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Accuracy Assessment of Static GNSS Positioning: A Comparison between Geodetic GNSS and Low-Cost Smartphone-Based GNSS Using Geo++ RINEX

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Abstract

The Global Navigation Satellite System (GNSS) has been widely applied in various positioning applications, ranging from navigation to high-precision geodetic surveying. Recent advances in smartphone technology have enabled the collection of raw GNSS observations using low-cost devices, offering an affordable alternative for positioning applications. One such solution is the Geo++ RINEX Logger application, which records raw GNSS observations in the Receiver Independent Exchange Format (RINEX) for post-processing. This study evaluates the positioning accuracy of a smartphone-based Geo++ RINEX Logger compared with a geodetic GNSS receiver using the static relative positioning method under different observation durations and processing approaches. Observations were conducted at the ITERA benchmark under open-sky conditions with observation durations of 5, 15, 30, 45, and 60 minutes and a 1-second sampling interval. The data were processed using commercial GNSS software (offline) and the BIG online processing service (nrtk.big.go.id) based on the WGS-84 datum. The results indicate that positioning precision improved with increasing observation duration, with the 60-minute observations producing the smallest standard deviations. Geo++ RINEX Logger achieved centimeter-to-decimeter precision but lower accuracy than the geodetic GNSS receiver due to the limitations of single-frequency observations and sensitivity to baseline length and satellite geometry. These findings demonstrate that Geo++ RINEX Logger is a promising low-cost solution for educational, practical, and non-high-precision surveying applications.

Keywords: Geodetic GNSS, Geo++ RINEX Logger, Low-Cost GNSS, positional accuracy, static relative method

1. Introduction

The development of mapping and positioning technologies in Indonesia has continued to advance, particularly through the utilization of the Global Navigation Satellite System (GNSS). GNSS-based positioning involves three main segments, namely the space segment, control segment, and user segment (Abidin, 2007; Bhatta, 2010; Kavanagh & Mastin, 2014). The user segment represents the component that directly interacts with positioning data through satellite signal receiving devices (receivers) (Abidin, 2007; Bhatta, 2010; Kavanagh & Mastin, 2014). Achieving high-precision positioning depends on several factors, including data quality, satellite geometry, receiver type, and observation conditions (Abidin, 2007; Bhatta, 2010). Among these factors, the quality of the GNSS receiver plays a crucial role in determining positioning accuracy. Geodetic GNSS receivers are widely recognized as the standard instruments for high-precision surveying and mapping applications due to their superior performance compared with navigation-grade and mapping-grade receivers (Abidin, 2007). Under appropriate observation and processing conditions, geodetic GNSS receivers are capable of providing positioning accuracy at the millimeter level (Abidin, 2007; El-Mowafy & Bilbas, 2016). However, the relatively high cost of geodetic GNSS equipment, ranging from tens to hundreds of millions of Indonesian Rupiah, remains a major obstacle for practitioners, researchers, and educational institutions in acquiring such instruments.

As an alternative, low-cost GNSS receivers have emerged as a more affordable solution, typically costing less than IDR 28,000,000 (Bramanto et al., 2016). Although these devices are theoretically capable of performing positioning functions similar to those of geodetic GNSS receivers, their positioning performance and accuracy still require further investigation. Recent technological developments have also been supported by the widespread adoption of the Android operating system, which is open-source and facilitates the development of GNSS-based mobile applications (Aggrey et al., 2020; Mahato et al., 2024).

Recent advances in GNSS technology have significantly expanded its accessibility through the integration of GNSS chipsets into smartphones, driven by the miniaturization of hardware components and reductions in manufacturing costs (Uradzi´nski & Mieczysław, 2020). The widespread availability of GNSS-based applications has enabled users to perform positioning tasks conveniently for various practical purposes by simply installing the required applications on their mobile devices. However, most of these applications do not provide access to raw GNSS observation data, thereby limiting their use for detailed post-processing and high-precision positioning applications. Raw GNSS observations are essential for post-processing techniques, which are widely employed in scientific and geodetic applications, such as the establishment of geodetic control points and precise positioning. Consequently, considerable research efforts have focused on developing GNSS-based applications capable of recording raw observation data, enabling more comprehensive post-processing and improving the reliability of positioning results (Uradzi´nski & Mieczysław, 2020).

One promising application is Geo++ RINEX Logger, which was developed to record raw GNSS observations through the Android Application Programming Interface (API) (*About Geo++ RINEX Logger*, 2024). The application can collect signals from multiple GNSS constellations, including GPS, GLONASS, Galileo, BeiDou (BDS), and QZSS, utilizing carrier frequencies such as L1, L5, E1B, E1C, and E5A. The recorded observations are stored in the standard Receiver Independent Exchange Format (RINEX), enabling subsequent post-processing using conventional GNSS processing software (*About Geo++ RINEX Logger*, 2024). Furthermore, Geo++ RINEX Logger supports both static and kinematic observation methods, which are commonly employed in geospatial surveying and mapping activities.

Numerous studies have investigated the positioning accuracy of smartphone-based GNSS applications by comparing different smartphone GNSS solutions (Atunggal & Rokhmana, 2016) as well as comparing smartphone-based GNSS with conventional geodetic GNSS receivers (Rizkiansyah et al., 2024; Uradzi´nski & Mieczysław, 2020). Previous research has also examined coordinate deviations under various observation scenarios, including open-sky and obstructed environments (Asis et al., 2024), and different observation schemes. In addition, several studies have evaluated the positioning performance of the Geo++ RINEX Logger application (Uradzi´nski & Mieczysław, 2020). However, studies assessing the positioning accuracy of Geo++ RINEX Logger remain limited in Indonesia, where geographical and environmental conditions differ considerably from those reported in previous studies. For example, research conducted in Olsztyn, northern Poland, reported positioning accuracies ranging from 1 to 4 cm using Geo++ RINEX Logger (Uradzi´nski & Mieczysław, 2020). These findings cannot be directly generalized to Indonesian conditions due to differences in satellite visibility, atmospheric characteristics, and environmental settings.

Therefore, this study evaluates the positioning precision of a smartphone-based Geo++ RINEX Logger by comparing it with a geodetic GNSS receiver under identical static relative observation conditions at the campus of Institut Teknologi Sumatera. The comparison is based on the standard deviations (σ) of the three coordinate components, namely Easting, Northing, and Height. This study is expected to provide a comprehensive assessment of the feasibility of Geo++ RINEX Logger as a practical and cost-effective alternative for geospatial surveying and mapping applications, benefiting general users, surveying practitioners, researchers, and students.

2. Methodology

This research aims to assess the positioning accuracy of static relative GNSS observations acquired using a geodetic GNSS receiver and a smartphone-based GNSS platform utilizing the Geo++ RINEX Logger application. The study was conducted at the campus of Institut Teknologi Sumatera, where two benchmark stations were selected for observation. Benchmark ITR-2 was established as the reference station (base), while Benchmark ITR-0 was used as the rover station. The observations were referenced to the WGS-84 datum and expressed in a topocentric coordinate system. The known coordinates of Benchmark ITR-2 were Easting 534,940.234 m, Northing 9,407,886.691 m, and ellipsoidal height 106.467 m.

To ensure consistency, GNSS observations using both the geodetic receiver and the Geo++ RINEX Logger application were conducted under the same observation environment and measurement scheme. The resulting coordinates were processed using relative static positioning techniques and subsequently analysed to evaluate the positional accuracy of the smartphone-based observations relative to the geodetic GNSS solution. This approach enables an objective assessment of the potential applicability of Geo++ RINEX Logger for cost-effective geospatial surveying and mapping activities.

Data acquisition was conducted in two separate observation sessions. In the first session, both Benchmark ITR-2 and Benchmark ITR-0 were observed using geodetic GNSS receivers. In the second session, Benchmark ITR-2 remained the reference station and was observed using a geodetic GNSS receiver, while Benchmark ITR-0 was observed using the Geo++ RINEX Logger application installed on an Android smartphone. Each observation session was performed for 60 minutes with a 1-second recording interval. A minimum satellite elevation angle of 10° was applied, and all observations were referenced to the WGS-84 datum. The observation data were subsequently divided into five different observation durations, namely 5, 15, 30, 45, and 60 minutes, to investigate the influence of observation duration on positioning accuracy.

The collected GNSS data were processed using two different approaches. First, offline processing was carried out using commercial GNSS data processing software. Second, online processing was performed through the National Real-Time Kinematic (NRTK) service provided by the Badan Informasi Geospasial (BIG) via the NRTK BIG Platform website. Both processing methods generated coordinate solutions for the reference station (ITR-2) and rover station (ITR-0) corresponding to each observation duration. For accuracy assessment, the resulting coordinates were compared with the reference coordinates obtained from the geodetic GNSS observations conducted during the first observation session.

Coordinate differences were calculated for each observation duration and processing method, both offline and online, using the three coordinate components: Easting, Northing, and Height. The calculations were performed for measurements obtained from both the geodetic GNSS receiver and the Geo++ RINEX Logger application. The reference coordinates used in this analysis were derived from the geodetic GNSS observations.

In addition, the standard deviation (σ) was computed for each combination of observation method and observation duration to evaluate the precision and stability of the positioning results. The coordinate differences and standard deviation values were subsequently analysed to compare the positioning performance of the geodetic GNSS receiver and the Geo++ RINEX Logger application within the context of static relative GNSS observations.

3. Results and Discussion

The results of this study consist of the estimated coordinates of the observation point, namely Benchmark ITR-0, obtained from both the first and second observation sessions, as well as a comparative analysis of the resulting positioning solutions.

3.1 Positioning Results Using Geodetic GNSS

The GNSS data processing results obtained from both commercial GNSS processing software and the online processing service provided by BIG indicate variations in coordinate estimates and positioning precision across different observation durations. These variations reflect the influence of observation time on the quality of the positioning solution. Table 1 presents the coordinates of the rover station (ITR-0) derived from (a) offline processing using commercial GNSS software and (b) online processing through the NRTK BIG platform. The table also includes the corresponding standard deviation (σ) values for each observation duration segment, which were used to evaluate the precision and stability of the positioning results.

Table 1. Position Coordinates of the Observation Point Obtained from Geodetic GNSS Measurements.

Duration (minutes)	E (m)	N (m)	H (m)	σ_E (mm)	σ_N (mm)	σ_H (mm)
5 (a)	534878,191	9407441,539	107,101	0,2	0,3	0,1
5 (b)	534883,456	9407445,166	107,087	10,7	27,6	34,3
15 (a)	534878,190	9407441,540	107,103	0,1	0,2	0,1
15 (b)	534883,492	9407445,308	107,160	3,7	2,6	5,4
30 (a)	534878,191	9407441,540	107,100	0,1	0,1	0,1
30 (b)	534883,445	9407445,136	107,144	1,8	2,1	4,2
45 (a)	534878,190	9407441,540	107,100	0,1	0,1	0,01
45 (b)	534883,551	9407445,061	106,998	2,0	4,3	5,3
60 (a)	534878,189	9407441,540	107,099	0,1	0,1	0,01
60 (b)	534883,443	9407445,264	107,149	0,4	0,5	1,0

The GNSS data processing results presented in Table 1 reveal differences in positioning precision between the offline processing approach using commercial GNSS software and the online processing approach through the BIG platform. In general, offline processing was able to produce coordinate solutions and standard deviation values at the sub-millimetre level for all observation durations, whereas online processing yielded coordinate accuracies at the sub-centimetre level with standard deviations ranging from millimetre to centimetre order. These results indicate that the offline processing method provides superior precision compared to the online approach.

The largest standard deviations for both processing methods were observed at the 5-minute observation duration. For offline processing, the standard deviations were recorded as σ_E = 0.2 mm, σ_N = 0.3 mm, and σ_H = 0.1 mm. In contrast, the online processing results exhibited significantly larger standard deviations, reaching σ_E = 10.7 mm, σ_N = 27.6 mm, dan σ_H = 34.3 mm. This difference suggests that short observation durations substantially affect the stability of the positioning solution (Taufiqurrahman et al., 2025), particularly in systems that rely on automated processing and real-time correction services, such as those employed by online GNSS processing platforms (Hadi, 2019; Syetiawan & Chabibi, 2021).

Overall, the coordinate solutions obtained from the online service exhibited a pattern similar to those derived from offline processing, although slight differences in coordinate values and standard deviations were observed. These discrepancies may be attributed to differences in processing algorithms, correction models, and the quality of reference data utilized by each processing method (Ramadhon, 2024; Ramadhon et al., 2020). Coordinate differences between the two approaches were further analysed to identify potential positional deviations.

In general, both processing methods demonstrated a consistent trend in which GNSS positioning accuracy improved with increasing observation duration, with the offline method providing higher precision across nearly all observation intervals. This finding is consistent with the fundamental principles of GNSS surveying, where longer observation periods provide a larger number of measurements and allow for improved satellite geometry, resulting in more favourable Dilution of Precision (DoP) values (Hadi, 2019; Ramadhon et al., 2020). Furthermore, extended observation sessions enhance carrier-phase ambiguity resolution and improve the mitigation of atmospheric effects, including ionospheric and tropospheric delays, thereby producing more accurate and reliable positioning results (Standar Nasional Indonesia, 19-6724-2002 Tentang Jaring Kontrol Horizontal, 2002; Taufiqurrahman et al., 2025).

3.2 Positioning Results Using Geodetic Geo++ RINEX Logger

The GNSS data processing results obtained from commercial GNSS software and the BIG online processing service demonstrate variations in coordinate solutions and positioning precision across different observation durations. Table 2 presents the coordinates of the rover station (ITR-0) derived from (a) offline processing using commercial GNSS software and (b) online processing through the nrtk.big.go.id platform. The corresponding standard deviation (σ) values for each observation duration segment are also provided to evaluate the precision and stability of the positioning results obtained from observations collected using the Geo++ RINEX Logger application.

Table 2. Position Coordinates of the Observation Point Obtained from Geo++ RINEX Logger GNSS Observations.

Duration (minutes)	E (m)	N (m)	H (m)	σ_E (mm)	σ_N (mm)	σ_H (mm)
5 (a)	534879,408	9407439,685	103,338	0,189	0,461	0,201
5 (b)	534883,241	9407444,828	106,803	0,190	0,214	0,422
15 (a)	534880,057	9407439,893	105,106	0,120	0,269	0,120
15 (b)	534884,482	9407444,334	106,880	0,116	0,137	0,255
30 (a)	534880,229	9407439,848	106,610	0,099	0,194	0,095
30 (b)	534884,737	9407446,245	108,240	0,090	0,106	0,183
45 (a)	534880,273	9407440,011	106,429	0,093	0,167	0,089
45 (b)	534884,888	9407444,197	107,859	0,082	0,094	0,157
60 (a)	534880,784	9407439,889	106,881	0,089	0,143	0,084
60 (b)	534885,805	9407443,747	107,702	0,087	0,079	0,136

Data processing using the Geo++ RINEX Logger application demonstrated varying levels of positioning accuracy depending on the processing method employed. As shown in Table 2, both offline and online processing results produced coordinate solutions with differences reaching the sub-meter level across all observation durations. The offline processing results yielded coordinate standard deviations at the centimetre level, whereas the online processing results exhibited coordinate deviations ranging from centimetres to decimetres. These findings indicate that, despite relying on a smartphone-based platform, Geo++ RINEX Logger can provide reasonably accurate positioning results when processed using the static relative positioning method in an offline environment. Similar to the results obtained from the geodetic GNSS observations, the trend presented in Table 2 shows that increasing the observation duration generally leads to smaller standard deviation values, indicating improved positioning precision.

The significant differences in coordinate standard deviations between the Geo++ observations and the geodetic GNSS observations can be attributed primarily to differences in receiver specifications, particularly in terms of the recorded signal frequencies. Geodetic GNSS receivers can track both L1 and L2 signals (dual frequency), enabling more effective mitigation of ionospheric delays and consequently improving positioning accuracy (Abidin, 2007; Arjiansah et al., 2016). In contrast, Geo++ RINEX Logger records only L1 signals (single frequency) (*About Geo++ RINEX Logger*, 2024), making it more susceptible to signal propagation errors caused by atmospheric effects and multipath interference (Arjiansah et al., 2016; Ogaja, 2022). These limitations directly affect the magnitude of the coordinate standard deviations, especially in high-precision applications such as geodetic surveying (Bramanto et al., 2016). The recorded GNSS signals used in the position determination process with the Geo++ application are illustrated in Fig 1.

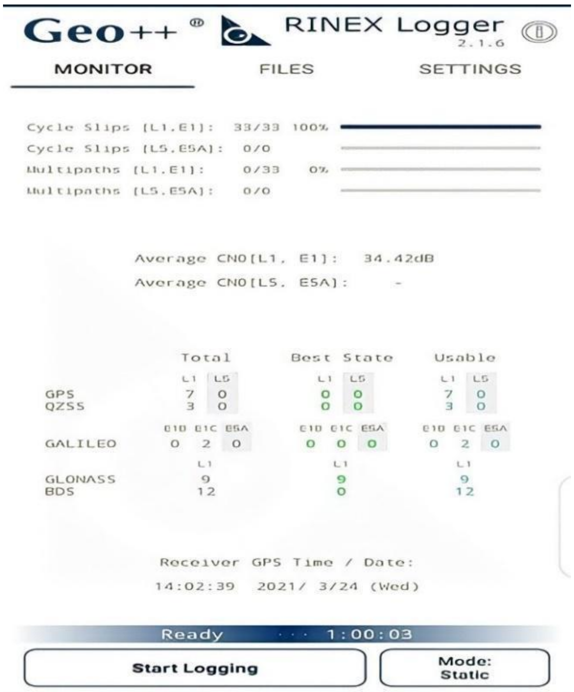

Figure 1. GNSS Signal Recording during Observations Using Geo++ RINEX Logger

In addition to the limitations associated with the recorded signal frequencies, Fig 3 illustrates that the Geo++ RINEX Logger application captures only L1 signals from each tracked satellite, without support for additional frequencies such as L2 or L5, which are commonly available in geodetic GNSS receivers. This limitation directly affects positioning accuracy, particularly for short-duration observations where the ability to mitigate atmospheric errors and resolve carrier-phase ambiguities is more restricted.

3.3 Comparative Analysis of Geodetic GNSS and Geo++ RINEX Logger

The coordinate differences and standard deviations between the Geodetic GNSS receiver and the Geo++ RINEX Logger, obtained from both offline and online data processing, are presented graphically in Fig 2. The graph illustrates the variation in coordinate differences and standard deviation values as a function of observation duration, which serves as a key indicator for evaluating the positioning precision of each method. This visualization facilitates a comparative analysis of the geometric performance between the professional-grade GNSS receiver (Geodetic GNSS) and the smartphone-based GNSS platform (Geo++ RINEX Logger), while also demonstrating the consistency and stability of the positioning results over different observation periods.

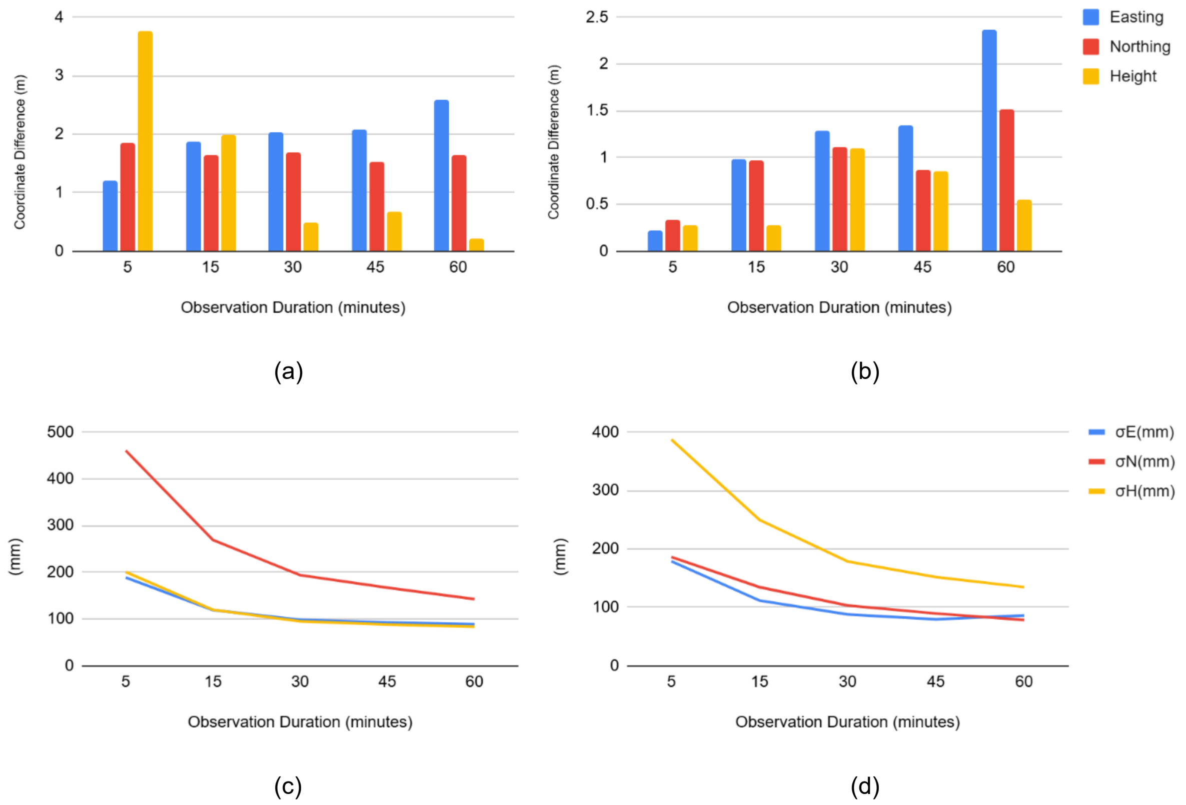

Figure 2. Comparison of Geodetic GNSS and Geo++ RINEX Logger Coordinates from (a) Offline Processing, (b) Online Processing, and Comparison of Coordinate Standard Deviations between Geodetic GNSS and Geo++ RINEX Logger from (c) Offline Processing and (d) Online Processing.

Based on Fig. 2, which presents the coordinate differences and standard deviations obtained from both offline and online processing of Geodetic GNSS and Geo++ RINEX Logger observations, distinct patterns can be observed among the horizontal (Easting and Northing) and vertical (Height) position components with respect to observation duration. The coordinate difference plots (Fig. 2a and 2b) show that the discrepancies in all three coordinate components generally exhibit increasing and fluctuating trends as the observation duration increases, for both offline and online processing results. However, the vertical coordinate differences derived from offline processing (Fig. 2a) display a decreasing trend, indicating that longer observation periods contribute significantly to the stability and accuracy of the height component (Taufiqurrahman et al., 2025). Smaller coordinate differences indicate better positioning accuracy (Khomsin et al., 2020).

In contrast, the standard deviation differences shown in Fig. 2c and 2d for the Easting, Northing, and Height components exhibit a significant decreasing trend with increasing observation duration. This behaviour suggests that coordinate stability improves as the observation time becomes longer, likely due to enhanced convergence of the static GNSS processing solution (Bhatta, 2010; Taufiqurrahman et al., 2025).

Furthermore, a comparison between offline and online processing results indicates that the online processing service available through the NRTK BIG platform generally provides higher positioning accuracy, as reflected by smaller coordinate differences and lower standard deviation values. One possible explanation for this discrepancy is the difference in the number of reference stations used during data processing. The online processing approach utilizes five InaCORS reference stations—CWJP, CBJY, CMEN, CKMN, and CKRI—which are automatically selected based on their proximity to the observation point (ITR-0). Reference stations play a crucial role in providing differential corrections during GNSS data processing (Abidin, 2007; Bhatta, 2010; Kresnawan & Panuntun, 2025). In contrast, the offline processing performed using commercial GNSS software relied on only a single reference station, namely Benchmark ITR-2. Although the baseline length between ITR-2 and the rover station was relatively short, the use of a single reference station was insufficient to achieve positioning accuracy comparable to that obtained from a multi-reference-station configuration. Network design theory suggests that the strength and reliability of GNSS positioning solutions are influenced by both baseline geometry and the number of reference stations involved in the adjustment process (Kurniawan et al., 2019). These findings indicate that Geo++ observations processed using only Benchmark ITR-2 as the reference station yielded lower positioning accuracy than those processed using multiple InaCORS stations.

Nevertheless, the offline processing results demonstrate that the Geo++ RINEX Logger application can produce coordinate solutions with progressively improved precision as the observation duration increases. Although its positioning accuracy remains lower than that of the geodetic GNSS receiver, the Geo++ solution achieved performance within the centimetre-to-decimetre range at the 60-minute observation duration. This finding suggests that Geo++ RINEX Logger may be suitable for certain limited surveying applications, provided that sufficiently long observation periods are employed and appropriate data processing procedures are applied. However, it should be noted that the coordinate solutions generated by Geo++ tend to be relatively precise but not necessarily accurate due to the presence of systematic biases that cannot be fully mitigated using single-frequency (L1-only) observations. Consequently, the overall positioning performance of Geo++ remains inferior to that of geodetic GNSS receivers, particularly for applications requiring high precision, such as geodetic surveying and deformation monitoring.

The results of this study demonstrate that observation duration plays a critical role in determining the quality of positioning solutions obtained from the Geo++ RINEX Logger application, regardless of whether the data are processed offline or online. In general, longer observation durations lead to improved coordinate accuracy, as indicated by decreasing standard deviations and reduced coordinate differences relative to the geodetic GNSS reference solution. These findings are consistent with the convergence principles underlying static GNSS data processing. Moreover, the results support the notion that reference station selection, baseline length, and satellite geometry quality are key determinants of GNSS positioning performance, particularly when using low-cost GNSS receivers. Therefore, to improve the accuracy and precision of Geo++-based positioning solutions, it is recommended to optimize reference station selection, minimize baseline length, extend observation duration, and employ processing configurations that provide favourable satellite geometry.

4. Conclusion

This study demonstrates that observation duration and data processing methods have a significant influence on the accuracy and precision of GNSS positioning results. Among the evaluated observation durations, the 60-minute observation period produced the smallest standard deviations (<1 mm) for both the Geo++ RINEX Logger application and the geodetic GNSS receiver, indicating the highest level of positioning precision.

The results show that Geo++ RINEX Logger is capable of achieving positioning precision within the centimetre-to-decimetre range. However, its positioning accuracy remains inferior to that of the geodetic GNSS receiver due to the limitations of single-frequency technology and its sensitivity to long baselines and satellite geometry. These findings suggest that Geo++ RINEX Logger has considerable potential as a smartphone-based positioning solution for applications that do not require high-precision geodetic surveying. Although it cannot yet match the performance of professional geodetic GNSS receivers, it provides a practical and cost-effective alternative for a wide range of routine geospatial applications.

Future research should further investigate the performance of smartphone-based GNSS under varying satellite visibility conditions, multipath environments, different baseline lengths, and diverse smartphone models. In addition, rigorous statistical validation is recommended to improve the reliability, robustness, and broader applicability of mobile device-based GNSS positioning systems.

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