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RESEARCH ARTICLE

Galileo–NavIC Hybrid Operation Towards Improved Performance and User Benefits

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Abstract

Galileo and NavIC, respectively, are two operational global and regional satellite-based navigation systems maintained by civilian authorities. Hybrid operation of a global and a regional system offers advantages for the user community within the service area of the regional system. In view of the signal structure similarity of Galileo and NavIC, hybrid operation of the two systems has been studied from India and surrounding regions to explore the possible complimentary benefits. Based on long-term, real-time observations from two locations within the NavIC central region and validated simulations, Galileo and NavIC constellations were found to supplement each other. In the central region, relatively poor Galileo availability is supplemented by NavIC and in the boundary areas Galileo supports inferior NavIC visibility. The time- and location-dependent low-elevation angle problem for the Galileo satellites is supplemented by NavIC signals transmitted from GEO and GSOs for seamless and improved operation. In terms of typical satellite visibility within the constrained satellite visibility conditions, satellite geometry and signal strength, the Galileo–NavIC hybrid operation offers user benefits over the Indian region as well as over the entire NavIC service area extending from east Africa to west Australia. Real-time data collected from survey grade GNSS receivers and compact GNSS module clearly indicates the improved solution quality of the hybrid operation compared to each of the individual constellations. The results would be beneficial for the user community in exploiting the benefits of the Galileo and NavIC concurrent operation.

Keywords GNSS · Galileo · NavIC · DOP · Satellite visibility · Solution quality

Introduction

Global Positioning System (GPS), developed by USA and Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS), developed by Russia are the two global systems since the beginning of the satellite navigation era. The systems have made notable contributions to various types of applications (Montenbruck et al., 2014). The Third Global Navigation Satellite System, Europe's Galileo, became operational since late 2015 to offer continuous and precise positioning service (Dach et al., 2006). The next global system developed by China—BeiDou, abbreviated as BDS, is operational since 2020 (Xu et al., 2013; Yang et al., 2020). The systems provide global high-accuracy positioning, navigation and timing (PNT) services.

Regional navigation systems—Navigation with Indian Constellation (NavIC) developed by India and Quasi-Zenith Satellite System (QZSS) developed by Japan are now in operation along with their global counterparts (QZSS Constellation and Information, 2020; IRNSS - Indian Regional Navigation Satellite System, 2016; Santra et al., 2019b; Sarkar, 2016). All these systems together are now being covered under the generic name of Global Navigation Satellite System (GNSS).

NavIC is developed by Indian Space Research Organization (ISRO) and is fully operational since 2017 with a constellation consisting of 7 satellites (IRNSS, 2016; Sarkar, 2016). The typical constellation pattern of NavIC offers various advantages, including seamless navigation

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solutions in constrained visibility situations over the service region, though the satellite geometry of NavIC is inferior in comparison with the other systems (Santra et al., 2019b).

Retaining other advantages of NavIC, the problem related to the satellite geometry may be taken care of through hybrid operation of NavIC with other global systems (Ma et al., 2019). Efforts for successful GPS-NavIC operation from India has been presented in Santra et al. (2019b) and Mishra et al., (2018) and primary results on GLONASS+NavIC hybrid operation has been reported in Sarkar et al. (2019); GPS+NavIC and GLONASS+NavIC compatible survey grade and compact, low-cost modules from many manufacturers are now commercially available. A comparative analysis between classical differencing and ISB differencing over multi-GNSS has been carried out and improved positioning accuracy has been obtained in ISB differencing method (Mi et al., 2019).

NavIC and Galileo operations have been individually compared based on snapshot results in Kuna et al. (2020), but no report on Galileo+NavIC hybrid operation from India can be found. Systematic studies on the Galileo usability from India reveal two problems for the standalone Galileo operation—(i) limited satellite visibility and thereby, inferior geometry of the standalone Galileo constellation in comparison with other global systems, and (ii) the problem of receiving Galileo signals only from high elevation angles during some parts of the day as shown in Fig. 1 from GNSS Laboratory Burdwan, India (GLB) (Lat 23.2545°N, Lon 087.8468°E) (Mahato et al., 2020) for data collected during 2017. In Fig. 1, the maximum elevation angle variation of the individual as well as GPS+GLONASS+Galileo hybrid constellation is presented under an open-sky condition. It is seen that, over long time periods of a day, all Galileo satellites remain below 60° elevation angle, and all the visible satellites concurrently may go down even to elevation angles ~ 40°; the time span of such a situation is longer for Galileo in comparison with other global systems. In such a situation, if the Galileo-only user remains within a constrained visibility situation (e.g. within urban canyon or under forest canopy) where signals from the lower elevation angles (15°–20°) are blocked, the number of usable satellites sometimes may not be sufficient for solution and/or the degraded satellite geometry results in inferior solution quality. As the consequence, a standalone seamless, precise navigation solution becomes difficult and, in some cases, a user may completely lose the solution without having enough satellites for use. Simulated results show that a large part of the globe is affected by this problem (Mahato et al., 2020).

During similar situations involving only GPS, NavIC is found to augment the satellite space service volume (Santra et al., 2019b). In cases of Galileo also, NavIC satellite signals may support Galileo over the entire NavIC service region towards a seamless, precision navigation solution through a Galileo+NavIC hybrid operation.

Considering the potential of complementary operation, similarity of operating frequencies, signal structure of Galileo and NavIC, and civilian operators of both systems, it is of ample interest to study the Galileo+NavIC concurrent operation over the NavIC service region. This has not been done earlier and detailed results of such a new study are presented in this manuscript.

The objective of the work presented in this manuscript is to concurrently use two satellite-based navigation systems-Galileo and NavIC, a global and a regional system to study the performances in hybrid operation to explore the benefits for the user community within the regional system's service area. Firstly, the improvement in the satellite visibility and geometry (PDOP) is presented for Galileo–

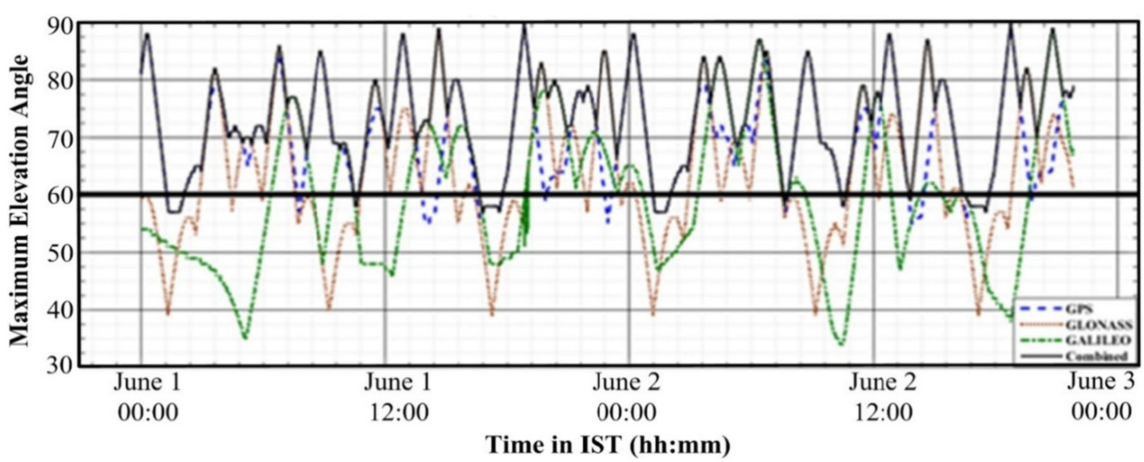

Fig. 1 Variation of maximum elevation of tracked satellites in standalone and in hybrid GNSS operation observed during June 2017 from GLB, India. The horizontal black line corresponds to 60° elevation angle (Mahato et al., 2020) (color figure online)

NavIC hybrid operation in the open sky or slightly degraded-visibility situations; then we have studied the contribution of NavIC in position solution accuracy in hybrid operation. Finally, the position solution quality of Galileo, NavIC and Galileo–NavIC constellation are compared to understand the advantages of the hybrid operation. The discussion starts with a brief description of Galileo and NavIC constellation signal structure as the background.

Galileo and NavIC Systems and Signal Structure

Galileo is planned to provide a global precise and guaranteed positioning service by offering dual frequency as a standard, and to be interoperable with GPS and GLONASS (Navigation European Space Agency, 2015). With the launch of the first pair of "In-Orbit Validation" (IOV) Galileo satellites on 21st October 2001, additional "Full Operational Capability" (FOC) satellites were launched from 2014 to 2018 to have a 26-satellite constellation. As on 20 January 2021, out of the 26 Galileo satellites in the constellation, 25 are in operation and 1 is in an unavailable state (European GNSS Service centre—Constellation Information, 2021). In 2013, the first successful Galileo-only position fix from India was reported (Bose et al., 2013). Brief results of Galileo-only performance under a fully operational Galileo constellation situation are also presented in this manuscript subsequently.

NavIC is a regional navigation system developed to provide PNT information for India and the surrounding regions. The constellation of 7 satellites was completed in April 2016; among these, 3 satellites are in Geostationary Earth Orbit (GEO) placed at 32.5°E, 83°E and 131.5°E longitude and the rest 4 (two in each orbit) satellites are in Geosynchronous Orbit (GSO) with an inclination of 29° having their equator crossings at 55° E and 111.75°E longitude. Such an arrangement ensures continuous radio visibility of all the satellites from the central service area as shown in Fig. 7. The system is planned to provide Standard Positioning Services (SPS) and the restricted/authorized service (RS) using two frequencies, one in the L5 band (1164–1189 MHz) with 24 MHz bandwidth and the unique other in the S (2483.5–2500 MHz) band with 16.5 MHz bandwidth (Dan et al., 2020; Department of Space, Government of India, 2015; IRNSS, 2016; Mandal et al., 2016).

Galileo transmits signal in the E1/E5a/E5b/E5/E6 band of frequencies (Xin et al., 2020); as per the Aeronautical Radio Navigation Service (ARNS), Galileo E5 signal is transmitted in the Lower L band (1151–1214 MHz) as shown in Fig. 2 (IRNSS ICD, 2017). It is interesting to note that the NavIC L5 signal and GALILEO E5a signals are transmitted in a partly overlapped frequency spectrum.

The mathematical expressions for baseband NavIC navigation signals for SPS is given by

$$s_{\mathrm{sps}}(t) = \sum_{i=-\infty}^{\infty} C_{\mathrm{sps}}\left(|i|_{L\_\mathrm{sps}}\right) \cdot d_{\mathrm{sps}}\left(|i|_{\mathrm{CD\_sps}}\right) \cdot \mathrm{rect}_{\mathrm{TC,SPS}}\left(t - iT_{c,\mathrm{sps}}\right) \tag{1}$$

and the RS BOC Pilot Signals by

$$s_{\mathrm{rs\_p}}(t) = \sum_{i=-\infty}^{\infty} C_{\mathrm{rs\_p}}\left(|i|_{\mathrm{L\_rs\_p}}\right). \mathrm{rect}_{\mathrm{TC,rs\_p}}\left(t - iT_{C,\mathrm{rs\_p}}\right). SC_{\mathrm{rs\_p}}(t, 0) \tag{2}$$

The NavIC RS data and pilot BOC signals are sin BOC.Similarly, Galileo E5 signal components are represented by the following equations:

$$e_{\mathrm{E5a}-I}(t) = \sum_{i=-\infty}^{\infty} \left[C_{\mathrm{E5a}-I,}|i|_{L_{\mathrm{E5a}-I}} d_{\mathrm{E5a}-I,[i]_{DC_{\mathrm{E5a}-I}}} \mathrm{rect}_{T_{C,\mathrm{E5a}-I}}\left(t - iT_{C,\mathrm{E5a}-I}\right)\right] \tag{3}$$

$$e_{\mathrm{E5a}-Q}(t) = \sum_{i=-\infty}^{\infty} \left[C_{\mathrm{E5a}-Q,}|i|_{L_{\mathrm{E5a}-Q}} \mathrm{rect}_{T_{C,\mathrm{E5a}-Q}}\left(t - iT_{C,\mathrm{E5a}-Q}\right)\right] \tag{4}$$

From the above four equations, it is observed that Galileo and NavIC frequency modulation techniques are similar, and they share the same lower L frequency band as shown in Fig. 2. This observation is also interesting for the exploration of Galileo–NavIC hybrid operation to study the possible benefits.

NavIC SPS and RS signals use BPSK and BOC modulation on the L5 signal and the Galileo uses AltBOC modulation on E5a and E5b. Galileo MBOC modulation technique is used for E1a, E1b and E1c bands (Carrier frequency 1575.42 MHz). NavIC navigation data @50 bps (1/2 rate FEC encoded) is modulo-2 added to PRN code chipped at 1.023 Mcps as identified for the SPS service. Each carrier is modulated by three signals namely, BPSK (1), Data channel BOC (5, 2) and Pilot channel BOC (5, 2) (Department of Space, Government of India, 2015; Galileo, 2016; IRNSS ICD, 2017).

Methodology of the Experiment and Results

In this manuscript, results for repeated real-time experiments scattered over a long period of time and well-validated simulations are presented for individual and hybrid constellations.

Data for individual Galileo, NavIC and hybrid Galileo–NavIC are recorded from two locations, Burdwan (L1) and Chandannagar (L2) situated in the eastern part of India as

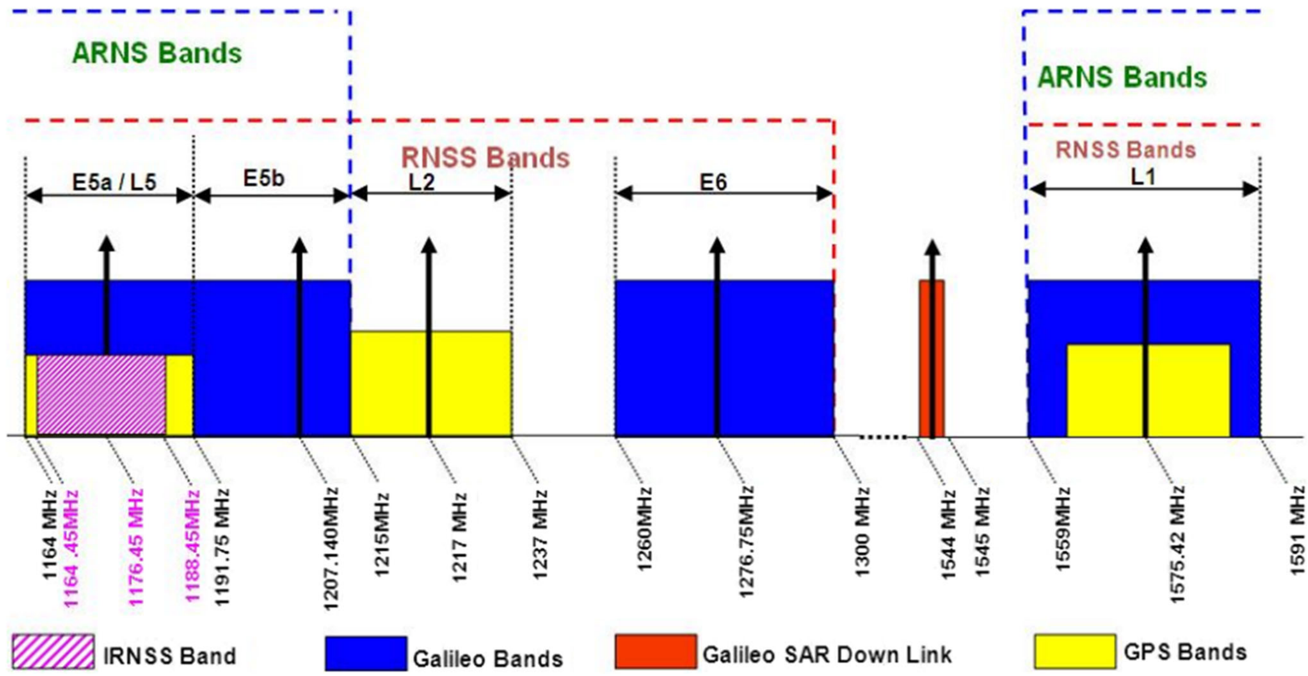

Fig. 2 Spectrum for Radio Navigation Satellite Services in L Band (IRNSS ICD, 2017) (color figure online)

shown in Fig. 3 and Table 1. To avoid systematic biases, the same receiver-antenna combination is used to collect data for Galileo, NavIC and Galileo–NavIC constellations at each of the locations (Defraigne et al., 2013).

From the NMEA data streams recorded at each of the locations (L1 and L2), observation time, navigation solutions, satellite geometry information in terms of DOP values, and information about all used satellites are extracted for all epochs. The results of the real-time experiments and the simulations are presented in subsequent subsections.

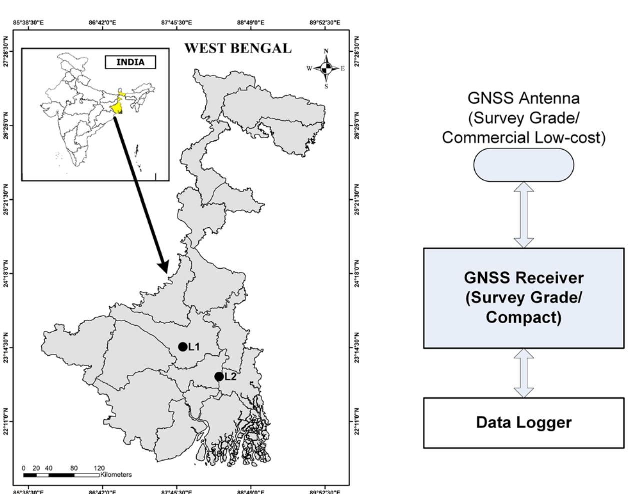

Fig. 3 Data recording plan: recording locations GLB (L1) and Chandannagar (L2) in West Bengal, India (left) and the data recording setup schematic (right)

Satellite Visibility

In 2013, it was observed from India that only during some parts of the day 04 Galileo satellites were concurrently visible those may be used for Galileo-only 3d solution (Bose et al., 2013). Since 2016 onwards, when NavIC became available, we also studied NavIC satellite visibility along with Galileo. The nominal average visibility of Galileo and NavIC satellites over a day from GLB (L1) shows the expected enhancement of average number of visible satellites from 2017 onwards as shown in Fig. 4 (left). Currently, 6 out of 7 NavIC satellites are working for navigation purpose because IRNSS 1G GEO satellite is observed as not functioning from early 2020 and therefore, the average NavIC visibility decreased in 2020.

"*Skyplots*" for individual and hybrid Galileo–NavIC constellations are used to study the satellite visibility as shown in Fig. 5 on January 2020 (from L1) and January 2021 (from L2); the Galileo satellites are marked with "L" and the NavIC satellites with "I." As expected, Figs. 4 and 5 show a better Signal in Space (SiS) scenario in hybrid operation with higher number of usable satellites towards redundancy of signal availability.

Increased scatter of the satellites for hybrid operation in each quadrant of the sky shown in Fig. 5 leads to an improved satellite geometry vis-à-vis the individual constellations. The typical constellation structure of NavIC and the associated satellite visibility is supplemented by Galileo through the presence of satellites in the upper two quadrants of the sky. NavIC, in turn, enhances the total

Table 1 Data recording setup and plan

Location (location Id)	Coordinate	Survey grade receiver and antenna combination	Compact, low-cost module used	Data type	Data rate
GNSS Laboratory Burdwan (GLB), The University of Burdwan, India (L1)	23.2545°N, 87.8468°E	*Javad* Delta receiver with *Leica* AR25 antenna	*Telit* SL869T3-I and *Allystar* 1205 with commercial GNSS antennas	National Marine Electronics Association (NMEA)	1 Hz
Chandannagar, India (L2)	22.8728°N, 88.3647°E	*Javad* TRIUMPH LS receiver with *Javad* GrAnt G5T Antenna	–		

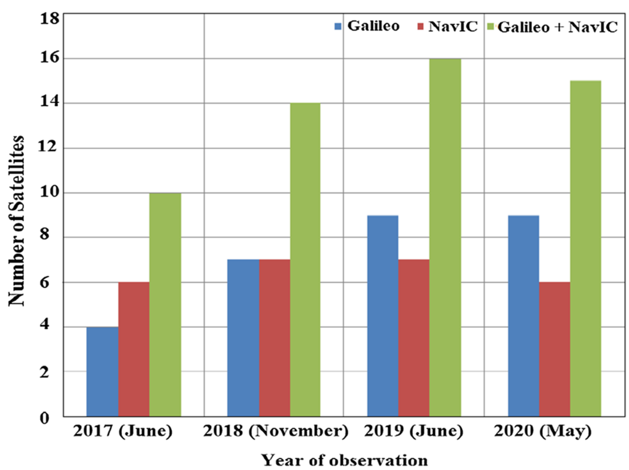

Fig. 4 Average number of visible Galileo and NavIC satellites (color figure online)

number of satellites, e.g. from 5 in Galileo-only operation to 11 in hybrid operation as shown in Fig. 5. Another interesting observation is the proximity of 2 Galileo satellites in the sky during some periods from the observation points [e.g. satellites L31 and L33 in Fig. 5 (left) during and L1 and L26 in Fig. 5 (right)]. In such situations, Galileo-only operation would result in inferior satellite geometry, and any obstruction from the direction would obstruct 2 Galileo signals simultaneously degrading the geometry and solution quality further. As per the figures, the situation is supplemented by the NavIC satellite signals from other directions. Therefore, from the satellite visibility viewpoint, NavIC and Galileo complement each other providing better satellite visibility, redundancy and scattered presence in the sky for improved solution quality.

In the next effort, the visibility of NavIC and Galileo constellations is studied over the entire NavIC service region using a robust and well-validated simulation software. A MATLAB based software utility, GNSS Satellite Look Angle Predictor (GSLP) (Dan et al., 2019), developed at GLB for the prediction of GNSS satellite look angles and simulation of trajectories is used for the purpose. The utility uses NORAD Two Line Element (TLE) files as input (Kelso, 2000), and then calculates the number of visible GNSS satellites based on their look angles from any observation location on the globe.

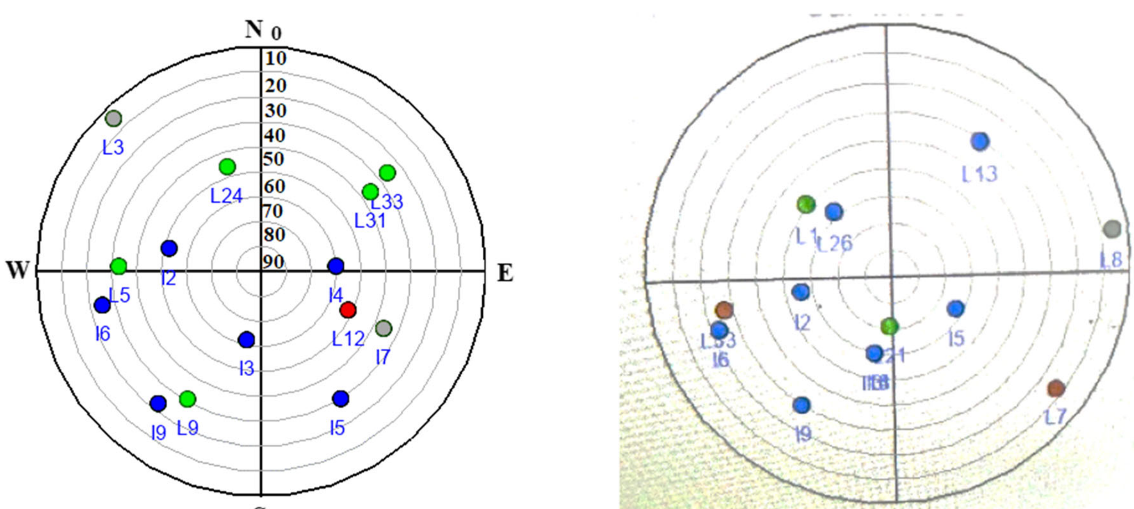

Fig. 5 Skyplot for Galileo–NavIC hybrid constellation from GLB, India, 20 January 2020 (left) and from Chandannagar, India, 18 January 2021 (right) (color figure online)

A few observation locations (e.g. in central India, and on the boundary of the region extending up to 1500 km from the geographical boundary of India) scattered over the NavIC central service area, and on the boundary of the extended service area (regions within 30°S to 50°N Latitude and 30°E to 130° E) are selected for the simulation as shown in Table 2 (Dan et al., 2020; IRNSS, 2016; Santra et al., 2019b). Using the GSLP utility, Galileo and NavIC satellite visibility with 15° elevation masked conditions are calculated for each of the observation points for every 4 h of 1 May 2020. Results for the locations situated on the boundary of the extended region are shown in Fig. 6, and those for the central service region are shown in Fig. 7.

It is seen from Fig. 6 that at 15° elevation masked condition, over the north-eastern to the south-western boundary of the NavIC extended service area, the relatively lower Galileo visibility (4–7 satellites) is well supplemented by the NavIC satellites resulting in at least 8 satellites for use. Towards the eastern direction covering the east and south-east Asian countries, the maximum satellite visibility reaches 11 to 12; while for the south and south-western extended service region, the maximum number may reach 12 despite relatively lower Galileo-only satellite visibility during some parts of the day. In the western to north-western parts of the NavIC extended service region, Galileo supports the relatively lower NavIC visibility (3–4 satellites) in a complimentary manner to ensure the visibility of a total of 7–12 satellites. In the northern direction over central Asia, the hybrid operation ensures 9–12 satellites for use.

The simulated satellite visibility results for the points on the central NavIC service area in central India (Point M) and the cardinal and ordinal points extending up to 1500 km from the Indian geographical boundary are shown in Fig. 7. For the NavIC central service area, and clockwise from the north-east to southern locations, Galileo visibility is found to be relatively worse; it may even go down to 3 satellites around 16:00 UTC (23:30 IST). These areas cover parts of the densely populated south-Asian countries and habitats, where blocking of the lower elevation angles is a common feature due to high-rise buildings situated beside moderately wide roads. Good visibility of NavIC satellites over the region ensures 8 to 14 usable satellites in hybrid operation. Over the south-western part of the NavIC central service region, each of Galileo and NavIC has comparable visibility of 6–7 satellites, ensuring 12–14 total satellites for use. In the western and north-western sides, however, Galileo together with NavIC ensures the total visibility of 8 to 12 satellites. It is noteworthy that the NavIC GEO satellites located at 32.5°E and 132.5°E (Fig. 6) remain continuously visible over east African countries and Far East Asian countries respectively, and may provide unobstructed signals from high elevation angles.

Therefore, both the real-time data and the simulation-based studies clearly indicate the advantages of Galileo–NavIC hybrid operation towards continuous satellite visibility, redundancy of signals and better satellite geometry in comparison with any of the individual constellations.

Now, a similar analysis (as presented in Fig. 1) involving the maximum elevation angle of all the visible Galileo and NavIC satellite for May 2020 are shown in Fig. 8. It is seen that in case of Galileo–NavIC hybrid operation, during those time spans when all the Galileo satellites are low in elevation (e.g. around epoch 21,600 or 54,000), NavIC GEO and GSO satellites ensure signal availability from high elevation angles (always higher than 55°) to supplement the situation to always obtain a sufficient number of satellites for use even within constrained visibility situations towards seamless position solution and an improved satellite geometry compared to the standalone Galileo operation.

Satellite Geometry

Satellite geometry or distribution pattern of the GNSS satellites used for navigation plays an important role in the accuracy of navigation solutions (Banerjee et al., 1997; Verma et al., 2019). We studied the satellite geometry of the hybrid Galileo–NavIC constellation in terms of PDOP (Position Dilution of Precision), HDOP (Horizontal DOP) and VDOP (Vertical DOP) values, as these are the associated DOP parameters with position solution. It is earlier reported that the standalone DOP values for NavIC are higher in comparison with the other global systems due to

Table 2 Position coordinates of the simulation locations

Location	M	N2	NE1	E1	SE1	S1	SW1	W1	NW1
Latitude (°N)	24.119	50.0	40.552	25.846	11.676	− 5.411	5.904	21.785	37.173
Longitude (°E)	77.697	77.50	93.091	110.166	96.311	77.731	64.335	54.475	59.718

Location	NE2	E2	ESE2	SE2	S2	SW2	WSW2	W2	NW2
Latitude (°N)	50.0	25.0	− 2.083	− 30	− 30	− 30	− 2.083	25.0	50.0
Longitude (°E)	130.0	130.0	130.0	130.0	77.50	30.0	30.0	30.0	50.0

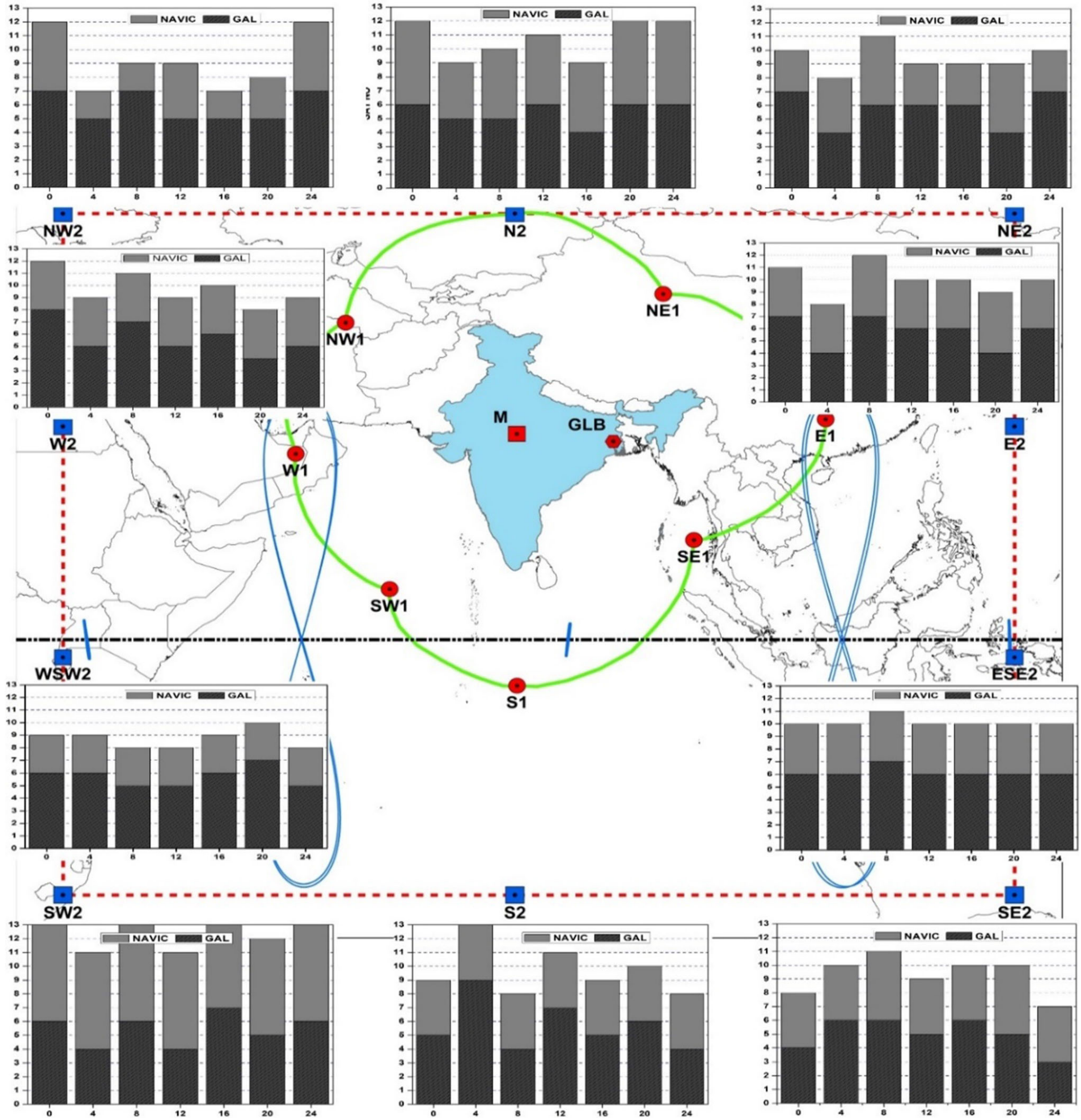

Fig. 6 Galileo and NavIC satellite visibility on the boundary of the NavIC extended service region [marked with dotted red line] with 15° elevation mask. The blue lines show the NavIC satellite footprints, the dark columns are for Galileo, and the grey columns are for NavIC. Simulated results using GSLP for 01 May 2020, time in UTC (color figure online)

the typical constellation structure of NavIC. For Galileo, the DOP values are better than those for NavIC, but the values are slightly higher than the other constellations (Verma et al., 2019). Close observation of Fig. 5 reveals the occasional clustering of 2 Galileo satellites in a particular direction of the sky leads to worse satellite geometry and higher DOP values. DOP values of the individual and hybrid constellations from location L2 using the survey grade Javad Triumph LS Multi-GNSS receiver for 42 h @1 Hz from September 2020 are shown in Table 3.

Next, NMEA data collected from location L1 using a compact, low-cost GNSS module for NavIC, Galileo and Galileo with NavIC for 24 h each @1 Hz during May 2020 are analysed and the corresponding PDOP values are

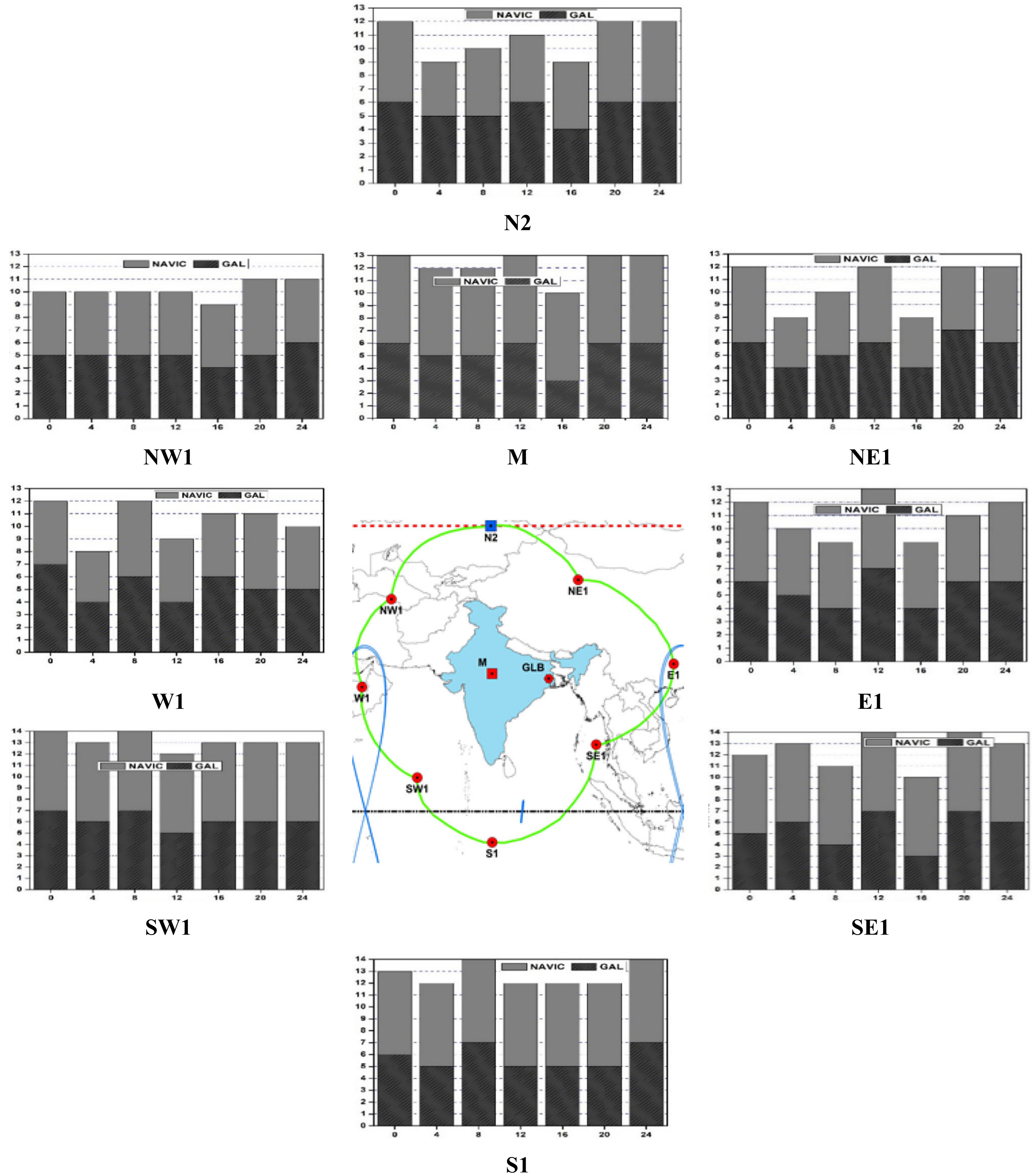

Fig. 7 Galileo and NavIC satellite visibility with 15° elevation mask from central India and on the boundary of the NavIC primary service region marked in green curved lines. The dark columns are for Galileo and the grey columns are for NavIC. Simulated results using GSLP for 01 May 2020, time in UTC (color figure online)

shown in Fig. 9; the PDOP values in hybrid operation remains mostly below 2.0, lower than each of the individual cases. The improved satellite geometry observed from two different locations for long time periods as shown in Table 3 for location L2 and in Fig. 9 for location L1

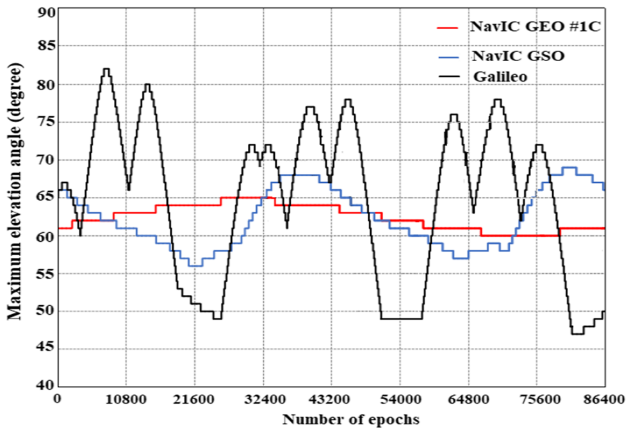

Fig. 8 Max elevation angle of Galileo and NavIC satellites from GLB, Burdwan, India (May 2020, 24 h (86,400 epochs), NMEA data @1 Hz from compact GNSS module) (color figure online)

highlights the advantage of the hybrid operation that in turn supports higher solution accuracy.

Satellite Signal Strength

The Signal-to-Noise Ratio or SNR value is used to measure the signal strength of the received signal by the GNSS receiver. It is an indication of the level of noise present in the measurement and plays a significant role in the performance of the acquisition and tracking stages of a GNSS receiver (Hetet, 2000). Sample SNR values obtained from the NMEA data streams from the JAVAD DELTA (L5 for NavIC and E5a for Galileo) receiver at location L1 for Galileo PRN # 5 and NavIC PRN# 3 are selected for the comparison and the results are shown in Fig. 10. It is observed that Galileo E5a signal strength is slightly lower than NavIC L5 signal but have higher stability as reported in Dutta and Bose (2020). Higher signal strength of NavIC and the stability of Galileo signals would support robust signal acquisition and stable operation in Galileo–NavIC hybrid operation, especially for the compact, low-cost GNSS modules used for mass-market applications.

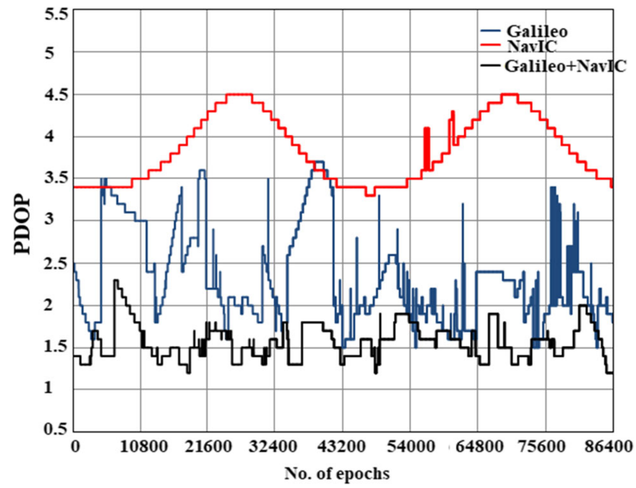

Fig. 9 PDOP variation in Galileo (20 May 2020), NavIC (22 May 2020) and Galileo–NavIC hybrid (21 May 2020) operation from GLB, Burdwan India (L1) (color figure online)

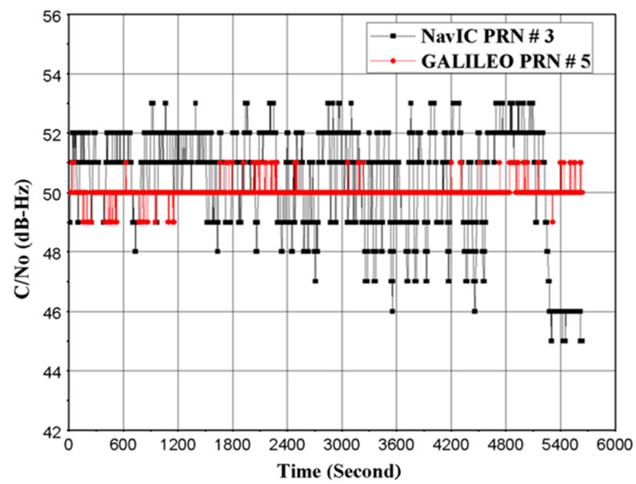

Fig. 10 Signal strength variation of Galileo E5a and NavIC L5 signal during concurrent operation on 01 November 2019 from GLB, India (L1) (color figure online)

Position Solution Quality

Position solution quality is the major parameter for the assessment of any system designed to provide precise location information. For hybrid GNSS operation, the issue

Table 3 Dilution of Precision (DOP) values in standalone and hybrid operation modes in September 2020 (Total epochs: 149,100, 42 h) from Chandannagar, India (L2)

Constellation	PDOP				VDOP				HDOP			
	Max	Min	Avg	Standard deviation	Max	Min	Avg	Standard deviation	Max	Min	Avg	Standard deviation
Galileo	5.74	1.52	2.13	0.63	4.27	1.36	1.97	0.61	2.86	0.83	1.28	0.53
NavIC	5.89	1.88	3.71	0.47	3.99	2.40	3.23	0.49	2.77	1.60	2.46	0.37
Galileo–NavIC	3.44	1.37	1.85	0.23	1.42	1.26	1.29	0.13	0.77	0.73	0.95	0.13

of Inter System Biases has not been specifically considered by the authors, as the solutions from standard survey grade or commercial compact receivers are directly used for the studies.

The position solution quality for Galileo–NavIC hybrid operation is first explored by studying the position solutions obtained by sequential addition of increasing NavIC signals with all the used Galileo signals. For this, the antenna reference coordinates are known a priori using the online Precise Point Positioning (PPP) method provided by the AUSPOS Service from Geoscience Australia (Online GPS Processing Service, Australian Government, Geoscience Australia, 2008). The survey grade GNSS receiver at location L2 with the antenna placed in the reference location is initially operated in Galileo-only mode. Increasing number of NavIC satellites are then sequentially added along with these Galileo satellites. Data for each case with (Ga+In) number of satellites (Ga = number of Galileo satellites, 6 here, In = number of NavIC satellites, increasing sequentially from 0 to 5) are collected @1 Hz each on 7 October, 2020. Around 15 min' data was collected for each case to maintain a similar Galileo visibility and PDOP value. 2-dimensional (2d) and 3-dimensional (3d) instantaneous position errors with respect to the reference coordinate are calculated using the following equations as described in Verma et al. (2019), and the results are shown in Table 4.

$$(\mathrm{PE})_{3\mathrm{d}} = \sqrt{\Delta h^2 + (\Delta L_n \times R \times \cos L_t)^2 + (\Delta L_t \times R)^2} \tag{5}$$

$$(\mathrm{PE})_{2\mathrm{d}} = \sqrt{(\Delta L_n \times R \times \cos L_t)^2 + (\Delta L_t \times R)^2} \tag{6}$$

where $(\mathrm{PE})_{3\mathrm{d}}$=3d position error, $(\mathrm{PE})_{2\mathrm{d}}$=2d 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/minute of arc.

The results shown in Table 4 indicate that the sequential addition of NavIC signal(s) with all existing Galileo signals helps in the gradual improvement of solution quality. Improvement of satellite geometry expressed in terms of PDOP, VDOP and HDOP are also observed.

Next, to compare the NavIC (L5), Galileo (E5a) and Galileo (E5a)-NavIC (L5) hybrid solution quality, 2d position solutions scatter plots for more than 40 h data @1 Hz collected during September 2020 from Chandannagar, India (L2) are pictorially represented in Fig. 11. This figure clearly shows the better position solution quality in case of NavIC-Galileo hybrid solutions compared to the individual standalone modes.

For a better comprehension of the improvement of the solution quality in hybrid operation, Galileo, NavIC and Galileo–NavIC hybrid data collected from L2 are used. As described earlier, the reference point (RP) coordinates are found out using AUSPOS online PPP service (Online GPS Processing Service, Australian Government, Geoscience Australia, 2008). 2d and 3d solution precision parameters—Distance Root Means Square (2DRMS), Circle of Error Probable (CEP), Spherical Error probable (SEP) and Mean Radial Spherical Error (MRSE) are calculated for each set of data following (Santra et al., 2019a); the results are shown in Table 5 along with the positional error values w.r.t the RP.

Tables 4 and 5, and Fig. 11 present the improved solution quality for the hybrid operation. Therefore, considering the major objective of any satellite navigation system, the solution quality, Galileo–NavIC hybrid operation is clearly found to be beneficial for the users within the NavIC service region.

The discussions on solution quality presented till now are based on data collected using the survey grade GNSS receivers and now most of the major GNSS survey grade receiver manufacturers are producing Galileo and NavIC L5 enabled receivers. These costly instruments can be used for high-end applications or for research purposes. For mass-market applications, compact, low-cost and power efficient GNSS modules are required, which are capable of concurrently using the signals from both constellations to exploit the benefits of the hybrid operation. Such modules from a few manufacturers are now commercially available. A brief description of such modules which obtained from the respective commercial datasheets are presented in

Table 4 Average and standard deviation of errors with increasing number of NavIC with 6 Galileo signals on 7 October 2020 from Chandannagar, India (L2); data collection span for each case ≅ 15 min

No of NavIC satellites used	Average error (m)		Std dev of error (m)		Average		
	2d	3d	North	East	PDOP	VDOP	HDOP
0	0.65	0.80	0.29	0.16	2.43	2.08	1.25
1	0.38	0.61	0.16	0.14	2.40	2.02	1.30
2	0.34	0.44	0.15	0.11	2.35	2.02	1.20
3	0.29	0.31	0.12	0.09	2.23	1.93	1.10
4	0.27	0.30	0.10	0.08	1.77	1.44	1.02
5	0.14	0.10	0.05	0.05	1.69	1.34	1.02

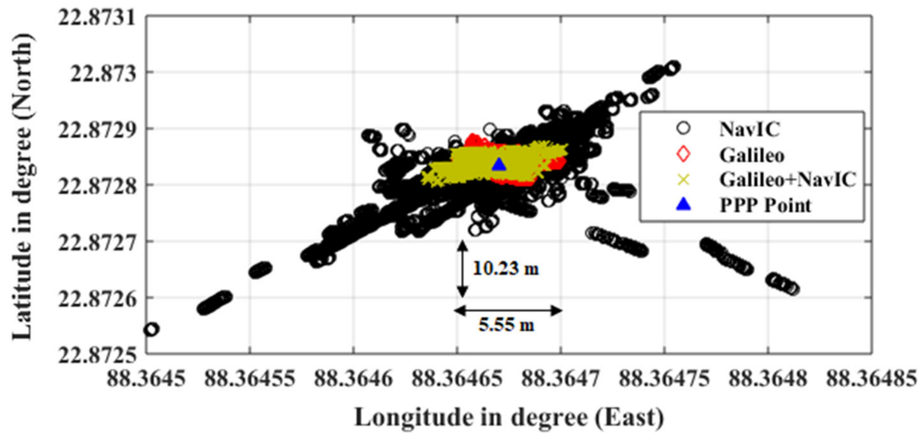

Fig. 11 Scatter plot of solutions obtained using NavIC (L5), Galileo (E5a) and Galileo–NavIC hybrid operation from Chandannagar, India (color figure online)

Table 5 Precision and accuracy comparison of static Galileo, NavIC and Galileo–NavIC hybrid solutions in open-sky condition in during September 2020 (reference coordinate found out through AUSPOS online service) (total epochs: 149,100; approximately 42 h)

Constellation	Accuracy				Average Error		
	2DRMS	CEP	SEP	MRSE	Latitude	Longitude	Altitude
NavIC	8.2622	3.3795	6.2900	7.8552	3.5641	2.0888	6.6812
Galileo	2.9314	1.2171	1.9134	2.3473	1.1891	0.8568	1.9268
Galileo–NavIC	2.4814	1.0821	1.8166	2.1087	1.1696	0.6553	1.5160

Table 6. This information would be beneficial for the solution developers who are interested to utilize and exploit the benefits of Galileo–NavIC hybrid operation for the users situated within the NavIC service region.

NMEA data from such a compact, low-cost GNSS module together with a low-cost commercial antenna is collected from location L1 at @1 Hz for a randomly chosen time span of 1.30 h each in NavIC, Galileo and Galileo–NavIC hybrid modes. The precision and accuracy of solution w.r.t the average coordinate is calculated, and the results are shown in Table 7. These values along with the results for the survey grade receivers confirm the improvement in solution quality for hybrid operation compared to standalone operation using compact, low-cost GNSS modules.

Conclusion

This paper presents the potential and advantages of using Galileo–NavIC hybrid operation within the NavIC service region, specifically for the central service region that includes India and the surrounding countries based on real-time data collected from two locations for short and long durations using survey grade and low-cost, compact GNSS receivers. With growing interest in the use of hybrid navigation systems, the use of Galileo with NavIC in a complementary manner would be beneficial for exploiting the civilian GNSS business potential in the Indian Ocean region. Such a hybrid global-regional system provides enhanced satellite visibility, better satellite geometry and improved solution quality. Operating in the same frequency

Table 6 Galileo and NavIC enabled compact GNSS modules/OEM boards (non-exhaustive list, data collected from respective product brochures from the manufacturers)

Manufacturer (Model)	No of channels	Galileo	NavIC L5	NavIC S	Galileo dual frequency
Allystar (TAU 1205)	40	•	•		•
Telit (SL869T3-I)	48	•	•		
Elena (B2B/B2D)	128	•	•	•	
NTLabs (NTL104)	128	•	•	•	•
Septentrio (Mosaic X5)	448	•	•		•
Hexagon (PIM 7500)	181	•	•		•
Novatel (OEM 7720)	555	•	•		•
MAXIM (MAX2771)	–	•	•		•

Table 7 Solution quality comparison of Galileo, NavIC and Galileo–NavIC hybrid solutions in open-sky condition using compact GNSS receiver module and low-cost commercial antenna (data collected from L1 on 22 June 2020, 1.30 h in each case)

Constellation	Precision (m)				Peak to peak values (m)		
	2DRMS	CEP	SEP	MRSE	East error	North error	Up error
NavIC	15.459	6.457	9.837	11.399	22.483	24.092	48.0
Galileo	9.568	3.981	8.764	11.469	16.686	26.882	70.0
Galileo+NavIC	6.878	2.766	4.529	5.482	16.223	11.652	25.7

band, Galileo and NavIC (L5) would complement each other in obtaining enhanced signals availability towards redundancy of usable signals. The typical constellation pattern of NavIC ensures signal availability from high elevation angles and Galileo, in turn, ensures signal availability from the northern quadrants of the sky towards improved satellite geometry and improved solution quality. Readily available compact, low-cost Galileo–NavIC enabled modules would help in GNSS-based application development exploiting the benefits of dual system operation. In future, It would be of interest to study the hybrid operation of NavIC with other global navigation systems (e.g. with GLONASS and with GLONASS+Galileo), the results of which would be beneficial for the GNSS user community from India and other countries situated within the NavIC service area.

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Declarations

Conflict of interest The authors confirm that there is no conflict of or competing interest for the work presented in the manuscript.

Ethics approval and consent to participate The work does not contain any subject and therefore the consent to participate is not applicable.

References

Banerjee, P., Bose, A., & Mathur, B. S. (1997). A study on GPS PDOP and its impact on position error. *Indian Journal of Radio and Space Physics, 26*, 107–111.

Bose, A., Das, S., Malik, R., & Dutta, D. (2013). GALIEO-only position fix from India: First experience. *Coordinates, IX*, 37–41.

Dach, R., Schaer, S., & Hugentobler, U. (2006). Combined multi-system GNSS analysis for time and frequency transfer. In *Proceedings of the 20th European frequency and time forum* (Vol. 23, pp. 530–537).

Dan, S., Santra, A., Mahato, S., & Bose, A. (2020). NavIC performance over the service region: Availability and solution quality. *Sadhana, 45*(144), 1–7. https://doi.org/10.1007/s12046-020-01375-52647589

Dan, S., Santra, A., Mahato, S., Rakshit, P., & Bose, A. (2019). GSLP: A GNSS satellite visibility simulation tool. *Journal of Information and Optimization Sciences, 40*(8), 1753–1761. https://doi.org/10.1080/02522667.2019.1703267

Defraigne, P., Aerts, W., Harmegnies, A., Petit, G., Rovera, D., & Uhrich, P. (2013). Advances in multi-GNSS time transfer. In *Joint European frequency and time forum & international frequency control symposium (EFTF/IFC)* (pp. 508–512). https://doi.org/10.1109/EFTF-IFC.2013.6702126.

Department of Space, Government of India. (2015, September 29). Retrieved from June 26, 2019, from http://www.isro.gov.in/spacecraft/satellite-navigation.

Dutta, D., & Bose, A. (2020). Study on variation of GNSS Signal Strengths from India. *Indian Journal of Radio & Space Physics., 48*(3), 64–71.

European GNSS Service Centre—Constellation Information. (2021). In *2013 Joint European frequency and time forum & international frequency control symposium* (pp. 508–512). Retrieved from January 21, 2021. https://doi.org/10.1109/EFTF-IFC.2013.6702126.

Galileo ICD. (2016). Retrieved from November 24, 2019, from https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo-OS-SIS-ICD.pdf.

Hetet, S. (2000). *Signal-to-noise ratio effects on the quality of GPS observations*. University of New Brunswick.

IRNSS - Indian Regional Navigation Satellite System. (2016 08 March). Retrieved from April 07, 2019, from http://www.isac.gov.in/navigation/irnss.jsp.

IRNSS ICD. (2017). Retrieved from January 12, 2020, from https://www.isro.gov.in/sites/default/files/irnss_sps_icd_version1.1-2017.pdf.

Kelso, T. S. (2000). *Updated TLEs of orbitron*. Retrieved from April 06, 2019, from https://www.celestrak.com/NORAD/elements/.

Kuna, D., Santhosh, N., Perumalla, N. K. (2020). Preliminary analysis of standalone Galileo and Navic in the context of positioning performance for low latitude region. In *Third international conference on computing and network communications* (Vol. 171, pp. 225–234).https://doi.org/10.1016/j.procs.2020.04.024

Ma, X., Tang, C., & Wang, X. (2019). The evaluation of IRNSS/NavIC system's performance in its primary and secondary service areas—Data quality, usability and single point positioning. *Acta Geodaetica Et Geophysica, 54*(1), 55–70. https://doi.org/10.1007/s40328-019-00246-8

Mahato, S., Santra, A., Dan, S., Verma, P., Banerjee, P., & Bose, A. (2020). Visibility anomaly of GNSS satellite and support from regional systems. *Current Science, 119*(11), 1774–1782.

Mandal, S., Samanta, K., Dutta, D., & Bose, A. (2016). IRNSS capabilities: An initial study using IGS receiver. In *Computational science and engineering* (pp. 147–150).

Mi, X., Zhang, B., & Yuan, Y. (2019). Multi-GNSS inter-system biases: Estimability analysis and impact on RTK positioning. *GPS Solutions, 23*(3), 81. https://doi.org/10.1007/s10291-019-0873-8

Mishra, D., Banik, S., & Bhatnagar, S. (2018). Evaluation of intersystem interference between NavIC GPS and Galileo. *Communications on Applied Electronics, 7*(12), 7–11.

Montenbruck, O., Steigenberger, P., Khachikyan, R., Weber, G., Langley, R., Mervart, L., & Hugentobler, U. (2014). IGS-MGEX: Preparing the ground for multi-constellation GNSS science. In *4th International colloquium on scientific and fundamental aspects of the Galileo system*, Prague (pp. 42–49).

Navigation European Space Agency. (2015). Retrieved from December 21, 2019, from http://www.esa.int/Our_Activities/Navigation/Galileo_and_EGNOS.

Online GPS Processing Service, Australian Government, Geoscience Australia. (2008). Retrieved from May 03, 2019, from https://www.ga.gov.au/scientifictopics/positioningnavigation/geodesy/auspos.

QZSS constellation information. (2020). Retrieved from April 14, 2020, from https://sys.qzss.go.jp/dod/en/constellation.html.

Santra, A., Mahato, S., Dan, S., & Bose, A. (2019a). Precision of satellite based navigation position solution: A review using NavIC data. *Journal of Information and Optimization Sciences, 40*(8), 1763–1772. https://doi.org/10.1080/02522667.2020.1714893

Santra, A., Mahato, S., Mandal, S., Dan, S., Verma, P., Banerjee, P., & Bose, A. (2019b). Augmentation of GNSS utility by IRNSS/NavIC constellation over the Indian region. *Advances in Space Research, 63*(9), 2995–3008. https://doi.org/10.1016/j.asr.2018.04.020

Sarkar, S. (2016). *Studies on evolution of the satellite based navigation techniques towards a complete GNSS*. Doctoral dissertation, The University of Burdwan.

Sarkar, S., Mahato, S., Santra, & Bose, A. (2019). GLONASS: Present and future. *UNOOSA workshop on the applications of global navigation satellite systems*, Suva (pp. 25–28).

Verma, P., Hajra, K., Banerjee, P., & Bose, A. (2019). Evaluating PDOP in multi-GNSS environment. *IETE Journal of Research*. https://doi.org/10.1080/03772063.2019.1666750

Xin, S., Geng, J., Guo, J., & Meng, X. (2020). On the choice of the third-frequency Galileo signals in accelerating PPP ambiguity resolution in case of receiver antenna phase center errors. *Remote Sensing, 12*, 1315. https://doi.org/10.3390/rs12081315

Xu, J., Yang, Y., Li, J., He, H., & Guo, H. (2013). Integrity analysis of COMPASS and other GNSS combined navigation. *Science China Earth Sciences, 56*(9), 1616–1622. https://doi.org/10.1007/s11430-013-4647-9

Yang, Y., Mao, Y., & Sun, B. (2020). Basic performance and future developments of BeiDou global navigation satellite system. *Satellite Navigation, 1*(1), 1–8. https://doi.org/10.1186/s43020-019-0006-0