Impact of space weather events on satellite-based navigation

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[1] Detrimental effects of the equatorial ionospheric irregularities on satellite-based communication and navigation systems have been studied over the past few decades as space weather events have the potential to seriously disturb the technological infrastructure of modern society. The present paper tries to understand operational compliance of Global Positioning System (GPS) receivers to International Civil Aviation Organization (ICAO) standards under scintillation conditions by recording the received phase of the L1(1575.42 MHz) signal from two stations, namely Calcutta situated near the northern crest of the Equatorial Ionization Anomaly and Siliguri, situated beyond the northern crest, at a subionospheric latitude separation of 4° along the same meridian. A causative approach is adopted whereby GPS phase scintillations have been monitored and receiver performance prior to loss of lock and cycle slips have been analyzed during August–October 2011 at Calcutta and September 2011 at Siliguri. The received phase at GPS-L1 frequency has often been found to fluctuate at kilohertz, often megahertz rates, thereby causing carrier-tracking loop malfunctions. It should be borne in mind that normal GPS receivers' carrier-tracking loops have a typical dynamic range of 14–18 Hz. Cycle slips have been observed with durations far exceeding ICAO specified levels for high dynamic platforms like aircrafts. Differences in cycle slips between Calcutta and Siliguri indicate possible evolution of irregularity structures even across small subionospheric swath. Significant improvement in present understanding of GPS phase scintillations should be developed and implemented in receiver designs prior to application of Satellite Based Augmentation System services for civil aviation, particularly in the geophysically sensitive equatorial region.

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1. Introduction

[2] Effects of the ionosphere on communication and navigation systems present an interesting as well as intriguing problem to the scientific community involved in the studies of the physics of plasma instabilities and equatorial ionospheric irregularities. Space weather refers to adverse conditions on the Sun, the solar wind, and in the Earth's magnetosphere, the ionosphere, and the thermosphere. Intense space weather events pose one of the biggest threats to Satellite-Earth communication links causing total outages of signals in GPS, Differential GPS (DGPS), Satellite Based Augmentation System (SBAS), and Global Navigation Satellite System (GNSS). The equatorial ionospheric irregularities generated mainly over the magnetic equator in the early evening hours introduce amplitude and phase scintillations on transionospheric satellite links. GPS signals traversing such irregularities can be distorted by a disturbed ionosphere, and a receiver will then compute an erroneous position or fail to compute any position. As the GPS signals are used for a wide range of applications, any space weather event which makes GPS signal unreliable, can impact the society significantly.

[3] Conventional sensor-based navigation infrastructure is gradually being augmented by SBAS through GNSS, which aims to improve performance and as well as enhance safety. One of the major deterrents to successful implementation of SBAS may be linked to intense space weather events affecting transionospheric satellite links even under magnetically quiet conditions in the equatorial region. These effects have a pronounced dependence on solar activity levels which roughly follow 11 year periodicity with the next maximum predicted during 2013–2014.

[4] Influence of postsunset equatorial scintillations on position accuracies of GPS-based navigation and communication system have been extensively addressed [*Bandyopadhyay*

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et al., 1997; *Kintner et al.*, 2001, 2004; *DasGupta et al.*, 2004; *de Paula et al.*, 2010]. *Bandyopadhyay et al.* [1997] discussed cases of carrier-to-noise (CNO) ratios and Position Dilution of Precision (PDOP) fluctuations observed on GPS links during scintillation from Calcutta situated near the northern crest of the Equatorial Ionization Anomaly (EIA) during solar minimum period. Degradation of position accuracies during intense scintillation events as frequently encountered on GPS links observed from Calcutta during high sunspot number years have been reported in *DasGupta et al.* [2004]. Impact of the relative motion between drifting ionospheric irregularities and GPS satellite vehicles on the receiver tracking loop performance, particularly under conditions of resonance, may lead to higher probability of loss of lock due to the longer duration of the amplitude fades [*Kintner et al.*, 2001, 2004]. Moving receivers, particularly onboard high dynamic platforms like aircraft, may be subject to situations where a predominant east-west motion of the receiver may match velocities with eastward drifting irregularities resulting in enhanced scintillations rather than receivers having a north-south component of motion where resonance will occur only for specific orientations and projection angles [*Rodrigues et al.*, 2004]. Effects of the interplay between the GPS satellite trajectories and the drifting ionospheric irregularities on the receiver performance have been studied from the geophysically sensitive Indian longitude sector during the vernal equinox of 2004 [*DasGupta et al.*, 2006]. Under the Conjugate Point Equatorial Experiment (COPEX), *de Paula et al.* [2010] presented zonal spaced GPS (1.575 GHz) and VHF (250 MHz) receivers' data collected simultaneously at two magnetic conjugate sites of the COPEX geometry, namely Boa Vista and Campo Grande. The results showed the coexistence of kilometer (VHF) and hundred-meter scale (GPS L band) irregularities into the underlying depletion structure. *Carrano et al.* [2005] characterized and modeled the effects of scintillation on GPS position accuracy using data recorded at Ascension Island during March 2002. This paper discusses the duration of SBAS service outages depending on the duration and severity of ionospheric scintillations, geometry of the satellites in view, and the recovery time of the equipment. A case study of deep signal fading on all satellite links in view recorded at Ascension Island in 2001 has been reported by *Seo et al.* [2009] highlighting the importance of short reacquisition time under frequent deep signal fading. *Moraes et al.* [2011] presented a comprehensive study of high-rate GPS scintillation measurements from Brazil near the Equatorial Anomaly under high solar activity conditions.

[5] One of the deepest solar minima, possibly since Maunder minima, occurred during 2006 to early 2010 when only four cases of GPS scintillations were observed from Calcutta on 2 February 2008, 25 September 2008, 8 October 2009, and 13 March 2010. Two of these events, namely the ones occurring on 8 October 2009 and 13 March 2010 have been reported in *Paul et al.* [2011] and a third one on 25 September 2008 has been presented in *Das et al.* [2012].

[6] The basic objective of GNSS is to provide collectively worldwide Positioning, Navigation, Timing (PNT) determination capability available from the core satellite constellation comprising of GPS, Global Navigation Satellite System (GLONASS), and Galileo. Combining GPS, GLONASS, and Galileo, an average of 15 satellites are expected to be in view from any point on the surface of the Earth. Ionospheric scintillations may cause amplitude fades in excess of 20 dB-Hz on GPS channels at equatorial locations. This figure assumes importance in view of the fact that conventional communication receivers have a typical dynamic range of 25–30 dB-Hz. Errors introduced in the phase tracking loop of a GPS receiver introduces "cycle slips," while dithering of the tracking frequency in the frequency tracking loop of the receiver produces "loss of lock". These fades could cause cycle slips and stress the receiver to lose lock on the transmitted signals only to be reacquired at a later time leading to intermittent availability of service. From the operational standpoint, cases of rapid and intense fluctuations of the amplitude and phase of the received signal prior to loss of lock, which severely stresses the performance of the tracking loops, have not been extensively studied from the equatorial region, with the exception of notable results being obtained from the South American sector [*Carrano et al.*, 2005; *Seo et al.*, 2009; *Moraes et al.*, 2011]. This lacuna possibly resulted from lack of access to received carrier phase of GPS signals. Strong phase scintillations have the potential to stress phase lock loops (PLL) in GPS/GNSS receivers resulting in loss of phase lock and frequent cycle slips, thereby impeding carrier phase measurements [*Humphreys et al.*, 2005]. Information related to threshold performance levels of receiver tracking loops are extremely vital, particularly for high dynamic platforms like aircrafts and safety-of-life applications that rely on integrity, accuracy, and availability [*RTCA*, 2006]. This issue provides sufficient motivation to ascertain the level of compliance of GPS measurements at equatorial latitudes to aeronautical approach with vertical guidance (APV) performance requirements as specified by the International Civil Aviation Organization (ICAO).

[7] GPS receivers operating at L band frequencies normally utilize semicodeless techniques to track the encrypted L2 (1227.6 MHz) P(Y) signal. Carrier-to-noise ratio (CNO) may be degraded by 15–35 dB as a result of semicodeless tracking [*Woo*, 1999]. GPS modernization program is focused on addition of new navigation signals L2C and L5 (1176.45 MHz) to the GPS constellation. The L2C signal will be dedicated for civilian applications, while L5 is exclusively reserved for aviation navigation services. Overall robustness of this dual-frequency mechanism to ionospheric scintillations could be ascertained during the upcoming solar maximum through a study of correlated scintillations.

[8] Although phase scintillations have been studied over the past three decades, records of GPS phase fluctuations during intense space weather events have been sparse from the Indian longitude sector [*Paul et al.*, 2011]. The present paper reports observations of GPS phase scintillations

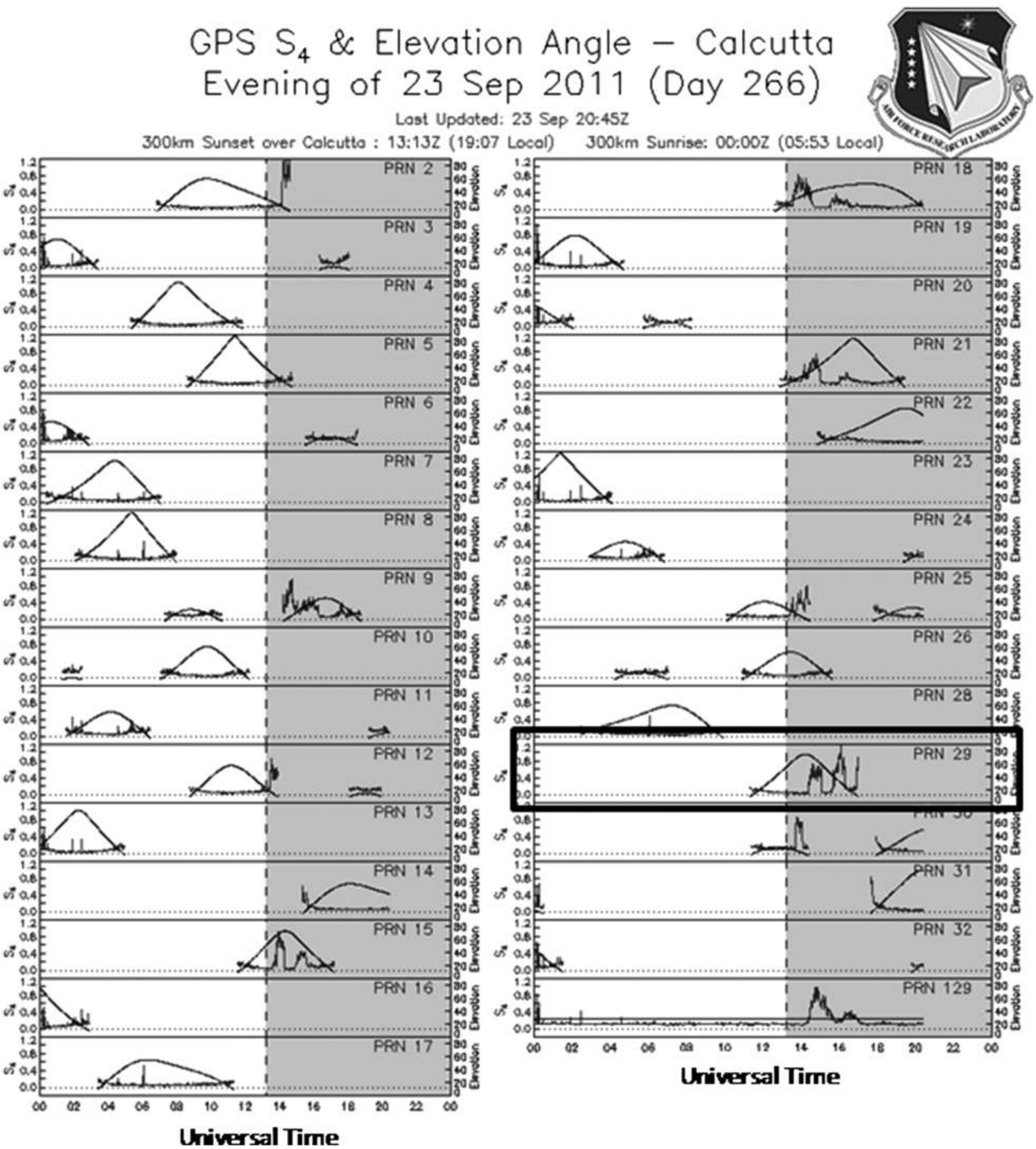

Figure 1. Variation of S_4 and elevation with Universal Time as observed from Calcutta on the SCINDA website http://capricorn.bc.edu/scinda/india on 23 September 2011.

observed during intense space weather events under magnetically quiet conditions from Calcutta (22.58°N, 88.38°E geographic; 32°N magnetic dip) during August through October 2011 and from Siliguri (26.72°N, 88.39°E geographic; 40°N magnetic dip) during September 2011. Operation of dual-frequency GPS receivers from this chain of stations provided the capability of tracking equatorial ionospheric irregularities from locations around the northern crest of the equatorial ionization anomaly (EIA) to locations beyond the northern crest. The present study tries to develop a causative understanding behind loss of lock and cycle slips using the received carrier phase of GPS L1 (1575.42 MHz) signals from Calcutta and Siliguri. Operational compliance of GPS receivers to ICAO standards

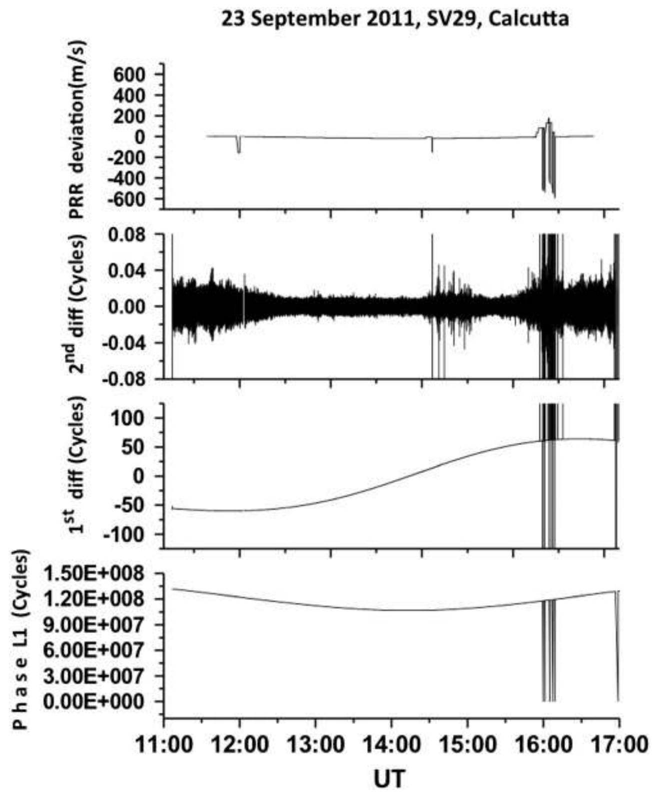

Figure 2. Variation of received phase at GPS L1, first successive difference, second successive difference, and PDOP, on SV29 link observed from Calcutta on 23 September 2011 during 11:00–17:00 UT.

under intense ($S_4 > 0.6$) ionospheric scintillations, frequently encountered in the equatorial and low-latitude regions, needs rigorous validation in view of possible applications by SBAS. However, efforts to design receivers to tackle adverse ionospheric conditions are still in their infancy, possibly due to noncognitive approaches adopted. The physics behind receiver loss of lock and cycle slips need quantification under most stringent conditions likely to be encountered in the low latitudes during postsunset hours of equinoctial months.

2. Data

[9] The Space Weather group at the Institute of Radio Physics and Electronics (IRPE), University of Calcutta, Calcutta (22.58°N, 88.38°E geographic; 32°N magnetic dip) presently operates dual-frequency software-based GPS capable of measuring TEC and phase of the GPS L1 and L2 signals. The software GPS receiver operational at Calcutta provides output like satellite vehicle number, their elevation, azimuth, carrier-to-noise (CNO) ratios at GPS L1 and L2, S4, and TEC with the option of user-defined sampling rates. The user can also select the outputs that need to be logged out of all the available parameters. While amplitude scintillation index can be directly derived, phase scintillation data requires preprocessing before obtaining the phase scintillation index and other related ionospheric parameters. The received carrier phase data from a particular GPS satellite vehicle has major contribution from the geometrical path length, and minor contributions from the free space Doppler and the ionosphere. The data was sampled at a very fast rate of 0.02 s (50 Hz). Thus, taking the difference between two consecutive samples would eliminate the common terms, namely the path length and the free space Doppler, assuming the satellite movement to be negligible over this short time interval. This process gives at its output, the ionospheric contribution [*Paul et al.*, 2011].

[10] IRPE has been an active station under the international Scintillation Network Decision Aid (SCINDA) program since November 2006. This group also operated a dual-frequency GPS receiver at the Department of Physics, North Bengal University, Siliguri (26.72°N, 88.39°E geographic; 40°N magnetic dip) located more or less along the 88°E meridian during September 2011 on a campaign mode thereby having the capability of tracking equatorial ionospheric irregularities from locations around the northern crest of the EIA to locations at 40°N magnetic dip.

[11] After the abnormally prolonged minima of the solar cycle spanning 2006 through 2010, scintillation activity has dramatically been enhanced in 2011 with 38 nights of intense ($S_4 \geq 0.6$) GPS L band scintillations during February–April 2011 and 22 nights during August–October 2011, observed from Calcutta, situated near the northern crest of the Equatorial Ionization Anomaly (EIA) in the Indian longitude sector. Cases of intense ($S_4 > 0.6$) scintillations affecting different GPS links during two equinoctial periods, February–April, 2011 and August–October, 2011, observed from Calcutta, situated underneath the northern crest of the EIA and during September 2011 from Siliguri located beyond the northern crest, have been characterized on the basis of elevation (>15°), carrier-to-noise ratios (CNO) at L1 frequency, PDOP, pseudorange rate (PRR) and received phase at L1 to understand the impacts on navigational accuracy. In order to eliminate slow fluctuations in CNO arising out of GPS satellite vehicle movements, the deviations of CNO from the moving averaged values have been shown at L1 frequency. Pseudorange rate (PRR) refers to time derivative of satellite pseudorange. PRR represents the time rate of change of TEC along a particular SV link without combining TEC temporal gradients from different sections of the sky affected by varying ionization gradients.

3. Results

[12] Plots of GPS S_4 and elevation angle are obtained as a function of Universal Time on different GPS links observed by the SCINDA receiver from Calcutta on the website http://capricorn.bc.edu/scinda/india. Data recorded at Calcutta and Siliguri have been analyzed over the entire period of observation. The results for 23 September 2011 are being presented as a representative case. Figure 1 shows the variation of elevation and S_4 on different GPS links as observed from Calcutta on 23 September 2011. On 23 September 2011, a magnetically quiet day with a

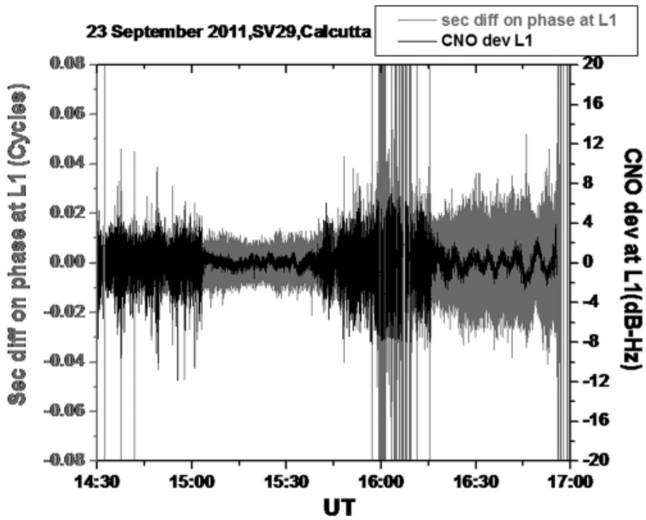

Figure 3. Variation of second successive difference of phase and CNO at L1 on SV29 link observed from Calcutta on 23 September 2011 during 14:30–17:00 UT.

sunspot number of 59, a number of GPS links, namely, SV9, 15, 18, 21, 29, and geostationary SV129 (elevation: 27°, azimuth: 106°) were found to experience intense amplitude scintillations ($S_4 > 0.6$) during 13:00–18:00 Universal Time. Two distinct patches of scintillations may be identified on the SV15 and SV29 links. Highlighting SV29 as a representative case, Figure 2 shows the variation of received phase at GPS L1, its first successive difference, second successive difference, and pseudorange rate (PRR) deviations during 11:00–17:00 UT. The lowermost panel which shows the variation of the received phase at GPS L1 frequency is not detrended, and hence, ionospheric effects are not pronounced. It is predominantly influenced by the phase contributions arising from the geometrical path as explained in the Data section. The second successive difference of phase at L1 clearly shows patches of phase scintillations around 14:30 UT and again around 16:00 UT. Phase scintillations on SV29 were stronger around 16:00 UT of 23 September 2011 compared to the patch around 15:00 UT. However, SV29 was at a higher elevation angle of 60° around 15:00 UT and a lower elevation of 40° around 16:00 UT. The second successive difference eliminates nonionospheric contributions in the received phase. The PRR deviations are found to have close correspondence with the occurrence of phase scintillations with significant deviations around 16:00 UT. PRR shows the temporal gradient of TEC along SV29 link as observed from Calcutta. Figure 3 shows the plot of second successive difference of phase and CNO deviation at L1 on SV29 as observed from Calcutta over the time interval 14:30–17:00 UT. Fluctuations in CNO deviations ~ 15 dB-Hz could be noted around 16:00 UT. Enlarging the section over the time period 15:55–16:10 UT, clear breaks in the received phase at L1 or cycle slips could be identified over the time interval 16:00–16:10 UT as shown in Figure 4. The moving average of the received phase at L1 frequency and its deviations were calculated for SV29 during the time interval 15:50–16:15 UT and plotted in Figure 5. Clear gaps in the received phase could be noted around 16:00 UT and 16:05 UT which were marked as cycle slip durations. In order to check proper functioning of the receiver, variation of the received phase and CNO at L1 for other satellites on that date not affected by scintillations were plotted over the same time interval as SV29 and found to be continuous without any break in the received phase. The rate of change of phase just prior to loss of lock were estimated and found to be 2.23 Kc/s, 199 c/s, and 3.41 Kc/s, respectively for three cases indicated in Figure 5. Such high rates of phase fluctuations are unacceptable as conventional GPS receivers have a carrier-tracking loop bandwidth of 18–25 Hz. Rates of

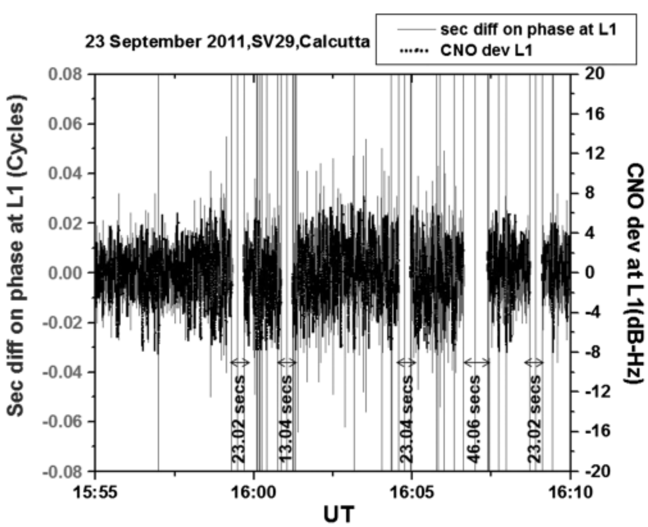

Figure 4. Cycle slips on SV29 link, observed from Calcutta on 23 September 2011 during 15:55–16:10 UT.

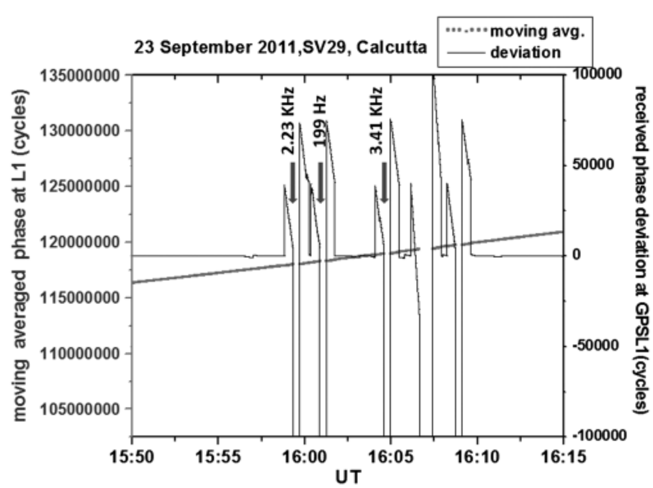

Figure 5. Moving average of the received phase at L1 frequency and its deviations for SV29 during 15:50–16:15 UT as observed from Calcutta on 23 September 2011.

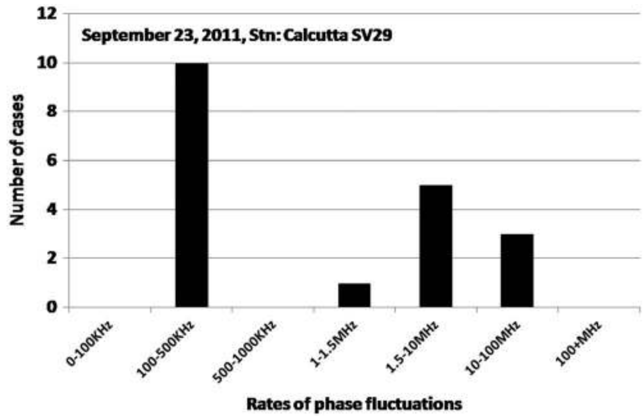

Figure 6. Rates of phase fluctuations corresponding to all cycle slips noted on SV29 on 23 September 2011 from Calcutta.

phase fluctuations corresponding to all the cycle slips noted on SV29 on 23 September 2011 were calculated and shown in Figure 6. Majority of phase fluctuation rates were found to be of 100–500 Kc/s. Similar exercise to compute durations of cycle slips was performed for all magnetically quiet dates during August through October 2011. Durations of cycle slips from all GPS satellites above an elevation of 15° were calculated for the period August through October 2011 for magnetically quiet days at GPS L1 and shown in Figure 7. It is found that although majority of cycle slips were of 1–2 s duration, there were more than 250 cases when the receiver lost lock of the signal for 20–30 s and about 100 occasions when the loss of lock was in excess of 60 s. The latter values are considerably higher and unacceptable as per signal-in-space (SIS) performance requirements for APV approach specified by the ICAO which stipulates a Time-to-Alert (TTA) of 10 s for APV I and 6 s for APV II operations [*ICAO*, 2006]. Results from Siliguri for 23 September 2011 showed significant loss of lock on SV29 during 16:00–16:30 UT

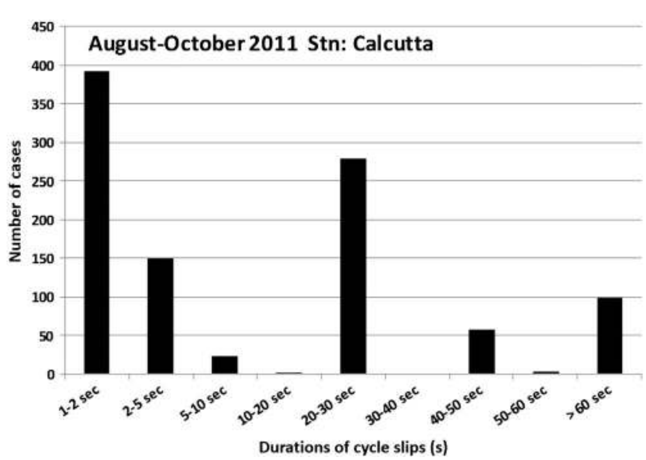

Figure 7. Number of cycle slips on all SV links observed from Calcutta on magnetically quiet days during August–October 2011.

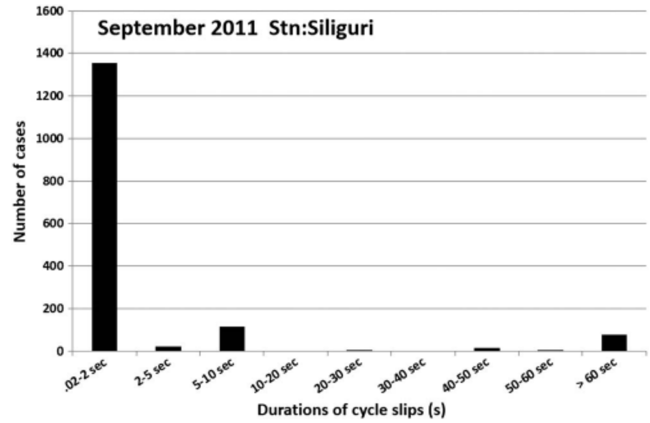

Figure 8. Number of cycle slips on all SV links observed from Siliguri on magnetically quiet days during September 2011.

with a maximum of 607 s at 16:30 UT. Figure 8 shows the statistics of cycle slip durations observed from Siliguri over September 2011 for magnetically quiet days combining the results from all satellites above an elevation of 15° and affected by intense amplitude scintillations ($S_4 > 0.6$). In this case also, 13 cases of cycle slips were noted with durations of 40–50 s and 76 cases with durations in excess of 60 s thereby rendering SBAS services unavailable. It should be noted that large number of cycle slips were observed from Siliguri with 0.02–2 s duration. However, they are not significant from the point of view of ICAO standards.

4. Discussions

[13] Severe space weather events have the potential to cause serious damage to the technological infrastructure on which society relies. The present paper studies cases of phase scintillations observed from two stations, Calcutta, situated virtually underneath the northern crest of the EIA in the Indian longitude sector, and Siliguri, located beyond the northern crest. Nature of phase fluctuations prior to cycle slips were characterized on the basis of the rate of fluctuations which, when exceeded, the carrier phase tracking loop bandwidth of the receiver caused cycle slips. This gave a causative understanding behind the performance of GPS receivers under ionospheric scintillations likely to be encountered by any operational or planned GNSS. Values of loss of lock observed during February–April and August through October 2011 at Calcutta and during September 2011 at Siliguri are much higher than ICAO standards and unacceptable for applications in high dynamic platforms like civil aviation at low latitudes. Cycle slip durations from a particular GPS satellite, in excess of the Time-to-Alert (TTA) for APV I and APV II approaches for aircrafts as specified by ICAO, indicate introduction of errors in the position information calculated by receivers onboard high dynamic platforms. This may result in severe compromise of service deliverables on the part of SBAS and may jeopardize human lives if applied to civil aviation.

Differences in cycle slip statistics for the same period observed from two stations, Calcutta and Siliguri, which essentially cover an almost identical ionospheric swath (at 350 km), forms one of the most significant findings from the present study. Although a case by case correspondence between the evolutionary nature of the irregularities and its impact over a distributed baseline like that between Calcutta and Siliguri has not been studied so far, results from a VHF spaced aerial measurement performed at Calcutta on a continuous basis since 2011 indicate that on 23 September 2011, irregularity characteristic velocities were large and decorrelation times small during postsunset hours at VHF. These two parameters indicate randomness of the medium of propagation and dynamic nature of the evolving irregularities respectively. Hence, large characteristic velocities and small decorrelation distances signify rapidly changing irregularity structure which may result in different radio link performances even across a limited subionospheric swath such as that between Calcutta and Siliguri. The issue of evolution of irregularity structures even across relatively short baselines needs to be studied in further details.

[14] It has been suggested that adapting the signals to possible bandwidth enhancements may assist in improving GPS receiver's carrier-tracking loop performance [*Ganguly et al.*, 2004]. When phase and amplitude scintillations are detected, the loop bandwidth is adaptively increased. When a deep amplitude fade occurs, there is no signal to track; only the PLL loses lock. The Frequency Locked Loop (FLL) portion of the loop is activated at this point of time to facilitate reacquisition of the signal as it recovers from the fade. One major drawback of the above scheme is that wider bandwidth tracking loops introduce more noise and thereby necessitates trade-off between the above two conflicting requirements. There are efforts globally to understand the design of receiver carrier phase tracking loops necessary to maintain lock even in the presence of severe equatorial scintillations [*Humphreys et al.*, 2010]. But these models tend to underestimate the effects of severe equatorial scintillations by failing to understand the essential feature of deep power fades (>15 dB) associated with abrupt phase transitions. Significant improvements in the present understanding of GPS phase fluctuations under scintillation conditions are necessary coupled with intensive observational campaigns at geophysically sensitive locations such as near the northern crest of the EIA.

[15] **Acknowledgments.** This research has been sponsored in part by the Ministry of Human Resource and Development through the TEQIP Program at the University of Calcutta and the Asian Office of Aerospace Research and Development (AOARD), Japan through the SCINDA program of the U.S. Air Force. One of the authors (B.R.) acknowledges the support of Indian Space Research Organisation (ISRO) through the CAWSES-India Phase II Research Fellowship at the S.K. Mitra Center for Research in Space Environment, University of Calcutta. The authors acknowledge the support provided by the Department of Physics, North Bengal University, India in operating the GPS receiver.

References

Bandyopadhyay, T., A. Guha, A. DasGupta, P. Banerjee, and A. Bose (1997), Degradation of navigational accuracy with the Global Positioning System during periods of scintillation at equatorial latitudes, *Electron. Lett.*, *33*(12), 1010–1011.

Carrano, C. S., K. M. Groves, and J. M. Griffin (2005), Empirical characterization and modeling of GPS positioning errors due to ionospheric scintillation, Proc. Ionospheric Effects Symp., (IES-2005), USA.

Das, T., B. Roy, A. DasGupta, and A. Paul (2012), Impact of equatorial ionospheric irregularities on transionospheric satellite links observed from a low-latitude station during the minima of solar cycle 24, *Indian J. Radio Space Phys.(Spl. Issue on Low-Latitude upper atmosphere–ionosphere-plasmasphere system in a record low solar minimum in Asian sector)*, *41*, 247–257.

DasGupta, A., S. Ray, A. Paul, P. Banerjee, and A. Bose (2004), 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.

de Paula, E. R., M. T. A. H. Muella, J. H. A. Sobral, M. A. Abdu, I. S. Batista, T. L. Beach, and K. M. Groves (2010), Magnetic conjugate point observations of kilometer and hundred-meter scale irregularities and zonal drifts, *J. Geophys. Res.*, *115*, A08307, doi:10.1029/2010JA015383.

Ganguly, S., A. Jovancevic, A. Brown, M. Kirchner, and S. Zigic (2004), Ionospheric scintillation monitoring and mitigation using a software GPS receiver, *Radio Sci.*, *39*, RS1S21, doi:10.1029/2002RS002812.

Humphreys, T. E., M. L. Psiaki, B. M. Ledvina, and P. M. Kintner (2005), GPS carrier tracking loop performance in the presence of ISs, Proc. ION GNSS 2005, Institute of Navigation, Long Beach, CA.

Humphreys, T. E., M. L. Psiaki, and P. M. Kintner Jr. (2010), Modelling the effects of ionospheric scintillation on GPS carrier phase tracking, *IEEE Trans. Aerosp. Electron. Syst.*, *46*(4), 1624–1637.

International Civil Aviation Organization, ICAO (2006), *Standard and Recommended Procedures (SARPS), Annex 10, Aeronautical Telecommunication*, Radio Navigation Aids, vol. I, 6th ed.

Kintner, P. M., H. Kil, T. L. Beach, and E. R. de Paula (2001), Fading timescales associated with GPS signals and potential consequences, *Radio Sci.*, *36*(4), 731–743.

Kintner, P. M., B. M. Ledvina, E. R. de Paula, and I. J. Kantor (2004), Size, shape, orientation, speed, and duration of GPS equatorial anomaly scintillations, *Radio Sci.*, *39*, RS2012, doi:10.1029/2003RS002878.

Moraes, A. O., F. S. Rodriguez, W. J. Perrella, and E. R. de Paula (2011), Analysis of the characteristics of low-latitude GPS amplitude scintillation measured during solar maximum conditions and implications for receiver performance, *Surv. Geophys.*, *33*(5), 1107–1131, doi:10.1007/s10712-011-9161-z.

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.

Rodrigues, F. S., E. R. de Paula, M. A. Abdu, A. C. Jardim, K. N. Iyer, P. M. Kintner, and D. L. Hysell (2004), Equatorial spread *F* irregularity characteristics over Sao Luis, Brazil, using VHF radar and GPS scintillation techniques, *Radio Sci.*, *39*, RS1S31, doi:10.1029/2002RS002826.

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, T. Y. Chiou, and P. Enge (2009), Characteristics of deep GPS signal fading due to ionospheric scintillation for aviation receiver design, *Radio Sci.*, *44*, RS0A16, doi:10.1029/2008RS004077.

Woo, K.T. (1999), Optimum semi-codeless carrier phase tracking of L2, Proceedings of the ION GPS-99, Nashville, Tennessee, September, 1999.

Erratum

Ashish DasGupta did not intend to be listed as the second author of the originally published article. With the unanimous support of the remaining authors and the editor, this has since been corrected in the xml and this version may be considered the authoritative version of record.