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Hypersonic sliding target tracking in near space

Xiang-yu ZHANG [a,*], Guo-hong WANG [a], Zhen-yu SONG [b], Jiao-jiao GU [a]

[a] *Institute of Information Fusion, NAAU, Yantai 264001, China*

[b] *Department of Scientific Research, NAAU, Yantai 264001, China*

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Abstract

To improve the tracking accuracy of hypersonic sliding target in near space, the influence of target hypersonic movement on radar detection and tracking is analyzed, and an IMM tracking algorithm is proposed based on radial velocity compensating and cancellation processing of high dynamic biases under the earth centered earth fixed (ECEF) coordinate. Based on the analysis of effect of target hypersonic movement, a measurement model is constructed to reduce the filter divergence which is caused by the model mismatch. The high dynamic biases due to the target hypersonic movement are approximately compensated through radial velocity estimation to achieve the hypersonic target tracking at low systematic biases in near space. The high dynamic biases are further eliminated by the cancellation processing of different radars, in which the track association problem can be solved when the dynamic biases are low. An IMM algorithm based on constant acceleration (CA), constant turning (CT) and Singer models is used to achieve the hypersonic sliding target tracking in near space. Simulation results show that the target tracking in near space can be achieved more effectively by using the proposed algorithm.

Keywords: Near space; Hypersonic velocity; High dynamic bias; Tracking; Maneuvering

1. Introduction

In recent years, with the continuously appearing of near space hypersonic vehicles, such as X-43 [1] and X-51A [2], the defense against rapid strike weapons has become an urgent problem to be solved. The near space target is different from the traditional aerodynamic target [3] and the satellite orbital target [4]. It has its unique hypersonic sliding trajectory [5], and can rapidly attack any target in the world in two hours, but the existing warning defense system is unable to track and intercept the threat target effectively. Therefore, it is necessary to research the tracking of hypersonic sliding target in near space.

The domestic & foreign researches have been still in the primary stage for the study of target tracking in near space. The target trajectory, from launch to impact, is divided into three major phases [6]: boost, coast, and reentry. The boost phase of motion, which lasts from launch to thrust burnout, was discussed in Ref. [7] where the vehicle is accelerated to the designed altitude and velocity for beginning a sliding trajectory. The coast phase, sustaining the motion of skidding to the desired range, was analyzed in Ref. [8]. And the reentry phase, beginning when the sustaining burns are discontinued, was discussed with the state augment tracking methods in Ref. [9].

In view of the tracking of this sliding trajectory target, a modified constant turning (MCT) model was proposed to enhance the performance of tracking high maneuvering target [10]. A variable structure multiple model tracking algorithm based on the directed graph (DG-VSMM) was proposed to further overcome the weakness of maneuvering target tracking with the single model [11]. And in Refs. [12,13], the IMM tracking algorithm is considered one of the most dependable methods in the field, and the robust tracking can be achieved through the interaction among different models.

* Corresponding author.

E-mail address: zxy627289467@sina.com (X.Y. ZHANG).

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However, all the researches above are based on the analysis of target maneuvering, but have not considered the influence of target hypersonic velocity. Nevertheless, the target in near space moves at a hypersonic velocity, and the hypersonic velocity makes a great difference on radar detection and tracking.

From Ref. [14] we know that the linear frequency modulated (LFM) signal is one of the most famous radar signals, which is of large time-bandwidth product, and can significantly improve the signal-to-noise (S/N) ratio when the matching filter is performed. But the disadvantage of this signal is that it is not sensitive to the Doppler shifts [15]. While the Doppler shifts exist as the target moves at a radial velocity. That is to say, the radar detection and tracking are inevitably affected by the radial velocity. In the case of low radial velocity, this property from target echo can be approximately neglected. But when the target moves at a hypersonic velocity, the effect of Doppler shift on the target tracking has not been discussed for hypersonic movement of the target, and a solving method has not been mentioned yet in the existing references.

In this paper, we firstly analyze the influence of target hypersonic movement on radar detection and tracking. Then the measurement models of hypersonic sliding target tracking in near space are established, and the high dynamic biases which are caused by the target hypersonic movement are eliminated through the radial velocity estimation and the cancellation processing method. Finally, an IMM tracking algorithm based on the CA, CT, and Singer models are utilized to further achieve the tracking of hypersonic sliding target in near space.

2. Influence of target hypersonic movement on radar measurements

Since the LFM signal is one of the most famous radar signals, which is of large time-bandwidth product, and can significantly improve *S/N* ratio when the matching filter is performed. The PC (pulse compression) radar which emits LFM signal) is selected to discuss the problem of hypersonic target tracking in near space.

We assume that the PC radar emits the LFM signal

$$s(k) = \mathrm{rect}\left(\frac{k}{\tau}\right)\cos\left(2\pi f_0 k + \pi\mu k^2\right) \tag{1}$$

where $\mathrm{rect}(k/\tau) = 1,\ |k| \le (1/2)\tau$, τ is the emitting pulse width, f_0 is the central carrier frequency, $\mu = B/\tau$ is the FM rate, B is the FM band width.

When the target moves at a radial speed of v, the received signal at time k can be expressed as follows

$$s_r(k) = \mathrm{rect}\left(\frac{\gamma(k-t_0)}{\tau}\right)\cos\left(2\pi f_0\gamma(k-t_0) + \pi\mu\gamma^2(k-t_0)^2\right) \tag{2}$$

where $t_0 = (2R_0/c)$, R_0 is the target distance at time t_0, c is the light speed, $\gamma = 1 + (2v/c)$.

At this time, if the matched filtering technique is used to the received signal $s_r(k)$, the output of the matching filters can be expressed as

$$\begin{aligned} s_o(k) = {} & (\tau - |k-t_0|)\frac{\sin[\pi(\mu|k-t_0| + f_d)(\tau - |k-t_0|)]}{\pi(\mu|k-t_0| + f_d)(\tau - |k-t_0|)} \quad |k-t_0| < \tau \\ & \exp\left\{j\pi\mu\left(-k^2 - t_0^2 - 2f_d t_0\right)^2\right\}\exp\left\{j2\pi(\mu(k-t_0) + f_d)\left(t_0 + \frac{k}{2}\right)\right\} \end{aligned} \tag{3}$$

where $f_d = (2v/c)f_0$ is the target Doppler shift. Then according to the maximum signal-to-noise ratio criterion, the signal $s_o(k)$ has a maximum value at time $k = t_0 \pm (f_d/\mu)$. That is to say, the radar measurements are inevitably affected by the following dynamic biases

$$\Delta r = \frac{f_d}{\mu}c = \frac{2vf_0\tau}{B} = \frac{2v\tau}{B\lambda}c \tag{4}$$

In order to evaluate the influence of target hypersonic movement on the tracking of near space target, the relative analysis is as follows.

1) When the target moves at a hypersonic velocity, the high dynamic biases will be brought into the radar measurements of the near space target. For example, when the target in Fig. 1 moves at a constant velocity of $V = 5$ km/s and the motion direction relative to the radar is $\psi_k = 10^\circ$, the target distance and attitude are $r_k = 600$ km and $h_k = 20$ km, respectively, the radar wavelength is $\lambda = 0.15$ m, and the pulse width and band width of the linear FM signal are $\tau = 600$ µs and $B = 1.5$ MHz, respectively, the high dynamic biases caused by the target hypersonic movement can reach to

$$\Delta r_k = \frac{2\tau c}{B\lambda}V\cos(\psi_k)\frac{\sqrt{r_k^2 - h_k^2}}{r_k} \approx 7.8\ \mathrm{km} \tag{5}$$

while the measurement errors of the conventional radar are 100m around. That is to say, the high dynamic biases, which seriously affect the tracking of near space target, can not be neglected.