

Visibility anomaly of GNSS satellite and support from regional systems

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In a multi-GNSS (global navigation satellite system) environment with operational GPS, GLONASS and Galileo Satellites, the Asia–Oceania region is expected to get better benefits of a large number of GNSS satellites for use. However, it is witnessed that during some parts of the day, no GNSS satellite is present above 60° elevation angle from many parts of the earth, including India. Real-time data from India show the regular absence of usable GPS satellites above 60° elevation angles during some parts of the day; addition of GLONASS and Galileo satellites does not improve the situation much. From Burdwan, West Bengal, India at least twice a day, no GNSS satellite is found above 60° elevation angles for more than 30 min. Simulation study for scattered places of India and data from IGS Centres confirm similar observations, except for the extreme northern region. The global scenario also supports these observations, while the individual operator's country is free from the problem using their own navigational system. The consequences of the problem affect GNSS-based solutions; for locations with obstruction of GNSS signals from low elevation angles, the concurrent occurrence of this incidence poses a threat for seamless GNSS-based navigation through intermittent loss of solution and degraded solution quality. Regional navigation satellite systems (RNSS) help mitigate this problem within the respective service regions. For a large part of the globe, the problem may be allayed using GNSS–RNSS hybrid operation. The result would be important for location-specific GNSS mission planning in strategic, life and safety-critical applications.

Keywords: GNSS, regional systems, satellites, visibility anomaly.

MULTI-global navigation satellite system (GNSS) has gained popularity with the fully operational global constellations – GPS, GLONASS and Galileo, that support redundant global availability of a large number of satellites^{1,2}. Especially for the Asia–Oceania region, there is better availability of multi-GNSS signals in comparison to other parts of the globe, and the advantages and poten-

tials of multi-GNSS have been explored by several researchers^{3–6}. However, even with a large number of available GNSS satellites, they are not always favourably distributed over the sky for use. It is witnessed that during some parts of the day, all GNSS satellites do not have sufficiently high elevation angles^{7–9}. Under the open sky or in aviation applications, this issue does not impact the position solution. Nevertheless, for constrained visibility environments like urban areas with high-rise buildings or forest environments, signals from the lower elevation angles are obstructed and during these periods there may not be enough satellites from high elevation angles. The combined situation may result in a loss of solution or degraded solution quality. Therefore, it is interesting to study the time-specific problem of non-availability of GNSS satellites and the possible mitigation methods. Here, the objectives are to study: (i) the unavailability of GNSS satellites above 60° elevation angles; (ii) the situation from different parts of India and the world through simulations; (iii) the effects of this situation on solution quality while operating within a constrained visibility location, and (iv) contribution of the regional satellite navigation systems (RNSS) to mitigate the situation.

Study on the unavailability of GNSS satellites above 60° elevation angle

Primary observation from GNSS Laboratory, Burdwan (GLB), India

Primary observations are found using multi-GNSS data in the 'open sky' condition; absence of GPS satellites above 60° elevation angles for some parts of the day was noted during 2015–16 (ref. 10). A subsequent detailed study showed repetition of the situation even in the presence of a large number of GPS/GNSS satellites above 10° elevation angles; such typical examples are shown in Figure 1 *a* and *b* for GPS and GPS + GLONASS + Galileo respectively. It is seen that addition of GLONASS and Galileo constellations does not always improve the situation much, and there are periods when no satellite is found for use above 60° elevation angle, which is taken as the lower boundary of high elevation angle. For the case

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Table 1. Observation of low visibility of satellites from GNSS Laboratory, Burdwan (GLB), India

Date	Constellation	Time span for maximum elevation <60° (hours IST)	Duration (T; min)
01/06/2017	GPS	01:16:18 – 02:04:03	47
		13:50:03 – 14:32:18	42
		16:29:48 – 17:44:03	74
		22:49:48 – 23:08:03	18
	GLONASS	00:00:00* – 00:05:03	05
		00:22:33 – 02:51:18	149
		08:13:18 – 10:46:33	153
		15:26:33 – 15:50:18	23
		16:23:48 – 18:52:33	148
	Galileo	00:00:00* – 05:10:45	310
		08:13:33 – 09:23:18	55
		09:55:45 – 01:20:42	206
		16:39:33 – 18:49:33	130
GPS + GLONASS + Galileo	01:16:18 – 02:04:03	47	
	16:39:33 – 17:44:03	64	
02/06/2017	01:12:18 – 01:59:48	47	
	16:35:48 – 17:40:03	64	

*Below 60° starts from the previous day.

Table 2. Representative samples for the absence of GNSS satellites above 60° elevation angles in hybrid operation using *Orbitron* (simulation Location: GLB, India)

Date	Period with maximum elevation <60° for GPS + GLONASS + Galileo hybrid operation	Duration (T; min)	Maximum elevation of all visible satellites during T (degrees)
02/05/2017	03:21:09 – 04:08:24	47	59
02/05/2017	18:39:05 – 19:49:21	70	
04/05/2017	03:12:54 – 03:59:54	47	
04/05/2017	18:23:33 – 19:40:49	77	
06/05/2017	03:04:34 – 03:52:04	48	
06/05/2017	18:15:20 – 19:31:56	76	

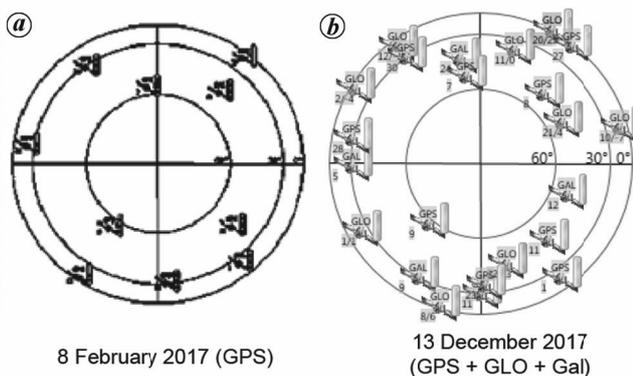


Figure 1. Typical ‘skyplots’ for all tracked satellites below 60° elevation angles from GLB, India for (a) GPS and (b) GPS + GLONASS + Galileo. For (b), 20 GNSS satellites are present above 10° elevation. This situation occurs twice a day for >20 min duration.

presented in Figure 1b, even in presence of 8 GPS, 7 GLONASS, 5 Galileo, none is found above 60° elevation.

To systematically analyse the situation, maximum elevation angles of satellites from individual and hybrid

operation are studied. The periods (T, say) for which the elevation angles of all the satellites are <60° are presented in Tables 1 and 2 for T > 10 min. It is noted that for the individual constellation, the problem of ‘no satellite above 60°’ occurs several times over the day with increasing durations for GPS, GLONASS and Galileo satellites respectively.

Now, even in tri-constellation hybrid operation, complete absence of GNSS satellite above 60° elevation angles occurs if such condition arises concurrently for each of the individual constellations. The situation leads to an unfavourable condition for seamless navigation. However, a hybrid operation helps to complement the visibility of individual constellations. For hybrid multi-GNSS constellation, non-availability of any GNSS satellite above 60° elevation angle over a long period from GLB, India may be seen from the data in Tables 1 and 2 during May and June 2017; the situation is witnessed twice a day with periods of more than 30 min.

To visually inspect the situation, results for 1–3 June 2017 are shown in Figure 2 where the variation of maximum elevation angles of individual and hybrid constellation shows systematic repetition of ‘no GNSS above 60°’.

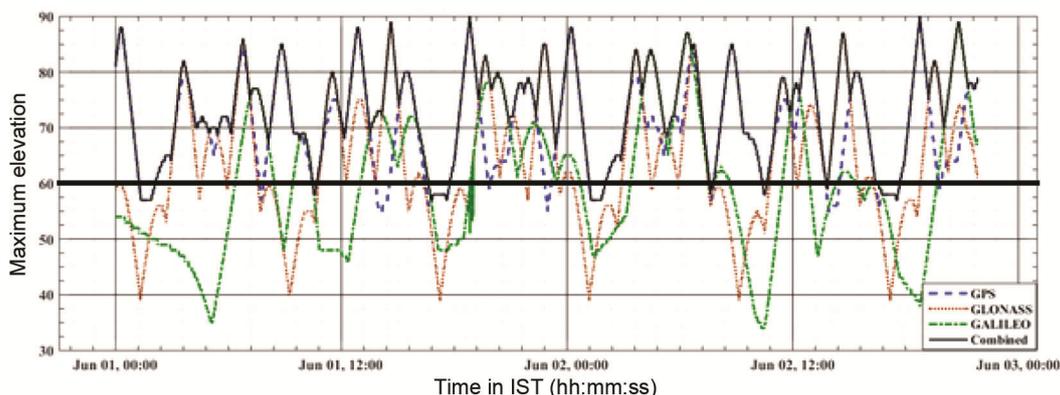


Figure 2. Variation of maximum elevation of satellites in standalone and hybrid GNSS operation observed during June 2017 from GLB, India. The thick black line corresponds to 60° elevation angle.

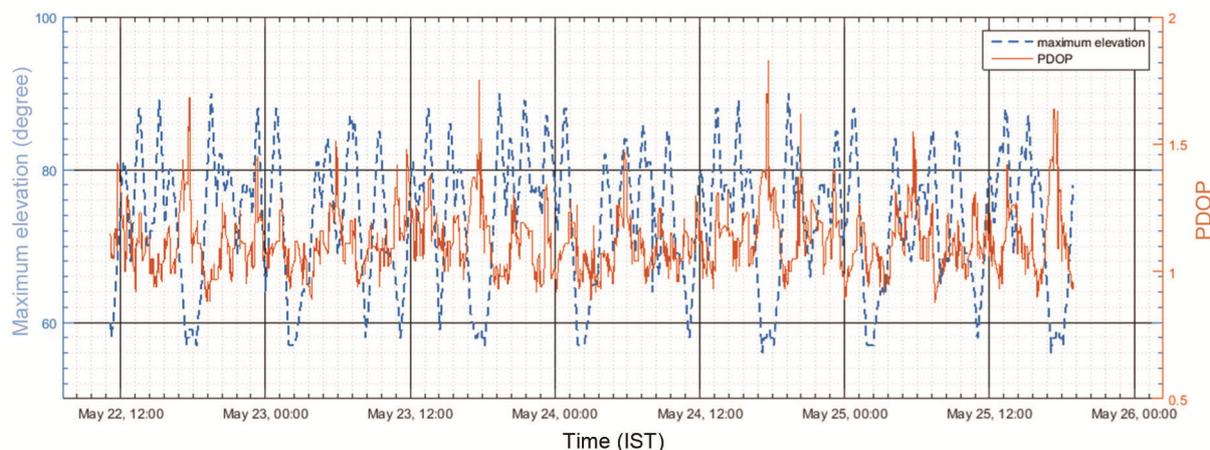


Figure 3. Variation of maximum elevation of satellites and satellite geometry, 22–26 May 2018, GLB, India.

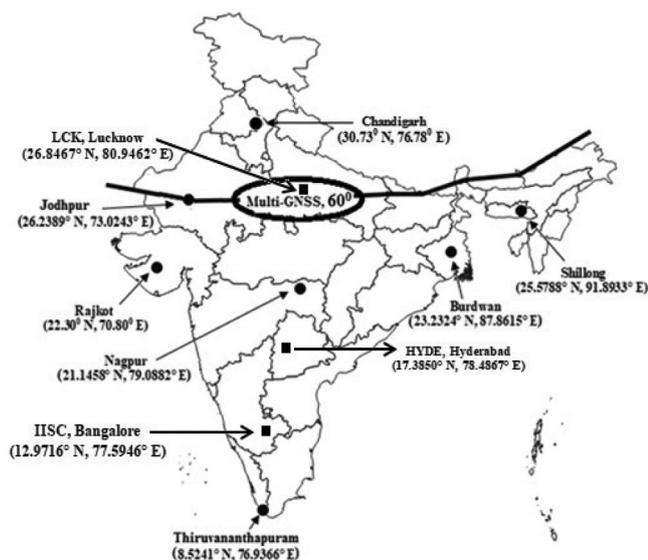


Figure 4. Contour (dark line marked with ‘Multi-GNSS 60°’) below which the problem of non-availability of GNSS satellites from >60° elevation angles exists during some parts of the day in India. The squares show IGS station locations¹⁴.

In many cases, the hybrid operation maximum elevation curve follows the GPS curve, pointing towards better visibility of GPS satellites from the region vis-à-vis the other two constellations. Figure 3 shows variation of maximum elevation of hybrid constellation satellites and satellite geometry during May 2018 from GLB, India. The long-term (2015–2018) observation establishes the phenomenon to be a general one and indicates higher Precision Dilution of Position (PDOP) values during the condition.

Simulated observations for GNSS visibility from India

Using *Orbitron*, a popular simulation software¹¹, GNSS satellite visibility from GLB, India was calculated using the latest two-line element (TLE) files obtained from the Celestrack website¹². The results show the situation of non-availability of GNSS satellites above 60° elevation angles for more than 30 min twice a day from GLB, India. The simulated results agree well with the real-time data and results presented in Table 1 and Figure 2.

Table 3. Absence of GNSS satellites above 60° elevation angles in tri-constellation hybrid operation (simulation using *Orbitron*)

Observation location	Date	Time with max elevation is less than 60° (<i>T</i>) (hours IST) for hybrid operation		Duration (<i>T</i> ; min)	Maximum elevation of all tracked satellites during <i>T</i> (degree)	
Thiruvananthapuram	16/05/2017	02:40:13	–	03:10:40	31	59
	12/12/2017	12:03:00	–	12:53:00	50	
	24/04/2018	03:13:00	–	03:44:00	31	
Nagpur	16/05/2017	02:50:17	–	03:41:07	51	
	12/12/2017	12:33:00	–	13:24:00	51	
	24/04/2018	03:25:00	–	04:14:00	49	
Rajkot	16/05/2017	11:49:16	–	12:53:25	64	
	12/12/2017	21:28:00	–	22:11:00	43	
	24/04/2018	12:24:00	–	13:19:00	54	
Shillong	16/05/2017	17:43:14	–	19:01:25	78	
	12/12/2017	03:38:00	–	04:45:00	67	
	24/04/2018	18:19:00	–	19:35:00	76	
Jodhpur	16/05/2017	11:40:00	–	11:49:00	09	
	12/12/2017	21:18:00	–	21:22:00	04	
	24/04/2018	12:15:00	–	12:22:00	08	

In our next study on GNSS high-elevation visibility problem over the Indian region, we employed simulated data using *Orbitron* for six scattered locations of India – Thiruvananthapuram, Nagpur, Rajkot, Shillong, Jodhpur and Chandigarh (Figure 4). GPS + GLONASS + Galileo satellite visibility was simulated for few consecutive days during two campaigns separated by nearly seven months; Table 3 shows the results. Absence of all GNSS satellites above 60° elevation during some parts of the day was observed from five places situated in the middle to southern parts of India. For Chandigarh in northern India, this problem was not witnessed. The interesting observations from Table 3 are: time span of the absence of satellites from high elevation angles increases with the sequential shift of the observation point from south to north and for locations further north of the country, the problem disappears.

Next, simulation was performed using an in-house developed utility that uses GNSS TLE files, System Tool Kit (*STK*)¹³ and *MatLab*. The utility first calculates the satellite orbital positions, which are passed to a Matlab program to finally generate the GNSS satellite visibility patterns for any user-specified location. These results are validated using both real-time data and *Orbitron* – therefore, either the *Orbitron* or this utility can be used for generalized GNSS satellite visibility study, and both have been used for the studies presented here.

GPS data from three IGS stations of India, viz. Lucknow (LCK), Hyderabad (HYDE) and Bengaluru (IISc)¹⁴ were used and satellite elevation angles calculated from the RINEX data using *RTKLib*¹⁵. Figure 5 shows the maximum elevation angles of tracked satellites. Real-time data from the IGS stations also support our findings; IISc situated at the southern part of India is prone to the problem for maximum duration, while in the case of LCK the

periods of the problem are shorter. Considering the location-dependent nature of the problem, next we analysed its global pattern of occurrence.

GNSS low visibility study over the globe

To extend the study over the globe, simulated results for global observation points separated by 5° each in latitude and longitude were found using the in-house developed tool described earlier in the text. Figure 6 shows the locations, where such situations occur for a span of >20 min over a day. To validate the global simulated results, IGS GPS data for two locations, viz. Addis Ababa, Ethiopia (ADIS) situated in the affected region, and Quincy, USA (QUIN) situated outside the affected area were used¹⁴. Representative results are shown in Figure 7 that support the simulated results presented in Figure 6 and our findings.

Therefore, the non-availability of GNSS satellites from high elevation angles during some part of the day is a repetitive, systematic global problem. The phenomenon is location-specific, being prominent around the low- to mid-latitude zones that include India, and both the polar regions (Figure 6). It can be seen from Figure 6 that the scenario of ‘unavailability of GPS satellites above 60° elevation angle’ does not occur in most parts of USA. Similarly over Russia ‘unavailability of GLONASS satellites above 60° elevation angle’ does not generally occur. This observation is perhaps associated with the constellation design issue, as the affected time shifts in a systematic manner.

The scenario of ‘unavailability of GNSS satellites above 60° elevation angle’ occurs for some time each day over many parts of the globe even for an operational tri-band hybrid multi-GNSS operation. The lower number of available satellites for location-specific conditions and

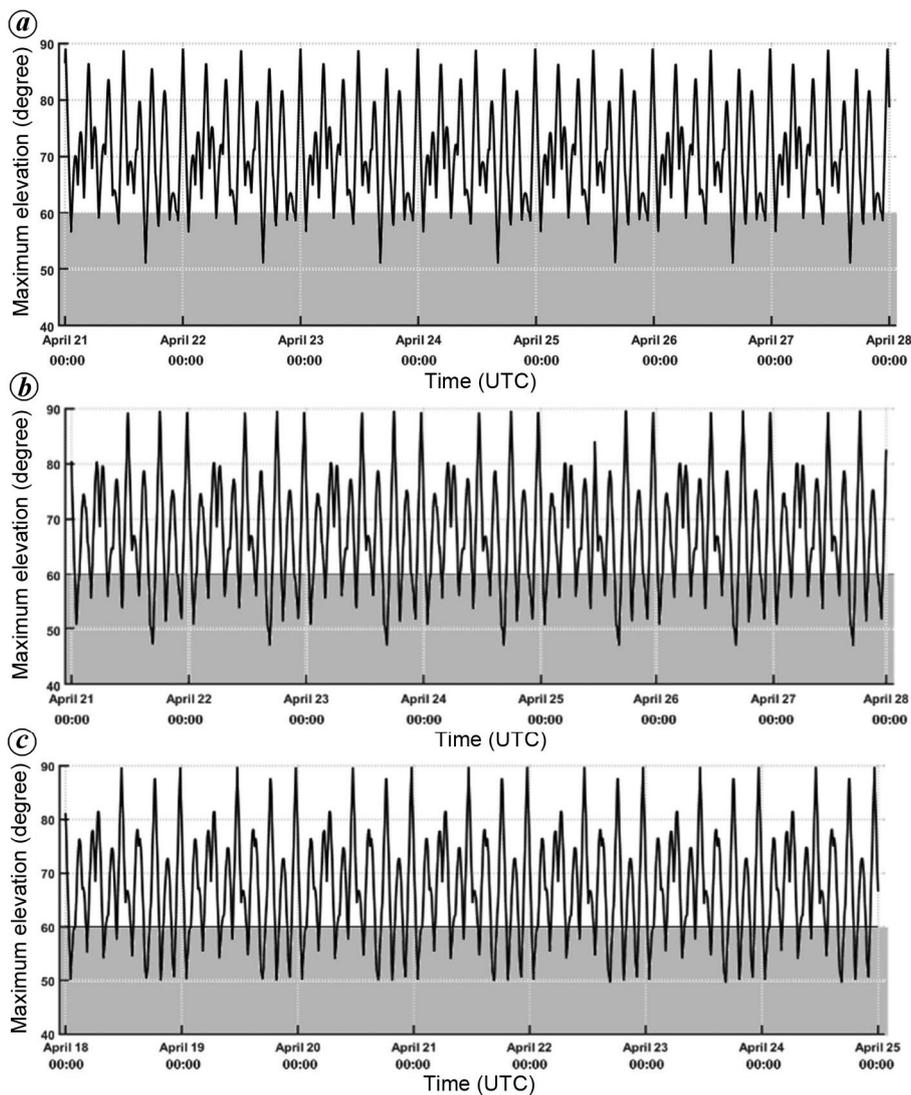


Figure 5. Variation of maximum elevation angle of GPS satellites from IGS stations (a) Lucknow (LCK), (b) Hyderabad (HYDE) and (c) Bengaluru (IISc) India, April 2018.

overall inferior geometry during these situations may affect seamless positioning and degrade the solution quality, as discussed subsequently. Nevertheless, in general, enough GNSS satellites are present all the time, irrespective of elevation issues in the open-sky condition.

Effects of unavailability of GNSS satellites above 60° elevation angle in navigation

First, we consider the results of a study from India on the visibility of GNSS satellites in constrained situations¹⁶. By intentionally masking the elevation angle up to 45° for the GPS + GLONASS operation, we found that even in the presence of 8–10 satellites in each of the GPS and GLONASS constellations, only 3–4 could be used. Thus, if the GNSS satellite visibility is obstructed from low to

mid regions of the sky, a single constellation-based solution may not be possible in many cases. This study was conducted during arbitrary periods without considering the currently discussed GNSS visibility problem. Now let us consider both the location- and time-specific situations together, i.e. a GNSS user is within a location where the satellite visibility is restricted by obstructions (e.g. high-rise buildings, foliage) concurrently during the periods of ‘no GNSS satellite above 60° elevation’^{9,17} (e.g. as shown in Table 1). In such situations, satellite visibility from the lower angles is obstructed by location-specific conditions, and signals from high elevation angles are unavailable due to time- and location-specific conditions. As a result, seamless navigation is seriously impaired. The situation is particularly relevant for Indian conditions, where buildings or foliage are present on the sides of narrow roads/lanes. Studies were

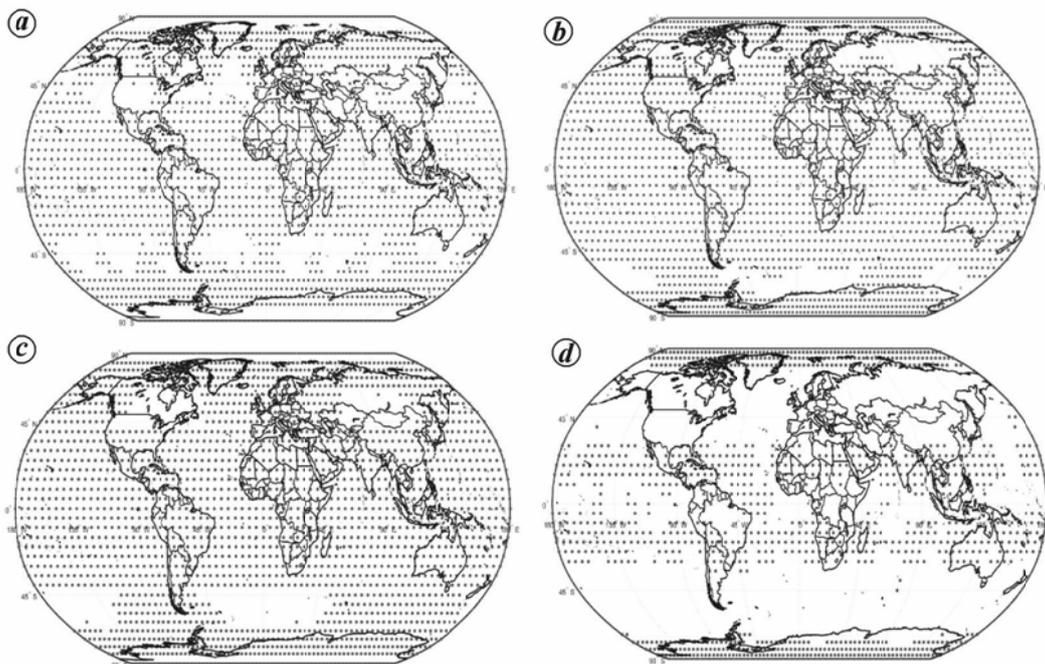


Figure 6. Locations of time-specific GNSS visibility problem over the globe. The dark dots show locations where all (a) GPS, (b) GLONASS, (c) Galileo and (d) GPS + GLONASS + Galileo satellites lie below 60° elevation angle for more than 20 min over a day; 24 April 2018 and 6 April 2019.

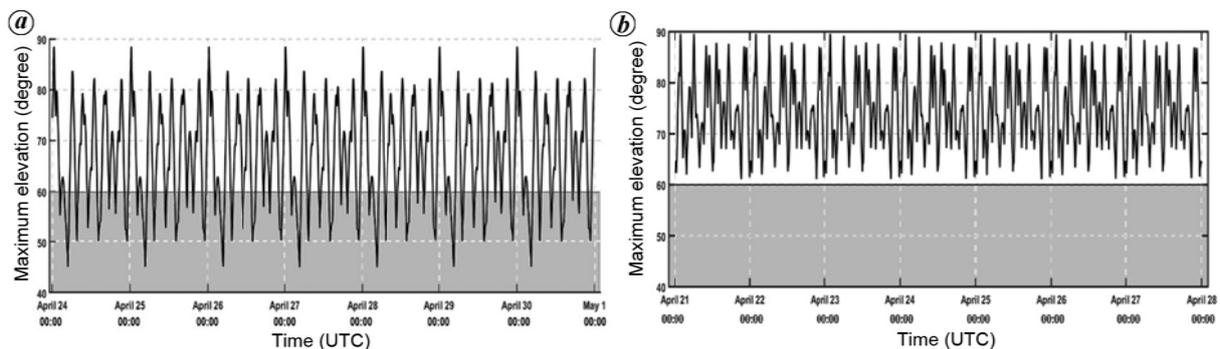


Figure 7. Variation of maximum elevation angle of GPS satellites from IGS station (a) Addis Ababa (8.9806°N , 38.7578°E , Ethiopia (ADIS), 24 April–1 May 2018 and (b) Quincy (42.2529°N , 71.0023°W), USA (QUIN), 21–28 April 2018.

conducted to observe the effects using real-time experiments.

In the case of one experiment, a car-mounted GNSS receiver moving at 15–20 kmph speed on the roads (4–5 m wide) of a densely populated area of Kolkata, India, intermittently failed to receive at least four satellite signals, and therefore could not provide position solution during the affected period of ‘no satellites above 60° condition’⁹. In another case, a motorbike-mounted GNSS receiver moved within an urban canyon region of Burdwan through the same route during the affected period (onward journey) and normal condition (return journey). During the affected period, lower solution success rate was observed than the normal period, and the solution quality had also degraded¹⁷.

To compare the hybrid GNSS solution quality during the affected and normal periods, a static survey was conducted using a GPS + GLONASS + Galileo survey-grade receiver from a constrained city environment (Figure 8 a). Representative skyplots of the two situations are shown in Figure 8 b and c respectively. Position solutions for the affected and normal periods were analysed. Figure 8 d and Table 4 show the results. Lower success probability (93.4% in comparison to 100%) and inferior solution quality during the affected period of ‘no GNSS above 60° elevation angle’ were observed comparing the associated solution quality parameters, distance root mean square (DRMS), circular error probable (CEP), spherical error probable (SEP), mean radial spherical error (MRSE)¹⁸.

Table 4. Comparison of position solution in normal and affected periods for static tri-constellation hybrid operation in constrained city environment of Burdwan, India on 14 July 2018

Condition (time, IST)	Total epochs (average PDOP)	Total solution obtained (solution success)	Maximum variation (m)			2DRMS (m)	CEP (m)	SEP (m)	MRSE (m)
			Latitude	Longitude	Altitude				
Normal (06:53–07:10 and 08:24–09:14)	4012 (3.05)	4012 (100%)	41.8	5.64	26.08	11.74	4.22	5.45	6.97
Affected period (07:10–08:24)	4441 (6.23)	4146 (93.35%)	46.94	30.05	126.05	11.8	4.87	11.30	15.17

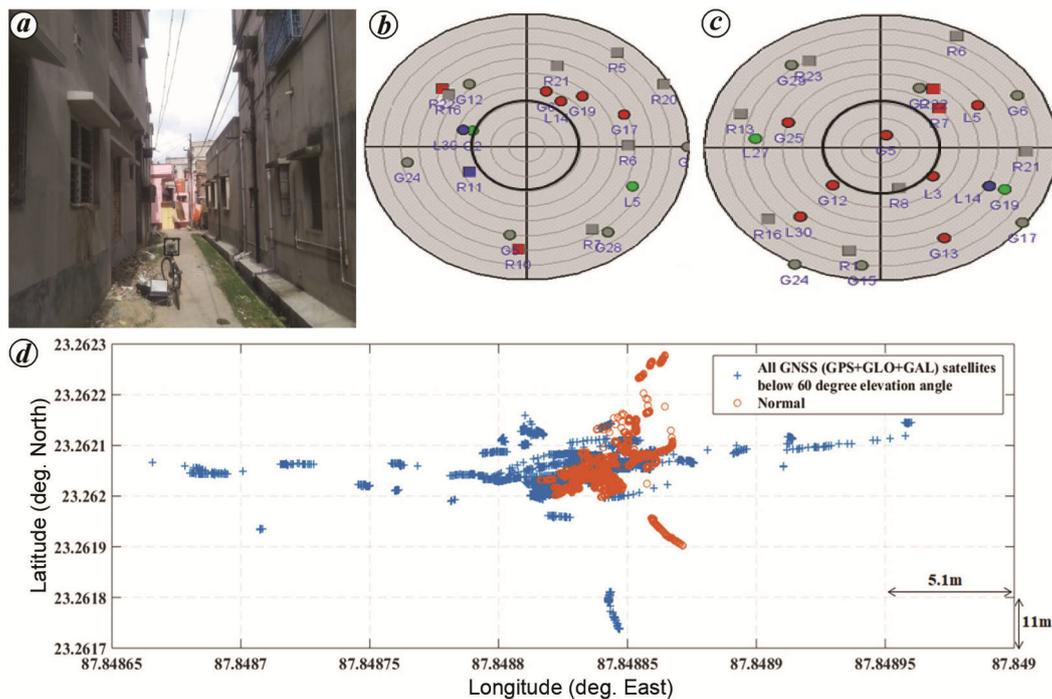


Figure 8. Comparison of solution quality in GPS + GLONASS + Galileo hybrid operation within a constrained city environment of Burdwan, India, 14 July 2018. *a*, Survey location; *b*, Skyplot of the GPS + GLONASS + Galileo hybrid operation with ‘no satellite above 60°’ at 07:27:50 UTC; *c*, Skyplot of the GPS + GLONASS + Galileo hybrid operation during normal condition; the black circle represents 60° elevation circle; *d*, Comparison of two-dimensional position solutions during affected and normal periods.

These real-time exercises prove the predicted problem of intermittent loss of solutions and degraded solution quality due to location-specific insufficient satellite conditions and the inferior satellite geometry during the periods of ‘no GNSS satellites above 60° elevation angle’.

Benefit of regional navigation satellite systems to mitigate this visibility problem

NAVigation with Indian Constellation (NavIC) and Quasi Zenith Satellite System (QZSS) are the two operational RNSS from India and Japan^{19,20}. This section presents the contribution of the RNSS to mitigate the aforesaid visibility problem of GNSS. Using the method discussed

above, the visibility status for GNSS + RNSS satellites was generated (Figures 9 and 10).

From Figures 6*d* and 9*a*, mitigation of the visibility problem can be witnessed for Japan, its neighbouring regions, and the northern and eastern parts of Australia when QZSS is added with GPS + GLONASS + Galileo; at least one satellite always remains present for use above 60° elevation angle. Similarly, Figures 6*d* and 9*b* suggest mitigation of the problem for India, its surrounding regions, the southern and eastern parts of Africa, and west to the north-western part of Australia when NavIC is added with GPS + GLONASS + Galileo constellations. In Figure 9, all periods of the problem >20 min have been added together to show the cumulative time of such events over a day. Now, if both QZSS and NavIC are used together with GPS + GLONASS + Galileo, the

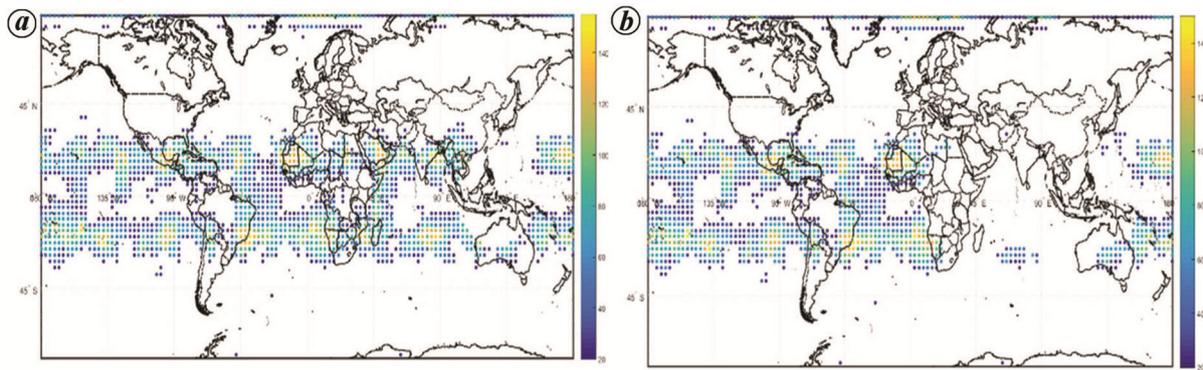


Figure 9. Location of GNSS visibility problem over the globe during some parts of the day, 3 December 2018. The dark dots show locations where (a) all GPS + GLONASS + Galileo + QZSS satellites and (b) GPS + GLONASS + Galileo + NavIC satellites lie below 60° elevation angles for >20 min over a day. The vertical colour bars show cumulative time span of the problem over the day.

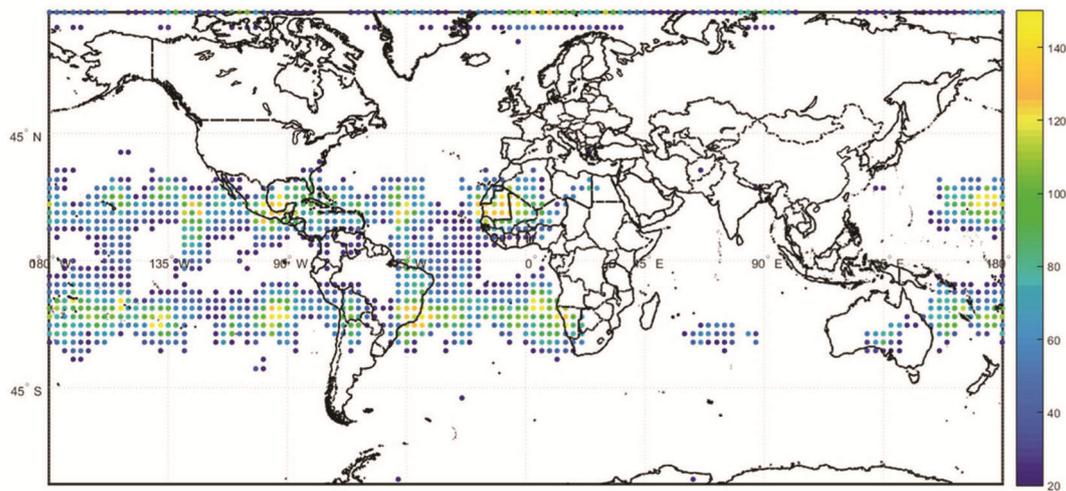


Figure 10. Location of navigation satellite visibility problem over the globe, 3 December 2018. The dark dots show locations where all GPS + GLONASS + Galileo + NavIC + QZSS satellites lie below 60° elevation angles during some parts of the day. The colour bar on the right shows cumulative time span of the problem over the day.

global scenario is presented in Figure 10. Comparison of Figures 6 and 10 reveals that using the regional navigation systems together with GNSS, the problem of non-availability of GNSS satellites above 60° elevation angle is alleviated for a large part of the globe, ensuring seamless and accurate navigation solutions.

Concluding remarks

This article discusses the location- and time-specific problem of GNSS signal visibility. From real-time observations and simulations, it is found that in the southern to mid-northern parts of India, the problem of GNSS satellite visibility from higher elevation angles exists during some parts of the day. For the extreme northern part and further north of the country, the problem disappears. Through simulation results supported by real-time data, similar global situations are witnessed depending on the location of observation.

The situation does not affect the serviceability of GNSS in open view of the sky, but within degraded visibility conditions like urban canyons, forest roads or deep trenches where the signals from lower elevation angles are simultaneously blocked, this typical problem leads to severe impairment of continuous GNSS-based solution and accuracy, most importantly, for safety-critical applications.

Proper integration of the regional systems – NavIC and QZSS satellites with GPS/GNSS helps improve the situation over the respective regional service systems. With the help of QZSS + NavIC, degradation of satellite visibility within constrained environments can be resolved from the middle to eastern parts of the globe supporting seamless position solution and improved solution quality.

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