Performance Analysis of a NavIC Aided Multi-GNSS Receiver in Low Latitude Region

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Abstract

Global navigation satellite systems (GNSS) play a vital role in positioning navigation and timing solutions across range of applications. This study focuses on analysing the accuracy and precision of Position, Velocity and Timing (PVT) solutions using a multi frequency, multi constellation GNSS receiver with a particular focus on the Indian Regional Navigation Satellite System (IRNSS) or Navigation with Indian Constellation (NavIC). Data is collected at the GNSS lab in Ramaiah Institute of Technology (RIT) located in the Bengaluru urban region during the months of May-August 2024 using the ELENA R1B GNSS module and the ELENA ELNAA3A tri-band antenna at a sampling frequency of 1 Hz. This study presents a performance evaluation of multi-constellation GNSS data, focusing on key positioning accuracy metrics Signal-to-Noise Ratio (SNR), Circular Error Probable (CEP), Distance Root Mean Square (2DRMS), and Spherical Error Probable (SEP) across eight epochs using data from NavIC, GPS, and GLONASS. The analysis emphasizes the role of satellite geometry, particularly Vertical Dilution of Precision (VDOP) and Position Dilution of Precision (PDOP), and SNR in influencing spatial accuracy. Results show that NavIC and GPS consistently deliver stable SNR (~43 dB-Hz and ~41 dB-Hz, respectively), while GLONASS exhibited greater variability, affecting accuracy in select epochs. The lowest CEP (0.42 m) and 2DRMS (1.02 m) occurred under optimal geometry (VDOP ≤ 0.85), while highest errors CEP of 1.33 m and SEP of 2.32 m were recorded when PDOP exceeded 1.06. Despite minor fluctuations in geometry and signal quality, positioning metrics remained reliable, with SEP generally below 2.5 m, indicating the robustness of multi-GNSS integration.

Keywords: Accuracy, GPS, IRNSS/NavIC, Multi-constellation Global Navigation Satellite Systems (GNSS), Navigation, Precision

1. Introduction

Global Navigation Satellite Systems (GNSS) have revolutionized positioning, navigation, and timing (PNT) solutions, becoming indispensable in various fields such as transportation, agriculture, disaster management, and autonomous systems. GNSS refers to a constellation of satellites providing geospatial positioning with global coverage, allowing users to find out their precise position and time anywhere on Earth. Prominent GNSS constellations include GPS (USA), GLONASS (Russia), Galileo (EU), BeiDou (China), and regional systems like the Indian Regional Navigation Satellite System (IRNSS), also known as NavIC and QZSS from Japan [1].

GNSS operates across multiple frequency bands, including L1, L2, and L5, to transmit signals that users can process to calculate their positions [2]. However, GNSS signals are susceptible to different errors such as ionospheric and tropospheric delays, multipath effects, satellite clock drifts, and orbital inaccuracies. Such errors can impair GNSS solutions' precision and dependability, particularly in challenging environments [3].

The advent of multi-constellation as well as multi-frequency receivers has significantly enhanced GNSS performance. Multi-frequency receivers mitigate ionospheric errors by utilizing signals transmitted at different frequencies, while multi-constellation setups improve satellite visibility and positioning accuracy by integrating data from multiple GNSS systems. Precision and accuracy are critical aspects of GNSS performance, quantified using parameters such as CEP, 2DRMS, SNR, satellite availability, and Dilution of Precision (DOP) [4].

Despite the advancements in global systems, regional navigation solutions like NavIC are essential for providing localized enhancements in accuracy and reliability. NavIC, developed by the Indian Space Research Organisation (ISRO), focuses on the Indian subcontinent and surrounding areas, offering improved coverage and performance. Its tri-band signals, including L5 and S-band, are tailored for regional applications and are crucial in mitigating errors under diverse geographic and climatic conditions [5]. Owing to these advantages, NavIC is increasingly being adopted in applications such as disaster warning systems, precision3 agriculture, terrestrial navigation and marine fisheries, where dependable and accurate regional navigation is critical.

This research focuses on analysing the precision, reliability and robustness of position solutions derived from NavIC integrated multi-GNSS data. By evaluating performance based on key positioning metrics, such as CEP, 2DRMS, SEP and the influence of satellite geometry particularly PDOP and VDOP on various days across months, this study aims to understand the consistency and integrity of NavIC signals in a multi-constellation setup. The results are expected to contribute towards understanding practical utility of NavIC integrated multi-GNSS solutions in operational navigation environments.

2. Background Work

Recent studies underscore the precision of satellite-based navigation systems, with particular emphasis on the Navigation with Indian Constellation (NavIC). Foundational overviews of Global Navigation Satellite Systems (GNSS) discuss the historical development and fundamental principles that support advancements in satellite navigation technology [1]. Effective use of GNSS in real life applications requires quantification of precision levels acquired from GNSS receivers, and there are several parameters defined for the same. Standard statistical estimates such as 2DRMS and CEP for 2-dimensional position solutions and SEP and MRSE for 3 dimensional position solutions can be used to examine the precision of solutions [3][4] and [6]. The precision of location solution provided by low-cost single frequency receivers has been determined by calculating the up (vertical) and horizontal (north and east) errors [7]. Research has shown that utilizing multi-frequency signals particularly from modern constellations such as GPS, GLONASS, Galileo, and the Indian Regional Navigation Satellite System (IRNSS), can substantially mitigate errors associated with ionospheric delays. Studies indicate that receivers operating on L5 frequencies can achieve reduced positioning errors compared to those relying solely on L1 frequencies, which is particularly relevant for urban areas in India where signal degradation is common due to high-rise buildings and other obstructions [8]. Further evaluations of compact, low-cost, dual-frequency GNSS modules demonstrate that these systems offer enhanced accuracy and reliability compared to single-frequency modules, broadening access to advanced navigation technology [2].

The Indian Regional Navigation Satellite System (IRNSS), also known as NavIC, has emerged as a significant advancement in regional GNSS applications, offering enhanced positioning reliability in India and surrounding areas [9]. IRNSS or NavIC, provides regional positioning services specifically tailored for India, offering additional satellite coverage that enhances positioning accuracy in both urban and rural settings. Research has indicated that integrating IRNSS signals with those from other global constellations can significantly improve reliability and accuracy, particularly in regions with challenging topography and dense urban environments [10] and [11]. Building on this, the significance of sophisticated data analysis and error mitigation strategies is emphasized in the examination of parameters affecting the accuracy of NavIC position solutions [12]. In order to offer insights on satellite availability and positioning quality, NavIC's performance throughout its service territory has been examined using quantitative measurement criteria such as CEP, DRMS, SEP, etc. [13] Environmental and temporal variations significantly affect GNSS performance, as shown in statistical analyses of NavIC receivers [5] and [14]. Key factors such as atmospheric conditions, satellite geometry, and multipath effects directly influence positioning accuracy, underscoring the need for optimized receiver design [15].

The preliminary results on NavIC-based positioning accuracy assessment conducted by [16], reporting early-stage performance using key statistical indicators. A statistical assessment of NavIC receiver in standalone as well as hybrid mode using accuracy metrics such as CEP, DRMS and SEP in [17] and [18]. While these contributions are valuable, they are either limited to dual-constellation configurations (mostly GPS+NavIC), rely on controlled experimental conditions, or focus on short-duration or special-event analyses. Limited research has systematically assessed real-world positioning performance using a triple-constellation setup (GPS + NavIC + GLONASS) over an extended period focusing on the low latitude regions.

This study bridges the existing gap by presenting a multi-epoch, field-based analysis that correlates DOP and SNR with position accuracy metrics (CEP, 2DRMS, SEP) in an Indian urban environment. It further establishes the reliability and scalability of regional systems like NavIC, alongside global constellations, for consistent GNSS performance in low-latitude regions such as the Indian subcontinent paving the way for more resilient applications.

3. Methodology

This research primarily focuses on the precision and accuracy analysis of various GNSS constellations, including the Indian Regional Navigation Satellite System (IRNSS). Data were collected over a period of four months, with two days selected from each month one representing cloudy sky and the other clear sky conditions. The study holds paramount significance since it is conducted from May to August 2024, with May and June constituting the pre-Monsoon and June and July forming the core of the Monsoon season in India. The study also is topographically significant since the experiment is performed in the city of Bengaluru Urban, situated at an average altitude of 920 m (3020 ft) above mean sea level(msl), which is higher than most urban centres in India. The location map of the receiver is shown in Figure 1.

3.1 Experimental Setup and Methodology

For data collection, an ELENA R1B multi-GNSS module is employed, paired with the ELENA ELNAA3A tri-band antenna, an indigenously developed component designed to support multiple GNSS frequencies is used at the GNSS Lab, MSRIT, Bengaluru (Figure 2). This configuration enhances signal reception quality and multi-constellation compatibility, thereby improving the precision and reliability of the position solutions. Data acquisition was managed through the ELENA data logger software, enabling real-time observation and storage of the collected GNSS signals. Data was recorded for one-hour sessions across various days on different months, aligning with different weather conditions to capture diverse environmental impacts as indicated in Table 1 below. The data was logged at a frequency of 1 Hz, ensuring a high-resolution dataset for subsequent analysis. The process for determining precision parameters is outlined in the following steps:

Step I: The mean and standard deviation of position solution (longitude, latitude, altitude) for a number of epochs are computed.

Step II: Since altitude has already been measured in meters, convert the longitude and latitude standard deviations from degrees to meters.

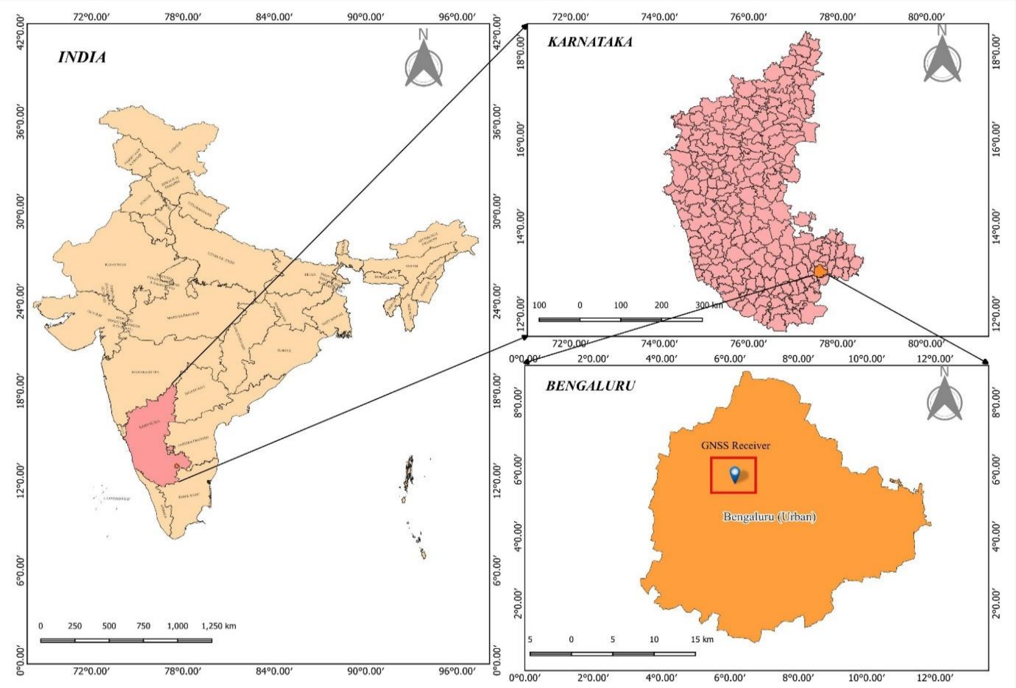


Figure 1: Location map of the receiver stationed at MSRIT, Bengaluru

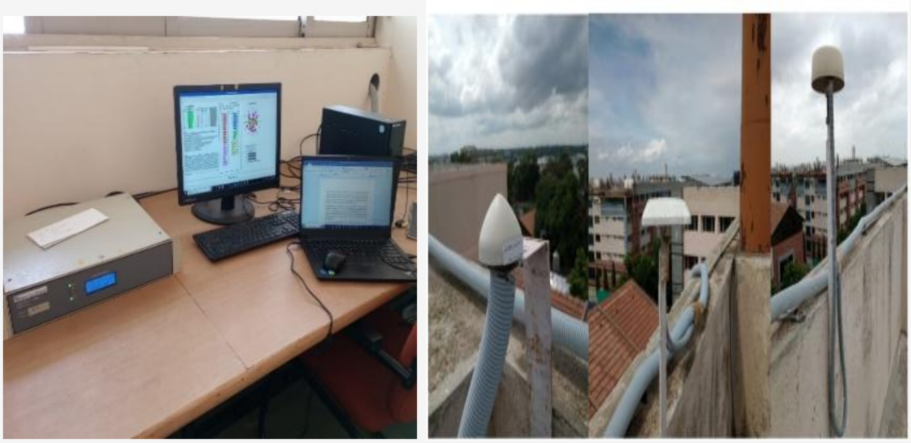


Figure 2: Experimental setup with Base station receiver with supporting software and Elena tri-band antenna at MSRIT lab

Table 1: Atmospheric conditions on selected GNSS observation days

Date	Weather Condition	Average Temperature (°C)	Average Humidity (%)	Average chance of precipitation (%)
11 May 2024	Clear sky	31.0	52.0	4.0
17 May 2024	Cloudy Sky	25.5	77.0	63.0
11 June 2024	Clear sky	26.0	74.0	27.0
9 June 2024	Cloudy Sky	28.0	63.0	74.0
19 July 2024	High Rainfall	23.5	80.0	79.0
23 July 2024	Low Rainfall	25.5	72.0	12.0
7 August 2024	High Rainfall	25.0	78.0	64.0
10 August 2024	Low Rainfall	25.0	77.5	11.5

Step-III: Utilize the mean and standard deviations obtained in Step-II to compute the precision parameters.

3.2 Parameters of Evaluation

The key parameters commonly used to evaluate the precision and accuracy of GNSS systems are elaborated in the upcoming section.

3.2.1 Root mean square (RMS) error

The average difference between the anticipated and actual values of a statistical model is measured by the root mean square error, or *RMS*. It is the residuals' standard deviation in mathematics given by Equation 1 [3].

$$RMS^2 = \left\{ \frac{1}{n} \sum_{i=1}^{n} \left(x_i - \bar{x} \right)^2 \right\} + \left(\bar{x} - a \right)^2$$

Equation 1

Where $\{x_i\}$ is a set of n random samples, $\bar{x}$ indicates the mean and a denotes accepted constant value. Alternatively, the *RMS* can be determined from Equation 2:

$$RMS^2 = \sigma^2 + (\bar{x} - a)^2$$

Equation 2

Where:
σ is standard deviation
$(\bar{x} - a)$ indicates the estimates of the bias.

RMS equates to standard deviation when mean numerical value itself is considered as constant accepted value considering true value is unknown. The accuracies and precision of GNSS position solution is determined using the same concept. Errors in longitude and latitude, expressed in degrees, are converted into their corresponding distances using the Equations 3 to 5 [4]:

$$\varepsilon_y = 1852\sigma_y^{'}$$

Equation 3

$$\varepsilon_x = 1852\sigma_x^{'} \cdot \cos(lat_{avg})$$

Equation 4

$$\varepsilon_z = \sigma_z$$

Equation 5

Where:

ε_x, ε_y, and ε_z are the errors in longitude, latitude and altitude, respectively

$\sigma_y^{'}$ is the standard deviation of latitude

$\sigma_x^{'}$ is the standard deviation of longitude

lat_{avg} is average latitude

For the computation of the above mentioned precision parameters we consider, ε_x as σ_x, ε_y as σ_y, and ε_z as σ_z (ellipsoidal height on WGS 84 datum). This consideration along with Equations (3), (4) and (5) holds key for this process. Therefore, Standard Devn of the solution in east direction (mtr) is defined by σ_x whereas σ_y defines the standard deviation in the north direction. σ_z is the vertical standard error with regards to reference point, the mean value [1]in the present scenario.

3.2.2 Dilution of precision (DOP)

DOP is a geometric factor that reflects how the relative positions of satellites impact the accuracy of GNSS-derived positions. It measures the "strength of configuration" of the satellites in view. HDOP (Horizontal DOP) indicates accuracy of the horizontal position (latitude and longitude), while VDOP (Vertical DOP) indicates accuracy of the vertical position (altitude). PDOP (Positional DOP) indicates combined 3D positional accuracy (latitude, longitude, and altitude). Table 2 indicates the DOP value ratings [19] acceptable for efficient computation of position solutions.

3.2.3 Signal-to-noise ratio (SNR)

SNR is the ratio of the power of the GNSS signal to the power of background noise, typically expressed in decibels (dB). A higher SNR indicates a stronger and clearer signal, which is essential for accurate position computation. SNR is measured for each satellite individually, as received by the GNSS receiver. Signals having SNR greater than 45dB are termed as good signals, while moderate signals vary from 30dB to 45dB and weaker signals less than 30dB [19].

3.2.4 Twice distance root mean square (2DRMS)

It quantifies the horizontal positional error in GNSS data [1].

$$2DRMS = 2\sqrt{\sigma_x^2 + \sigma_y^2}$$

Equation 7

Equation 7 denotes the radius of the enclosing circle which has the mean numerical value as the center and inside which 95.8% - 98.2% of position solutions fit in.

3.2.5 Circle of error probable (CEP)

Similar to *2DRMS*, *CEP* takes horizontal position error into account. It is defined as the radial distance of the enclosing circle that is centered at the actual position and contains the position estimate with a 50% probability. CEP is defined in Equation 7:

$$CEP = 0.62\sigma_y + 0.56\sigma_x \text{, provided that } \frac{\sigma_y}{\sigma_x} > 0.3$$

Equation 7

Circular Error Probable defines the radius of the circle that contains 50% of the position solutions. For example, a *CEP* of 4 meters means that 50% of the position solutions are within 4 meters of the true location in the horizontal plane. In open-sky conditions, modern multi-GNSS receivers typically achieve horizontal positioning accuracy with a *CEP* of less than 2 meters, owing to high signal-to-noise ratio (*SNR*) and favourable satellite geometry [20].

3.2.6 Spherical error probable (SEP)

SEP provides a 3D accuracy measure, taking into account errors in all three axes (latitude, longitude, and altitude). While *CEP* emphasizes only on horizontal accuracy, *SEP* provides a more comprehensive measure of positional accuracy by incorporating vertical errors as well. *SEP* is derived from the variances of the position errors along *X, Y*, and *Z* axes. Assuming errors are normally distributed, *SEP* is expressed in Equation 8:

$$SEP = 0.51(\sigma_x + \sigma_y + \sigma_z)$$

Equation 8

Table 2: Optimal DOP ratings

DOP Value	Rating	Description
<1	Ideal	For applications requiring highest levels of precision
1-2	Excellent	Accurate for all but sensitive applications
2-5	Good	Minimum precision for decision making
5-10	Moderate	Position solutions to be used for basic calculations only
10-20	Fair	Indicates rough estimate of current solution
>20	Poor	Measurements should be discarded

4. Results and Discussions

4.1 Comparison of Dilution of Precision (DOP)

Dilution of Precision (DOP) parameters provide a quantitative measure of the geometrical strength of satellite configurations and directly affect the accuracy of GNSS position solutions. In this study, Position DOP (PDOP), Horizontal DOP (HDOP), and Vertical DOP (VDOP) values were analysed across eight observational days (Figure 3), to evaluate the consistency and reliability of the GNSS receiver performance.

1. Position DOP (PDOP):

The PDOP values across the dataset remain within the ideal to excellent range (generally < 2) (Figure 3), suggesting favourable satellite geometry throughout the observations. The lowest PDOP was recorded on July 23 (0.9782), and the highest on June 19 (1.2327). Despite fluctuations, the variation remains within a narrow band (≈0.25), indicating that the three-dimensional satellite configuration remained geometrically robust over time.

2. Horizontal DOP (HDOP):

HDOP values ranged from 0.4619 (June 11) to 0.5844 (June 19). These values suggest highly precise horizontal solutions, reinforcing the suitability of the receiver for applications requiring accurate lateral positioning. The narrow spread of HDOP as indicated in Figure 3 (all values well below 1) points to strong consistency in horizontal satellite geometry across all observation days.

3. Vertical DOP (VDOP):

VDOP values exhibited a slightly higher variability compared to HDOP, ranging from 0.8531 (July 23) to 1.0826 (June 19). Although vertical accuracy typically exhibits more susceptibility to error due to satellite geometry and tropospheric delay, these VDOP values are still within acceptable operational limits, particularly for non-critical vertical applications.

The overall DOP statistics reflect excellent satellite geometry, with values well below standard thresholds for concern (PDOP < 2, HDOP < 1, VDOP < 2). The consistency of HDOP and PDOP values across clear and cloudy days further confirms the temporal stability of satellite configurations in the observation area, providing confidence in the baseline GNSS environment. The relatively stable VDOP also supports the conclusion that the receiver offers balanced performance across both horizontal and vertical axes. It can be inferred from these findings that the receiver maintains consistent access to well-distributed satellites, and external factors (e.g., multipath, signal obstruction, or atmospheric interference) are more likely contributors to positional variance than satellite geometry.

4.2 Comparison of Signal to Noise Ratios in a Multi-Constellation Scenario

Figure 4 presents the average Signal-to-Noise Ratio (SNR) values recorded for NavIC, GPS, and GLONASS constellations over eight observational epochs between May and August. NavIC consistently shows the highest SNR among the three constellations, with values ranging from 42.37 dB-Hz to 44.02 dB-Hz. Its regional focus and geostationary-like configuration may also contribute to its stable signal performance in India. GPS SNR values remain stable, clustering around 41 dB-Hz, indicating consistent signal reception quality. GLONASS exhibits the greatest variability, with values dipping as low as 35.97 dB-Hz (May 17) and peaking at 41.73 dB-Hz (August 7). This may reflect lower satellite elevation angles or less favourable signal modulation characteristics compared to GPS and NavIC.

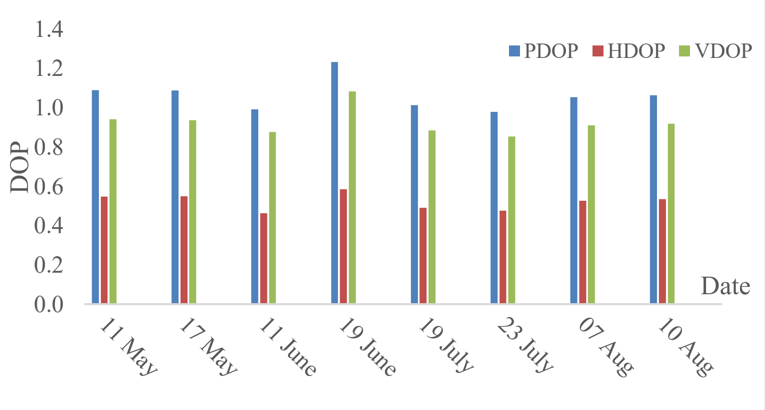


Figure 3: PDOP, HDOP, VDOP values observed at the MSRIT Lab

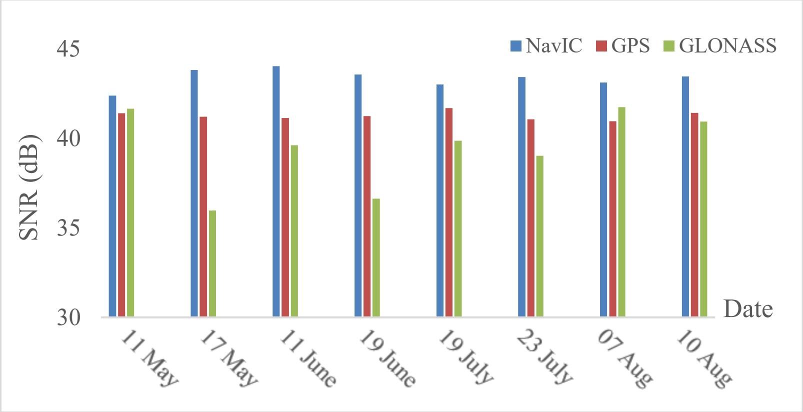


Figure 4: Comparison of SNR of different of different satellite navigation systems

A cross-reference with environmental conditions shows that cloudy days (e.g., May 17, June 19) generally align with lower SNR values, particularly for GLONASS. However, GPS and NavIC appear less affected, indicating better resilience to atmospheric attenuation as can be observed from Figure 4. Higher SNR values are typically associated with lower positional errors. This is corroborated by the CEP and SEP results obtained in the study, where days with higher average SNR (e.g., June 11) correspond to lower positioning errors, and vice versa (e.g., August 10).

4.3 Comparison of Circular Error Probable (CEP) and Distance Root Mean Square (2DRMS)

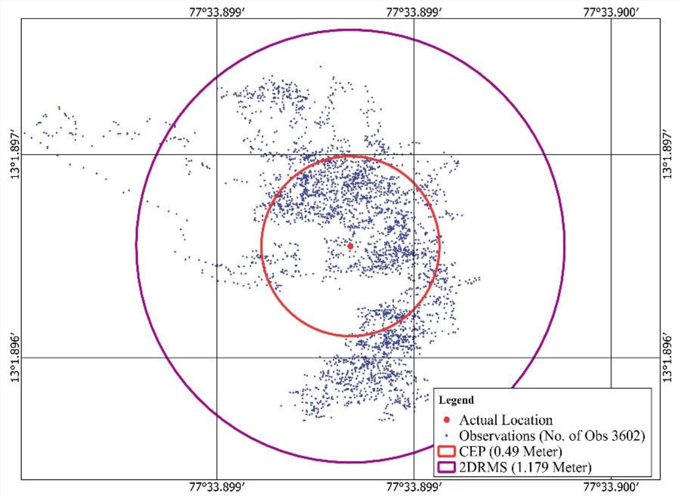
Precision parameters CEP,2DRMS and SEP are calculated across four months on days having contrasting weather conditions in multi-constellation mode (GPS+NavIC+GLONASS) using Elena R1B receiver in static condition at the GNSS Lab in RIT, Bengaluru. In the post-processing part, the observed positions are exported to QGIS 2.7 and scatter plots are plotted to give a precise view of the real-time position solutions observed by the receiver. The points inside the inner circle lie inside CEP and the points lying within the outer circle lie inside the 2DRMS range. For all scatter plots, axis scales are provided to ensure direct comparison across scenarios.

Throughout the observation period from May (pre-monsoon) to August (monsoon), multi-constellation GNSS performance in the Bengaluru urban region remained robust under both clear and cloudy sky conditions as observed from the scatter plots in Figures 5, 6, 7 and 8. CEP values during May and June, generally ranged between 0.42m and 1.03m, while 2DRMS values remained low, between 1.06m and 2.50m, indicating consistent and precise positioning. Slight variability indicating increasing trend particularly observed during the peak monsoon months of July and August, with CEP increasing up to 1.33m and 2DRMS reaching 3.40m. Minor fluctuation resulting in increased CEP (June 19) (Figure 6) is attributed to poorer signal strength (SNR of GLONASS dropping to 36.63dB-Hz) observed occasionally. However, these fluctuations were minor and well within acceptable GNSS accuracy thresholds. Given that L-band GNSS signals are inherently resistant to cloud and precipitation-related attenuation, the observed variations are likely due to indirect environmental factors such as increased multipath from wet surfaces, localized signal reflections, or urban obstructions rather than direct atmospheric effects. These results reaffirm the reliability and precision of multi-constellation GNSS systems across seasonal transitions in urban Indian environments.

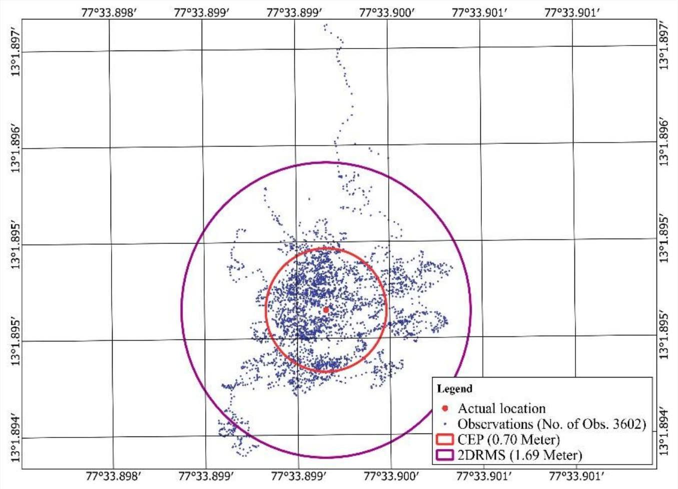
4.4 Spherical Error Probable (SEP) Analysis

A graphical depiction of Spherical Error Probability (SEP) in Figure 8 gives an understanding on the 3D position solutions offered by the multi-constellation setup during the observation period. The lowest SEP values were observed on June 11 (0.60 m) and July 23 (0.95 m). These epochs coincided with low VDOP (≤ 0.88) and relatively balanced SNR across all three constellations, indicating strong geometry and signal reliability. In contrast, the highest SEP values were recorded on August 10 (2.32 m) and June 19 (1.89 m). Both days were characterized by elevated PDOP (≥ 1.06) and high VDOP (≥ 1.08), reflecting poor satellite elevation distribution and diluted geometry.

The drop in GLONASS SNR had a notable impact on SEP, particularly on May 17 (35.97 dB-Hz) and June 19 (36.63 dB-Hz). This minor degradation in one constellation’s signal quality significantly affects overall positioning by a small margin integrity despite consistent GPS and NavIC SNR.

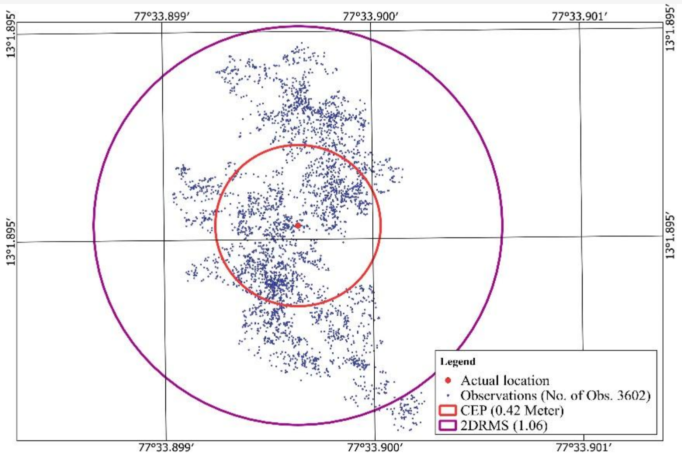


(a)



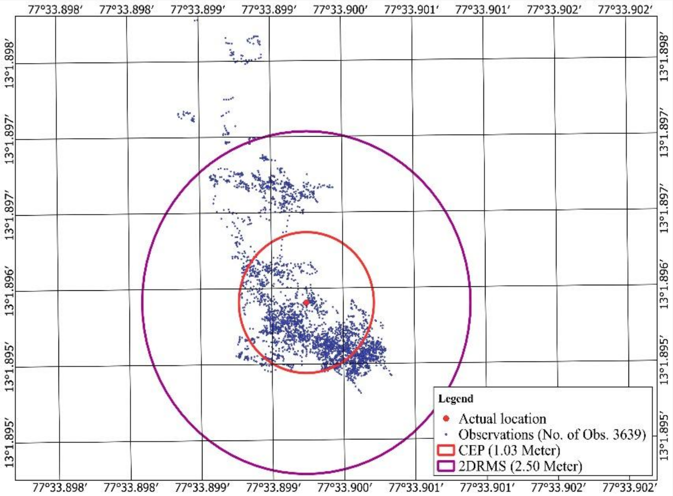
(b)

Figure 5: CEP and 2DRMS under varied environmental conditions in May 2024: (a) clear sky conditions and (b) cloudy sky conditions



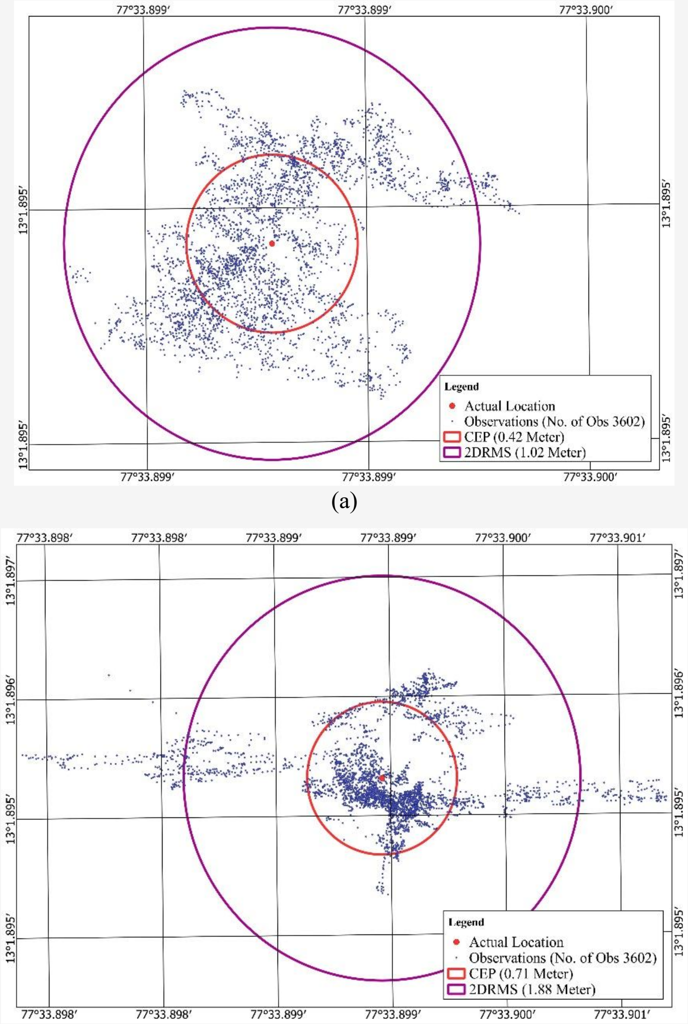
(a)

Figure 6: CEP and 2DRMS under varied environmental conditions in June 2024: (a) clear sky conditions and (b) cloudy sky conditions (Continue next page)



(b)

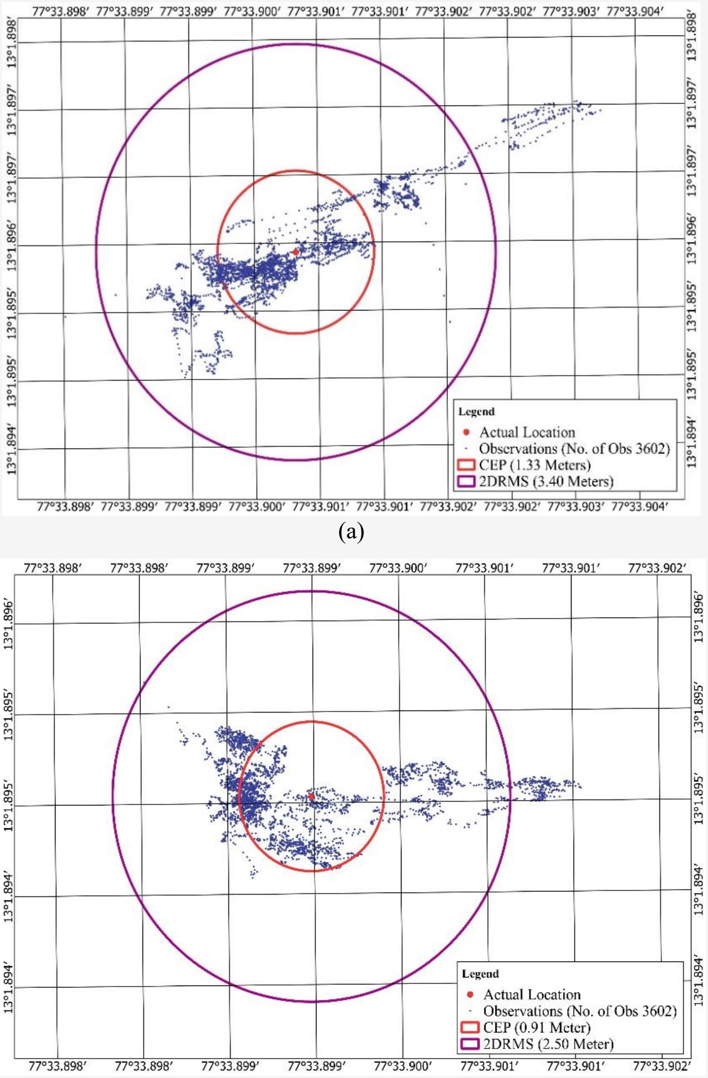
Figure 6: CEP and 2DRMS under varied environmental conditions in June 2024: (a) clear sky conditions and (b) cloudy sky conditions (Continue from previous page)



(a)

(b)

Figure 7: CEP and 2DRMS under varied environmental conditions in July 2024: (a) clear sky conditions and (b) cloudy sky conditions



(a)

(b)

Figure 8: CEP and 2DRMS analysis under varied environmental conditions for the month of August: (a) clear sky conditions and (b) cloudy sky conditions

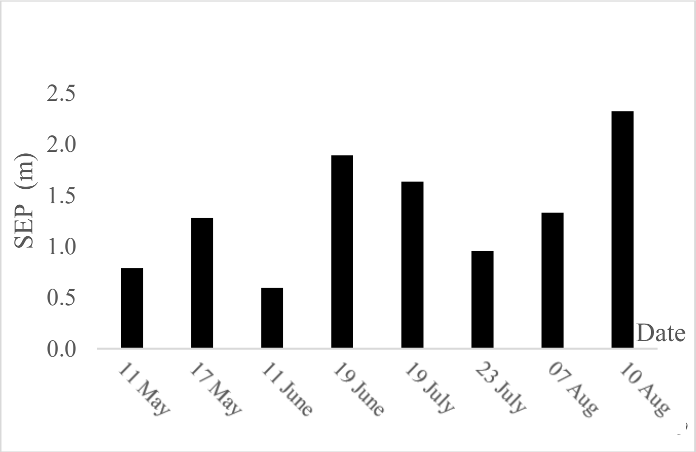


Figure 9: SEP trends in varied environmental conditions across May-August 2024

While the Spherical Error Probable (SEP) metric shows minor variation across epochs, its overall trend indicates consistent reliability under stable system conditions as observed in Figure 9. Minor fluctuations are expected due to inherent GNSS dynamics such as satellite handovers, receiver noise, and real-time geometry changes. Even though SEP is influenced by SNR and DOP variations, its composite nature, constellation redundancy, and consistently strong signals from core systems (NavIC and GPS) ensure that it remains stable and within acceptable bounds for most epochs.

5. Conclusion

This study conducted a comprehensive evaluation of GNSS positioning performance using key accuracy metrics Circular Error Probable (CEP), Distance Root Mean Square (2DRMS), and Spherical Error Probable (SEP) across eight observation epochs from May to August. The results confirm that satellite geometry, particularly Vertical Dilution of Precision (VDOP) and Position Dilution of Precision (PDOP), has a direct and measurable influence on positional accuracy. The average latitude, longitude and altitude of the GNSS Station across the epochs are observed to be 13.0315 °N, 77.5649 °E and 856.0874 m (Ellipsoidal height) respectively. The lowest CEP (0.42 m) and 2DRMS (1.02 m) were observed on July 23, corresponding to the most favourable geometric conditions (VDOP: 0.85, HDOP: 0.47), while the best SEP (0.60 m) occurred on June 11, supported by the highest NavIC SNR (44.02 dB-Hz) and lowest VDOP (0.88). In contrast, August 10 showed the highest CEP (1.33 m) and SEP (2.32 m) due to elevated PDOP (1.06) and a relatively flattened satellite configuration.

Despite minor fluctuations in individual epochs often due to slight changes in GLONASS SNR or geometric dilution CEP, 2DRMS, and SEP remained within reliable bounds, typically below 1 m for CEP, under 2 m for 2DRMS, and within 2.5 m for SEP across most epochs. This consistency demonstrates the robustness and operational reliability of multi-constellation GNSS configurations, particularly when supplemented with strong and stable signals from NavIC and GPS. The findings reinforce that GNSS positional accuracy is highly dependable under well-monitored system parameters, even without external corrections or augmentation.

6. Limitations and Future Scope

The present study focuses on three satellite combination GPS, NavIC and GLONASS. Additionally, the analysis can be expanded to include additional constellations such as Galileo and BeiDou for broader global performance comparisons. The error metrics were computed on select days at a static location across four months. Further studies can incorporate observations round the year for different terrains covering various environmental factors. Incorporating elevation-angle-based satellite weighting and multipath mitigation strategies can enhance accuracy in semi-urban or obstructed environments. Future research can also explore real-time, DOP-aware satellite selection algorithms to dynamically optimize accuracy based on live geometry. Further, real-time time-series analysis of error metrics could enable predictive modelling for GNSS reliability, and machine learning techniques can be employed to correlate DOP, SNR, and positioning accuracy to build intelligent GNSS correction frameworks suitable for precision applications.

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