MICRO-MOTION FEATURE EXTRACTION OF SPACE TARGET BASED ON PARAMETRIC SPARSE REPRESENTATION WITH INCOHERENCE SIGNALS

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INTRODUCTION

The micro-motion feature of space targets can provide important information for automatic radar target recognition. Therefore, in recent years, micro-motion feature extraction of space target has always been research hotspot in radar signal processing field.

So far, the techniques for micro-motion feature extraction can be grouped into two categories. The first category is based on narrowband radar, almost all the existing techniques are analyzing the modulation of echo signal phase caused by the micro-motion and extracting the micro-motion feature parameters via some related processing for the phase. Obviously, the signal coherence is required to be preserved in these existing methods. However, due to the high-velocity motion of the space target, the coherent accumulation time within a range gate is very short, and the signal coherence of the echo signal from different range gate is hard to be guaranteed. The other category is based on wideband radar, almost all the existing techniques are based on the range–slow-time images, and the existing methods are studied with the premise that the translational compensation has been done precisely, which will hard to be satisfied with the incoherence echo signals caused by the range gate changes during the target observation.

In summary, both the micro-motion feature extraction methods based on narrowband radar and that based on wideband radar can not deal with the problem caused from the change of range gate, thus their applications are limited in practice. To solve the problem above, this paper aims the wideband radar and proposes a novel micro-motion feature extraction method based on parametric sparse representation, which is available for the no-coherence signals. In this method, the parametric sparse representation dictionary of the echo signal is established firstly, and then the Doppler sensitivity of the kind of signals which consist of several sub-pulses with stepped frequency is used to estimate the instantaneous velocity of each scatters in target, finally, the micro-motion feature parameters can be extracted via fitting the obtained instantaneous velocity according to the mathematical expression of m-D effect.

M-D EFFECT IN WIDEBAND IMAGING RADAR

The Geometry of a radar and a spinning target is shown in Fig. 1. The target velocity of the translational motion is denoted as $\boldsymbol{v}=[v_X, v_Y, v_Z]^{\mathrm{T}}$, and the target is rotating around the target center with angular velocity $\boldsymbol{\omega}=[\omega_x, \omega_y, \omega_z]^{\mathrm{T}}$.

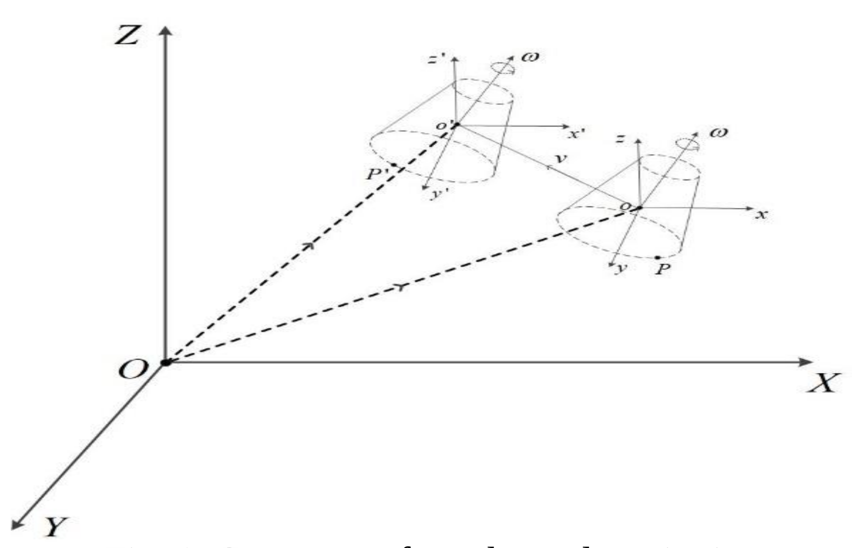


Fig. 1 Geometry of a radar and a spinning target

The step-frequency chirp signal is made up of a series of bursts, each of which consists of a sequence of linear frequency modulate (LFM) sub-pulses with stepped carrier frequency. Taking the origin o be the reference point, after the "dechirp" processing, the coarse-resolution range profile obtained from the *i*-th sub-pulse at slow-time t_m can be obtained

$$S_d(i,f,t_m)=\sigma_p\cdot T_1\cdot \mathrm{sinc}\left(T_1\left(f+\frac{2\mu}{c}\Delta R_p(i,t_m)\right)\right)\cdot\exp\left(-j\frac{4\pi}{c}(f_c+i\Delta f)\cdot\Delta R_p(i,t_m)\right)\cdot\exp(j\theta(t_m)) \quad (1)$$

where $\theta(t_m)$ is the phase error at slow-time t_m, and $\Delta R_p(i,t_m)=R_p(i,t_m)-R_0$, $R_p(i,t_m)$ is the distance between the *p*-th scatterer and radar at the time of transmitting the *i*-th sub-pulse at slow-time t_m.

According to the geometry shown in Fig. 1, $\Delta R_p(i,t_m)$ can be written as

$$\Delta R_p(i,t_m)=\frac{X_o v_X+Y_o v_Y+Z_o v_Z}{\sqrt{X_o^2+Y_o^2+Z_o^2}}t_m+\left\|\overrightarrow{o'P'}\right\|\cos(\Omega t_m+\varphi)\sin\varepsilon+iT_r v_P(t_m)=\Delta R_{p0}(t_m)+iT_r v_P(t_m) \quad (2)$$

where

$$v_p(t_m)=\frac{\mathrm{d}R_P(i,t_m)}{\mathrm{d}t_m}=\frac{X_o v_X+Y_o v_Y+Z_o v_Z}{\sqrt{X_o^2+Y_o^2+Z_o^2}}-\Omega\left\|\overrightarrow{o'P'}\right\|\sin(\Omega t_m+\varphi)\sin\varepsilon \quad (3)$$

Generally, the displacement of scatterer in a burst cannot exceed the coarse range resolution. Therefore, Eq (1) can be rewritten as

$$S_d(i,f,t_m)=\sigma_p\cdot T_1\cdot \mathrm{sinc}\left(T_1\left(f+\frac{2\mu}{c}(\Delta R_{p0}(t_m))\right)\right)\cdot\exp\left(-j\frac{4\pi}{c}(f_c+i\Delta f)\cdot(\Delta R_{p0}(t_m)+iT_r v_p(t_m))\right)\cdot\exp(j\theta(t_m)) \quad (4)$$

Sampling $S_d(i,f,t_m)$ in the frequency domain at $f=-2\mu\Delta R_{p0}(t_m)/c$ and taking discrete Fourier transform in terms of , the high- resolution range profile (HRRP) peaks at

$$F_f'=-\frac{2}{c}\cdot\Delta f\cdot\Delta R_{p0}(t_m)-\frac{2}{c}f_c\cdot T_r\cdot v_p(t_m)-\frac{4}{c}\cdot\Delta f\cdot i\cdot T_r\cdot v_p(t_m) \quad (5)$$

From Eq (5), we can see that: the first term on the right side denotes the real position information of the target scatter during the burst time at t_m; the second item denotes the peak displacement of the target scatter in HRRP caused by the target motion (ie. the velocity $v_p(t_m)$), and it can be seen that $v_p(t_m)$ is larger, the displacement is more obvious; and the last term is the coupling term between $v_p(t_m)$ and *i*, and it will make the peaks of the HRRP expanded.

Obviously, due to the Doppler sensitivity, the peak displacement and expanded in HRRP will bring negative impacts for target imaging, and the target velocity should be estimated and compensated to obtain the real position information of target scatter. From another point of view, we can use the peak displacement and expanded effect to get the velocity of target scatter, and then extract the target micro-motion characteristic parameters according to Eq (3).

MICRO-MOTION FEATURE EXTRACTION BASED ON PARAMETRIC SPARSE REPRESENTATION

In this paper, a velocity estimation method based on parametric sparse representation is proposed to get the velocity information of each scatters of the target. In the framework of compressed sensing (CS) theory, parametric sparse representation can be introduced to improve the adaptive ability of signal processing. Parametric sparse representation refers to adding unknown target parameters into the traditional fixed sparse representation dictionary, and realizing the accurate matching between the parametric dictionary and sampling signal through parameter optimization. That means the unknown target parameters can be estimated by dynamically representing the sampling signal through a parametric dictionary. As a result, the performance of sparse signal representation can be improved and the better signal reconstruction results can be obtained.

In terms of (5), for a certain slow-time, it can be represented as

$$S_d(i,t_m)=\sigma_p\cdot T_1\cdot\exp\left(-j\frac{4\pi}{c}(f_c+i\Delta f)\cdot(\Delta R_{p0}(t_m)+iT_r v_p(t_m))\right)\cdot\exp(j\theta(t_m)) \quad (6)$$

Denote the target echo signal as the vector $\boldsymbol{S}_d=[S_d(0,t_m),\dots,S_d(i,t_m),\dots,S_d(N-1,t_m)]^{\mathrm{T}}$, and discrete the interested area along the range direction into *Q* sub-bins. Then, (15) can be represented as

$$\boldsymbol{S}_d=\mathbf{D}(\boldsymbol{v}(t_m),\theta(t_m))\boldsymbol{\sigma}+\boldsymbol{E},\quad \boldsymbol{\sigma}=[\sigma_1,\dots,\sigma_q,\dots,\sigma_Q]^{\mathrm{T}} \quad (7)$$

where

$$\mathbf{D}(\boldsymbol{v}(t_m),\theta(t_m))=[\boldsymbol{d}_1,\dots,\boldsymbol{d}_q,\dots,\boldsymbol{d}_Q]\qquad \boldsymbol{v}(t_m)=[v_1(t_m),\dots,v_q(t_m),\dots,v_Q(t_m)]$$

$$\boldsymbol{d}_q=\begin{bmatrix}\exp\left(-j\frac{4\pi}{c}(f_c+0\cdot\Delta f)\cdot(R_q+0\cdot T_r v_q(t_m))\right)\cdot\exp(j\theta(t_m))\\ \vdots\\ \exp\left(-j\frac{4\pi}{c}(f_c+(N-1)\cdot\Delta f)\cdot(R_q+(N-1)\cdot T_r v_q(t_m))\right)\cdot\exp(j\theta(t_m))\end{bmatrix}$$

Obviously, only when the velocity and the phase error in the parametric dictionary are equal to the real velocity of the target scatter and the real phase error of target echo signal, can the highly matching between the parametric dictionary and the target echo signal be realized, and the reconstructed $\boldsymbol{\sigma}$ be focused well. Therefore, when $\boldsymbol{v}(t_m)$ and $\theta(t_m)$ are unknown, it is necessary to consider the reconstruction of $\boldsymbol{\sigma}$ and the estimation of $\boldsymbol{v}(t_m)$ and $\theta(t_m)$ together, and the joint optimization model can be established as

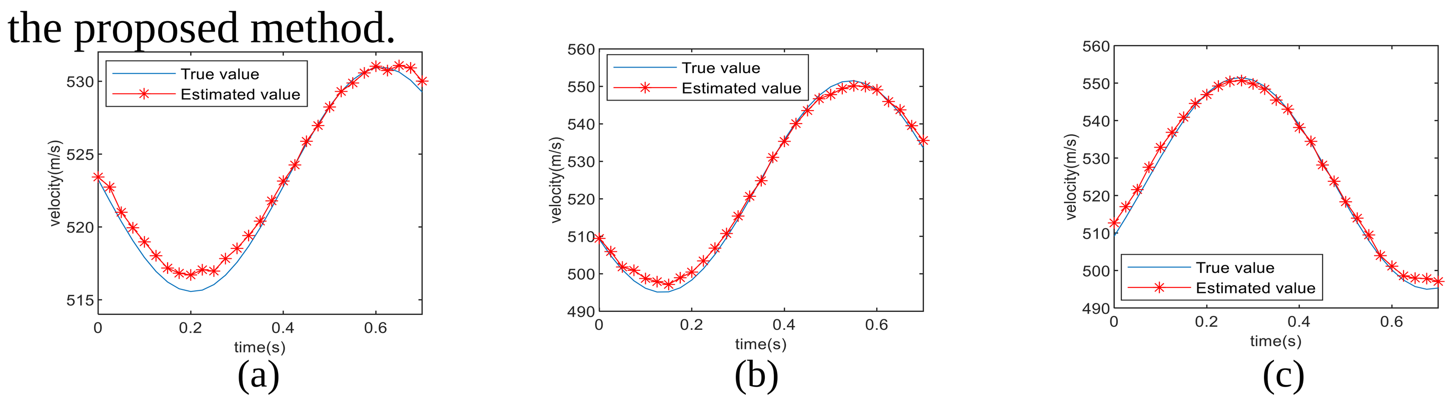
$$\{\boldsymbol{v}(t_m),\theta(t_m),\boldsymbol{\sigma}\}=\arg\min\|\boldsymbol{\sigma}\|_0\quad \text{s.t}\quad \boldsymbol{S}_d=\mathbf{D}(\boldsymbol{v}(t_m),\theta(t_m))\boldsymbol{\sigma} \quad (8)$$

To solve the joint optimization problem above, $\boldsymbol{\sigma}$, $\boldsymbol{v}(t_m)$ and $\theta(t_m)$ can be carried out in an iterative fashion. So far, we have get the velocity information of each scatters. However, in general, there are several scatterers on the target, and the correlation of the velocity of each scatterer should be considered. In this paper, we intend to deal with the velocity correlation problem based on sliding window tracking method. On the basis, the velocity information of each scatters can be obtained separately. Then, according to (3), the least square method can be used to fit the velocity information of each scatters, and the target micro-motion characteristic parameters estimation Ω, r, d and φ can be obtained, where $d=(X_o v_X+Y_o v_Y+Z_o v_Z)/\sqrt{X_o^2+Y_o^2+Z_o^2}$, $r=\left\|\overrightarrow{o'P'}\right\|\sin\varepsilon$. In addition, from the obtained micro-motion characteristic parameters, we can get the target scatter distribution information, so as to obtain the target high-resolution imaging results.

SIMULATIONS

Assume that f_c=35GHz,T_r=93.75μs,$\Delta f=4.6875$MHz,$N=64$,$B=300$MHz,$B_1=4.6875$MHz,T_1=2.93μs, T_p=6ms,(X_o,Y_o,Z_o)=(3,4,5)km,$\boldsymbol{v}=[300,200,400]^{\mathrm{T}}$ m/s, $\boldsymbol{\omega}=(\pi,2\pi,\pi)^{\mathrm{T}}$ rad/s. The target consists of three scatters, which are located at (1,0 ,0)m, (3,1.5,1.5)m and (-3,-1.5,-1.5)m. Gaussian noise with SNR=5dB is added into the echo signal.

With the proposed method, the velocity information of each scatters can be obtained, as shown in Fig 2. From Fig 2, we can see that the estimated velocity of the three scatters is very consistent with the real value. On this basis, the micro-motion characteristic parameters of the target scatters can be obtained by fitting the velocity of each scatters according to the target motion mode shown as (3), and the results are shown in Table 1, then the target imaging results can be obtained, as shown in Fig 3. The results are basically consistent with the real values, which can validate the effectiveness of the proposed method.



(a) (b) (c)

Fig. 2 Velocity information of target scatters. (a) Scatter 1. (b) Scatter 2. (c) Scatter 3.

Table 1 Micro-motion characteristic parameters of the target scatters

	d	Ω	r_1	r_2	r_3	φ_1	φ_2	φ_3
True	523.26	7.70	1	3.67	3.67	0	0.52	2.62
Estimation	523.89	7.38	0.93	3.51	3.55	0.02	0.59	2.76

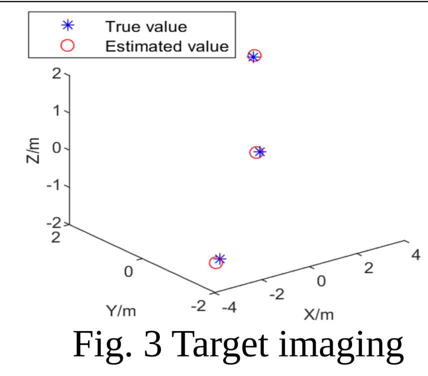


Fig. 3 Target imaging

CONCLUSION

The proposed method can achieve good performance with incoherence signals, while the traditional method is not available. Although the spinning target is taken as an example, the proposed method is also applicable to other micro-motion forms, which only needs to adjust the fitting equation according to the target micro-motion form.

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