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Accurate Estimation the Scanning Cycle of the Reconnaissance Radar Based on a Single Unmanned Aerial Vehicle

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ABSTRACT In modern warfare, as a long distance detection equipment, a reconnaissance radar is crucial to monitor the sensitive regions and the intelligence of airborne targets. It is important for the opponent to identify the tactical information about the enemy's reconnaissance radar. It has a great influence on the war. Scanning cycle of the monitoring radar is an important parameter for the counterreconnaissance of the hostile radar source in the electronic countermeasure. Since the pulse Doppler (PD) radar is one of the most widely used type in modern reconnaissance radar domains, this paper focuses on scanning cycle estimation of the reconnaissance radar (PD radar) using a single unmanned aerial vehicle (UAV). We propose an effective method to reconstruct the main-beam pattern (MBP) curve of the radar antenna based on the norm approximation algorithm, and then the reconstructed MBP curve of the radar antenna is exploited to estimate the scanning cycle of the reconnaissance radar. By hovering the UAV at the same place, the scanning cycle of the reconnaissance radar can be estimated according to the reconstructed MBP curve. In the simulation section, we check the validity and robustness of the proposed method through the performance comparison with the Cramer–Rao lower bound.

INDEX TERMS Reconnaissance radar, scanning cycle, unmanned aerial vehicle (UAV), main-beam pattern (MBP), norm approximation.

I. INTRODUCTION

With the development of the information technology, various radars have been widely used in modern warfare [1], [2]. In particular, reconnaissance radar, such as the early warning radar, has played an important role in obtaining the intelligence of the airborne targets [3], [4]. Thus, by deploying the counter-reconnaissance of the hostile radar in the electronic warfare (EW) in advance, the tactical technical information such as the position and the scanning style of the hostile radar can be obtained by using technical methods, such as identification, analysis, calculation and localization. Those method are beneficial to determine the composition of the enemy's defense system and find out the monitoring blind zone. Moreover, it can guide the corresponding jammers and weapons to destroy the enemy's defense system [5], [6]. Undoubtedly, the counter-reconnaissance of the hostile radar can directly affect the victory and defeat of the warfare [7], [8].

The scanning cycle of the radar antenna is an important technical parameter to identify the hostile reconnaissance radar source in the electronic countermeasure (ECM) [9], [10]. The signals radiated from the modern reconnaissance radar are complex. Comparing with the parameters such as constantly changing agile frequency, waveform coding etc., the scanning cycle of the radar antenna remains relatively stable. Although the scanning cycles of different radar types are generally different, once the radar type is determined, it cannot be changed [11]. In particular, the possibility of modifying the radar antenna's scanning cycle is quite small when the scanning mode is unchanged. Therefore, if the scanning cycle of the hostile reconnaissance radar is obtained, more characteristic parameters of the radar source can be properly estimated. Firstly, the obtained scanning cycle of the hostile radar antenna can provide effective evidences to estimate the radar type and the scanning angle range. Moreover, it also helps to deduce the composition of the enemy defense systems and find out the monitoring blind area [12], [13]. Secondly, for the passive localization of the hostile reconnaissance radar based on the time difference of arrival (TDOA), an accurate estimation of the radar antenna's scanning cycle is beneficial for improving the localization performance [14], [15]. Thirdly, is useful to set the parameters of the jammer such as the number, the positions distribution, transmitting power, and so on [16], [17].

In order to detect the targets of all directions, the antenna of the reconnaissance radar rotates circularly with a constant angular speed for monitoring a larger angle scanning scope [18]. The receiver of the opposite side captures a set of the radar pulses during each rotation period of the reconnaissance radar. It is modulated by the main beam pattern (MBP) of the radar antenna. Generally speaking, the scanning cycle of the radar antenna can be evaluated according to the reference time of different received radar signals at a fixed position [19], [20]. Assumed that the reference time of the i-th pulse set is t_i, the reference time of the j-th pulse set is t_j, then the scanning cycle of the radar antenna is calculated via $T = (t_j - t_i)/(j - i)$. The reference time of the radar radiation can be described as the received time of a certain pulse [21].

Traditionally, there are three methods that take different pulses in the received radar signal to evaluate the reference time. The first method is to detect the rising edge of the first pulse in the received radar pulse set as the reference time [22]. The trip point of the first pulse's amplitude is taken as the reference time, which is easy to be distinguished and has an accurate performance. However, due to the amplitude of the first pulse is usually low. The estimation error is larger when the transmission loss is serious in poor environment. The second method is to utilize the receipt time of the largest amplitude pulse in the received pulse set as the reference time [23], which takes the advantage that the MBP of the radar antenna is commonly a symmetric unimodal function [24]. It is obvious that we can get a better performance when the azimuth beamwidth of the MBP is narrow. Although it exists several pulses with the largest amplitude when the azimuth beamwidth of the MBP is wide, it introduces a performance degradation. For the third method, the average arrival time of all the received pulses modulated by the MBP of the radar antenna is calculated as the reference time [25]. This method has a higher stability, but it needs a higher computational complexity. Furthermore, the independence of the pulse is necessary, otherwise the estimation performance is worse when the received pulses overlaps with each other.

In addition to the characteristics mentioned above, these methods have some unavoidable drawbacks. Due to the modulation of the radar antenna's MBP, the amplitudes of the received pulses are different from each other. Moreover, if the rotation speed of the radar antenna and the scanning cycle have not an exact division relationship, the sequences of the two received radar pulse sets are inconsistent with each other. In other words, the time interval of the first pulse or the largest amplitude pulse between the two separated scanning cycles is not integer multiples of the scanning cycle, which can result in a large estimation error. Furthermore, for the most commonly land based monitor equipments, it is difficult to completely capture the radar signals because of the affection of the complex topography or the earth curvature. Even though the monitoring equipments can be fixed on the air early warning (AEW), it is easy to be discovered and shot down for the large radar cross section (RCS).

Recently, the monitoring technologies based on the unmanned aerial vehicle (UAV) become a hotspot in the business applications and the scientific researches, which has many advantages. In particular, the small size and light weight of the UAV make it undetectable for the smaller RCS [26], [27]. In this paper, we identify the scanning cycle of the hostile reconnaissance radar based on the radar pulse sets by using a single UAV. When the UAV finds out the radar pulses during its flying monitoring period, it captures the pulse sets of several scanning cycles of the radar antenna. Taking full advantages of the radar antenna rotation as well as the UAV flying movement and combining the time information and the amplitude information of each received radar pulse, the MBP curve of the radar antenna can be reconstructed using the norm approximation method. Then the scanning cycle of the radar antenna is estimated depending on the time difference of the obtained MBP curves. We adopt the method proposed in [28] to approximate the MBP curve of the reconnaissance radar, and take the corresponding time of the maximum point of the reconstructed MBP curve as the reference time. Because the reconnaissance radar of the pulse doppler (PD) radar has been widely used in modern radar domain [29], we focus on the MBP curve approximation of the PD radar to estimate its scanning cycle in this paper. The proposed method is appropriate for the conventional reconnaissance radar.

The rest of the paper is organized as follows. Section II presents the system model for estimating the reconnaissance radar's scanning cycle based on a single UAV. In section III, we propose the methods to reconstruct the MBP curve of the radar antenna and estimate the scanning cycle of the reconnaissance radar (PD radar). Furthermore, the theoretical Cramer-Rao lower bound (CRLB) is also derived in this section, which is utilized as a benchmark to test the precision of the estimation performance. Simulation results and performance comparison are presented in Section IV. The conclusions are drawn in Section V.

II. SYSTEM MODEL

As shown in Fig. 1, we consider estimating the scanning cycle of the reconnaissance radar based on a single UAV. In the Cartesian coordinate system, the reconnaissance radar is fixed at $\mathbf{s}_o = [x_o, y_o, z_o]$. The antenna of the radar source emits continuous pulses and rotates with a constant azimuth angular velocity Ω radians per second. The scanning cycle of the reconnaissance radar can be calculated via $T = \Pi/\Omega$, where Π is the scanning scope of the radar antenna. Generally speaking, Ω and Π are the confidential parameters for the

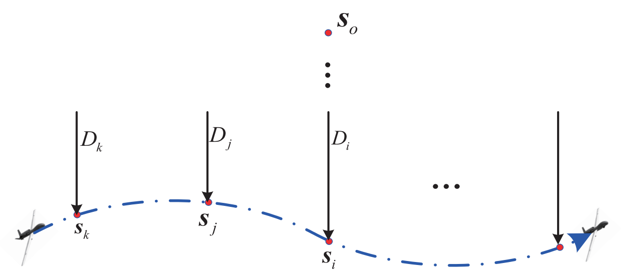

FIGURE 1. System model of scanning cycle estimation based on a single UAV.

radar owner, which means it is difficult to obtain the accurate values through traditional technologies.

As depicted in Fig. 1, the UAV is flying in the air to monitor the hostile reconnaissance radar. At time t_k, the position of the controllable UAV is $s_k = [x_k, y_k, z_k]$, which can be obtained by the airborne positioning equipment, such as the global position system (GPS). D_k is the distance between the radar s_o and the UAV at time t_k, $D_k = \|s_k - s_o\|_2$. Due to the high radiation power of the radar source, the operating range of the reconnaissance radar is normally more than several hundreds kilometers [14]. Thus, the distances D_k, D_j and D_i are drawn as a set of parallel lines in Fig. 1.

When the receiver loaded on the UAV detects the radar signal during its flying period, it captures several radar pulse sets $\boldsymbol{X}_k, \boldsymbol{X}_j, \boldsymbol{X}_i$ of the k-th, j-th and i-th radar antenna rotation cycles at positions s_k, s_j, and s_i. Each of these received pulse sets is a pulse series and is modulated by the MBP curve of the radar antenna. The values of the parameters k, j and i represent the numbers of the radar antenna rotation period respectively. Since the received pulse sets are similar with each other, we only present the method for addressing the pulse set $\boldsymbol{X}_k$ in the following sections. The received radar pulse set $\boldsymbol{X}_k$ can be expressed as

$$\begin{aligned}\boldsymbol{X}_k &= \sum_{n=1}^{N} A_{k,n} rect(\frac{t - nT_r}{\tau}) \\ &= rect(\frac{t}{\tau}) \sum_{n=1}^{N} A_{k,n} * \delta(t - nT_r), \qquad (1)\end{aligned}$$

where $n = 1, 2, \cdots, N$ and N is the total number of the radar pulses. $A_{k,n}$ is the corresponding amplitude of each pulse. $rect(t/\tau)$ represents the rectangular function, which means $rect(t/\tau) = 1$ when $0 \leqslant t \leqslant \tau$ and $rect(t/\tau) = 0$ when $T_r > t > \tau$. T_r is the pulse repetition period, and the pulse repetition frequency (PRF) is $f_r = 1/T_r$. τ is the time length of the radar pulse in seconds. $\delta(t)$ is unit pulse function and the notation $(*)$ stands for the convolution operation.

To improve the efficiency of the detection performance, some types of the reconnaissance radar have very high PRF, such as the pulse doppler (PD) radar [29]. That means each pulse in the received radar signal $\boldsymbol{X}_k$ is repeated M times, which can be explained by using the example depicted in Fig. 2. In the example, the pulse repeat time is set as $M = 5$ and θ_3 is the 3 dB azimuth beamwidth of the radar antenna's MBP. Then the total number of the received radar pulses in each set can be expressed as $N = (\theta_3/\Omega)$PRF. Generally, the repeat time M of each radar pulse can be obtained by the pulse detection equipment in the receiver.

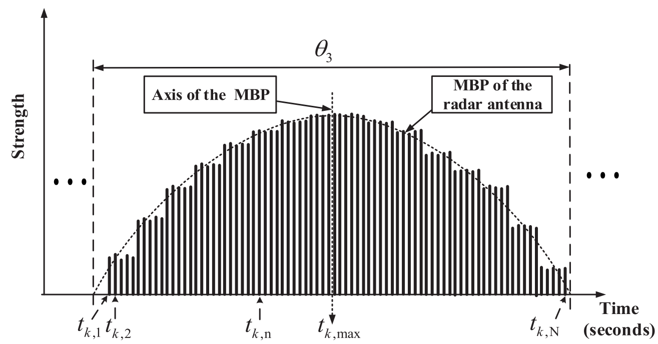

FIGURE 2. Example of the received pulse set emitted by the PD radar.

As depicted in Fig. 2, because of the fluctuation of the atmospheric attenuation coefficient, the strength of each repeated radar pulse in $\boldsymbol{X}_k$ has a slight floating. Combining the total number of the received radar pulses N and the detectable pulse repeat time M, we can devide the received signal $\boldsymbol{X}_k$ into M small sets and each set contains N_p radar pulses, namely $N = MN_P$. Using the matched filter in the receiver to process $\boldsymbol{X}_k$, we obtain the average strengths $\boldsymbol{E}_k$ and the corresponding time $\boldsymbol{t}_k$ of the received radar pulses, given as

$$\begin{aligned}\boldsymbol{E}_k &= [E_{k,1}, E_{k,2}, \ldots, E_{k,n}, \ldots, E_{k,N}]^T, \\ \boldsymbol{t}_k &= [t_{k,1}, t_{k,2}, \ldots, t_{k,n}, \ldots, t_{k,N}]^T. \qquad (2)\end{aligned}$$

Three important parameters should be obtained in advance to estimate the scanning cycle of the reconnaissance radar according to the method outlined in this paper. One is the time interval $\Psi_{k,j}$ between the two received radar pulse sets $\boldsymbol{X}_k$ and $\boldsymbol{X}_j$. They are captured by the UAV at $\boldsymbol{s}_k$ and $\boldsymbol{s}_j$. We propose an entirely different but effective method to estimate the time interval $\Psi_{k,j}$. The method approximates the MBP curve of the reconnaissance radar's antenna firstly, and then estimates the time interval parameter through $\Psi_{k,j} = t_{k,\max} - t_{j,\max}$. As depicted in Fig. 2, $t_{k,\max}$ and $t_{j,\max}$ are the peak time of the corresponding MBP curves. The other parameters are the corresponding radar antenna rotation period numbers k and j of $\boldsymbol{X}_k$ and $\boldsymbol{X}_j$, which can be achieved by the counter in the receiver. Finally, the scanning cycle of the reconnaissance radar is estimated according to the parameters $\Psi_{k,j}$, k and j.

III. PROPOSED METHOD

In this section, the principle of the norm approximation algorithm for reconstructing the MBP curve of the radar antenna is presented firstly. Afterwards, the procedures of the time interval estimation methods based on the MBP curve reconstruction is proposed. Then the scanning cycle of the PD radar (reconnaissance radar) is calculated based on the component analysis of the obtained time interval. Finally, the Cramer-Rao lower bound (CRLB) of the scanning cycle estimation is analyzed for the performance comparison in the simulation section.

A. PRINCIPLE OF THE NORM APPROXIMATION ALGORITHM

In practical applications, the MBP curve of the radar antenna is implicit in the fluctuant change of the received radar pulses, the mathematical model of which is typically unknown. However, it can be approximated using the norm approximation algorithm. For simplicity, the expression $G(t)$ is used to represent the MBP curve of the radar antenna in the following section. The norm approximation algorithm for $G(t)$ is to find out an explicit expression to well matching the obtained radar pulses at the corresponding receiving time.

As the algorithms mentioned in [28], we have a conclusion that the least squares (LS) ℓ_2 approximation algorithm, which puts very small weight on the small residuals but strong weight on the large residuals, has a better performance than the absolute residuals ℓ_1-norm approximation and the Chebyshev maximin ℓ_∞-norm approximation for reconstructing the MBP curve of the radar antenna. Therefore, the LS ℓ_2 approximation algorithm is employed to reconstruct the MBP curve $G(t)$ of the radar antenna in this paper. For the received radar signal $\boldsymbol{X_k}$, it is assumed that the objective function of the LS ℓ_2 approximation algorithm is $f(t_k, \boldsymbol{\alpha}_k)$, where $\boldsymbol{\alpha}_k$ represents the undetermined coefficients need to be estimated. For the effectiveness and the low complexity, the polynomial of the power function is taken as the base function in the following approximation algorithm. The residuals error $\boldsymbol{e}_k$ during the MBP reconstruction process can be expressed as

$$\boldsymbol{e}_k = [e_{k,1}, e_{k,2}, \ldots, e_{k,n}, \ldots, e_{k,N}]^T \tag{3}$$

where $e_{k,n} = f(t_{k,n}, \boldsymbol{\alpha}_k) - E_{k,n}, n = 1, 2, \ldots, N$.

The purpose of the LS ℓ_2-norm approximation algorithm is to minimize the sum squares of the residuals $\boldsymbol{e}_k$. The estimation method for calculating the undetermined coefficient $\boldsymbol{\alpha}_k$ for the LS ℓ_2-norm approximation method is

$$\hat{\boldsymbol{\alpha}}_k = \arg\min_{\boldsymbol{\alpha}_k} \sum_{l=1}^{N} (e_{k,l})^2, \tag{4}$$

where arg min stands for the argument of the minimum.

For the signals emitted by the PD radar, where each pulse is repeated by M, we propose two methods to reconstruct the MPB curve and estimate the time interval in this section. One is firstly to fit the MBP curve and estimate the time interval parameter M times separately, and then calculate the average value as the expected parameter. The other one is to calculate the average strength of each repeated radar pulse and the corresponding time firstly, and then fitting the MBP and estimate the time interval parameter. These two methods are equally suitable to the traditional reconnaissance radar when $M = 1$.

B. PROCEDURES OF THE TIME INTERVAL ESTIMATION

Here, we present the procedures of the two different methods mentioned above to approximate the MPB curve and estimate the time interval of the PD radar. The two methods are named the fitting then averaging (FTA) method and the averaging then fitting (ATF) method, respectively.

1) FITTING THEN AVERAGING METHOD (FTA)

The fitting then averaging method divides the processed PD radar pulse set $\boldsymbol{E}_k$ into M small sets according to the pulse repeated time M firstly, then the MBP curves of the radar antenna are reconstructed using the LS ℓ_2 approximation algorithm. Finally, the anticipate time interval parameter of the received radar signal is estimated by averaging the obtained M time interval parameters, which are calculated through the maximum point of each reconstructed MBP.

The procedures of the fitting then averaging method as follows:

Step I: Dividing the radar pulse set $\boldsymbol{E}_k$ into M small sets, the m-th radar pulse set and the corresponding time can be expressed as

$$\begin{aligned} \boldsymbol{E}_k^m &= [E_{k,1}^m, E_{k,2}^m, \ldots, E_{k,N_p}^m]^T, \\ \boldsymbol{t}_k^m &= [t_{k,1}^m, t_{k,2}^m, \ldots, t_{k,N_p}^m]^T. \end{aligned} \tag{5}$$

Step II: For each small set, the LS ℓ_2 approximation algorithm is exploited to approximate the MBP curve of the radar antenna, where the polynomial of the power function is taken as the base function. One has

$$\begin{aligned} \hat{\boldsymbol{\alpha}}_k^m &= \arg\min_{\boldsymbol{\alpha}_k^m} \sum_{l=1}^{N_p} (e_{k,l}^m)^2 \\ &= \operatorname{argmin}_{\boldsymbol{\alpha}_k^m} \sum_{l=1}^{N_p} (\boldsymbol{H}_k^m \boldsymbol{\alpha}_k^m - E_{k,l}^m)^2, \end{aligned} \tag{6}$$

where $m = 1, 2, \ldots, M$; $\hat{\boldsymbol{\alpha}}_k^m$ is the parameter needed to be estimated; $e_{k,l}^m$ represents fitting residual; $\boldsymbol{H}_k^m = [\boldsymbol{I}_{N_p}^m, \boldsymbol{t}_k^m, (\boldsymbol{t}_k^m)^2, \ldots, (\boldsymbol{t}_k^n)^L]^T$; and L is the orders of the base function.

Step III: Solving eq. (6) by

$$\begin{aligned} \hat{\boldsymbol{\alpha}}_k^m &= [\alpha_{k,0}^m, \alpha_{k,1}^m, \ldots, \alpha_{k,L}^m]^T \\ &= [(\boldsymbol{H}_k^m)^T \boldsymbol{H}_k^m]^{-1} (\boldsymbol{H}_k^m)^T \boldsymbol{E}_l^m. \end{aligned} \tag{7}$$

Step IV: Reconstructing the MBP curve of the radar antenna by using the obtained parameter $\hat{\boldsymbol{\alpha}}_k^m$ and the polynomial of the power function, one has

$$\begin{aligned} \hat{G}_k^m(t) &= [\boldsymbol{I}_{N_p}^m, \boldsymbol{t}_k^m, (\boldsymbol{t}_k^m)^2, \ldots, (\boldsymbol{t}_k^m)^L]^T [\alpha_{k,0}^m, \alpha_{k,1}^m, \ldots, \alpha_{k,L}^m]^T \\ &= \boldsymbol{H}_k^m \hat{\boldsymbol{\alpha}}_k^m. \end{aligned} \tag{8}$$

Step V: Finding out the peak time $t_{k,\max}^m$ and $t_{j,\max}^m$ of the obtained m-th MBP curves $\hat{G}_k^m(t)$ and $\hat{G}_j^m(t)$ of the radar antenna's k-th and j-th rotation cycle by

$$t_{k,\max}^{m} = \arg\max_{t} \left\{ \hat{G}_k^m(t) \right\}, \tag{9}$$

$$t_{j,\max}^{m} = \arg\max_{t} \left\{ \hat{G}_j^m(t) \right\}, \tag{10}$$

where arg max represents the argument of the maximum.

Step VI: Calculation the time interval parameter of the m-th small set via

$$\Psi_{k,j}^{m} = t_{k,\max}^{m} - t_{j,\max}^{m}. \tag{11}$$

Step VII: Averaging the obtained M time intervals of the received radar signals $\boldsymbol{E}_k$ and $\boldsymbol{E}_j$ to obtain the wanted time interval parameter $\Psi_{k,j}$, namely,

$$\Psi_{k,j} = \frac{1}{M} \sum_{m=1}^{M} \Psi_{k,j}^{m}. \tag{12}$$

2) AVERAGING THEN FITTING METHOD (ATF)

Since the averaging then fitting method has similar procedures with the fitting then averaging method, we just present their difference here. In the step I, the averaging then fitting method averages each repeated radar pulse and the corresponding sample time, given as

$$\begin{aligned} \boldsymbol{E}_k &= [E_{k,1}, E_{k,2}, \ldots, E_{k,N_p}]^T, \\ \boldsymbol{t}_k &= [t_{k,1}, t_{k,2}, \ldots, t_{k,N_p}]^T, \\ E_{k,l} &= \frac{1}{M} \sum_{m=1}^{M} E_{k,l}^{m}, \quad t_{k,l} = \frac{1}{M} \sum_{m=1}^{M} t_{k,l}^{m}, \end{aligned} \tag{13}$$

where $m = 1, 2, \ldots, M$ and $l = 1, 2, \ldots, N_p$. In the step II to IV, the averaging then fitting method approximates the MBP curve $\hat{G}_k(t)$ and $\hat{G}_j(t)$ of the radar antenna by using the data of eq. (13). In the step V, the the peak time $t_{k,\max}$ and $t_{j,\max}$ are found out and the final time interval parameter can be obtained via the equation $\Psi_{k,j} = t_{k,\max} - t_{j,\max}$ in the step VI.

C. METHOD TO ESTIMATION THE SCANNING CYCLE T

Due to the rotation of the radar antenna and the movement of the UAV flying, the obtained time interval contains different parts. To accurately estimate the scanning cycle T of the reconnaissance radar, it is sensible to thoroughly decompose the components included in the obtained $\Psi_{k,j}$.

Theoretically, $\Psi_{k,j}$ contains two parts. The first part $\Delta\hat{\tau}$ is the rotating time of the radar antenna during the UAV flying to capture $\boldsymbol{X}_k$ and $\boldsymbol{X}_j$, namely,

$$\Delta\hat{\tau} = \beta T + \frac{\Phi_{k,j}}{\Omega} = (k-j)T + \frac{\Phi_{k,j}}{\Omega}, \tag{14}$$

where $\beta = k - j$ is the cycle difference of the radar antenna rotation when the UAV captures the signals $\boldsymbol{X}_k$ and $\boldsymbol{X}_j$. $\Phi_{k,j}$ is the extra angle when the radar antenna rotates more than β cycles but less than $\beta + 1$ cycles. If the flight direction of the UAV is same as the radar antenna rotation direction, $\Phi_{k,j} \geq 0$, otherwise $\Phi_{k,j} \leq 0$.

The second part $\Delta\tilde{\tau}$ is the extra time difference in $\Psi_{k,j}$ introduced by the extra transmission distance of radar signals, which is caused by the flying movement of the UAV. If the UAV flies close to the radar, $\Delta\tilde{\tau} < 0$; if the UAV flies away from the radar, $\Delta\tilde{\tau} > 0$. Then

$$\Delta\tilde{\tau} = \frac{\Delta r_{k,j}}{c}, \tag{15}$$

where $\Delta r_{k,j} = D_k - D_j$ is the extra transmission distance of radar signals, which contains the unknown position $\boldsymbol{s}_o$ of the radar source. c is the radar signal propagation speed.

Therefore, $\Psi_{k,j}$ can be expressed as

$$\Psi_{k,j} = \Delta\hat{\tau} + \Delta\tilde{\tau} = \beta T + \frac{\Phi_{k,j}}{\Omega} + \frac{\Delta r_{k,j}}{c}. \tag{16}$$

To accurately estimate the scanning cycle T of the PD radar (reconnaissance radar), the UAV is controlled to hover in the same place to capture the radar pulse sets several times, such as $\boldsymbol{X}_k$, $\boldsymbol{X}_j$ and $\boldsymbol{X}_i$. Due to the UAV has no displacement during the radar signal receiving, the estimated time interval parameter $\Psi_{k,j}$ is only determined by the radar antenna scanning cycle, which means $\Delta r_{k,j} = 0$ and $\Phi_{k,j} = 0$ in eq. (16). Combining the obtained radar antenna rotation cycle numbers k and j, the scanning cycle of the radar antenna can be calculated as

$$\hat{T}_{k,j} = \frac{\Psi_{k,j}}{k-j}. \tag{17}$$

Generally speaking, the receiving time of the radar pulse set $\boldsymbol{X}_k$ is very short (in general case less than 0.5s), we assume the position of the UAV has no offset during its hovering. Obviously, the accuracy of the time interval parameter $\Psi_{k,j}$ between the k-th and the j-th radar antenna rotation period is important for the scanning cycle T estimation, which could be obtained from the method proposed above. Meanwhile, the cycle numbers k and j of the radar antenna rotation are obtained through the counter in the receiver, where the counter work like that add one each time when the receiver captures one radar pulse set.

D. CRLB OF THE TIME DELAY ESTIMATION

Cramer-Rao lower bound (CRLB) provides a performance reference for all unbiased estimators, which can be used for both theoretical analysis and performance comparison. Stein [30] has derived the analytical CRLB expression for the time interval or the time difference of arrival (TDOA) of the radar pulse signal as

$$\sigma_{t_R} = \frac{0.55}{B_s\sqrt{BN\tau\gamma}}, \tag{18}$$

where N is the number of the received radar pulse; τ is the radar pulse time length; B_s represents the bandwidth of the received signal; B represents the bandwidth of the noise; γ is the effective input signal to noise ratio (SNR) and $BN\tau$ is the correlation gain.

In this paper, the obtained time interval $\Psi_{k,j}$ between $\boldsymbol{X_k}$ and $\boldsymbol{X_j}$ can be virtually taken as the TDOA of the received radar signals. Both of them are established based on the same principle. Utilizing the relationship between the scanning cycle $T_{k,j}$ and the time interval parameter $\Psi_{k,j}$ revealed in (17), it is easily to deduce the CRLB of the scanning cycle estimation based on the fact that the exact number of the radar antenna rotation cycle can be easily obtained by the counter in the receiver. The CRLB of the radar antenna's scanning cycle estimation is

$$\sigma_T = \frac{\sigma_{t_R}}{\beta^2} = \frac{\sigma_{t_R}}{(k-j)^2}. \tag{19}$$

IV. SIMULATIONS AND PERFORMANCE ANALYSIS

The shipboard reconnaissance radar AN/SPS49 made by Raytheon company is taken as the radar source in this section. Without specification in the following simulations, the default values of the simulation parameters are shown in Table 1.

TABLE 1. Default values of the simulation parameters.

PARAMETERS	DEFAULT VALUE
Frequency	$f = 851 \sim 942MHz$
Surveillance Range	$5.6 \sim 474km$
Transmitting Power	$P_{\max} = 360kW, P_{\text{avg}} = 13kW$
Azimuth Rotation Rate	$\Omega = 36^o$/second
Scanning azimuth of radar antenna	$\Pi = 360^o$
Scanning period of radar antenna	$T = 10$seconds
3dB Azimuth Beamwidth	$\theta_3 = 3.3^o$
Pulse Repetition Frequency	$\text{PRF} = 2000Hz$
Repetition time of each Pulse	$M = 1, 5, 10$
Radar pulse length	$\tau = 125\mu s$
Cycle difference number	$\beta = 3$
Sampling Frequency	$F_s = 20MHz$
Main Beam Pattern Type	Gaussian function
Initial Position of the UAV	$\mathbf{s}_0 = [-50, -50, 4.5]^T km$
Position of the Radar source	$\mathbf{s}_o = [30, 30, 0.5]^T km$

Generally, the MBP curve $G(t)$ of the radar antenna mainly has three different types of the approximation function, i.e., Gaussian function, Sinc function and Cosine function. We take the Gaussian function as the MBP of the reconnaissance radar, which is used to modulate the radar pulses in the emitter. Its expression is

$$G(t) = \exp[-4\ln\sqrt{2}(\Omega/\theta_3)^2 t^2]. \tag{20}$$

There are two notes should be illustrated before the implementation of the simulation. Firstly, it can be found out from Table 1 that the maximum transmission power of the radar source is more that 360 KW, which means the received signal to noise ratio (SNR) is relatively high. For example, when the transmission power of the radar source is $p_s = 100$ KW, the frequency is $f = 900$ MHz, the received noise is $p_n = -100$ dBm, the transmission distance is $d = 300$ Km, the received SNR is about 38 dB in free-space. Therefore, the span of the received SNR is set as 20dB $\sim$ 50dB in the following simulations. Secondly, the value of the radar pulse repeated number M and the numbers of the radar antenna rotation cycle k and j during the UAV capturing the radar pulse sets are determined by the hardware of pulse detection device and the counter in the receiver respectively, which are not the focus of this paper. Therefore, we assume that their values have been obtained exactly before the following compute simulations.

Here, we simulate and analyze the estimation performance of the radar antenna's scanning cycle T using the proposed methods. The factors, such as the received SNR, the repetition time M of each pulse and the radar pulse length τ are taken into account in the simulations. Meanwhile, we compare the estimation performance with CRLB to verify the validity of the proposed methods. The estimation accuracy of T is evaluated by

$$\sigma(T) = \sqrt{\sum_{\gamma=1}^{\Gamma} (\hat{T}_{k,j}^{(\gamma)} - T)^2 / \Gamma}, \tag{21}$$

where $\hat{T}_{k,j}^{(\gamma)}$ is the estimation value of the γ-th simulation, and $\Gamma = 10^3$.

A. SENSITIVITY OF T ESTIMATION TO THE RECEIVED SNR

The estimation performance of the radar antenna scanning cycle T using the proposed two methods is compared with the received SNR increasing, when each received radar pulse is repeated by $M = 1, 5, 10$ times. When the cycle difference number of the two received radar pulse sets is $\beta = 3$ and the radar pulse length is $\tau = 125\mu s$, the estimation performance of the scanning cycle T versus the SNR is shown in Fig. 3.

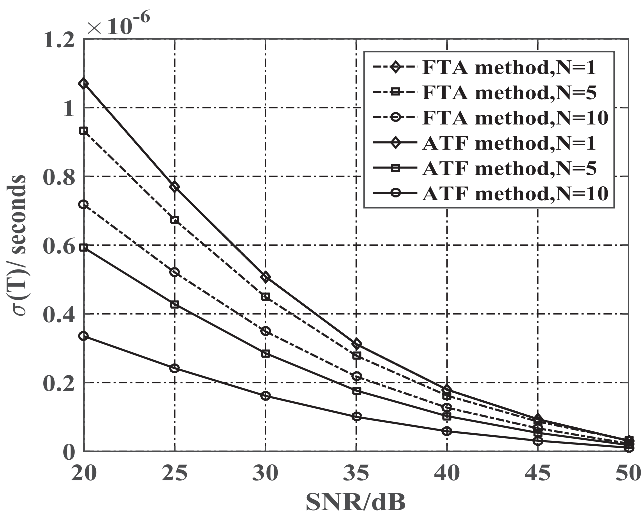

FIGURE 3. Sensitivity of scanning cycle T estimation to the received SNR.

As illustrated in Fig. 3, the accuracy of the scanning cycle T estimation becomes better overall as the received SNR increasing. The reason is that the received noise signals are more accurate with the increase of the SNR. On the other hand, for both the FTA method and the ATF method, they have the same estimation performance when $M = 1$, while the accuracy becomes better as M increase. Specifically, it is more accurate when $M = 10$ than $M = 5$, and the performance is the worst when $M = 1$. The reason is that the more times radar pulse repeated, the more information are collected by the receiver on the UAV. However, when the received SNR is high enough, this performance difference becomes unobvious and the estimation performances of T tend to a comparable performance (less than 0.1μs) when the received SNR more than 50 dB.

We also find out from Fig. 3 that the ATF method has better estimation accuracy than the FTA method, for example, the performance of the AFT method is more accurate when $M = 5$ than the FAT either $M = 5$ or $M = 10$. We explain this phenomenon based on the principle of the two methods. As described in the section III, the FTA method approximates the MBP curve of the radar antenna using different pulse sets firstly, then average the estimated $\Psi_{k,j}$ to calculate the scanning cycle T. While, the ATF method averages the repeated radar pulse firstly, which could eliminate the received noise.

B. SENSITIVITY OF T ESTIMATION TO THE RADAR PULSE LENGTH τ

The radar pulse length τ represents the duration time of each pulse, which has great influence on the scanning cycle T estimation. In this simulation, we analyze the estimation accuracy performance of T versus τ. When the cycle difference of the two received radar pulse sets is $\beta = 3$ and the received SNR = 30 dB, the estimation performance of scanning cycle T versus τ is shown in Fig. 4.

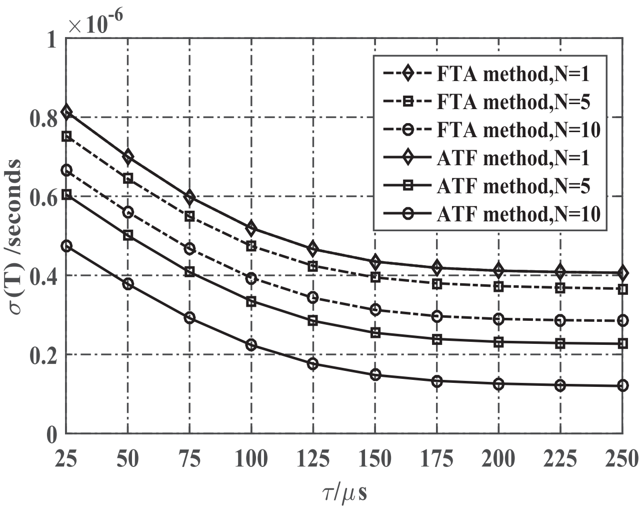

FIGURE 4. Sensitivity of T estimation to the radar pulse length τ.

As shown in Fig. 4, the estimation performance of the radar antenna scanning cycle T becomes better as the radar pulse length τ increases. That because the sampling number $S = F_s\tau$ of every radar pulse becomes large as τ increases, which improves the accuracy of the measurement parameters $\boldsymbol{E_k}$ and $\boldsymbol{t_k}$ in eq. (2). Moreover, the performance improvement of scanning cycle T estimation becomes inconspicuous and meets a relatively good performance when $\tau > 125\mu s$. Consequently, the proposed algorithm can reach a satisfactory estimation performance for radar antenna scanning cycle with suitable pulse length τ.

C. PERFORMANCE COMPARISON OF THE T ESTIMATION

To illustrate the validity of the proposed method, we compare the estimation performance of the ATF method with the state-of-art method and the CRLB. As indicated in the section I, the performances of the rising edge of the first pulse method and the largest amplitude pulse detection method largely depend on the capabilities of the corresponding hardware. In this simulation, we take the method of correlation reversed accumulation (CRA) [25] as the comparison scheme, which is used in the area of the time of arrival (TOA) estimation for the radar pulse. In this simulation, the CAR method is employed to estimation the time interval of the two received radar pulse sets, and then the scanning cycle of the radar antenna is estimated according to (17). When $M = 10$ and $\tau = 125\mu s$, the estimation performances of the CAR method and the ATF method as well as the corresponding CRLB are shown in Fig. 5.

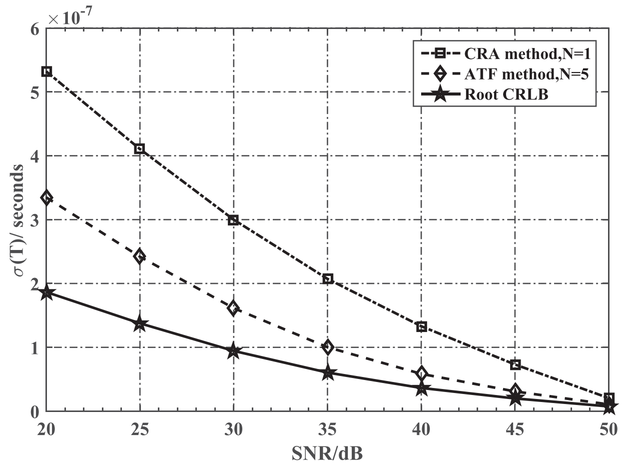

FIGURE 5. Performance comparison of the T estimation.

As can be seen from Fig. 5, the estimation error $\sigma(T)$ of the ATF method is almost reduced half than the CAR method when SNR > 25dB, which means the ATF method has more than 3 dB performance gain than the CRA method. This is also depending on the noise suppression characteristic of the ATF method. Meanwhile, we find out that as the increasing of the received SNR, the estimation performance of the ATF method can attain the theoretical CRLB accuracy.

V. CONCLUSION

Reconnaissance radar is the most important information sources to obtain the intelligence of the airborne targets in modern warfare. The parameter of the scanning cycle is significant for the opponent to detect and identify the reconnaissance radar source in the electronic countermeasure (ECM) domain. In this study, we proposed an effective method to accurately estimate the scanning cycle of the reconnaissance radar based on a single UAV. Taking full advantages of the movement of the UAV and the circulating rotation of the radar antenna, two methods were proposed to reconstruct the MBP curve of the PD radar (reconnaissance radar) antenna, then the obtained MBP curves were used to estimate the scanning cycle. Based on the computer simulation, we can draw a conclusion that the proposed ATF method is effective and robust to estimate the scanning cycle of the reconnaissance radar source, which could reach the CRLB performance when the received SNR is high.

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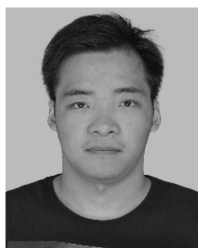

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