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Study of multi-frequency GNSS scintillations and relative robustness of multi-constellation signals under adverse ionospheric conditions from an anomaly crest station

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ABSTRACT

The phenomenon of ionospheric scintillations remains an enigma to the space science community and a major challenge to the SBAS system designers even after more than six decades of extensive research. Ionospheric scintillations significantly perturb both amplitude and phase of transionospheric satellite signals often resulting in complete outage of the signal leading to severe degradation of services of satellite-based communication and navigation systems which may pose life-critical conditions, particularly for high dynamic platforms like aircrafts [1]. The equatorial latitudes are particularly affected as post-sunset scintillations during the equinoxes often exhibit amplitude fades exceeding the typical dynamic ranges of receivers.

GPS modernization program is focused on addition of new navigation signals L2C and L5 to the GPS constellation. The L2C signal will be dedicated for civilian applications and it is expected to replace the semi-codeless L2P(Y) signal. The L5 is exclusively reserved for aviation navigation services and is designed with a protected spectrum, higher power, and greater bandwidth to support life-critical and high performance applications. Overall robustness of this multi-frequency mechanism to ionospheric scintillations could be ascertained through a study of correlated scintillations.

GNSS broadcast signals on more than one frequency so that a correction of the delay through the ionosphere can be determined. For instance, dual-frequency GPS receivers track L1/L2 signals to form ionosphere-free pseudorange and carrier phase observables. This ionosphere free combination is effective in mitigating the error due to the first order ionospheric effect. While the first order ionospheric term accounts for tens of meters compared to higher-order errors, the higher order ionospheric effects are becoming more relevant with growing precision GNSS applications involving high dynamic platforms like aircrafts.

A multi-constellation multi-frequency GNSS receiver capable of tracking GPS, GLONASS, GALILEO and SBAS geostationary satellites at multiple frequencies (L1, L2, L5; G1, G2, G3; E1, E6, E5a) is operated at Calcutta (22.58°N, 88.38°E geographic; magnetic dip: 32°N) situated in the anomaly crest region in the Indian longitude sector since April 2013. It provides at its output elevation, azimuth, time

(UTC), carrier-to-noise ratios (CNO) and amplitude scintillation index S_4 at a sampling interval of 1minute. Special emphasis was given to analyzing signals from satellite vehicles equipped to transmit L5 frequency. The equinoctial period of February-April 2014 was selected for the present analysis as the month of March 2014 witnessed intense (S4>0.6) amplitude scintillations on GPS on all days. It was found that SV1, SV5 and SV24 transmitted L5 other than L1 and L2. An elevation mask of 20° was selected for analysis of the GPS scintillation data.

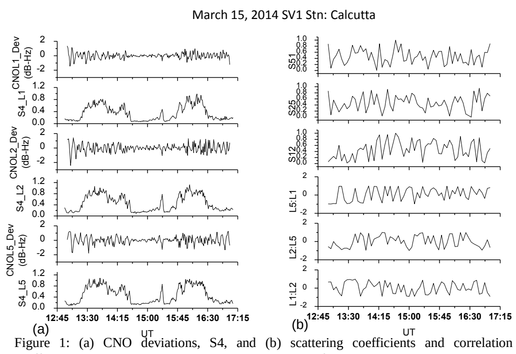

Figure 1: (a) CNO deviations, S4, and (b) scattering coefficients and correlation coefficients measured on SV1 link at L1, L2 and L5 frequencies during scintillation on March 15, 2014 from Calcutta

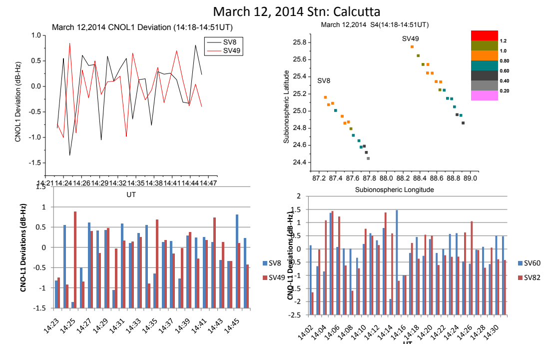

Figure 2: (a) CNO-L1 deviations observed on SV8 and SV49 sharing a common ionospheric volume observed from Calcutta at L1 frequency during scintillation on March 12, 2014 (b) Corresponding S4 indices marked on the 350-km subionospheric tracks of SV8 and SV49 (c) bar plot of CNO-L1 deviations for SV8 and SV49 (d) bar plot of CNO-L1 deviations for SV60 and SV82

During March 2014, post-sunset L-band scintillations at L1, L2 and L5 were noted on March 1-12, 14-17, 19 and 22-27 as recorded from SV1, 5 and 24 from Calcutta. Carrier-to-Noise (CNO) ratio deviations and S4 indices were calculated from these satellites transmitting L1, L2 and L5 frequencies. Correlations were measured between CNO deviations at the three frequencies for samples of 3 minute intervals. In order to understand the impact of different nature of scattering of transionospheric satellite signals at the three frequencies, three scattering coefficients were defined as

S12 = [CNO-L1 deviation ~ CNO-L2 deviation]/[CNO-L1 deviation + CNO-L2 deviation] (1)

S25 = [CNO-L2 deviation ~ CNO-L5 deviation]/[CNO-L2 deviation + CNO-L5 deviation], (2)

And,

S51 = [CNO-L5 deviation ~ CNO-L1 deviation]/[CNO-L5 deviation + CNO-L1 deviation]. (3)

The scattering coefficients were estimated every minute during a scintillation patch.

Figure 1 shows a representative case for SV1 link observed on March 15, 2014. Three distinct patches of scintillations could be identified, namely, from 13:15-14:30UT, 15:25-15:30UT and 15:40-16:50UT respectively on all the three frequencies as evident from the CNO deviations and S4 indices plot plotted in Figure (a). Figure 1(b) shows the scattering coefficients and correlation coefficients during the above time interval. High values of scattering coefficient S51 and S25 are noted around 14:00UT which corresponds to S4~0.6-0.8. The correlation coefficients L1:L2 and L2:L5 were found to be anti-correlated during this time. This process was repeated for the whole month of March 2014 and significant decorrelation in the signals were found to be mostly associated with high values of the scattering coefficient and intense scintillations (S4>0.6).

Efforts were made to study the relative robustness of GPS, GLONASS and GALILEO satellite signals present in a common ionospheric volume during periods of ionospheric scintillations as determined from relative fluctuations of detrended CNO and S4 indices. During March 2014, it was found that at any instant of time, 8 GPS, 8 GLONASS and 2 GALILEO satellites were visible from Calcutta above an elevation of 15°. Intense GPS and GLONASS scintillations (S4>0.6) were noted on several days mainly during local premidnight hours. In addition, intense scintillations on GALILEO SV 81, 82, 89 and 90 were observed on March 12, 25 and 26, 2014 and constitute perhaps some of the first reporting of ionospheric scintillation on GALILEO links from India. Detrended CNO fluctuations at L1 frequency were studied on days for time intervals when a pair of satellites from different constellations (GPS, GLONASS and GALILEO) exhibited ionospheric scintillations over a common volume of 5°×5°. On March 12, 2014, it was found that SV 8, 9 from GPS and SV 49 from GLONASS showed intense scintillations during 14:06-14:51UT over a common ionospheric volume 24.4°-26.2°N, 86.2°-89°E with peak-to-peak fluctuations nearly 60% less in GLONASS compared to GPS during some periods as shown in Figures 2(a) and (c). The corresponding S4 indices are shown on the 350-km subionospheric tracks of SV8 and SV49 in Figure 2(c). On that date, GLONASS SV 60 and GALILEO SV 82 exhibited intense scintillations over a common ionospheric volume during 13:57-14:30UT with almost 75% more fluctuations on the GALILEO link during some time over the above interval as evident from Figure 2(d). Similar analyses have been done for other dates in March 2014. This information is necessary for application of spatial diversity technique towards planning communication and navigation signal distribution in space under periods of ionospheric scintillations using interoperability of satellites from different constellations to improve the performance of SBAS.

As future GNSS receivers will transmit three frequencies for civilian applications, namely, L1, L2, and L5 in case of GPS, G1, G2 and G5 by GLONASS and E1, E6 and E5a by GALILEO, this will provide more advanced three-frequency correction schemes for which knowledge of correlation of different frequency pairs (L1/L2, L1/L5, L2/L5) under scintillation conditions is desirable. A significant factor in decorrelating the signals arises from the different phase decorrelation effects due to diffraction of signals from local random inhomogeneities of the ionosphere frequently found to develop in the equatorial region during post-sunset hours. Thus the three frequency regime is effectively controlled by different scattering mechanisms particularly with respect to coherence distances [2, 3]. Understanding the correlation of signal fades across multiple frequencies is important to assess their collective mitigation effectiveness. If signal fades at two frequencies are highly correlated, the actual aim of the frequency diversity scheme would be defeated. Lack of correlation between pairs of GNSS frequencies has been suggested to adversely affect positioning accuracy.

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