

On the Relation between Auroral “Scintillation” and “Phase without Amplitude” Scintillation: Initial Investigations

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Abstract

The ionosphere, being a plasma, affects any radio signal passing through it by introducing a phase advance and a group delay in the signal. Occasionally, due to electron density irregularities in the ionosphere, the radio signal can experience rapid amplitude and phase fluctuations called scintillation. Scintillation can sometimes be intense enough to cause a Global Positioning System (GPS) receiver to lose lock on a signal, thus making it a significant aspect to consider in GPS-based positioning, navigation, and timing systems. Quantitative information about scintillation is usually obtained from parameters called the scintillation indices. The most commonly used GPS scintillation indices are S_4 and σ_ϕ that quantify scintillation in power and phase of the GPS signal, respectively. Recent studies have shown that at high latitudes, the probability of occurrence of phase scintillation is greater than amplitude scintillation. These events are called “phase without amplitude” scintillation. In this study, the relation between these events and auroral scintillation is analyzed. As an initial step, data from the Canadian High Arctic Ionospheric Network and 10 more GPS stations located in Canada was used simultaneously along with data from 11 Canadian THEMIS all-sky imagers. Preliminary investigations reveal that phase fluctuations associated with aurora can be the main reason behind “phase without amplitude” scintillation. Spectral studies of differential-carrier-phase TEC were also performed to support this hypothesis.

1. Introduction

Scintillation or fast fluctuations in the signal’s amplitude and phase are important when dealing with signals from satellite navigation systems, like GPS, as these scintillation can introduce errors in the measurement and sometimes can lead to loss of signal. Scintillation in received amplitude and phase of GPS signals is quantitatively represented by S_4 and σ_ϕ respectively. S_4 represents the normalized standard deviation of the detrended amplitude while σ_ϕ represents the standard deviation of the detrended phase. The accuracy of these indices is important as they are used to create scintillation models, which are used in prediction as well as understanding the physics behind scintillation. Studies [1, 2] which dealt with GPS scintillation observed at high latitudes have indicated that there is a higher probability of phase scintillation occurrence compared to amplitude scintillation. These studies have also shown that these “phase without amplitude” scintillation events observed at high latitudes are mainly due to the use of a default detrending cut-off frequency (0.1 Hz), which is designed for low latitudes. The cut-off frequency that has to be used for high latitude data should take into account the change in Fresnel frequency due to different irregularity dynamics present in higher latitudes. This Fresnel frequency is important because amplitude scintillation is Fresnel filtered while phase scintillation is not; hence Fresnel frequency demarcates the boundary between scintillation and slower ionospheric variations [1, 2]. Recently, it has been shown that use of a wavelet detrending filter with a cut-off frequency of ~0.19 Hz and a new phase scintillation index (σ_{CHAIN}) can significantly reduce “phase without amplitude” scintillation [2]. But the basic question of what high latitude physical phenomenon is causing these fluctuations, which makes σ_ϕ over-estimated when using a GPS scintillation receiver with 0.1 Hz cut-off frequency, is still unanswered.

2. Data Analysis

In an attempt to answer this question, TEC fluctuations associated with aurora were analyzed and compared with phase scintillation values to see if there is a relation between these two. For this, an auroral event that has occurred on 17 March 2013 at 06:00 UT-12:00 UT was chosen as an initial data set. During this period, the Kp index was above 5. Time History of Events and Macroscale Interactions during Substorms (THEMIS) Canadian All Sky Imagers (ASI) [3, 4] were used to observe and analyze how the aurora evolved during this period. In order to see how the aurora influences the GPS signals, data from GPS stations of the Canadian High Arctic Ionospheric Network (CHAIN) [5], International GNSS Service (IGS) (<http://igscb.jpl.nasa.gov/>), and Natural Resources Canada (NRCan) (<http://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php>) were used. Even though the main interest of this study is σ_ϕ , it was decided that a pseudo phase fluctuation index, rate-of-change of TEC Index (ROTI) (Equation 1) [6] would be used in place of σ_ϕ . This is mainly because, except for CHAIN, there are not yet many GPS scintillation receivers present in the auroral region in Canada. ROTI can be calculated from total electron content (TEC), which, in turn, can be calculated from observables in the RINEX observation files obtained from these GPS stations [6]. In this study, phase observables (L1 and L2) with 1 sec resolution were used to calculate differential phase TEC.

$$\text{ROTI} = \sqrt{\langle \text{ROT}^2 \rangle - \langle \text{ROT} \rangle^2} \quad (1)$$

$$\text{ROT} = \frac{\Delta \text{TEC}}{\Delta t} \quad (2)$$

Here ROTI is the standard deviation of ROT calculated every minute and ROT stands for rate-of-change of TEC, which is calculated every second. These calculated ROTI values were then colour coded using the following ranges: ROTI < 0.2 = green, 0.2 < ROTI < 0.4 = orange and ROTI > 0.4 = red. These colour-coded values were then mapped to their respective satellite's ionospheric pierce point at a height of 110 km using the elevation angle and azimuth values obtained with respect to the receiver's position using RINEX navigation files and GPS Tool Kit (GPSTk) (<http://www.gpstk.org>). An example of this can be seen in Figure 1, where colour-coded satellite PRNs which had ROTI < 0.2 can be seen in green and while satellites PRNs which had 0.2 < ROTI < 0.4 can be seen in orange and ROTI > 0.4 are seen in red. In order to analyse the spectral content of TEC fluctuations, differential phase TEC was detrended using the wavelets method [2]. A cut-off frequency of 0.08 Hz was used so that all frequencies above 0.1 Hz could be analysed. It should be noted that the maximum frequency that one could obtain here was 0.5 Hz given the 1-Hz cadence of the data.

3.RESULTS

3.1 Effect of Aurora on Fresnel Frequency

Recent study [7] has shown that GPS satellite signals get affected while passing through an aurora but it was never shown why phase scintillation is not accompanied by amplitude scintillation in these cases. In an attempt to understand this, the effect of aurora on Fresnel frequency was considered. Fresnel frequency of a satellite affected by an auroral patch was calculated using formulas mentioned in [1, 2]. Figure 1 shows the evolution of an auroral patch (shown enclosed in blue dots) at three different times at 08:17 UT, 08: 19 UT and 08:21 UT on 17 March 2013. The coordinates of the patch were calculated every minute and from them, velocity of the patch was deduced. The average velocity of this auroral patch was found to be about ~1100 m/s towards the east. To obtain the relative drift between satellites and auroral patch, velocity of the GPS satellite (PRN 2), which was in the vicinity of that patch was also calculated. The velocity of that satellite, calculated from its ionospheric pierce points, at a height of 110 km was 33 m/s towards the west. Using this information and the formula for Fresnel frequency given by [1, 2], we found that Fresnel frequency for this particular satellite PRN 2 was ~5 Hz. This clearly shows that the Fresnel frequency can be shifted to very high frequencies during auroras and its nowhere near 0.1 Hz which is the default value which the receiver assumes. The implications of this will be discussed in Section 4.

3.2 Effect of TEC on σ_ϕ

Figure 2 shows scintillation indices (S_4 and σ_ϕ), differential phase, TEC, and ROTI for an event observed at Taloyoak (geog. coord: 69.54°N, 266.44°E), a CHAIN GPS scintillation receiver station, on 17 March 2013 between 9:30 and 11:00 UT. It can be clearly observed that S_4 is very small and less than 0.1 while σ_ϕ reached a maximum of ~0.3. This is clearly a case of “phase without amplitude” scintillation. Now, if ROTI is observed, a clear resemblance between σ_ϕ and ROTI can be clearly seen. Figure 3 shows the wavelet scalogram of detrended differential phase TEC. Wavelet detrending with 0.08 Hz cut-off frequency was performed using the methods proposed by [2]. In Figure 2, two peaks at 9:45 UT and 10:30 UT in σ_ϕ and ROTI are clearly seen. Correspondingly, signatures of these peaks are also seen in the

scalogram (Figure 3). The frequency range of these signatures is between 0.1 to 0.3 Hz, where most of the relative power is buried. This analysis was repeated for a few more satellites and similar results were obtained.

4. Discussion and Conclusion

To understand why phase scintillation is not always accompanied by amplitude scintillation, the effect of auroras on Fresnel frequency is analysed. In this study, Fresnel frequency was calculated for a satellite which was in the path of an auroral patch. The value obtained was around 5 Hz which is very near to the noise floor of the NovAtel GSV 4004B GPS receiver used to collect the observations, which is around 8 -10 Hz [2].

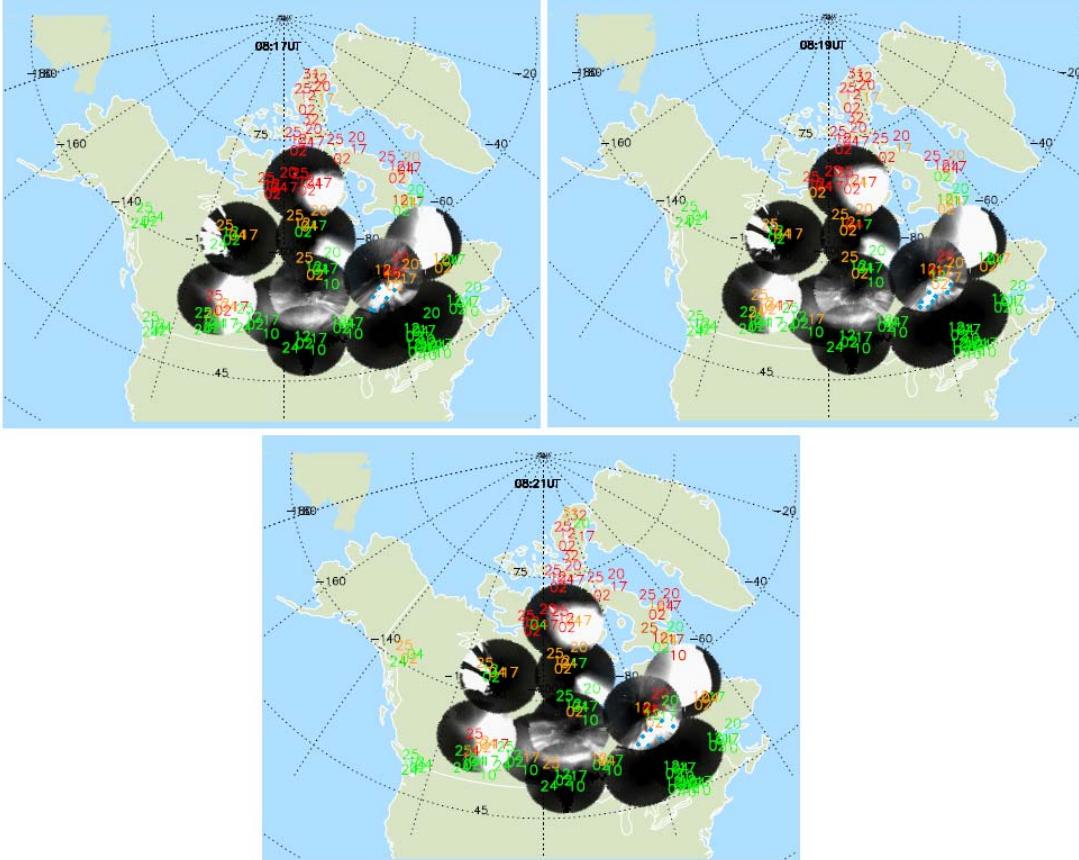


Figure 1: Evolution of the auroral patch (enclosed in blue dots) as seen by THEMIS ASI. Colour-coded GPS satellite PRNs can also be seen. Green represents $\text{ROTI} < 0.2$, orange = $0.2 < \text{ROTI} < 0.4$, red = $\text{ROTI} > 0.4$.

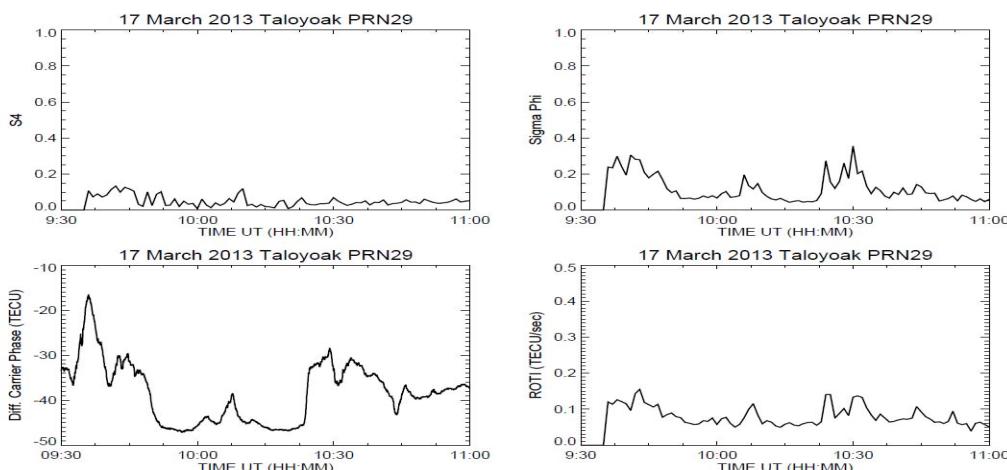


Figure 2. S_4 , σ_ϕ , differential carrier phase TEC, and ROTI as observed on GPS satellite PRN 29 at Taloyoak on 17 March 2013 between 09:30 and 11:00 UT. Relation between σ_ϕ and ROTI can be observed.

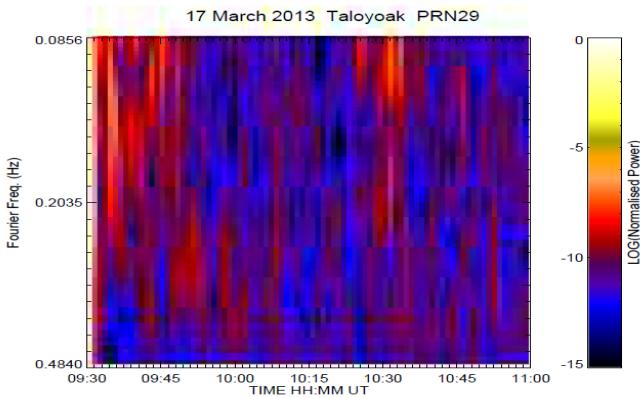


Figure 3: Scalogram of detrended differential phase TEC. Signatures of fluctuations can be clearly seen at 9:45 UT and 10:30 UT with a frequency range mainly between 0.08 and 0.2 Hz.

This result indicates that it would be hard to distinguish between receiver noise and amplitude scintillation. A clear correlation between ROTI and σ_ϕ was observed in Figure 2. We think that this correlation is mainly due to the fact that TEC changes, which are lower in frequency, influence σ_ϕ because these low frequency components have more power compared to higher frequency components (Figure 3) and also these low frequency components are not eliminated during detrending, as the detrending filter's cut-off frequency is under estimated. Using 0.1 Hz default cut-off frequency allows these low frequency TEC changes (0.1 - 0.3 Hz as seen in Figure 3) to contribute to σ_ϕ and thus over estimating it. Even though the Fresnel frequency should be the theoretical cut-off frequency for the detrending filter, one could imagine that even if the cut-off frequency was as high as 0.2 Hz, most of these low frequency contributions would be eliminated [2].

These results seem to indicate perhaps “phase without amplitude” scintillations are mainly due to fluctuations associated with aurora and one is not able to distinguish amplitude scintillation, which has frequencies close to noise as well as very low spectral power. Hence to get a clear picture, receivers with an estimate of Fresnel frequency as well as low noise thresholds are needed. These low thresholds would make it easier to distinguish frequencies higher than 5 Hz, which is a possible Fresnel frequency at high latitudes. There is also a need for new detrending methods and new indices which would give better and accurate quantitative description of scintillation [1, 2]. The nomenclature of GPS phase fluctuations perhaps should also be reconsidered. Phase fluctuations associated with aurora should be distinguished from phase scintillation (frequencies above Fresnel frequencies) so that both fluctuations can be studied separately and thoroughly. It should be noted that these are still initial results and we are in a process of analyzing more data sets to get a clearer and concrete picture.

5. References

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