
|----------|------|-----------------|-------------------|---------------|----------------------|---------------------|
| Geodetic | Est1 | 15              | 15                | GPS (L1, L2, L2C) + GLONASS (L1, L2) + GALILEO (E1, E5) | 1.967               | 20 September 2020   |
|          | Est2 | 15              | 15                | GPS (L1, L2, L2C) + GLONASS (L1, L2) + GALILEO (E1, E5) | 1.025               | 20 September 2020   |
|          | Est3 | 15              | 15                | GPS (L1, L2, L2C) + GLONASS (L1, L2) + GALILEO (E1, E5) | 1.342               | 20 September 2020   |
|          | Est4 | 15              | 15                | GPS (L1, L2, L2C) + GLONASS (L1, L2) + GALILEO (E1, E5) | 2.292               | 20 September 2020   |
|          | Est5 | 15              | 15                | GPS (L1, L2, L2C) + GLONASS (L1, L2) + GALILEO (E1, E5) | 1.525               | 20 September 2020   |
|          | Est6 | 15              | 15                | GPS (L1, L2, L2C) + GLONASS (L1, L2) + GALILEO (E1, E5) | 1.629               | 20 September 2020   |
|          | ISL1 | 15              | 15                | GPS (L1) | 3.717                |                      |
|          | ISL2 | 15              | 15                | GPS (L1) | 0.8617               | 23 September 2020   |
|          | ISL3 | 15              | 15                | GPS (L1) | 1.171                |                      |
| Low-cost | LCSF | 1               | 15                | GPS (L1) | 2.06                 | 23 September 2020   |
|          | LCDF | 2               | 15                | GPS (L1, L2, L2C) + GLONASS (L1, L2) + GALILEO (E1, E5b) + BEIDOU (B1) | 2                   | 23 September 2020   |
| References Station | CULC | 15              | 15                | GPS (L1, L2, L2C) + GLONASS (L1, L2) + GALILEO (E1, E5) | 24                  | According to observations |

The collected GNSS data was analyzed for Quality Check using TEQC program (similar results can be obtained with G-Nut/Anubis software [37,38]) to determine the degree of affectation of the signal [1,37,38], in the urban area [1]. The mean value of the quality checks parameters from TEQC was derived following a standard statistical method. As per IGS guidelines, the multipath effect average (MP) was calculated by the linear combination of carrier phase and pseudorange in L1 and L2 in m with recommended values not above 0.30 m in L1 and L2 [39]. The integrity (INT) is theoretically calculated considering the complete observations, and the recommended value is >95% [1]. Cycle slips were calculated from the carrier phase as per the relationship CSR = 1000/(o/slps) [40,41]; where “o/slps” is the number of observations between cycle slips. Theoretically, the recommended value must be less than 1 per 1000 observations [42]. The signal-to-noise ratio average (SNR) values were considered as ≥36 dB Hz in L1 and L2 [36].

2.3. GNSS Data Processing and Analysis

To assess the performance of the PPP method as well as its achieved precision, results were compared with the static relative method considering two cases such that in case 1, low-cost and geodetic receivers with dual and single frequency are utilized. In case 2, data was processed in the static relative method considering the CULC reference station of the National Institute of Statistics and Geography, which is located at approximately 20 km, using low-cost and geodetic receivers with dual and single frequencies. Once the coordinates were obtained, the solutions from the dual-frequency geodetic receiver were taken as the reference for the comparison study, using the official reference frame in Mexico (ITRF08 at epoch 2010.0) [15,43]. In order to evaluate the results obtained by the PPP method, standard deviation was evaluated according to the “Circle of Probable Error” (CEP) and “Vertical Positioning Accuracy” (EPV) [43]. Mexican gravimetric geoid version 2010 (GGM10) was also used for evaluation with a resolution of 2.5 min of arc, approximately 4.5 km, and a standard deviation of 20 cm, which represent the geoid height as measured in vertical direction [44]. The observation time was set following that presented by [26] based on the PPP method, taking into account that to obtain a horizontal precision of 2 cm, a convergence time of 60 min is necessary. ISL2 station does not meet this
criteria, however, it can be considered to evaluate the same convergence time through a single-frequency receiver [45] in an urban area. The static relative method was conditionate to the Mexican CORS at 15 s, in the case of the PPP method, the observation was decimate to 30 s [46] according to the new actualization for the CSRS-PPP software. The summary of the parameters used for processing the observations using the PPP and the static relative method are presented in Table 4.

Table 4. Summary of parameters used in the PPP and static relative positioning methods.

| Parameters for PPP Method | Parameters for static relative positioning |
|--------------------------|---------------------------------------------|
| **Software** | **Software** |
| CSRS-PPP [46] | Topcon Tools [53] |
| **Observable** | **Observable** |
| Code & Phase | L1 & L2; L1 |
| **Elevation cut off angle (deg)** | 7.5 | 15° |
| **Satellite orbits** | Precise (IGS) | **Receiver antenna phase center correction** |
| **Satellite products input** | CLK-RINEX | IGS antex |
| **Sampling rate (s)** | 1, 2, 15 | **Method** |
| **Troposphere model** | Saastamoinen [47] | Static relative |
| **Relativistic effects** | Corrected [48] | **Sampling rate (s)** |
| **Receiver antenna phase center correction** | PPP-AR [49] with the new actualization [50] | 1, 2, 15 |
| **Ambiguity resolution** | Applied [51] | |
| **Phase wind-up-effect** | Applied [52] | |
| **Solid Earth Tides correction** | ITRF | |
| **Reference Frame** | |

3. Results

3.1. Quality Check of GNSS Observations

The results of the quality check of the stations considering four parameters (INT, MP, CSR, SNR) are presented in Table 5; however, for the single frequency receivers, it was not possible to analyze the quality of the observations because at least two frequencies are required. The linear combination between carrier phase and pseudo-range observations in L1 and L2 is necessary for the estimation of the root mean square (RMS) [54]. The percentage of the integrity of the stations varied between 78% and 100%, the obtained results could be related to the locations (urban areas). CULC presented the highest quality values, due to being a reference station with open sky. The minimum recommended value for the integrity is 95%, where only CULC1, CULC2 and, CULC3 stations with 97%, 100% and 100%, respectively, exceeded this value. The stations named “CULC1-3” are the same, the assigned number is for proper identification for the static relative process. EST5 and CULC4 stations are within the limit as shown in Figure 5 (where the horizontal red line represents the recommended value). The rest of the stations do not show a good integrity performance, which is related to the surrounding environment. The LCDF station has the lowest integrity with 78%.
Table 5. Results of quality check of the GNSS observations results.

| Receiver | Station | Integrity (%) | MP1 (m) | MP2 (m) | CSR | SNR1 (dB-Hz) | SNR2 (dB-Hz) |
|----------|---------|---------------|---------|---------|-----|--------------|--------------|
| Geodetic | EST1    | 89            | 0.27    | 0.31    | 2.11| 42.48        | 35.94        |
|          | EST2    | 86            | 0.39    | 0.26    | 15.63| 46.44        | 35.45        |
|          | EST3    | 84            | 0.20    | 0.19    | 0.44| 42.69        | 40.59        |
|          | EST4    | 86            | 0.25    | 0.31    | 0.39| 44.31        | 40.51        |
|          | EST5    | 95            | 0.33    | 0.41    | 0.09| 44.58        | 41.48        |
|          | EST6    | 84            | 0.19    | 0.25    | 0.21| 42.68        | 41.84        |
|          | CULC1   | 97            | 0.34    | 0.40    | 0.22| 46.68        | 42.14        |
|          | ISL1    | None          | 42.00   | None    | None|              |              |
|          | ISL2    | None          | 41.40   | None    | None|              |              |
|          | ISL3    | 42.96         | data    |         |     |              |              |
|          | CULC2   | 100           | 0.34    | 0.42    | 0.21| 46.49        | 42.20        |
| Low-cost | LCSF    | 100           | None    | 0.37    | 0.38| 0.23         | 41.14        |
|          | CULC3   | None          |         | 0.38    | 0.23| 46.20        | None         |
| Low-cost | LCDF    | 78            | 0.65    | 0.45    | 1.76| 40.28        | 40.17        |
|          | CULC4   | 95            | 0.35    | 0.39    | 0.53| 46.04        | 42.01        |

Figure 5. Integrity. Red line: 95% of integrity [36].

LCDF shows the highest degree of multipath effect in both bands and may be related to the observation time and the percentage of integrity. However, CULC1, 2, 3, and 4, despite showing a good percentage of integrity and a longer observation time, also exceed the value recommended by the IGS of 0.30 m for the multipath effect as shown in Figure 6, where the stations with the least affectation are EST3 and EST6.

With the signal-to-noise ratio and the multipath effect, a weak SNR would be expected in most stations, since both variables have an inversely proportional behavior [55], however, this only occurs in the stations EST1, EST3, and EST6. The other stations show a directly proportional relationship, where EST1 shows a strong signal in L1 and a weak signal in L2. Furthermore, other dual-frequency receivers show strong signals on both bands, as well as the single-frequency receivers shown in Figure 7, where the red line shows the limit between strong signals ≥ 36 dBHz and weak signals < 36 dBHz, being a quality check parameter that reflects the signal tracking and capturing performance.
Figure 5. Integrity. Red line: 95% of integrity [36]. LCDF shows the highest degree of multipath effect in both bands and may be related to the observation time and the percentage of integrity. However, CULC1, 2, 3, and 4, despite showing a good percentage of integrity and a longer observation time, also exceed the value recommended by the IGS of 0.30 m for the multipath effect as shown in Figure 6, where the stations with the least affectation are EST3 and EST6.

Figure 6. Multipath effect (MP1 and MP2). Red line: maximum value of 0.30 m for the multipath effect [36].

Figure 7. Signal-to-noise ratio (SNR). Red line: 36 dB-Hz according to [41].

Figure 8 shows the number of cycle slips per 1000 observations (CSR) where the recommended value by the IGS is 1 (1000/(o/slps)), which is represented by the red line [36]. It is evident that EST2 has the highest amount of loss in the carrier phase with 15.63 (1000/(o/slps)), with EST1 and LCDF also exceeding the recommended value. None of the evaluated stations show a performance of 100% in the quality indicators. This is generally related to the station environment, receiver type, and operating time. The stations in which the quality check was performed have three acceptable variables out of six (MP1, MP2, SNR1, SNR2, CSR, INTEGRITY). Based on the standard proposed by the IGS (Figure 9), the EST3 and EST6 stations have the best performance, complying with five of the six variables analyzed.
Analysis of Probable Error Circle (CEP) and Vertical Positioning Accuracy (EPV) of the GNSS Observations

The analysis of the CEP and the EPV was carried out considering the norm for geodetic works in Mexican territory. In the PPP method, it is found that not every station with dual-frequency receivers complies with the regulations to establish stations in the national geodetic network densifications, while only stations EST1, EST3 and EST5 comply with the regulations without using the GGM10 model (Table 6 and Figure 10). It is inferred that the PPP technique in urban areas may not be feasible, since the limit exceeds that established by regulations for vertical control. On the other hand, if the GGM10 model is not used (Table 6), the accuracy achieved for the vertical component can be utilized for the vertical control (EST1, EST3 and EST5). In the rest of the cases, the obtained values for PPP-EPV with GGM10 geoid are outside of the reference parameter, with the single frequency receivers obtaining the worst values (Table 6). The obtained results are correlated with the low accuracy achieved in the PPP method by using single frequency receivers. The low-cost dual-frequency receivers have a similar performance to geodetic receivers; however, they have better performance than the low-cost and geodetic single-frequency receivers, as evident by CEP and EPV values. When not affected by the environment of an urban area, the low-cost dual-frequency receiver can be considered for the densification of the national reference geodetic network [15]. Low-cost single-frequency receivers may be feasible to utilize depending upon the environment and the observation time.
Table 6. Results of the CEP and EPV of Precise Point Positioning according to the INEGI technical standard.

| Station | $\sigma_\phi$ (m) | $\sigma_\lambda$ (m) | $\sigma_\delta$ (m) | CEP95 | EPV95/GGM10 | EPV95 |
|---------|------------------|---------------------|-------------------|-------|-------------|-------|
| Est1    | 0.011            | 0.038               | 0.043             | 0.060 | 0.409       | 0.084 |
| Est2    | 0.023            | 0.049               | 0.066             | 0.088 | 0.428       | 0.129 |
| Est3    | 0.013            | 0.024               | 0.046             | 0.045 | 0.402       | 0.090 |
| Est4    | 0.033            | 0.057               | 0.132             | 0.110 | 0.448       | 0.259 |
| Est5    | 0.011            | 0.047               | 0.050             | 0.071 | 0.416       | 0.098 |
| Est6    | 0.013            | 0.056               | 0.057             | 0.084 | 0.426       | 0.112 |
| ISL1    | 0.526            | 0.758               | 1.304             | 1.571 | 3.105       | 2.027 |
| ISL2    | 0.889            | 1.725               | 1.297             | 3.199 | 6.282       | 2.542 |
| ISL3    | 0.667            | 1.254               | 1.487             | 2.263 | 4.648       | 2.915 |
| LCSF    | 0.733            | 2.033               | 1.780             | 3.385 | 6.646       | 3.489 |
| LCDF    | 0.041            | 0.232               | 0.254             | 0.334 | 0.763       | 0.498 |

Figure 10. Differences in the CEP and EPV of Precise Point Positioning according to the INEGI technical standard. (a) EPV with inclusion of geoidal model GGM10; (b) EPV without inclusions of geoidal model GGM10.

Table 7 shows the results of the CEP and EPV calculations for the static relative method according to the INEGI technical standard (Table 7 and Figure 11). The resulting values of the EPV are similar, regardless of the equipment used. In regard to the values obtained for the vertical component, the dual-frequency geodetic receivers present the best result. Dual and single frequency low-cost and single-frequency geodetic (ISL1-3) receivers achieve similar values. However, if the GGM10 model were not considered, all the values would be suitable for the densification of the geodetic system, with a difference of ~6 mm solutions achieved in the vertical component. In the case of CEP analysis, the maximum permissible value is fulfilled for the establishment of the national geodetic system.

3.3. Comparative Analysis of PPP and Static Relative Methods in Urban Areas

Table 8 shows the standard deviation obtained from the static relative and PPP methods. For the static relative method, the standard deviation is in the order of mm. For the stations where the dual-frequency geodetic receiver was used, the standard deviation is in the order of mm, even in the stations where there are obstructions to the antenna. For the stations where the single frequency geodetic receiver was used, the values are approximately 3 mm. On the other hand, the dual and single frequency low-cost receivers have similar behavior to single-frequency geodetic receivers; however, it is in the vertical component where the most affected values were found (centimeter level). Thus, it could be related to the non-calibration antenna.
Table 7. Results of the CEP and EPV of the static relative method according to the INEGI technical standard.

| Station | \(\sigma_\phi\) (m) | \(\sigma_\lambda\) (m) | \(\sigma_h\) (m) | \(CEP_{95}\) | \(EPV_{95}\) GGM10 | \(EPV_{95}\) |
|---------|-----------------|-----------------|-----------------|-------------|-----------------|-------------|
| Est1    | 0.001           | 0.001           | 0.003           | 0.002       | 0.392           | 0.006       |
| Est2    | 0.001           | 0.001           | 0.004           | 0.002       | 0.392           | 0.008       |
| Est3    | 0.001           | 0.001           | 0.004           | 0.002       | 0.392           | 0.008       |
| Est4    | 0.002           | 0.001           | 0.004           | 0.004       | 0.392           | 0.008       |
| Est5    | 0.002           | 0.001           | 0.003           | 0.004       | 0.392           | 0.006       |
| Est6    | 0.001           | 0.001           | 0.004           | 0.002       | 0.392           | 0.008       |
| ISL1    | 0.001           | 0.001           | 0.004           | 0.002       | 0.392           | 0.008       |
| ISL2    | 0.004           | 0.004           | 0.011           | 0.010       | 0.393           | 0.022       |
| ISL3    | 0.002           | 0.002           | 0.004           | 0.005       | 0.393           | 0.008       |
| LCSF    | 0.005           | 0.004           | 0.011           | 0.011       | 0.393           | 0.022       |
| LCDF    | 0.006           | 0.005           | 0.014           | 0.013       | 0.393           | 0.027       |

Figure 11. Differences in the CEP and EPV of the static relative method according to the INEGI technical standard. (a) EPV with inclusion of geoidal model GGM10; (b) EPV without inclusions of geoidal model GGM10.

Table 8. Standard deviations obtained with PPP in CSRS-PPP and the static relative method.

| Station | PPP | Static Relative |
|---------|-----|-----------------|
|         | \(\sigma_\phi\) (m) | \(\sigma_\lambda\) (m) | \(\sigma_h\) (m) | \(\sigma_\phi\) (m) | \(\sigma_\lambda\) (m) | \(\sigma_h\) (m) |
| Est1    | 0.011 | 0.038 | 0.043 | 0.001 | 0.001 | 0.003 |
| Est2    | 0.023 | 0.049 | 0.066 | 0.001 | 0.001 | 0.004 |
| Est3    | 0.013 | 0.024 | 0.046 | 0.001 | 0.001 | 0.004 |
| Est4    | 0.033 | 0.057 | 0.132 | 0.002 | 0.001 | 0.004 |
| Est5    | 0.011 | 0.047 | 0.05  | 0.002 | 0.001 | 0.003 |
| Est6    | 0.013 | 0.056 | 0.057 | 0.001 | 0.001 | 0.004 |
| ISL1    | 0.526 | 0.758 | 1.034 | 0.001 | 0.001 | 0.004 |
| ISL2    | 0.889 | 1.725 | 1.297 | 0.004 | 0.004 | 0.011 |
| ISL3    | 0.677 | 1.254 | 1.487 | 0.002 | 0.002 | 0.004 |
| LCSF    | 0.733 | 2.033 | 1.780 | 0.005 | 0.004 | 0.011 |
| LCDF    | 0.041 | 0.232 | 0.254 | 0.006 | 0.005 | 0.014 |

The precision of the PPP method is less in comparison to the static relative method, as is evident in Figure 12. For the static relative method, dual and single-frequency geodetic and low-cost receivers show similar levels of precision. In the PPP method, the single-frequency geodetic receiver (ISL1-3) has the lowest accuracy, reaching 1.5 m. Similar behavior is found in the low-cost single-frequency receiver (LCSF), with a standard deviation of less than 2 m. The presented behavior in ISL1-3 and LCSF stations could be related to the fact that they are single frequency receivers and cannot eliminate some positioning error compared to double frequency ones. Therefore, the low-cost dual-frequency receiver (LCDF) has...
a similar performance to geodetic dual-frequency receivers; however, it is less accurate. These results are expected since the low-cost receivers do not have antenna calibration parameters; however, the observation time was subjected to the recommendations of [26] for the convergence of the method. In Table 9, the absolute difference between each method is presented, which is expressed in m. The geodetic dual-frequency occupations (Est1-Est6) show a latitudinal and longitudinal difference less than 1.7 cm and 4.4 cm, respectively. The maximum differences shown by the geodetic single-frequency occupations (ISL1-3) for longitude is about 40 cm. The low-cost receivers with double (LCDF) and single (LCSF) frequency show similar behavior, where the biggest difference established between them is in longitude. Such behavior could be related to the PPP positioning technique apparently. The coordinate estimations of ISL1-3, LCSF and LCDF stations showed maximum dispersions in longitude ($\sigma \sim$ 2 m). It showed the maximum difference in comparison with the relative positioning method with standard deviations less than 1 cm (Table 8) and a difference of less than 2.6 cm for the geodetic receiver between both techniques.

![Figure 12](image_url)  
**Figure 12.** Mean standard deviation in the static relative method and PPP.

| Station | PPP Latitude $\phi$ | PPP Longitude $\lambda$ | Static Relative Latitude $\phi$ | Static Relative Longitude $\lambda$ | Absolute Difference (m) |
|---------|---------------------|--------------------------|-------------------------------|------------------------------------|------------------------|
| Est1    | 24°49’30.08338”     | 107°22’27.15461”         | 24°49’30.08334”               | 107°22’27.15543”                 | 0.001                  |
| Est2    | 24°49’26.71575”     | 107°22’32.28890”         | 24°49’26.71594”               | 107°22’32.28866”                 | 0.006                  |
| Est3    | 24°49’12.91581”     | 107°22’6.947523”         | 24°49’12.91597”               | 107°22’6.948373”                 | 0.005                  |
| Est4    | 24°49’18.56371”     | 107°22’6.076943”         | 24°49’18.56325”               | 107°22’6.077783”                 | 0.014                  |
| Est5    | 24°49’20.16515”     | 107°22’19.02893”         | 24°49’20.16461”               | 107°22’19.02901”                 | 0.017                  |
| Est6    | 24°49’22.40932”     | 107°22’23.46387”         | 24°49’22.40888”               | 107°22’23.46528”                 | 0.014                  |
| ISL1    | 24°49’29.47144”     | 107°22’28.30265”         | 24°49’29.47180”               | 107°22’28.28866”                 | 0.011                  |
| ISL2    | 24°49’32.25445”     | 107°22’28.37184”         | 24°49’32.25431”               | 107°22’28.37979”                 | 0.004                  |
| ISL3    | 24°49’29.49046”     | 107°22’31.66493”         | 24°49’29.49481”               | 107°22’31.66485”                 | 0.135                  |
| LCSF    | 24°49’29.54900”     | 107°22’28.34920”         | 24°49’29.54870”               | 107°22’28.36196”                 | 0.009                  |
| LCDF    | 24°49’28.91285”     | 107°22’27.65888”         | 24°49’28.91444”               | 107°22’27.66884”                 | 0.049                  |

Figure 13 shows the sum of the differences in coordinates (latitude and longitude) in m, where a large difference is found on the single frequency geodetic receiver (ISL1-3) and low-cost receivers (LCSF and LCDF). This may be due to the fact that the antenna of the low-cost GNSS receiver does not have an IGS calibration or circular polarized antenna (irregular gain pattern and low multipath suppression) [56].
Table 10 shows the results of the absolute differences of the orthometric, and ellipsoidal heights obtained from the PPP and static relative methods in m. The differences in orthometric heights for the dual-frequency geodetic receivers (Est1–Est6) show a maximum of 9 cm in the EST2 station. The values obtained in both methods are similar, they are not sensitive to the inclusion of the GGM10 model. The single-frequency geodetic receivers (ISL1-2), on the other hand, showed constant difference of 0.5 m.

Table 10. Heights obtained using the GGM10 model and the absolute differences.

| Station | Orthometric Height with PPP (m) | Orthometric Height with Static Relative (m) | Absolute Differences | Ellipsoidal Height with PPP (m) | Ellipsoidal Height with Static Relative (m) | Absolute Difference |
|---------|---------------------------------|--------------------------------------------|----------------------|--------------------------------|--------------------------------------------|---------------------|
| Est1    | 39.33                           | 39.38                                      | 0.05                 | 11.72                          | 11.77                                      | 0.05                |
| Est2    | 38.15                           | 38.24                                      | 0.09                 | 10.53                          | 10.62                                      | 0.09                |
| Est3    | 39.00                           | 39.04                                      | 0.04                 | 11.40                          | 11.44                                      | 0.04                |
| Est4    | 39.54                           | 39.56                                      | 0.02                 | 11.94                          | 11.96                                      | 0.02                |
| Est5    | 39.42                           | 39.44                                      | 0.02                 | 11.81                          | 11.83                                      | 0.02                |
| Est6    | 38.78                           | 38.80                                      | 0.02                 | 11.17                          | 11.19                                      | 0.02                |
| ISL1    | 39.76                           | 39.18                                      | 0.58                 | 12.15                          | 11.56                                      | 0.59                |
| ISL2    | 38.41                           | 38.03                                      | 0.38                 | 10.80                          | 10.42                                      | 0.38                |
| ISL3    | 38.18                           | 38.18                                      | 0.00                 | 10.56                          | 10.57                                      | 0.01                |
| LCSF    | 38.77                           | 37.90                                      | 0.87                 | 11.16                          | 10.29                                      | 0.87                |
| LCDF    | 40.37                           | 40.38                                      | 0.01                 | 12.76                          | 12.76                                      | 0.00                |

The low-cost receivers of single frequency (LCSF) show the greatest differences with less than 90 cm, which suggests that the solutions are not consistent with or without the GGM10 model. On the other hand, low-cost dual frequency (LCDF) receivers show 1 cm of absolute difference. This difference is due to the inclusion of the GGM10 model, as the difference is 2 mm when the GGM10 model is omitted. Through hours of positioning, it is possible to achieve precision for the vertical component up to 5 mm with the inclusion of high-quality antennas. Solutions of 10 mm were obtained in the vertical component in ~2 h of observation time, using dual frequency low-cost antennas and the GGM10 model. The accuracies are low for the PPP method in both low-cost receivers, however, it presents better accuracy than the geodetic and low-cost single-frequency receivers as shown in Figure 14. The obtained PPP accuracy may be subject to signal degradation in the case of geodetic and low-cost single-frequency receivers (ISL1-3, LCSF) as well as a low-cost dual-frequency receivers (LCDF).
4. Conclusions

We performed a comparative study and assessment of signals from low cost GNSS receiver data collected through a survey campaign in selected sites in the urban areas. The data collection sites were selected in such a way that the antenna is surrounded by objects that degrade the signals. The detailed data analysis using the PPP and static relative methods, following the standard accuracy regulations in Mexico, concludes the following.

- Low-cost GNSS receivers are sensitive to the multipath effect, which directly impacts positioning. However, the static relative method presents the best solution in urban environments. The antenna that is generally used with low-cost receivers turns out to be a viable option.

- The PPP method is most suited to use in clear environments, however, in urban areas it is considerably affected (where the vertical component is the most affected). Nevertheless, it is possible to use the low cost GNSS in areas where the buildings and vegetation degrade the received signal. Similarly, the PPP and static relative methods are feasible options for the establishment of a geodetic point in urban areas using low-cost dual-frequency GNSS receivers.

- The ANN-MB-00 antenna is highly affected by the multipath effect generated by the environment near to the antenna location, likewise, it has a poor design for mitigating the multipath effect. The combination of the ANN-MB-00 and ZEP-F9P receiver is suitable for precise measurements and provides centimeter accuracy, provided it has sufficient horizon exposure. The static relative and PPP methods show a mm and cm level accuracy, respectively. In both cases, the obtained precision is not dependent only on the antenna and receiver, but also on the processing method and applied models.

- Single-frequency receivers present similar results in both methods, even when they have the antenna calibration parameters, unlike low-cost receivers. On the other hand, the observation time considerably affects the solution, resulting in a similar behavior in the low-cost receivers.

- The heights are affected depending on the geoid model, however, the differences remain constant whether or not the GGM10 model is used. Nevertheless, for the low-cost receiver of single frequency (LCSF), the precision in height was lowest, being highly affected by the urban environment.

- The static relative method achieved the best performance, enabling usage of low-cost receivers in urban areas. Therefore, the use of dual-frequency low-cost GNSS receivers is recommendable, with the static relative method for the geodetic works where the requirement of accuracy is in order of cm. This is achievable on geodetic baselines
with 20 km or less. The vertical component continues to be a problem, nevertheless, the LCDF is constant in both methods with or without inclusion of the GGM10 model.

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