Imaging Analysis of Space Target in Bistatic ISAR

Shaochuang Ma[1, a], Qiang He[1,b] and Baofeng Guo[1,c *]

[1]Department of Electronic and Optical Engineering, Ordance Engineering College, Shijiazhuang, P.R.China

[a]529206646@qq.com, [b]qhe1228@gmail.com, [c]guobao_feng870714@126.com

Keywords: Bistatic ISAR; Space target; Image analysis; Bistatic angle

Abstract. Bistatic angle is an important characteristic parameter of bistatic inverse synthetic aperture radar (ISAR), which is different from monostatic ISAR. Based on the echo model of bistatic ISAR, the impact of time-varying bistatic angle to imaging plane and quality is analyzed. The image distortion mechanism is studied and the distortion angle is estimated. The simulation experiment verified the correctness of the imaging analysis. The research in this study is significant for the selection of imaging segment, and provides evidence for the following data processing.

Ⅰ Introduction

Bistatic radar is the system whose transmitter and receiver are placed in different places and the based line length can be compared with the target distance. The work mode makes the radar has outstanding advantages in the fight of “Four Threats” [1]. Bistatic ISAR is the ISAR system based on bistatic radar platform. It receives non-backscatter echo of target and imagings, which can get more target information compared with the monostatic radar [2]. So, the bistatic radar becomes the research focus [1].

The difference between bistatic ISAR and monostatic ISAR lies in the synchronization problems [3] and bistatic angle [4].Given the baseline of bistatic Radar is too long, it’s difficult to implement high-precision time synchronization under the current conditions, so that the BP (Back Projection, BP) algorithm and PFA (Polar Format Algorithm, PFA) algorithm [5] are greatly restricted or even fail. To reduce the synchronization accuracy, it is necessary to employ the algorithm who has low requirement for synchronization, such as RD (Range Doppler, RD) algorithm.

Imaging plane analysis is the basic problem of imaging, and bistatic angle is an important parameter of imaging analysis. At present, most of the studies on bistatic ISAR are under the assumption that bistatic angle is an approximate constant [6], which makes the bistatic ISAR has no essential difference with the monostatic ISAR. In fact, the time-varying bistatic angle makes the bistatic ISAR imaging plane change significantly, and the imaging range axis and cross range axis are not orthogonal in many cases. In reference [7], the bistatic ISAR imaging plane is determined based on the method of target rotation vector analysis, but the effect of time-varying bistatic angle on imaging quality is ignored.

Time-varying bistatic angle makes the rotational speed is not balanced relative to the transmitter and receiver, which causes image distortion. Meanwhile, the scale factor of range cell and Doppler cell changes, which results in the phenomenon of migration through resolution cells. Besides, the bistatic ISAR image distortion will further cause migration through Doppler cells, and it changes the imaging quality. Imaging analysis provides an important basis to select imaging segment and simplify subsequent processing algorithms, and it has a great guiding significance for the implementation of imaging experiments.

Based on the need for space target surveillance and imaging, the study on imaging plane is performed.

First the bistatic ISAR echo model is built. Then the image distortion mechanism is analyzed and ISAR image distortion angle is estimated. Finally, the imaging simulation is carried out, which confirmed the correctness of the imaging analysis.

Ⅱ Bistatic ISAR echo model of Space target

The imaging model of bistatic ISAR is shown in Fig.1. Where, T is the transmitting station, R is the receiving station, L is the radar baseline length, E is the position of equivalent monostatic radar.

We assume that target moves smoothly at the speed of V in space and the imaging starting time is t_0, the center of mass of target is O, bistatic angle is b_0. Right-hand rectangular coordinate system xOy is established with target center being the origin and bistatic angle bisector being the y axis. The coordinate of scatter P is $\left(x_P, y_P\right)$ in xOy. d is the length of OP and a_0 is the angle between OP and x axis. At the time t_m, the center of target moves to O_m. Coordinate system $x'O_m y'$ is obtained by coordinate system xOy moving horizontally. Coordinate system uO_2v is established with O_m being the origin and bistatic angle bisector being the v axis. The coordinate of scatter P is $P_m\left(x_{Pm}, y_{Pm}\right)$ in uO_2v. a_m is the angle between OP and u axis. The change of view angle of equivalent monostatic radar is q_m.

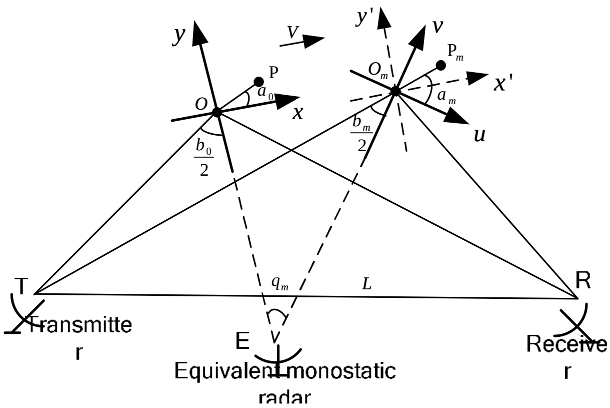


Figure 1. The imaging model of bistatic ISAR

Assuming that the two radars are ideal synchronous, and the transmitter emits chirp signal with period of T_{PRT}, we have

$$s_t\left(\hat{t}, t_n\right) = \mathrm{rect}\left(\frac{\hat{t}}{T_p}\right)\exp\left\{ j2p\,(f_c t + \frac{1}{2} m \hat{t}^2) \right\} \tag{1}$$

where, $\mathrm{rect}(u)$ is the rectangular window function defined as $\mathrm{rect}(u)=1$ if $|u| \le 0.5$ and $\mathrm{rect}(u)=0$ otherwise, $\hat{t}$ is the fast time, $t_m = mT_{PRT}$ $(m = 0,1,2,...)$ is the transmitting time named slow time. t is the total time and $\hat{t} = t - t_m$. T_p is the pulse width. f_c is the carrier frequency. m is the chirp rate.

The base band signal is

$$s_b\left(\hat{t},t_m\right)=\text{rect}\left(\frac{\hat{t}}{T_p}\right)\exp\left(jpm\hat{t}^2\right) \tag{2}$$

Assuming that scattering coefficient of P is s_P. And the echo received by the receiver at the time t_m can be written as

$$s_r\left(\hat{t},t_m\right)=s_P\cdot\text{rect}\left(\frac{\hat{t}-R_{Pm}/c}{T_p}\right)\cdot\exp\left(j2p\left(f_c\left(t-\frac{R_{Pm}}{c}\right)+\frac{1}{2}m\left(\hat{t}-\frac{R_{Pm}}{c}\right)^2\right)\right) \tag{3}$$

where, R_{Pm} is the total distance from $P_m\left(x_{Pm},y_{Pm}\right)$ to receiver and transmitter.

Convert the echo to zero-IF through coherent local oscillator, and pulse compression is completed employing a matched filter as $H(f)=S_b^*(f)$. The result of pulse compression is as follows

$$s_{if\_c}\left(\hat{t},t_m\right)\approx s_P T_p\cdot\text{sinc}\left[mT_p\left(\hat{t}-\frac{R_{Pm}}{c}\right)\right]\exp\left(-j2p\,f_c\frac{R_{Pm}}{c}\right) \tag{4}$$

Its spectrum can be expressed as

$$S_{if\_c}\left(f,t_m\right)=S_{if}\left(f,t_m\right)H(f)=\left|S_b(f)\right|^2\exp\left[-j2p\left(f_c+f\right)\frac{R_{Pm}}{c}\right] \tag{5}$$

Equation (4) is the range profile.

Let R_{TO},R_{RO} represent the distance from the target center to the transmitter and receiver, respectively. In bistatic radar system, the target size is far less than the distance from target to radar, i.e., $d = R_{TO},R_{RO}$. Let R_{TPm}, R_{RPm} represent the distance from scatter P_m to transmitter and receiver, respectively. Because $a_m=q_m+a_0$, then R_{TPm}, R_{RPm} can be expressed as

$$R_{TPm}=R_{TOm}+d\cos\left(\frac{p}{2}-\frac{b_m}{2}-\left(a_0+q_m\right)\right) \tag{6}$$

$$R_{RPm}=R_{ROm}+d\cos\left(\frac{p}{2}+\frac{b_m}{2}-\left(a_0+q_m\right)\right) \tag{7}$$

The total distance from P_m to transmitter and receiver is

$$R_{Pm}=\left(R_{TPm}+R_{RPm}\right)=\left(R_{TOm}+R_{ROm}\right)+2\left(x_P\sin q_m+y_P\cos q_m\right)\cos\frac{b_m}{2} \tag{8}$$

Let $R_{Om}=R_{TOm}+R_{ROm}$, then

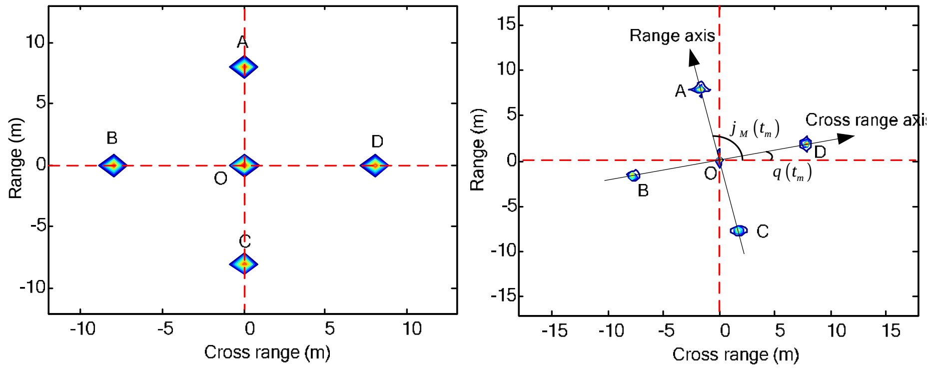
$$R_{Pm}=R_{Om}+2\left(x_P\sin q_m+y_P\cos q_m\right)\cos\frac{b_m}{2} \tag{9}$$

Rotation angle q_m and bistatic angle b_m are the function of slow time t_m, denoted respectively as

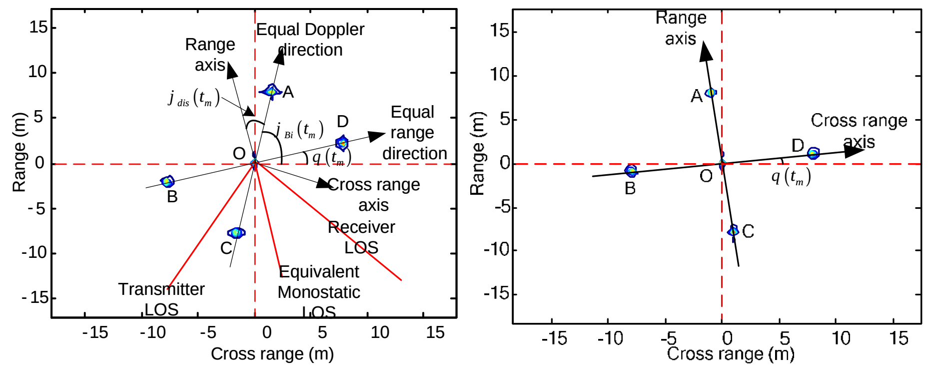
$q(t_m)$, $b(t_m)$. Then the range profile after ideal motion compensation can be written as

$$s_{if\_c}(\hat{t},t_m) = s_P T_p \cdot \text{sinc}\left[mT_p \left(\hat{t} - \frac{2(x_P \sin q(t_m) + y_P \cos q(t_m))}{c} \cos\frac{b(t_m)}{2} \right) \right] \cdot \exp\left[-j2p f_c \frac{2(x_P \sin q(t_m) + y_P \cos q(t_m))}{c} \cos\frac{b(t_m)}{2} \right] \quad (10)$$

III Imaging distortion of bistatic ISAR



(a) Scatter model (b) Monostatic ISAR instantaneous image



(c) Bistatic ISAR instantaneous image of translational motion (d) Bistatic ISAR instantaneous image of turntable model

Figure 2. Imaging results of monostatic ISAR and bistatic ISAR

In bistatic ISAR, the range axis is the direction of bistatic angle bisector, and the cross range axis is determined by the effective rotational vector of target relative to the transmitter and receiver. The direction is always perpendicular to the Doppler direction, so that the relationship between range axis and cross range axis will not remain perpendicular and the image will be distorted.

The phase term of range profile as equation (10) after motion compensation can be expressed as follows:

$$f = -2p \frac{f_c}{c}\left(2x_P \sin q(t_m) + 2y_P \cos q(t_m)\right)\cos\frac{b(t_m)}{2} \quad (11)$$

To facilitate the analysis, the scatter model is built as shown in Fig.2(a). Fig 2. (b) ~ (d) are the instantaneous imaging results employing monostatic ISAR, bistatic ISAR translational motion model and bistatic ISAR turntable model at the time t_m.

Monostatic ISAR can be regarded as a bistatic ISAR whose transmitter and receiver are placed in the same place, i.e., $b\left(t_m\right)\equiv 0$. Then the phase term can be expressed as

$$f_M = -2p\,\frac{f_c}{c}\left(2x_P \sin q\left(t_m\right) + 2y_P \cos q\left(t_m\right)\right) \tag{12}$$

Doppler frequency can be obtained

$$f_{d\_M} = -\frac{1}{2p}\frac{df_M}{dt_m} = \frac{2f_c}{c}\left[\left(x_P q'\left(t_m\right)\cos q\left(t_m\right) - y_P q'\left(t_m\right)\sin q\left(t_m\right)\right)\right] \tag{13}$$

We can get the angle between zero-Doppler line and data line

$$j_M\left(t_m\right) = \frac{p}{2} - q\left(t_m\right) \tag{14}$$

The positive or negative of $q\left(t_m\right)$ depends on the rotational direction of target, and $q\left(t_m\right)$ is positive when target rotates clockwise, otherwise negative. Equation (14) indicates that the range axis is always perpendicular to the cross range axis. The distortion will not occur in the image as shown in Fig 2. (b).

When imaging employing bistatic ISAR translational motion model, as shown in Fig 2. (c), the equal range direction is perpendicular to equivalent monostatic radar LOS. It is obvious that the equal range direction is not perpendicular to equal Doppler direction. That is to say, the image is distorted. The Doppler frequency can be expressed as

$$f_{d\_Bi} = \frac{2f_c}{c}\left[\left(x_P \cos q\left(t_m\right) - y_P \sin q\left(t_m\right)\right)q'\left(t_m\right)\cos\frac{b\left(t_m\right)}{2} - \left(x_P \sin q\left(t_m\right) + y_P \cos q\left(t_m\right)\right)\frac{b'\left(t_m\right)}{2}\sin\frac{b\left(t_m\right)}{2}\right] \tag{15}$$

We assume that the angle between zero-Doppler direction and the data line is $j_{Bi\_0}\left(t_m\right)$. Then $j_{Bi\_0}\left(t_m\right)$ can be obtained by equation (15)

$$j_{Bi\_0}\left(t_m\right) = \tan^{-1}\left[\frac{2q'\left(t_m\right)\cos q\left(t_m\right)\cos\frac{b\left(t_m\right)}{2} - b'\left(t_m\right)\sin q\left(t_m\right)\sin\frac{b\left(t_m\right)}{2}}{2q'\left(t_m\right)\sin q\left(t_m\right)\cos\frac{b\left(t_m\right)}{2} + b'\left(t_m\right)\cos q\left(t_m\right)\sin\frac{b\left(t_m\right)}{2}}\right] \tag{16}$$

where, $q'\left(t_m\right) = w\left(t_m\right)$ is equivalent rotational angular velocity. The obtained angle range is $\left(-p/2, p/2\right)$ according to the equation (16), and we need to correct the range to $\left(0, p\right)$ by the following equation

$$j_{Bi}\left(t_m\right) = \begin{cases} j_{Bi\_0}\left(t_m\right) & j_{Bi\_0}\left(t_m\right) \geq 0 \\ p + j_{Bi\_0}\left(t_m\right) & j_{Bi\_0}\left(t_m\right) < 0 \end{cases} \tag{17}$$

Because the equal Doppler direction is orthogonal to cross range axis and the equal range direction is orthogonal to range axis, more over, the range axis is always the bistatic angle bisector direction, we can define the distortion angle as the angle between equal Doppler direction and range axis. Then the distortion angle $j_{dis}\left(t_m\right)$ can be expressed as

$$j_{dis}(t_m) = \frac{p}{2} - [j_{Bi}(t_m) + q(t_m)] \tag{18}$$

where, $[j_{Bi}(t_m) + q(t_m)]$ is the angel between equal Doppler direction and equal range direction. The sign of $j_{dis}(t_m)$ depends on the position of equal Doppler direction and equal range direction. If the equal Doppler direction is in the clockwise direction of range axis, $j_{dis}(t_m)$ is positive. Otherwise, $j_{dis}(t_m)$ is negative.

Bistatic ISAR turntable imaging is a special case of bistatic ISAR imaging. In this case, the bistatic angle does not change and $b'(t_m) = 0$. We can obtain that $j_{Bi}(t_m) + q(t_m) = p/2$ from equation (16), and in this case $j_{dis}(t_m) = 0$, that is, the image does not distort in case of bistatic ISAR turntable imaging, as shown in Fig 2.(d). The range axis and cross range axis are orthogonal.

From the above analysis, because of the time-varying bistatic angle, translation motion of the target causes that the equivalent rotation speed relative to transmitter and receiver is unbalanced , which results in image distortion.

Ⅳ Bistatic ISAR Imaging Simulation

To verify the correctness of imaging analysis in this paper, the imaging simulation of space target is carried out. The simulation scenario and the target scatter model are shown in Fig.3 and Fig. 4. The simulation parameters are shown in Tab. 1. Note that, because the distance from radar to space target is very large, to ensure the high SNR, the pulse width is generally big, at the same time, to avoid the range ambiguity, the PRF is quite small as 50Hz in the simulation.

TABLE 1. Simulation parameters of bistatic ISAR

Parameter Name	Parameter Value	Parameter Name	Parameter Value
Carrier Freq.	10 GHz	Integration Time	5.12 s
Signal Bw	800 MHz	Radar Baseline Length	500Km
Sample Freq.	1 GHz	Range Alignment Method	Envelope Cross Correlation
Pulse Width	10 us	Phase Autofocus Algorithm	DCT
PRF	50 Hz		

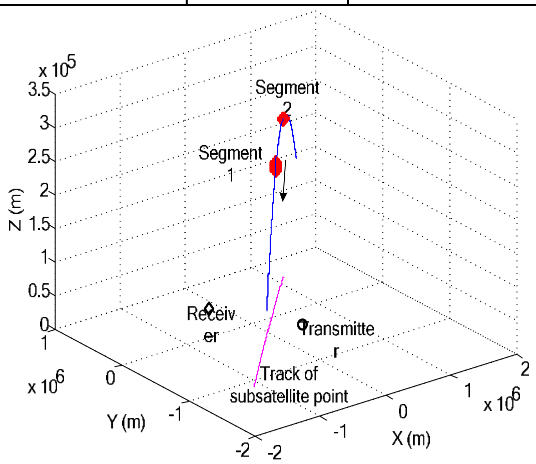


Figure 3. Simulation scenario

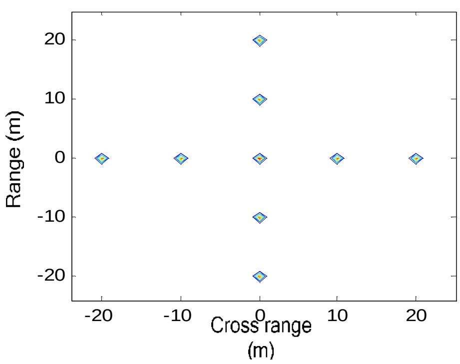
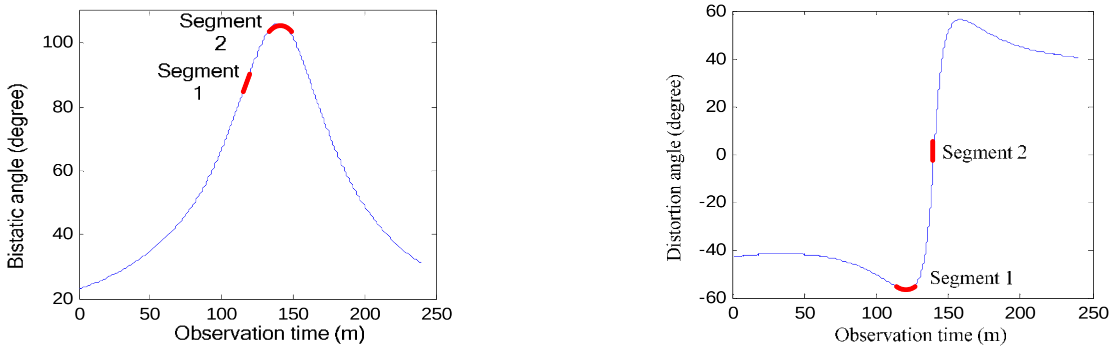


Figure 4. Scatter model

The total observation time of bistatic radar to space target is 240 seconds. During observation, the bistatic angle and imaging instantaneous distortion angle change curves are shown in Fig.5(a) and (b). Two imaging segments are selected for the simulation. The bistatic angle changes fiercely but the imaging distortion angle is smooth in segments 1. The segment 2 is just the opposite.



(a) Bistatic angle change curve during observation (b) Image distortion angle change curve during observation

Figure 5. Important parameter change curves during observation

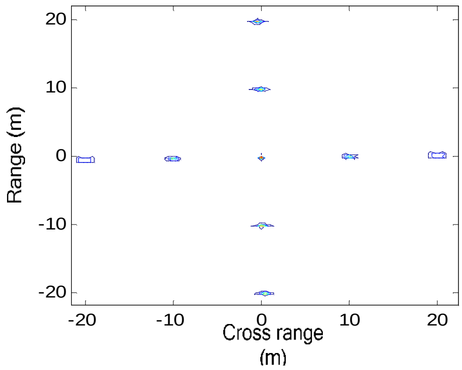


Figure 6. Bistatic ISAR imaging result of turntable model

TABLE 1. Simulation parameters of different segments

Parameter Name	Parameter Value	
	Segment 1	Segment 2
Integration angle	2.10°	1.97°
The amount of change of bistatic angle	6.10°	0.28°
Mean of bistatic angle	92.42°	105.86°
The change amount of distortion angle	0.25°	25°
Range Resolution	0.271 m	0.311 m
Cross Range Resolution	0.584 m	0.724 m

The simulation parameters of the two segments are shown in Tab. 2. The RD imaging result of turntable model is illustrated in Fig.8, the scatter model and integration angle are the same as the two segments. The imaging result of segment 1 is shown in Fig.7. The image has serious distortion and the quality is obviously worse than Fig.6. After calculation the distortion angle is -56.45° which coincides with the theoretical value as -56.45°. The imaging result of segment 2 is shown in Fig.8. Comparing with the turntable model imaging result, the mainlobe of cross range direction broadens seriously, though the two has almost the same integration angle. The reason is that the tiny change of bistatic angle causes the large change of imaging distortion angle. The angle changes about 25° during imaging, which results in migration through multiple

Doppler cells and the cross range blur occurs.

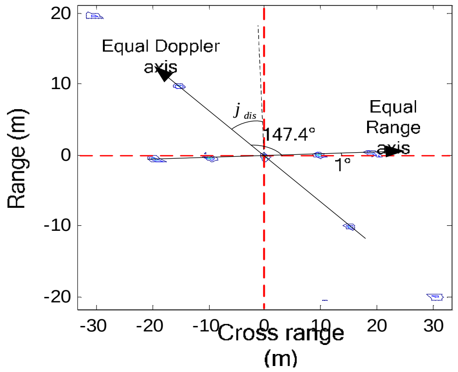


Figure 7. Imaging result of segment 1

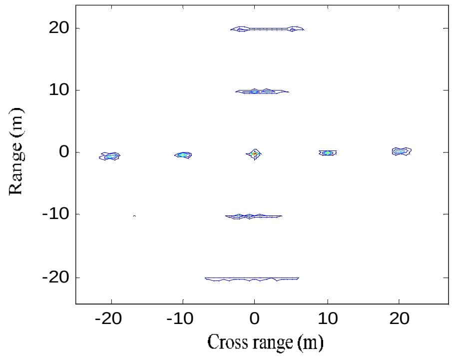


Figure 8. Imaging result of segment 2

As shown in the simulation results, the existing of bistatic angle makes bistatic ISAR is different from the monostatic ISAR. The time-varying bistatic angle causes the distortion of ISAR image. Moreover, the change degree of bistatic angle and image distortion is disproportionate in value. In bistatic ISAR the migration through resolution cell is the result of equivalent rotation relative to bistatic radar and time-varying bistatic angle. To ensure the imaging quality and simplify the algorithm processing, we should select the imaging segment whose bistatic angle and the distortion angle are both constants.

Ⅴ Summary

Bistatic angle is an important parameter of bistatic ISAR, which is different from monostatic ISAR. First, the bistatic ISAR echo model is established. Then, the image distortion mechanism is studied and the distortion angle is estimated. The imaging simulation of space target is carried out, and the result shows the correctness of analysis in this paper. The research in this study is significant for the selection of imaging segment, and provides evidence for the following data processing.

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