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A low complexity algorithm for across range unit effect correction of the moving target via range frequency polynomial-phase transform

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ABSTRACT

Based on the moving target detection, this paper proposes a low complexity algorithm for moving target across range unit effect correction on the basis of the range frequency polynomial-phase transform, utilizing which to remove the coupling of the range frequency and the slow time, then the across range unit effect can be corrected effectively. The algorithm does not need to search the target's parameters and estimate the Doppler ambiguity integer, and its computational complexity is low. The simulation results have proved the effectiveness of the proposed algorithm.

1. Introduction

Radar is capable of detecting, recognizing and tracking the moving targets in all weather conditions. As a result, the radar technology is more and more widely used in civilian and military fields [1,2]. The detection of ground vehicles, aircrafts, and other moving targets is one of the main applications of radar [3–5]. However, along with the continuous development of modern science and technology, the targets for detection move faster and faster, which easily causes the across range unit (ARU) effect of the echo within a coherent processing interval (CPI). When that happens, the energy of the echo will be dispersed in different range cells, and can not be accumulated effectively, which makes the targets more difficult to be detected [5].

At present, there are a lot of methods to solve the problem of the ARU effect correction [3,4,6–16], which include: Radon transform (RT) [6,7], Hough transform (HT) [8,9], Radon–Fourier transform (RFT) [10,11]. This kind of methods is to directly search the track of the echo in the range cell-slow time domain to solve the problem and complete the target detection at the same time. And another type of methods is to firstly correct the echo with the ARU effect to the same range cell, and then the energy of the echo within a range cell is accumulated effectively to realize target detection. It includes the Keystone transform [3,4,12,13] and the frequency domain compensation method [14–16]. While using the Keystone transform to correct the ARU effect of the echo of the high-speed target with Doppler ambiguity, the Doppler ambiguity integer needs to be estimated and the accuracy of which will affect the performance of the ARU effect correction directly [13]. On the other hand, the frequency domain compensation method involves the search operations of the speed parameter of the moving target, thus it requires much higher computation complexity [14].

This paper put forward a new kind of algorithm to correct the ARU effect. This method carries out range frequency polynomial-phase transform (RFPPT) on the echo within the range frequency-slow time domain to decouple the range frequency and the slow time, thus laying a foundation for the following target detection and parameter estimation. The proposed method has greatly reduced the amount of calculation with a good effect of the ARU effect correction and it does not need to estimate the Doppler ambiguity integer of the target during the process.

The reminder of the paper is organized as follows. In Section 2, the signal model is presented. In Section 3, the low complexity algorithm for ARU effect correction is proposed. In Section 4, we analyze the norm of the selection of the lag-time. In Section 5, the computational complexity analysis is proposed, and the computational complexity of the proposed method is compared with some methods. In Section 6, we evaluate the performance of the proposed method based on some simulation experiments. In Section 7, the conclusions are given.

2. The signal model of the moving target

The echo of the moving target can be represented as

$$\begin{aligned} s_r(t', t_m) &= A_1 p\left[t' - \frac{2r(t_m)}{c}\right] \exp\left[-j2\pi f_c \frac{2r(t_m)}{c}\right] \\ &= A_1 p\left[t' - \frac{2(r_0 + v_0 t_m)}{c}\right] \exp\left[-j2\pi f_c \frac{2(r_0 + v_0 t_m)}{c}\right] \end{aligned}$$

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$$\begin{aligned}&= A_1 p\left[t' - \frac{2(r_0+v_0t_m)}{c}\right]\exp\left[-j2\pi\frac{2(r_0+v_0t_m)}{\lambda}\right]\\ &= A_1 p\left[t' - \frac{2(r_0+v_0t_m)}{c}\right]\exp\left[-j\frac{4\pi}{\lambda}(r_0+v_0t_m)\right]\\ &= A_1 B\big(t',t_m\big)\exp\left[-j\frac{4\pi}{\lambda}(r_0+v_0t_m)\right] \qquad (1)\end{aligned}$$

where, $p(\cdot)$ is the envelope of the echo, $p(t') = \operatorname{sinc}(B_s t')$, $\operatorname{sinc}(\cdot) = \sin(\pi x)/\pi x$, B_s is the bandwidth of the echo. And the $B(t', t_m)$ can be written as

$$B\big(t',t_m\big) = p\left[t' - \frac{2(r_0+v_0t_m)}{c}\right] = p\left[t' - \frac{2r_0}{c} - \frac{2v_0t_m}{c}\right] \qquad (2)$$

where A_1 is the amplitude of the echo, t' is the fast time, $t_m = mT_r$ is the slow time, $m = 0, \ldots, M-1$, M is the number of the pulses, T_r is the pulse repetition interval, c is the speed of light, f_c is the carrier frequency, $\lambda = \frac{c}{f_c}$ is the wave length. $r(t_m) = r_0 + v_0 t_m$ is the radial range between the moving target and the radar, r_0, v_0 denote the initial distance between the target and the radar, the initial target radial velocity, respectively.

As is shown in the formula (2), the envelope of the echo is a function of the slow time t_m, the position of the envelope changes with the slow time, and the ARU effect of the echo is reflected in this term [4]. The ARU effect can be corrected effectively if the position of the envelope is not relevant to the slow time t_m.

Carrying out the Fourier transform (FT) along t'-axis of (1), the range frequency-slow time distribution of the echo can be expressed as [11,13]

$$\begin{aligned}W(f,t_m) &= A_1 P(f)\exp\left[-j2\pi f\frac{2(r_0+v_0t_m)}{c}\right]\\ &\quad\times\exp\left[-j\frac{4\pi}{\lambda}(r_0+v_0t_m)\right]\\ &= A_1P(f)\exp\left(-j2\pi f\frac{2r_0}{c}\right)\exp\left(-j2\pi f\frac{2v_0t_m}{c}\right)\\ &\quad\times\exp\left[-j\frac{4\pi}{\lambda}(r_0+v_0t_m)\right]\\ &= A_1P(f)\exp\left(-j2\pi f\frac{2r_0}{c}\right)\exp\left(-j2\pi f\frac{2v_0t_m}{c}\right)\\ &\quad\times\exp\left(-j\frac{4\pi}{\lambda}r_0\right)\exp\left(-j\frac{4\pi}{\lambda}v_0t_m\right)\\ &= A_1P(f)\exp\left(-j2\pi f\frac{2r_0}{c}\right)\varphi(f,t_m)\\ &\quad\times\exp\left(-j\frac{4\pi}{\lambda}r_0\right)\exp\left(-j\frac{4\pi}{\lambda}v_0t_m\right) \qquad (3)\end{aligned}$$

where

$$\operatorname{rect}(u) = \begin{cases}1, & |u| \le \frac{1}{2}\\ 0, & |u| > \frac{1}{2}\end{cases} \qquad (4)$$

$$P(f) = \operatorname{rect}\left(\frac{f}{B_s}\right) \qquad (5)$$

$$\varphi(f,t_m) = \exp\left(-j2\pi f\frac{2v_0t_m}{c}\right) \qquad (6)$$

where, f is the range frequency domain with respect to fast time t', $P(f)$ is the Fourier transform of $p(t')$, B_s is the bandwidth of the signal. It can be seen from (3) and (6) that the ARU effect in (2) is reflected in the coupling of the range frequency domain f and v_0t_m, the ARU effect can be corrected effectually if the coupling of the f and v_0t_m is removed effectively [15].

3. The principle of the proposed algorithm

Using the idea of the polynomial phase transform [17] which can reduce the order of the complex signal, a low complexity algorithm for moving target ARU effect correction based on RFPPT is proposed in this paper. It can remove the coupling of the range frequency domain f and v_0t_m, and then the ARU effect can be corrected effectively.

When the velocity of the target is high enough to lead to the Doppler ambiguity phenomenon, the ARU effect can also be corrected by proposed method. Next, the moving targets are divided into two categories, the low-speed targets without the Doppler ambiguity phenomenon, and the high-speed targets with the Doppler ambiguity problem. Based on these two categories of the moving targets, the principle of the proposed algorithm is discussed below.

3.1. Low-speed target (without Doppler ambiguity phenomenon)

When the moving target is without the Doppler ambiguity, the formula (3) can be written as

$$\begin{aligned}W(f,t_m) &= A_1P(f)\exp\left(-j2\pi f\frac{2r_0}{c}\right)\exp\left(-j\frac{4\pi}{\lambda}r_0\right)\\ &\quad\times\exp\left(-j2\pi f\frac{2v_0t_m}{c}\right)\exp\left(-j\frac{4\pi}{\lambda}v_0t_m\right) \qquad (7)\end{aligned}$$

Making the RFPPT on $W(f, t_m)$

$$\begin{aligned}R(f) &= W(f,t_m)\big[W(f,t_m-\tau)\big]^*\\ &= \begin{bmatrix} A_1P(f)\exp(-j2\pi f\frac{2r_0}{c})\exp(-j\frac{4\pi}{\lambda}r_0)\\ \times\exp(-j2\pi f\frac{2v_0t_m}{c})\exp(-j\frac{4\pi}{\lambda}v_0t_m)\end{bmatrix}\\ &\quad\times\begin{Bmatrix} A_1P(f)\exp(-j2\pi f\frac{2r_0}{c})\exp(-j\frac{4\pi}{\lambda}r_0)\\ \times\exp[-j2\pi f\frac{2v_0(t_m-\tau)}{c}]\exp[-j\frac{4\pi}{\lambda}v_0(t_m-\tau)]\end{Bmatrix}^*\\ &= \begin{bmatrix} A_1P(f)\exp(-j2\pi f\frac{2r_0}{c})\exp(-j\frac{4\pi}{\lambda}r_0)\\ \times\exp(-j2\pi f\frac{2v_0t_m}{c})\exp(-j\frac{4\pi}{\lambda}v_0t_m)\end{bmatrix}\\ &\quad\times\begin{Bmatrix} A_1P^*(f)\exp(j2\pi f\frac{2r_0}{c})\exp(j\frac{4\pi}{\lambda}r_0)\\ \times\exp[j2\pi f\frac{2v_0(t_m-\tau)}{c}]\exp[j\frac{4\pi}{\lambda}v_0(t_m-\tau)]\end{Bmatrix}\\ &= A_1^2\big|P(f)\big|^2\exp\left(-j2\pi f\frac{2v_0t_m}{c}\right)\exp\left(j2\pi f\frac{2v_0t_m}{c}\right)\\ &\quad\times\exp\left(-j2\pi f\frac{2v_0\tau}{c}\right)\exp\left(-j\frac{4\pi}{\lambda}v_0t_m\right)\\ &\quad\times\exp\left(j\frac{4\pi}{\lambda}v_0t_m\right)\exp\left(-j\frac{4\pi}{\lambda}v_0\tau\right)\\ &= A_1^2\big|P(f)\big|^2\exp\left(-j2\pi f\frac{2v_0\tau}{c}\right)\exp\left(-j\frac{4\pi}{\lambda}v_0\tau\right)\\ &= A_1^2\left|\operatorname{rect}\left(\frac{f}{B_s}\right)\right|^2\exp\left(-j2\pi f\frac{2v_0\tau}{c}\right)\exp\left(-j\frac{4\pi}{\lambda}v_0\tau\right)\\ &= A_1^2\operatorname{rect}\left(\frac{f}{B_s}\right)\exp\left(-j2\pi f\frac{2v_0\tau}{c}\right)\exp\left(-j\frac{4\pi}{\lambda}v_0\tau\right)\\ &= A_1^2P(f)\exp\left(-j2\pi f\frac{2v_0\tau}{c}\right)\exp\left(-j\frac{4\pi}{\lambda}v_0\tau\right) \qquad (8)\end{aligned}$$

where, the "$*$" denotes the conjugation, τ is the lag time (constant) and $\tau = 5T_r$ [18,19]. It can be seen from (8) that the range frequency domain f is coupled with τ, and there is no coupling