Regionally based alarm index to mitigate ionospheric scintillation effects for GNSS receivers

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Abstract

An approach to mitigate the effect of ionospheric scintillation on GNSS (Global Navigation Satellite System) users in the European region using TEC (total electron content) at 1 Hz rate is presented. The TEC in the study is derived using raw GPS (Global Positioning System) observations obtained from the EUREF networks. The study also presents derivation of a geographic mesh-map warning of the expected standard deviation of phase jitter in receiver carrier tracking loops, information which would help to mitigate scintillation effects in GPS software receivers.

1. Introduction

According to Yeh and Liu (1982), ionospheric scintillation can be modeled based on a phase changing irregular screen which diffracts the wave while propagating through it. The distortion of the wavefront results in constructive or destructive interference of different “wavelets” at a ground-based receiver resulting in amplitude fading and phase changes. The rapid fluctuation in the phase of the received signal can stress the PLL (phase-locked loop) while it is tracking the signal. Neglecting the effect of the geomagnetic field and collisions, the phase advance of the GNSS (Global Navigation Satellite System) signal along the line of the complete (assumed straight line) path through the ionosphere can be determined as given by equation (1).

\[ \phi = \frac{q^2}{2\varepsilon_0 m_e c f^2} \int_{l_{path}} n_e dl \]  

(1)

where \( q \) is charge of electron, \( m_e \) mass of electron, \( \varepsilon_0 \) permittivity of free space, \( c \) the speed of light in vacuum, and \( f \) the carrier frequency in Hz; \( \int_{l_{path}} n_e dl \) is the TEC where \( n_e \) is the electron density at any point distance \( l \) along the length of the satellite to receiver path. Inserting the numerical values of the physical constants in equation (1) yields the phase of the GNSS signal as given in equation (2), where it can be seen that the phase depends upon the TEC for the path

\[ \phi = \frac{40.3}{cf} \text{TEC} \]  

(2)

and can be measured experimentally using equations and observables as given below,

\[ \text{TEC} = \frac{f_1^2 f_2^2}{40.3 (f_2^2 - f_1^2)} (P_1 - P_2) \] 

(3a)

\[ \text{TEC} = \frac{-f_1^2 f_2^2}{40.3 (f_2^2 - f_1^2)} (\Phi_1 - \Phi_2) \] 

(3b)

here \( f_1 \) and \( f_2 \) are L1 and L2 GPS frequencies, pseudoranges (\( P \)), and phase observations (\( \Phi \)) for the corresponding frequencies. During ionospheric storms, time-varying ionospheric irregularities which drift through the ionosphere with velocities up to about 1000 m/s alter the TEC values, so altering the received phase as given by equation (2). In the last two decades, some studies [Pi et al., 1997; Basu et al., 1988, 1999; Beach and Kintner, 1999; Mendillo et al., 2000; Krankowski et al., 2005; Alfonsi et al., 2011; Tiwari et al., 2013a; Pi et al., 2013] have shown strong correlation of the time derivative of TEC with scintillation indices. The scintillation indices also quantify the level of stress in the tracking loop. In the GISTM (GPS Ionospheric Scintillation and TEC Monitoring) receivers, the 50 Hz ADR (accumulated Doppler range) samples, output from PLL, are used for scintillation index estimation; the higher the phase scintillation, the higher the PLL stress. In order to only measure the ionospheric scintillation effect, the 50 Hz ADR samples require detrending which eliminates the lower fading frequencies due to satellite motion, receiver and satellite
clock drift, and, at least partially, the multipath. This is achieved when, for example, the ADR is detrended using a sixth-order Butterworth high-pass filter with a 0.1 Hz cutoff frequency [Van Dierendonck et al., 1993].

Depending on the sensitivity of the receiver, a threshold value of power is required for any GPS receiver to lock a satellite; the quality of the received signal can be represented in terms of C/No (Carrier to Noise ratio). The typical value of C/No for a GPS receiver acquisition is 33 dB-Hz, while between 26 and 30 dB-Hz of C/No is required to maintain lock. The receiver correlates the carrier and code replicas with the incoming signal to compute I and Q pairs of the signal over 1 ms. The I and Q pairs are used to compute the WBP (wideband power) and NBP (narrowband power) over 20 ms as defined in equations (4a) and (4b), respectively [Van Dierendonck et al., 1996].

$$WBP = \sum_{i=1}^{20} (I_i)^2 + (Q_i)^2$$  \hspace{1cm} (4a)

$$NBP = \left( \sum_{i=1}^{20} I_i \right)^2 + \left( \sum_{i=1}^{20} Q_i \right)^2$$  \hspace{1cm} (4b)

The amplitude fluctuation can be measured in terms of the amplitude scintillation index which depends upon the received signal strength/intensity ($I = A^2 / 2$). The signal strength as in equations (4a) and (4b) can be determined using detrended data of WBP and NBP which can be accomplished by using a sixth order Butterworth filter with 0.1 Hz cutoff frequency [Van Dierendonck et al., 1993]. The signal strength can then be found using equation (5), and then the amplitude scintillation (S4) can be obtained from equation (6) [Van Dierendonck et al., 1993].

$$I = \frac{NBP - WBP}{(NBP - WBP)_{LPF}}$$  \hspace{1cm} (5)

$$S4 = \sqrt{\langle I^2 \rangle - \langle I \rangle^2} / \langle I \rangle^2$$  \hspace{1cm} (6)

The $<.>$ denotes the mean of the corresponding value for a 1 min time interval. To study the effect of the ionosphere on a GPS receiver, the S4 index can be used. Correspondingly, the phase scintillation is quantified by using the phase scintillation index which is usually obtained from the detrended carrier phase [Van Dierendonck et al., 1993; Forte and Radicella, 2002]. The C/No can be computed using the WBP represented as shown in equation (7) [Kintner et al., 2007]

$$C/No = 10 \log \left[ \left( \frac{WBP}{\eta} - 1 \right) \cdot 50 \right]$$  \hspace{1cm} (7)

where $\eta$ is the noise term and is assumed to be the addition of the noise of the signal and the replica signal. The constant 50 in equation (7) is the sampling rate, here assumed to be 50 Hz. The above equation will be used in computing the threshold for the receiver locking. The C/No is the deciding parameter for signal acquisition, and it depends on the WBP as shown in equation (7). As the amplitude and phase changes resulting from scintillation are random, they cannot be corrected, and thus, the best policy is to consider a mitigation method. During the scintillation, the intensity of a received GPS signal can be reduced so that it sometimes falls below the sensitivity (threshold) of the receiver. The extra disturbance of the phase of the signal, also associated with the scintillation, can cause the carrier tracking loop of a GPS receiver to lose lock so that the pseudorange from that satellite cannot be utilized in the receiver position determination. This then can have very serious consequences, e.g., in aviation and marine navigation, and can introduce positional errors in geodetic surveying. The next section discusses the carrier tracking loop of a generic GPS receiver and the effects of ionospheric scintillation on the carrier tracking loop.

2. Ionospheric Scintillation and Generic GPS Receiver

In the GPS receiver, the front-end down-converts the GPS frequency to a lower intermediate frequency (IF) which is then used in acquisition and demodulation of the navigation data stream in the code and carrier tracking loops in order to determine the receiver’s position. Equation (8) represents the GPS signal (single-frequency CA (Coarse Acquisition) code) $S(t)$ at the IF frequency without any additional noise or
ionospheric scintillation. However, during ionospheric scintillation, altered phase and/or amplitude distortions the GPS signal $S(t)$, modifying it to the modified signal $R(t)$ as shown in equation (9):

$$S(t) = AC(t)D(t)\cos \left(\alpha_{0}\ell t + \phi\right)$$

(8)

where $A$ is the received amplitude, $C(t)$ is $C/A$ code, $\alpha_{0}\ell$ is the down converted (from L1/L2) carrier frequency, $D(t)$ is the navigation data bit at a 50 Hz sample rate, and $\alpha_{0}\ell t + \phi$ together is the nominal phase.

$$R(t) = A'C(t)D(t)\cos \left(\alpha_{0}\ell t + \delta\phi\right)$$

(9)

where $A'$ and $\delta\phi$ characterize the modified amplitude and extra carrier phase perturbation that can result from ionospheric scintillation. The $R(t)$ signal in equation (9) passes through the code and carrier tracking loop, where the $C/A$ is removed using the code delay loop. During phase scintillation, $\delta\phi$ (the phase perturbation in equation (9) can be very large and sometimes, according to the Thumb rule in [Kaplan and Hegarty, 2006], cycle slips occur when $\delta\phi$ exceeds a given threshold, i.e., the standard deviation of $\delta\phi$ (1 $\sigma$), phase jitter above $15^\circ$ ($\sigma_{\delta\phi} > 15^\circ$). The level can, however, vary with the bandwidth of the PLL which can be appropriately altered if the scintillation level is known or can be at least be approximately predicted by, for example, using a regional alarm index. Although it is not possible for a generic GPS receiver to mitigate scintillation effects on its own, studies have shown that ionospheric scintillation can be mitigated using GPS software receivers [Ganguly et al., 2004; Tiwari et al., 2011] which basically update their loop parameters, e.g., increasing the loop bandwidth based on some prediction model such as Wide Band Modeling (WBMOD) or a regional alarm index [Tiwari et al., 2011].

2.1. Effect of Scintillation on Carrier Tracking Loop

The performance of a GPS receiver depends upon phase error measurements because it is directly related to the tracking threshold; if the measured phase error exceeds the tracking threshold then the receiver loses lock. In Kaplan and Hegarty (2006), the major sources of phase error are stated to be the phase jitter and dynamic stress error and, as a rule of thumb, the threshold $3\sigma$ jitter given in equations (10a) and (10b) must not exceed one fourth of the pull-in of the PLL discriminator as

$$3\sigma_{PLL} = 3\sigma_{j} + \theta_{e} \leq 90^\circ$$

(10a)

$$3\sigma_{PLL} = 3\sigma_{j} + \theta_{e} \leq 45^\circ$$

(10b)

where $\sigma_{j}$ is the $1\sigma$ phase jitter from all sources and $\theta_{e}$ is the dynamic stress in terms of threshold values. The pull-in range for dataless is $360^\circ$ and for data modulated is $180^\circ$; therefore, the $1\sigma$ threshold for dataless is $90^\circ$ and $45^\circ$ for data modulated. Hence, $\sigma_{PLL}$, the threshold for the arctangent discriminator is given by

$$\sigma_{PLL} = \sqrt{\sigma_{PLL}^2 + \sigma_{osc}^2} \leq 15^\circ$$

(11)

where $\sigma_{PLL}$ is the $1\sigma$ thermal noise, $\sigma_{j}$ is the $1\sigma$ vibration-induced oscillation, and $\sigma_{osc}$ is the Allan variance-induced oscillator jitter. In the above equation, the phase jitter due to scintillation was not specifically considered although the effects of ionospheric scintillation are one of the major sources of error in carrier tracking of any GPS receiver [Conker et al., 2003; Hegarty, 1997; Knight and Finn, 1998]. Further, Tiwari et al. [2011], Forte [2012], and Aquino and Sreeja [2013] show that the calculated PLL error, using the Conker et al. [2003] formula due to phase and amplitude scintillation, is significant. The relationship between amplitude and phase scintillation and tracking error variance at the output of the PLL was derived by Hegarty [1997] and Knight and Finn [1998], and is given in equation (12):

$$\sigma_{\phi}^2 = \sigma_{\phi_2}^2 + \sigma_{\phi_4}^2 + \sigma_{osc}^2$$

(12)

where $\sigma_{\phi}^2$ is the tracking error variance; $\sigma_{\phi_2}^2$ is error variance component related to phase scintillation; $\sigma_{\phi_4}^2$ is error variance component related to thermal noise and intensity scintillation, and $\sigma_{osc}^2$ is the error variance component from oscillator noise. The tracking error variance in equation (13) is defined in Conker et al. [2003], who, considering phase and weak amplitude scintillation ($S_{sc} < 0.707$), derived the thermal noise tracking error in the presence of scintillation as given in the second term of equation (13).

$$\sigma_{\phi}^2 = \frac{\pi T}{kT_{n0}^2 \sin \left(\frac{2k+1-\rho\ell}{2k}\right)} + \frac{Bn}{(C/2)A} \left[1 + \frac{1}{2(C/2)A} \left(1 - 2S_{sc}^2 L_{1}\right)\right] + \sigma_{osc}^2$$

(13)
where $Bn$ is the bandwidth in a generic GPS receiver, with third-order PLL, the $Bn$, noise bandwidth ranging between 10 and 15 Hz [Van Dierendonck et al., 1996]. $S_a$, the amplitude scintillation index, must have a value less than 0.707 for the formula to be valid. The prediction integration time is $\eta$ and is equal to 0.02 s for PLL tracking. The phase scintillation is obtained from the power spectra parameters ($T$, $p$) of the carrier phase as employed in, e.g., Conker et al. [2003] and Rino [1979]. In the carrier tracking loop, the numerically control oscillator generates the replica of the incoming carrier wave, and the discriminator compares the incoming and the replica carrier waves. The output of the discriminator is fed to the low-pass filter to reduce the phase error in the loop. Usually, the PLL filter takes time to minimize based on the phase error or variance. If the variance of the phase error is large, then the time to lock will be larger, and during conditions where the variance of phase error exceeds the threshold value, the PLL may lose lock. During an ionospheric storm, the rapid random fluctuations in electron density increase the phase error in the PLL. The PLL filter takes a longer time to minimize and finally causes loss of lock if it crosses the threshold time lock. In equation (13), it can be seen that, $S_4$ and the spectral parameters $T$, $p$ are required in order to estimate phase jitter, which are not available in normal generic and surveying GPS receivers although C/No can be used to derive thermal phase jitter but not phase jitter due to phase scintillation. In this study, the time derivative TEC index derived in Tiwari et al. [2013a] is used to estimate phase jitter due to phase scintillation (discussed in next section). Furthermore, a regional area mitigation approach is also proposed using the expected standard deviation of PLL error mapped into a latitude-longitude ($10^\circ \times 5^\circ$) mesh of grid blocks for the European region, which can help users to update their tracking parameters for robust tracking.

3. Experimental Setup and Methodology

In this study, GPS data at 1 Hz archived from the EUREF network stations for deriving TEC values over Europe have been used in deriving an analogous phase scintillation index which is further used in the estimation of the expected PLL error for a generic GPS receiver with given specification: third-order PLL and 15 Hz bandwidth. The overall method is executed in four steps: (i) estimation of TEC at a 1 Hz rate from the EUREF network of GPS receivers, (ii) estimation of the analogous phase scintillation index using the TEC for every minute, (iii) determination of the expected PLL error variance using the analogous phase scintillation index, and (iv) determination of the expected values of the PLL error over a latitude-longitude area region divided into $10^\circ \times 5^\circ$ (longitude x latitude) area grid blocks each averaged over 5 min. These four steps are discussed below.

Essentially, the program designed in this study requires raw observations (phase and pseudorange) and the ephemeris files as input. First, the TEC is estimated using equation (3a) after which the observation data passes through the quality control processing unit which includes cycle slip detection in the phase observation. The phase measurements are susceptible to cycle slips which can be due to strong ionospheric scintillation. At high latitudes, this generally results from small-scale ionospheric electron density irregularities causing rate of change of phase variations, which exceed the tracking loop bandwidth. Generally, more cycles slips are observed on L2 in comparison to L1. In order to estimate TEC using equation (3b), the cycle slips have to be detected and corrected, if possible. The Wideline detection criterion is used for cycle slips detection [Blewitt, 1990] for the case that the cycle slip occurs in only one of the L1 and L2 signals. It is corrected based on the trend (we used Kalman filter) of the collected observations except in case of phase jumps in the L1 or L2 phase observation that last for 5 s or more as then the data are discarded. The differential code biases for all satellites are also provided for further adjustment. Tiwari et al. [2013a] derived an analogous phase scintillation index, $\sigma_{\psi\theta}$ given in equation (14).

$$\sigma_{\psi\theta} = \sigma(\chi(M), v_p) \times \sigma_{\text{VTEC}'}_{\text{HPF}}$$

$$\sigma(\chi(M), v_p) = \frac{2\pi S 40.3}{c f} \left(\chi(M), v_p\right)$$

$$\sigma_{\text{VTEC}'}_{\text{HPF}} = \left[\frac{1}{n-1} \sum_{i=1}^{n} \text{VTEC}_{\text{HPF}} - \text{VTEC}_{\text{HPF}}\right]^{1/2}$$

where $\sigma(\chi(M), p)$ is the elevation weighted function given in equation (15), and $S$ is a scaling constant of 0.003 (this is user defined based on the application), $\chi(M)$ is a mapping function based on Satellite
Vehicle (SV) elevation angle at two consecutive epochs, \( \sigma_{\text{VTEC}_{\text{rot}}} \) is the normalized standard deviation of the high-pass filtered Rate of change of TEC (ROT), and \( \nu_p \) is the radial ionospheric Pierce Point (IPP) velocity.

The estimated index is derived from EUREF network of receivers, the receiver biases are different for different receivers, and the index is used to alert the user of possible PLL error during the scintillation period. But for Precise Point Positioning or for surveying application where centimeter level of accuracy is needed in positioning, one can derive the \( S \) scaling constant for an individual receiver using the least squares fitting technique for a few days of data. This new index uses a high-pass filtered ROT collected at a 1 Hz rate which shows a good correlation with the standard phase scintillation observed during geomagnetic storms at high latitudes and was found to be well correlated with the spectral parameter \( p \) (slope of the phase Power Spectral Density (PSD)) for a range of values of the \( Kp \) index [Tiwari et al., 2013b]. The diurnal and seasonal variation of the analogous phase scintillation index also seemed to be well correlated with \( p \) for a 1 year data set collected at Trondheim, which is consistent with observations of Wernik et al. [2004].

In the phase jitter estimation using the Conker et al. [2003] formula, the spectral parameters \((p, T)\) are required for the estimation of the PLL variance. These values can either be derived from the psd of the 50 Hz raw data \((p \ the slope of phase psd when plotted on log-log axes and \( T \) its magnitude at 1 Hz) or using scintillation indices [Strangeways, 2009] which greatly reduce the processing time by eliminating the need for all the fast Fourier transforms necessary for determining the spectral parameters directly in the frequency domain. However, the processing time could be reduced even further if the need to determine the spectral parameters was obviated altogether. As an application of the analogous phase scintillation index, Tiwari et al. [2013b] used estimated analogous scintillation phase index data from a NovAtel GISTM receiver installed at Trondheim and derived a model for the expected PLL phase variance of a generic receiver during moderate to strong phase scintillation condition given by equation (17).

\[
\sigma_{\phi p}^2 = r \times \sigma_{\text{VTEC}_{\text{rot}}}^2
\]  

where \( r \) is the scaling factor derived from straight line fitting of \( \sigma_{\text{VTEC}_{\text{rot}}}^2 \) with the PLL phase jitter due only to the phase scintillation as determined using the Conker et al. [2003] formula, then \( \sigma_{\phi p}^2 \) can be obtained from equation (17). In this model, the estimated PLL variance is for high latitudes and hence rather weak amplitude scintillation can be assumed which is considered to be a valid assumption for this case commensurate with the observations presented in Aarons [1997], Coker et al. [2004], Tiwari et al. [2010], and many others. In Aquino and Sreeja [2013], the second-order polynomial was found to be the best fit for jitter with just the phase jitter, although this phase scintillation would be correlated with other parameters such as amplitude scintillation, \( C/No \), and oscillator noise. Thus, it may not be an optimal fitting for determining a model for phase jitter for a range of these correlated parameters.

According to equation (12), the thermal phase jitter depends on \( S4 \) whereas in Van Dierenendock et al. [1993], the \( S4 \) parameter depends upon the WBP and NBP given in equations (4a) and (4b), respectively; and in Kaplan and Hegarty [2006], \( C/No \) only is considered sufficient for the estimation of thermal phase jitter. The \( C/No \) measures the degradation of signal intensity due to extra modulation in the received intensity and is alone a sufficient parameter for this estimation for high-latitude locations where only weak amplitude scintillation is observed. Figure 1 (left) shows the standard deviation of thermal phase jitter (third-order loop, \( Bn = 15 \, \text{Hz} \)) obtained by using second term of equation (13) with \( S4 = 0.3 \) and without amplitude scintillation. The zoomed-in plot shows how close the values of phase jitter are with \( S4 = 0.3 \) and without amplitude scintillation for \( C/No \) values up to 30 dB, while Figure 1 (right) shows the difference between the Conker et al. [2003] and Kaplan and Hegarty [2006] models where closeness of phase jitter values with \( S4 = 0.3 \) level scintillation and without is quite apparent. This is the usual case for the high-latitude region.

If the \( C/No \) measurements are not recorded, then the user can use an estimated \( C/No \) for a surveying antenna using equation (19) [Tiwari et al., 2013b].

\[
\sigma_{\phi p}^2 = \frac{Bn}{1 + \frac{1}{2 \nu_p C/No VTEC_{ IPP}}}
\]

\[
\sigma_{\phi p}^2 = \frac{1}{c} (C/No)^{a-1/\c} + b
\]

where \( a, b, c \) are constants \((a = 51.94, b = 0.0093, c = 0.7305)\) and \( E \) is the elevation angle. The constants are derived for different loop orders. The oscillator noise, \( \sigma_{\phi osc}^2 = 0.01 \, \text{rad}^2 \), is taken to be the same as
employed by Hegarty [1997]. Using equation (13), the phase jitter due to amplitude scintillation, oscillator, and analogous phase scintillation (used to replace the standard phase scintillation index) can be obtained as

$$\sigma^2_\phi = \sigma^2_\phi^p + \sigma^2_\phi^T + \sigma^2_\phi^{osc} \quad (20)$$

$$\sigma^2_\phi = \rho \times \sigma^2_{TEC_{HPF}} + \frac{Bn[1 + \frac{1}{2(C/NO_{L1} - C/A)}]}{(C/NO_{L1} - C/A)} + \sigma^2_{\phi^{osc}} \quad (21)$$

The above PLL phase variance ($\sigma^2_\phi$) can be used in a software receiver for updating the tracking loop parameter or by using the weighted covariance model discussed in Aquino et al. [2009].

The regional alarm index $\sigma_{\phi R}$ is obtained for alerting GNSS users and is derived from the analogous phase scintillation index as given in equation (22)

$$[\sigma_{\phi R}]_{ij} = \sum_{n=1}^{\text{nsat}} \sum_{k=1}^{k_{ij}} \sigma_{\phi R}(n, t) : \begin{cases} [\text{Lat}_{\phi R}]_{ij} = (65 + (k \times i) - k) : [65 + (k \times (i + 1)) - k] \\ [\text{Lon}_{\phi R}]_{ij} = (-15 + (k \times j) - k) : [-15 + (k \times (j + 1)) - k] \end{cases} \quad (22)$$

where $i$ and $j$ define the region, $k$ represents 5 min data samples observed from the SV, and the upper and lower latitudes are 65° and 35°, respectively, and similar for longitude. The epochs ($k$) and latitude and longitude grid can be user defined; the smaller the grid size, the better the resolution although this of course also requires a sufficiently dense spatial distribution of the GPS receivers in the given network.

4. Result and Discussion

In order to validate the proposed model for phase jitter using TEC, two geomagnetic storms events observed on 24 April 2012 and 17 March 2013 were selected. Since the $Kp$ index is the global index for representing the level of geomagnetic storm, it may not be optimum as a measure of localized geomagnetic activity. In this study, the Earth’s magnetic field from Dombas (62.07°N, 9.11°E) is used which is close to the installed GISTM receiver at Trondheim (63.41°N, 10.4°E) and is used for measuring the storm intensity. On 24 April 2012, as can be seen in Figure 2, the Earth’s $H$ and $Z$ magnetic field components show a strong fluctuation between 00:00 and 04:00 UT which results from a geomagnetic storm near Dombas in the auroral region. During such a storm, the transionospheric GPS signal suffers a significant amount of phase scintillation [Skone et al., 2008, 2009; Tiwari et al., 2010] and the resulting anticipated effect on the carrier tracking loop of a GPS receiver. Thus, modeled phase jitter using the TEC derivative and phase jitter derived from the Conker et al. [2003] formula are investigated in the time domain for the same period of the storm.

In Figure 3, the modeled phase jitter is indicated as a solid red line, while the Conker formula-derived phase jitter is shown as a solid blue line. These are shown for PRNs 03, 06, 11, 14, 18, 19, 20, and 21 with a 20° elevation cutoff being applied to all the visible PRNs. The effect of storm can easily be seen in Figure 3. The storm was strong between 00:00 and 03:00 UT with a correspondingly large PLL error. The pattern in the fluctuation of the modeled phase jitter and that determined using the Conker et al. [2003] formula is very
Figure 2. Earth magnetic field measurements using the fluxgate magnetometer at Dombas (62.07°N, 09.11°E) show the magnetic storm started at midnight on 24 April 2012.

A similar geomagnetic storm was recorded on 17 March 2013 and is employed for studying the effectiveness of the modeled phase jitter using TEC. Figure 4 shows the Earth’s magnetic field strength at Dombas, and it can be seen from the figure that a negative fluctuation in the $H$ component was recorded with a large value at 18:00 UT but with only small values after 20:00 UT until strong again around 22:00 UT. In order to study the effect of the geomagnetic storm, the modeled and Conker et al. estimated phase jitters from 17:00 to 23:00 UT are presented in Figure 5. From 17:00 to 17:55 UT there was no evidence of a geomagnetic storm, but the modeled and Conker et al. [2003] phase jitters at 18:00 UT show a strong jump which is a clear indication of effect of a geomagnetic storm on the carrier tracking loop. The pattern of the modeled phase jitter is similar to that derived using the Conker et al. [2003] formula, but, similar to the previous result, the...
modeled phase jitter seems to be an overestimate, and there are many cases where the modeled phase jitter had a high value. Especially for PRN 21, this could then cause a false alarm but this is difficult to conclude because GISTM receiver may lose lock during strong scintillation, and in that situation, the GISTM receiver can indicate very high scintillation during the reacquisition period resulting in outlier which should be ignored. Also, during the same period, other locked PRNs show strong modeled phase jitter which is consistent with the Conker et al. [2003] phase jitter determination. This implies that the model phase jitter

Figure 4. Earth magnetic field measurements using the fluxgate magnetometer at Dombas (62.07°N, 09.11°E), close to Trondheim, show the effect of a magnetic storm which started at 18:00 UT on 17 March 2013.

Figure 5. The red lines represents the modeled PLL jitter using the TEC derivative time series for a GPS receiver (PLL $B_n = 15$ Hz, third order), the blue lines are the determined PLL error obtained from Conker et al. [2003] formula using the Strangeways [2009] method of spectral parameter determination and the appropriate elevation angle.
is useful for measuring the level of effect of geomagnetic storm on carrier tracking loops. The effect of a second storm between 22:00 and 23:00 UT can also be seen in the modeled phase jitter.

In addition to the case studies discussed above, a statistical study was also made for further validation. The modeled and Conker et al. [2003] calculated phase jitters are estimated for 1 year (October 2011 to September 2012) from Trondheim. To obtain these results, an elevation mask of 20° and an SV lock time more than 120 s were employed; phase scintillation values above 2.5 rad were considered as outliers and ignored. The data points are further arranged into two sets of categories, a strong geomagnetic storm ($K_p > 5$) data array and a moderate geomagnetic storm ($K_p = 5$) data array. The modeled and Conker et al. [2003] phase jitters were correlated for both conditions. Figure 6 (left) shows the correlation when $K_p > 5$ (considered strong geomagnetic storms) and the 95% confidence interval of line fitting is indicated as the red solid line with a correlation of 76.61%. Thus, the correlation between the phase jitters is very good, the best fit is found in the region between 8° and 12° so that the probability of getting a false alarm is low. Similar results are seen for the data set when $K_p = 5$, although the correlation coefficient of 65.58% is smaller than that for the $K_p > 5$ data arrays. The PLL error is susceptible to many sources of errors, the Conker method is an analytical method based on the spectral parameters $T$, $p$, and $S_4$. In this work, $T$ and $p$ parameters are computed using phase and amplitude scintillation indices as input parameters required for the [Strangeeways, 2009] model; in GISTM receivers, there are some phase scintillation (phi60 ≥ 2.5) outliers which are discarded while computing $T$ and $p$ parameters, but the new index can still be computed but shows an overestimated value of PLL error which is considered to be good for alerting the user.

4.1. Regional Alarming Index for Ionospheric Threat

The standard deviation of the PLL error of the installed NovAtel GPS receiver (technical specification of carrier tracking loop: third order, 15 Hz bandwidth) at Trondheim (62.6°N, 10.41°E) is compared under...
Figure 8. (top) The standard deviation of estimated PLL error (green solid circles) for the NovAtel GPS receiver observed when Kp was above 5 at Trondheim for 1 year, blue solid circles show the analogous phase scintillation index for the same time period. (bottom) The same set of observation at Kp = 5.

two cases: phase jitter variation determined using the phase scintillation $\sigma_\phi$ and amplitude scintillation (S4) indices, and phase jitter variation determined using the analogous phase scintillation index ($\sigma_{\phi a}$) and amplitude scintillation index (S4). In Figure 7 (left), the standard deviation of the PLL error is shown with respect to $\sigma_{\phi a}$ and S4; it is clear from the figure that the influence of phase scintillation on the PLL error is significantly larger than that of the amplitude scintillation, and this result is also consistent with the finding in Skone et al. [2005]. Figure 7 shows the standard deviation of the PLL error, for data collected from Trondheim (62.6°N, 10.41°E) on 17 March 2013 using a NovAtel GISTM receiver, for S4 and the standard scintillation index (Figure 7, left), and S4 and analogous phase scintillation index (Figure 7, right). According to the results in this figure, moderate (S4) and moderate phase scintillation can lead to 11° phase jitter, while combined moderate (S4) and moderate to strong phase scintillation can lead to rather high values of the phase jitter that can exceed the 15° (1\sigma) phase jitter threshold [Kaplan and Hegarty, 2006] which can lead to cycle slips. In Figure 7 (right), the dependence of the phase jitter is shown as determined using $\sigma_{\phi a}$ and S4, the obtained pattern of phase jitter variation seems to be consistent with the results observed in Figure 7 (left) based on (S4) and the analogous index. However, based on the similar distributions and consistent correlation of the modeled and analytical Conker et al. [2003] determined phase jitters, it is clear that the analogous phase scintillation index is a reliable phase scintillation indicator and so could be used as the basis of a regional alarm index. Thus, the analogous phase scintillation index derived from the TEC 1 Hz data is a promising tool to indicate the level of ionospheric threat. Similar to our high-pass filter TEC based index and its correlation with scintillation Alfonsi et al. [2011] also showed how rate of change of the ROT together with its RMS value can be used to indicate scintillation conditions. The expected correlation between both ROT and RMS of ROT with scintillation is presented: the study highlights (i) high ROT and high RMS of ROT shows predominate phase and amplitude scintillation, (ii) high ROT and low RMS of ROT also represents high scintillation, while low ROT and low RMS of ROT do not indicate scintillation.

Figure 8 presents two sets of observations for two different Kp values, the analogous phase scintillation index and the determined phase jitter observed for a period of 1 year at Trondheim for Kp > 5 in Figure 8.
Figure 9. EUREF network, red solid triangles are GPS stations capable of recording raw observations at 1 Hz. Grid of $10^\circ \times 5^\circ$ considered, the numeric value in each grid is the number of satellites viewed above $20^\circ$ elevation.

Based on the investigation made, it is found that the analogous phase scintillation can be used for alerting probable ionospheric threat to a ground-based GPS receiver at a high latitude in near real time.

4.1.1. Regional Alarming Index for European Region
For a regional alert in the European region, GPS observations from the EUREF network were used in estimating the analogous phase scintillation; the solid red triangles in Figure 9 indicates the geographic location of GPS stations capable of recording raw phase and code observations for both frequencies L1 and L2 at 1 Hz.

The EUREF network has a dense network of dual-frequency GPS receivers; each receiver is capable of recording observations at 1 Hz. As discussed in the experimental setup methodology section, the mesh grid of $10^\circ \times 5^\circ$ (longitude by latitude) producing 24 grid blocks delineated for the selected area map, i.e., $35^\circ$ to $65^\circ$ N and $-15^\circ$ to $25^\circ$ E. The alarming regional analogous index is computed for every region by averaging the analogous phase scintillation indices for all the satellite paths existing for all the receivers in the region. Each region is selected to include a sufficient number of receiving stations to ensure good reliability of the determined regional analogous index. The alarming regional analogous phase index is the average of all the analogous phase indices observed within a 5 min period for the particular block. The time average of 5 min is employed based on the assumption that the ionosphere does not change significantly in this time period. In Figure 9, the number given in each grid block represents the minimum number of GPS satellites visible on average at any location inside the grid block. The analogous phase index is derived every minute so that five such indices can be derived for every visible satellite in the averaging period. Then the total number of observations is 5 times the sum of the number of visible satellites at each receiver location in the respective grid block. The arithmetic mean of the analogous phase scintillation array indices in each region is then termed the regional analogous phase scintillation $\sigma_{R\phi}$ and is further used in defining the ionospheric threat level. The threat level is defined based on three conditions, (i) $\sigma_{R\phi} < 0.2$ rad (green) represents no ionospheric threat, (ii) $0.2 < \sigma_{R\phi} < 0.4$ rad (yellow to amber) represents a moderate level of threat, (iii) $0.4 < \sigma_{R\phi}$ rad (red) represents a severe ionospheric threat and probability of cycle slip occurrences.

In order to validate the above index, a network of four GISTM receivers within Europe (solid red triangles in Figure 10) is used to measure the standard phase scintillation index for the L1 frequency. Figure 10 (top row) shows phase scintillation indices recorded from the GISTM receivers binned to a grid of $10^\circ \times 5^\circ$ regions and averaged over 5 min. In order to have consistency with the derived regional analogous phase scintillation index, indices are averaged and binned in the same way; Figure 10 (bottom row) shows the regional
Figure 10. (top row) The phase scintillation index measurement from the GISTM receivers (red triangle is location of receivers) on 17 March 2013 from 18:00 to 18:25 during a geomagnetic storm period. (bottom row) The regional analogous phase scintillation index derived from EUREF GPS receiver for the same period.

analogous phase scintillation index, $\sigma_R\phi$ derived from the EUREF GPS receiver data. In Figure 10 (top row), strong phase scintillation is observed at 18:00 UT, 18:05 UT, and 18:25 UT. This is due to a geomagnetic storm which can be identified from the geomagnetic field variations in Figure 4 and lasts 25 min commencing at 18:00 UT and having a corresponding effect on the L1 signal over this period seen from the strong phase scintillation indices shown in Figure 10. The regional analogous phase scintillation index ($\sigma_R\phi$) depicted in Figure 10 (bottom row) at 18:00 UT, 18:05 UT, and 18:25 UT are well correlated with the phase scintillation observed by the GISTM receivers. Although, there is a slight difference in the modeled regional index compared with the measured scintillation, this is due to the fact that the number of observations used in the regional-based index are comparatively more than those from the GISTM network, but it is nevertheless considered to be good enough to alert the user in the given region.

Figure 11. (top row) The phase scintillation index measurement from the GISTM receivers (red triangle is location of receivers) on 17 March 2013 from 21:10 to 21:25 during a geomagnetic storm period. (bottom row) The regional analogous phase scintillation index derived from EUREF GPS receiver for the same period.
A moderate-strong level of scintillation at Trondheim is observed at 21:10 UT, 21:20, and 21:25 UT as can be seen in Figure 5, while the variation in the Earth’s magnetic field in Figure 4 is evidence of a moderate geomagnetic storm. Similar to the processes described in the previous paragraph, the measured scintillation index is obtained using the GISTM receivers and is shown in Figure 11 (top row). The regional analogous phase scintillation index is depicted in Figure 11 (bottom row) for the same time of 21:10 and 21:20 UT. The moderate level of the regional analogous phase index and scintillation at 21:25 UT can be seen to be well correlated comparing the right-hand figures in Figure 11 (top and bottom rows). The results obtained from the new index are consistent with the expected effect of geomagnetic storms and also capable of measuring the corresponding level of threat.

Considering potential applications, since these threats are produced in real time and the method based on a reliable GPS network, it can be used for alerting any GNSS users in the mapped high-latitude region to the threats. There can, however, be cases when not enough measurements are made in the grid blocks, and so for that area the derived analogous phase scintillation index is not considered reliable. Insufficient observations or lack of data in any mesh grid can lead to a false alarm and in order to avoid such a situation, we consider we need at least five observations (the threshold) in the 5 min period. In order to distinguish between a statistically reliable estimated regional analogous phase index and a nonreliable one, a grid boundary shown as a blue dotted line is included to denote this as shown in Figure 11. A minimum of five sets of observation are required for the index to be considered reliable; this helps users avoid a false alarm in that particular grid.

5. Conclusion

The variance of the dynamic phase error derived using high-pass filtering of the TEC time derivative is used in the estimation of the phase jitter due to phase scintillation and further, the expected standard deviation of the PLL phase error estimated. The modeled PLL phase error variance was well correlated with the Conker et al. [2003] derived phase jitter for measurements made during geomagnetic storms. The two selected days were based on the storms recorded on 24 April 2012 and 17 March 2013, and the effect of the auroral storms on the PLL can be identified using both models. The derived model was also verified statistically by considering 1 year of data from a high-latitude recording station; the following points are concluded based on this study:

Strong geomagnetic storm (Kp > 5): A linear correlation of modeled phase jitter was obtained using Conker’s formula; the correlation is 76.6% obtained based on a 95% confidence of linear fitting; for moderate geomagnetic storms (Kp = 5): the correlation of 65.58% was obtained. The correlation for moderate storms is weaker than for the strong storms case (65.6%) but is still quite good. The time series of modeled and Conker phase jitters are also obtained, and the similarity in the pattern of the variation of both can be seen.

A regional analogous phase scintillation index is derived using TEC at 1 Hz from the EUREF network enabling an expected variance of the phase error due to ionospheric phase scintillation. The regional analogous phase index is well correlated with the phase scintillation obtained from the GISTM receivers. Thus, this index could be useful in providing an alarm for high-scintillation receiving areas where there would be a threat to accurate GNSS positioning due to PLL phase errors or loss of lock. Considering the question of latency, first, the obtained raw observations from EUREF passes through the quality check and is then used in the TEC estimation, all done in real time. The time required for filtering the TEC derivatives is approximately 4 s. The estimation of the analogous phase index and the arithmetic mean of the analogous phase indices for one region take less than 1 s, and thus, the total latency of this determination for the whole region is less than 5 s. This could be reduced using parallel processing techniques.

The TEC derived model has a number of advantages over the Conker et al. phase jitter calculation, listed as follows: (i) for the modeled phase jitter, there is no need of 50 Hz raw observation data which reduce the computer memory required, (ii) the processing required is also reduced because it is not necessary to derive the \( T \) and \( \rho \) parameter from the slope of the phase PSD method which is computationally expensive and also is still faster even than the less computationally extensive method of finding these parameters from the two scintillation indices and estimated Fresnel frequency [Strangeways, 2009], (iii) the phase jitter over a wide region can be forecasted using a GPS network.
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