Implementation of Advanced Carrier Tracking Algorithm Using Adaptive-Extended Kalman Filter for GNSS Receivers

P. Babu Sree Harsha and D. Venkata Ratnam, Senior Member, IEEE

Abstract—Use of Global Navigation Satellite Systems (GNSS) receivers for real-time applications has improved significantly all over the world. The main problem with the designed receivers is their failure to function under harsh environmental conditions because of the structured phase-locked loop (PLL) architecture. One of the most critical phenomena that cause signal degradation in GNSS receiver is ionospheric scintillations, which create disturbances in amplitude and phase of the received signal. The problem in signal acquisition and tracking, even in the severe canonical fades (deep amplitude fading correlated with reference to half cycle phase jumps), can be mitigated using robust and adaptive carrier tracking algorithms. The autoregressive exogenous modeling parameters are useful in estimating the amplitude and phase scintillations. The proposed adaptive-extended Kalman filter (AEKF) approach works as an effective carrier tracking algorithm maintaining a balance in dual problems faced by PLL-based receivers, i.e., (estimation versus mitigation) and (dynamics versus noise reduction) tradeoff. The developed AEKF algorithm performed well for synthetic Cornell scintillation monitor data and for Global Positioning System L1 PRN 12 data collected around 21.30 H (local time) on October 24, 2012, in Rio de Janeiro, Brazil, with GNSS Software Navigation Receiver.

Index Terms—Adaptive-extended Kalman filter (AEKF), autoregressive exogenous (ARX) modeling, canonical fades, ionospheric scintillation.

I. INTRODUCTION

IONOSPHERIC scintillations can be considered as the principal reason for degradation in the received signal strength for any globally available Global Navigation Satellite Systems (GNSS) receiver [1]. They disturb the signal in-phase (I) and quadrature-phase (Q) components at the front-end of the receiver. The effect of scintillation can be observed from the amplitude and phase drawn from I and Q values [2]. There is a correlation between the scintillated amplitude and phase, which can be termed as canonical fades (severe amplitude variations with half-cycle phase jumps) [3]. Mitigating these scintillations is difficult with available GNSS receiver architectures because of their fixed design issues [4], which are suitable only in clear propagation conditions.

The phase dynamics caused by the relative motion between the satellite and the receiver is one of the countable tasks for the GNSS receiver. The mass-market GNSS receivers designed by phase-locked loop (PLL) architecture consist of a PLL discriminator, a loop filter, a carrier generator, and a numerically controlled oscillator [5]. The loop filter has a constant bandwidth and a fixed order [6], [7]. Due to the fixed bandwidth, the receiver cannot mark a difference between noise occurrences and phase dynamics. There should be a tradeoff in bandwidth improvement because noise reduction requires a lower bandwidth and phase dynamics requires a larger bandwidth. The traditional carrier tracking algorithm involves a PLL architecture, which cannot estimate high phase dynamics and is also unsuccessful in stringent propagation conditions.

There is a need for implementation of a robust and adaptive carrier tracking algorithm to work even in severe propagation conditions. Copious research has been conducted in the advancement of carrier tracking algorithm by implementing multi-PLL, PLL-FLL, PLL-neural networks, and Wavelet-PLL. Lopez-Salcedo et al. gave a detail survey on robust carrier tracking algorithms [8]. One of the approaches is using the Kalman filter (KF) techniques. A KF is a two-state approach, which involves prediction and estimation. Many papers have proposed this approach dealing with the phase dynamics scenario and scintillations [6]–[10]. Research has also been conducted in the area of tracking phase dynamics and mitigation of ionospheric phase scintillations adaptively using autoregressive (AR) modeling, leaving the amplitude scintillations [7]. Hence, the research necessity was felt to implement a robust carrier tracking algorithm using an adaptive-extended Kalman filter (AEKF) including phase dynamics, amplitude and phase scintillations, and achieving adaptive behavior by varying measurement noise [11] using AR exogenous (ARX) modeling [12].

The contributions in this letter are as follows: 1) modeling the phase and amplitude scintillations with ARX modeling; 2) tracking and mitigation phenomenon has been discussed; 3) work out a new AEKF algorithm for carrier tracking; and 4) mitigation of scintillations for both Cornell scintillation monitor (CSM) and real-time data for both EKF and AEKF techniques has been inspected.

Manuscript received January 23, 2016; revised March 31, 2016 and May 17, 2016; accepted June 11, 2016. Date of publication July 7, 2016; date of current version August 5, 2016. This work was supported by the Department of Science and Technology, New Delhi, India, SR/FST/ESI-130/2013(C) FIST program and by the University Grants Commission (UGC), New Delhi, File No: F. 301/2013(SAII)/RA201416GEANP5585. The authors are with the Department of Electronics and Communication Engineering, Koneru Lakshmiah University, Guntur 522502, India (e-mail: dvratnam@kluniversity.in).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LGRS.2016.2581207

II. Modeling Ionospheric Scintillations

The received baseband signal from correlator output samples In and Qn are given by

\[ \text{In} = \frac{\text{ADT}_c}{2} R(T_s) \text{sinc} \left( \frac{\Delta w T_c}{2} \right) \cos \phi + X_n \]  
\[ \text{Qn} = \frac{\text{ADT}_c}{2} R(T_s) \text{sinc} \left( \frac{\Delta w T_c}{2} \right) \sin \phi + Y_n \]

where \( A \) is the received signal amplitude; \( D \) is the navigation message data bit; \( T_c \) is the C/A code period; \( \text{sinc}(u) = (\sin u)/u \); \( \Delta w = wD - wo \), in which \( wD \) and \( wo \) are the Doppler and center frequencies of the received signal, respectively; \( \phi \) is the phase offset; and \( R(T_s) \) is the C/A code correlation function given by

\[ R(T_s) = \begin{cases} 1 - \frac{|T|}{T_{\text{chip}}} & \text{if } |T| < T_{\text{chip}} \\ 0 & \text{otherwise}. \end{cases} \]  

Assuming that \( T_{\text{chip}} = 1/1.023 \) ms, the length of the C/A code chip and \( X_n \) and \( Y_n \) are zero-mean independent Gaussian random variables with white noise spectra [2]. The amplitude and phase of the signal are estimated by

\[ (A_n)_{T_s} = \left( \sqrt{\text{In}^2 + \text{Qn}^2} \right)_{T_s} \]  
\[ (\theta_n)_{T_s} = \left( \text{atan} \left( \frac{\text{Qn}}{\text{In}} \right) \right)_{T_s} \]

where \( (A_n)_{T_s} \) gives the amplitude of the correlator output, \( (\theta_n)_{T_s} \) gives the phase of the correlator output, \( n \) is the data bit number, \( T_s \) is the sampling time, and In and Qn are the in-phase and quadrature-phase correlator sample outputs.

Various types of PLL phase discriminators are globally available in GNSS receivers [5]. The phase scintillation derived in (5) is from an arc-tangent phase discriminator from a GNSS Software Navigation Receiver, i.e., GSNRx, developed by the University of Calgary [13], whereas the simulated CSM data also use the ATAN (arc-tangent) PLL phase discriminator [7]. The amplitude scintillation index \( (S4) \) is useful in estimating the effect of ionospheric scintillations [2] on real-time data, as given in the following:

\[ S4 = \frac{\delta T_s}{\mu T_s} \left( \sqrt{ \frac{\text{E}(\text{WBP})^2 - \text{E}(\text{WBP})^2}{\text{E}(\text{WBP})} } \right)_{T_s} \]  
\[ \text{WBP} = \sum_{n=1}^{N} \{\text{In}^2 + \text{Qn}^2\} \]

where \( N \) is the length of the data record for each sampling time, \( \delta T_s \) is the standard deviation taken for the received signal wide band power, and \( \mu T_s \) is the mean of the received signal wide band power for each sampling time \( T_s \).

The wide band power \( \{\text{WBP}\} \) is given by the \{In\} in-phase component and \{Qn\} quadrature-phase component of the received complex baseband signal as given in (7).

\[ \text{III. EKF Approach in GNSS Carrier Tracking} \]

The state-of-the-art approach is behind the enormously successful implementation of Kalman filter in the signal processing field. The KF well suits for GNSS signal tracking and estimation [8]. The GNSS baseband received signal \{yk\} can be modeled as

\[ y_k = A_k e^{i\theta_k} + \eta_k \]

where \( k \) is the discrete time for a given discrete time interval \((tk = kT_s)\); \( A_k \) is the signal amplitude at the output of correlator over sampling time \( T_s \); \{\( A_k = C_k \) \( \{x_k\}_k\)\}, which includes the original signal amplitude \( (C_k) \) and scintillation effects \( (\{x_k\}_k) \); \( \theta_k \) is the signal phase at the output of the correlator over sampling time \( T_s \) which includes both dynamics and scintillations, \( \{\theta_k = \theta_d, k + \theta_s, k(\text{rad})\} \) and are independent of each other, which helps in the formulation of the state space model; and Gaussian measurement noise \( \eta_k \sim N\{0, \sigma_n^2\} \) includes both amplitude \( \eta_n, k \sim N\{0, \sigma_n^2\} \) and phase noises \( \eta_{\theta}, k \sim N\{0, \sigma_{\theta}^2\} \) useful in the estimation of process noise \( \{w_k\} \) which are obtained from the variances of ARX modeling in Table I.

A standard PLL architecture has a loop filter with IIIrd order Butterworth filter characteristics, which can be inferred to third-order Taylor-series expansion. The three-state input vector for the standard KF is given by \( x_k^{(1)} = [\theta_{d,k} f_{d,k} f_{r,k}]^T \). \( \theta_{d,k} \) is the phase dynamics input for standard KF state space formulation, which is given in (9). \( \theta_{o} \) (rad) is a priori fixed random constant.

### TABLE I

<table>
<thead>
<tr>
<th>ARX Parameters for CSM and Brazil Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>S4 Max</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>1.09</td>
</tr>
<tr>
<td>2.05</td>
</tr>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>2.0</td>
</tr>
</tbody>
</table>

Modeling the CSM amplitude and phase using the AR process can help in estimating the coefficients of the data to the carrier tracking algorithm [7]. However, for highly dynamic and nonlinear systems, it is more suitable to use the ARX modeling technique that uses least-squares recursion implementation which is appropriate for state-of-the-art algorithms. A hydrological flood forecasting model uses ARX modeling [12], which inspired us to implement it for GNSS carrier tracking algorithms. The ARX(p) modeling has a generalized form of \( \Psi_k(l) = \sum_{i=1}^{N} \beta_{k-i} \Psi_{k-i}(l) + \eta_k \), where \( \Psi_{k-i}(l) \) gives the previous model input values, \( \beta_{k-i} \) represents the coefficients of the modeled time series data, and \( \eta_k \) is the mean square error obtained from the observed and fitted value by the model.
The amplitude and phase scintillations is given by

$$ f = \frac{\theta_{d,k}}{2\pi} \left( \frac{f_{d,k}kT_s + \frac{1}{2}f_{r,k}k^2T_s^2}{f_{d,k}kT_s + \frac{1}{2}f_{r,k}k^2T_s^2} \right). \quad (9) $$

The standard KF does not work in severe scintillation conditions because of linear modeling characteristics [4]. Vila-Valls et al. gave an adaptive-KF methodology with AR(p) modeling including dynamics and phase scintillation [7], which has a significant advancement but tends to ignore the amplitude scintillation condition. The extended Kalman filter approach proposed by Vila-Valls has an enormous impact in both amplitude and phase scintillations [6]. However, this model developed under fixed AR-orders and remains a nonadaptive approach even though it makes a clear path for nonlinear measurement vector implementation. A clear understanding of the EKF algorithm with state space formulation for amplitude and phase scintillation equations can be seen in [6]. The results obtained through KF and EKF approaches are included for performance evaluation.

IV. NEW AEKF APPROACH IN MITIGATION OF SCINTILLATIONS

A new way of implementing the AEKF algorithm with different filter orders for amplitude and phase scintillations and also including adaptive measurement noise vector for discrete time of $k$ is given in this section. Fig. 1 gives a clear idea on the working of the AEKF estimation and scintillation mitigation algorithm. The modeled ARX order coefficients are directly driven to process the equation of the state space model. The measurement noise $\{R_k\}$ acts as an adaptive gain controller for the proposed algorithm, which helps in effective scintillation mitigation. The measurement vector $\{H_k\}$ is linearized with priori state input vector $X_{k/(k-1)}$ given by $\{H_k = h_k(x_{k/(k-1)})\}$. The initial covariance noise $\{Q_k\}$ is a time-variant quantity and adjusted as per knowledge on dynamic model ($w_k$).

The $m \times 1$-state input vector including phase dynamics, amplitude, and phase scintillations is given by

$$ x_k^{(1)} = [\theta_{d,k} f_{d,k} f_{r,k} \theta_{s,k} \theta_{s,k-1} \cdots p1 \ \bar{p}_{s,k} \ \bar{p}_{s,k-1} \cdots p2]^T \quad (10) $$

where $\theta_{s,k}$ (rad) is the phase scintillation state input with variable order-p1 and $\bar{p}_{s,k}$ is the amplitude scintillation state input with variable order-p2.

The process equation for the $m$-state AEKF can be modeled as

$$ x_k^{(2)} = K x_{k-1}^{(1)} + c1 + w_k. \quad (11) $$

The process noise ($w_k$) $\sim \{N(0, Q_k)\}$ describes the mismatches in the dynamic model, and $c1$ is the amplitude controllability parameter that helps in correct amplitude tracking selected according to the ARX constant value. The $m \times m$ new state transition matrix $K$ is given in (12), $K_d$ is to track phase dynamics, and $K_s$ is to mitigate amplitude and phase scintillations

$$ K = \begin{bmatrix} K_d & 0_{3 \times (p1+p2)} \\ 0_{3 \times (p1+p2)} & K_s \end{bmatrix} $$

$$ K_d = \begin{bmatrix} 1 & T_s & T_s^2 \\ 0 & 1 & T_s \\ 0 & 0 & 1 \end{bmatrix} $$

$$ K_s = \{\text{diag}(\beta_{p1,1}, \cdots \beta_{p1,p1}; \beta_{p2,1}, \cdots \beta_{p2,p2})\}. \quad (12) $$

$T_s$ is the sampling time, and $\beta_{p1,1}$ and $\beta_{p2,2}$ are the coefficients obtained from ARX modeling for phase and amplitude scintillations, respectively. The noise covariance matrix is given by $Q_k = \text{diag}(Q_{d,k} \eta_{ph,k} \eta_{fr,k} 0 \cdots (p1 + p2))$, and $Q_{d,k}$ is a priori fixed and depends on a priori covariance value $\{P_k\}$.

The new AEKF approach deals with the measurement noise variance that varies accordingly for every sampling time interval in the received data given by

$$ R_k = \begin{bmatrix} \sigma_{\theta}^2 & 0 \\ 0 & \sigma_{\eta}^2 \end{bmatrix}, $$

$$ \sigma_{\eta}^2 = \frac{1}{8\pi^2c/\text{noTs}} \left( 1 + \frac{1}{2c/\text{noTs}} \right). \quad (13) $$

The noise variance $\sigma_{\eta}^2$ depends on $c/\text{no}$ values obtained for each second. Initial covariance $\{P_k\}$ was adjusted accordingly from C/No estimation techniques [7].

The performance of the standard-KF, EKF, and proposed AEKF algorithms evaluated by coefficient of efficiency (CE) [12] is defined as

$$ \text{CE} = 1 - \left( \sum_{i=1}^{N} [q(i) - \bar{q}(i)]^2 \right) \sqrt{\sum_{i=1}^{N} [q(i) - \bar{q}(i)]^2} \quad (15) $$

where $q(i)$ is the raw scintillation data for time-period $i$ (s), $\bar{q}(i)$ is the simulated scintillation data for time period $i$ (s), and $\bar{q}$ is the average value for the raw scintillation data for a data record of length $N$. The algorithm should reach a unity CE value to perfectly track and mitigate the scintillations.

V. RESULTS AND DISCUSSIONS

In this letter, we evaluate our proposed algorithm for both synthetic and real-time data. CSM can provide synthetic ionospheric scintillation data to assess the performance of the proposed methods for different scintillation conditions as per
user interest, i.e., (catastrophic, strong, moderate, and weak) scintillations. We have to select the key parameters like $S_4$ index, correlation coefficient $\rho$, length of data record, and C/No (carrier-to-noise ratio) in a graphical user interface (GUI) which provides the In (in-phase component) and Qn (quadrature-phase component) values. The time resolution of the CSM data can be adjusted either to 10 ms (or) 20 ms, i.e., GUI can provide 50 Hz (or) 100 Hz data. In this letter, 100-Hz time resolution CSM data are considered. The severe scintillation condition parameters are tuned for CSM synthetic data with designed parameters of $S_4 = 0.8$, $(c/no) = 35$ db, and $T_s = 10$ ms.

From CSM time-histories, we chose the simulated data for severe scintillation condition $(0.6 \leq S_4 \leq 0.8)$. By observation from Fig. 2(a), it is clear that the ARX(2) power spectral density (psd) estimate is well suited for amplitude scintillation, and from Fig. 2(b), ARX(1) is more apt for CSM phase scintillation. The ARX parameters obtained for CSM data are given in Table I.

The initial state values for dynamics with aeronautical Doppler parameters with frequency shift $\{f_d, k = 2625.7(\text{Hz})\}$, frequency rate $\{f_r, k = 105(\text{Hz/s})\}$, and initial dynamic phase $\{\theta_{d,k}\}$ varied from $(-\pi, \pi)\text{rad}$ are selected. The parameters are useful in mitigation and tracking of amplitude and phase scintillations. The correct tracking and mitigation can be seen in Fig. 3. The dotted ellipse in phase scintillation clearly reflects the amount of mitigation by the proposed AEKF method.

The proposed technique is also tested with I and Q millisecond correlation values of PRN 12 with 1-ms time resolution data recorded at 21.30 H (local time) on October 24, 2012, in Rio de Janeiro, Brazil, by GSNRx [13]. In order to verify the effect of scintillation on real-time I and Q data, the amplitude scintillation index ($S_4$) [2] parameter is estimated using (6). The scintillation index obtained is in the range of $\{\text{min} 0.0097 \leq S_4 \geq 1.0594(\text{max})\}$, indicating the severe scintillation condition (Fig. 4). The signal amplitude is severely scintillated at the time instants between 21:30:30 and 21:30:40, and the amplitude scintillation index reaches 1.0594, i.e., catastrophic conditions.

Fig. 5(a) shows the amplitude scintillation modeling for real-time data which conveys that the ARX(2) psd estimate suits better than ARX(1) and ARX(3). It is also clear from Fig. 5(b) that the ARX(1) psd estimate follows real-time phase scintillation. The identified ARX modeling parameters for real-time Brazil data are given in Table I. Tracking and mitigation of amplitude and phase scintillations for Brazil data can be seen in Fig. 6. The dotted ellipse shows the phase mitigation for sudden transition that occurred at local time (21.30 H) to the next 6750–6800-ms duration by the proposed AEKF method. Performance evaluation of the proposed techniques is analyzed using the CE indicator. It is observed that AEKF outperforms the other models for real-time amplitude (0.9814) and phase (0.8144) data. Similarly, for synthetic data, the proposed method performs better than the existing models.

There is an improvement of 3.23% change for AEKF and EKF amplitude and 13.73% (AEKF and EKF) and 29.34% (AEKF and KF) phase scintillation real-time Brazil data from Table II. For CSM data, there is an improvement of 25.59% for AEKF and EKF amplitude and 10.32% (AEKF and EKF) and 37.9% (AEKF and KF) phase scintillations can be seen from Table II. It showcases the usefulness of the proposed methodology compared with existing techniques for both synthetic and real-time data.
VI. CONCLUSION

The adaptive way of choosing ARX(p1) and ARX(p2) orders for phase and amplitude scintillations directly from the In and Qn correlator samples signifies a new implementation in carrier tracking. The AEKF algorithm taking the criteria of measurement noise variance as gain controller helps in giving high CE values. This approach is useful in working directly on preprocessed raw data, which will help in the development of advanced and robust GNSS receivers.

TABLE II

<table>
<thead>
<tr>
<th></th>
<th>Brazil Data</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CE</td>
<td>Amplitude</td>
<td>Phase</td>
<td></td>
</tr>
<tr>
<td>KF</td>
<td>-</td>
<td>0.521</td>
<td></td>
</tr>
<tr>
<td>EKF</td>
<td>0.9491</td>
<td>0.6771</td>
<td></td>
</tr>
<tr>
<td>A-EKF</td>
<td>0.9814</td>
<td>0.8144</td>
<td></td>
</tr>
</tbody>
</table>

|        | CSM Data    |          |          |
| CE     | Amplitude   | Phase    |          |
| KF     | -           | 0.542    |          |
| EKF    | 0.7052      | 0.8178   |          |
| A-EKF  | 0.9611      | 0.921    |          |

ACKNOWLEDGMENT

The authors would like to thank Dr. L. P. S. Fortes and Dr. G. Lachapelle for releasing the data from the joint research project carried out by the Brazilian Institute of Geography and Statistics (IBGE), the University of the State of Rio de Janeiro (UERJ), and the Position, Location and Navigation (PLAN) Group of the Department of Geomatics Engineering, University of Calgary (UofC), in 2012–2013.

REFERENCES
