Target Signal Separation of Missile Group Based on Micro-motion Frequency Correlation

Zhongtao Tao¹, Shaoqing Yang¹
¹ Department of Gun, Dalian Naval Academy, Dalian, Liaoning, 116018, China
*Corresponding author’s e-mail: xysqlsxx@126.com

Abstract. Object micro-motion feature extraction method for isolated targets is relatively mature, but the resolution and micro-motion feature extraction method for group targets still needs further research. Ballistic missiles in the middle of the throw-off process is taken to be the example, when the false target is released. A method of target separation by micro-Doppler frequency is proposed, and the target is modeled. A parameterized expression is given. The narrow band echo is processed by STFT and the time-frequency plane is obtained. After that, the BM3D algorithm is used to filter and reduce noise to smooth the curve. The improved Viterbi algorithm is used to extract the micro-Doppler curve of the group target. Finally, the Fourier transform is performed. According to the frequency correlation, the group target is separated, and the simulation verified this method.

1. Introduction
Micro-motion is a small movement of the subject itself except for the target subject's translation, such as target’s vibration, rotation, and pitch [1]. When group target resolution is performed, since multiple targets are located in the same beam of the radar antenna, and echo signals are superimposed on each other in the time-frequency domain. The previous feature extraction method for isolated targets is no longer effective, and the micro-motion signals is an effective method processing method. The micro-Doppler effect refers to the physical phenomena generated by the micro motion of objects and their components in radar detection, and is of great significance for improving the detection and resolution capabilities of the radar as well as radar imaging and target recognition capabilities. The micro-Doppler effect reflects the fine motion characteristics of the target [2,3]. The micro-motion characteristics of different targets are generally different. Generally speaking, the ground-stop vehicle group can distinguish military vehicles such as tanks through the micro-motion characteristics of the engine [4-6]. It can even distinguish the type of engine by the speed. Military helicopter rotors often perform multiple actions due to tactical maneuvers, and their tactical actions can be identified through changes in their echo characteristics. Ballistic missiles will separate out false targets in the middle of its track to prevent other missiles from intercepting. Because of the different movement characteristics such as nutation and precession between the released target and the true warhead, they can also be distinguished by their echo characteristics.

2. Echo modeling of micro-motion group target
In the middle of the ballistic missile's operation, the missile will release other targets including warheads, light and heavy decoys, attitude controllers, chaff and debris, which will have different micro-movements at high initial speeds. Warheads tend to remain stable due to high-speed spins, and will keep precession after being disturbed. Light and heavy decoys do not have posture control and
generally sway. Chaff and other small objects will randomly rol l over at high speed. The rotating target will keep rotating at a certain speed. In the echo of a single beam of the radar, these objects overlap each other, which makes it difficult to extract the signal.

The separation of rotating targets and cone warheads is relatively less researched. Xu et al. proposed a method of denoising through SVD by micro-motion cycles and Gaussian smoothing, but this method only proposed a method to separate two targets, and did not discuss about more complicated cases. At the same time, denoising by SVD, the Gaussian smoothing method and using the Viterbi algorithm to extract the curve is limited by its own algorithm [4]. For example, the SVD matrix massive calculation, and the Gaussian process’s less-effectiveness in the multi-featured high-dimensional space is reduced. This paper takes the better BM3D denoising algorithm and the improved Viterbi algorithm to extract the final curve, which optimizes the process. This method can distinguish the state of the warhead and the rotating target in a more complex situation.

2.1. Model of precession Target
In order to specifically describe the spatial movement of the group of targets to the radar, a precession target model and a rotating target model are established.

As shown in Figure 1, in the model of the cone target’s precession, the symmetry axis of the cone and the rotation axis of the cone intersect at point \( O \), the precession’s angular velocity is \( \omega_1 \), and the precession angle is \( \theta \). The angle between the line of radar sight and the cone’s symmetry axis is \( \beta \), which is the attitude angle, and the angle between the line of radar sight and the precession axis is \( \alpha_1 \).

When the attitude angle satisfies the condition \( \beta \in (0, \varepsilon) \cup (\pi / 2, \pi - \varepsilon) \), three great scattering centers \( A, B, C \) can be observed, and when the attitude angle satisfies \( \beta \in (0, \pi / 2 - \varepsilon) \), two great scattering centers \( A \) and \( C \) can be observed. \( O - XYZ \) is the global coordinate system. \( o - x_0y_0z_0 \) is the cone-shaped projectile’s coordinate system. \( z_0 \) axis is the direction of the projectile's spin axis. \( o - x'y'z' \) is the relative coordinate system, and \( o - x'y'z' \) is parallel to \( O - XYZ \).

![Figure 1. Radar observation diagram.](image)

Under high-frequency approximation conditions, the target has optical scattering characteristics, and the echo can be equivalent to the sum of several strong scattering centers’ echoes. Through
geometric deduction, the relationship between attitude angle and time satisfies equation (1), where $\varphi_0$ is the initial phase.

$$\beta(t) = \arccos(\cos \theta \cos \alpha + \sin \theta \sin \alpha \sin(\omega t + \varphi_0))$$

(1)

Assuming that scattering center $A$ and $C$’s coordinate is $(x_A, y_A, z_A)$ and $(x_C, y_C, z_C)$. The distance the scattering center moves due to precession is equation (2).

$$\begin{align*}
R_A &= \sqrt{x_A^2 + y_A^2 + z_A^2} \cos \beta(t) \\
R_C &= \sqrt{x_C^2 + y_C^2 + z_C^2} \cos \phi(t) \cos \beta(t) + \sqrt{x_C^2 + y_C^2 + z_C^2} \sin \phi(t) \sin \beta(t)
\end{align*}$$

(2)

$\phi$ is the angle between the scattering centers $A$ and $C$ in the relative coordinate system.

2.2. Rotating target model

As shown in Figure 2, the scattering center on the rotating target can be analysed. Assuming that the target's center of mass is $O'$, a relative coordinate system $(x', y', z')$ which is parallel to the global coordinate system is established with $O'$ as the coordinate origin. The rotation angular velocity of the target is $\omega_2$, and $ON'$ is the rotation axis, whose angle with the radar line of sight is $\alpha_2$, and $\phi_p$ is the initial azimuth angle. The rotation matrix of the target at the time $t$ is defined as $T_t$. When $t=0$, the position of $P$ in the relative coordinate system is $r_p = (x_p, y_p, z_p)^T$.

![Figure 2. Diagram of rotating scattering center](image)

After derivation, we can find that the displacement of the scattering center caused by rotation is equation (3).

$$R_p(t) = r_p(t) n = z_p \cos \gamma + (x_p^2 + y_p^2)^{1/2} \sin \gamma \cos(\omega_2 t + \phi_p)$$

(3)

2.3. Radar model

The radar emission signal is set as a single-frequency pulse to make it more representative. The baseband echo signal can be obtained after orthogonal two-channel’s demodulation, which is equation (4):
\[ S_x(t) = \sum_{l=1}^{L} \sigma \exp[j \frac{4\pi f}{c} R(t)] \]  

(4)

c is the speed of light, and \( f \) is the frequency of the carrier, \( R(t) \) represents the displacement of the scattering center when micro-motion happens. After the time-frequency analysis of the above formula, the micro-Doppler variation of the scattering center can be obtained:

\[ f(t) = \frac{2f}{c} \frac{dR(t)}{dt} \]  

(5)

3. Echo processing
The radar echo contains micro-motion information. In order to process these echo data better, the following preprocess is performed on the echo.

3.1. Time-frequency Conversion
It can be seen from equation (5) that the time-frequency expression of the radar echo contains the scattering center’s parameter information, and the target scattering center parameter can be obtained by extracting the time-frequency curve parameter by using short-time Fourier transform to achieve signal acquisition. The short-time Fourier transform is suitable for the extraction of time-varying signals. It obtains the signal through a narrow window function and its Fourier transform can be evaluated. Assuming that \( h(t) \) is a window function with a short time width. When it slides along the time axis, then the short-time Fourier transform of signal \( a \) is defined as equation (6).

\[ STFT = \int_{-\infty}^{+\infty} s(\tau) h^*(\tau-t)[\exp(j\omega\tau)]^{-1} d\tau \]  

(6)

3.2. BM3D noise reduction and smoothing
Not only the target signal but also a lot of noises exist on the time-domain graph after the time-frequency transformation. In order to improve the accuracy of parameter extraction, it is necessary to perform noise reduction on the time-frequency plane. Traditional image noise reduction methods have better results knowing the source of noise. However, in the case where the frequency domain distribution of the image is unknown, this problem cannot be solved well. BM3D denoising combines spatial denoise and transform denoise both. Extremely high peak signal-to-noise ratio can be obtained. The BM3D algorithm first turns two-dimensional image into a three-dimensional stack. This step is to search for similar blocks, and then group similar blocks into a three-dimensional stack. Then transform these three-dimensional stacks into frequency domain. After performing 3D collaborative filtering in the frequency domain, the final result is obtained by inverse transforming and mixing the images.

3.3. Using improved viterbi to separate curves
The micro-Doppler curves of group targets are modulated by micro-motion parameters, structural parameters and radar angle of view. The modulation characteristics corresponding to different targets are different, so there will be some overlap in time and frequency. Viterbi is a dynamic programming estimation algorithm that seeks the hidden state of a sequence. It can estimate the instantaneous frequency of each component signal from a time-frequency diagram. Let \( N \) be the number of sampling points, \( k(n) \) be the paths of the curves on the time-frequency plane, \( K \) be the set of all possible paths in the entire time-frequency distribution, \( p(x, y) = p(|x-y|) \) be the penalty function of \(|x-y|\), \( q(x) \) be the penalty function of \( GD(n, k(n)) \). Using the double penalty function for the judgment of the same curve is more accurate than the traditional Viterbi algorithm. The penalty function is a type of function that is to optimize nonlinear programming problems. The penalty function can be used to transform the constrained objective function into an unconstrained objective
function. The penalty functions $p(x,y)$ and $q(x)$ represent the instantaneous rate of change of frequency and the importance of a frequency point at a certain moment. Therefore, the minimum estimation of instantaneous frequency is equation (7).

$$\hat{f}(n) = \arg \min_{k(n) \in \mathbb{K}} \left[ \sum_{n=1}^{N-1} p(k(n),k(n+1)) + \sum_{n=1}^{N-1} q(GD(n),k(n+1)) \right]$$

(7)

3.4. Separate targets using frequency correlation
It can be seen from equation (2) that the micro-Doppler of the scattering center of the projectile meets the sine law, whose frequency is $\frac{\omega_1}{2\pi}$. The scattering center of the bottom surface of the projectile does not meet the standard sine law, because its motion is equivalent to adding an offset component. But its frequency is as same as the cone top. The rotation frequency of the scattering center on the rotating target is $\frac{\omega_2}{2\pi}$. Obviously, the scattering centers on the same target have the same period, and different targets do not have this correlation. According to this, the objects in the group target can be separated.

Therefore, the micro-motion information in the group target can be separated and judged by a monopulse radar echo signal according to the following procedure.

4. Simulation and Analysis
The group target is set to be composed by a cone warhead target and a rotating target. The cone warhead target has four scattering centers $A_1$, $B_1$, $A_2$, $B_2$ that can be observed. the rotating target has four scattering centers $P_1$, $P_2$, $Q_1$, $Q_2$. The coordinates of the scattering centers $A_1$ and $A_2$ in the relative coordinate system is $(1.6,1.2,2.8)$ and $(0.8,0.6,-1.4)$. The coordinates of $B_1$ and $B_2$ in the relative coordinate system is $(1.0,0.6,1.2)$ and $(0.5,0.3,0.6)$. The precession angle $\theta=10^\circ$ and the cone rotation angular velocity $\omega_1=4\pi rad / s$. The position of the scattering center $P_1$, $P_2$, $Q_1$, $Q_2$ in the relative coordinate system is $(-0.6,-0.4,-1.0)$, $(-0.3,-0.2,-0.5)$, $(0.3,0.3,0.5)$, $(0.6,0.6,1.0)$. The rotation angular velocity $\omega_2=2\pi rad s^{-1}$. The carrier’s frequency of the narrow-band radar is $f=8GHz$, and the pulse repetition frequency is $1000Hz$. The observation time is $2s$. The signal-to-noise ratio is $5dB$. The angle between the pulse ray and the precession axis is $\alpha_1=50^\circ$, and the angle between the pulse ray and the rotation axis is $\alpha_1=80^\circ$.

After using the short-time Fourier transform to obtain the time-frequency plane of the original echo, BM3D is used for noise reduction processing. After the noise reduction, in order to avoid the impact
of the curve’s burrs on the time-frequency conversion, the time-frequency plane needs to be smoothed. The result is extracted by the improved Viterbi algorithm, and finally the result is obtained by Fourier transform, as shown in the figure:

![Figure 4. Fourier transform of extracted curve](image)

After filtering out the zero frequency component, it can be seen that the peak frequency of the curve is distributed in 2 different positions, and the amplitude relationship corresponds to each other. So it can be seen that there are 4 targets in the group target, and the frequency distribution is in two parts. Through the amplitude, it can be seen that there are four targets of two kinds.

5. Conclusion
In this paper, the middle range of the ballistic missile’s launch when the throwing of the induced target happens is taken to be the object of discussion. The separation of the micro-Doppler curve of the multi-scattering center is studied. After the time-frequency plane is obtained, the BM3D denoising, smoothing filtering, and Viterbi operator extraction are carried out. After Fourier transform, the two groups of target signals are separated according to the frequency dependence of the target.

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