The Effects of Ionospheric Irregularities on the Navigational Receivers and Its Mitigation

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Abstract. The performance of navigational receivers using satellite-based navigation technology can be severely affected by the presence of time-varying electron-density fluctuations in the ionosphere which can cause amplitude and phase perturbations at the receiver resulting in loss of phase lock at the carrier tracking loop due to cycle slip and hence unavailability of the navigation services. This paper studies the effects of amplitude and phase fluctuations at high latitudes due to the irregular ionosphere and, their effects on the receiver performance by using real time raw data from the Global Positioning Systems (GPS) satellites. The paper also suggest the use of adaptive software-based receiver model or modified hardware receivers to mitigate the effects of amplitude and phase fluctuations due to irregular ionosphere.

Keywords: GPS · Software receiver · Ionospheric scintillation
Tracking jitter · Phase locked loop

1 Introduction

The Navigational receivers are widely used by both the civilians and military for location-based services. Almost, all of these receivers uses satellite-based navigation technologies such as GPS, GLONASS, Galileo etc. The satellites used by these navigation systems are placed into the outer space having an altitude of more than 20,000 kms. The signals from these satellites have to pass through the ionosphere (a heavily ionized medium) which is a layer of the Earths atmosphere which may contain time-varying electron density irregularities as a result of a geomagnetic storm or increased solar activity and therefore can cause amplitude and phase fluctuations in the trans-ionospheric signals such as those received by the navigational receivers [1–3]. These amplitude and phase fluctuations due to the irregular behaviour of the electrons movement in the ionosphere

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are known as the ionospheric scintillation [4,5]. The amplitude fluctuations are termed as amplitude scintillation whereas phase fluctuations are termed as phase scintillation.

Phase scintillation is usually observed at high latitudes (above 60° geomagnetic latitude) due to the auroral phenomena, can occur any time of the day lasting from few minutes to several hours and may result in loss of phase lock at the carrier tracking loop resulting in degrading the receiver performance [5–8]. The phase scintillation does not affect the signal-to-noise ratio of the signal [9]. The amplitude scintillation, on the other hand, is more dominant near the equatorial latitudes (±20° geomagnetic latitude) which occurs due to plasma instabilities in the F-layer of the ionosphere. At low latitudes, the GPS signal passing through the ionosphere faces scattering and may add destructively to produce deep power fades which may result in dropping the signal-to-noise (S/N_o) ratio of the signal below the receivers lock threshold [10,11] and the satellites may be considered absent even if there are a number of satellites present [9]. The amplitude scintillation can introduce fading of upto 20 dB at L-band frequencies [6].

In this paper, the effects of amplitude and phase scintillations on the navigational receiver performance has been studied during geomagnetic storm conditions. For this study, raw GPS data have been used by installing GPS receivers at various parts of Europe based on their latitudinal positions. This paper also suggest a tracking phase jitter based carrier tracking loop technique which can be used in software receivers or hardware ones to improve the performance of all types of navigational receivers relying on satellite technology during disturbed ionospheric conditions which leads to strong amplitude and phase fluctuations.

2 Measuring the Ionospheric Scintillation

Ionospheric scintillation refers to rapid random fluctuations in the amplitude and/or phase of the received trans-ionospheric signals [12]. These fluctuations occur due to the disturbance in the Earths magnetic field whenever there is a geomagnetic storm which occurs when the heated plasma (electrically charged atoms and molecules) from the sun also known as the solar wind strikes the Earths magnetic field creating instabilities in the ionosphere plasma [6,13]. In order to measure the ionospheric scintillation due to disturbed ionosphere, NovAtel 4004B GPStation6 dual frequency receivers have been installed at different latitudinal positions around Europe as shown in Fig. 1.

The GPS transmit signals using several frequency bands such as $L1$ (1575.42 MHz), $L2$ (1227.6 MHz), $L3$ (1381.05 MHz), $L4$ (1379.913 MHz) and $L5$ (1176.45 MHz). At a particular time, there are usually 24 active satellites in the constellation of GPS. The $L1$ and the $L2$ frequency bands are widely used by both the civilians and military for navigation purposes. The $L1$ signal uses the Coarse acquisition (C/A) and the $P(Y)$ codes whereas the $L2$ signal uses only the $P(Y)$ code for GPS signal transmission [6].

The C/A code is a 1 ms long pseudorandom code (PRN) sequence having a chipping rate of 1.023 MHz and each satellite in the GPS has a unique C/A code.

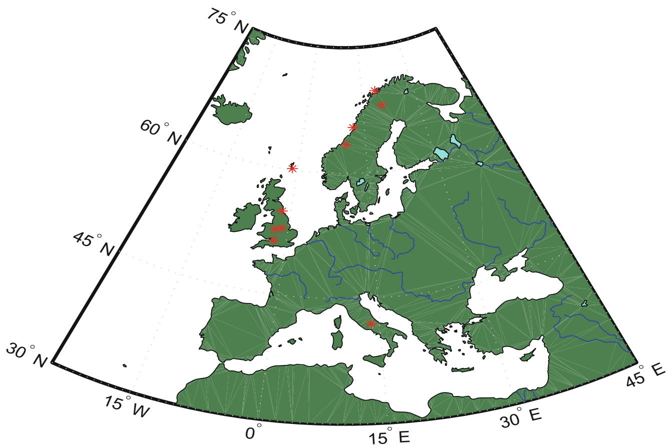

Fig. 1. GPS receiver stations installed at different latitudes around Europe for recording the scintillation activity [6].

The C/A code is available free of cost to all users. The $P(Y)$ code, on the other hand, is a 266 days long PRN code with a chipping rate of 10.23 MHz. This code is available to military only. The GPS signal on the $L1$ and $L2$ frequencies also contain the navigation data at 50 Hz which contains the information about the satellites orbit, time, position and the path that satellites follow when orbiting the Earth. This information is used at the receiver for position estimation.

The mathematical model of the GPS $L1$ and $L2$ signals [6] can be given as

$$S_{L1}(t) = A_c c(t) d(t) \cos(\omega t + \phi) + A_p P(t) d(t) \cos(\omega t + \phi) \tag{1}$$

$$S_{L2}(t) = A_{L2} P(t) d(t) \cos(\omega t + \phi) \tag{2}$$

where S_{L1} and S_{L2} are the $L1$ and $L2$ signals, A_c and A_p are the C/A and $P(Y)$ signal amplitudes at $L1$ and $L2$ frequencies respectively. A_{L2} is the $L2$ signal amplitude, $d(t)$ is the navigation data at 50 Hz, ω is the carrier frequency, $c(t)$ is the C/A code and $P(t)$ is the $P(Y)$ code. In case, the received signal is affected by the amplitude and phase fluctuations after passing through the ionospheric irregularities [6], (1) and (2) can be re-written as

$$S_{L1}(t) = A_c\ \delta A_c\ c(t) d(t) \cos(\omega t + \phi + \delta\phi) + A_p\ \delta A_p P(t) d(t) \cos(\omega t + \phi + \delta\phi) \tag{3}$$

$$S_{L2}(t) = A_{L2}\ \delta A_{L2}\ P(t) d(t) \cos(\omega t + \phi + \delta\phi) \tag{4}$$

where $\delta A_c, \delta A_p$ and δA_{L2} represents the fading in the amplitudes of the signals at the $L1$ and $L2$ frequencies respectively and $\delta\phi$ are the phase fluctuations. The phase scintillation is normally denoted by σ_ϕ index and is the square root of the standard deviation of the $\delta\phi$ over a certain time period usually taken as 60 s [6]. The amplitude scintillation, on the other hand, is the normalized standard deviation of the signal intensity ($\delta I = \delta A^2$) over a 60 s interval [6] given as

$$S_{4T} = \frac{\sqrt{E[\delta I^2] - (E[\delta I])^2}}{E(\delta I)} \tag{5}$$

where $E[]$ is the mean value. In the presence of ambient noise, the final equation for the amplitude scintillation index denoted by S_4 can be given as

$$S_4 = \sqrt{\frac{E[\delta I^2] - (E[\delta I])^2}{[E(\delta I)]^2} - \frac{100}{S/N_o}\left[1 + \frac{500}{19S/N_o}\right]} \tag{6}$$

where S/N_o is the signal-to-noise ratio. The signal intensity δI can be found as

$$\delta I = \frac{(NBP - WBP)}{(NBP - WBP)_{LPF}} \tag{7}$$

where NBP and WBP are the low pass filtered (LPF) narrowband and wideband powers respectively and can be given as

$$NBP = \left(\sum_{k=1}^{N} i_k\right)^2 + \left(\sum_{k=1}^{N} q_k\right)^2 \tag{8}$$

$$WBP = \sum_{k=1}^{N} \left(i_k^2 \ + \ q_k^2\right) \tag{9}$$

where i and q are the in-phase and quadrature components of the received signal generally summed over a 20 ms interval, i.e., $N = 20$, to find the NBP and WBP. Using (9), the carrier-to-noise ratio, C/N_o, of the received signal can be found as

$$C/N_o = 10 \log\left[\left(\frac{WBP}{N} - 1\right) \times 50\right] \tag{10}$$

3 Scintillation Effects on the Receiver Performance

In order to record the scintillation activity, the experimental setup used is shown below in Fig. 2. This is one of the receiver station out of several receiver stations around Europe which is setup in the Department of Electrical Engineering, Newcastle University, Newcastle Upon Tyne, UK. The similar setup has been used at other stations as well.

To determine the ionosphere effects on the receiver performance due to fluctuations in the amplitude and/or phase of the received signal, we selected one of our high latitude receiver stations installed at Trondheim, Norway (63.42° N, 10.4° E). The scintillation activity at Trondheim is shown in Fig. 3 on 24 April, 2012. Due to being located at high latitudes, there is a always high possibility of scintillation occurrence whenever there is a solar storm or a geomagnetic

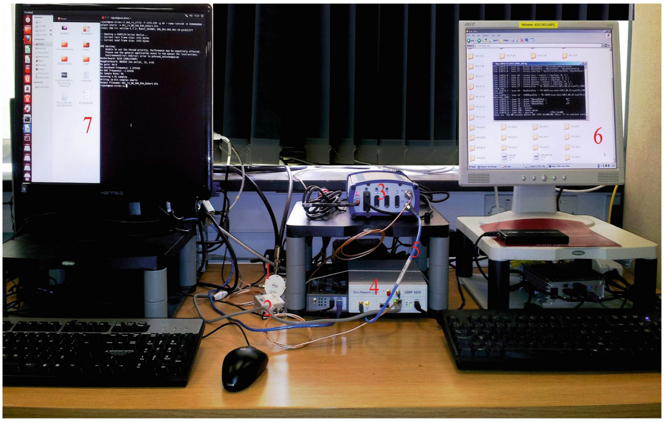

Fig. 2. Experimental setup for recording the scintillation activity using the NovAtel GSV4004B GPS Receiver. (1) Amplifier connected to the roof mounted GPS antenna; (2) splitter to split the signal between Novatel receiver and USRP2 N210 for raw data recording; (3) Novatel GPS receiver; (4) Universal Software Radio Peripheral 2 (USRP2) N210 front end device; (5) oscillator output from (3) to (4); (6) Scintillation data recording using the Novatel receiver; (7) GPS Raw data recording using USRP2 N210 device for signal acquisition and tracking manually by using a software receiver [12].

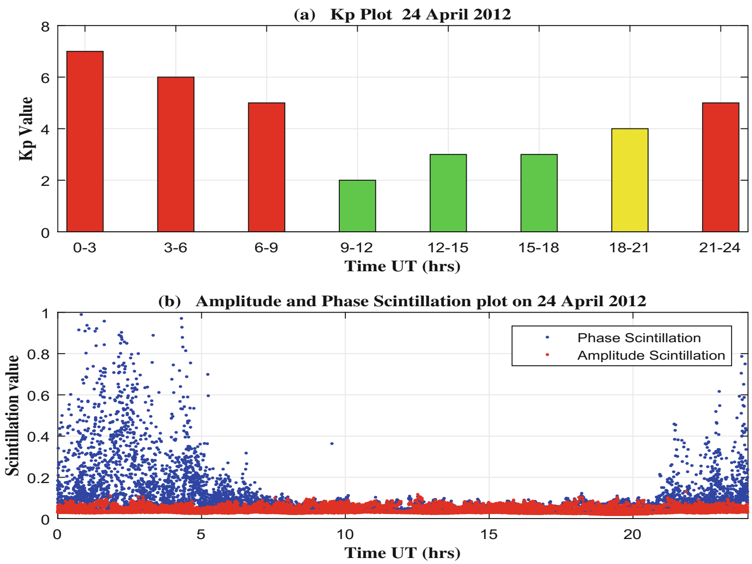

Fig. 3. Geomagnetic field activity and Scintillation observed at Trondheim, Norway on 24 April, 2012 (Color figure online)

storm. Figure 3(a) shows the geomagnetic field activity on 24 April, 2012 by using a planetary index Kp. This index is used to represent the disturbance in the Earth's magnetic field on a scale of 0 to 9 where Kp values of less than 4 means that there is no storm and no significant scintillation activity will occur, Kp value of 4 means that there might be a chance of amplitude and/or phase scintillation occurrence and Kp values of 5 or greater than 5 means that there is a high possibility of scintillation occurrence. The Kp index updates every 3 h with an estimate of the past 3 h values.

The red bars in Fig. 3(a) shows that there is a strong geomagnetic storm between 00:00 to 09:00 universal time (UT) and from 21:00 to 24:00 UT as the Kp index is either 5 or greater than 5. Between 09:00 to 21:00 UT, there was no storm while from 18:00 to 21:00 UT there was only a geomagnetic disturbance. Figure 3(b) shows the amplitude and phase scintillation activity for all the satellites on 24 April, 2012 that were locked by the GPS receiver. Strong phase scintillation was observed on all the satellites between 00:00 to 06:00 and from 21:00 to 24:00 UT as can be seen by the blue dots in Fig. 3(b). However, no significant amplitude scintillation was observed between these hours due to the station being located at high latitudes as explained earlier.

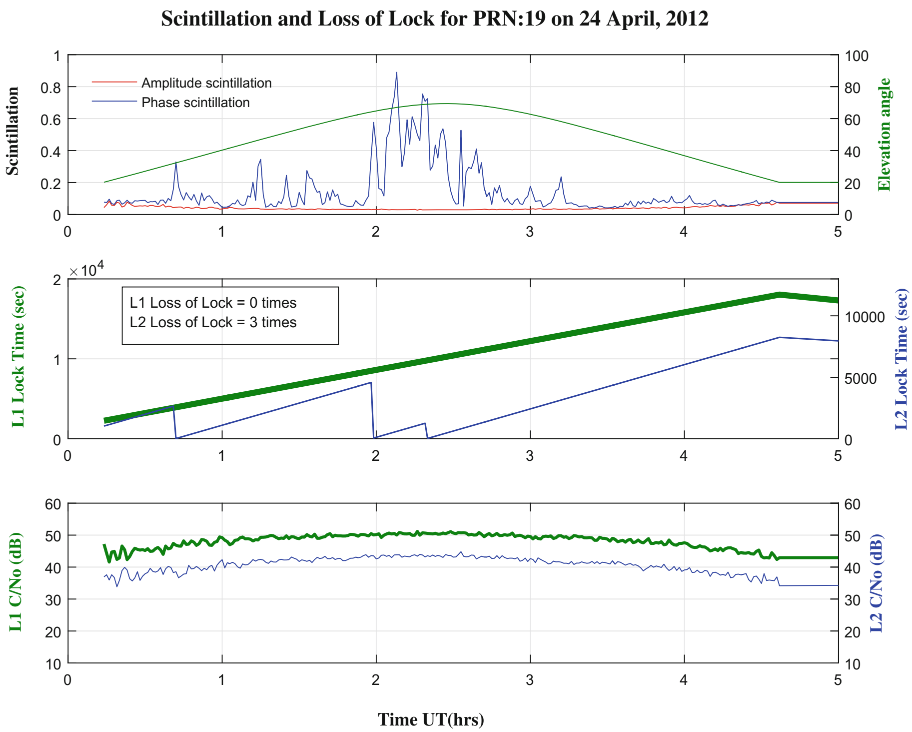

Fig. 4. Scintillation activity and the loss of lock occurrence for PRN 19 on 24 April, 2012.

Figure 4 shows the results of one of the satellites, i.e., PRN 19 that was locked by the Trondheim GPS receiver between 00:00 to 05:00 UT on 24 April, 2012 during the geomagnetic storm time. The top graph in Fig. 4 represents the amplitude and phase scintillation on PRN 19 along with the elevation angle. It should be noted that the satellite is considered to be locked when the elevation angle is greater than 20° in order to avoid spurious values which occured due to tall buildings or obstacles and does not contribute to amplitude and phase fluctuations introduced by the ionosphere. The middle graph in Fig. 4 shows the loss of tracking loop lock at the $L1$ and $L2$ frequencies whereas the bottom graph in Fig. 4 shows the C/N_o for the $L1$ and $L2$ signals. There are 32 satellites in the GPS system out of which only 24 are used for navigation. These 32 satellites are usually represented by $PRN1, PRN2, PRN3$ upto $PRN32$ where PRN stands for pseudo random number which is unique for each satellite in the GPS.

It can be seen in Fig. 4 that due to the strong phase scintillation, the $L2$ signal frequently lost lock whereas the $L1$ signal stayed in contact and provided the navigation services as usual. The reason for the $L2$ signal frequent loss of lock compared to the $L1$ signal is due to the critical frequency of the ionosphere. Frequencies close to the critical frequency are more affected by the ionosphere disturbance compared to the higher frequencies. The phase scintillation does not affects the signal-to-noise ratio as can be seen in the bottom graph in Fig. 4 which

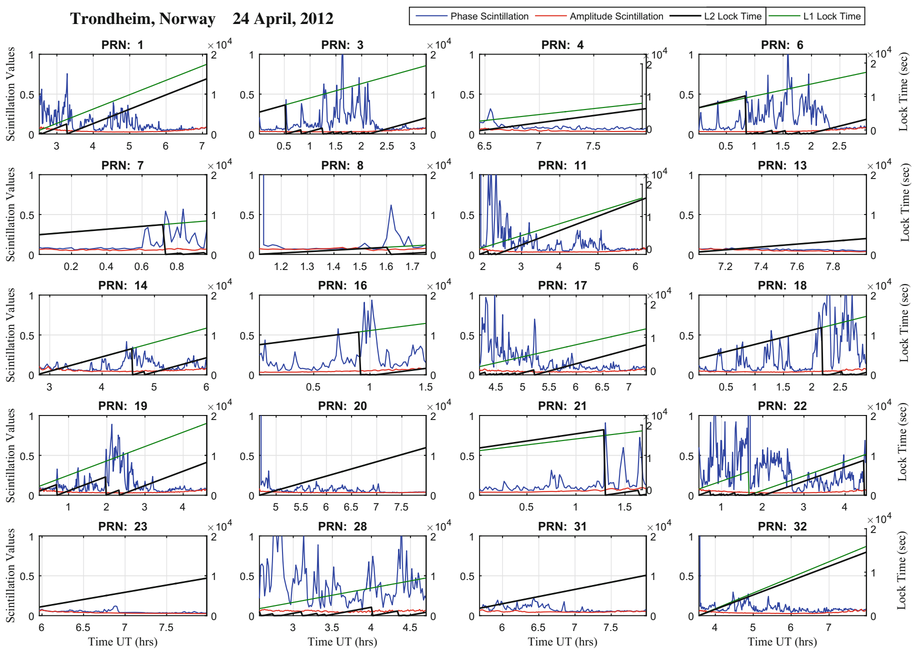

Fig. 5. Loss of signal lock by the tracking loop of the GPS receiver at the $L1$ and $L2$ frequencies for the satellites that were present between 00:00 to 09:00 UT.

is the C/N_o graph of the signal. The frequent loss of lock at the $L2$ frequency means unavailability of the navigation service during the time when the tracking loop is in reacquisition state after loss of lock. It is to mention that the $L2$ signal is used by the military for surgical and war related activities and for carrying out space based operations. Unavailability of the navigation services at the $L2$ frequency can affect the strategic activities of a nation and can lead to serious problems for the military and for carrying out space operations.

Figure 5 shows the loss of lock at the $L1$ and the $L2$ signals on all the satellites that were present between 00:00 to 09:00 UT. Some of the satellites were present only for a short period of time while others for a longer period of time. Strong phase scintillation was observed on some of the satellites such as PRN 3, 11, 16, 17, 18, 19, 22 and 28 whereas the other PRN's faced weak to moderate scintillation. It should be noted that the scintillation may not occur at all the satellites with equal intensity because only those satellites are disturbed which passes through the ionospheric irregularities which is a random occuring phenomenon due to the random movement of free electrons in a grouped form. Table 1

Table 1. Loss of Lock at the $L1$ and $L2$ frequency signals on the satellites that were present between 00:00 to 09:00 UT during the geomagnetic storm.

PRN	# of Loss of Lock at L1 frequency	# of Loss of Lock at L2 frequency
1	0	1
3	0	10
4	0	0
6	0	9
7	0	2
8	0	1
11	0	4
13	0	0
14	0	2
16	0	2
17	0	9
18	0	10
19	0	3
20	0	0
21	0	2
22	1	14
23	0	0
28	0	10
31	0	0
32	0	0

highlights the total number of loss of lock for each of the satellite in Fig. 5. It can be observed in Table 1 that the GPS receiver continuously lost lock to almost all the satellites at the $L2$ frequency but only PRN22 lost lock at the $L1$ frequency. The reason for the $L2$ signal being more susceptible to the ionospheric scintillation is due to its critical frequency close to the critical frequency of the ionospheric layer. The amplitude scintillation along with phase scintillation can cause more harm and has the ability to affect all kind of satellite communications as it not only affects the tracking loop but also introduces signal fading [14].

4 Scintillation Mitigation

The amplitude scintillation is more dominant at low latitudes and since most of our receivers are installed at high latitudes so, this paper will focus on mitigating the effects of scintillation for high latitude regions only. The scintillation effects on the navigational receivers can be mitigated by using the tracking phase jitter approach as suggested by [6, 12]. The phase jitter is the standard deviations of the phase fluctuations in the incoming signal. This approach updates the tracking loop parameters during the runtime when the signal tracking is in process by increasing or decreasing the noise bandwidth of the phase locked loop (PLL). [6, 12] methods estimates the tracking phase jitter using the formula given in (11). Once the tracking phase jitter is estimated, it can then be used to update the tracking loop parameters of a receiver either by using the software receiver or by using hardware modifications in a receiver [15] which could be able to update the tracking parameters during run time.

$$\sigma^2_{\phi e} = \frac{\pi T}{k f_n^{p-1} \sin\left(\frac{(2k+1-p)\pi}{2k}\right)} + \frac{\bar{B_n}}{C/N_o} \times \left[\frac{1}{1-S_4^2} + \frac{1}{2T_I C/N_o(1-3S_4^2+2S_4^4)}\right] + \sigma^2_{\phi osc} \quad (11)$$

where p is the phase power spectral density (PSD), T is the spectral strength of the phase PSD at 1 Hz, B_n is the noise bandwidth, f_n is the tracking loop natural frequency, k is the loop filter order and $\sigma_{\phi osc}$ is the phase variance due to oscillator noise. The advantage of using [6, 12] method is that the spectral parameters can be estimated using the amplitude and phase scintillation which was not possible by using these two parameters.

5 Conclusion

This paper has discussed the effects of the ionospheric irregularities also known as ionospheric scintillation on the navigational receiver performance using the GPS data from the high latitude regions. It is observed that the navigational receivers at high latitudes during the disturbed ionosphere are mostly affected by the phase scintillation which introduces rapid fluctuations in the phase of the received signal resulting in loss of lock at the tracking loop of the receiver due to cycle slip. During a geomagnetic storm, the irregular ionosphere was acting as the main cause of non-functionality of the receiver. It has been suggested in this paper that the effects of scintillation particularly phase scintillation can be mitigated by estimating the tracking phase jitter of the received signal which is not only simple in terms of implementation but can be used both in hardware or software receivers or a combination of both.

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