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Assessment of GLONASS and GALILEO signal characteristics during periods of ionospheric scintillations from an anomaly crest location

Samiddha Goswami[(1)], Ashik Paul [(1)]
(1)Institute of Radio Physics and Electronics, University of Calcutta, Kolkata, India
e-mail: sgrpe_rs@caluniv.ac.in

Abstract

Multi-frequency GNSS transmissions have provided the opportunity for testing the applicability of the principle of frequency diversity for scintillation mitigation. Multi-frequency scattering from ionization density irregularities within the same L-band are often the attributed cause behind simultaneous decorrelated signal fluctuations. The present paper aims to provide a quantitative estimate of the decorrelation in carrier-to-noise (C/N_0) ratio fluctuations and corresponding amplitude scintillation indices S_4 at GLONASS L1 and L2 and GALILEO E1 (L1BC) and E5a, and attempts to derive a frequency-dependent scattering parameter which could act as a proxy indicator of the signal decorrelation using GNSS measurements from Calcutta located in the anomaly crest region in India. Results from the anomaly crest station at Calcutta indicate that for 81.9% of scintillation time for GLONASS and 50.9% of scintillation time for GALILEO on March 12, 2014, the signals are decorrelated. It is important to note that it is only during these time intervals that the principle of frequency diversity could be applied for scintillation mitigation.

1. Introduction

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 [*Roy and Paul.,* 2013]. The equatorial latitudes are particularly affected as post-sunset scintillations during the equinoctial periods often exhibit amplitude fades exceeding the typical dynamic ranges of receivers.

One of the major deterrents to successful implementation of SBAS may be linked 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. These phenomena have the potential to cause serious damage to the technological infrastructure on which society relies. Understanding the correlation of signal fades across two 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. As GNSS satellites will broadcast three frequencies enabling more advanced three frequency correction schemes, understanding the correlation between different frequency pairs under scintillation conditions is extremely important [*Gherm et al.,* 2011]. Previously, the assessment of the contribution of diffraction for range errors in the dual-frequency regime using a hybrid model has been reported in literature [*Gherm et al.,* 2006a; 2006b].

The present paper aims to provide proportion of time during scintillation patches that decorrelations are found across GLONASS L1 and L2 and GALILEO E1 (L1BC) and E5a frequencies associated with high S_4, corresponding high values of scattering coefficients and large receiver position deviations thereby seriously compromising the performance of satellite based navigation system, during passage through ionospheric irregularities, recorded from Calcutta located in the anomaly crest region in India. This information will be essential for understanding the applicability of frequency diversity techniques for scintillation mitigation, and has not been reported in literature from this longitude sector for GLONASS and GALILEO.

2. Data and Methodology

A multi-constellation, multi-frequency GNSS receiver is operational at the Institute of Radio Physics and Electronics, University of Calcutta, 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. This receiver is capable of tracking GPS, GLONASS, GALILEO and SBAS geostationary satellites at multiple frequencies L1 (E1 in case of GLONASS) – 1575.42MHz, L2 (E5a in case of GALILEO) – 1227.6MHz, L5 – 1176.45MHz). It provides at its output elevation, azimuth, time (UTC), carrier-to-noise ratios (C/N_0) and Total Electron Content (TEC) at 50Hz (0.02s) sampling rate whereas amplitude scintillation index (S_4) has been recorded at 1 minute sampling interval. C/N_0 deviations have been calculated by subtracting the moving averaged values over a running time interval of 90 minutes from the instantaneous measurement of C/N_0.

The equinoctial month of February-April 2014 was selected for the present analysis as the month of March 2014 witnessed intense (S4>0.6) amplitude scintillations on GLONASS on all days. 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. An elevation mask of 15° was selected for analysis of the GLONASS and GALILEO scintillation data in order to avoid multipath effects.

To observe any difference in amplitude scintillations at different frequencies, correlations were measured between C/N_0 deviations recorded at the two frequencies separately for samples of amplitude scintillations of 3 minute interval for $S_4 \geq 0.2$. It should be understood that the analysis of multi-frequency scattering of GNSS signals from ionization density irregularities and its application for scintillation mitigation using the principle of frequency diversity is relatively new with limited reports in literature and needs quantification for possible applications to Satellite Based Augmented System (SBAS). Thus in the absence of any universally recognized parameter for quantifying the decorrelation of a pair of GNSS signals, a simple yet convenient mathematical formulation for such quantification has been devised and named as scattering coefficient. The scattering coefficient across a pair of frequency could be defined as the difference of C/N_0 fluctuations normalized with respect to the sum of those fluctuations. It is a dimensionless quantity where low values close to zero indicate strong correlation between the signals. In order to understand the impact of different nature of scattering of transionospheric satellite signals at the two frequencies, two scattering coefficients (S) have been defined in the analysis, namely,

$$Sglo = \frac{[C/No - L1\ deviation \sim C/No\ -\ L2\ deviation]}{[C/No - L1\ deviation\ +\ C/No\ -\ L2\ deviation]} \tag{1}$$

$$Sgal = \frac{[C/No - E1\ deviation \sim C/No\ -\ E5a\ deviation]}{[C/No - E1\ deviation\ +\ C/No\ -\ E5a\ deviation]} \tag{2}$$

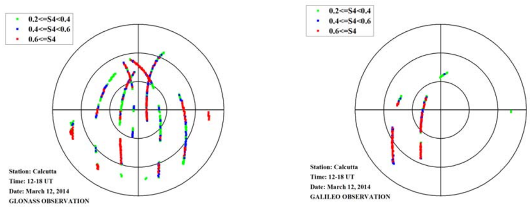
The scattering coefficients were estimated for every 3-minute sample of the C/N_0 deviation

In the present analysis efforts have been made to find differences, if any, in L-band amplitude scintillations observed on GLONASS and GALILEO links at L1 and L2 (E1 and E5a respectively in case of GALILEO) frequencies from the same satellite over the same period of time. If the effects of ionospheric irregularities at different frequencies are identical, then the principle of frequency diversity could not be applied for scintillation mitigation. The major objective in this paper is to find the proportion of time each day during scintillation events that decorrelation between intense C/N_0 fluctuations and high values of S_4 are associated with high values of the associated scattering coefficient for that frequency pair. A representative case for March 12, 2014 has been shown in this paper.

3. Results

During February – April 2014, intense equatorial ionospheric scintillations with $S_4>0.6$ were recorded on several days from Calcutta. During periods of intense scintillations, strong scattering of transionospheric signals occur when the drifting ionization density irregularity structures intersect satellite links, in contrast to moderate or weak scintillation period when $S_4<0.6$. Detailed discussion of signal scattering from inhomogeneities in electron density distribution could be found in *Briggs and Parkin* [1963] *Singleton and Lynch* [1962], *Singleton* [1970], *Rino* [1979(a), 1979(b)] and *Carrano et al.,* [2012]. The present availability of multiple frequencies transmitted from GNSS satellites makes it useful for studying the scattering of signals from ionization density irregularities across the two frequency regime, namely L1 and L2 (E1 and E5a for GALILEO). In this paper, a representative case for SV59 of GLONASS and SV82 of GALILEO links observed from Calcutta on March 12, 2014 has been illustrated.

The sky plots for March 12, 2014 from Calcutta for



(a) (b)

Figure 1. Sky plots of satellites affected by amplitude scintillations for March 12, 2014 from Calcutta, for (a) GLONASS and (b) GALILEO.

GLONASS and GALILEO are shown in Figures 1(a) and 1(b), respectively. The satellite tracks are affected by different levels of amplitude scintillations, namely, mild ($0.2<S_4\leq 0.4$), moderate ($0.4<S_4\leq 0.6$) and intense ($S_4>0.6$) during that time period. The different levels of scintillations are indicated by different colours on the subionospheric tracks. In Figure 1(a) and 1(b), it can be observed that eight GLONASS satellite links and two GALILEO satellite links are affected by intense scintillation during pre-midnight hours from Calcutta.

In this paper, representative cases for SV59 (GLONASS) and SV82 (GALILEO) links observed from Calcutta on March 12, 2014 has been illustrated. On SV59 link observed during 14:00-17:00 UT on March 12, 2014, high values of scattering coefficient (S_{glo}) for the frequency pair L1, L2 were noted around 14:29-14:33, 14:53-15:01, 15:09-15:17, 15:29-15:37 and 15:49-15:57 UT which corresponds to $S_4 \sim 0.6$-1.0 and low C/N_0 correlation coefficients. Out of 83 minutes of observed scintillations on L1 and L2 links, 68 minutes of such cases with low correlation coefficient of C/N_0, high values of scattering coefficient and scintillation indices were found on the SV59 link on March 12, 2014. Thus the condition of decorrelated C/N_0 fluctuations associated with high S_4 and high scattering coefficients is found to be valid for 81.9%

of the scintillation patch duration for L1 and L2 frequencies on the SV59 link.

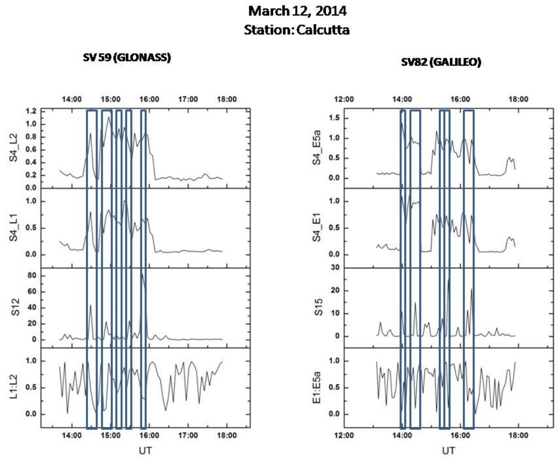


Figure 2. : Variation of (a) correlation coefficient of C/N_0 deviations at L1 and L2 in dB-Hz with scattering coefficient S_{Glo}, S_4 index at L1, S_4 index at L2 for SV59 and (b) correlation coefficient of C/N_0 deviations at E1 and E5a in dB-Hz with scattering coefficient S_{Gal}, S_4 index at E1, S_4 index at E5a for SV82 during 13:00-18:00 UT of March 12, 2014.

Similarly, for SV82 link observed during 13:00-18:00 UT on the same day, high values of scattering coefficient (S_{gal}) for the frequency pair E1, E5a were noted around 13:59 - 14:03, 14:27-14:31, 15:15-15:23, 15:35-15:39 and 16:15-16:23 UT which corresponds to S_4~0.6-1.4 and low C/N_0 correlation coefficients. Out of 55 minutes of observed scintillations on E1 and E5a links, 28 minutes of such cases with low correlation coefficient of C/N_0, high values of scattering coefficient and scintillation indices were found on the SV82 link on March 12, 2014. Thus the condition of decorrelated C/N_0 fluctuations associated with high S_4, high scattering coefficients and large receiver position deviations is found to be valid for 50.9% of the scintillation patch duration for E1 and E5a frequencies on the SV82 link.

4. Discussions

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. While periods of decorrelation of signal fades at multiple frequencies could be used for scintillation mitigation, such decorrelation between pairs of GNSS frequencies has been suggested to adversely affect positioning accuracy. This information will be essential for understanding the applicability of frequency diversity techniques for scintillation mitigation for GLONASS and GALILEO and has not been reported in literature from this longitude sector.

The multi-frequency regime is effectively controlled by different scattering mechanisms particularly with respect to coherence distances [*Gherm et al.,* 2006a; 2006b]. 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.

It is true that frequency coherence depends on mean frequency as well as the separation frequency. It is precisely for this reason that statistical correlation of signal fades across a pair of frequencies for several intervals of time during patches of scintillations spanning two equinoxes does not provide an exact one to one correspondence with S4, scattering coefficient and position deviations. Uncorrelated values of C/N_O fluctuations at L1:L2 (E1:E5a) indicate different scattering mechanisms particularly around times of high S_4 even within the same L-band possibly due to dynamic evolving nature of equatorial ionospheric irregularities. This issue is of serious concern in view of application of the multiple frequencies for higher precision positioning information. Different nature of C/N_0 fades at L1 and L2 (E1 and E5a respectively in case of GALILEO) could be utilized for frequency diversity mechanism for minimizing effects of intense irregularities. Non-simultaneity of C/N_0 fades in terms of crests and troughs may be applied for scintillation mitigation. Thus the multi-frequency regime is effectively controlled by different scattering mechanisms particularly with respect to coherence distances. Application of frequency and spatial diversity using multi-frequency and multi-constellation GNSS for scintillation mitigation in real time operational systems is indeed a complicated procedure. The present paper attempts to address a part of this problem by correlating signal fades across the dual frequency GLONASS and GALILEO signals to evaluate proportion of correlated signal time during scintillation patches. This proportion calculated over different locations may help in developing strategy for frequency selective positioning mechanism during periods of intense scintillation.

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