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Long Time Integration for High Speed Target Detection Based on RadonKT-LVT

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Abstract. In this paper, a computationally efficient long-time integration and parameters estimation method via Keystone transform (KT), Radon Transform (RT) and Lv’s Transform (LVT) is proposed. Firstly, the KT-Radon is used to eliminate the range cell migration (RCM) of the echo after pulse compression, then using LVT to obtain the long-time integration and parameters estimation of high-speed target with acceleration motion. Compared with the GRFT algorithm, the proposed method only needs one dimensional search for range. Compared with the KT-FRFT algorithm, there is no need to search Doppler fold factor in this proposed method. So the proposed method doesn’t suffer from huge computation cost and obtain a good tradeoff between the computational cost and detection performance in comparison with the above algorithms. Finally, several experiments are provided to demonstrate the effectiveness of RadonKT-LVT.

1. Introduction

With the development of technology, more and more high-speed targets with low radar cross section (RCS) appear in the radar searching area. And with the widely equipped of phase array antennas and ubiquitous technology, the long time integration processing is widely believed to be an effective way to increase the detection/estimation performance. However, the range cell migration (RCM) and Doppler frequency migration (DFM) would occur during the long time integration because of the complex motions of targets (i.e., high speed and acceleration, etc.), which may degrade the performance of traditional moving target detection (MTD).

Usually, the parametric-searching methods such as keystone transform (KT) [1] and Radon-Fourier transform (RFT) [2] are supposed to eliminate the RCM. In particular, KT can correct RCM by rescaling the slow time axis but it needs to do decouple and fold factor searching in the time-frequency domain. However, RFT still needs to perform a jointly searching along range and velocity directions. In order to detect high speed targets, these two methods will suffer from a lot of computation cost in searching parameters.

To remove the DFM induced by acceleration, the generalized Radon Fourier transform (GRFT) [3] is proposed by adding acceleration searching dimension. Meanwhile, a method combining KT and fractional Fourier transform (KT-FRFT) [4] is introduced to do a long time integration. A method combining GRFT and Lv’s transform (LVT) [5] is proposed to accumulate in the centroid frequency and chirp rate (CFCR) domain. The computational cost of these two methods are still very huge.
Motivated by the previous works, we propose a computationally efficient method to correct the RCM and estimate motion parameters of the moving target. Firstly, we use RT to indicate the fold factor of KT, then we can do the keystone transform by none factor searching. After that, the coherent accumulation of target energy and parameter estimation about velocity and acceleration could be obtained by the LVT. Compared with the GRFT and KT-FRFT, RadonKT-LVT is computationally efficient and exhibits a better detection ability. Compared with MTD and RFT, RadonKT-LVT can have a better performance in lower SNR because of the correction of RCM and DFM.

The rest is arranged as follows. Section 2 constructs the signal model and Section 3 proposes the RadonKT-LVT algorithm. Section 4 shows the result of experiments. Finally, a conclusion is given in Section 5.

2. Signal model

Suppose that the radar transmits a linear frequency modulated (LFM) signal as follows

$$s(t) = \text{rect} \left( \frac{t}{T_p} \right) \exp \left( j \pi K t^2 \right) \exp \left( j 2\pi f_c (t + t_m) \right)$$

where $t$ is the fast time, $t_m = m T_r$, $T_r$ denotes the pulse repetition time, $T_p$ is the pulse duration, $K$ is the frequency modulated rate, $f_c$ is the carrier frequency, $m = \frac{M}{2}, \ldots, \frac{M}{2}$ denotes the transmitted pulse number index, $M$ is the number of coherent integrated pulse which is usually used to be the integer power of 2.

The received baseband signal of a moving target can be stated as

$$s_r(t) = A_s \text{rect} \left( \frac{t - 2R(t_m) / c}{T_p} \right) \exp \left( j \pi K \left( t - 2R(t_m) / c \right) \right) \exp \left( -j \frac{4\pi}{\lambda} R(t_m) \right)$$

where $A_s$ is the amplitude of the received signal, $R(t_m)$ is the instantaneous range between radar and target and $\lambda$ denotes the wavelength of the transmitted signal.

After pulse compression, the compressed signal in the range time domain can be presented as [6]

$$s_{cm}(\hat{t}, t_m) = A_s \sin \left( B \left( \frac{\tau - 2R(t_m)}{c} \right) \right) \exp \left( -j \frac{4\pi}{\lambda} R(t_m) \right)$$

where $A_s$ denotes the signal amplitude and $B$ denotes the bandwidth of the transmitted signal.

Considering a maneuvering target, the $R(t_m)$ can be expressed as $R(t_m) = R_0 + v t_m + \frac{1}{2} a t_m^2$, where $R_0$ is the initial range from radar to the target, and $v, a$ denote the target’s real radial velocity and acceleration. Usually, the pulse repetition frequency (PRF) of the radar system is low and the velocity of the maneuvering target is high lead to the doppler ambiguity. The radial velocity [7] can be expressed as $v = v_0 + K v_{amb}$, where $v_{amb} = \lambda / 2T_r$ is blind velocity, $v_0 = \text{mod}(v, v_{amb})$ is the unambiguous velocity and $K$ is folded factor.

From (3), it can be seen from this that RCM is caused by $v$ and $a$. During the increasing integration time, RCM will reduce the gain of accumulate. However, the quadratic phase caused by acceleration (DFM) can also diffuse the energy of target.

After performing Fourier transform to the fast time $\hat{t}$, the compressed echo in the range frequency domain can be transfered as
\[ s_m(f, t_m) = A_r \text{rect}\left(\frac{f}{B}\right) \exp\left[-j \frac{4\pi}{c} (f + f_c) \left(R_0 + v_f t_m + \frac{1}{2} a t_m^2\right)\right] \times \exp\left[-j \frac{4\pi}{c} fK_{amb} t_m \right] \] (4)

3. Proposed method Based on RadonKT and LVT

3.1. Range cell migration correction

From (4), there exists a linear and quadratic coupling between \( f \) and \( t_m \). Usually the linear one occupies the main position of RCM due to the high speed of target. Therefore, the keystone transform (KT) is used to eliminate the linear coupling and its scaling formula is as follows

\[ t_m = f_c / (f + f_c) t_n \] (5)

where \( t_n \) denotes the scaled slow time after KT. Applying the (5) to (4), we can obtain

\[ s_{KT}(f, t_n) = A_r \text{rect}\left(\frac{f}{B}\right) \exp\left[-j \frac{4\pi R_0}{\lambda} \left(1 + \frac{f}{f_c}\right)\right] \times \exp\left[-j \frac{4\pi v_f t_n}{\lambda} \right] \times \exp\left[-j \frac{4\pi fK_{amb} t_n}{\lambda} \frac{f}{f + f_c}\right] \exp\left[-j \frac{4\pi \frac{a t_n^2}{f_c}}{\lambda} \frac{f}{f + f_c}\right] \] (6)

In the narrowband of radar system \( f \ll f_c \), we can have \( \frac{f_c}{f + f_c} \approx 1, \frac{f}{f + f_c} \approx \frac{f}{f_c} \). So (6) can be approximately expressed as

\[ s_{KT}(f, t_n) \approx A_r \text{rect}\left(\frac{f}{B}\right) \exp\left[-j \frac{4\pi R_0}{\lambda} \left(1 + \frac{f}{f_c}\right)\right] \times \exp\left[-j \frac{4\pi v_f t_n}{\lambda} \right] \times \exp\left[-j \frac{4\pi fK_{amb} t_n}{\lambda} \frac{f}{f_c}\right] \] (7)

It can be seen from (7) that the coupling between \( v_f \) and \( f \) has been eliminated but the migration caused by folded factor \( K \) still exists. Usually, we compensate the folded factor by searching the possible \( K' \). That is to construct a compensation function as follows

\[ H(f, t_n; K') \] (8)

After multiplying (8) by (7) and performing the inverse FFT along the \( f \) dimension, we have

\[ s_{KT}(f, t_n; K') = A_r \sin c\left[ B \left(f - \frac{2R_0}{c} \frac{2(K - K')}{c} v_{amb} t_n \right) - j \frac{4\pi}{\lambda} \left(R_0 + v_f t_n + \frac{1}{2} a t_n^2\right) \right] \times \exp\left[-j \frac{4\pi v_f t_n}{\lambda} \right] \times \exp\left[-j \frac{4\pi fK_{amb} t_n}{\lambda} \frac{f}{f_c}\right] \] (9)

If and only if \( K' = K \), the RCM is totally eliminated (assuming that \( |\omega (NT)^{2/3} | < \Delta r, \Delta r \) is half of one range cell). And the efficient of target’s energy integration can reach the max peak. However, due to the higher and higher speed of maneuvering target the searching times will be more and more big. Finally, the computation load will be very heavy and can’t meet the instant processing requirements.
So we use the radon transform (RT) to get the real folded factor instead of the searching method. The definition of RT is as follows:

Creating a two-dimensional plane \( f(x, y) \) and doing the integration along a line \( l \) of \( f(x, y) \).

The integration in the \( \rho - \theta \) domain can be expressed as [8]

\[
R(\rho, \theta) = \iint f(x, y) \delta(\rho - x \cos \theta - y \sin \theta) \, dx \, dy
\]

(10)

where \( \rho \) is the minimum distance between the line \( l \) and the origin of the coordinates in \( f(x, y) \), \( \theta \) is the angle between the line \( l \) and the X axis and \( \delta(x) \) is the Dirac’s function.

It can be obtained from the (9) that the peak position between adjacent pulse in \( \hat{t} \) domain is:

\[
\Delta_{\rho} = \frac{2K_{\text{amb}}}{c} T_{s} = \frac{2KT_{s}}{c} \lambda f_{c} = \frac{K}{s}
\]

(11)

So in the whole integration time, these peak positions construct a line with a slope \( k \) can be represented as \( k = \frac{K_{c}}{f_{c}} \). The slope \( k \) which has the maximum value in the RT domain can be transformed to the folded factor \( \hat{K} \). The estimation formula can be expressed as:

\[
K' = \tan\left(\arg \max_{\theta} \left| \text{Radon}\left(\text{abs}\left(s_{\text{KT}}(\hat{t}, t_{n})\right), \theta\right)\right| f_{c} / f_{s}
\]

(12)

Then we can construct the compensation function \( H(f, t_{n}; K') \) to make the target echo signal within the same original range cell.

3.2. **DFM correction and parameters estimation**

In the last section, we use the RadonKT method to eliminate the RCM and there only exists the DFM of the target echo signal. It can be obtained from (9) that the signal after KT along the slow time axis at \( \hat{t} = t_{0} \) is a LFM signal. We can use the fast time-frequency analysis algorithm for LFM signal—LVT to correct the DFM and estimate the maneuvering parameters of target. As we can obtain the centroid frequency and chirp rate of LFM signal, we would get the velocity and acceleration of the maneuvering target.

Firstly, we defined the parametric symmetric instantaneous autocorrelation function (PSIAF) as follows [9]

\[
R_{0}^{C}(t_{n}, \tau_{n}) = s_{\text{KT}}\left(t_{n} + \frac{\tau_{n} + b}{2}\right) s_{\text{KT}}^{*}\left(t_{n} - \frac{\tau_{n} + b}{2}\right)
\]

(13)

\[
= A_{0} \exp\left[j2\pi f_{0}(\tau_{n} + b) + j2\pi k_{0}(\tau_{n} + b)t_{n}\right]
\]

where \( \tau_{n} \) denotes a lag variable and \( b \) is a constant time delay related to a scaling operator.

And where [10]

\[
f_{0} = f_{d} = \frac{v_{0}}{2\lambda} \quad k_{0} = \frac{2a}{\lambda}
\]

(14)

It can be seen from the (13) that there exists the coupling between \( t_{n} \) and \( \tau_{n} \). The scaled transform is constructed to remove the coupling as follows

\[
t_{n} = \frac{t_{k}}{h(\tau_{n} + b)}
\]

(15)
where \( t_k \) denotes the scaled time and \( h \) is the scaled factor. Then we can have
\[
R_k^c(t_k, \tau_n) = A^2 \exp \left[ j2\pi f_0 (t_k + b) + j2\pi \frac{k_0}{h} t_k \right]
\]  
(16)

It can be seen from the above that the coupling has been eliminated. Usually, we set \( b = 1 \) and \( h = 1 \), then perform 2-D FFT on \( R_k^c(t_k, \tau_n) \). We can obtain
\[
L_0(f, \gamma) = \text{FFT} \left\{ \text{FFT} \left[ R(t_k, \tau_n) \right] \right\} = A_0 \exp \left( j2\pi f \right) \sin c \left( f - f_0 \right) \sin c \left( \gamma - k_0 \right)
\]  
(17)

where \( A_0 \) the amplitude after performing 2-D FFT.

It can be seen from the above that the energy of LFM signal is accumulated as a peak in the CFCR domain by using LVT method. And the estimated value of \( v_0 \) and \( a \) can be obtained as
\[
\hat{v}_0 = 2\lambda \hat{f}_0 \quad \hat{a} = \frac{1}{2} \lambda \hat{k}_0
\]  
(18)

4. Computational complexity analysis

The computational complexity of the proposed method is analyzed in the follows in the lights of the number of complex multiplications.

Set that \( N_r, N_p, N_v, N_a, N_k \) represent the number of range cells, pulse numbers, searching velocity numbers, searching acceleration numbers and searching folded factor numbers in KT compensation. For Radon-KT, the computation complexity [11] is \( O( N_r N_p \log_2 N_p) \). For LVT, the computation complexity [12] is \( O( N_r^2 \log_2 N_r + N_r N_p) \). Thus, the total computation complexity of RadonKT-LVT is in the order of \( O( N_r N_p \log_2 N_p) \). For GRFT proposed in [3], the computation complexity is \( O( N_r N_v N_a N_p \log_2 N_p) \). As for the KT-FRFT, the computation complexity of FRFT in signal after KT without radon transform is \( O( N_r^2 N_p \log_2 N_p) \). Hence, its total computation cost is \( O( N_r N_v N_a N_p \log_2 N_p) \).

Under the assumption that \( N_r = N_p = N_v = N_a = N \) and \( N_k \log_2 N_p = N \), the computation cost of GRFT method is \( O( N^4 \log_2 N) \) and the KT-FRFT method has computation cost of \( O( N^4) \). However, the computation cost of proposed method is \( O( N^3 \log_2 N) \). It can be seen from above that GRFT has more computation cost than proposed method due to the three-dimension searching process while the proposed method can remove RCM and DFM and the estimate the velocity and acceleration with only one-dimension searching in range dimension.

5. Experiments and Discussions

The radar parameters in the following simulation experiments are showed in Table 1

| Simulation parameters | Carrier frequency | Bandwidth | Pulse width | Sample frequency | Pulse repetition frequency | Pulse number |
|-----------------------|------------------|-----------|-------------|------------------|---------------------------|-------------|
| values                | 1GHz             | 2MHz      | 400us       | 2MHz             | 800Hz                     | 1024        |

Suppose there is a point target with 1000m/s initial radial velocity and 30m/s² acceleration. After adding Gauss white noise to the echo of target, the SNR before pulse compression (PC) is -20dB.
First of all, the long time integration ability of RadonKT-LVT for the target is evaluated in Figure 1. Figure 1(a) shows the target echo before PC which is completely buried in noise. The PC result is shown in Figure 1(b), which shows that RCM happens. Figure 1(c) shows the integration result along different polar angles. It can be seen from the figure that there is an obvious peak in the figure. Once we obtain the position of the peak, we can immediately estimate the folded factor according to (13). Then we can perform KT to correct the RCM as is shown in Figure 1(d). After eliminating the RCM, there still exists DFM. So LVT is performed to focus the energy and the result in CFCR domain is shown in Figure 1(e). We estimate the moving parameters of target by confirming the position of the peak in LVT result. The estimated velocity and acceleration are $1000.22 \text{ m/s} / \text{ms}$ and $29.67 \text{ m/s}^2$. The result shows that the proposed method has high estimation precision of maneuvering parameters. As for comparison, the classic MTD method is used under the same environment shown in the Figure 1(f).

![Figure 1](image1.png)

Figure 1. Simulation results based on RadonKT-LVT. (a) target echo before PC. (b) PC result. (c) Radon result. (d) KT result. (e) LVT result. (f) MTD result.

However, when the SNR before PC is dropped to -30dB, the integration result with MTD method can’t detect the target in Figure 2(a) and the integration with RFT method still has poor detection result in Figure 2(b) with serious blind sidelobe phenomenon. As can be seen from Figure 2(c) that the proposed method can still have obviously better result.

![Figure 2](image2.png)

Figure 2. Simulation results of different methods. (a) MTD result. (b) RFT result. (c) RadonKT-LVT result
6. Conclusions
A long time integration approach combining the RadonKT and LVT (i.e., RadonKT-LVT) is presented to keep a balance between detection ability and computational cost of target with high speed and acceleration motion. The RCM of target echo can be effectively eliminated by using the improved KT based on RT. Then estimating the target’s velocity and acceleration. Results of simulation experiments have verified the effectiveness of the RadonKT-LVT algorithm.

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