Impact of multi-constellation satellite signal reception on performance of satellite-based navigation under adverse ionospheric conditions

Ashik Paul[1,2], Krishnendu Sekhar Paul[1] and Aditi Das[2]

[1]Institute of Radio Physics and Electronics, University of Calcutta, Calcutta, India

[2]S. K. Mitra Center for Research in Space Environment, University of Calcutta, Calcutta, India

ashik_paul@rediffmail.com

Abstract

Application of multi-constellation satellites to address the issue of satellite signal outages during periods of equatorial ionospheric scintillations could prove to be an effective tool for maintaining the performance of satellite-based communication and navigation without compromise in accuracy and integrity. A receiver capable of tracking GPS, GLONASS and GALILEO satellites is operational at the Institute of Radio Physics and Electronics, University of Calcutta, Calcutta, India located near the northern crest of the Equatorial Ionization Anomaly (EIA) in the Indian longitude sector. The present paper shows increased availability of satellites combining GPS, GLONASS and GALILEO constellations from Calcutta compared to GPS-only scenario and estimates intense scintillation-free ($S_4 < 0.6$) satellite vehicle look angles at different hours of the post-sunset period 19:00-01:00LT during March 2014. A representative case of March 1, 2014 is highlighted in the paper and overall statistics for March 2014 presented to indicate quantitative advantages in terms of scintillation-free satellite vehicle look angles that may be utilized for planning communication and navigation channel spatial distribution under adverse ionospheric conditions. Number of satellites tracked and receiver position deviations has been found to

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2016RS006076

show a good correspondence with the occurrence of intense scintillations and poor user receiver-satellite link geometry. The ground projection of the 350-km subionospheric points corresponding to multi-constellation shows extended spatial coverage during periods of scintillations ($0.2<S_4<0.6$) compared to GPS.

Introduction

Multi-constellation satellite signal reception capability has provided an important tool for enhancing the performance of satellite based navigation system under conditions of intense ionospheric scintillations as experienced during equinoctial months of high sunspot number years at equatorial locations. The equatorial ionosphere is characterized by sharp latitudinal gradients of ionization for a major part of the day existing till about 22:00LT. Transionospheric satellite links operating near the crests of the Equatorial Ionization Anomaly (EIA) experience unusually large range errors and range error rates through such steep ionization gradients which may be particularly hazardous for reliable operation of high dynamic platforms like an aircraft [*DasGupta et al.*, 2006].

Global Navigation Satellite System (GNSS) comprises of the constellations GPS, GLONASS, GALILEO and SBAS, Ground-Based Augmentation System (GBAS), and Aircraft Based Augmentation System (ABAS). The basic function of GNSS is to provide collectively world-wide Positioning, Navigation, and Timing (PNT) determination capability available from one or more satellite constellations. Presently there are 31 operational GPS satellites while GLONASS has declared full-operational constellation of 24 'healthy' satellites. Combining GPS, GLONASS and GALILEO constellations, an average 15 satellites are expected to be in view.

One of the major deterrents to successful implementation of satellite-based communication and navigation service is related to sharp latitudinal gradients of ionization occurring during the daytime and intense Space Weather events in the post sunset hours, affecting transionospheric satellite links particularly in the equatorial region [*Carrano and Groves*, 2010; *Humphreys et al.*, 2010a; *Paul et al.*, 2011; *Roy and Paul*, 2013; *Das et al.*, 2014]. Ionospheric scintillations may cause amplitude fades in excess of 20dB-Hz on GNSS channels at equatorial locations. This figure assumes importance in view of the fact that conventional communication receivers have a typical dynamic range of 25-30dB-Hz. These fades could cause cycle slips, and stress the receiver to lose lock on the transmitted signals to be re-acquired at a later time leading to intermittent availability of service.

Deep and frequent signal fading as observed during solar maxima at equatorial latitudes can lead to frequent loss of carrier tracking lock of GPS receivers. The loss of these satellites can significantly reduce navigation availability. However the spatial diversity of GNSS satellites (GPS, GLONASS, GALILEO and COMPASS) can mitigate the impact of ionospheric scintillations on satellite-based navigation, of particular importance being application to high dynamic platforms like aircrafts. A GNSS receiver may briefly lose some satellites simultaneously, but if the receiver can track a minimum of four satellites with good geometry, navigation is still possible [*Kaplan and Hegarty*, 2006]. In addition to the intensity of scintillations, the number of satellites affected by scintillations is also a very important factor since a greater number of satellites under lower scintillation intensity may be more problematic for GNSS-based aviation than less number of satellites with much higher scintillation intensity [*Seo et al.*, 2011].

GNSS amplitude scintillation studies from Dakar (magnetic latitude: 5.88°N) in Africa near the magnetic equator observed during late 2012 to early 2014 highlight longitudinal variations in its occurrence over this region [*Akala et al.*, 2016]. The severity and longer duration of equatorial scintillations and its resultant effect on GPS performance have been compared with the high-latitude occurrence of scintillations [*Jiao and Morton*, 2015]. Reports of the effects of equatorial ionospheric scintillations on EGNOS are available in literature [*Arenas et al.*, 2016].

In determining navigation solutions, the number of satellites that are lost simultaneously to deep fading is very vital. A receiver with fast reacquisition capability will reduce the chance of simultaneous losses of satellites to deep fades, thereby providing better navigation performance. WAAS MOPS requirement stipulates that for satellite signal outages of 30s or less when the remaining satellites provide GDOP ≤6, the equipment shall reacquire the satellite within 20s from the time the signal is reintroduced [*RTCA*, 2006]. Applicability of these conditions to the highly dynamic equatorial ionosphere has to be tested and validated before implementation. There is sufficient motivation to test the applicability of this condition to equatorial anomaly locations where daytime ionization gradients introduce large range errors and night-time ionization density irregularities cause C/N_0 fades and cycle slips more intense compared to mid-latitudes even under magnetic quiet conditions.

Earlier during 1999-2002, combined GPS-GLONASS receivers were operated at some locations in India where it was reported that availability of GLONASS satellites were limited from equatorial locations [*Banerjee et al.*, 2002]. Studies conducted earlier have reported that the detrimental effects of the sharp latitudinal gradients of ionization occurring in the equatorial region may be limited if sufficient number of satellite links are available at high elevation angles in excess of 60° [*Paul et al.* 2005].

It has been observed using TEC measured in 2004 along a chain of stations located more-or-less along 77°E meridian under the Indian SBAS program GAGAN that the median grid scale of latitude and longitude for TEC variation less than 3TECU (for an acceptable range error of 50cm) varied from (0.64°-0.87°) × (0.23°-0.49°) at elevation angles greater than 70° [*Paul et al.*, 2011]. It should be borne in mind that these figures were arrived at during a moderate sunspot number period. Thus more stringent requirements may be imposed during solar maximum period. With the increased number of satellites under GNSS resulting in large number of ionospheric pierce points, availability of sufficient satellite links at varying elevation angles may result in improved accuracy and hence less stringent requirement for grid size even under the highly dynamic equatorial ionosphere.

Data

A multi-constellation GNSS receiver capable of tracking GPS, GLONASS and GALILEO satellites at L1 (1575.42MHz), L2 (1227.6MHz) and L5 (1176.45MHz) frequencies is operational at the Institute of Radio Physics and Electronics (IRPE), University of Calcutta (22.58°N 88.38°E geographic; magnetic dip: 32°N), Calcutta, India since April 2013. It provides at its output elevation, azimuth, time (UTC), carrier-to-noise (C/N_0) ratio and amplitude scintillation index S_4 at a sampling interval of 1minute. The receiver position data are available at 50Hz sampling. Analyses of amplitude scintillations measured by the S_4 index have been done for all satellite vehicles observed from Calcutta during 13:00-19:00UT of March 2014. An elevation mask angle of 15° has been chosen to eliminate the effects of multipath on the GPS and GNSS observations [*Parkinson and Spilker*, 1996]. On a particular satellite track, portions with $0.2< S_4 <0.6$ above an elevation of 15° have been selected to identify intense scintillation-free condition. Satellite elevation and azimuth range over this section of the track have been noted for every hour during 19:00-01:00LT on every night of March 2014. The 99 percentile value of all such elevation and azimuth range for each hour over the entire month has been calculated using the standard formula available. The number of GPS and multi-constellation satellites tracked available from the receiver has been utilized to understand the effects of the ionospheric irregularities from early evening hours to local midnight. In this paper, satellite vehicle links are ray paths of radio signals transmitted from the satellite to the user receiver.

A dual-frequency GPS receiver is operational at the Institute of Radio Physics and Electronics, University of Calcutta under the international SCIntillation Network Decision Aid (SCINDA) program of the US Air Force since November 2006. The receiver provides at its output satellite elevation, azimuth, carrier-to-noise (C/N_O) ratio, S_4, and UTC at 1minute sampling and the position data with 1s sampling, which are uploaded to the website http://capricorn.bc.edu/scinda/india and available to authorized users. Receiver position information in terms of latitude and longitude are available from the SCINDA receiver operational at IRPE. In the present paper, receiver position deviations have been studied from GPS and GNSS receiver to understand relative advantages of observing multiple constellations. In order to maintain uniformity, the plots of receiver position deviations use a scaled down sampling rate of 1Hz for the multi-constellation receiver.

Classification of intensity of amplitude scintillation could be done on the basis of Scintillation Index [SI(dB)] [*Whitney et al.*, 1969] and S_4 index [*Briggs and Parkin*, 1963]. The Scintillation Index (SI) values 4-8dB correspond to the range $0.2<S_4\leq0.4$, 8-15dB correspond to $0.4<S_4\leq0.6$ while SI≥15dB correspond to $S_4>0.6$ [*Whitney*, 1974]. SI of 4-8dB qualify as mild scintillation, 8-15dB is moderate scintillation while SI≥15dB occurs under intense scintillations. According to scattering theory, an SI of 15 dB corresponds to a signal fade of 12 dB. A fade of more than 10 dB may cause loss of receiver lock on the satellite-based navigation systems. Assuming that the receiver has a fade margin of less than 12 dB, the link will be disrupted under the chosen intensity of scintillations [*Ray et al.*, 2003]. An increase in the amplitude fade margin may be achieved by narrowing the receiver loop bandwidth, but this would make the receiver vulnerable to phase fluctuations.

This paper presents a representative case for March 1, 2014 during 19:00-23:00LT when most of the intense scintillation cases were encountered and an overall statistics for March 2014 to stress the importance of application of spatial diversity technique to plan communication and navigation signal distribution in space under periods of ionospheric scintillations which may result in severe outages resulting in compromise of performance of satellite-based communication and navigation services.

Results

Availability of multi-constellation satellites during different hours of a day was studied from Calcutta for March 2014. Figure 1 shows the availability of GPS, GLONASS and GALILEO satellites from IRPE on a particular day, March 23, 2014. The values indicate total number of GPS, GLONASS and GALILEO satellites tracked during every hour over a 24 hour period from 06:00LT of March 23, 2014. Significantly larger number of transionospheric satellite links were available instantaneously, particularly during 16:00-22:00LT when 12 GPS, 7 GLONASS and 2 GALILEO satellites were tracked. In comparison normally 10-12 satellites are observed under GPS-only scenario. This improved geometry thereby provides scope for application of spatial diversity techniques to improve navigation position solutions during ionospheric scintillations.

During March 2014, it is extremely important to note that intense GPS scintillations with S_4>0.6 were recorded on all 31 nights from Calcutta on SV links above an elevation mask of 15°. Sky plots corresponding to 350-km subionospheric tracks of the satellites affected by amplitude scintillations during that time interval were plotted to understand the changing look angles affected by different levels of amplitude scintillations every hour, namely, mild ($0.2<S_4\leq0.4$), moderate ($0.4<S_4\leq0.6$) and intense ($S_4>0.6$) during that time period. The different levels of scintillations are indicated by different colours on the subionospheric tracks.

Figure 2 shows the sky plots of SV links affected by different levels of scintillations during 19:00-20:00LT of March 15, 2014 for (a) GPS and (b) combining GPS, GLONASS and GALILEO. It could be understood that the number of SV links either unaffected ($S_4<0.2$) or mildly affected ($0.2<S_4<0.4$) are much more when combining GPS, GLONASS and GALILEO observations as shown in Figure 2(b).

On March 1, 2014, intense amplitude scintillations ($S_4>0.6$) and associated fluctuations in carrier-to-noise ratios (C/N_0) were noted on 6 GPS and 8 GLONASS links above an elevation mask of 15° during 19:00-01:00LT. In order to quantify the relative advantage of using multi-constellations compared to GPS-only situation particularly under ionospheric scintillation condition, proportion of satellite vehicle (SV) look angles unaffected by intense scintillations ($S_4<0.6$) every hour during 19:00-01:00LT was estimated to assess the improvement, if any, and applicability of the principle of spatial diversity for ionospheric scintillation mitigation.

Figures 3(a) and 3(b) show the spatial distribution of satellites links affected by different levels of scintillations during 19:00-20:00LT observed from Calcutta on (a) GPS and (b) GNSS (GPS, GLONASS and GALILEO combined) on March 1, 2014. Figures 3(c) and 3(d) represent sky plots of GPS and GNSS SV links respectively affected by different levels of scintillations during 20:00-21:00LT from Calcutta. The different coloured circles represent different intensities of scintillations.

Figure 4 shows the spatial distribution of satellites links affected by different levels of scintillations on March 1, 2014 observed from Calcutta during 21:00-22:00LT on (a) GPS and (b) GNSS (GPS, GLONASS and GALILEO combined), and 22:00-23:00LT on (c) GPS and (d) GNSS (GPS, GLONASS and GALILEO combined).

The 99 percentile values of elevation range of SVs unaffected by scintillations during 19:00-20:00LT was estimated to be 48.2° using GNSS while it was 49.32° using only GPS. The 99 percentile values of azimuth range of SVs unaffected by scintillations during 19:00-20:00LT was 73.9° using GNSS in comparison to 74.34° when using GPS. The corresponding figures for unaffected satellite elevation range during 20:00-21:00LT were found to be 30.45° using multi-constellation compared to 23° using GPS only. The 99 percentile values of azimuth range of SVs unaffected by scintillations during 20:00-21:00LT were found to be 10° using multi-constellation compared to 7° using GPS only. Thus increased availability of SV look angles unaffected or mildly affected by scintillations when using GNSS compared to GPS-only case will definitely help in planning alternative strategies for diversion of communication and navigation traffic during periods of signal outages.

The 99 percentile values of elevation range of SVs unaffected by scintillations during 21:00-22:00LT and 22:00-23:00LT were found to be 29.38° and 32.62° using multi-constellations compared to 14.3° and 28.62° when using only GPS. The corresponding range of unaffected azimuth values during 21:00-22:00LT and 22:00-23:00LT at 99 percentile level showed improved values of 26° and 22.38° using GNSS in contrast to 24.68° and 10.38° when using GPS.

This process of estimating scintillation-free SV look angles when using multi-constellation was performed every evening during March 2014 thereby providing system designers with figures to validate the suggestion of the concept of spatial diversity for scintillation mitigation. Variabilities were noted in the scintillation-free look angle ranges at different hours which may be attributed to the temporal behaviour of equatorial ionospheric scintillations.

Figure 5 shows the overall results combining the values of intense scintillation-free (S_4<0.6) range of (a) elevation and (b) azimuth angles for different SV links over the entire month of March 2014 during 19:00-01:00LT. It is noted that predominantly there is an improvement in availability of intense scintillation-free range of look angles for SV links at all hours for elevation. The percentage improvement when using GPS and GNSS was calculated to be 10% to a maximum of 44% in terms of elevation angle swath. For azimuth, the percentage improvement was more, typically in the range of 28%-47%, with the exception of 21:00-22:00LT and 00:00-01:00LT when marginal decrement in availability ~ 2% and 5% respectively was noted.

Figure 6 shows the number of GPS and GNSS satellites tracked every hour during 19:00-23:00LT on March 1, 2014 from Calcutta. The red dots indicate the number of multi-constellation satellites, combining GPS, GLONASS and GALILEO while the black dots represent the number of GPS satellites. It is observed that during 20:00-21:00LT and 21:00-22:00LT, the number of GPS satellites tracked dropped to a minimum value of 5 and 4 respectively. During the same interval of time, the minimum number of GNSS satellites tracked were 9 and 8 respectively. It is interesting to note that during 20:00-21:00LT and 21:00-22:00LT, intense scintillations with S_4>0.6 occurred on a number of GPS satellite links as evident from Figures 3(c) and (d), and 4(a) and (b) respectively.

The position information provided by a GPS receiver is eventually a measure of the ability of the system to perform under various adverse ionospheric conditions, notable among them being ionospheric scintillations. Figures 7(a) and (b) show~~s~~ the receiver position deviations in latitude and longitude respectively, measured in meters, every hour at 1 second interval during 19:00-23:00LT of March 1, 2014 using GPS as well as GNSS. The points marked in black correspond to GPS observations while those in red are for GNSS. The less spread of the points when using GNSS highlight the improvement obtained in position determination under conditions of scintillations when using multi-constellation compared to GPS. The deviations in position are calculated by taking the instantaneous position differences from the mean position, estimated during 05:00-06:00LT of March 1, 2014. Maximum latitude and longitude deviations are found to be about 7m using GPS during 20:00-21:00LT and 21:00-22:00LT. During these time intervals, number of GPS satellites tracked dropped to 5 and 4 respectively. It is important to note that during these time intervals, almost all the GPS links tracked from Calcutta were affected by intense scintillations as evident from Figures 3(c) and 4(a) respectively. In comparison, some GNSS links other than GPS were available and unaffected by intense scintillations as shown in Figures 3(d) and 4(b). Figures 8(a) and (b) show the composite plot for the month of March 2014 showing latitude and longitude deviations respectively during 19:00-01:00LT. The 99 percentile values of latitude and longitude deviations measured every hour for different days of the whole month have been plotted in this figure.

Table 1 shows the 99 percentile values of maximum latitude and longitude deviations in position of the receiver every hour during 19:00-01:00LT every day for the month of March 2014. Percentage improvements in position accuracy using GNSS compared to GPS are also indicated in the table. Every hour, less deviation~~s~~ in receiver position are noted when using multi-constellation compared to GPS.

Figures 9(a)-(f) show~~s~~ the ground projections of the 350-km ionospheric pierce points (IPP) available every hour during 19:00-01:00LT using GPS and multi-constellation for the whole month of March 2014 during periods of scintillations having $0.2<S_4<0.6$. The black curve joins the points marking the outer extent of the IPPs using GPS while the red curve shows the same for GNSS. During 20:00-21:00LT, latitudinal improvement in IPP extent is found to be about 2°, while during 21:00-22:00LT, longitudinal enhancement in IPP extent is about 4°, when using multi-constellation. Distinctly larger area of availability of multi-constellation satellite links unaffected by intense scintillations could be seen compared to GPS thereby providing definite advantage when using spatial diversity.

Discussions

The geometry of GNSS constellations follow a pre-defined pattern ensuring availability of at least 18-20 satellites (combining GPS, GLONASS and GALILEO) at any time from any point on the surface of the Earth. Generation and subsequent development of ionospheric irregularities from early evening to midnight local times from a station like Calcutta has been documented using GPS transmissions [*DasGupta et al.*, 2004]. The results presented in this paper gives a combined information of the above two factors thereby providing quantitative estimates for using multi-constellation satellite links for position-fixing under conditions of ionospheric scintillations.

The morphology of equatorial ionospheric scintillations highlighting its origin and subsequent development from early evening to late night hours has been studied extensively. From the perspective of GNSS based navigation, it is important that satellite links should be available and should not experience intense ionospheric scintillations so as to be usable for accurate position determination by the receiver. From the stand-point of GPS receivers, it has been frequently observed from stations like Calcutta situated in the anomaly crest region that 6-8 satellite links have been affected by intense scintillations leaving only 3-4 usable links which thereby reduces the accuracy of position-fixing. This problem could be solved if an effective strategy of interoperability of satellites across different constellations could be developed when using GNSS receivers capable of receiving signals from GPS, GLONASS and GALILEO simultaneously. Larger number of usable satellite links provides greater number of satellite combinations and hence better optimization possibilities for the receiver while determining its position [*Kaplan and Hegarty*, 2006]. It had been understood that availability of satellite links will be increased once multi-constellation GNSS signals are being received. However the exact number of satellites and their variability in terms of availability at different hours of a day has not been extensively studied from the geophysically sensitive Indian longitude sector post 2002 when GLONASS constellation had degenerated to a few satellites only. Figure 1 addresses this issue and quantifies the number of satellites typically available every hour from Calcutta. The sky plots in Figures 2, 3 and 4 showing spatial distribution of amplitude scintillations affecting satellite links observed from Calcutta clearly demonstrate the advantages that accrue once multi-constellation satellite signals are received, as a possible mechanism to maintain acceptable level of accuracy during periods of ionospheric scintillations. Availability of satellite links (which follows a pre-determined orbital geometry) is more when using multi-constellations compared to GPS-only condition. Observation of ionospheric scintillations (caused by intersection of drifting ionospheric irregularities with satellite links) follows an established morphology of irregularity occurrence. The results presented in this paper shows improvement in performance of satellite-based positioning when using multi-constellation only when 1) satellite links are available following their pre-defined orbital trajectory, and 2) are not affected by intense amplitude scintillations following the morphology of occurrence of ionospheric irregularities. Thus the values of intense scintillation-free look angles arrived at are a combination of the above two factors. Although the number of satellite links affected by scintillations may be more when using multi-constellation, the number of links unaffected may be also more. Accuracy of position-fixing could be retained when more number of intense scintillation-free satellite links are available in the user receiver's range of reception. Impact of scintillation on GNSS receiver performance using various low latitude datasets using multiple phase screen formulation and specific application to LPV 200 guidance for aircrafts have been reported [*Ghafoori and Skone*, 2015; *Seo et al.*, 2014].

The information on the range of intense scintillation-free elevation and azimuth angles observed over the month of March 2014 from Calcutta shows improved user receiver and satellite geometry every hour during 19:00-01:00LT when using GNSS compared to GPS, which usually corresponds to the period of intense amplitude scintillations at L-band. Further, the values available from Calcutta situated near the northern crest of the Equatorial Ionization Anomaly (EIA) correspond to some of the worst-case figures and could serve as a benchmark for the international Space Weather community. Thus better position accuracy should be obtained corresponding to improved satellite-user geometry in terms of availability of larger scintillation-free elevation and azimuth angles of satellite vehicle links at a particular hour. Deviations in receiver position from the mean are high ~7m during periods of intense scintillations on the representative case of March 1, 2014 coupled with non-availability of sufficient number of unaffected GPS links as shown in Figures 6 and 7. The composite plot for March 2014 in Figure 8 shows maximum latitude deviation equivalent to 12m when using GPS and 6m when using GNSS during 21:00-22:00LT. The corresponding equivalent longitude deviations are 12m for GPS during 22:00-23:00LT and 5m for GNSS during 20:00-21:00LT. Modelling of receiver position deviations during periods of scintillations at equatorial latitudes could serve as an accurate diagnostic measure during Space Weather events. However present understanding of background ionospheric processes preceding ionospheric irregularity generation coupled with receiver hardware and software response during periods of signal outages, is an evolving topic which needs significant advancement before implementation. It is important to note that *DasGupta et al.* [2004] had also shown GPS position deviations from Calcutta for measurements made in February 2001 (Figures 3 and 4 from that paper) where the deviations did not follow a well-defined distribution during periods of scintillations.

Figure 9 shows the 350-km ionospheric pierce points (IPPs) corresponding to GPS and multi-constellation satellites showing scintillations having $0.2<S_4<0.6$ i.e. unaffected by intense scintillations. Hence the outer bounds of these satellite tracks when joined provides the spatial area over which satellites are unaffected by intense scintillations during a particular period of time. Hence for multi-constellations, this area is more indicating greater coverage area of satellite tracks unaffected by intense scintillations compared to GPS-only which is helpful in maintaining a certain level of accuracy in the performance of the system. An extended area of coverage of IPPs ~ 2° in latitude and 4° in longitude are noted from Figure 9 when using GNSS compared to GPS. This implies application of larger grid size and hence less number of reference stations to address the issue of large spatial gradient of ionization existing in the equatorial region during a major part of the day, and occurrence of ionospheric irregularities during post-sunset hours.

In the next decade, the GNSS environment is going to undergo a major transformation. First, two more GNSS core constellations are expected to be launched/augmented, GALILEO and COMPASS over the existing GPS and GLONASS. When these constellations are in their final operational capability, there will be three times more ranging sources. Secondly, GPS and the new core constellations will broadcast signals in two frequencies L1 and L5 (E5a or b for GALILEO). These signals will be available for civil aviation, allowing users to cancel the pseudorange errors due to the ionosphere. The relative robustness of these different frequencies needs to be assessed under intense scintillation conditions. Thus application of frequency diversity techniques as well as the concept of spatial diversity suggested in this paper could serve as a potent combination in combating equatorial ionospheric scintillations.

Acknowledgements

This research has been sponsored in part by the University Grants Commission (UGC), Govt. of India through the Centre of Advanced Study (CAS) program at the Institute of Radio Physics and Electronics, University of Calcutta, Calcutta, India. The authors acknowledge Asian Office of Aerospace Research and Development (AOARD) for providing the SCINDA data (https://capricorn.bc.edu/scinda/india). The GPS and multi-constellation data used in this paper are available with Prof. A. Paul (ashik_paul@rediffmail.com).

References

Akala, A.O., A. Awoyele and P.H. Doherty (2016), Statistics of GNSS amplitude scintillation occurrences over Dakar, Senegal, at varying elevation angles during the maximum phase of solar cycle 24, *Space Weather*, doi:10.1002/2015SW001261.

Arenas, J., E. Sardon, A. Sainz, B. Ochoa and S. Magdaleno (2016), Low-latitude ionospheric effects on SBAS, *Radio Sci.*, doi:10.1002/2015RS005863.

Banerjee, P., A. Bose and A. DasGupta (2002), The usefulness of GLONASS for positioning in the presence of GPS in the Indian subcontinent, *J. Navig.*, 55, 463-475.

Briggs, B.H., and J.A. Parkin (1963), On the variation of radio star and satellite scintillation with zenith angle, *J. Atmos. Terr. Phys.*, *25*(6), 339-366.

Carrano, C. S., and K.M. Groves (2010), Temporal decorrelation of GPS satellite signals due to multiple scattering from ionospheric irregularities, *Proc. of the 2010 Institute of Navigation ION GNSS Meeting*, pp. 361–374, Institute of Navigation, Portland, Oreg.

Das, A., K.S. Paul, S. Halder, K. Basu, K. and A. Paul (2014), Characteristics of equatorial ionization anomaly (EIA) in relation to transionospheric satellite links around the northern crest in the Indian longitude sector, *Ann. Geophys.*, 32, 91-97, doi:10.5194/angeo-32-91-2014.

DasGupta, A., S. Ray, A. Paul, P. Banerjee and A. Bose (2004a), Errors in position-fixing by GPS in an environment of strong equatorial scintillations in the Indian zone, *Radio Sci.*, *39*, RS1S30, doi:10.1029/2002RS002822.

DasGupta, A., A. Paul, S. Ray, A. Das and S. Ananthakrishnan (2006), Equatorial bubbles as observed with GPS measurements over Pune, India, *Radio Sci.*, *41*, RS5S28, doi:10.1029/2005RS003359..

Engavale, B., A. Bhattacharyya (2005), Spatial correlation function of intensity variations in the ground scintillation pattern produced by equatorial spread-F irregularities, *Ind. J. Radio & Space Phys.*, 34, 23-32.

Ghafoori, F. and S. Skone (2015), Impact of equatorial ionospheric irregularities on GNSS receivers using real and synthetic scintillation signals, *Radio Sci.*, doi:10.1002/2014RS005513.

Jiao, Y. and Y.T. Morton (2015), Comparison of the effect of high-latitude and equatorial ionospheric scintillation on GPS signals during the maximum of solar cycle 24, *Radio Sci.*, doi:10.1002/2015RS005719.

Kaplan, E.D. and C. Hegarty (Eds.) (2006), *Understanding GPS: Principles and Applications*, 2nd Ed., Artech House, Norwood, MA.

Humphreys, T. E., Psiaki, M. L., Ledvina, B. M., Cerruti, A. P. and P. M. Kintner Jr. (2010a), Data-driven testbed for evaluating GPS carrier tracking loops in ionospheric scintillation, *IEEE Trans. Aerosp. Electron. Syst.*, 46(4), 1609–1623.

Li, G., B. Ning., H. Yuan (2007), Analysis of ionospheric scintillation spectra and TEC in the Chinese low latitude region, *Earth Planets Space*, 59, 279-285.

Parkinson, B.W., J.J. Spilker (1996), *Global Positioning System: Theory and Applications*, American Inst. of Aeronautics and Astronautics, Inc.

Paul A., A. Das, S.K. Chakraborty and A. DasGupta (2005), Estimation of satellite-based augmentation system grid size at low latitudes in the Indian zone, *NAVIGATION*, *52*, 15-22.

Paul, A., A. Das, and A. DasGupta (2011), Characteristics of SBAS grid sizes around the northern crest of the equatorial ionization anomaly, *J. Atmos. Sol. Terr. Phys.*, 73, 1715–1722.

Paul, A., B. Roy, S. Ray, A. Das, and A. DasGupta (2011), Characteristics of intense space weather events as observed from a low latitude station during solar minimum, *J. Geophys. Res.*, 116, A10307, doi:10.1029/2010JA016330.

Ray, S., A. DasGupta, A. Paul, P. Banerjee (2003), Estimation of minimum separation of geostationary satellites for satellite-based augmentation system (SBAS) from equatorial ionospheric scintillation observations, *J. Navigation*, 56, 137-142.

Roy, B. and A. Paul (2013), Impact of space weather events on satellite-based Navigation, *Space Weather*, 11, 680–686, doi:10.1002/2013SW001001.

RTCA, Inc. (2006), Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, RTCA DO-229D, December 13.

Seo, J. T. Walter and P. Enge (2011), Correlation of GPS signal fades due to ionospheric scintillation for aviation applications, *Adv. Space Res.*, doi:10.1016/j.asr.2010.07.014

Seo, J. and T. Walter (2014), Future dual-frequency GPS navigation system for intelligent air transportation under strong ionospheric scintillation, *IEEE Trans. Intelligent Transportation Systems*, 15, 5, doi:10.1109/TITS.2014.2311590.

Whitney, H.E. (1974), Notes on the relationship of scintillation index to probability distributions and their uses for system design, *Rep. AFCRL-TR-74-0004*, AD778092, Air Force Cambridge Research Lab., Hanscom AFB., Ma., USA.

Whitney, H.E., J. Aarons, and C. Malik (1969), A proposed index for measuring ionospheric scintillations, *Planet Space Sci.*, *17*(5), 1069-1073.

Figure Captions

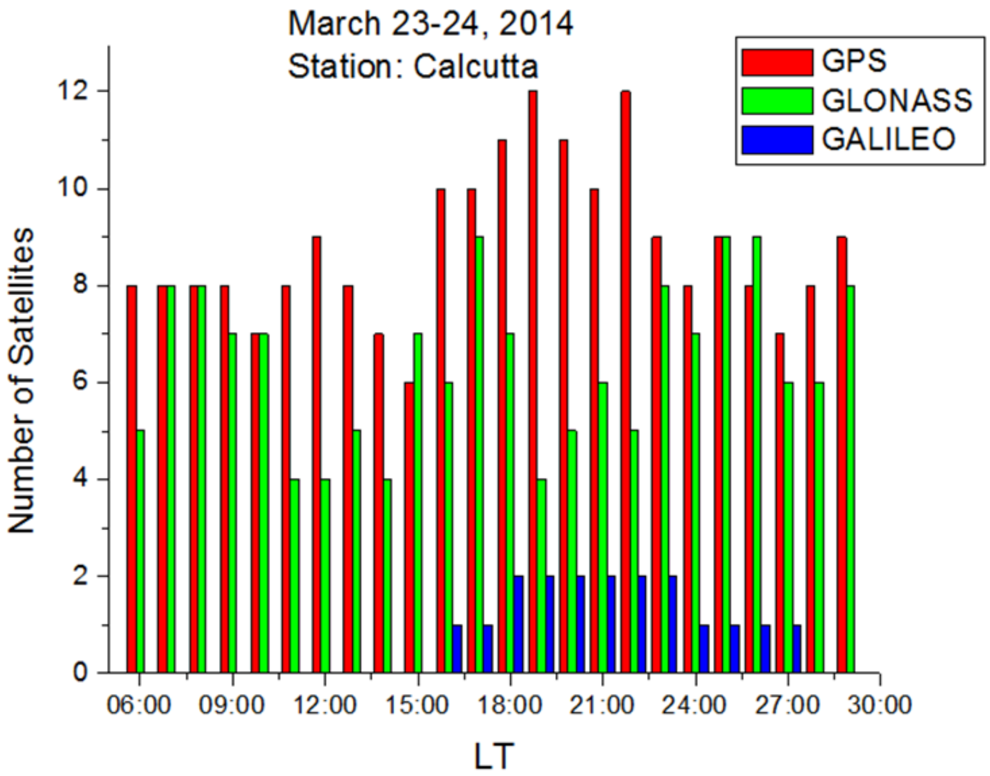


Figure 1: Availability of GPS, GLONASS and GALILEO satellites from IRPE, Calcutta over a 24 hour period from 06:00LT of March 23, 2014

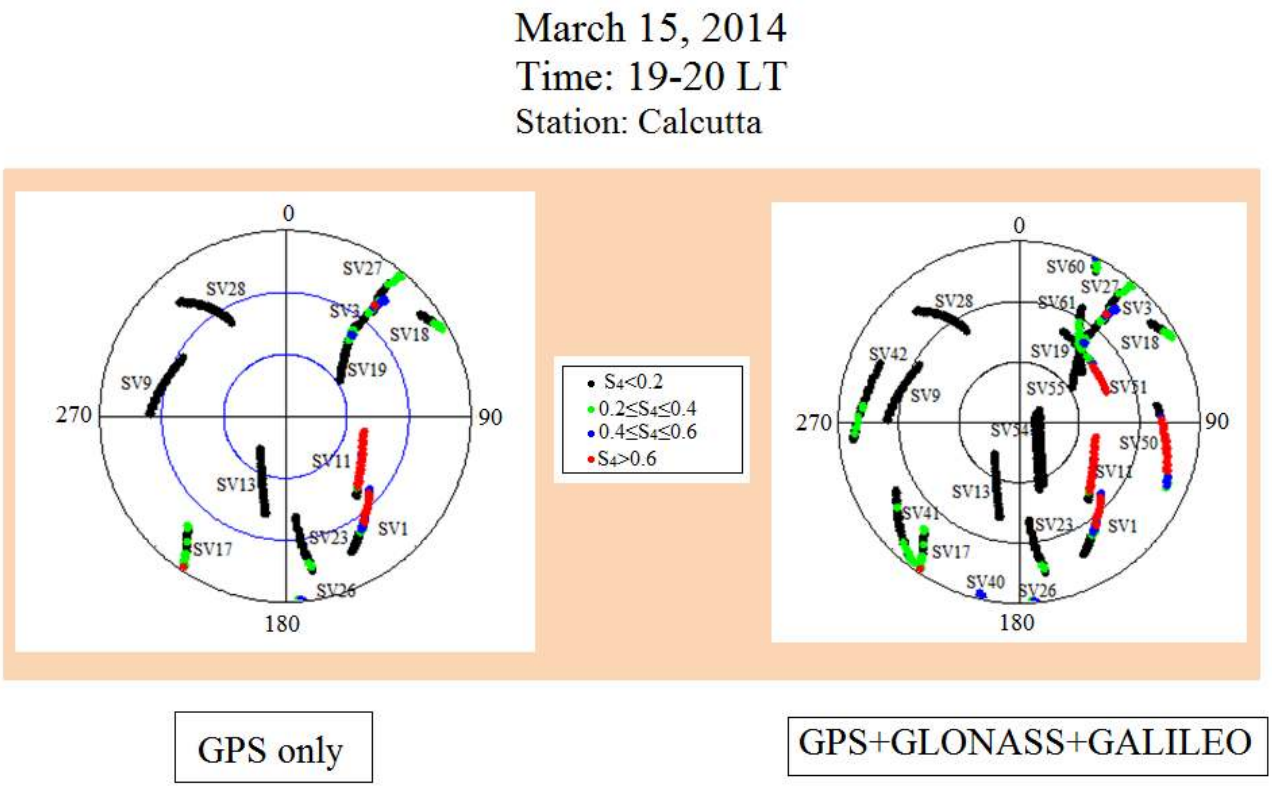


Figure 2: Spatial distribution of (a) GPS and (b) GNSS combining GPS, GLONASS and GALILEO satellite links affected by different levels of scintillations during 19:00-20:00LT of March 15, 2014 as observed from Calcutta. The different colours on the 350-km subionospheric tracks of the satellites indicate varying levels of amplitude scintillations.

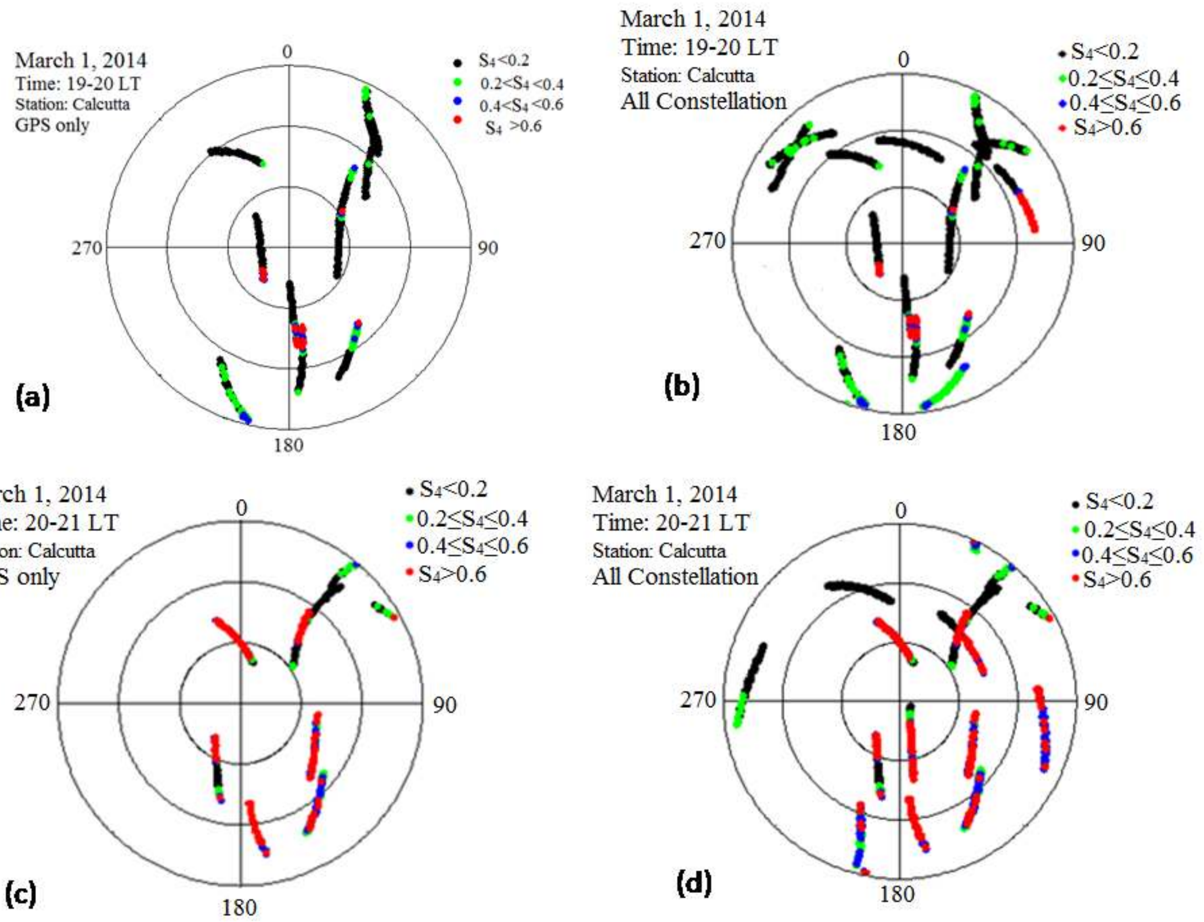


Figure 3: Spatial distribution of satellites links affected by different levels of scintillations on March 1, 2014 observed from Calcutta during 19:00-20:00LT on (a) GPS and (b) GNSS (GPS, GLONASS and GALILEO combined), 20:00-21:00LT on (c) GPS and (d) GNSS (GPS, GLONASS and GALILEO combined).

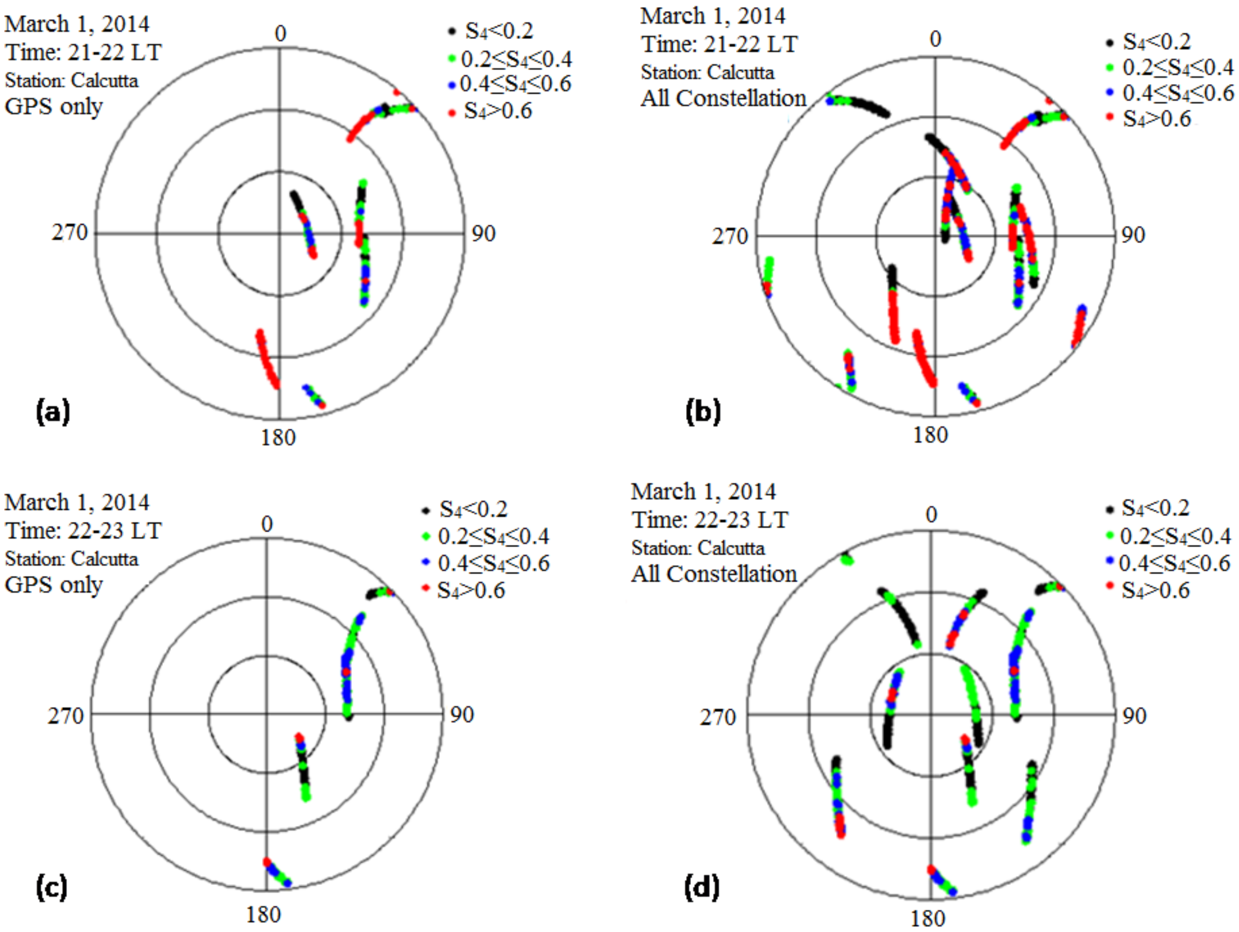


Figure 4: Spatial distribution of satellites links affected by different levels of scintillations on March 1, 2014 observed from Calcutta during 21:00-22:00LT on (a) GPS and (b) GNSS (GPS, GLONASS and GALILEO combined), 22:00-23:00LT on (c) GPS and (d) GNSS (GPS, GLONASS and GALILEO combined).

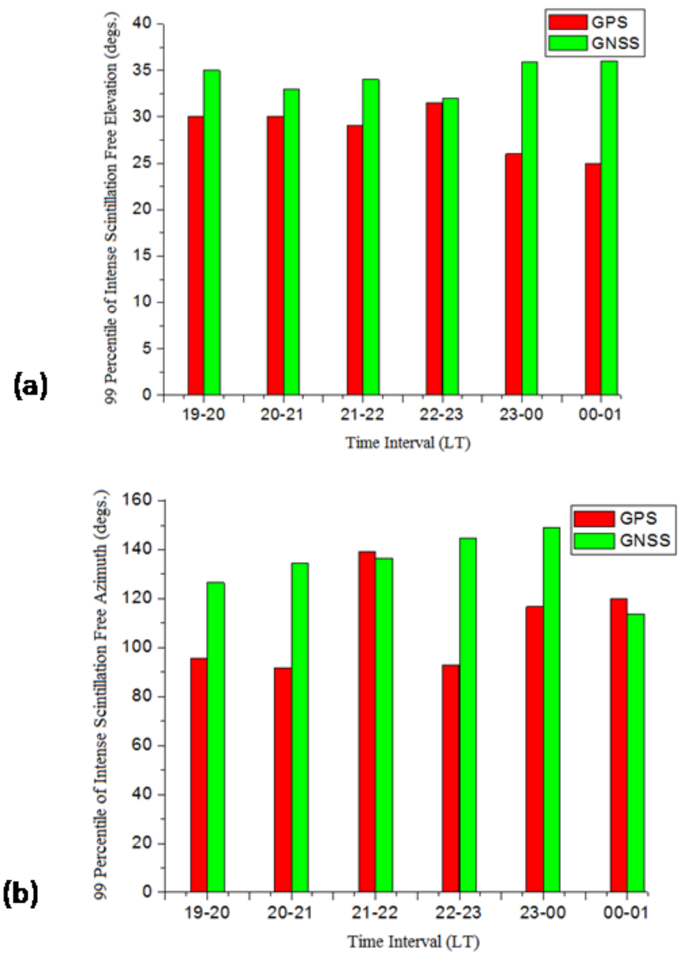


Figure 5: 99 percentile values of range of (a) elevation and (b) azimuth angles of GPS and GNSS (combining GPS, GLONASS and GALILEO) satellite links unaffected by intense scintillations (S_4<0.6) every hour during 19:00-01:00LT of March 2014.

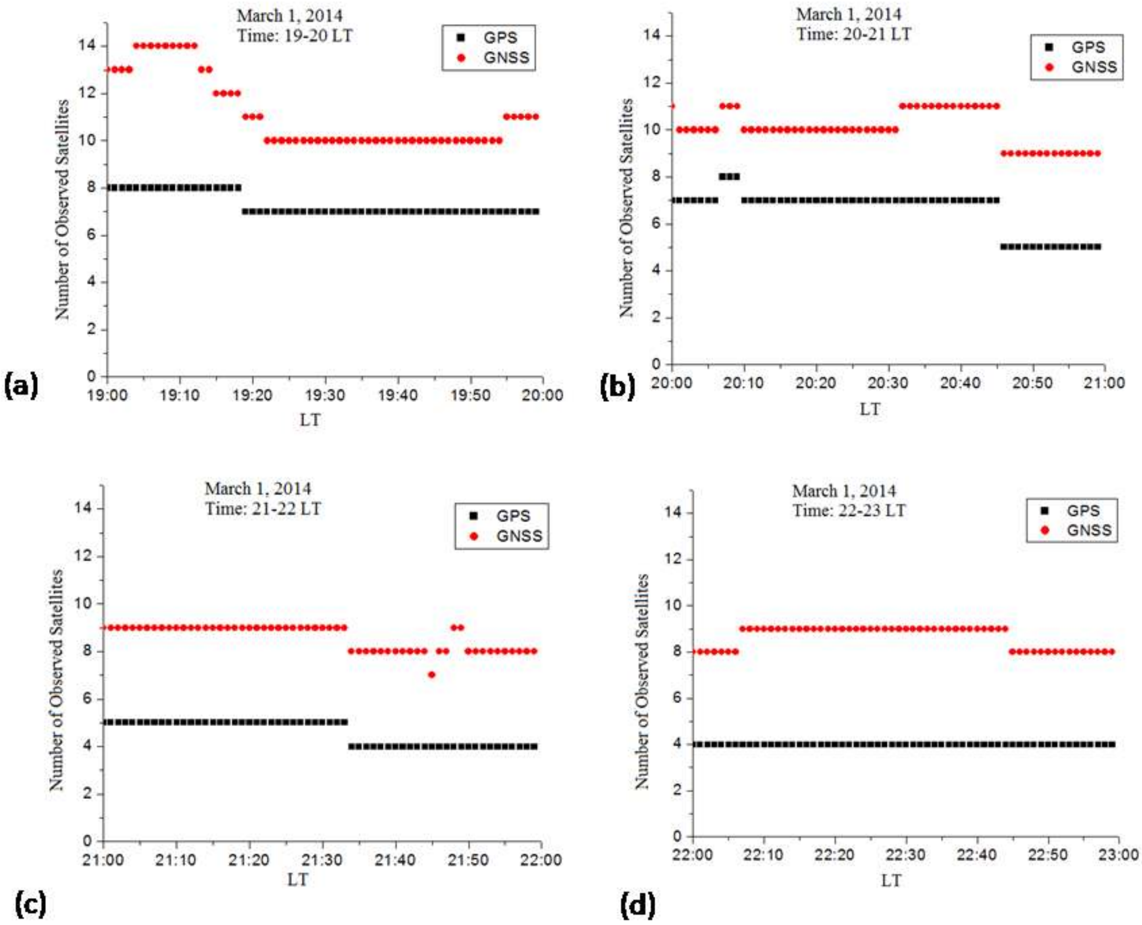


Figure 6: Number of GPS and GNSS satellites tracked every hour during 19:00-23:00LT on March 1, 2014 from Calcutta. The red dots indicate the number of multi-constellation satellites, combining GPS, GLONASS and GALILEO, while the black dots represent the number of GPS satellites.

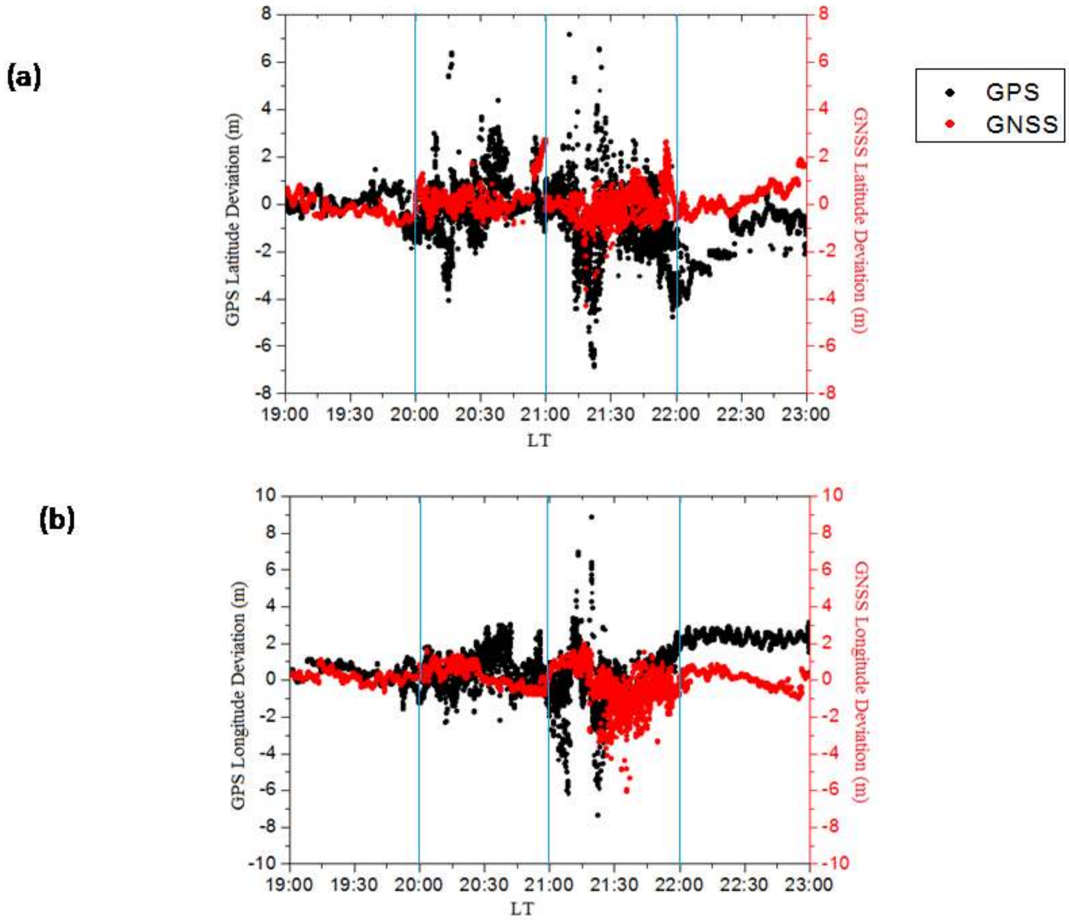


Figure 7: Receiver (a) latitude and (b) longitude deviations when using GPS and multi-constellation measured in meters during 19:00-23:00LT on March 1, 2014 at Calcutta. The black points correspond to GPS while the red ones indicate GNSS.

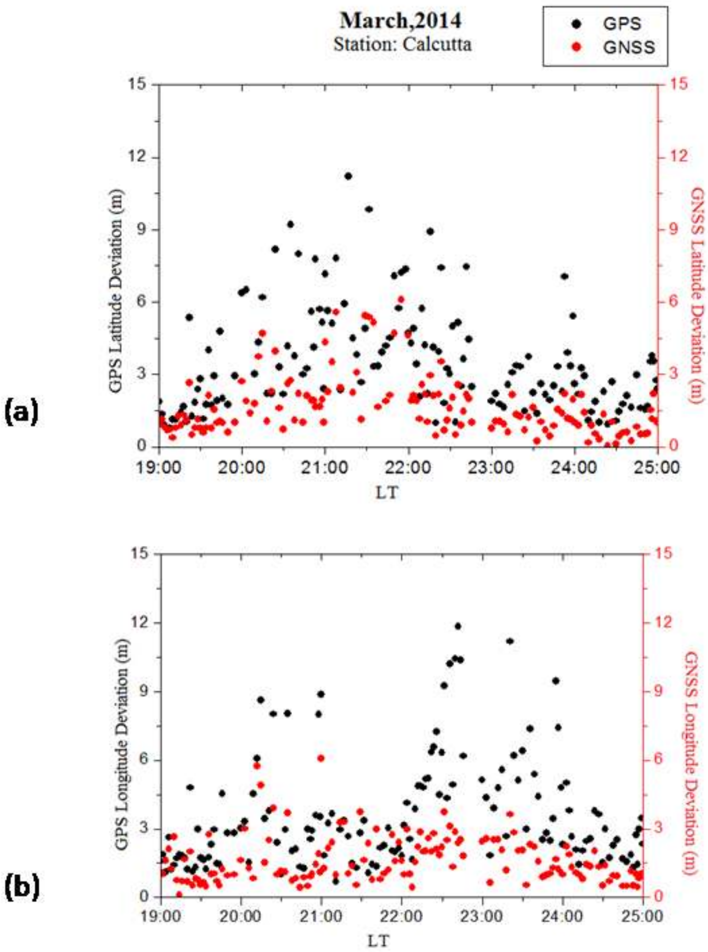
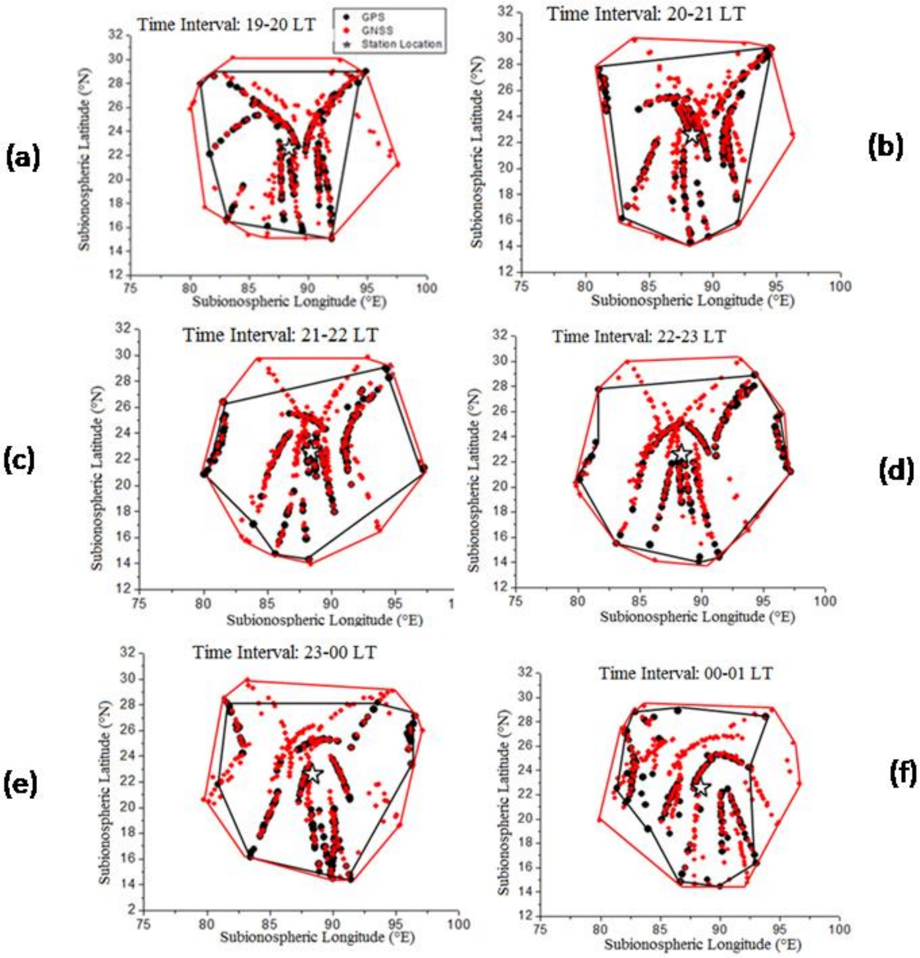


Figure 8: Composite plot for the month of March 2014 showing 99 percentile position errors of the receiver (a) latitude and (b) longitude, expressed in metres, during 19:00-01:00LT of different days. The black points show GPS positioning errors while the red ones indicate GNSS positioning errors.



Figures 9(a)-(f): The ground projections of the 350-km ionospheric pierce points (IPP) of GPS and multi-constellation satellites unaffected by intense scintillations ($0.2<S_4<0.6$) available every hour during 19:00-01:00LT using GPS and multi-constellation for the whole month of March 2014 during periods of scintillations ($S_4>0.2$). The black curve joins the points marking the outer extent of the IPPs using GPS while the red curve shows the same for GNSS.

Time Interval (LT)	GPS		GNSS		(%) Improvement in GNSS	
	Latitude (m)	Longitude (m)	Latitude (m)	Longitude (m)	(%) latitude	(%) longitude
19:00-20:00	5.204493	4.725453	2.52193	2.721461	51.54%	42.41%
20:00-21:00	8.973147	8.491938	4.544896	5.552485	49.35%	34.61%
21:00-22:00	10.92086	9.759777	3.593018	3.642461	67.10%	62.68%
22:00-23:00	8.600179	11.53458	3.402197	3.59561	60.44%	68.83%
23:00-00:00	6.684848	10.80234	2.197789	3.448261	67.12%	68.08%
00:00-01:00	3.720023	4.732148	2.191457	2.186338	41.09%	53.80%