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Performance Evaluation of Standalone NavIC for the Indian Missile Program

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ABSTRACT

Global Positioning System (GPS) is used for navigational purposes in the missiles during developmental, trials, and war scenario deployment. In this paper, the authors demonstrate typical time and location-dependent visibility problems of the GPS satellites for the elevation angles higher than 60° over a large part of the Indian sub-continent and the adjoining water bodies over the Bay of Bengal and Arabian Sea, which has the potential to adversely affect the missile flights during developmental trials and war scenarios, especially for the low elevation cruise missiles. The Indian regional navigation satellite constellation NavIC can effectively mitigate this visibility problem and ensure system independence from a strategic viewpoint. In this work, the standalone position solution quality of NavIC is evaluated statistically and compared with GPS from the Test Range. Promising results will encourage using the Indian constellation NavIC to ensure better position solution quality and system independence from a defence perspective.

Keywords: GPS; NavIC; Test range; Position solution; DOP; Missile

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) is essential in missile testing and flights[1-2]. Multi-constellation GNSS now has multiple components- GPS of USA, GLONASS of Russia, Galileo of European Union, Beidou of China are the global constellations, and NavIC of India and QZSS of Japan are the regional constellations; it is seen that most of these constellations are controlled by foreign entities[3-5]. Combined use of all the constellations is generally practised in most civilian applications, termed multi-constellation use[5]. For the Indian defence requirements till now, GPS has primarily been used in almost all kinds of systems because of its early operation, availability, popularity, and reliability[1-2]. GLONASS was also considered an active alternative to GPS for Indian strategic applications. Still, the degradation of the GLONASS constellation due to the lack of active replenishment during early 2000 hindered this effort[6-7].

During the Kargil war scenario, GPS was denied in the conflicting region. This was the primary reason for the inception of the Navigation with Indian Constellation (NavIC/ IRNSS) project by the Indian Government[8], which has finally been implemented and maintained by the Indian Space Research Organization (ISRO). The NavIC project has faced initial technological challenges because of its distinct differentiators from the other constellations, mainly because of the use of the S-band and L-band[9]. Initial progress was slow; thus, commercial popularity was less than GPS for civilian and defense applications in India. However, slowly but steadily, this regional constellation has gained importance and popularity in both civilian and defence use from India[10-11].

In this manuscript, to begin the discussion, a typical location- and time-specific visibility problem of the GPS satellites over the Indian region has been highlighted. Special emphasis was placed on the water bodies surrounding the

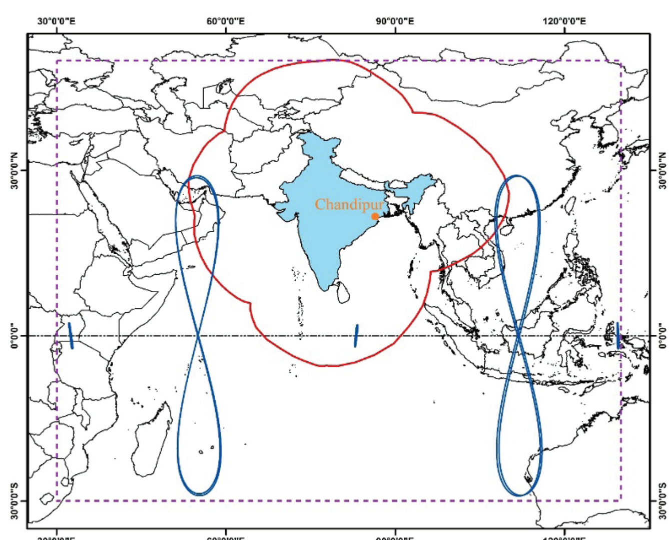

Figure 1. NavIC visibility boundary of Primary (red line) and secondary (Purple dot line) region and data collection location marked as orange.

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Eastern and Western sides of the country, where longer-range ammunition test trails are conducted, and these areas are also crucial for Indian Naval operations. The augmentation of GPS satellites with NavIC for such cases to mitigate this typical problem has been studied and discussed in detail. As an essential step towards the standalone use of NavIC for defence-critical applications, the characterisation of NavIC has been carried out further in this work for the Indian Test Range to understand and quantify the merits and challenges. Thus, this is a novel report on the standalone and hybrid NavIC performance for strategic defence applications, including the application of the Indian Navy.

The NavIC constellation consists of 7 satellites, of which three are placed in Geostationary Earth Orbit (GEO) and four in two Inclined Geosynchronous Orbits (IGSO). The primary service area of NavIC is the region within 1500 km from the Indian landmass, while the region lying between 30° South latitude to 50° North, 30° to 130° East longitude beyond the primary service area is known as the secondary or extended service area; the footprints of the NavIC satellites and the coverage areas are shown in Fig. 1. NavIC offers some distinct differentiators compared to the other global and regional constellations. The initially allotted frequency bands were L5 (frequency 1164–1189 MHz and bandwidth 24 MHz) and S-band (frequency 2483.5–2500 MHz band with 16.5 MHz)10-11; the S-band of operation is new to the GNSS community and has some definite merits and challenges concerning system design for the space and user segment. The wide separation between the L5 and S bands impacts the design and implementation of dual-frequency NavIC receivers and antenna[11-15]. It also affects the position solution quality using dual frequency NavIC receivers compared to the dual frequency GNSS receivers operating on L-band only. From a defence perspective, one definite advantage of the S-band operation is the low probability of jamming in this frequency, as most commercially available jammers only operate in the L band. In general, NavIC has certain definite advantages over GPS and other constellations. Those include signal availability from high elevation angles from India, the scope for calibration of the S-band radar ranges using S-band NavIC signals, and the benefits in ionospheric research because of the typical constellation structure; the details are presented in Goswami[11,15-18], *et al.*

The Indian Test Range is situated on the eastern Indian coast[19] over a distributed geographical area in the Bay of Bengal and various other locations in the periphery where various arrangements are placed to obtain accurate tracking data of the Missiles Under Test (MUT). Presently, Indian Test Range activities fall within the primary and secondary service regions of NavIC. Also, on the Western side, the Arabian Sea is an important area for the Indian Navy[20] because of strategic reasons within the Primary service area of NavIC. Thus, presently, all types of flight tests are covered fully in the service region of the present constellation of NavIC, and this work is crucial in understanding the performance of NavIC for the Indian test and related applications.

In the configuration of NavIC with seven satellites in the constellation, in standalone operation, it is claimed to offer an accuracy of less than 20 meters in open service (OS) and 5 meters in Restricted Service (RS)[12-14] within its primary service region. Expanding the NavIC constellation from 7 to 11 will enhance the service coverage area and increase the precession and accuracy parameters in the primary and secondary service areas.

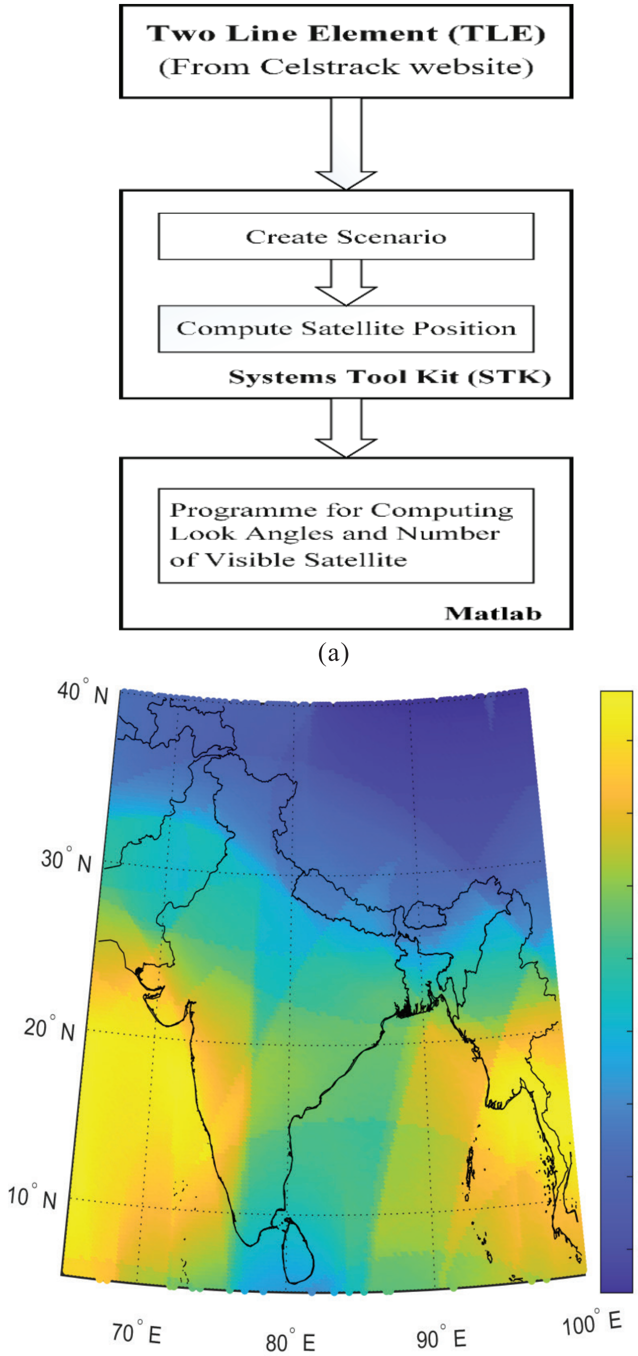
Earlier, many researchers have reported on the solution qualities of GPS, NavIC, and a combination of GPS+NavIC from India[9,11,15-16] but those works have not extensively checked the position performance for all possible combinations of GPS (L1) and NavIC, e.g., NavIC L5, NavIC S, NavIC (L5+S), GPS +NavIC L5, GPS+NavIC S, and GPS+NavIC, which is done in this work.

In the subsequent sections, the typical visibility problem of the GPS satellites over the Indian subcontinent region is presented together with the possible mitigation methods using NavIC, followed by the experiment and results on the comparison of solution quality performances in various constellation combinations.

2. TYPICAL VISIBILITY PROBLEMS OF GPS SATELLITES OVER INDIA AND SURROUNDING REGIONS

It has been repeatedly observed that there is a typical location- and time-specific GPS satellite visibility problem over India; during some periods of any day, over a large portion of India, no GPS satellite is available from higher elevation angles (>60°). During this period, if the user is within the visibility-constrained environment, where signals from the lower elevation angles are blocked due to natural and/ or artificial objects, the solution quality degrades- even leading to complete loss of position solutions[5]. The affected region also covers the Indian Test Range and the Bay of Bengal, which are crucial for GPS-based strategic applications. To study the problem in detail, the GPS satellite visibility pattern is studied through validated simulations using an in-house developed utility combining the recent Two Line Element (TLE) files for the GPS satellites[21], System Tool Kit (STK) from Analytical Graphics[22], and Matlab. This utility[23] uses the TLE text files to calculate the satellite orbital positions by STK. The results are then passed on to the Matlab program, which generates the visibility patterns of GPS satellites for any user-specified location. The results finally predict the non-availability of GPS satellites above 60° elevation angles for more than 15 minutes of cumulative time over a day. The non-availability of GPS satellites above 60° elevation angle for different locations in and around India is shown in Fig. 1 on 20 June 2023.

This non-availability of GPS satellites above 60° elevation for recognisable periods over the area of interest in the Test Range and over the Bay of Bengal areas is critical from the Indian defence perspective. The flights of the MUTs, which usually maintain a very low height of 5-10 meters during the terminal cruise phase, may not receive signals from the satellites from high elevation angles. During these periods, if the lower elevation angles during this phase are blocked, enough satellites for seamless navigation may not be available, and the satellite geometry may be poor, causing degraded solution quality or complete outage of position solutions. This



(a)

(b)

Figure 2. (a) Flowchart of the in-house developed GPS satellite visibility prediction simulation tool; and (b) Extent of the typical GPS visibility problem over the Indian region and the accumulated time of occurrence for different locations. The color bar on the right represents the accumulated time over a day during which no GPS satellite is visible above 60° elevation angles for 15 min. or more at the location. (Date of TLE data: 20th June 2023)

will directly affect the estimation of the trajectory of the MUTs as the position solution quality may be affected in the onboard GPS receiver. This outage of GPS signals is reflected in real-life GPS data collected from the MUTs through telemetry systems in the test range[24]. The same situation is also eminent over a substantial strategically important area of the Arabian Sea. This threat must be mitigated, and NavIC, combined with GPS, is a possible solution. This will also ensure self-reliance and system independence for defence applications from India.

Furthermore, incorporating NavIC into Indian missile systems will provide an additional competitive advantage[25]. NavIC offers superior benefits in countering multipath interference compared to GPS due to its utilisation of Binary Offset Carrier (BOC) modulation, unlike the Binary Phase Shift Keying (BPSK) scheme employed by GPS[9]. This advantage stems from the enhanced multipath-mitigation performance enabled by the narrower correlation peak achievable through the BOC modulation. This attribute is essential, particularly when considering the MUTs maintaining low cruising altitude and encountering enhanced multipath problems over land and sea surfaces. In tandem with dual frequency NavIC receivers, the system achieves a better resolution of the atmospheric Total Electron Content (TEC) compared to GPS[15]. This enhanced performance is attributed to the frequency separation between L5 and S frequencies in NavIC, a distinction from the L1 and L2 frequencies employed by GPS.

This attribute gains special significance in regions with equatorial characteristics, such as India, where accurate TEC estimation is essential. Furthermore, NavIC employs real-time ionospheric model corrections, further bolstering its superiority over GPS[26-27]. A notable drawback of GPS receivers is their finite time requirement for reacquisition and locking onto new satellite signals during signal fluctuations or complete signal loss. This issue arises due to the distinct pseudo-random (PN) codes each GPS satellite utilises. This phenomenon is unfavourable for implementation in high-reactivity missile systems. NavIC, however, circumvents this concern by its signal design. Additionally, NavIC boasts a superior and faster ephemeris update rate compared to GPS[11]. Moreover, the NavIC constellation's restricted code holds specific value for Indian defence applications. In summation, using NavIC technology confers many benefits, positioning it as a frontrunner in enhancing the capabilities of Indian defence applications.

The foregoing discussions establish the importance of NavIC for Indian defence applications. Therefore, the next important aspect is to study the accuracy and precession parameters of the standalone and hybrid NavIC operation for such strategic applications. For this purpose, extensive experiments have been performed, and the data analysed is based on the real-time data collected from the Indian Test Range, which is described in the subsequent sections.

3. DATA COLLECTION PLAN AND IMPLEMENTATION TO STUDY THE NAVIC PERFORMANCE

For the present study, data was collected from four locations (L1, L2, L3 & L4) as shown in Fig. 3 of the location, which is situated within the primary service region of the NavIC during June-July 2021. Though closely spaced, the four locations have varied terrain environments- one on the seashore, one on an island surrounded by vegetation, one on the plain land, and the last on a hilltop. However, the exact terrain of the locations is not revealed in the manuscript due to strategic requirements. An IRNSS-GPS-SBAS (IGS) receiver developed jointly by ISRO and Accord Software and Systems Pvt. Ltd. that can use L5, L1, and S bands of NavIC is engaged for data collection. The data collection schematic is shown in Fig. 4; data was collected in a laptop in GPS, NavIC L5, NavIC S, NavIC (L5+S), GPS+NavIC L5, GPS+NavIC S, and GPS+NavIC (L5+S) modes from the IGS receiver. Collected data is statistically analysed for the values of peak-to-peak variation in latitude, longitude, and altitude. Also, the two-dimensional (2d) and three-dimensional (3d) precession parameters are calculated following the formulas used by Santra[28], *et al*.

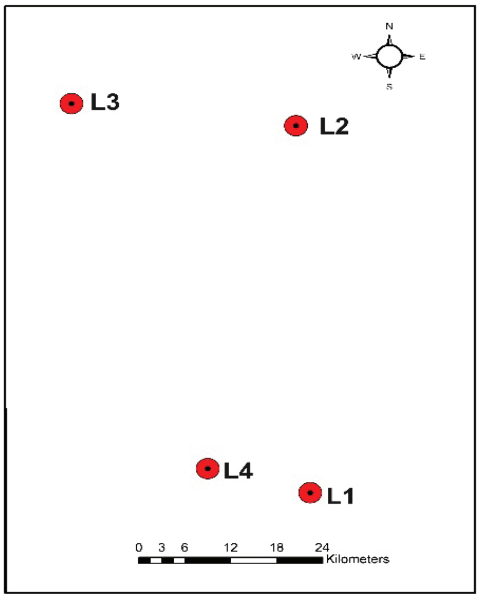


Figure 3. Data collection locations with varying terrain conditions.

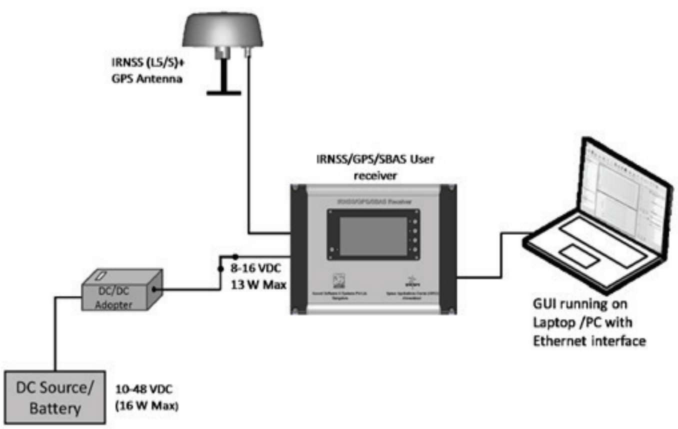


Figure 4. Data recording schematic diagram using the IRNSS-GPS-SBAS (IGS) receiver.

NMEA (National Maritime Electronic Association) data was recorded in the computer over the USB port, and receiver-specific raw data was collected over the TCP/IP port. Using software provided by the vendor, the acquired raw data was transformed into .csv and Receiver Independent Data Exchange Format (RINEX) files; useful ASCII data was retrieved from the NMEA files.

4. RESULTS AND DISCUSSIONS

Various statistical parameters are used to quantify the performance of the navigation systems under consideration. 2DRMS (Distance Root Mean Square) is a statistical measure frequently used in geospatial and navigation contexts to quantify the accuracy of position measurements in two-dimensional space (latitude and longitude). Essentially, 2DRMS provides a single value representing the overall scatter or error in position data, offering insight into the precision and consistency of location measurements. In satellite navigation, the Circle of Error Probable (CEP) is a statistical measure defining a circular boundary within which 50 % of position measurements are expected to fall. It represents the accuracy of a navigation system's positioning capability.

Like the Circle of Error Probable (CEP) in two dimensions, the Sphere of Error Probable (SEP) estimates the positioning accuracy in three-dimensional space, accounting for errors in both horizontal and vertical dimensions. A smaller SEP value indicates better accuracy and tighter clustering of position measurements around the actual position. Mean Radial Spherical Error (MRSE) is another metric used to quantify the accuracy of position measurements in three dimensions for satellite navigation solutions that represent the average radial distance between a set of measured positions and their corresponding actual or intended positions, all calculated with respect to a common centre. The solution quality matrices Circle of Error Probable (CEP), Spherical Error Probable (SEP), and Mean Radial Spherical Error (MRSE) are computed using Eqn. 1 to Eqn. 4 following Santra[28], *et al.*

$$2DRMS = 2\sqrt{\sigma_x^2 + \sigma_y^2} \quad (1)$$

$$CEP = 0.62\sigma_y + 0.56\sigma_x; \quad provided\ that\ \frac{\sigma_y}{\sigma_x} \succ 0.3 \quad (2)$$

$$SEP = 0.51\left(\sigma_x + \sigma_y + \sigma_z\right) \quad (3)$$

$$MRSE = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \quad (4)$$

The solution quality parameters for different combinations in standalone and hybrid GPS and NavIC operations are shown in Table 1. For the position solution of all the locations, GPS only 2DRMS is found to be within 1.7 m, CEP within 1.1 m, SEP within 1.6 m, and MRSE within 2m; in NavIC L5-only operation, 2DRMS lies within 4.5 m, CEP within 1.7 m, SEP within 2.8 m, and MRSE within 3.8 m; in NavIC S-only operation, 2DRMS within 6m, CEP within 2.5 m, SEP within 2.3 m and MRSE within 4.8 m; combination of NavIC L5 and S provides 2DRMS 4.2 m, CEP 1.6 m, SEP within 2.5 m and MRSE within 3.5 m.

However, combination with GPS+NavIC L5 provides 2DRMS within 1.32 m, CEP within 1.1 m, SEP within 1.3 m, MRSE within 1.7m and GPS+NavIC S provides 2DRMS within 1.4 m, CEP within 1.05 m, SEP within 1.4 m, MRSE within 1.5 m; whereas GPS+NavIC (L5+S) provides 2DRMS within 2 m, CEP within 1.6 m, SEP within 1.7 m, MRSE within 2.2 m. Thus, the best 2D and 3D position solutions are provided in GPS+NavIC S combinations.

Satellite geometry is one of the crucial factors for navigation accuracy as it determines the quality of the

Table 1. Comparison of position solution quality for standalone and hybrid GPS and NavIC solutions in open sky, static operation during June-July 2021 (Data volume for each set: 24 hrs, 86,400 epochs @1 Hz)

Location	Mode	Precision parameters (m)				Standard deviation (m)		
		2DRMS	CEP	SEP	MRSE	E	N	U
L1	GPS L1	1.595	1.079	1.565	1.950	0.773	1.041	1.645
	NavIC L5	4.250	1.697	2.641	3.172	0.898	1.925	2.355
	NavIC S	5.388	2.136	2.097	5.017	1.086	2.465	4.232
	NavIC (L5+S)	4.044	1.578	2.465	3.148	1.040	1.940	4.206
	GPS+NavIC L5	1.310	1.067	1.333	1.650	0.607	0.651	1.416
	GPS+NavIC S	1.239	1.020	1.233	1.490	0.497	0.590	1.268
	GPS+NavIC (L5+S)	1.877	1.184	1.693	2.202	0.679	0.647	1.992
L2	GPS L1	1.540	1.021	1.512	1.968	0.232	0.136	0.634
	NavIC L5	4.272	1.590	2.734	3.868	0.274	0.573	0.591
	NavIC S	5.335	2.345	2.262	4.902	0.286	0.603	0.606
	NavIC (L5+S)	4.181	1.541	2.357	3.463	0.508	2.027	1.302
	GPS+NavIC L5	1.311	1.028	1.426	1.498	0.192	0.278	0.366
	GPS+NavIC S	1.179	1.041	1.305	1.351	0.242	0.172	0.468
	GPS+NavIC (L5+S)	1.900	1.375	1.634	2.176	0.353	0.278	0.612
L3	GPS	1.755	1.074	1.492	1.918	0.420	0.827	1.679
	NavIC L5	4.162	1.626	2.792	3.120	1.433	0.668	1.412
	NavIC S	5.812	2.170	2.416	4.610	1.124	0.844	2.770
	NavIC (L5+S)	4.183	1.597	2.240	3.366	0.928	0.574	1.871
	GPS+NavIC L5	1.309	1.069	1.235	1.444	0.583	0.758	1.081
	GPS+NavIC S	1.196	1.044	1.228	1.317	0.345	0.727	1.629
	GPS+NavIC (L5+S)	1.874	1.467	1.518	2.198	0.463	0.814	1.307
L4	GPS	1.714	1.074	1.407	1.798	0.450	0.729	1.580
	NavIC L5	4.387	1.486	2.219	3.708	0.626	1.831	1.895
	NavIC S	5.352	1.987	2.140	4.775	1.626	1.445	3.085
	NavIC (L5+S)	4.097	1.222	2.327	3.482	1.139	2.556	2.633
	GPS+NavIC L5	1.929	1.521	1.627	2.188	0.379	0.536	0.990
	GPS+NavIC S	1.130	1.029	1.127	1.127	0.398	0.326	1.485
	GPS+NavIC (L5+S)	1.836	0.754	1.494	1.903	0.782	0.480	1.667

Table 2. Comparison of average dilution of precision of GPS, NavIC and GPS+NavIC hybrid solutions in open sky condition in during July 2021 at Locations L1 to L4

Location	MODE	GDOP	PDOP	HDOP	VDOP	TDOP
L1	GPS	2.403	2.109	0.994	1.854	1.149
	NavIC	5.061	4.078	2.407	3.290	2.996
	GPS+NavIC	1.896	1.556	0.794	1.334	1.082
L2	GPS	2.007	1.768	0.869	1.538	0.949
	NavIC	4.460	3.616	2.144	2.912	2.610
	GPS+NavIC	1.941	1.592	0.763	1.397	1.111
L3	GPS	1.979	1.758	0.904	1.504	0.906
	NavIC	4.667	3.790	2.159	3.112	2.722
	GPS+NavIC	1.729	1.420	0.762	1.196	0.986
L4	GPS	2.130	1.872	0.956	1.602	1.012
	NavIC	4.248	3.475	2.002	2.833	2.438
	GPS+NavIC	1.786	1.473	0.789	1.242	1.009

positioning signals received by a GNSS receiver[29]. An optimal geometry, with satellites spread out across the sky and at different elevations, reduces the potential for position errors caused by signal interference, signal blockage, or geometric dilution of precision (GDOP), ultimately resulting in more accurate and reliable GPS positioning. To understand better, the DOP values are presented in Table 4 for all four locations due to varied terrain environments.

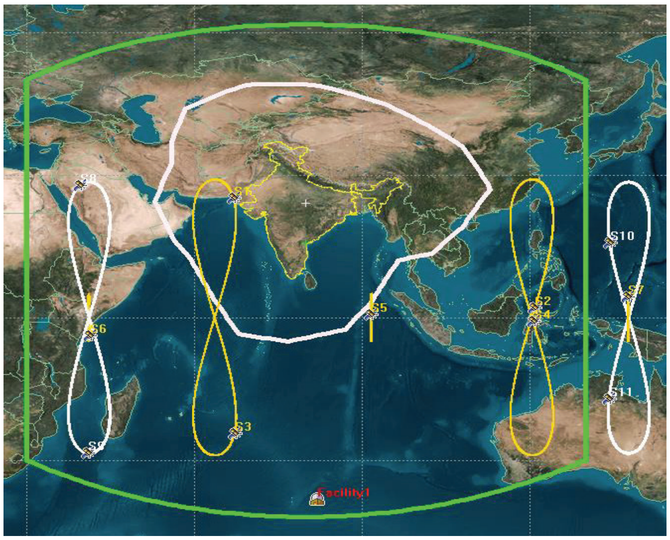


Figure 5. NavIC Expansion plan[29].

The satellite constellation geometries are quantitatively shown in Table 2 in terms of Dilution of Precision (DOP) values- for geometric (GDOP), position (PDOP), horizontal (HDOP), vertical (VDOP), and time (TDOP). NavIC DOP values are considerably worse than GPS values due to the typical constellation configuration of only seven satellites (6 operational throughout the data recording period); hybrid operation offers better satellite geometry than any of the individual constellations.

The constellation and service area of NavIC are expected to grow in the future. According to the current plan, more satellite launches will enhance the NavIC constellation from 7 to 11 satellites, as indicated in Fig. 5. The geometric Dilution of Precision (GDOP) for the Indian region is anticipated to be within 2.5, with 11 satellites in orbits[30]. A NavIC satellite (NVS 1, PRN #10) was launched on May 21, 2023[31], which will broaden the service area and improve the DOP values.

Thus, standalone NavIC signals can be utilised for defence applications to achieve self-reliance during both peace and war scenarios and will help in a significant paradigm shift in the GNSS environment for the Indian Sub-continent.

5. CONCLUSIONS

This work presents the importance of NavIC as the satellite-based navigation for the Indian strategic applications for self-reliance. Specifically for the Test Range applications, this work presents the advantages and performance of NavIC using real-time data and well-designed simulation. It is seen that the typical problem of time- and the location-specific problem of GPS in obtaining signals from high elevation angles is mitigated using NavIC both in the eastern Indian side under the areas of interest for the Indian Test Range and in the strategically important area of the western part. The achievable precision of NavIC L, S, and L+S dual frequency operation is also presented using real-time data from multiple locations in the Test Range. It is noted that, with six operational NavIC satellites in the constellation, GPS+ dual band NavIC provides the best satellite geometry and solution quality. However, as per situational demand, standalone NavIC can provide precision below 5 m 2DRMS solution, sufficient for most Test Range requirements. This work, based on real data, thus shows the positioning capability of NavIC for Test Range applications.

NavIC differential mode of operation (dNavIC) and Real Time Kinematic (RTK) are now under active research phases; future implementation would noticeably improve the position solution quality. Precise Point Positioning (PPP) for NavIC constellations is also under progress, which will enhance the standalone NavIC performance and support RTK. Future NavIC base stations operating close to strategic places will improve solution accuracy when NavIC rovers are used with NavIC RTK and PPP solutions. Together with the expanded operational area, a network of NavIC reference stations or a constantly operational network of reference stations (CORS) would improve the continuity and utility of NavIC for critical defence applications.

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