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NavIC performance over the service region: availability and solution quality

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Abstract. Navigation with Indian Constellation (NavIC) is designed and deployed by Indian Space Research Organization (ISRO) as an indigenous, regional navigational system to provide precise PVT information over the Indian region and surrounding areas. This paper presents a detailed analysis of NavIC visibility under open sky and constrained condition over the service region using an in-house developed simulation tool, the effects of NavIC satellite geometry on single-point solution accuracy and NavIC single and dual frequency solution performances. The results show the potential of NavIC as an alternative navigation system for India and the neighbouring countries in south and south-east Asia, and over an economically important area containing major sea-routes. Even in constrained-visibility conditions, NavIC with its typical constellation design can offer seamless navigation solution over a large region of the globe; the unique S-Band NavIC signal supports enhanced accuracy for stand-alone operation. The results would be beneficial for understanding the potential of NavIC for the user community.

Keywords. IRNSS; NavIC; visibility; PDOP; accuracy; precision.

1. Introduction

Global Navigation Satellite System (GNSS) provides precise positioning, velocity and timing (PVT) information. Currently many global (GPS, GLONASS, Galileo, BeiDou) and regional (NavIC and QZSS) systems are in operation and all signals are available from the Indian region due to the typical geographic location. But from strategic viewpoint and for system independence, a self-regulating and indigenous navigation systems is planned and implemented by Indian Space Research Organization (ISRO)- Indian Regional Navigation Satellite System (IRNSS) with operational name NavIC (Navigation with Indian Constellation). The space segment of NavIC consists of 7 satellites- 4 in Geosynchronous and 3 in Geostationary orbits, and NavIC Standard Positioning Service (SPS) signals are transmitted on L5 and S frequency bands [1]. NavIC central service area includes India and 1500 kilometres around the Indian boundary; the extended service may also be obtained over a region lying between 30° S to 50° N Latitude and 30° E to 130° E. It covers the Indian Ocean, world's third largest oceanic divisions containing major sea routes connecting the Middle East, Africa and East Asia with Europe and the Americas, and provides maritime route for nearly 40% of the world's offshore oil transportation [2, 3]. As a new regional constellation with satellites in GEO or GSO, NavIC has attracted the interest of the global stakeholders [3–5]. This encouraged the researchers to assess the availability, accuracy and signal characteristics of NavIC in standalone or in hybrid operation with GPS.

Studies on NavIC and its capabilities can be found from Indian and international researchers emphasizing the growing interest and potential of NavIC. Studies on NavIC and NavIC+GPS hybrid satellite geometry and the improvement in hybrid operation is found in [6–8]. Advantages of the geosynchronous satellites in terms of visibility in NavIC+GPS operation is predicted using STK-based simulation from India [9, 10]. Integration of NavIC L5 with GPS Block IIF (L5) and III (L5) observations showed improvement in the baseline estimation precision with respect to NavIC L5 only operation [11]. Analysis of the availability, reliability, geometry and potential of NavIC in hybrid operation with GPS and/or GLONASS through simulation are also presented [12]. A detailed study on SPS dilution of precision analysis for a grid of locations covering NavIC service area is presented in [3]. Results on NavIC SPS and RPS (Restricted Positioning Service) and satellite geometry from Christmas Island, Perth and Darwin, Australia are done [13]. Results on the initial assessment of hybrid NavIC L5 operation with GPS, Galileo and QZSS L5/E5a signals show the advantages of L5/E5a combination over L1/E1 operation [14]. A novel approach through estimated Differential Intersystem Biases (DIB) at

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L5 frequency for GPS, Galileo, QZSS and NavIC shows higher ambiguity resolution for the combined quad-constellation ($\sim$67%) than classically differenced observations for the individual constellations with a selected pivot satellite for each of the four constellations [15]. Integrating NavIC with GPS IIF, lower Ambiguity Dilution of Precision (ADOP), bootstrapped success rate and advantages of the combination have been studied. Better solution accuracy in hybrid (GPS L1+NavIC L5+S) operation in comparison to individual-frequency operation (L5 or S) of NavIC is also predicted [16].

In these studies, authors mostly have presented results based on simulation by dividing the service region into discrete increasing steps and considering only L5 NavIC signal. To assess the system performance, signal availability and satellite geometry is to be studied in more details, specifically for the central service region of India and surrounding countries. Another new attribute of NavIC is the use of S-Band signal that has not been taken into consideration. To have an exhaustive understanding of NavIC capabilities, more detailed analyses including S-Band signal are to be carried out and such efforts have been taken up in this work.

The objectives of this work are to explore the capabilities and advantages of NavIC over the service region in providing system independence and redundancy through (1) study of the NavIC availability over service area in open sky and constrained visibility conditions, (2) study of the impact of NavIC satellite geometry on solution accuracy and (3) study of the solution accuracy and precision of NavIC in L5 and S bands based on real-time data.

2. Simulation tool

To achieve the first objective, we developed a reliable simulation tool for extending the analysis over the entire service region by integrating *Systems Tool Kit (STK)* from Analytical Graphics Inc. [17] and *Matlab*. Two Line Element files (TLE) for all NavIC satellites [18] are downloaded from Internet and passed on to *STK* for computing the satellite positions in Earth Centre Earth Fixed (ECEF) coordinate system over a calendar day with a step size of 1 minute and the computed satellite positions are fed to *Matlab*. The schematic of the simulation blocks is shown in figure 1. To calculate the number of visible satellite and elevation, azimuth angles of the satellites, observation location sites are chosen separated by 0.5° each in latitude and longitude within the NavIC service region. 10° optimal elevation mask angle is considered in the simulation, higher than the recommended value of 5° [19]. The simulated results are validated with high confidence by comparison of the results with real-time NavIC data from different locations of India, for varying observation time and using multiple hardware configurations, and this validated

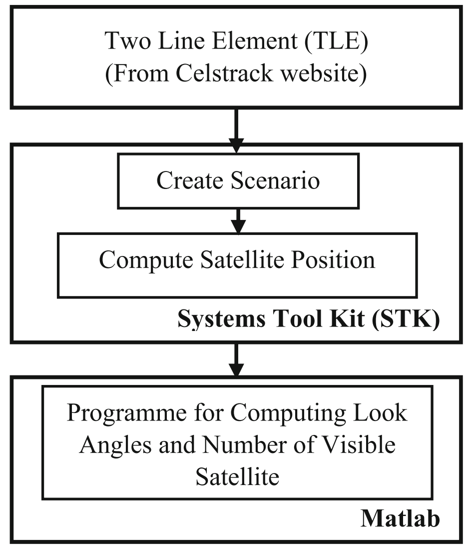


Figure 1. Block diagram of NavIC visibility prediction simulation tool

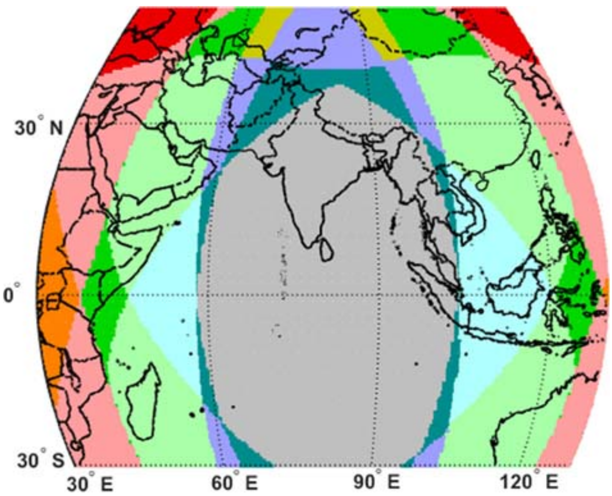
simulation tool is used for the general analysis over the service region.

3. NavIC visibility over the service region

Availability of any GNSS system is defined by the signal availability over a specified region and can be measured in terms of number of visible satellites from any location situated within it [20]. The simulation method discussed earlier is used to generate the NavIC satellite visibility patterns with 10° elevation mask over a day for the service region and the result is shown in figure 2. It may be seen that, except for a small area in the extreme north India, always 7 usable NavIC satellites are visible over the whole Indian landmass and at least 6 NavIC satellites are always visible from the whole country. For many adjacent regions of India or for several countries of the south-east Asia, a 7-satellite NavIC constellation would always be available. Except for the regions situated in extreme left and right top corners of the service areas, at least 4 NavIC satellites would always be visible for the users.

To realize the NavIC visibility pattern in constrained environments such as under deep foliage or within urban canyon where the low elevation angles are obstructed by man-made and/or natural objects, simulation of satellite visibility with 20° and 30° elevation masked condition is done for 24-hours and the results are shown in figure 3.

Figure 3(a) suggests that for 20° elevation masked condition, NavIC is capable to provide stand-alone position solution from India along with adjacent neighbouring countries. For more constrained condition of 30° elevation mask as shown in figure 3(b), the region for concurrent visibility of at least 4 NavIC satellites reduces along with



Colour Code	Maximum No. of Satellites	Minimum No. of Satellites
	7	6
	7	5
	7	4
	6	5
	6	4
	5	4
	5	3
	Always 7	
	Always 6	
	Always 4	

Figure 2. NavIC visibility over the service region with 10° elevation mask for one day

the NavIC-only solution probability. Users from southern India and Sri Lanka have the advantage of concurrently receiving 6–7 NavIC satellite signals even in such constrained situations while from the middle and northern part of India, the average number of visible NavIC satellites is 5 or less.

To have a closer look at the situation for the central service area, a simulation of the NavIC visibility for 30° elevation masked condition is done for 24hours and the result is shown in figure 4. Under such a degraded visibility condition, standalone NavIC position solution is not always possible for locations situated within an inverted triangular-shaped region having its tip nearly at (20° N, 80° E) and the region expands horizontally as the observation point moves northwards with increasing latitude. For the remnant parts of India, seamless NavIC stand-alone solutions are still possible. It is reported that in constrained visibility environments, NavIC significantly augments GNSS service over the Indian region [21]. The current simulation results confirm the results on the availability of NavIC satellites in all-in-view and/or within constrained environments. The results confirm the capability of NavIC and for confidence-building among the potential NavIC users from India and the adjacent regions [4].

4. Impact of satellite geometry on position solution

Satellite geometry, or distribution pattern of satellites in the sky, is quantitatively expressed in terms of Dilution of Precision (DOP) and affects the position solution accuracy. 3-dimensional (3d) RMS position error is proportional to Position Dilution of Precession (PDOP), the related DOP term for 3d solution, as given by the following equation (1)

$$3d\,Rms\,Position\,Error = UERE \times PDOP \tag{1}$$

where User Equivalent Range Error (UERE) represents the cumulative RMS values of other errors and biases. Thus, favourable DOP values play an important role in mission planning using any constellation. Detailed of the errors considered in the UERE calculation for NavIC Single Point Positioning (SPS) service can be found in [12].

An attempt is now made to study the effect of satellite geometry (or PDOP) on NavIC solution accuracy. Using long-term NavIC data recorded in dual-frequency (L5+S) mode, PDOP variations and its impact on position error are studied. Instantaneous 3d position errors for each observation epoch are calculated using the method described in [22] as per the following equation (2):

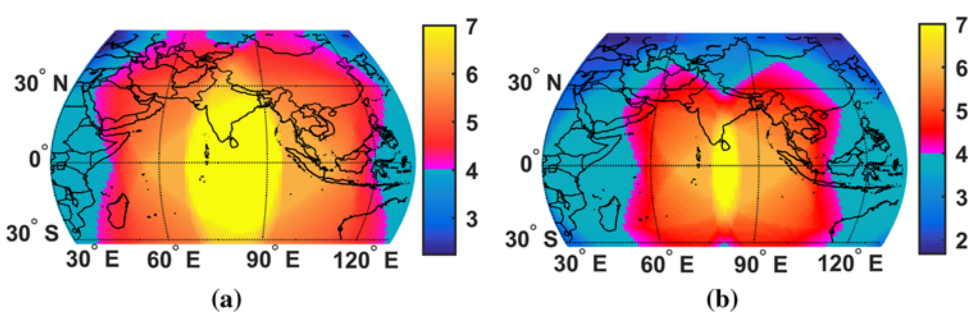
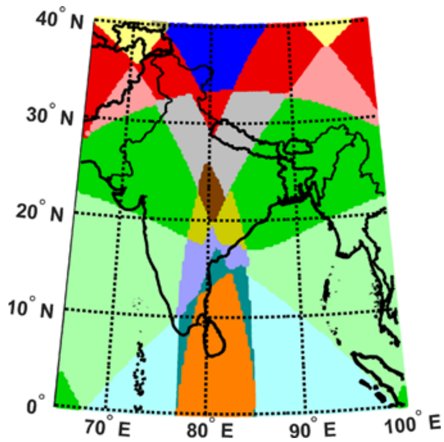


Figure 3. Average Number of visible NavIC satellite for (**a**) 20° and (**b**) 30° elevation masking; the colour bars on the right indicate the number of visible NavIC satellites



Colour Code	Maximum No. of Satellites	Minimum No. of Satellites
	7	6
	7	5
	7	4
	7	3
	6	5
	6	4
	6	3
	5	4
	5	3
	5	2
	4	3
	4	2
	Always 7	
	Always 6	

Figure 4. NavIC visibility over primary service region with 30° elevation mask for a day

$$(PE)_{3d} = \sqrt{\Delta h^2 + (\Delta L_n \times R \times \cos L_t)^2 + (\Delta L_t \times R)^2} \quad (2)$$

where, $(PE)_{3d}$ = 3d position Error, L_t = Nominal value of latitude of the observation location, Δh = (Instantaneous - reference) height (m), ΔL_n = (Instantaneous - reference) longitude (minute of arc), ΔL_t = (Instantaneous - reference) latitude (minute of arc), R = 1852 m/min of arc.

For NavIC, PDOP values approximately vary between 3.15 and 3.35 from GNSS Laboratory Burdwan (GLB), Burdwan, India in open sky condition. So, to get higher PDOP values for the study, elevation mask angles during signal reception using an IRNSS-GPS-SBAS (IGS) receiver are intentionally increased to 25° and 30°. This condition may be treated like a degraded visibility condition with obstruction from the lower elevation angles.

Instantaneous 3d position errors are analysed with respect to the PDOP values of corresponding epoch. For simplicity, the data are grouped based on PDOP value bins, e.g., PDOP values from 3 to 10 are divided into 28 groups each of width 0.25, and PDOP values from 10 to 22 are divided into 24 groups each of width 0.5. The error in position solution is calculated for each observation epoch and are grouped with the corresponding PDOP bins. Average and standard deviation in position errors for each of the individual PDOP bin are calculated and are shown against the higher boundary of PDOP range bin in figure 5. It is observed that average 3d position error lies below 6 m up to the PDOP value 6 and have modest standard deviations; for PDOP values higher than 6, the 3d error and the corresponding standard deviation of errors enhance considerably. It is also observed that the average NavIC-only 3d position error may vary from 3 to 13 m depending upon the location-specific satellite geometry. But within the central NavIC service area in and around India, the 3d error is expected to remain within 3 m as the PDOP values vary from 3.15 to 3.35 under open sky scenario.

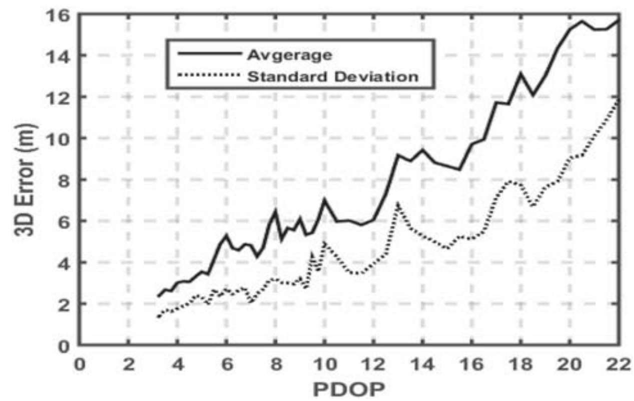


Figure 5. Variation of 3d position error with PDOP for NavIC

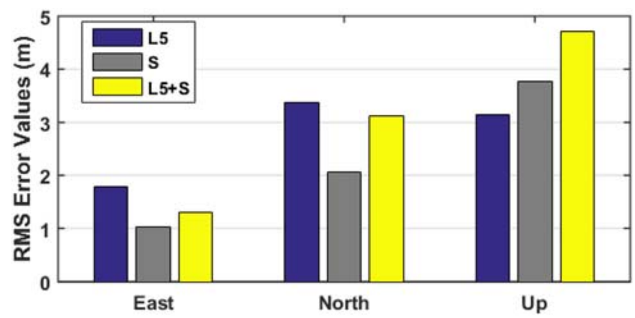


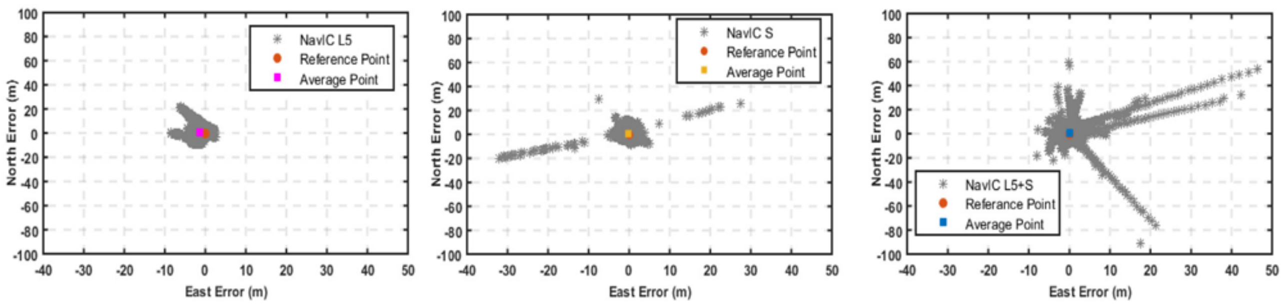
Figure 6. Single point solution (SPS) components in East, North and Up directions in NavIC L5, S and L5+S operation from GLB, Burdwan, February, 2019

5. Accuracy and precision of standalone NavIC positioning in L5 and S band

In this section, solution quality of NavIC is studied using real-time L5 and S-Band data. The latter being new in the GNSS family, its capability in position solution would be a point of interest for the GNSS/NavIC user community.

Table 1. Precision parameters and accuracy of position solution

Operation mode	Precision				2d Offset between reference point and average point (m)	3d Offset between reference point and average point (m)
	2DRMS (m)	CEP (m)	SEP (m)	MRSE (m)		
NavIC L5	6.9710	2.6799	3.8306	4.6502	1.5711	1.7059
NavIC S	4.5156	1.8064	3.2976	4.1306	0.3975	1.5264
NavIC L5+S	6.7318	2.6487	4.5385	5.6216	0.3715	1.4607



(**a**) Scatter plot of NavIC L5 solution (**b**) Scatter plot of NavIC S solution (**c**) Scatter plot of NavIC L5+S solution

Figure 7. (**a**) Scatter plot of NavIC L5 solution. (**b**) Scatter plot of NavIC S solution. (**c**) Scatter plot of NavIC L5+S solution

Ionosphere errors are reduced with increasing frequency; therefore, the carrier phase error margins are relatively small on S band [12]. NavIC position solution in L5, S and L5+S bands are studied to assess the solution quality in single and dual frequency operation, specifically within the central NavIC service area.

An L5+S band antenna at GNSS Laboratory Burdwan (GLB), India is used under open sky condition with the IGS receiver. The reference coordinate of the antenna (reference point) is found out using online service provided by AUSPOS (Australian Survey Department) [23]. NavIC data is recorded in each of the L5, S and L5+S modes for 24 h @1 Hz over three consecutive days.

Ionosphere grid model is used for single-frequency operation (L5 and S) and *ionofree* combination is used in L5+S dual-frequency operation. Position solutions obtained in the geodetic coordinate system are converted into East-North-Up (ENU) coordinate system [24] and then the precision parameters of solution, i.e., 2DRMS, CEP, SEP, MRSE are calculated from RMS of East error (σ_x), RMS of North error (σ_y), RMS of Up error (σ_z) using the equations (3–6) given below [25] and the results are shown in table 1. The table also contains the average offset values for 2d and 3d position solutions.

$$2DRMS = 2\sqrt{\sigma_x^2 + \sigma_y^2} \tag{3}$$

$$CEP = 0.62\sigma_x + 0.56\sigma_y; \text{provided that} \frac{\sigma_x}{\sigma_y} > 0.3 \tag{4}$$

$$SEP = 0.51\left(\sigma_x + \sigma_y + \sigma_z\right) \tag{5}$$

$$MRSE = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \tag{6}$$

where

$$\sigma_x = \sqrt{Var(X) - (\bar{x} - x_t)^2}$$
$$\sigma_y = \sqrt{Var(Y) - (\bar{y} - y_t)^2}$$
$$\sigma_z = \sqrt{Var(Z) - (\bar{z} - z_t)^2}$$

x_t, y_t and z_t = reference (true) coordinate values and $\bar{x}, \bar{y}, \bar{z}$ are average coordinate values.

Here the bias terms are $(\bar{x} - x_t)$, $(\bar{y} - y_t)$, $(\bar{z} - z_t)$ and we considered the bias terms zero when precision is calculated about its average values as described in [25].

East, North and Up errors for NavIC single (L5 and S) and dual-frequency (L5+S) operations are shown in figure 6. It is seen that the east errors are lower than the North and Up errors;

this is attributed to the typical East-West layout of the NavIC constellation. It is interesting to note the better performance of the S-Band operation in 2d horizontal coordinates. The effort is repeated using data from another place on a different day, and the results show similar nature. Further, an effort is made to see the 2d and 3d solution quality with respect to the reference point. Solution scatter plots along with the average and reference point coordinates are shown in figure 7 for the same set of data. It is observed that a greater number of outliers may be found in NavIC S and L5+S operations in comparison to L5 mode, but the average solution coordinate and reference point nearly coincide in S and L5+S hybrid operation.

Figure 6 and table 1, show that the 2d and 3d accuracies are best in L5+S NavIC hybrid mode that is attributed to the *ionofree* operation. From precision viewpoint, except for few outliers, the precision of position solution in horizontal plane is better for S band operation among all the NavIC operation modes. In case of 3d solution, the trends for the 3 operation modes are nearly similar. These results may help in understanding the potential and advantages of use of S-Band NavIC signal for positioning. The average offset error values shown in table 1 agree well with the results of error dependence on satellite geometry shown in figure 5.

6. Conclusion

This paper presents detailed analysis of the service volume of NavIC and its potential over the service region. Except for a small part in the north, 7 NavIC satellites are always present for the users from India. Over the extended service region, 4 NavIC satellites are always available for use except for few small areas near the edges. Therefore, under an open sky, almost from every location of the service region, 4 or more NavIC satellite are concurrently available for users that may support stand-alone NavIC solution or may help to supplement multi-GNSS operation. In a highly constrained environment also, NavIC can provide standalone solution over a large part of the globe. In the central operation region, under an open sky condition, 3d position error remains approximately within 3 m and for the complete service region it may go up to 13 m. The advantage of using S-Band signal of NavIC is witnessed through a comparison of the solutions in individual and dual-frequency operations. Results presented in this article would help in understanding the usefulness of NavIC from the central service region consisting of India and neighbouring countries, and for the entire service area as an active satellite navigation component to strengthen the Multi-GNSS environment.

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