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Simultaneous ISAR imaging of group targets flying in formation

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Abstract This paper proposes a novel inverse synthetic aperture radar (ISAR) imaging method based on second-order keystone transform (KT) and Sandglass transform for group targets flying in a formation with constant accelerated rectilinear motion in the same radar beam. First, range curvature and range walk of each sub-target among group targets are corrected by the second-order KT combined with the quadratic phase term compensation. After range alignment, the signals in each range frequency cell can be modelled as multiple chirp signals and then the Sandglass transform is utilized to cross-range imaging, which transforms the time–frequency distribution of the signals in each range frequency cell into beelines parallel to the slow time axis simultaneously. Finally, cross-range profiles of group targets in each range frequency cell are obtained via a projection of the perk of every scatterer in the two-dimensional accumulation plane onto the frequency axis. The advantage of the proposed method is that it can align range profiles of each sub-target simultaneously and image cross-range profiles directly without separating the returned signals, which simplifies the operation procedure. Simulation results are used to demonstrate the effectiveness of the proposed method.

1. Introduction

Inverse synthetic aperture radar (ISAR) imaging is a type of technique to acquire an image of a moving target.[1] An ISAR image of the target can be generated by coherently processing the returned signals at a different aspect angle relative to the radar.[2] When ISAR imaging is applied to imaging of multiple targets moving in a formation, the conventional motion compensation methods, which are suitable for a single moving target, cannot obtain a well-focused ISAR image due to the low correlation between adjacent range profiles.[1,3–5] For simplicity of presentation, multiple targets flying in a formation in the same radar beam are defined as group targets and the individual one among group targets is defined as sub-target.

Currently, methods for group targets ISAR imaging are mainly composed of two types. Time–frequency analysis algorithms are used in the first method for simultaneous motion compensation and imaging.[6,7] However, the time–frequency transforms are confronted with cross-terms or low frequency resolution. The second method images each sub-target via separating the returned signals. This method can be further

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summarized as two types. In the first type, the signals are separated with different parameters of each sub-target.[8–11] However, it is difficult to separate the signals when the difference of parameters of each sub-target is small. In the second type, the signals of each sub-target are separated from the bulk image.[12–14] In this method, motion parameters are estimated to generate the bulk image. However, this method is likely to fail when the precision of the estimated parameters is low.

In this paper, a simultaneous ISAR imaging method is proposed for group targets with constant accelerated rectilinear motion in the same radar beam. Firstly, the range curvature of group targets is corrected simultaneously by the second-order KT without knowing their accelerations and the fractional Fourier transform (FrFT) is utilized to estimate the Doppler chirp rate, followed by the quadratic phase term compensation. Then, the second-order KT is again used to correct range walk for all sub-targets. Secondly, because the slow time signals in each range frequency cell are multiple chirp signals after range alignment, the Sandglass transform, which is based on a scale transform, is used to transform the time–frequency distribution of the slow time signals in each range frequency cell into beelines parallel to the slow time axis simultaneously. Finally, cross-range profiles of group targets in each range frequency cell are obtained via projection of the perk of every scatterer in the two-dimensional accumulation plane onto the frequency axis. The proposed method avoids signals separation and can perform motion compensation and imaging simultaneously.

The remainder of this paper is organized as follows. After review of the group targets ISAR imaging model in Section 2 and Section 3 describes the proposed imaging algorithm. In Section 4, simulation results are presented to prove the effectiveness of the proposed method. Section 5 presents the conclusions drawn from this work.

2. Model of group targets ISAR imaging

2.1. Geometric model

The geometric model of two sub-targets flying towards the same direction with a uniformly rectilinear motion is shown in Fig. 1, where d and O are the distance and middle point between the two sub-targets, respectively, R is the distance from the radar to the middle point O, β is the angle between the target orientation and the x-axis, θ is the angle between the line-of-sight of the two sub-targets, and ϕ_1 and ϕ_2 are the angle between the target orientation and the line-of-sight from the radar to the sub-targets T_1 and T_2, v_1 and v_2 are the velocity of sub-targets T_1 and T_2, respectively. In Fig. 1, as the two sub-targets are close to each other, it is difficult to separate them in range domain. Thus, it lies on the Doppler difference of the two sub-targets to separate them in azimuth domain.

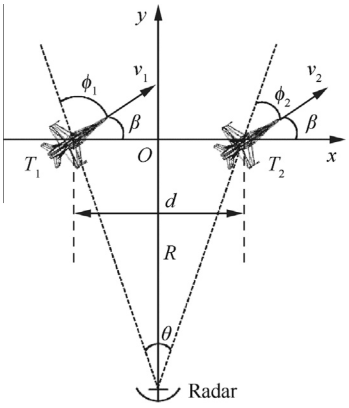

Fig. 1 Geometry of two sub-targets flying in a formation.

The initial radial velocity of the sub-targets T_1 and T_2 are $v_1 \cos\phi_1$ and $v_2 \cos\phi_2$, respectively. Then, when $d/R \ll 1$, θ is very small and the Doppler difference between the sub-targets T_1 and T_2 can be approximately expressed as

$$\begin{aligned}\Delta f_{T_{1,2}} &= f_{T_1} - f_{T_2} = \frac{2v}{\lambda}(\cos\phi_1 - \cos\phi_2)\\ &= -\frac{2v}{\lambda}\left(2\sin\frac{\phi_1+\phi_2}{2}\sin\frac{\phi_1-\phi_2}{2}\right)\\ &\approx \frac{2v}{\lambda}\frac{d}{2R}\sin\left(\phi_2 - \frac{d}{2R}\right)\end{aligned} \tag{1}$$

where λ is the wavelength. In Eq. (1), we assume that the velocity difference between the sub-targets T_1 and T_2 is small and their velocities are set to be v.

When the angle ϕ_2 is close to 0° or 180°, it is worth noting that the Doppler difference between the sub-targets T_1 and T_2 approaches to zero. In this case, they can be considered as a single target and the well-focused ISAR images of them can be obtained by the conventional motion compensation methods. However, if the Doppler difference between the sub-targets T_1 and T_2 is large, it is indicated that the sub-targets T_1 and T_2 have different Doppler history functions and cannot be considered as a single target. By applying the conventional motion compensation methods, the azimuth focusing of the sub-targets T_1 and T_2 cannot be well performed and they cannot be clearly imaged.

2.2. Signal model

Supposing that the radar transmits a total of M chirp pulses

$$S_{\mathrm{T}}(t) = p(t - mT_{\mathrm{r}})\exp[\mathrm{j}2\pi f_{\mathrm{c}}(t - mT_{\mathrm{r}})] \quad (m = 0, 1, \ldots, M-1) \tag{2}$$

where T_{r} denotes the pulse repetition interval, f_{c} denotes the carrier frequency, and $p(\cdot)$ can be expressed as

$$p(t) = \mathrm{rect}\left(\frac{t}{T_{\mathrm{p}}}\right)\exp\left(-\mathrm{j}\frac{\pi B t^2}{T_{\mathrm{p}}}\right) \tag{3}$$

where T_{p} denotes the pulsewidth and B denotes the bandwidth.

We assume that $S_{\mathrm{R}}(\hat{t}, t_m)$ denotes the echoes, where $\hat{t} = t - t_m$ and $t_m = mT_{\mathrm{r}}$ denotes the fast time and slow time, respectively. Then, for scatterer P, its echo can be expressed as

$$S_{\mathrm{R},P}(\hat{t}, t_m) = A_P p\left(\hat{t} - \frac{2R_P(t_m)}{c}\right)\exp\left[\mathrm{j}2\pi f_{\mathrm{c}}\left(\hat{t} - \frac{2R_P(t_m)}{c}\right)\right] \tag{4}$$

where A_P denotes the strength of scatterer P, $R_P(t_m)$ denotes the distance between the scatter P and the radar, c is the light speed.

After down conversion, Eq. (4) can be rewritten as

$$S'_{\mathrm{R},P}(\hat{t}, t_m) = A_P p\left(\hat{t} - \frac{2R_P(t_m)}{c}\right)\exp\left(-\mathrm{j}\frac{4\pi f_{\mathrm{c}}}{c}R_P(t_m)\right) \tag{5}$$