Performance evaluation of tracking NavIC L5 signals under scintillation conditions

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Abstract. Ionosphere scintillation causes rapid and abrupt fluctuations in the intensity and phase of the signal due to the ionosphere irregularities. It is proved to be detrimental to the effective functioning of navigation systems. The reliability and integrity of GNSS system is dependent on the performance of signal tracking loops of the GNSS receivers which are adversely affected during scintillation. The study presents the analysis of the impact of scintillation on the receiver performance particularly carrier tracking loops which may provide cues of handling scintillation signals and overcome its drastic influence on the receiver functioning. The performance of the carrier tracking loop under scintillation is analysed and evaluated in terms of signal locking ability, correlator power, carrier to noise ratio and tracking error. The methodology involves generating simulated scintillation signals based on statistical model and modulating the real NavIC L5 signals with simulated scintillations to generate scintillated signal to test the performance of the software implemented carrier tracking loop. The study concludes with possible strategies such as adaptable loop bandwidth and extending integration time to subdued scintillation effects on receiver performance.

Keywords: scintillation, carrier tracking loop, NavIC L5 GNSS receiver, carrier to noise ratio

1. Introduction
In addition to china and Japan, India has demonstrated self reliance in the navigation field by developing regional navigation system, IRNSS renamed as NavIC (Navigation with Indian constellation) with nine satellites in orbit. Advancement in the navigation field has extended the range and diversity of applications. Aviation and military sectors are extensively dependent on GNSS systems for their safe operation. The requirements of this sector are required to be more precise which is yet a challenge, since the ionosphere effects are the dominant factors in addition to ionosphere delay that degrade the performance of the GNSS receivers. Ionosphere scintillation is one such phenomenon affecting the performance of carrier tracking loops (CTL) of the GNSS receiver causing loss of signal which is very crucial for certain applications

Ionosphere scintillation refers to abrupt fluctuations in the amplitude and phase of navigation signal traversing the ionosphere layer of unstructured and irregular distribution of electron plasma bubbles. Carrier to noise ratio (C/N0) is direct measure of amplitude scintillation. Drastic fluctuation in the C/N0 of the signal with drop upto 20dBHz is illustrated in the figure 1 Occurrence of scintillation is triggered mainly by rate of change of electron density concentration in ionosphere layers, controlled by solar activity, time of the day and geographic location. High percentages of scintillation events are recorded on solar maximum years, in equatorial and low latitude regions [1].
In India, research studies [2] monitored scintillation events in the equatorial anomaly crest regions (Varanasi, Calcutta, Ahmadabad ($20^\circ$-$25^\circ$ geo magnetic latitude) and declared as the precursors for onset of scintillation activity. India’s major cities falling in low latitude regions particularly in anomaly crest regions are affected by scintillations regularly, barring a few other cities where rare occurrence is recorded. Moreover the performance [5] of signal tracking loop under scintillation conditions is tested by various researchers using GPS signals (L1 and L2) and recorded their observations. In this context, a study is conducted to evaluate the performance of the CTL under scintillations by tracking NavIC L5 signals. Scintillation signals are simulated based on Cornell scintillation model [9] using Matlab simulation platform and is modulated on to real L5 navigation signals to generate NavIC L5 scintillation test signals.

Various researchers use scintillation indices [3]: $S_4$ and $\sigma_p$ as a measure of magnitude of amplitude and phase scintillation respectively on the scale of zero to one. The $S_4$ index [4], defined as standard deviation of detrended signal intensity ($I$) over 60 seconds interval, is given by

$$S_4 = \sqrt{\left\langle (I^2) - \left\langle I \right\rangle^2 \right\rangle}$$

(1)

Where $\left\langle \right\rangle$ represents the average value of detrended signal intensity $I$. $S_4$ in the range $[0.7$-$1]$ is termed as severe scintillation which induces canonical amplitude fades, causing drop in C/N0 of the signal by as much as 20dBHz.

Amplitude scintillation causes deep signal fading and the resulting signal strength, below the detectable level of receiver, causes failure of signal acquisition. Successfully acquired signals on the other hand, are unable to be tracked due to C/N0 fluctuation, leading to loss of the signal [5]. Scintillation adversely affects the performance of the signal tracking loops of the GNSS receivers. Further, fluctuations in the phase of the signal cause drastic increase in phase error which will force the tracking loop into loss of lock mode. Tackling such scintillation signals can be dealt with by correct and detailed understanding of scintillation effects and suppressing either through mitigating the effects or intensifying the performance of tracking loops.

The main focus of the study is to analyse the scintillation effects on the receiver performance in terms of correlator power, C/N0 and loss of lock and analyse the possible strategies to limit the degrading effects on the receiver performance.

The paper is organized as follows: The first section begins with describing NavIC signal characteristics, followed by operation and limitations of signal tracking loops. Performance evaluation parameters are discussed next followed by a brief description of data sets used for testing. Methodology of simulation of scintillation signal based on statistical model is described next, followed by, studying the impact on carrier tracking loop (CTL) using simulated data sets. The paper concludes with results, discussion and possible strategies to overcome the effects of scintillation.

**Figure 1.** C/N0 variation of IRNSS L5 signal on 23\textsuperscript{rd} April 2015 is an indication of amplitude scintillation
2. NavIC signal characteristics

Navigation information constituting Ephemeris and Almanac data that describes orbital motion and position of satellites in orbits, is a 50 Hz navigation data which is encrypted with CA (Course acquisition) code which has chipping rate of 1.023MHz. Further it is binary phase shift keying (BPSK) modulated by L5 carrier signal of frequency 1176.45MHz. The received and sampled L5 signal is modeled as [6]

\[ S(t) = A \delta A (D(t_i) + C(t_i)) \cos(2\pi f_{c}t + \phi + \delta \phi(t_i)) + n(t_i) \]  

(2)

where \( A \) is the amplitude of the signal and \( \delta A \) amplitude fluctuations due to scintillation, \( \phi \) is the initial phase and \( \delta \phi \) fluctuations in phase due to phase scintillation, \( D(t_i) \), the navigation data, \( C(t_i) \) the CA code, \( n(t_i) \) thermal noise and \( f_{c} \) is the intermediate frequency of the received signal and \( t_i \) the sampling time.

Received and sampled L5 IF signal, given by (2) is processed by CTL and subsequently by delay locked loop (DLL) presented in detail in [7] with aim of tracking the signal and extracting the navigation data which is used in position determination. The CTL block diagram is illustrated in the figure 2

![Figure 2. Block diagram representation of carrier tracking scheme](image)

In brief, the operation of CTL is as follows: The received IF signal is down converted into baseband signal by premultiplying with replicated quadrature carrier signal resulting in Inphase (I) and Quadrature phase (Q) channels followed by integrating the samples for predetection integration time (PDI) time (T) in the range 1 to 20ms. The phase difference between incoming and replicated signal is detected by phase discriminator (PD), depending on the range of phase detection and signal to noise ratio (SNR) various PD [7] are used. Second order phase locked loop (PLL) with two quadrant arctangent PD is used in this study. The phase error estimation by 2 quadrant arctangent discriminator is given by

\[ \delta \phi = \tan^{-1}(Q/I) \]  

(3)

Loop bandwidth of the CTL is dictated by the noise bandwidth of the loop filter. The loop filter followed by the PD, filters the PD output for any noise before delivering to numerically controlled oscillator (NCO) for frequency adjustment. To ensure tracking of the signal without loss of lock and data loss, the total phase tracking error of a CTL from all sources should be less than 1 sigma phase jitter (15°) given by equation 4 [7]. The dominant source of error include phase error due to thermal noise and the dynamic stress error caused by line of sight (LOS) dynamics, in addition to phase error introduced by oscillator which is considered to be negligible.

\[ \sigma_T = \sqrt{\sigma_{th}^2 + \sigma_{osc}^2 + \frac{\sigma_d}{3}} \leq 15^\circ \]  

(4)
\( \sigma_{\text{th}}^2 \) is the thermal noise jitter given by

\[
\sigma_{\text{th}}^2 = \frac{360}{\pi} \frac{B_n}{c / n_a} \left( 1 + \frac{1}{2 T c / n_a} \right) \text{ deg}
\]

(5)

Where \( B_n \) is the loop noise bandwidth, \( c / n_a \) is the carrier to noise ratio and \( T \) is the integration time.

\( \sigma_{\text{osc}}^2 \), phase error due to oscillator vibration and instability, \( \sigma_d \) is the dynamic stress error which represents the dynamics of the signal. The dynamic stress error for second order PLL \([7]\) is given by

\[
\sigma_d = 0.2809 \frac{d^2 R}{B_n}
\]

(6)

where \( \frac{d^2 R}{dt^2} \) is line of sight acceleration between the receiver and satellite.

Under scintillation conditions, signal is subjected to deep fading with large phase variations, rendering the signal weak with high dynamics. Tracking such signal has the following impacts observed in the performance of the CTL: Increased phase error, drop in C/N0 and loss of lock of signal. The following section discusses on method of C/N0 and PLI estimation.

2.1. Carrier to noise ratio estimation

The tracking performance of CTL is measured by means of two parameters: C/N0 estimation at CTL output and Phase lock indicator (PLI). C/N0 estimation at the output of CTL helps determining whether C/N0 of the signal is above detectable threshold level and to determine the signal locking condition of the CTL. Based on C/N0, the response of the same in noisy environments (scintillations, multipath) can be controlled. Minimum C/N0 of the signal that is detectable by NavIC receiver is 33dBHz in L5 band \([8]\).

C/N0 is estimated based on narrow to wideband power ratio method \([10]\). Post correlator samples of prompt, I and Q channels in accumulation interval \( T \) (20msec) are divide into \( M(20) \) intervals and are used to compute wideband power \( (P_w) \) and narrow band power \( (P_n) \) as given by equations 7 & 8 and C/N0 as in equation (9) over the accumulation interval \( T \)

\[
P_n = \left( \sum_j I_{p_j} \right)^2 + \left( \sum_j Q_{p_j} \right)^2
\]

(7)

\[
P_w = \sum_j \left( I_{p_j}^2 + Q_{p_j}^2 \right)
\]

(8)

\[
c/n_o = \frac{M}{T} \frac{\overline{P_{n/w}} - 1}{M - \overline{P_{n/w}}}
\]

(9)

\( I_{p_j} \) and \( Q_{p_j} \) are Inphase and Quadrature phase samples of prompt channel and \( \overline{P_{n/w}} \) is averaged power over \( n \) iterations, \( j \) is the measurement epoch.

2.2. Phase lock indicator (PLI)

PLI measures the degree of maintaining lock on the signal by the CTL on the scale of -1 to +1. PLI= +1 represents state of best lock while -1 represents the loss of lock state. PLI is calculated using I and Q post correlator samples of the prompt channel \([12]\) or as cosine of the twice the phase error is given by

\[
\text{PLI} = \frac{(\sum_j I_{p_j})^2 - \overline{M} (\sum_j Q_{p_j})^2}{(\sum_j I_{p_j})^2 + \overline{M} (\sum_j Q_{p_j})^2} = \cos(2\delta_p)
\]

(10)
where $\delta \phi_j$ is the phase tracking error indented.

3. Data sets
NavIC, L5, intermediate frequency (IF) data is collected from NavIC receiver installed at research laboratory in Jain University Campus. Data at a intermediate frequency (IF) of 16.221MHz is sampled to obtain digitized IF samples which are modulated with simulated scintillations to synthesize NavIC L5 scintillation signal which is used as a test signal to evaluate the performance of CTL. CTL is more susceptible to scintillation effects than DLL as it involves tracking high frequency carrier signal and hence performance of CTL is evaluated in scintillation conditions.

4. Scintillation simulator model
The scintillation signal is simulated based on statistical scintillation model [9]. The model is driven by White Gaussian noise process $n(t)$ and two input parameters: $S_4$ and $\tau_0$ which are amplitude scintillation index and channel de-correlation time respectively. $\tau_0$ reflects rapidity of signal fluctuations with respect to intensity and phase. Amplitude scintillation follows Nakagami distribution [3], whose intensity variation is controlled by $S_4$ index while the phase spectrum follows a power law distribution. Amplitude scintillation is realized by passing $n(t)$ through LPF with $\tau_0$ as spectrum shaping parameter. This model can generate scintillation signals with amplitude fading accompanied by abrupt carrier phase changes.

Thus realistic scintillation signals $z(t)$ are simulated based on the above described simulation algorithm is shown in the figure 3 using Matlab simulation platform and through complex modulation, NavIC L5 signals are modulated by synthesised scintillation signals to generate NavIC L5 scintillation test signal. The complex modulation is given by

$$s_{\text{scint}}(t) = z(t) \bigotimes s(t)$$

where $z(t)$ is simulated scintillation signal and $S(t)$ is the NavIC L5 IF signal.

4.1. Scintillation simulation Results
The figure 4 illustrates simulation of scintillation signals for $S_4=0.5$ and $\tau_0=0.1$. The 600msec of IF data length of NavIC L5 is complex modulated for 40msec by simulated scintillation. Complex modulation involves adding phase scintillations to true IF signal phase ($\phi + \delta \phi$), and the magnitude of IF signal is modified by amplitude scintillations according to $(A + \delta A)$.
Simulation of scintillation

Figure 4. Simulation of amplitude (top) and phase scintillation (bottom) for $S_4=0.5$ and $\tau_0=0.1$

The resultant synthesized scintillation signal in intensity and phase is illustrated in figure 5

Figure 5. Amplitude and phase scintillation of NavIC L5 signal to generate a test signal

5. Methodology

The signal acquisition and carrier tracking loop is implemented as second order Costas - PLL and DLL loops, using Matlab simulation platform. The synthesised scintillation signal is used as a test signal to evaluate the performance of CTL. The following parameters: tracked phase error, estimated carrier to noise ratio, phase lock indicator (PLI), correlator power and extracted navigation data at the output of the tracking loop is analysed for the scintillation effects. The Correlator output power is computed based on the samples of the prompt channel, is given by

$$P_c = \sqrt{P_p^2 + Q_p^2}$$ (12)

In order to understand the effect of $C/N0$ fluctuations associated with amplitude scintillation on the performance of CTL, $S_4$ is set at moderate level 0.3 to 0.7 and $\tau_0$ to 0.1 to have minimal signal dynamics.
6. Results and Discussion

6.1. Impact of scintillation on the performance of carrier tracking loop
Amplitude scintillation causes fluctuations and drop in C/N0. Reduction in C/N0 is associated with increase in thermal noise, implying tracking of a low SNR signal. Hence the PD measurements are noisy and are less reliable. This will lead to increase in tracking error as shown in the figure 6. The PLI which is an indication of lock of signal is computed from the tracking error as per equation.10. Large phase error, if exceeds the pull in range of CTL (1 sigma threshold 15°) leads to loss of lock of the signal which is shown in the figure 9. The C/No estimated at the prompt channel output of CTL based on equation,9, shows drastic drop in signal power during scintillation period in the figure 8. Corresponding correlator power measurement is shown in the figure. The effect of amplitude scintillation is observed as loss of data of the extracted navigation data in the figure 10. The C/No estimated shows drop in signal power by as much as 12dB Hz during scintillation period (40ms) and picks up to a mean value of 44dB Hz in non scintillation period, as illustrated in Figure 8.

![Figure 6. Tracking phase error of PRN2](image)

![Figure 7. Prompt channel Correlator power](image)

![Figure 8. C/No estimated at CTL for PRN2](image)

![Figure 9. PLI variation of PRN2 signal](image)

![Figure 10. Extracted navigation data for PRN2 signal from In phase prompt channel](image)
6.2. Strategies of improving performance of CTL in scintillations

6.2.1. Variable loop bandwidth of tracking loop. The phase error due to thermal noise is inversely related to C/N0 and integration time (T) and directly to bandwidth (B). This is very significant relation implying phase error can be limited and maintained below the tracking threshold by narrowing the bandwidth or by extending the integration time. This strategy is useful for tracking low C/N0 signal. This is illustrated in the Figure 11. For T=20msec, C/N0 of 25dBHz and bandwidth= 20Hz, phase error is less than or equal to $15^\circ$ (1 sigma threshold) while at Bandwidth=30dBHz, phase error exceeds $15^\circ$ causing CTL to lose track of the signal.

![Figure 11. Variations of thermal phase error with respect to bandwidth and C/N0](image)

However under scintillations, phase error exceeds the threshold level and CTL lose track of signal for the following 2 conditions: one, scintillation induced signal fading and phase variations due to scintillations combined, increases phase error above the threshold leading to loss of lock. Second, inappropriate tracking bandwidth of the CTL will also lead to loss of signal. Hence a provision in CTL to adapt the bandwidth based on signal conditions minimizes the phase error towards reducing the probability of loss of lock.

The figure 12 illustrates variation in tracking phase error versus bandwidth for different scintillation conditions and the implication that can be derived is that tracking phase error varies not only with scintillation but with bandwidth as well, i.e., at some optimal bandwidth, phase error obtained is minimum. Hence tracking signal at variable bandwidth can be effective in dealing with scintillation rather than fixed loop bandwidth. Further, tuning the bandwidth according to changing signal condition reduces the probability of loss of lock. Corresponding PLI variations with respect to bandwidth substantiate the improvement in PLI for variable bandwidth as illustrated in the figure 13.

![Figure 12. Tracking phase error with respect to bandwidth for S4=0, S4=0.3, S4=0.5](image)
6.2.2. Pre-detection integration time (T)

Enhancing the pre-detection accumulation time (T) significantly improves the tracking of weak signals as signal power is accumulated for large accumulation time by averaging out the noise, this improves the SNR of the signal being tracked. The above explanation is justified from equation 5 as thermal noise is inversely related to integration time (T). For navigation data of 50Hz, T cannot exceed 20msec. The table.1 describes the improvement in PLI by increasing T for variable bandwidth.

**Table 1:** Tracking outcomes for variable PDI

| BW  | Phase lock indication(PLI) |
|-----|----------------------------|
|     | T=1ms | T=5ms | T=10ms | T=15ms |
| 10Hz| 0.42   | 0.54   | 0.62   | 0.72   |
| 15Hz| 0.6    | 0.62   | 0.72   | 0.78   |

**Conclusions**

The CTL is the heart of GNSS receivers as it is responsible for reliability and integrity of Navigation systems. However, the tracking performance is degraded during the period of scintillations. The study has presented the tracking of NavIC L5 signals under scintillations and the results has revealed the severe impact of scintillation on the performance of CTL in the form of low C/N0, loss of lock and loss of data. The methods to optimise the performance of CTL are variable loop bandwidth and extended integration time. Since Scintillation is random in nature, is effectively handled by adopting variable bandwidth i.e. tuning the tracking bandwidth according to signal conditions. The work is further extended to explore the Kalman filter based approach for tackling scintillations in navigation receiver.

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