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Mitigation of Ionosphere Scintillation Effects on Navigation Receiver using Kalman Filter Technique

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Abstract: Signal tracking loop in GNSS receivers play a major role of data extraction by tracking carrier phase. Under adverse signal conditions such as ionosphere scintillation, conventional tracking loops are less robust and hence are susceptible to loss of lock. Kalman filter's inherent ability to adapt to signal conditions is one of the desirable features which improve the tracking performance. The paper analyses Linear Kalman filter technique of tracking signals in Navigation receiver under scintillation conditions and presents the improvements obtained with Linear Kalman filter based tracking method over conventional tracking method. Performance parameters such as phase error, carrier to noise ratio, correlator power and phase lock indicator are analysed in addition to highlighting the tuning merits of Kalman filter. NavIC L5 band signal modulated with simulated scintillation is used as test signal to analyse the performance of the Kalman filter based tracking method.

Keywords: Kalman filter, Ionosphere scintillation, Phase tracking, Carrier to noise ratio, Phase lock indicator.

1. Introduction

Navigation signal transmitted from constellation of navigation satellites propagating through ionosphere encounters irregular structures with varying refractive index which results in refraction and diffraction. The former causes delay in the received signal known as ionosphere delay while the latter results in phenomena called ionosphere scintillation. The constructive and destructive interference of the signals as it propagates through disturbed ionosphere layers results in random fluctuations of phase and amplitude, known as ionosphere scintillation.

Scintillation is significantly observed in and around geomagnetic equator, low latitude regions witnesses moderate scintillation activity [1], rare scintillation events are recorded in high latitude regions and Polar Regions witnesses high scintillation activity. Further the scintillation occurrence is a statistical phenomenon, controlled by Total electron content (TEC) [2] of ionosphere. High probability of occurrence is recorded in the period of equinox and solstice, irrespective of solar activity and once the scintillation occurs it may span from 30minutes to several hours causing signal outages.

However continuous carrier phase observation of the received signal is needed for data demodulation and is an essential function of Global navigation satellite system (GNSS) receivers. GNSS refers to constellation of navigation satellites providing position and timing navigation data of global coverage. USA's GPS and Europe's Galileo are few examples of GNSS system. The received signal is traditionally tracked by Phase locked loop (PLL) in GNSS receiver and in some case Frequency locked loop assisted PLL [3]. Various researchers have put forth techniques of optimizing carrier tracking loop (CTL) which uses PLL by increasing loop order, increasing integration time for tracking signals depending on applications and signal conditions.

Conventional carrier tracking loop (CTL) is less robust in handling scintillation signals which are characterized as low carrier to noise ratio(C/No) and high dynamics. Further, fixed bandwidth of the loop inhibits from adapting to varying signal conditions. As a result, degradation in receiver performance, while tracking scintillation signals are observed such as of loss of lock, data errors, which strongly affects the integrity and continuity of the navigation system.

One of the innovative techniques of increasing the robustness of CTL particularly in tracking scintillation signal is Kalman filter (KF) and such a tracking method is known as KF based tracking loop. Various researchers have proposed versions of KF such as extended Kalman filter (EKF) and linear KF. Based on the observation, the KF operates on, two types of tracking architectures are demonstrated: Extended KF [4] estimates the parameters by assuming the inputs from Inphase (I) and Quadraturephase (Q) correlator outputs of tracking loops and is described as non linear model. Unlike EKF, which has increased complexity, linear KF is simple and it operates on observational output of phase discriminator of the tracking loop.

Ref. [5] demonstrates performance of KF based tracking by comparison with standard CTL in steady state conditions. And has shown through simulations KF has similar tracking performance with improved tracking sensitivity and smaller tracking noise bandwidth, under normal signal conditions. However has not highlighted the merits of KF in scintillation conditions. Ref. [6] has approached the problem of loss of phase lock observed very frequently while tracking weak(low C/No) signals using KF based tracking loop by varying loop gain and up-dation of KF iteration according to C/No of the signal. However the noise matrices and the tuning of KF are not highlighted.

The proposed Linear KF based tracking technique for tracking signals apart from being less complex provides accurate estimation of parameters in noisy conditions as it is based on mean square error (MSE) method of estimation. Furthermore KF is adaptable to the varying signal conditions i.e., noise bandwidth is made variable to signal levels. Moreover in adverse signal condition the KF noise covariance matrix can be tuned to make it adaptable to the system. The paper unambiguously presents the improvements obtained at varying stages of tracking loop by using KF based tracking. The proposed method is tested by tracking NavIC L5 signals in scintillation conditions.

The paper is organised is as follows: The first section presents the effects of scintillation on carrier tracking loops followed by merits of KF. The following next section briefs fundamentals of scintillation, factors inducing loss of lock in tracking. Basics of KF and system modelling are discussed in the next section. Briefing on the performance parameters is in the next section followed by methodology and the results

2. Impact of scintillation on signal tracking loop

Scintillation signal is characterized as a low C/No and a fast varying signal and therefore there are two challenges posed for successful tracking of the signal. One, acquiring and tracking weak (low C/No) signals, second, tracking high signal dynamics. If the C/No is below detectable threshold, the signal will go undetected. Though the signal is successfully acquired it may lead to number of reacquisition due to fluctuations in C/No. The more crucial fact is dealing with increase in phase error either due to increase in phase scintillation or inadequate bandwidth. If the total phase error of the tracking loop exceeds 15^0 it results in loss of phase lock [7] of the acquired signal. Further, large bandwidth is demanded for tracking fast variations (dynamics) in the signal while small bandwidth is sufficient to track weak signal thus there is trade off in tracking high signal dynamics and weak signal which cannot be handled with conventional tracking loop and with fixed loop parameters such as loop bandwidth. Hence, the traditional CTL is less robust in tracking scintillation signals. Loss of phase lock, cycle slips [8], errors in navigation data, drop in correlation power and increase in acquisition time are some of the degrading effects observed in the conventional CTL

3. Merits of Kalman filter based tracking over conventional

The loop noise bandwidth which plays significant role in controlling noise and tracking high signal dynamics is fixed irrespective of signal conditions which is a limitation in CTL. Moreover changing loop order to overcome this is cumbersome and may not be a feasible in real-time situations.

KF offer benefits over traditional such as adaptable loop gain and variable loop noise bandwidth. Tuning the KF [9] in terms of noise matrices is an added advantage of adapting loop specifications to varying signal conditions. Ability of adapting the loop gain in estimating the parameters with high accuracy based on MSE is one of the desirable features of KF in scintillation conditions.

Loss of lock to the acquired signal is major

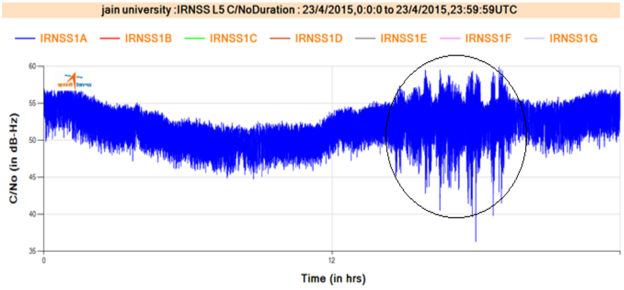

Figure.1 Plot of C/No variations as observed on 23rd April, 2015 during post midnight hrs is an example of occurrence of scintillation

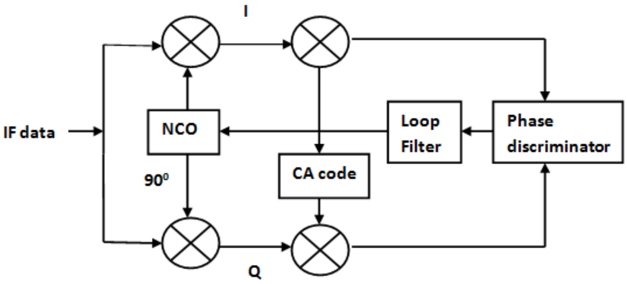

Figure.2 Conventional carrier tracking loop

setback while tracking scintillated signal by CTL which can be significantly improved with KF based tracking. Loss of lock may be triggered by inadequate bandwidth [6]. In other words bandwidth may be too small to track high signal dynamics or too large to hold on to low C/No or weak signals leading to loss of lock. Appropriate loop bandwidth is self adjusted as per signal conditions thereby reducing the probability of loss of lock. The ultimate aim is to ensure lock on to the signal which can be achieved with KF based tracking loop

4. Background study

4.1 Ionosphere scintillation

Preliminary observation of occurrence of scintillation is indicated by random fluctuations in C/No ratio of the received signal as shown in the Fig.1 The strength of amplitude scintillation is determined by computing scintillation index S4 [10].

$$S_4 = \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}} \qquad (1)$$

Where $\langle\rangle$ represents the average value of detrended signal intensity I phase scintillation index by

$$\sigma_\varphi = std(\delta\varphi) \qquad (2)$$

$\delta\varphi$ is the detrended carrier phase error. The range of S4 from 0.1 to 0.3 is graded as weak scintillation and from 0.3 to 0.7 as moderate scintillation and severe scintillation for S4 > 0.7 up to 1. Low latitude regions covering India experiences moderate amplitude scintillation and hence this paper mainly concentrates on amplitude scintillation only. Polar regions like Ancesion Island experiences phase scintillation while equatorial regions experiences both amplitude and phase scintillation

Due to lack of scintillation data, the scintillation signals are simulated based on Cornell scintillation model [11] and are modulated onto NavIC L5 signals to generate scintillation signal to test the performance of proposed KF based tracking technique.

The standard tracking loop is basically a Costas loop for tracking carrier phase and maintains synchronization with the received signal. The received signal is first wiped off the carrier and subsequently the CA code [12, 14] to extract the navigation data which is further utilized to compute user position. The efficiency of the tracking loop rely on the ability to correctly estimate the phase and remain synchronized with it. The detailed description of the conventional tracking loop shown in the figure is demonstrated in [7].

As demonstrated in [7], various detectors based on the (signal to noise ratio) SNR, linearity and range of phase detection, are used as phase discriminators (PD) in the tracking loop to detect the phase difference between the received signal and replicated signal. Arc tangent discriminator has phase range detection from –π/2 to +π/2, though the detection range is narrow, exhibits comparatively high linearity and is suitable in low SNR over others [7]. The PD output is given by

$$\text{Phase error} = \text{atan}(Q/I) \text{ radians} \qquad (3)$$

Where Q and I are quadrature phase and inphase samples of the tracking loop.

4.2 Phase tracking errors

The dominant source of phase error in the tracking loop is phase fluctuations and dynamic stress error. A rule of thumb for tracking threshold [7] is that 1 sigma phase jitter of tracking loop should not exceed 15^0 as given by

$$\sigma_T = \sqrt{\sigma_{th}^2 + \sigma_v^2 + +\sigma_A^2} + \frac{\sigma_d}{3} \leq 15^0 \qquad (4)$$

σ_{th}^2 is the phase jitter due to thermal noise is given by

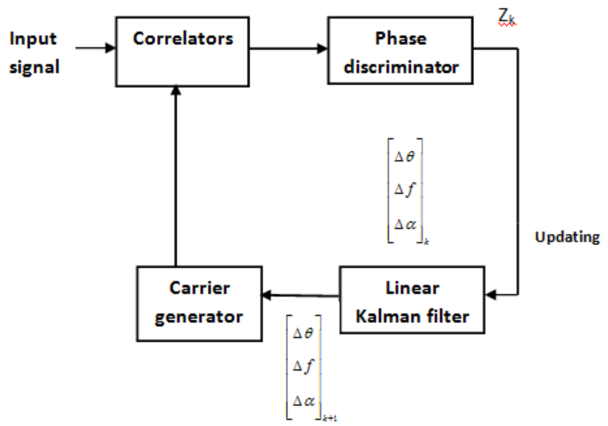

Figure.3 Block diagram of proposed Kalman filter based tracking method

$$\sigma_{th} = [\frac{B}{^{c}/_{no}}(1 + \frac{1}{2T\,^{c}/_{no}})]^{1/2} \quad \text{radians} \qquad (5)$$

Where B is the loop noise bandwidth, C/No is the carrier to noise ratio and T is the integration time
σ_v^2 is the vibration induced oscillator phase noise when the oscillator is subjected to mechanical vibrations.

σ_A^2 represents Allan deviation oscillator phase jitter. It is contributed by 3 different types of frequency noises (white frequency noise, Flicker noise and integrated frequency noise).

σ_d the dynamic stress error [6] caused by line of sight dynamics, represents the tracking loops inability to quickly respond to abrupt signal changes such as acceleration, jerk of the input phase. The dynamic stress error for second order PLL is given by

$$\sigma_d = 0.2809 \frac{(\frac{d^2R}{dt^2})}{B_n^2} \quad \text{degrees} \qquad (6)$$

Where d^2R/dt^2 is line of sight acceleration dynamics
The above described phase errors are modelled as system noise covariance matrix [13] Q of the Kalman filter given by

$$Q = \begin{bmatrix} S_{\delta\varphi} & 0 & 0 \\ 0 & S_{\delta f} & 0 \\ 0 & 0 & S_{\delta a} \end{bmatrix} \qquad (7)$$

$S_{\delta\phi}$, $S_{\delta f}$, are power spectral densities (PSD) [14] of the receiver oscillator noise and clock drift respectively and $S_{\delta a}$ is the PSD of line of sight acceleration changes

4.3 Kalman filter based carrier tracking

KF is basically a recursive algorithm, estimates the parameters of interest based on mean square error (MSE) method. The efficiency of KF significantly depends on the accurate state model representing the system under consideration. It operates in 2 stages [15], First stage estimates the priori states with the information/knowledge of the system in hand and updating the same by incorporating additional measurements in the second stage.

The Kalman filter based tracking loop is shown in the figure…. The Loop filter in the conventional tracking loop is replaced by KF.

$$\begin{bmatrix} \overset{\wedge -}{\Delta\theta} \\ \overset{\wedge -}{\Delta f} \\ \overset{\wedge -}{\Delta\alpha} \end{bmatrix}_{k+1} = \begin{bmatrix} 1 & \Delta t & \frac{\Delta t^2}{2} \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \overset{\wedge}{\Delta\theta} \\ \overset{\wedge}{\Delta f} \\ \overset{\wedge}{\Delta\alpha} \end{bmatrix}_k + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} w_\theta \\ w_f \\ w_\alpha \end{bmatrix} \qquad (8)$$

$[w_\theta \ w_f \ w_\alpha]$ is the process noise respectively of phase, frequency and Doppler frequency rate characterised as white Gaussian noise and is un correlated with each other. Hence noise covariance matrix Q is a diagonal matrix with autocorrelation functions along diagonal as given in Eq. (7). Δt is the integration time interval starts at time k ends at k+1.

The algorithm is initialised with a posterior state estimate $[\hat{x}_k]=[0]$ and estimates a priori state estimate $[\hat{x}_{k+1}^-]$ using dynamic process model given by Eq. (8).

A priori state estimate $[\hat{x}_{k+1}^-]$ is updated by incorporating the measurement z_{k+1} as given in Eq. (9).

$$z_{k+1} = atan(Q/I) + v_k \qquad (9)$$

v_k is the measurement noise. Here atan() [arctangent function] is used as phase discriminator. The measurement model is represented as

$$z_{k+1} = \begin{bmatrix} 1 & \Delta t & \frac{\Delta t^2}{3} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta f \\ \Delta\alpha \end{bmatrix}_k + vk \qquad (10)$$

Measurement noise v_k for arctangent phase discriminator is modelled as noise variance 'R' of KF and is given by

$$R = \frac{1}{2\frac{c}{n_0}T}\left(1+\frac{1}{2\frac{c}{n_0}T}\right) \tag{11}$$

Where c/n_0 is the Signal to noise ratio of the signal and T is the integration time.

The measurement update involves Kalman gain (K) weighing the error e_z which is the difference between the predicted state $[\hat{x}_k^-]$ and measured value z_{k+1} ,to reduce the error covariance and estimate the posteriori state estimate as given by Eq.(12).

$$\hat{x}_k = \begin{bmatrix} \hat{\Delta}\theta \\ \hat{\Delta} f \\ \hat{\Delta}\alpha \end{bmatrix}_{k+1} = \begin{bmatrix} \hat{\Delta}^-\theta \\ \hat{\Delta}^- f \\ \hat{\Delta}^-\alpha \end{bmatrix}_{k} + K[z_{k+1} - \hat{\Delta}^-\theta_{k+1}] \tag{12}$$

$K = [k_1\, k_2\, k_3]^T$ is the Kalman gain vector

$$\hat{\Delta}^-\theta_{k+1} = \hat{\Delta}^-\theta + \Delta t\,\hat{\Delta}^- f + \frac{\Delta t^2}{3}\hat{\Delta}^-\alpha \tag{13}$$

is the average phase error predicted as a priori state estimate.

$$\hat{\Delta}^-\theta_{avg} = \hat{\Delta}^-\theta_{k+1} \tag{14}$$

$$e_z = z_{k+1} - \hat{\Delta}^-\theta_{avg} \tag{15}$$

The noise covariance matrices Q and R represent respectively the system noise and measurement noise of KF may be computed online by tuning the KF or offline. In KF, loop parameters such as gain and bandwidth can be adapted to receive signal conditions. As, loss of lock is a severe condition that the tracking loop is subjected to in scintillation conditions, adapting loop bandwidth extends the signal locking threshold.

4.4 Tuning of Kalman filter

KF can be operated in offline or online mode. In offline mode, Q & R variances given in Eq. (5 and 9) are computed offline and are constant throughout the tracking time where as in online mode the noise matrices are updated every integration time and KF is tuned based on Q and R [16]. KF is tuned by updating co -variances matrices Q and R according to signal conditions. Based on the received strength, the C/No is estimated [17] and measurement noise covariance R is updated.

4.4 Phase lock indicator

The aim of tracking loop is to maintain lock on to the signal phase so as to extract the navigation data. The signal lock ability of the tracking loop is evaluated by phase lock indicator (PLI) [7] defined as cosine of twice the carrier phase given by *cos(2δΦ)* which takes the values from -1 to +1, with -1 indicating loss of lock and +1 indicating best match with signal. PLI of o.6 is considered as lock threshold below which it represents lose of lock indication.PLI is computed from I and Q values of the tracking loop as given by

$$\text{PLI}=\frac{\left(\sum_j^M I_{Pj}\right)^2-\left(\sum_j^M Q_{pj}\right)^2}{\left(\sum_j^M I_{Pj}\right)^2+\left(\sum_j^M Q_{pj}\right)^2} = \cos(2\delta\Phi_j) \tag{16}$$

5. Methodology

The improvement in phase tracking by the proposed KF based tracking is demonstrated by comparison with conventional PLL based tracking loop. Various parameters such as correlator power, C/No, phase error, phase lock indicator are some parameters analyzed for performance improvement.

The proposed tracking algorithm is tested on NavIC L5 band signals. The NavIC signals are modulated with simulated scintillations to generate test signals. NavIC L5, IF data is recorded from NavIC user Receiver at Jain university campus. The IF data is modulated with simulated scintillation based on Cornell scintillation model [12].

The realistic scintillation signals *z(t)* are simulated as given in the block diagram Fig. 4 using Matlab simulation platform. Through complex modulation, synthetic scintillation signals are modulated onto real NavIC L5 signals to generate scintillation test signal according to Eq. (17) as shown in the Fig.5.

$$s_{scint}(t) = z(t) \otimes s(t) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

where z(t) is simulated scintillation signal and S(t), the NavIC L5 signal and ⊗ represents the complex modulation symbol. Fig.5 illustrates the scintillation test signal.

6. Methodology

Unlike EKF, which has increased complexity, linear KF is simple and it operates on observational output of the phase discriminator. Researchers have addressed the loss of lock condition through different versions and architectures of KF [5, 6].

The conventional tracking loop, the block diagram illustrated in the Fig.2 uses first order low pass filter and the proposed linear KF based tracking in the Fig.3 are implemented and compared for performance. Mainly focuses at analyzing the improvements obtained at various stages of CTL by adopting linear KF over low pass filter. The advantages obtained with tuning of KF is demonstrated.

Fig.6 shows the phase error tracked by conventional tracking loop. During scintillation, the phase error has exceeded the locking threshold and thus looses lock. Fig.7 illustrates the tracking by Kalman filter. KF tracking is similar to conventional tracking in non scintillation conditions. In scintillation period the phase error tracked is such that it is well below the tracking threshold and thus helps in maintaining lock. This fact is attributed to self tuning nature of KF for varying signal conditions.

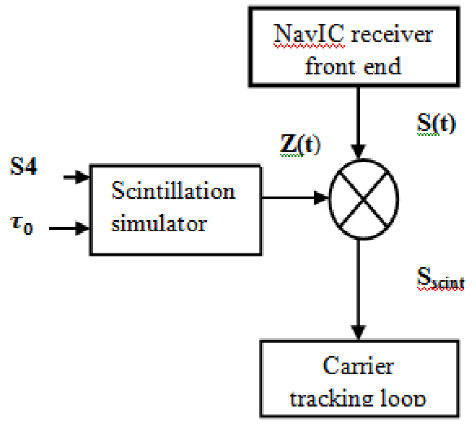

Figure.4 Methodology of simulation of scintillation signal

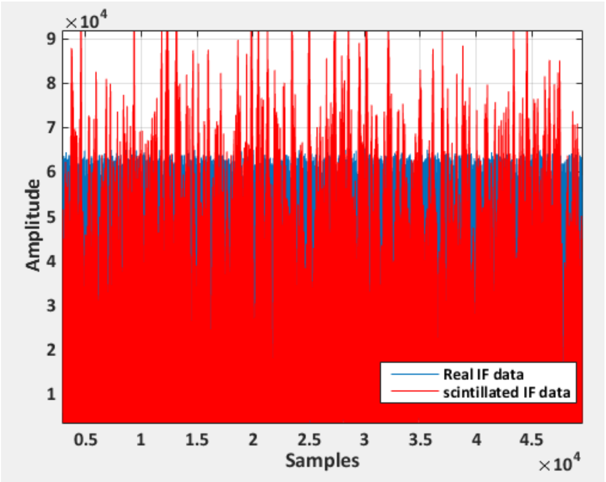

Figure.5 Generation of scintillation test signal

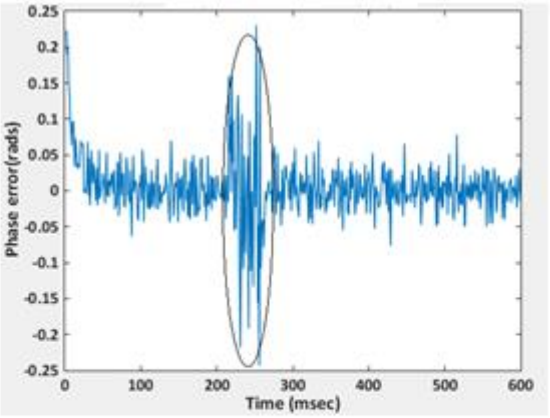

Figure.6 Phase error tracking by conventional CTL

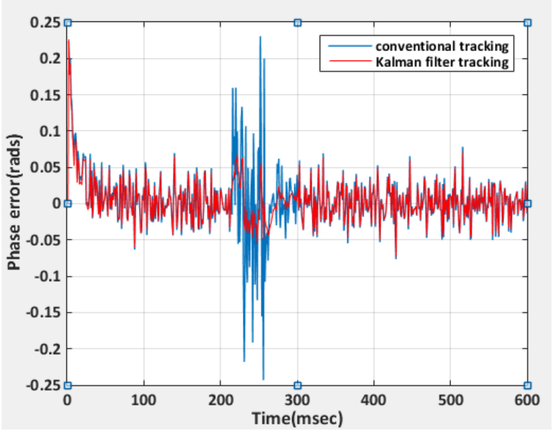

Figure.7 Comparison of phase error of KF method and conventional tracking for S4=0.2

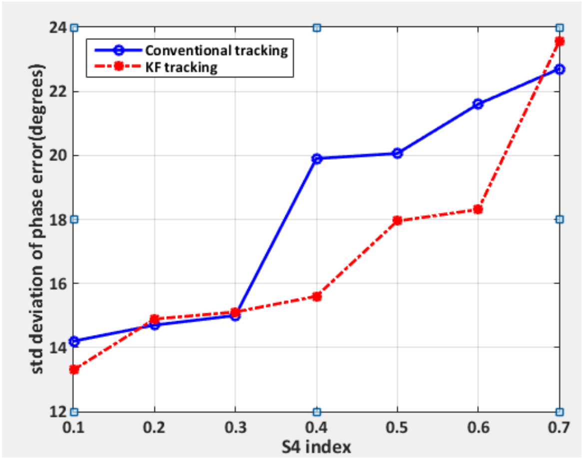

Figure.8 Comparison of standard deviation of phase error for KF and conventional tracking loop

Fig.8 shows the plot of phase error versus scintillation index S4 for conventional tracking loop and KF based tracking loop for S4 (0.1- 0.7). The phase error tracked by both methods are similar for S4<0.3. For S4>0.4 phase error tracked by KF based tracking is smaller than conventional method implying proposed KF based tracking loop is robust enough to lock onto the signal than the CTL.

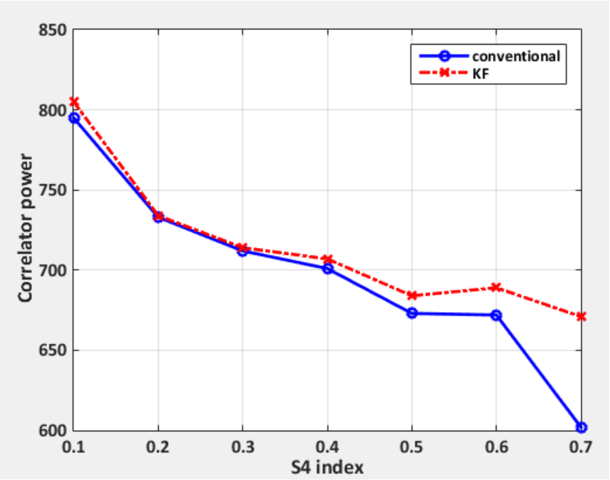

Figure.9 Correlator power calculated for KF and conventional tracking

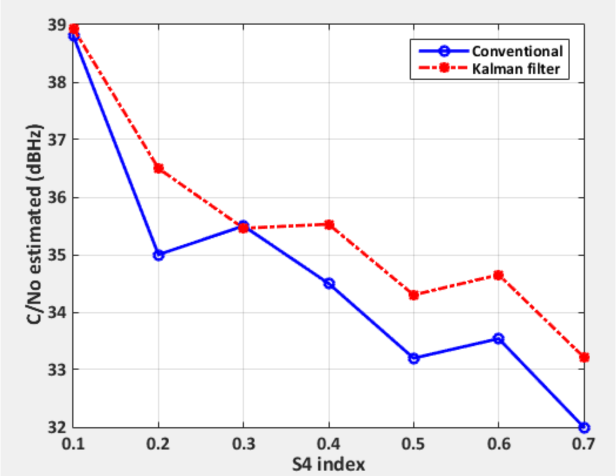

Figure.10 Comparison of C/No estimated for KF and conventional tracking

Fig.9 shows the plot of the average correlator power of tracked signal at the output of tracking loop for both tracking methods. Correlator power is computed as $\sqrt{I_p^2 + Q_p^2}$ where I_P and Qp are Inphase and quadrature phase samples. From the Fig.8. For S4 = 0.3, both methods more or less has identical correlator power and for S4> 0.4 correlator power drastically drops for increase in S4 in Conventional tracking unlike KF based tracking which shows comparatively improved correlator power.

Fig. 10 shows C/No estimated at the tracking loop output versus scintillation index (S_4), for both tracking methods. In CTL, C/No drastically drops below 33dB Hz for increase in S4 unlike KF based tracking which maintains C/No above 34dB Hz.

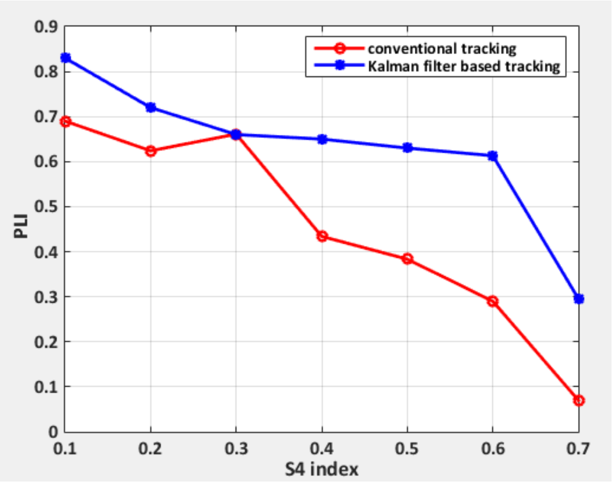

Figure.11 PLI comparison for KF and conventional tracking

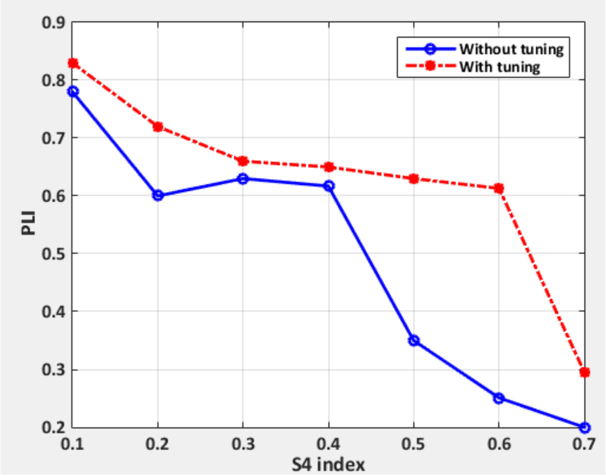

Figure. 12 Plot of improvement in PLI with tuning of KF

PLI is one of the important parameter to evaluate the phase lock ability of tracking loop. The Fig. 11 shows PLI for both cases for S4 (0.1-07) Both the methods maintain phase lock on to the signal for S4 upto 0.3, CTL looses lock for S4>0.3 as PLI <0.6 ,where as KF maintains lock for S4 upto 0.6 This implies loss of lock level threshold is extended with KF based tracking.

Fig.12 illustrates improvement in PLI obtained with tuning of KF. Noise covariance R of KF is updated according to estimated C/No and thus KF is tuned and the loop parameters are adapted. As illustrated without tuning the loop looses lock for S4=0.5 and the lock is restored at the same scintillation index by adapting the loop parameters by tuning KF. This implies the lock of threshold can be extended by tuning the KF.

7. Conclusion

Maintaining integrity continuity and positional service in navigation system strongly depends on the performance of tracking loop ability to maintain lock on the signal. The study has presented the results of tracking NavIC L5 signals under scintillations using conventional and linear Kalman filter method. The results demonstrate the conventional tracking and proposed method has similar tracking properties only in low level scintillations. In moderate scintillation, KF tracking exhibits improved performance in terms of increased C/No and correlator power and phase lock ability. More significantly, the extension of locking threshold is achieved with real-time tuning of KF. This promotes the use of KF based tracking loops over conventional CTL in scintillation conditions. Further, the work is extended to enhance the robustness of KF tracking in severe scintillation conditions and study the performance of the same on tracking real NavIC scintillation signals

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