WBMod Assisted PLL GPS Software Receiver for Mitigating Scintillation Affect in High Latitude Region

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Abstract

Ionospheric scintillation occurs for transionospheric radio waves propagating through random ionospheric irregularities, which affect the phase and/or amplitude observations made by the receiver. Generally, the scintillation induces excess carrier phase jitter in the phase lock loop (PLL) of the GPS receiver, and strong scintillation can cause a conventional PLL (ATAN [arctangent method], constant bandwidth Bn = 10 Hz) to lose phase lock resulting in no GNSS signal available at that time from the satellite path(s) affected. A PLL with a larger bandwidth is one solution to mitigate this but at the expense of extra phase noise, and this may not be an optimal solution during weak scintillation conditions. This study uses a novel WBMod (Wide Band Modeling) assisted PLL for robustness of availability of GPS services with lower introduction of extra phase noise. At the initial stage, an optimal PLL bandwidth is predicted using WBMod to stabilize the PLL during strong phase scintillation. A FAB (Fast Adaptive Bandwidth) PLL is used to minimize the phase error. To investigate this approach, a realistic scintillated signal is produced using 50 Hz raw GPS signal observations (carrier phase and intensity) collected at Yellowknife (Yell, 64.48˚ N, -114.52˚ E) in a Matlab-based GPS software receiver.

1. Introduction

Measures of rapid random fluctuations in phase and amplitude of the received signal are termed phase (σ_ϕ in radians) and amplitude scintillation (S_4) indices respectively. Currently, the largest error source in GPS (Global Positioning System) is due to the ionosphere and, as a consequence, the estimated positional error may range between 5 and 30 m. In addition, cycle slips cause degradation in GNSS performance and are observed during strong ionospheric scintillation. The scintillation levels are classified in three categories: strong scintillation (amplitude [$S_4 \geq 1.0$]; phase [$\sigma_\phi \geq 0.8$]), moderate scintillation (amplitude [$0.5 \leq S_4 \leq 1.0$]; phase [$0.4 \leq \sigma_\phi \leq 0.8$]), and weak scintillation (amplitude [$\leq S4 \leq 0.5$]; phase [$\leq \sigma_\phi \leq 0.4$]). The occurrences of ionospheric phase scintillation are prominent in the high latitude region, where auroral sub-storms produce electron density irregularities extending from 100 – 300 km altitude and relative electron density changes of 30-40 % over several hundred kilometers [1]. An appropriate ionospheric scintillation model in an adaptable GPS software receiver is considered a good candidate to mitigate scintillation.

The WBMod is an ionospheric climatological model that predicts the probability of phase scintillation and spectral parameters (T and p) as functions of geographic location, time, SSN (Sun Spot Number) and magnetic indices Kp/K [2], where T is strength parameter (*rad^2/Hz*) and p is the slope of the phase spectrum (PSD). WBMod *Version* 14.05, can predict the probability of ionospheric scintillation for GPS signals at high latitudes. It also predicts weak to moderate (not strong) amplitude scintillation (i.e. S_4 □ 0.7) but this is useful for the auroral region, where occurrence of phase scintillation is generally high compared to amplitude scintillation. For example, [3] observed S_4 at L1 GPS frequency less than 0.3 at Yellowknife, Canada, for a wide range of parameters during the years 2003 to 2007. Figure 1 illustrates the phase scintillation obtained from WBMod and the NovAtel MPC GPS receiver at Yellowknife. The basic trend is well correlated and well suited for a scintillation alarm system for GPS carrier tracking loops.

The tracking channel in the GPS receiver handles the acquired signal and consists of code and carrier tracking loops assembled in multiple channels. This work focuses on studying the performances of the carrier tracking loop during strong phase scintillation. The intermediate frequency, *IF,* is down-converted from the L1 frequency and then passed through the comparator in the PLL, generating phase error. The phase error signal is then passed through a low pass filter to remove high frequency noise using the conventional PLL method, ATAN (Arctangent). The output of

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ATAN is the input of the VCO (Voltage Control Oscillator) which generates the equivalent frequency to track the *IF* frequency. The overall loop continues until the phase error is minimized or reaches to zero.

During strong phase scintillation, the PLL takes a longer time to minimize the phase error resulting in cycle slips in the worst case. The level of phase error in the PLL depends on the order and bandwidth of the filter; thus, proper selection of these two parameters is necessary to design a robust GPS receiver. The generic GPS receiver uses a 3rd order filter with B_n = 10 Hz bandwidth; it works well in weak to moderate ionospheric scintillation but not in strong phase scintillation [4]. Figure 2 illustrates the simulated PLL phase error as a function of phase and amplitude scintillation for the high latitude region. For strong phase scintillation (≥ 0.8 rad) and weak amplitude scintillation, the PLL error can reach 15 degree which is the threshold for the PLL to lose lock [4]. Earlier research proposed a FAB (Fast Adaptive Bandwidth) PLL approach for robustness of the GPS receiver during strong ionospheric scintillation [4]. According to this method, the optimal bandwidth of the PLL is estimated iteratively using $[\sigma_{tPLL} + \phi_e / 3] \le threshold$ where σ_{tPLL} is the thermal noise and ϕ_e is the dynamic phase error. These parameters are functions of bandwidth B_n. Thus using a threshold limit of 15 degrees helps in estimating the optimal bandwidth for the PLL. The initial choice of bandwidth ranges between 15 and 20 Hz [4] which converges to an optimal value depending upon the phase error achieved iteratively every loop. The drawback of this algorithm is the initial choice of the bandwidth which is too wide for the moderate and weak scintillation cases and thus may well not be an optimal solution. This study estimates the initial optimal bandwidth for the PLL using WBMod predicted scintillation, which is then implemented in the FAB PLL to eliminate extra phase noise.

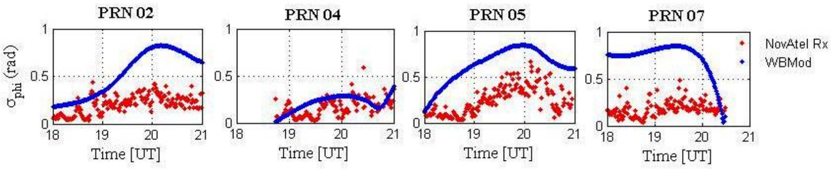

Figure 1 WBMod predicted phase scintillation (blue) and NovAtel MPC measured scintillation (red).

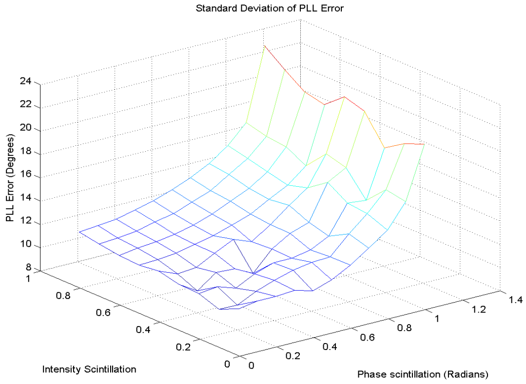

Figure 2 Generic GPS receiver (Bn = 10 Hz, T = 1 ms, ATAN) where PLL error above 15 is potential loss of lock.

2. Experimental Setup and Methodology

A NovAtel MPC (Modulated Precision Clock) GPS receiver with NovAtel-600 antenna was installed at Yellowknife (Yell; 62.48° N, 114.48° W), Canada. The receiver has a PLL of 3rd order with 10 Hz bandwidth and is equipped with special firmware capable of recording phase and amplitude scintillation indices in addition to the raw signal observations (carrier phase and signal intensity) at 50 Hz. Data from January 21, 2005 are selected as the goal period for this study. The phase scintillation for this event observed between 19:30 and 21:00 UT was very high and many channels of the PLL lost lock. The ADR (phase) of PRNs 2, 4, 5 and 7 are illustrated in the two left panels of Figure 3; sudden jumps in phase of PRNs 2 and 5 represent cycle slips. In this study, the IF signal of PRNs 2 and 5 (strong phase scintillation case [$\sigma_\phi \ge 1.0$]) and PRNs 4 and 7 (weak phase scintillation case [$0.2 \le \sigma_\phi \le 0.01$]) are simulated for a 30-second period (20:20:47 – 20:21:17 UT) using experimental phase and intensity data collected at 50 Hz at Yellowknife. In generating the simulated IF data, the carrier phase and signal intensity collected by the receiver at 50 Hz are detrended with 6th order high and low pass Butterworth filters, respectively, at a cut-off frequency of 0.1 Hz. The distribution of detrended carrier phase is Gaussian with zero mean while the amplitude is characterized by an m-

Nakagami distribution [5]. The amplitude and phase distributions are combined together using a bivariate normal transformation [6] to simulate the scintillated signal. The IF signal $S_{IF} = A\ Cos(\omega_{IF}) + Noise$ is simulated at frequency $\omega_{IF} = 9.548$ MHz, with sampling frequency 38.192 MHz for a 30-second time period; the noise here is the distributed scintillated signal (discussed above). It is then passed through the default settings of the PLL and WBMod-assisted PLL in the Matlab-based GPS software receiver. Thus there are two case results: 1) PLL similar to GPS receiver used in this experiment (3^{rd} order, B_n = 10 Hz); and 2) 3^{rd} order PLL with a Fast Adaptive Bandwidth (FAB) with an initial bandwidth predicted using WBMod.

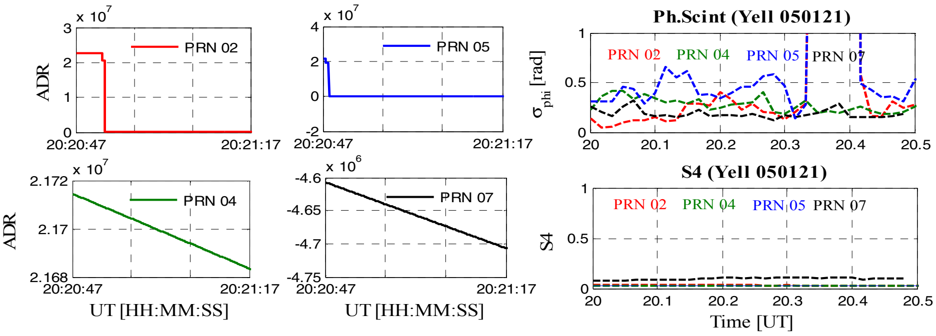

Figure 3 Left and middle panel are ADR (phase) of PRNs 2, 4, 5 and 7 collected at Yellowknife on January 21, 2005 where the discontinuities in ADR of PRNs 2 and 5 represent cycle slips. The right panel is the corresponding scintillation.

3. Results and Discussion

The number of cycle slips can be reduced by widening the PLL bandwidth although this introduces extra phase noise. Implementing the FAB PLL in a GPS software receiver is one solution in which the optimal PLL bandwidth is estimated using an iterative approach based on the standard deviation of phase error after the phase discriminator [4]. According to the PLL rule-of-thumb, the standard deviation of phase error after the discriminator can be expressed as Equation (1) [4]:

$$\sigma_{\phi,\varepsilon} = \left[\sqrt{\sigma_{\phi,T}^2 + \sigma_{osc}^2 + \theta_A^2} + (\theta_e/3) \right] \leq 15^\circ \tag{1}$$

where $\sigma_{\phi,T} = {}^{360}\!/_{2\pi} \sqrt{B_n / C/No \left[1 + \{1/2\,T_{coh} C/No\}\right]}$ is the 1-sigma thermal noise, $\theta_e = 0.4828 \left[\left(d^3R/dt^3 \right) / B_n^3 \right]$ is the dynamic stress of PLL error and σ_{osc} is the 1-sigma oscillator noise. The term θ_A is the Allan deviation induced oscillator jitter, *C/No* is the carrier to noise ratio (dBHz), T_{coh} is the coherent time, and d^3R/dt^3 represents Line of Sight (LOS) jerk. Note that σ_{osc} and θ_A do not contribute significantly in generating phase noise. Mathematically, it is a “while” loop and the initial value of bandwidth is normally high (e.g., 15-20 Hz) in order to capture the high dynamic state of phase error. Thus, even if there is not much phase variation, the system must start with a high bandwidth which may not be an ideal solution during weak to moderate scintillation. In this study, the initial bandwidth value is estimated using the predicted values of phase and amplitude scintillation from WBMod. The carrier tracking error variance $\sigma_{\phi,\upsilon}^2 = \sigma_{\phi_{\sigma_\phi}}^2 + \sigma_{\phi_T}^2 + \sigma_{\phi,OSC}^2$ can be estimated using amplitude and phase scintillation, where $\sigma_{\phi_{\sigma_\phi}}^2$, $\sigma_{\phi_T}^2$, and $\sigma_{\phi,OSC}^2$ are tracking error variances due to phase scintillation, thermal noise (this tracking variance also depend on amplitude scintillation) and receiver oscillator noise, respectively [7]. The details of these parameters can be found in [8]. The output of WBMod and $\sigma_{\phi,OSC}^2 = 0.1$ rad are used to estimate carrier tracking error variance (discussed above). Parameters of the WBMod scintillation model are predicted for 21 January, 2005 for three hours using the SSN (45) and the estimated K index (K = 7 for 18:00 to 21:00 UT) obtained from Meanook (54.67º N, 246.65º E) which is geographically close to Yellowknife. Furthermore, the C/No is modeled for high latitude as a function of elevation angle (*elv*) using a cubic fit $\left([C/No]_{L1} = -2.6e-005elv^3 - 0.0005elv^2 + 0.31elv + 35;\ elv > 10^\circ \right)$ to the observed C/No. Based on the output of WBMod, and *C/No*, the optimal bandwidth is estimated for $\sigma_{\phi,\upsilon} = 15^\circ$. The elevation angle is estimated using navigation files obtained from the CDDIS webpage. In Figure 4, the blue color represents the tracking performance of the PLL (for the generic GPS receiver); result for PRNs 2 and 5 show that the PLL required a few seconds to achieve lock. This is a very critical issue for PLL performance during strong phase scintillation when fast phase changes are observed, often resulting in cycle slips. Thus a GPS receiver with constant bandwidth is not an optimal solution, and thus, WBMod aided PLL in the software receiver estimates an optimal bandwidth according to the predicted ionospheric scintillation. The red color in Figure 4 (WBMod-aided results) shows better tracking performance compared to a constant bandwidth PLL. Observations for PRNs 4 and 7 do not include any significant phase noise. The extra phase noise is a future consideration for this study.

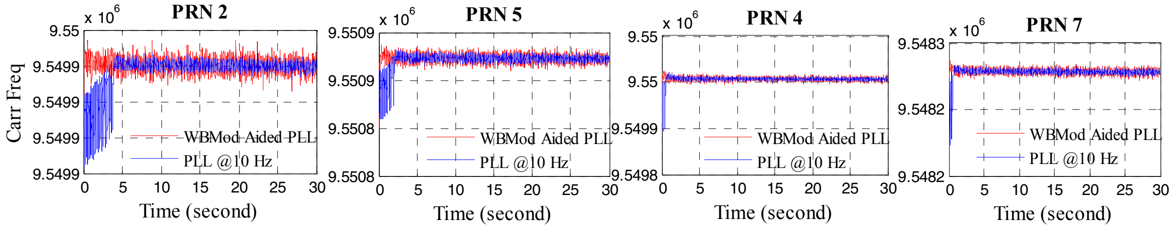

Figure 4 PLL behavior during simulated scintillation (phase scintillation = 1.22; S4 = .3) period.

4. Conclusion

In this work, the effect of strong ionospheric phase scintillation at high latitudes on a generic PLL, and a PLL assisted with WBMod in a GPS software receiver is investigated. The 3rd order PLL, with 10 Hz equivalent bandwidth noise (i.e. generic GPS receiver) suffers a series of cycle slips during strong phase scintillation. The realistic phase and amplitude scintillation are simulated from experimental GPS data collected from a NovAtel GPS receiver installed at the high latitude location Yellowknife. The simulated signal is tested for a constant bandwidth PLL and for a FAB PLL assisted with WBMod in the GPS software receiver. It is observed that the wider bandwidth PLL is robust during strong phase scintillation at high latitudes and performance is improved if the PLL bandwidth is predicted using the scintillation forecasting model WBMod. Furthermore the FAB PLL is implemented iteratively to reduce the level of phase error and this certainly assists in avoiding false alarm by WBMod.

5. Acknowledgement

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