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RESEARCH PAPER

Dilution of precision analysis over the Visakhapatnam region: a GPS &NavIC combined scenario

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Abstract
Dilution of Precision (DOP) plays a critical role in the performance of Global Navigation Satellite Systems (GNSS), directly influencing the accuracy of position estimation. DOP is a unitless factor that quantifies the impact of satellite geometry on positional uncertainty; it essentially magnifies potential errors based on the spatial arrangement of visible satellites relative to the receiver. It is commonly categorized into Horizontal DOP (HDOP), Vertical DOP (VDOP), and Position DOP (PDOP), each corresponding to specific dimensions of positional accuracy. A lower DOP value reflects well-distributed satellites in the sky and results in more precise positioning, while higher DOP values indicate poor geometry and degraded accuracy. These DOP values are fundamental to various GNSS applications, including navigation, vehicle tracking, precision agriculture, surveying, aviation, and autonomous systems. This study investigates the effect of satellite geometry in a multi-GNSS environment, particularly focusing on the combined use of GPS and NavIC constellations. The analysis is carried out over a defined period, assessing various DOP components. The results demonstrate that the integration of GPS with NavIC significantly improves satellite geometry and enhances overall positioning accuracy.

Keywords GPS · DOP · NavIC (Navigation with indian constellation) · Accuracy · Satellite geometry

Introduction

In today's world, attaining the best satellite geometry is crucial for accurate and reliable positioning. Satellite geometry refers to the spatial distribution of satellites as observed by a receiver. The errors caused by signal propagation can be reduced by the uniform distribution of these satellites and by improving the strength of the position calculations. GNSS plays a pivotal role in securing adequate satellite availability and better geometry (Rajasekhar et al. 2021), particularly in challenging environments like urban canyons or highly forested areas. The receiver can achieve better satellite visibility and less geometric dilution of precision (GDOP) by integrating multi-GNSS constellation results with high accuracy and reliability (Zhao et al. 2020; Li et al. 2015; Cai and Gao 2007; Teng and Wang 2014; Raja Sekhar et al. 2016; Wang et al. 2019; Gayathri et al. 2017). Satellite navigation systems have revolutionized modern technology applications by offering position, navigation, and time globally, referred to as GNSS (global navigation satellite system). GNSS is a network of satellites that broadcasts timing and orbital information, which is used for navigation and measuring the position of an Object (Pagoti and Vemuri Jan. 2022). satellite navigation system Navigation Satellite Systems (GNSS) data becomes a very important component in the study of earth's atmosphere, satellite positioning, and natural disasters (Shi et al. 2023). Signal is available anywhere on the earth where the user has a clear view of the sky. Applications of GNSS are traffic management, natural disaster recovery, climate change analysis and military observations.

There are several global GNSS constellations. Global Positioning Service (GPS) is a satellite-based navigation system developed by the US Department of Defense (DOD) in 1978(Bhattacharyya and Mute 2020). This is the first global positioning system with 31 operational satellites. GPS is a space-based radio navigation system. It provides precise position, velocity, and time determination anywhere on Earth under any weather conditions. It is freely accessible to anyone using a GPS receiver. The scientific use

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of GPS is increasing daily in the fields of military, civil, and commercial users. It is primarily used for navigation, map-making, and surveying. The Beidou Navigation Satellite System (BDS) is a global navigation satellite system introduced by the Chinese government that consists of geostationary and geosynchronous satellite systems (Xu et al. 2014). GLONASS is the Russian GNSS managed by the Russian Ministry of defence, having 22 active satellites (Sarkar and Bose 2016). GALILEO is the global navigation satellite system introduced by the European Union, which has 24 active satellites (Zhao et al. 2022). The Regional Navigation Satellite Systems (RNSS) provides better positioning services over a specific region and works similarly to the GNSS (Cai and Gao 2007). IRNSS/NAVIC is the regional navigation satellite system developed by India to provide accurate position, navigation, and timing services over India and its neighboring areas about 1500 km. NavIC (navigation with the Indian constellation) has 7 satellites in its orbit and provides two types of services: standard positioning services and restricted service (Ansari 2023). QZSS is a satellite-based augmentation system developed by Japan, ensuring superior performance in urban and mountainous environments (Kotla et al. 2019).

Despite GPS global coverage and high reliability, factors such as atmospheric interference, multipath errors, and satellite geometry influenced the performance of GPS. The accuracy of the GPS is limited by satellite geometry, user range error, signal degradation, multipath effects, satellite atomic clock, and receiver design quality (Rizos 2008). There are some techniques to reduce errors, but satellite geometry remains a crucial factor in achieving position accuracy. DOP (dilution of precision) measures the satellite geometry. It is a dimensionless number, also called GDOP (geometric dilution of precision). Position accuracy is high when GDOP is small (Rajasekhar et al. 2021). At least four satellites are required to achieve better geometry. In some cases, satellite geometry is low if more than four satellites of the same system are available. In such a case, multi-constellation approaches, such as integrating GPS with other navigation systems, are being developed. Satellite geometry is improved by the integration of this constellation, which reduces GDOP and helps improve position accuracy, especially in mountainous regions and urban canyons.

Many researchers demonstrate the importance of multi-constellation while estimating position accuracy. Integrating GNSS with other navigation systems gives better results than the standalone constellation (Raja Sekhar et al. 2016; Ansari 2023).

This study explores integrating GPS with regional navigation systems such as the NavIC constellation, which impacts group and position accuracy. This study analyzes data from both standalone and hybrid constellations. Research focuses on their collective impact on positional accuracy.

Research framework

Satellite navigation relies on precise distance measurements to calculate the position of the receiver. By using pseudo-range data from four or more satellites, the receiver's 3D coordinates and clock bias can be estimated. The accuracy of receiver coordinates is determined by pseudo-range measurements (Raja Sekhar et al. 2016).

The fundamental pseudo- range equation can be written as:

$$P = \rho + c\,(dT - dt) + d_{ion} + d_{trop} + e \tag{1}$$

where:

- P is the measured pseudo-range.
- ρ is true geometric distance from the satellite to the receiver antenna
- c is the light speed
- dT denotes clock offset of the receiver.
- dt refers to satellite clock bias.
- d_{ion} represents delay due to ionosphere
- d_{trop} is the delay caused by troposphere
- e includes measurement noise and multipath effect.

When satellite clock bias and atmospheric errors are known, pseudo-range equation can be expressed as:

$$P = \rho + c.dT + e \tag{2}$$

When a receiver has 'M' satellites in view, it must solve ' M ' equations. A minimum of four satellites is necessary to determine the receiver's position. Due to the nonlinear nature of pseudo-range measurements, they are typically simplified by assuming an *approximate* starting position for the receiver. Adjustments are then made to this initial position to determine the receiver's actual coordinates and clock offset. These equations can be organized into a matrix representation, with the GPS measurement equation represented as (Rajasekhar et al. 2021):

$$\delta P = A\delta U + n \tag{3}$$

where:

- δP is a pseudo range observations matrix

- A is a line of sight (LOS) matrix, with each element indicates the direction of the cosine vector from the receiver to the satellite.
- δU represents the state vector navigation error, which includes both the receiver's positional inaccuracies and the associated clock bias.
- n denotes the noise component affecting the measurement.

If more than four satellites are in view, the least square method estimates the receiver's position accurately. The Eq. 4 becomes as follows:

$$\delta U = \left(A^T A\right)^{-1} A^T \delta P \tag{4}$$

The matrix A includes the line-of-sight (LOS) vectors that define the directional relationship between the receiver and the observed satellites. The vector U, assumed to have a zero-mean, represents the error associated with the estimated position. The covariance of U can be determined by applying the generalized (or pseudo) inverse of matrix A. This approach provides insight into how satellite geometry influences the accuracy of position estimates.

$$\begin{aligned} cov\left(\delta U\right) &= E\left(\delta U \delta U^T\right) = E\left[\left(A^T A\right)^{-1} A^T \;\; \delta P \delta P^T A \left(A^T A\right)^{-T}\right] \\ &= \left(A^T A\right)^{-1} A^T \;\; dP \; dP^T A \left(A^T A\right)^{-T} \\ &= \left(A^T A\right)^{-1} A^T \;\; cov\left(dP\right) \;\; A \left(A^T A\right)^{-T} \end{aligned} \tag{5}$$

$cov\left(\delta P\right)$ Indicates pseudo range errors that are not correlated. A diagonal covariance matrix is obtained because it is statically independent. Assuming the variance of each satellite having equal range errors. Equation 5 becomes:

$$cov\left(\delta P\right) = \sigma^2{}_n \tag{6}$$

Equation 5 and 6 becomes:

$$E\left(\delta U \delta U^T\right) = \sigma^2{}_n \left(A^T A\right)^{-1} A^T A \left(A^T A\right)^{-T} = \sigma^2{}_n \left(A^T A\right)^{-T} \tag{7}$$

As $\left(A^T A\right)$ is symmetric, transpose is not required.

Therefore,

$$cov\left(\delta P\right) = \sigma^2{}_n \left(A^T A\right)^{-1} \tag{8}$$

$$\text{Let}, \boldsymbol{G} = \left(A^T A\right)^{-1} sothat cov\left(\delta P\right) = \sigma^2{}_n \boldsymbol{G} \tag{9}$$

Expanding above equation we get,

$$\begin{aligned} &\begin{bmatrix} \sigma_x^2 & cov\left(x,y\right) & cov\left(x,z\right) & cov\left(x,b\right) \\ cov\left(y,x\right) & \sigma_y^2 & 1 & cov\left(y,b\right) \\ cov\left(z,x\right) & 1 & \sigma_z^2 & cov\left(z,b\right) \\ cov\left(b,x\right) & 1 & 1 & \sigma_b^2 \end{bmatrix} \\ &= \sigma_n^2 \begin{bmatrix} G_{xx} & G_{xy} & G_{xz} & G_{xb} \\ G_{yx} & G_{yy} & G_{yz} & G_{yb} \\ G_{zx} & G_{zy} & G_{zz} & G_{zb} \\ G_{bx} & G_{by} & G_{bz} & G_{bb} \end{bmatrix} \end{aligned} \tag{10}$$

Satellite geometry will be measured with the help of these matrix elements.

Satellite geometry

The accuracy of the navigation satellite system, such as GPS and NavIC, is affected by the satellite geometry. It represents geometric locations seen by the receiver. For example, a representation of satellite geometry for two satellites is illustrated in Fig. 1, considering that the two satellites are in the center. Two arcs are drawn from each satellite. The initial arc is based on the actual distance separating the satellite and receiver as its radius, while the second arc is formed using the measured pseudo-range as the radius. The intersection of two arcs gives the possible user location (Meneghini and Parente 2020).

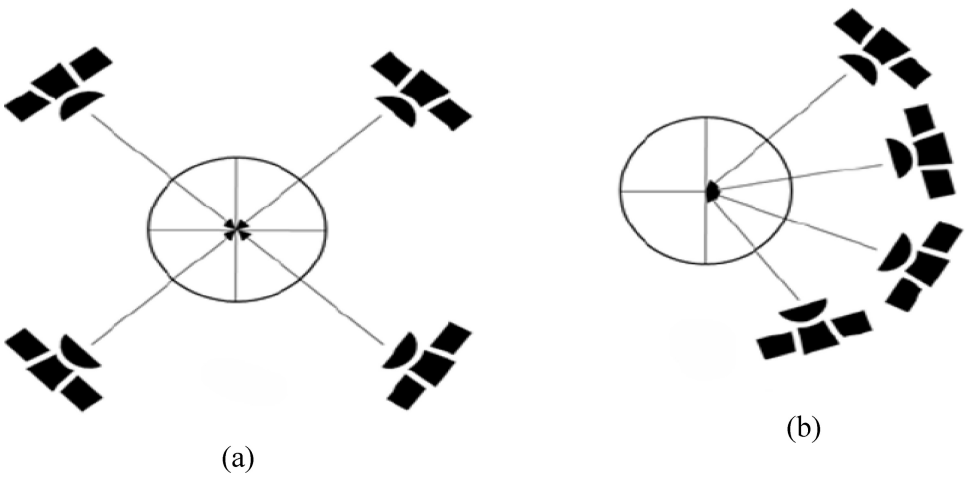


Fig. 1 (**a**) Good and (**b**) Poor satellite geometry

- When the satellites are widely spaced, Fig. 1(a), the small intersection area indicates lower uncertainty in position, resulting in good satellite geometry.
- The satellites are positioned close together, Fig. 1(b), the high inspection area indicates high position uncertainty, represents poor geometry.

To compute a user's position, a minimum of four satellites is essential. (Fig. 2 Meneghini and Parente 2020) illustrates good and poor satellite configurations using four satellites. When the satellites are well distributed, resulting in a lower GDOP value and more accurate positioning. If satellites are closer, a high GDOP is obtained, which indicates poor geometry. The best geometry can be achieved when one of the satellites is at the zenith, the remaining three form an equilateral triangle, and all four satellites form a tetrahedron shape.

Dilution of precision

Dilution of Precision (DOP) is mostly the geometry between the satellite and the receiver; it is a unitless factor that magnifies *errors* due to satellite geometry. DOP is also known as GDOP (Geometric Dilution of Precision). No observations are required to calculate DOP. Satellite orbit information or satellite almanac data is used to predict the DOP values. Dop is resolved into several types; each value is calculated using the diagonal elements of matrix G, which are independent of others (Cai and Gao 2007):

- Position Dilution of Precision (PDOP): measures the uncertainty in the three-dimensional position of the navigation solution.

$$PDOP = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}}{\sigma_n} = \sqrt{G_{xx} + G_{yy} + G_{zz}} \tag{11}$$

- Horizontal Dilution of Precision (HDOP): provides uncertainty in the navigation position's horizontal position (latitude and longitude).

$$HDOP = \frac{\sqrt{\sigma_x^2 + \sigma_y^2}}{\sigma_n} = \sqrt{G_{xx} + G_{yy}} \tag{12}$$

- Vertical Dilution of Precision (VDOP): indicates uncertainty in the vertical(altitude) of the navigation solution.

$$VDOP = \frac{\sigma_z}{\sigma_n} = \sqrt{G_{zz}} \tag{13}$$

- Time Dilution of Precision (TDOP): means uncertainty in the receiver clock.

$$TDOP = \frac{\sigma_b}{\sigma_n} = \sqrt{G_{bb}} \tag{14}$$

- Geometric Dilution of Precision (GDOP): GDOP defines the relation between position determination and measurement errors as a combination of all the other DOP's.

$$GDOP = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_b^2}}{\sigma_n} = \sqrt{G_{xx} + G_{yy} + G_{zz} + G_{bb}} \tag{15}$$

1/vol gives GDOP, where vol is formed by linking the four satellites and the receiver position, which is the volume of a tetrahedron. Maximum accuracy in point positioning is obtained when the satellites form a well-shaped tetrahedron around the receiver with the largest possible volume. In

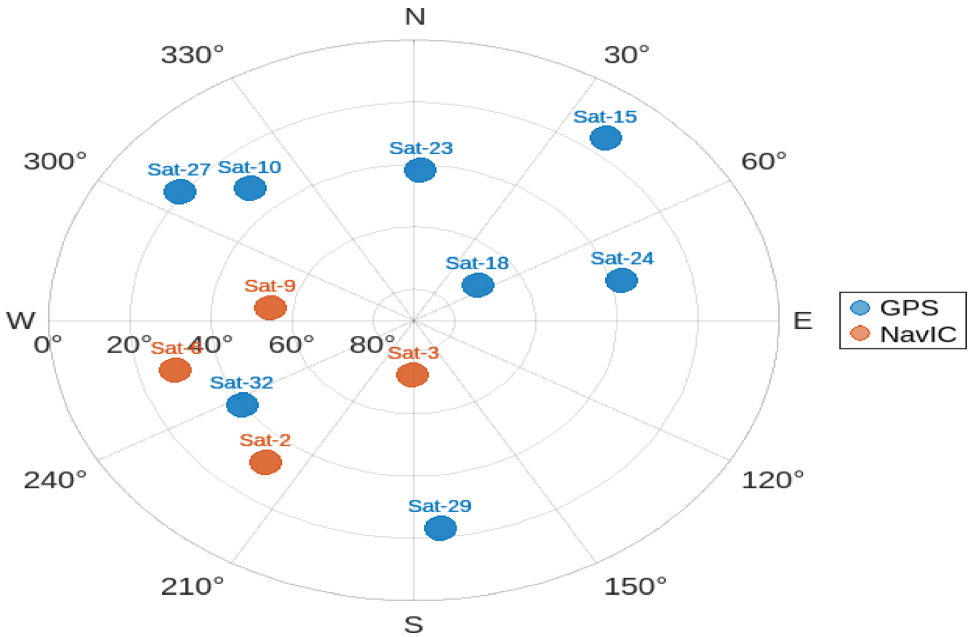


Fig. 2 Sky plot of all satellites in view at 8:00am

Table 1 DOP computation with all satellites at 8:00am

Constella-tion	PRN	Position			Azimuth Angle (in deg.)	Elevation Angle (in deg.)
		X	Y	Z		
GPS	23	1197244.723	14868621.4	21976633.07	1.838063301	41.5491317
	18	− 2731626.84	23634179.2	11625730.89	53.60401111	70.6364559
	29	395109.3241	21431899.2	− 15666448.12	174.4545144	23.044405
	15	− 13661997.41	8030525.54	20865083.7	38.96305741	14.7989432
	10	14943451.31	11478800.6	19025483.45	316.24588	31.3996419
	32	16808274.82	20538339.2	− 2456883.835	237.4374514	39.7670114
	27	19284606.06	7241591.01	16738496.37	305.5154442	18.8934966
	24	− 14789751.16	19170326	10046513.82	75.77468017	37.1261751
NavIC	2	24135090.4	30412280.1	− 16285283.34	218.672897	31.4968555
	3	5078350.33	41731262.4	2075588.792	181.218004	72.4389183
	6	35565921.8	22766457.5	− 791601.1114	254.775315	29.0471102
	9	25158606.7	31131890.6	13434531.72	276.598533	54.2615954

DOP values;

For GPS: GDOP-2.2085 PDOP-1.9537 HDOP-0.9072 VDOP-1.7303 TDOP-1.0299

GPS + NavIC: GDOP- 1.7976 PDOP-1.5703 HDOP-0.7863 VDOP-1.3593 TDOP-0.8748

such cases, the GDOP (geometric dilution of precision) is minimized, leading to improved position precision.

When signals from four satellites are used, GDOP can be directly computed and corresponds to the theoretical value derived from the geometry. For this, GDOP is widely used. In today's world, GDOP plays a significant role in determining positioning accuracy (Hollaus et al. 2006).

GPS position accuracy depends on both measurement errors and satellite geometry. User Equivalent Range Error (UERE) can represent measurement errors and biases and is determined as the square root of the several biases and error components. Positioning accuracy can be obtained by multiplying UERE with the Geometric Dilution of Precision (GDOP) (Liu et al. 2019).

$$GPS \text{ Position accuracy } = \text{ UERE} \times \text{ GDOP} \tag{16}$$

Receivers employ algorithms to choose a group of at least four satellites that yields the lowest GDOP. At least four satellites are necessary for positioning and clock offset estimation; more than four satellites are typically chosen to enhance the robustness and minimize accuracy degradation caused by subset selection. This method is widely applied in multi-GNSS constellations.

DOP terms can be interrelated as following relationship:

$$PDOP^2 = HDOP^2 + VDOP^2 \tag{17}$$

$$GDOP^2 = PDOP^2 + TDOP^2 \tag{18}$$

This study presents a novel, region-specific investigation into the enhancement of satellite navigation by integrating the global GPS constellation with India's regional NavIC system, analyzed explicitly over the Visakhapatnam region. While the general concept of multi-constellation GNSS is established, the originality of this work lies in its empirical assessment of NavIC's unique contribution—a system with a mix of geostationary and geosynchronous orbits—to improving satellite geometry and Dilution of Precision (DOP) in a localized Indian context. By collecting and processing real observational data from a permanent IGS station, the research moves beyond simulation to provide a practical validation of the significant accuracy gains achieved through this hybrid configuration. The results quantitatively demonstrate that the combined GPS + NavIC system consistently yields lower GDOP, PDOP, HDOP, VDOP, and TDOP values across a 24-h period, culminating in a tangible improvement in real-world positional accuracy, thereby offering a crucial insights for enhancing navigation precision and reliability for applications within the Indian subcontinent.

Results and discussions

Data from the Gitam University IGS station in Visakhapatnam (Lat-17.780868^{O}N & Lon-83.37606^{O}E) was collected on August 8, 2023, with a sampling interval of 15 s for analysis. The receiver-specific data was converted into the RINEX (Receiver Independent Exchange) format using NovAtel software. DOP values were computed for the entire day for standalone GPS and GPS + NavIC constellations.

At 08:00 h, 12 satellites, including GPS and NavIC, were visible. The LOS (line-of-sight) vectors along with the azimuth and elevation angle of each satellite at the particular epoch were determined. All DOP values (GDOP, PDOP, HDOP, VDOP) were calculated for standalone GPS and the combined GPS + NavIC constellation. The results are

Table 2 DOP computation with all satellites at 8:00pm

Constell-ation	PRN	Position			Azimuth Angle (in deg.)	Elevation Angle (in deg.)
		X	Y	Z		
GPS	2	− 15805307.29	16994078.2	13266368.34	65.5035155	31.758336
	7	− 3809348.872	24473427.5	9366976.46	76.04009894	70.4900075
	8	− 14920160.49	5159658.42	21333305.59	38.63452822	7.79520811
	9	2527800.887	21500348	− 15434550.42	180.0829077	24.097187
	13	17373533.03	4439972.27	19476736.62	314.7501106	13.5432545
	14	11037577.26	13653967.2	19996035.27	327.117423	38.7060061
	17	13321805.46	22892444.2	1247859.879	239.6065521	54.3515965
	19	16803651.16	19521629.7	− 7363199.194	226.8993935	30.5796902
	21	− 16349874.36	14068223.4	15403445.43	58.4026846	25.1320036
	30	3873265.924	20487000.4	16426075.63	350.9353888	62.9431595
NavIC	2	24373425.8	30350681.3	16367714.95	284.958703	54.4594304
	3	5280611.25	41855923.2	− 2092758.459	181.607824	65.8457591
	6	35506610.7	22593442.7	776066.7603	257.313697	29.7444972
	9	24883450	31118285.6	− 13620723.73	222.233192	34.5349779

DOP values;

For GPS: GDOP-1.7304 PDOP-1.5363 HDOP-0.8617 VDOP-1.2723 TDOP-0.7962

GPS + NavIC: GDOP- 1.5586 PDOP-1.3731 HDOP-0.7678 VDOP-1.1384 TDOP-0.7374

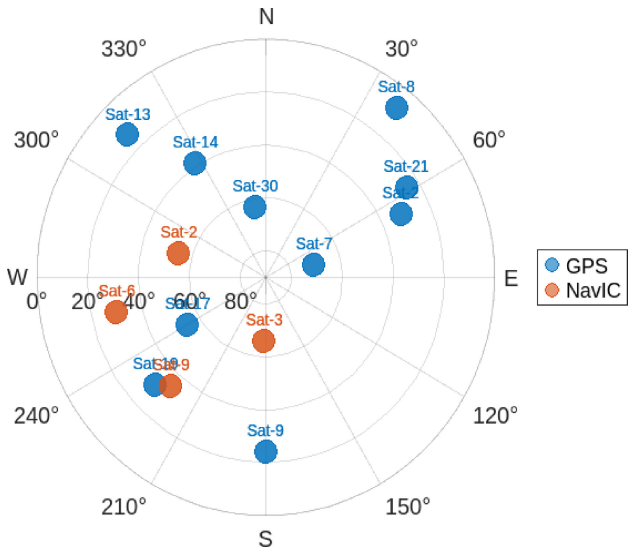


Fig. 3 Sky plot of all satellites in view at 8:00pm

presented in Tables 1 and 2. The satellite geometry is illustrated in the sky plot shown in Fig. 2

Table 1 represents all DOP values for GPS alone and GPS + NavIC. It clearly shows that combined constellation has better DOP values than GPS alone.

Figure 3 represents visibility of all satellites at 8:00 pm, there are 14 satellites available at that particular time. Line of sight vectors, position coordinates (X Y Z), azimuth and elevation angle of all these satellites mentioned in the Table 2. All DOP values are mentioned in Table 2 for two cases: for GPS alone and multi constellation. As per the table multi constellation gives better results.

Figures 4 & 5 shows the overall DOP for a whole day for GPS alone and GPS + NavIC constellation. From Fig. 4 the maximum GDOP value for GPS is 3.777631 and minimum GDOP value is 1.33675. From Fig. 5 the maximum GDOP value for GPS + NavIC is 2.44571571 and the minimum GDOP value is 1.15180941.

The Latitude &longitude variations for the day are shown in the Fig. 6 which is 8th august 2023.

Figure 7 shows the visible satellites for GPS and GPS + NavIC constellations. From Fig. 7, the maximum no. of satellites visible for GPS alone is 12. The maximum number of visible satellites for NavIC is 4. Figure 7 shows that maximum No. of visible satellites is 17. It is clear that by using a combined constellation, the visibility of the satellites also increased, which is the advantage of using a multi-constellation.

DOP values for every 2 h within a day is illustrated in the Table 3.the table represents no of satellites available in the particular time for GPS and GPS + NavIC. It is shown that GPS + NavIC gives DOP values in every 2 h than GPS standalone system.

Table 4 represents the position accuracy of standalone GPS and GPS + NavIC for every two hours by using Eq. (16). A typical UERE for any GNSS system is given to be between 3-6 m (Toldbo et al. 2022). In this,to analyze the performance, in terms of accuracy,5 m is considered as UERE, which is commonly used in GNSS performance analysis to represent range errors including ionospheric, tropospheric delays, multipath, and clock errors(Wang et al. 2024; Lee et al. 2008; Mukherjee et al. 2024). It can be observed that best accuracy of 6.958 m is achieved with GPS + NavIC combined constellation at 2Hrs of the day and the best accuracy for standalone GPS is 7.8895 m at 2Hrs of the day.

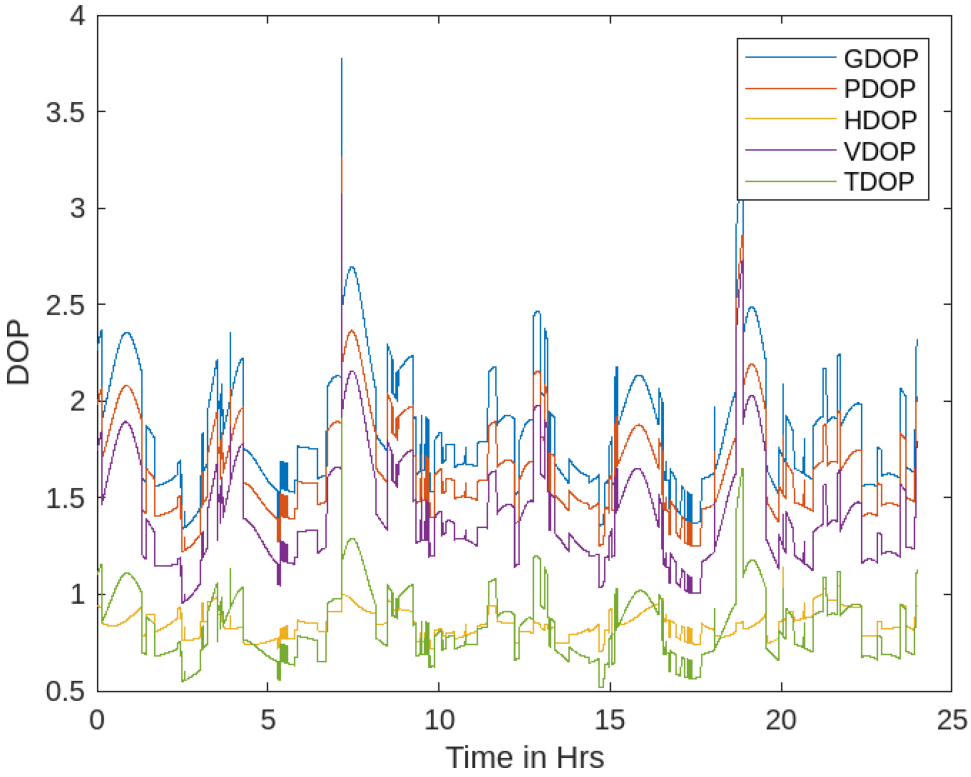


Fig. 4 DOP variations for stand-alone GPS

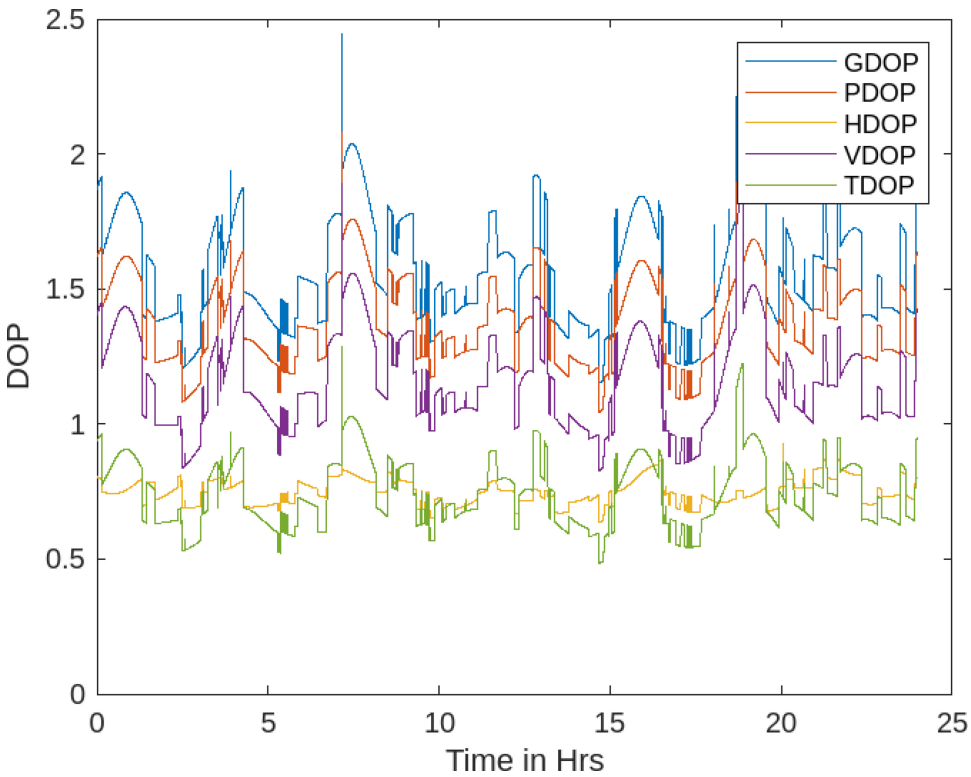


Fig. 5 DOP Variations for GPS + NavIC

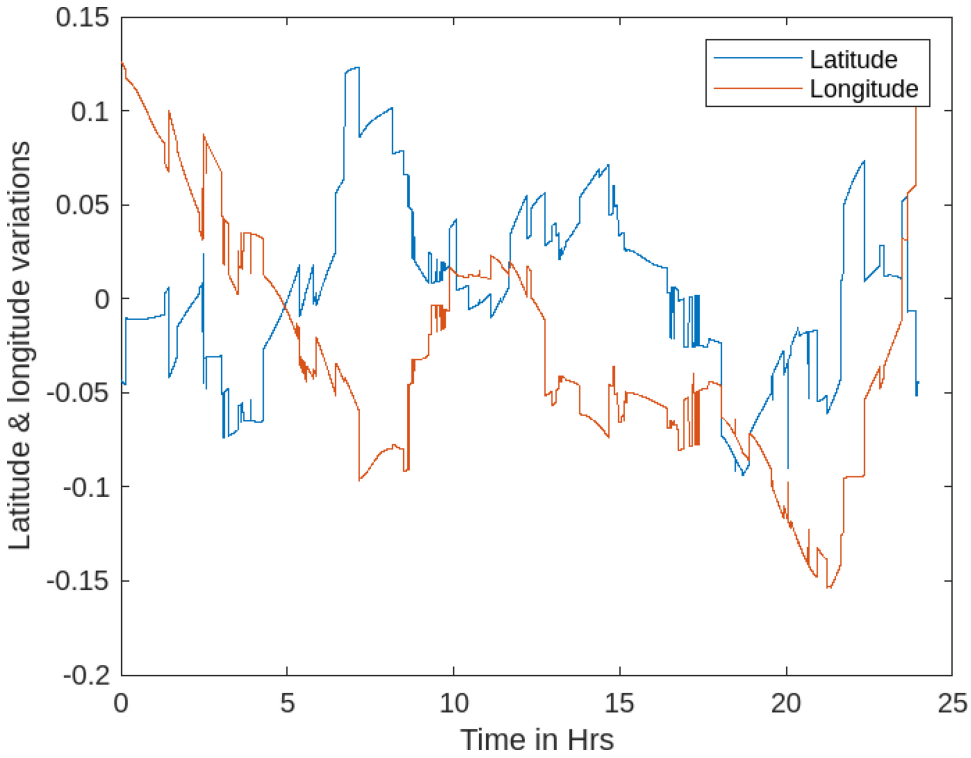


Fig. 6 Latitude &longitude variations

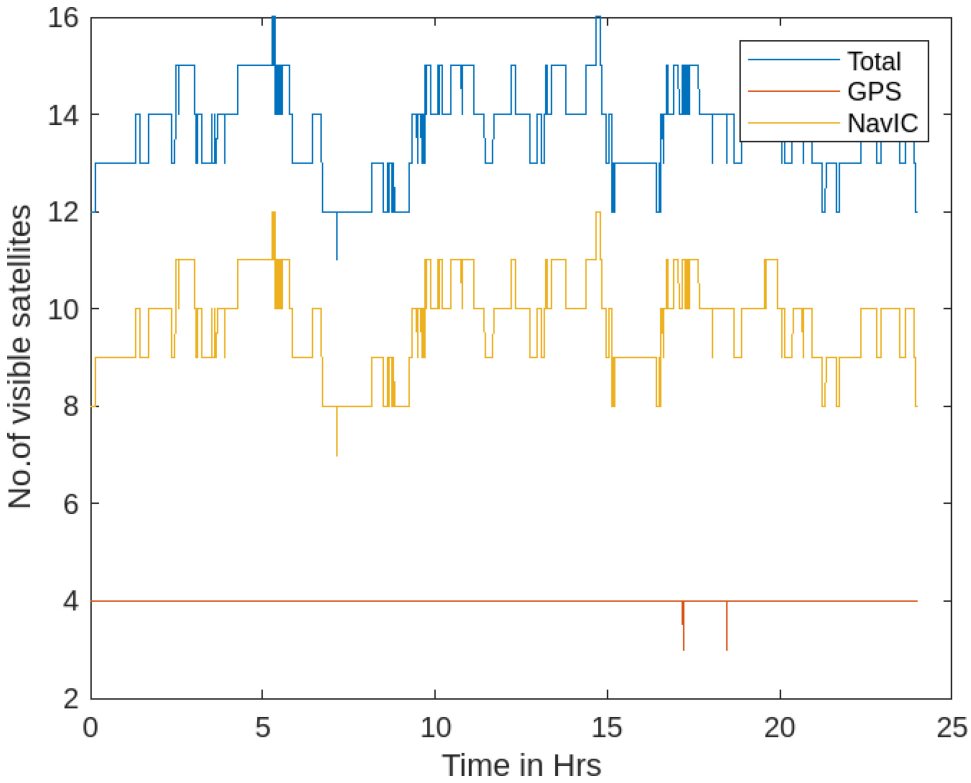


Fig. 7 No. of Visible Satellites. (GPS + NavIC)

Table 3 DOP analysis for every 2h

Time (in hrs.)	GPS PRN	NAVIC PRN	GDOP		PDOP		HDOP		VDOP		TDOP	
			GPS	GPS+NavIC	GPS	GPS+NavIC	GPS	GPS+NavIC	GPS	GPS+NavIC	GPS	GPS+NavIC
2	4	10	1.5779	1.3916	1.4177	1.2376	0.8316	0.7364	1.1481	0.9946	0.6928	0.6364
4	4	10	2.0912	1.7708	1.8519	1.5445	0.8226	0.7709	1.6592	1.3384	0.9712	0.8661
6	4	9	1.7619	1.5401	1.5801	1.3609	0.8582	0.7815	1.3267	1.1142	0.7794	0.7209
8	4	8	2.2085	1.7976	1.9536	1.5703	0.9071	0.7863	1.7302	1.3593	1.0299	0.8748
10	4	10	1.8292	1.5181	1.6423	1.3389	0.8182	0.7248	1.4241	1.1257	0.8053	0.7153
12	4	10	1.9247	1.6342	1.6949	1.4266	0.8531	0.7532	1.4646	1.2115	0.9121	0.7971
14	4	10	1.6547	1.3903	1.4995	1.2361	0.7949	0.7134	1.2715	1.0094	0.6997	0.6365
16	4	9	2.1073	1.8385	1.8491	1.6013	0.9139	0.8266	1.6074	1.3715	1.0107	0.9032
18	4	10	1.6248	1.4274	1.4629	1.2636	0.8188	0.7169	1.2122	1.0405	0.7071	0.6642
20	4	10	1.7304	1.5586	1.5363	1.3731	0.8611	0.7678	1.2723	1.1384	0.7962	0.7374
22	4	9	1.9557	1.7137	1.7159	1.4879	0.9348	0.8181	1.4388	1.2427	0.9382	0.8502
24	4	8	2.3168	1.8927	2.0232	1.6364	0.9372	0.8002	1.7931	1.4274	1.1287	0.9512

Table 4 Accuracy of the standalone GPS & GPS+NavIC combined consellation on the typical day

Time (in hrs.)	NavIC PRN	GPS PRN	Accuracy in meters	
			GPS	GPS+NavIC
2	4	10	7.8895	6.958
4	4	10	10.456	8.854
6	4	9	8.8095	7.7005
8	4	8	11.0425	8.988
10	4	10	9.146	7.5905
12	4	10	9.6235	8.171
14	4	10	8.2735	6.9515
16	4	9	10.5365	9.1925
18	4	10	8.124	7.137
20	4	10	8.652	7.793
22	4	9	9.7785	8.5685
24	4	8	11.584	9.4635

The flowchart for the proposed methodology is shown in Fig. 8.

Conclusion

Integration of GPS and NavIC in a multi-constellation GNSS configuration significantly enhances satellite geometry, leading to improving positioning accuracy. The multi -constellation results in lower GDOP and improves all DOP values compared to standalone GPS, resulting in a more stable and precise navigation solution. Additionally, the increased satellite visibility increases system reliability, ensuring better coverage and availability, especially in challenging environments. These results highlight the advantages of multi-constellation GNSS, demonstrating its ability to enhance positional applications through improved accuracy, robustness, and operational efficiency. Building upon this foundational analysis, future work will focus on expanding this multi-GNSS framework to include other global constellations like Galileo and GLONASS to achieve even greater robustness and global coverage, particularly in challenging urban environments. Further research will also investigate the development of advanced weighted-DOP satellite selection algorithms based on elevation and signal strength, and will explore the specific benefits of NavIC integration for high-precision techniques like Real-Time Kinematic (RTK) and Precise Point Positioning (PPP) to reduce convergence times.

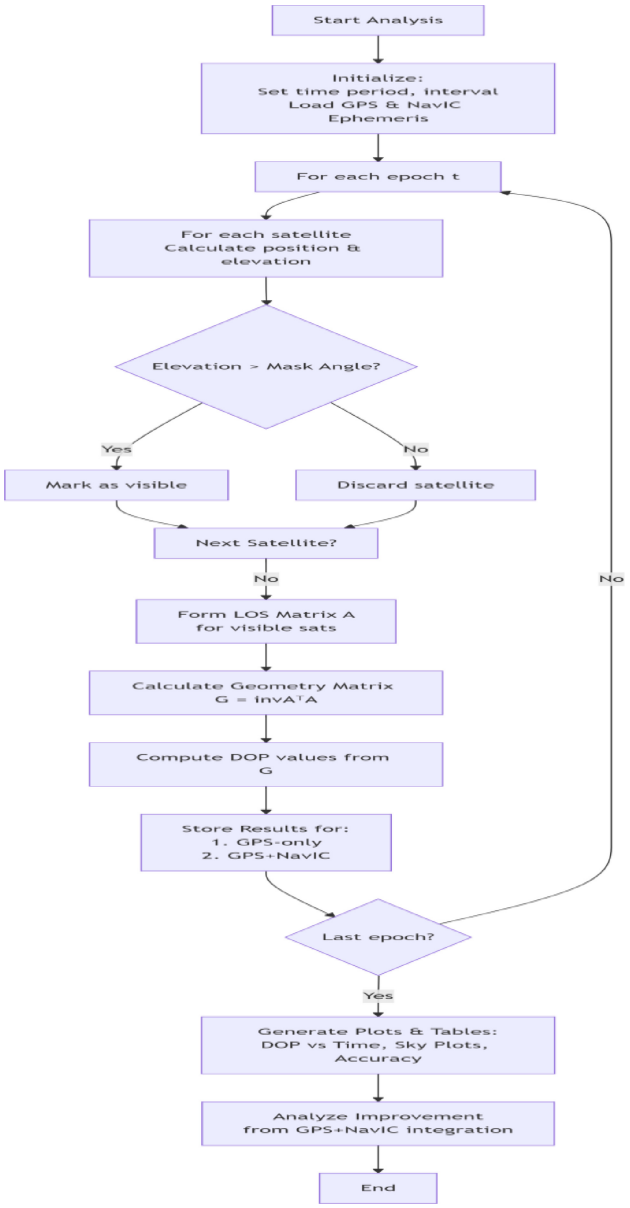


Fig. 8 Flowchart for the Proposed Methodology

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

Ansari, K.: Investigation of the standalone and combined performance of IRNSS and QZSS constellations over the Asia-Pacific region. Wirel. Pers. Commun. **130**(4), 2887–2901 (2023). https://doi.org/10.1007/s11277-023-10408-1

Bhattacharyya, S., Mute, D.: Kalman filter-based RAIM for reliable aircraft positioning with GPS and NavIC constellations. Sensors (Switzerland) **20**(22), 1–33 (2020). https://doi.org/10.3390/s20226606

Cai, C., Gao, Y.: Precise point positioning using combined GPS and GLONASS observations. J. Glob. Position. Syst. (2007). https://doi.org/10.5081/jgps.6.1.13

Gayathri, K.M., Thangadurai, N., Vasudha, M.P.: Positioning and signal strength analysis of IRNSS and GPS receiver in plain terrain along with foliage loss. Curr. Sci. (2017). https://doi.org/10.18520/cs/v112/i08/1738-1742

Hollaus, M., Wagner, W., Eberhöfer, C., Karel, W.: Accuracy of large-scale canopy heights derived from LiDAR data under operational constraints in a complex alpine environment. ISPRS J. Photogramm. Remote Sens. **60**(5), 323–338 (2006). https://doi.org/10.1016/j.isprsjprs.2006.05.002

Kotla, S. R., Fahmeen, S., Sultana, Q. and Reddy, D. K.: "Augmentation of navic with gps over indian region," International Journal of Advanced Trends in Computer Science and Engineering, vol. 8, no. 1.4 S1, pp. 202–205, 2019, https://doi.org/10.30534/ijatcse/2019/3181.42019.

Lee, Y.W., Suh, Y.C., Shibasaki, R.: A simulation system for GNSS multipath mitigation using spatial statistical methods. Comput. Geosci. **34**(11), 1597–1609 (2008). https://doi.org/10.1016/j.cageo.2008.01.004

Li, X., Zhang, X., Ren, X., Fritsche, M., Wickert, J., Schuh, H.: Precise positioning with current multi-constellation global navigation satellite systems: GPS, GLONASS, Galileo and BeiDou. Sci. Rep. **5**, 8328 (2015). https://doi.org/10.1038/srep08328

Liu, R., Wang, Y., Wang, J.: Evaluation on UERE and positioning accuracy of BDS. Chin. J. Space Sci. **39**(1), 118–128 (2019). https://doi.org/10.11728/CJSS2019.01.118

Meneghini, C., and Parente C.: "Temporal Analysis of GDOP to Quantify the Benefits of GPS and GLONASS Combination on Satellite Geometry of Precision); GPS (Global Positioning System); GLONASS (GlobalnayaNavigazionnayaSputnikovaya Sistema); Multi-GNSS (Global Navigation Satellite System) Constellation," 2020. [Online]. Available: www.ijacsa.thesai.org

Mukherjee, B., Gautam, P., Sain, K.: Machine learning assisted crustal velocity proxy: a case study over the Tibetan Plateau and its surroundings. J. Asian Earth Sci. **263**, 106004 (2024)

Pagoti, S.K., Vemuri, S.I.D.: Development and performance evaluation of Correntropy Kalman Filter for improved accuracy of GPS position estimation. Int. J. Intell. Networks **3**, 1–8 (2022). https://doi.org/10.1016/j.ijin.2022.01.002

Raja Sekhar, C., Dutt, V.B.S.S.I., Sasibhushana Rao, G.: GDoP estimation using simulated annealing for GPS and IRNSS combined constellation. Eng. Sci. Technol. Int. J. **19**(4), 1881–1886 (2016). https://doi.org/10.1016/j.jestch.2016.09.017

Rajasekhar, C., Dutt, V.B.S.S.I., Rao, G.S.: Weighted GDoP for improved position accuracy using NavIC and GPS hybrid constellation over Indian sub-continent. Int. J. Intell. Networks **2**, 42–45 (2021). https://doi.org/10.1016/j.ijin.2021.06.001

Rizos, C.: Multi-constellation GNSS/RNSS from the perspective of high accuracy users in Australia. J. Spat. Sci. **53**(2), 29–63 (2008). https://doi.org/10.1080/14498596.2008.9635149

Sarkar, S., Bose, A.: Studies on solution accuracy of GLONASS from India. Gyrosc. Navig. **7**(1), 39–49 (2016). https://doi.org/10.1134/S2075108716010119

Shi, J., Li, K., Chai, L., Liang, L., Tian, C., Xu, K.: Fast satellite selection algorithm for GNSS multi-system based on Sherman-Morrison formula. GPS Solut. (2023). https://doi.org/10.1007/s10291-022-01384-3

Teng, Y., Wang, J.: New characteristics of geometric dilution of precision (GDOP for multi-GNSS constellations. J. Navig. **67**(6), 1018–1028 (2014). https://doi.org/10.1017/S037346331400040X

Toldbo, C., Kiss, A., Törjék, N., Vázquez, C.A.T., Bényei, D.L., Therkelsen, M.: Deployment method and optimal placement of surface beacon navigation system for co-located lunar landings. Acta Astronaut. **193**, 432–443 (2022). https://doi.org/10.1016/j.actaastro.2022.01.003

Wang, Y., Zhao, X., Pang, C., Feng, B., Tong, H., Zhang, L.: BDS and GPS stand-alone and integrated attitude dilution of precision definition and comparison. Adv. Space Res. **63**(9), 2972–2981 (2019). https://doi.org/10.1016/j.asr.2017.11.032

Wang, Y., Sun, F., Wang, X., Gao, S.: Evaluation methods of BDS-3 ground-segment defensive capability oriented to satellite navigation countermeasures. Heliyon (2024). https://doi.org/10.1016/j.heliyon.2024.e30656

Xu, A., Xu, Z., Xu, X., Zhu, H., Sui, X., Sun, H.: Precise point positioning using the regional beidou navigation satellite constellation. J. Navig. **67**(3), 523–537 (2014). https://doi.org/10.1017/S0373463313000842

Zhao, L., Václavovic, P., Douša, J.: Performance evaluation of troposphere estimated from galileo-only multi-frequency observations. Remote Sens. (2020). https://doi.org/10.3390/rs12030373

Zhao, J., An, J., Wang, Z., Ai, S., Zhu, L., Zhang, B.: Signal quality and positioning performance of GPS/BDS-3/GLONASS/Galileo in polar regions. Adv. Space Res. **69**(6), 2541–2554 (2022). https://doi.org/10.1016/j.asr.2021.12.032

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