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# Study of the effects of adverse ionospheric conditions on satellite-based navigation performance observed from an anomaly crest location in the Indian longitude sector

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## Abstract

GPS amplitude and phase scintillations in terms of the index $S_4$ and $\sigma_\phi$ and the corresponding loss of lock in signal have been studied with consequent errors in receiver positions for the month of March, 2014 from Calcutta situated near the northern crest of the Equatorial Ionization Anomaly (EIA ). There are 42 and 59 cases of loss of lock in $C/N_O$ and phase respectively, all occurring during 13-18 UT, which is the local pre-midnight hours. For all the cases, duration of amplitude loss of lock is longer that phase loss of lock. Associated with such signal perturbations, deviations in receiver positions are found to occur having maximum values of 31.72m for latitude 85.2m for longitude during 15-16UT. Though 9.5% of the cases start when amplitude scintillation was moderate ($0.4<S_4 \leq 0.6$), 32.2% of the cases occurred when phase scintillation was moderate ($0.2<\sigma_\phi \leq 0.7$). While the number of satellites affected by moderate amplitude scintillation is 1 during 20:00-21:00UT (02:00-03:00LT) and does not occur thereafter, moderate phase scintillations are found to impact 3 GPS satellites even during 21:00-22:00UT (03:00-04:00LT). Number of satellites affected by weak phase scintillations was also more in number (8-9) compared to 2 for amplitude scintillations even during 22:00-23:00UT (local early morning hours).

## 1 Introduction

The knowledge of scintillation, which is random, intense and fast fluctuations of the amplitude and phase of a transionospheric signal, is important to determine the spatial and temporal distribution of the ionospheric irregularities and to understand the physical processes that lead to the formation of such irregularities. The amplitude and phase fluctuations of the recorded signal are statistically characterized by two major parameters, amplitude and phase scintillation indices, denoted respectively by $S_4$ and $\sigma_\phi$. The amplitude scintillation index, $S_4$ is defined as the ratio of the standard deviation of signal intensity and the average signal intensity [1]. The phase scintillation index is defined as the standard deviation of a linearly detrended phase data segment [2].

While amplitude and phase scintillations are mostly decoupled in the high latitudes and polar region [3], their correspondence, or lack of it, have not been conclusively established from the low latitudes, particularly from the equatorial anomaly region. Measurement of phase of the received signals from GNSS at high sampling rates of 50Hz provides an opportunity to characterize phase scintillations in terms of occurrence and intensity. The amplitude scintillation index $S_4$ could be correlated with resultant position deviations during periods of amplitude scintillations affecting GNSS [4]. Efforts to associate phase scintillation $\sigma_\phi$ (radians) with loss-of-lock of the signal resulting in cycle slips and position errors of the receiver have not been extensively reported from the Indian longitude sector. The issue of concern is that such events may occur even under geomagnetic benign conditions in the equatorial region, whereby increasing number of satellite links may be disrupted leading to significant deviations in position. The theories of amplitude and phase scintillation are well developed [5], experimental studies on phase scintillation are less compared to that on amplitude scintillation.

Simultaneous generation of ionospheric irregularities of various scale sizes have been established in literature highlighting the generation, evolution and decay of the structures. However simultaneous amplitude and phase measurements, as is available from GPS, may be leveraged to understand relative impacts of amplitude and phase scintillations as a function of time and advance present understanding on the impact of such structures on satellite signals.

The present paper reports studies, spread over March 2014, of amplitude and phase fluctuations of GPS signals resulting in loss-of-lock on a number of satellites and consequent degradation in position determination from the SCINDA station at Calcutta. Relative effects of amplitude and phase scintillations on GPS from the same station are also reported.

## 2 Data and Methodology

Institute of Radio Physics and Electronics, University of Calcutta is a station under the **SCIntillation Network Decision Aid (SCINDA) program** of US Air Force Research Laboratory and operates dual-frequency GPS receiver at L1 and L2 frequencies since 2006 within the framework of this program. During the vernal equinox of 2014, 60 nights of intense ionospheric scintillations (S4>0.6) were observed on different GPS L band frequencies from Calcutta. The location of Calcutta being near the northern crest of the Equatorial Ionization Anomaly (EIA) in the Indian longitudes, signal outages from this location are amongst the most severe.

This receiver records carrier-to-noise ratio ($C/N_O$) from each individual GPS satellite at sampling rates of 1Hz along with the satellite coordinates in terms of elevation and azimuth. $C/N_0$ deviations have been calculated by subtracting the moving averaged values over a running time interval of 10 minutes from the instantaneous measurement of $C/N_O$. Phase of the received signal is logged from each satellite at sampling rates of 50Hz and contain dominant contribution arising out of the geometrical path length between the satellite and the receiver. In addition, contribution exists due to relative motion between the slowly moving GPS satellite and the receiver. Detrending these components leaves the ionospheric contribution which during periods of satellite link interaction with ionization density irregularities may exhibit fluctuations referred to as phase scintillations.

The amplitude scintillation index $S_4$ and the phase scintillation index $\sigma_\phi$ (radians) have been provided by the receiver at 1 minute interval. Classification of intensity of amplitude scintillation could be done on the basis of scintillation index ($S_4$) [1].

In this paper intensities of amplitude and phase scintillations have been classified [6] as:

| | $S_4$ | $\sigma_\phi$ (radians) |
|---|---|---|
| Weak | 0.2-0.4 | 0.1-0.25 |
| Moderate | 0.4-0.6 | 0.25-0.7 |
| Intense | >0.6 | >0.7 |

The receiver positions are available every second. Receiver position deviations have been calculated by taking difference of instantaneous receiver position from that measured during early morning hours of 03-04LT when ionization densities are least. In order to avoid the effects of satellite multipath, an elevation mask angle of 15° has been used throughout the analyses.

## 3 Results

Analyses of amplitude and phase data observed from Calcutta have been done for the entire month of March 2014. A representative case (SV 7) of scintillation occurring on March 1, 2014 have been elaborated in this paper with a statistics for the whole month.

Figure 1(a) shows the C/N$_O$ deviation at L1 frequency (1575.42MHz) of GPS satellite SV7 during 12:00-18:30UT (LT=UT+06:00) of March 1, 2014. It can be observed that there are three C/N$_O$ fluctuation patches present in Figure 1(a). Figure 1(b) shows the received phase at L1 frequency from the same satellite during 12:00-18:00 UT of the same day for the same GPS satellite. The detrended phase shows patches of phase fluctuations as depicted in second frame of Figure 1(b). The duration of first patch first patch is 14:03-14:47UT with a break in between starting from 14:08UT.

In Figure 2(a) a section of the C/N$_O$ deviation is magnified and a break in data of 1544 seconds has been observed during 14:08:32-14:34:16UT. A section of the detrended phase magnified in Figure 2(b) during the interval 15:00-15:21UT shows clear break in the data of 1538 seconds during 14:08:32.980UT-14:34:11.000UT. In order to check if this beak in data is due to receiver malfunction, variation of the received phase and C/N$_O$ at L1 for other satellite which is not affected by intense scintillations were studied over the same time interval of the same day and found to be continuous without any break in the received phase. The corresponding amplitude scintillation index, $S_4$ and phase scintillation index $\sigma_\phi$ have been plotted for SV 7 for the same day in Figure 3.

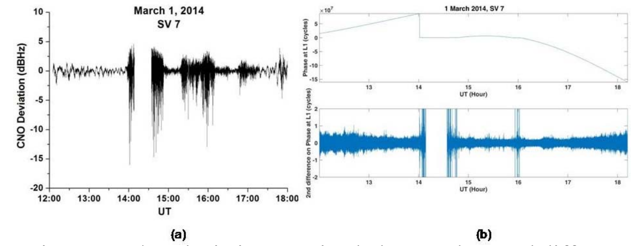


Figure 1: C/N$_O$ deviation, received phase and second difference of received phase at L1 frequency from SV 7 for March 1, 2014 from Calcutta

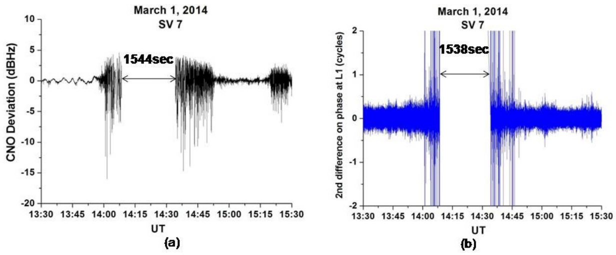


Figure 2: A section of the C/N$_O$ deviation and the second difference of received phase from SV 7 for March 1, 2014 from Calcutta.

In Figure 3 the satellite became visible above an elevation mask of 15$^o$ at 12:23UT. $S_4$ continued to be greater than 0.6 till 14:50UT with the highest value of 1.06 at 14:08UT. The variation of $S_4$ in Figure 3 clearly corresponds of the amplitude fluctuation patches present in Figure 1(a). Similarly for $\sigma_\phi$ the first patch started at 13:59UT with the value of 0.24 radians and exceeded a value of 0.7 radians at 14:02UT and after that its value became abnormally high till 14:49UT. It is interesting to note that during this interval the loss of lock of 1538 seconds started at 14:08UT as shown in Figure 2(b). A good correspondence is observed between the variation of $\sigma_\phi$ in Figure 3 and the phase fluctuation plot in Figure 1(b).

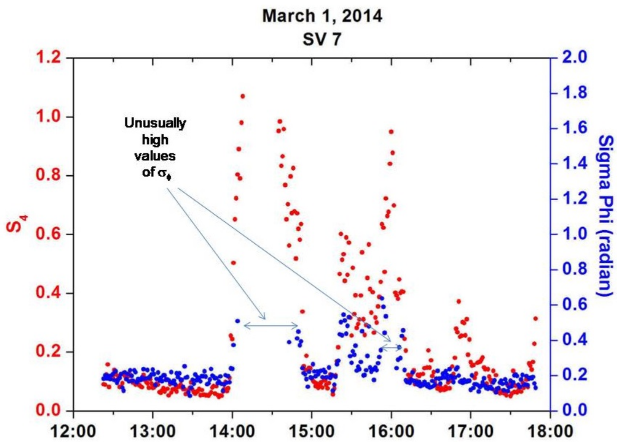


Figure 3: Plot of amplitude and phase scintillation from SV 9 and SV 7 for Match 1, 2014 from Calcutta

The corresponding receiver position deviations are shown in Figure 4 in frames of 1 hour interval each, starting from 12:00UT.

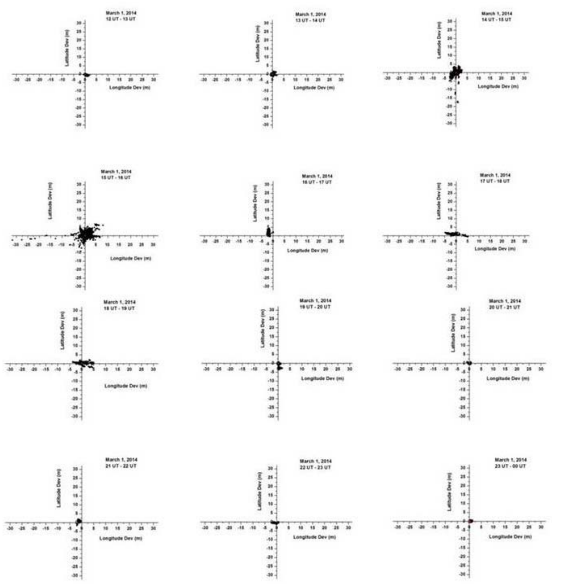

Figure 4: Receiver position deviations for each hour from 12 UT to 24 UT for March 1, 2014 from Calcutta

Maximum longitude deviation for March 2014 is found to be 31.72m on March 1 and the maximum latitude deviation is found to be 85.2m on March 2, both during 15:00-16:00UT.

Statistical representation of the number of GPS satellites observed from Calcutta during 12:00-24:00UT of March 1, 2014 and affected by different levels of amplitude and phase scintillations is given in Figure 5. The effects of intense phase scintillations affecting GPS satellites was extended (22:00-23:00UT) compared to intense amplitude scintillations (19:00-20:00UT). Another interesting phenomena to be noted from Figure 5 is that number of GPS satellites affected by moderate and weak phase scintillations continues to remain around 7 even until 23:00-24:00UT (local early morning hours) whereas number of satellite affected by moderate amplitude scintillation during local early morning hours was 1.

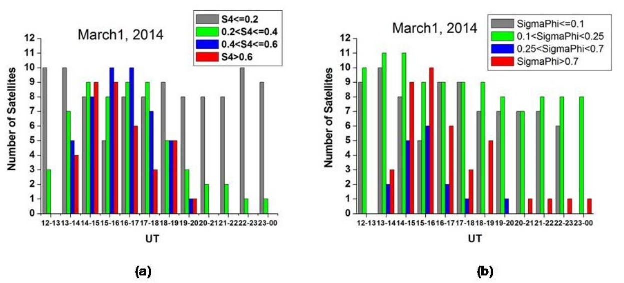


Figure 5: Number of GPS satellites observed from Calcutta during 12:00-24:00 UT of March 1, 2014 affected by different levels of amplitude and phase scintillations

The four panels in Figure 6 represent the statistics for loss of lock in C/N$_O$ for the whole month of March 2014. The total number of cases of loss of lock with duration greater than 6seconds is 42. Figure 6(a) shows the frequency distribution of duration of loss of lock in C/N$_O$. Figure 6(b) shows the frequency distribution of S4 observed before loss of lock in C/N0. In Figure 6(c) the duration of loss of lock is plotted against $S_4$ value before loss of lock. In Figure 6(d) the plot of position (latitude and longitude) deviations during the hour of loss of lock with duration of loss as index.

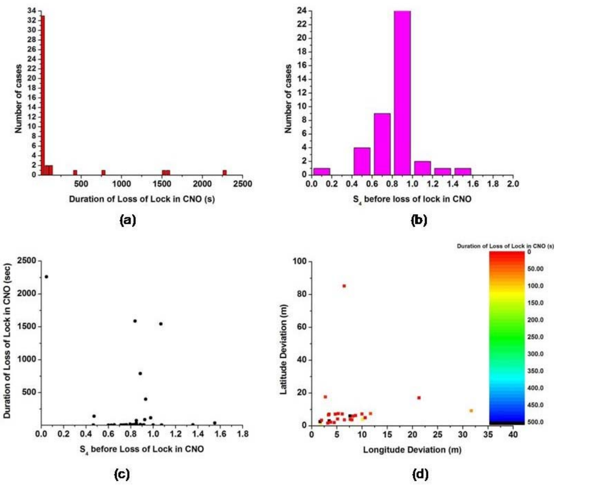


Figure 6: Statistics for loss of lock in CNO for the whole month of March 2014

Similarly, Figure 7 represents the statistics for loss of lock in phase for the whole month of March 2014 in four panels. The total number of cases of loss of lock with duration greater than 6seconds is 59. Figure 7(a) shows the frequency distribution of duration of loss of lock in phase. Figure 7(b) shows the frequency distribution of $\sigma_\phi$ observed before loss of lock which has been truncated to 1radian in order to eliminate the unusually high values of $\sigma_\phi$ (of the order of 10-10$^5$). The number of cases with unusually high $\sigma_\phi$ was 38 in number during the month of March 2014. The distribution presented in Figure 7(b) is based on 21 observations, the maximum (85.7%) of the distribution lies between 0.2 and 0.3. In Figure 7(c) the duration of loss of lock is plotted against $\sigma_\phi$ value before the loss of lock. Figure 7(d) is a plot of position (latitude and longitude) deviations during the hour of loss of lock with duration of loss as index.

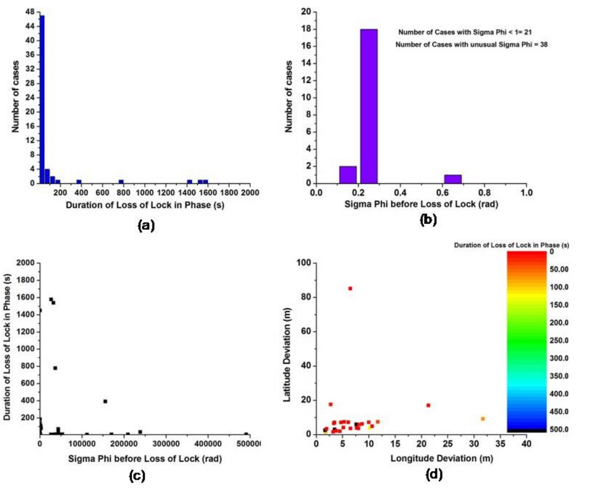


Figure 7: Statistics for loss of lock in phase for the whole month of March 2014

## 4 Discussions and Conclusions

Simultaneous coexistence of ionospheric irregularities of different scale sizes and their relative impacts on transionospheric satellite-based communication and navigation systems during the process of generation, evolution and subsequent decay, is an interesting issue to study even after several decades of intensive research from the equatorial region. The present paper reports, perhaps for the first time from the Indian sector, simultaneous impact assessment of satellite-based communication and navigation system to amplitude and phase scintillations over an entire month during moderate-to-high solar activity period of March 2014. The critical issue which comes out of the present study is that primarily during post-sunset to local midnight hours, number of GPS satellites experiencing intense, moderate and weak amplitude scintillations could be as high as 12 to 17 as indicated in Figure 5. Associated receiver position deviations during such intervals are severely compromised often.

After necessary detrending of the records of received phase and amplitude, gaps in data are identified attributed to loss-of-lock of the GPS L1 signal, which are 1538 seconds in phase and 1544 seconds in amplitude for SV7 as in Figure 2(a) and 2(b) with corresponding maximum position deviation of 17.6m in longitude and 3m in latitude and 31.7m in longitude and 9m in latitude respectively as shown in Figure 4. These values assume importance in the light of recommendations for Approach with Vertical Guidance (APV-I and II) by the International Civil Aviation Organization (ICAO) which states that the Time-to-Alert for APV-I is 10seconds and for APV-II is 6seconds [*ICAO*, 2006].

In order to understand the receiver performance in view of the ICAO recommendation, events of loss of lock with duration greater than 6seconds observed during March 2014 have been analyzed and presented in this paper. There are 42 events of loss of lock in C/N0 and 59 events of loss of lock in phase, all occurring during 13-18 UT, that is the local pre-midnight hours. Though 88% of the cases of loss of lock in $C/N_O$ start when scintillation was intense ($S_4$>0.6), 9.5% of the cases start when scintillation was moderate ($0.4<S_4 \leq 0.6$). In case of loss of lock in phase, 64.4% events occurred when phase scintillation was intense ($\sigma_\phi$ >0.7) while 32.2% occurred when phase scintillation was moderate ($0.25<\sigma_\phi \leq 0.7$). It is clear that the probability of occurrence of loss of lock even when scintillation is moderate is more in case of phase than in case of $C/N_O$. The unusually high values of $\sigma_\phi$ could be due to the fact that just before the occurrence of loss of lock the rate of phase fluctuation were much higher (of the order of KHz and MHz) than the carrier-tracking loop bandwidth (18-25Hz) of the conventional GPS receiver [7]. It is to be noted that for all the cases of loss lock, the retrieval of the phase following loss of lock is earlier than that of the amplitude of the signal.

Cases of satellites affected by intense phase scintillations are found to occur even during post-midnight hours. Also the number of GPS satellites experiencing different levels of phase scintillations is more than that for amplitude scintillations, particularly during post-midnight hours as evident from Figures 5(a) and (b). Scale sizes of ionospheric irregularities attributable for amplitude scintillations are limited to the Fresnel dimension whereas irregularities spread over a much broader spectrum of scale sizes may cause phase scintillations. Amplitude scintillations at GPS frequencies are normally caused by ionospheric irregularities of 300-400m scale sizes. As the larger scale size irregularities normally decay by local midnight hours, effects of amplitude scintillations are mostly confined from early evening hours till 18:00UT (24:00LT) for GPS. However remnants of the decaying large scale irregularities, which may persist during post-midnight hours, may trigger phase scintillations on GPS satellite links. Although GPS amplitude scintillations are primarily confined to local pre-midnight hours under geomagnetic quiet conditions, few cases occuring during post-midnight hours, possibly attributed to local generation or drifting ionospheric irregularities, have been reported in literature [*Das et al.*, 2014].

## 5 Acknowledgements

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