A Time Transfer Tracking Loop with Innovation-based Adaptive Kalman Filter in Dynamic Platforms

Yan Cheng
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
chengyan178@163.com

Xueyun Wang
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
xywang0130@163.com

Haifeng Wang
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
haifengwang203@163.com

Huijun Yang
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
ymjcasic203@163.com

Wenzhe Yang
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
ywzhecasic203@163.com

Liang Guo
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
642853387@qq.com

Shengkang Zhang
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
zhangsk@126.com

Jun Ge
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
13466728668@163.com

***Abstract*—Microwave two-way time transfer systems usually work in dynamic platforms, such as netted radar platforms, vehicles platforms, and so on. In static platforms, the microwave two-way time transfer system can achieve high precision time synchronization accuracy. However, in dynamic platforms, the time transfer system has poor robustness and synchronization accuracy. Accordingly, it is necessary to improve the time synchronization accuracy in dynamic systems. The time transfer modem is the core device of the microwave two-way time transfer system. The tracking loop is the key part of the modem. In dynamic platforms, the tracking loop is easy to lose lock and cannot work well. To enhance the tracking ability under complex dynamic conditions, an innovation-based adaptive Kalman filter tracking loop is proposed, which can adjust the noise covariances to adapt to the dynamic signals. The proposed tracking method has been applied to the time transfer receiver. According to the experimental results, compared with the traditional Phase Lock Loop (PLL) tracking method and the standard KF tracking loop, the proposed tracking loop has better tracking performance in dynamic conditions. This algorithm is of great significance for improving the time synchronization accuracy of complex dynamic collaborative networking systems.**

Keywords—Time transfer, Adaptive Kalman filter, tracking loop

I. INTRODUCTION

In dynamic collaborative networking systems such as radar and UAVs (Unmanned Aerial Vehicles), the key to collaborative work among different platforms is peer-to-peer time synchronization [1]. Therefore, high-precision time transfer systems typically need to work in complex scenarios such as dynamic conditions.

Now, the two-way time transfer technology is an important approach to achieve high-precision time synchronization [2][3]. The time transfer modem is the core device in the two-way time transfer system, which can modulate and demodulate the time transfer signal. In the demodulator, the tracking loop is a very important part. The high-precision time transfer modems are currently mainly working in static platforms. In dynamic platforms, the time transfer signal tracking loop in the demodulator is very fragile and easy to lose lock. The performance of the tracking loop will limit the performance of the entire time synchronization system. Accordingly, it is significant to enhance the performance of the time transfer tracking loop in dynamic platforms.

The Kalman filter (KF) algorithm has been applied to the carrier tracking loop in the Global navigation satellite system receivers to improve the tracking ability in dynamic and weak signal environments [4]. Reference [5] applied the KF algorithm in the tracking loop to enhance the tracking ability in weak signal environments. However, the KF estimation performance mainly relies on the noise statistical characteristics. In dynamic conditions, the real noises are time-varying. The KF algorithm with the fixed noise covariances cannot reflect the real noise statistical characteristics. The inaccurate noise covariances may degrade the KF estimation performance, and even cause divergence. Therefore, the adaptive Kalman filtering (AKF) algorithms should be applied in the tracking loop under dynamic conditions.

Many AKF methods have been employed in other areas, such as unmanned surface vehicles [6], positioning systems [7], inertial navigation systems [8], and so on. At present, there is no suitable AKF tracking algorithm applied to time transfer signal tracking loops. Hence, it is necessary to design proper AKF algorithms in the time transfer tracking loop.

This paper proposes an innovation-based AKF tracking loop to improve the tracking performance in dynamic conditions. The adaptive factor is applied to adjust the process noise covariances, which can enhance the self-adaptability in dynamic conditions. We employed the proposed tracking loop in the time transfer software receiver. According to the experimental results, in variable acceleration dynamic conditions, the proposed tracking algorithm can achieve stronger robustness than the traditional PLL tracking and the KF tracking.

II. Two-way Time Transfer Model

A. Microwave Two-way Time Transfer

The structure of the microwave two-way time transfer is shown in Fig. 1. Node 1 receives the microwave signal from node 2 to obtain the pseudo-range T_1. Similarly, the node 2 receives the microwave signal from the node 1 to obtain the pseudo-range T_2. By subtracting T_1 and T_2, the time difference results between the two atomic clocks can be obtained.

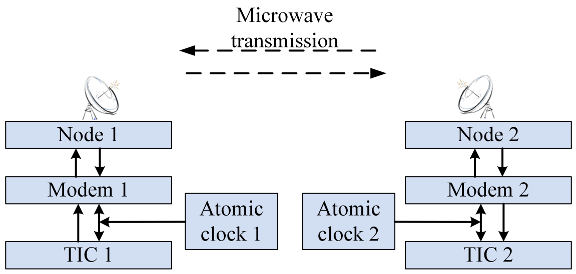

Fig. 1. Structure of the microwave two-way time transfer principle (TIC: time-interval counter)

B. Time Transfer Signal Model

The microwave two-way time transfer usually employs the code division multiple access (CDMA) system. The pseudo-random noise (PRN) code is widely used for the microwave time transfer signal. Because the autocorrelation of PRN code shows a clear peak value and the cross-correlations of different PRN codes are small. Therefore, in the same frequency channel, different PRN signals can be transmitted simultaneously.

For the node n in the time transfer system, the received signals can be expressed as follows:

$$x(t)=\sum_{n=1}^{M} A_n c_n(t-\tau_n)\cos(\omega_n t+\varphi_n)+w(t)$$

(1)where n denotes the transmit node n. A_n denotes the signal magnitude. c_n represents the transmit PRN signal. τ_n is the code delay. ω_n denotes the carrier frequency. φ_n denotes the carrier phase. $w(t)$ denotes the Gaussian white noise.

III. Proposed Innovation-based AKF Time Transfer Tracking Method

A. Time Transfer Tracking Loop

In Fig. 1, it can be seen that the modem is the most important part of the two-way time transfer systems. The modem contains the transmitter and receiver. The transmitter generates the timing signal which is modulated onto the RPN codes and carrier signals. The receiver demodulates the microwave signal into the time information.

For the receiver, the tracking loop is one of the most important modules. The tracking loop of the modem is shown in Fig. 2. The digital intermediate frequency (IF) signals are divided into the I channel and the Q channel. The I channel is multiplied by the local sin carrier, and the Q channel is multiplied by the local cos carrier. Then, the signal is multiplied with the local replication PRN signal to wipe off the PRN signal and obtain the integration signal. The integration values of the two channels are input into the phase discriminator to obtain the phase error. Then in the loop filter, it iterates with phase errors to obtain the carrier phase and frequency and update the carrier numerically controlled oscillator (NCO). The tracking loop iterates until the local replication carrier signal is the same as the input carrier and the timing information is demodulated.

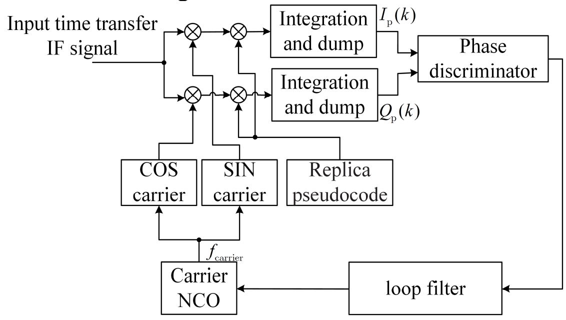

Fig. 2. The tracking loop of time transfer modem

B. KF-based Tracking Loop

In the two-way time transfer system, the tracking loop usually employs the phase lock loop (PLL) [9]. However, due to the fixed bandwidth of the PLL, the PLL is easy to lose lock when the modem is working under complex dynamic platforms. The KF has better self-adaptivity, which has been employed in the tracking loop.

For the time transfer tracking loop, the space state model of the KF tracking is shown below:

$$\mathbf{x}_k=\mathbf{\Phi}\mathbf{x}_{k-1}+\mathbf{n}_{k-1} \tag{2}$$

$$\mathbf{z}_k=\mathbf{H}\mathbf{x}_k+v_k \tag{3}$$

where (2) represents the state equation, and (3) represents the measurement equation. $\mathbf{x}_k$ denotes the state vector, and is defined as $\mathbf{x}_k=\begin{bmatrix}\Delta\varphi_k & \omega_k & \alpha_k\end{bmatrix}^{\mathrm{T}}$. $\Delta\varphi_k$, ω_k and α_k denote carrier phase error, Doppler frequency error and Doppler frequency rate, respectively. $\mathbf{\Phi}$ denotes the state transition matrix, is defined as $\mathbf{\Phi}=\begin{bmatrix}1 & T & T^2/2\\ 0 & 1 & T\\ 0 & 0 & 1\end{bmatrix}$. $\mathbf{z}_k$ is the measurement vector, and is defined as the results of the phase discriminator. $\mathbf{H}=\begin{bmatrix}1 & T/2 & T^2/6\end{bmatrix}$ is the measurement matrix. $\mathbf{n}_k$ denotes the process noise matrix, and v_k denotes the measurement noise matrix. According to the state space model of the time transfer KF-based tracking loop, the KF iteration process is as follows:

$$\hat{\mathbf{x}}_k^-=\mathbf{\Phi}\hat{\mathbf{x}}_{k-1} \tag{4}$$

$$\hat{\mathbf{P}}_k^-=\mathbf{\Phi}\hat{\mathbf{P}}_{k-1}\mathbf{\Phi}^{\mathrm{T}}+\mathbf{Q}_{k-1} \tag{5}$$

$$\mathbf{K}_k=\hat{\mathbf{P}}_k^-\mathbf{H}^{\mathrm{T}}\left(\mathbf{H}\hat{\mathbf{P}}_k^-\mathbf{H}^{\mathrm{T}}+\mathbf{R}_k\right)^{-1} \tag{6}$$

$$\hat{\mathbf{x}}_k=\hat{\mathbf{x}}_k^-+\mathbf{K}_k\left(\mathbf{z}_k-\mathbf{H}\hat{\mathbf{x}}_k^-\right) \tag{7}$$

$$\hat{\mathbf{P}}_k=\left(\mathbf{I}-\mathbf{K}_k\mathbf{H}\right)\hat{\mathbf{P}}_k^- \tag{8}$$

where $\mathbf{Q}_k$ is the process noise covariance matrix and $\mathbf{R}_k$ denotes the measurement noise covariance matrix. $\mathbf{K}_k$ denotes the Kalman gain.

C. Proposed Innovation-based AKF Tracking Loop

When time transfer systems work under complex conditions, the fixed covariance matrix in KF tracking cannot reflect the real time-varying noise statistics. The inaccurate noise covariance in KF tracking algorithm may degrade the estimation performance, and even lose lock. To enhance the KF tracking ability in complex dynamic conditions, we proposed an innovation-based adaptive KF algorithm to adjust the process noise covariance matrix.

An adaptive factor λ_k is applied to adjust the process noise covariance matrix in the KF algorithm, that is

$$\hat{\mathbf{P}}_k^- = \mathbf{\Phi}\hat{\mathbf{P}}_{k-1}\mathbf{\Phi}^{\mathrm{T}} + \lambda_k \mathbf{Q}_{k-1} \tag{9}$$

The adaptive factor can improve the accuracy of the $\mathbf{Q}_{k-1}$ value, thereby enhancing the accuracy of the Kalman gain during the iteration process, and ultimately improving the estimation accuracy of the state vector.

The computation of the adaptive factor is based on the innovation sequence. The innovation sequence is defined as:

$$\mathbf{d}_k = \mathbf{z}_k - \mathbf{H}\hat{\mathbf{x}}_k^- \tag{10}$$

When the KF tracking theoretical model perfectly matches the actual system, the innovation sequences obey the Gaussian white noise sequences. This indicates that all useful information in the innovation sequence has been extracted by the filter. Then the innovation sequences can obey the principle of orthogonality:

$$\mathrm{E}[\mathbf{d}_{k+j}\mathbf{d}_k^{\mathrm{T}}] = 0,\ k=1,2\cdots,\quad j=1,2\cdots \tag{11}$$

Accordingly, the adaptive factor is obtained by the orthogonal principle of innovation sequences. Because when the KF tracking system works in complex dynamic conditions, there are modeling errors for the KF system. Then the state estimation deviates from the actual state of the system, and it will inevitably manifest in the innovation sequences. If we adjust the adaptive factor λ_k to force the innovation sequences to obey the principle of orthogonality, the filtering system maintains effective tracking of the actual system state. If there are no modeling errors, the adaptive factor λ_k will be converted to 1.

According to [10], if the equation $\mathrm{E}[\mathbf{d}_{k+j}\mathbf{d}_k^{\mathrm{T}}] = 0$ holds, the following equation should be satisfied:

$$\hat{\mathbf{P}}_k^-\mathbf{H}^{\mathrm{T}} - \mathbf{K}_k\mathbf{C}_k = 0 \tag{12}$$

where $\mathbf{C}_k = \mathrm{E}[\mathbf{d}_k\mathbf{d}_k^T]$ denotes the covariance matrix of innovation sequences.

Substituting (6) into (12), it can be obtained that

$$\hat{\mathbf{P}}_k^-\mathbf{H}^{\mathrm{T}}\left\{\mathbf{I} - \left(\mathbf{H}\hat{\mathbf{P}}_k^-\mathbf{H}^{\mathrm{T}} + \mathbf{R}_k\right)^{-1}\mathbf{C}_k\right\} = 0 \tag{13}$$

Because $\hat{\mathbf{P}}_k^-$ and $\mathbf{H}^{\mathrm{T}}$ are positive-definite matrices, the sufficient condition of (13) is

$$\left(\mathbf{H}\hat{\mathbf{P}}_k^-\mathbf{H}^{\mathrm{T}} + \mathbf{R}_k\right)^{-1} \bullet \mathbf{C}_k = \mathbf{I} \tag{14}$$

Substituting (9) into (14), it can be obtained that

$$\mathbf{C}_k = \mathbf{H}\mathbf{\Phi}\hat{\mathbf{P}}_{k-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{H}^{\mathrm{T}} + \mathbf{R}_k + \lambda_k\mathbf{H}\mathbf{Q}_{k-1}\mathbf{H}^{\mathrm{T}} \tag{15}$$

Then,

$$\lambda_k = \frac{\mathbf{C}_k - \mathbf{H}\mathbf{\Phi}\hat{\mathbf{P}}_{k-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{H}^{\mathrm{T}} - \mathbf{R}_k}{\mathbf{H}\mathbf{Q}_{k-1}\mathbf{H}^{\mathrm{T}}} \tag{16}$$

For the convenience of calculation, we perform trace operations, namely,

$$\lambda_k = \frac{\mathrm{tr}(\mathbf{C}_k - \mathbf{H}\mathbf{\Phi}\hat{\mathbf{P}}_{k-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{H}^{\mathrm{T}} - \mathbf{R}_k)}{\mathrm{tr}(\mathbf{H}\mathbf{Q}_{k-1}\mathbf{H}^{\mathrm{T}})} \tag{17}$$

To ensure system stability, the adaptive factor λ_k should be greater than 1, namely,

$$\lambda_k = \max\left\{1,\ \frac{\mathrm{tr}(\mathbf{C}_k - \mathbf{H}\mathbf{\Phi}\hat{\mathbf{P}}_{k-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{H}^{\mathrm{T}} - \mathbf{R}_k)}{\mathrm{tr}(\mathbf{H}\mathbf{Q}_{k-1}\mathbf{H}^{\mathrm{T}})}\right\}\ k=1,2\cdots \tag{18}$$

Accordingly, the innovation-based AKF tracking loop is shown in Fig. 3. The loop filter has been replaced by the proposed innovation-based AKF algorithm.

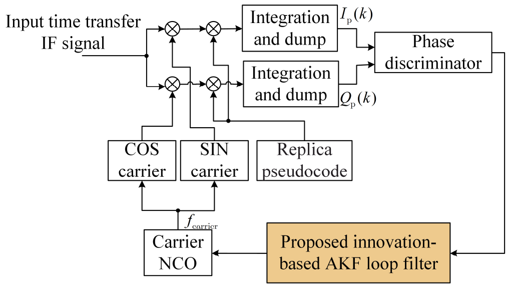

Fig. 3. The innovation-based AKF tracking loop diagram

IV. Experimental Validations

To verify the tracking ability of the proposed time transfer tracking method, we have carried out an experiment to test and analyze the algorithm. We compare the proposed innovation-based AKF tracking with the traditional PLL tracking and the KF tracking.

A. Experimental Setup Description

We have set up the simulated dynamic signal testing platform, and the test platform diagram is shown in Fig. 4. The hydrogen atomic clock provides high-performance frequency and time standards for the entire measurement system. The frequency distribution amplifier distributes and amplifies the 10MHz frequency signal, providing it as a frequency reference to the modem and channel simulator, respectively. The pulse distribution amplifier distributes and amplifies the 1PPS (1 Pulse Per Second) signal, providing it as a time reference to the modem. The time transfer modem generates time transfer signals, which are then processed through a channel simulator to generate the dynamic signals. The digital intermediate frequency signal is then generated through a collector and enters the software receiver system to verify the tracking algorithms. Fig. 5 demonstrates the field test platform.

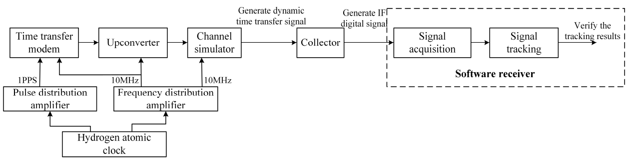

Fig. 4. The test platform diagram

Fig. 5. The field test platform

In the time transfer modem, the output IF signal frequency is 70MHz, and the code rate is 1Mchip/s. In the collector, the IF frequency is set to 4.17MHz, and the sampling rate is 62MHz. the C/N_0 of the input signal is set to 60dB-Hz.

B. Results Analysis

To verify the tracking ability of the proposed tracking method in complex dynamic conditions, we have set up a simulated dynamic scene with variable acceleration in the channel simulator. The velocity, acceleration, and acceleration changes of the simulated dynamic signal are shown in Fig. 6.

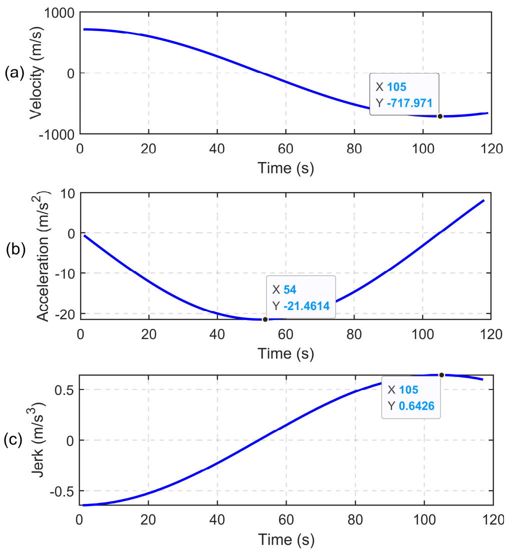

Fig. 6. The velocity, acceleration, and jerk changes of the simulated signals: (a) The changes of the velocity; (b) The changes of the acceleration; (c) The changes of the jerk

Fig. 7 demonstrates the C/N_0 estimations of the three tracking algorithms. The C/N_0 estimations are obtained by the tracking stage in the receiver according to the correlation values. Hence, the C/N_0 estimation results can reflect the tracking performance. In Fig. 7, it can be observed that the KF tracking and the proposed innovation-based AKF tracking can obtain accurate C/N_0 estimations with 60dB-Hz. However, the traditional PLL tracking loses lock and obtains inaccurate C/N_0 estimations. In addition, comparing the KF tracking and the proposed innovation-based AKF tracking, the proposed tracking achieves faster convergence speed in complex dynamic conditions.

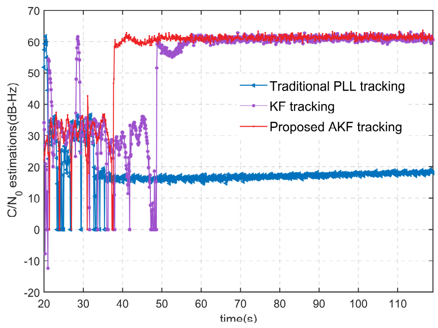

Fig. 7. The C/N_0 estimation results of the three tracking algorithms.

Accordingly, in variable acceleration conditions, the traditional PLL tracking with fixed bandwidth cannot tolerate dynamic pressure. However, the bandwidth of the KF tracking and the proposed AKF tracking are related to the Kalman gains. The variable Kalman gains can result in the variable bandwidth, which can adapt to the dynamic signals. Due to the variable process noise covariance matrix in the proposed AKF tracking, the proposed AKF tracking achieves stronger adaptability than the KF tracking with fixed process noise covariances.

V. Conclusions

An innovation-based AKF tracking algorithm is proposed to improve the tracking robustness in complex dynamic conditions. We applied the adaptive factor to adjust the process noise covariance matrices to compensate for noise modeling errors and adapt to the input time-varying signals.

To evaluate the proposed algorithm, the proposed tracking loop has been employed in the time transfer software receiver and the time transfer signal of the modem has been applied to verify the tracking algorithm. The experimental results demonstrate that the proposed tracking method can enhance the tracking robustness under complex dynamic platforms than the traditional PLL tracking and the KF tracking.

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