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RESEARCH ARTICLE

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High-speed ground moving target detection research using triangular modulation FMCW

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Abstract The frequency modulated continuous wave (FMCW) radar has the characteristics of low probability of interception, good hidden property and the ability to counter anti-radiation missiles. This paper proposes a new method for high-speed ground moving target detection (GMTD) using triangular modulation FMCW. According to the characteristic of the opposite range shift induced by the upslope and downslope modulation FMCW, the upslope and downslope are imaged, respectively. After compensation of continuous motion of the platform and time difference between upslope and downslope signals for imaging, the moving target can be detected through displaced phase center antenna (DPCA) technology. When the moving target is detected, the moving target image is extracted, and correlation processing is used to obtain the range shift, which can be used to estimate the target radial velocity, and further to find the real position of the target. The effectiveness of this method is verified by the result of computer simulation.

Keywords ground moving target detection (GMTD), triangular modulation frequency modulated continuous wave (FMCW), correlation processing

1 Introduction

The combination of frequency modulated continuous wave (FMCW) technology and synthetic aperture radar (SAR) techniques can lead to lightweight, cost effective, low power consuming imaging sensors of high resolution [1], which makes it easy to mount on a small unmanned aerial vehicle, or even on aeromodelling. Since we adopt dechirp-on-receive technology, the received signal is mixed with the transmitted signal in the receive path, producing a beat signal with narrow bandwidth; the demand for video receive channels, A/D samples and processing rate is not severe. Otherwise, using the FMCW technology can realize the miniaturization of the radar system, such as the ‘MiSAR’ system by ENDS, which has an onboard weight of just about 4 kg.

Ground moving target detection (GMTD) is one of the most important tasks of a radar and also the main mission of battlefield surveillance. Conventional single channel SAR usually adopts frequency domain filtering method for moving target detection, which often requires high pulse repetition frequency (HPRF), and can hardly be applied to the case with Doppler spectrum ambiguities, especially when the ambiguous Doppler spectrum falls in the main lobe clutter, since it is impossible to design a filter that not only filters out the moving target signal, but also suppresses the stationary target signal at the same time. This paper studies the high-speed ground moving target detection method using triangular modulation FMCW, which is applied to the case with Doppler spectrum ambiguities. Through analysis of the characteristic of the moving target echo, we illustrate that the moving target has opposite shift in the range direction in the upslope and downslope FMCW images. According to this characteristic, the moving target can be detected by image subtraction after taking some compensation procedure. For the detected moving target, its images are extracted, and correlation processing is conducted to estimate the range shift, compute the radial velocity and locate the moving target to its original position. In Ref. [2], standard interferometric deformation techniques are used to estimate range shift, since the range shift may exceed the wave length, which causes the phase generating 2π ambiguities, leading to the range shift estimate being not correct; correspondingly, the target cannot be located to its real position.

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2 Triangular modulation FMCW signal description

The frequency of FMCW signal is a function of time, and there are two major modulation forms: sawtooth modulation and triangular modulation. This paper adopts the triangular modulation FMCW signal for analysis. As shown in Fig. 1, the solid line is the instantaneous frequency of the transmitted signal and the dashed line is the frequency of the received signal, with the beat signal frequency shown below. From Fig. 1, we can see that the transmitted signal's frequency changes triangularly with time, and target echo is a replica of the transmitted signal, just with a time delay $\tau = 2R/c$, where R is the target range, and c is the speed of light. During the modulation period, the frequency of the beat signal is partially positive and partially negative, which is due to the upslope and downslope modulation rate.

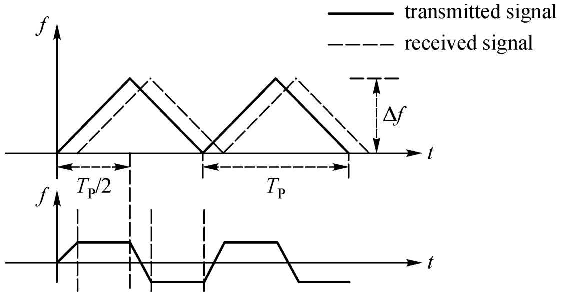

Fig. 1 Time frequency relation of triangular modulation FMCW signal

For a stationary target, the beat signal is a sinusoidal signal for upslope or downslope part with frequency proportional to range, so the beat signal includes the information of target distance. The form is

$$f_b = \frac{\Delta f}{T_p}\frac{4R}{c}, \tag{1}$$

where f_b is the beat signal frequency, Δf is the transmitted signal bandwidth, and T_p is the pulse width.

When the target has radial velocity relative to radar, the frequency of the beat signal will shift along the frequency axis. In this case, the beat signal includes the information of target distance and velocity.

3 Moving target signal model analysis using triangular modulation FMCW

The transmitted signal of FMCW radar is a function of time. Its particular working mode determines that the radar transmits signal in a continuous way. For a moving target, it is imaged smeared in range and shifted in azimuth because of its radial velocity and defocused as a consequence of its cross-range velocity and radial acceleration [3]. In the following analysis, we mainly consider the influence of radial velocity, and neglect the influence of radial acceleration and cross-range velocity. Figure 2 shows the geometry model, and it is easy to get the instantaneous slant range

$$R'(t;R_0) = \sqrt{(R_0 - v_r t)^2 + (vt)^2}, \tag{2}$$

in which R_0 is the nearest range, v_r is the radial velocity of the target, v is the platform velocity, and t is the complete time ($t = t_m + \hat{t}$, t_m is azimuth slow time, $\hat{t}$ is range fast time). Expand the instantaneous slant range $R'(t;R_0)$ with Taylor series at $t = 0$ and approximate to quadratic term, which yields

$$R'(t;R_0) \approx R_0 - v_r t + \frac{v^2 t^2}{2R_0}. \tag{3}$$

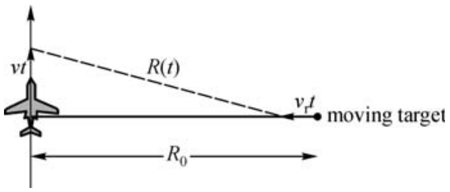

Fig. 2 Moving target geometry model

Substitute $t = t_m + \hat{t}$ into Eq. (3). Then

$$\begin{aligned} R' &\approx R_0 - v_r t_m - v_r \hat{t} + \frac{v^2 t_m^2}{2R_0} + \frac{v^2 \hat{t}^2}{2R_0} + \frac{v^2 t_m}{R_0}\hat{t} \\ &\approx \sqrt{R_0^2 + v^2 t_m^2} + \frac{v^2 \hat{t}^2}{2R_0} + \frac{v^2 t_m}{R_0}\hat{t} - v_r t_m - v_r \hat{t}. \end{aligned} \tag{4}$$

In the above equation, the value of $v^2\hat{t}^2/(2R_0)$ is very small so it can be neglected. Let $R = \sqrt{R_0^2 + v^2 t_m^2}$. Then $(v^2 t_m / R_0)\hat{t} \approx (v^2 t_m / R)\hat{t}$, and R' can be further expressed as

$$R' \approx R + \left(\frac{v^2 t_m}{R}\right)\hat{t} - v_r t_m - v_r \hat{t}. \tag{5}$$

For FMCW SAR, the dechirp-on-receive signal can be written as [4]

$$s(\hat{t},t_m) = A\mathrm{rect}\left[\frac{\hat{t}-2R'(\hat{t},t_m)/c}{T_\mathrm{p}}\right]\exp\left[-\mathrm{j}\frac{4\pi}{\lambda}R'(\hat{t},t_m)\right] \times \exp\left[-\mathrm{j}\frac{4\pi}{c}\gamma(R'(\hat{t},t_m)-R_\mathrm{ref})\left(\hat{t}-\frac{2R_\mathrm{ref}}{c}\right)\right] \times \exp\left[\mathrm{j}\frac{4\pi\gamma}{c^2}(R'(\hat{t},t_m)-R_\mathrm{ref})^2\right], \tag{6}$$

where A is a complex constant, T_p is the pulse width, λ is the carrier wave length, R_ref is the reference range, and γ is range signal modulation rate; for the triangular modulation FMCW signal, it has the characteristic of upslope and downslope modulation. Substitute Eq. (5) into Eq. (6) and simplify

$$s(\hat{t},t_m) = A\mathrm{rect}\left[\frac{\hat{t}-2(R-v_\mathrm{r}t_m)/c}{T_\mathrm{p}}\right]\exp\left(-\mathrm{j}\frac{4\pi}{\lambda}R\right) \times \exp\left(-\mathrm{j}\frac{4\pi}{\lambda}\frac{v^2t_m}{R}\hat{t}\right)\exp\left(\mathrm{j}\frac{4\pi}{\lambda}v_\mathrm{r}t_m\right)\exp\left(\mathrm{j}\frac{4\pi}{\lambda}v_\mathrm{r}\hat{t}\right) \times \exp\left[-\mathrm{j}\frac{4\pi}{c}\gamma(R-v_\mathrm{r}t_m-R_\mathrm{ref})\left(\hat{t}-\frac{2R_\mathrm{ref}}{c}\right)\right] \times \exp\left[\mathrm{j}\frac{4\pi\gamma}{c^2}(R-R_\mathrm{ref})^2\right]. \tag{7}$$

Observe the above signal expression: the first exponential term includes the azimuth phase history, which affects the azimuth focus; the second exponential term includes the Doppler frequency shift [5], introduced by the platform's continuous motion while radar transmitting and receiving signals. Since it is a linear term about azimuth slow time, it can lead to range cell migration, and usually compensated in the azimuth frequency domain; the third exponential term is also a linear term about azimuth slow time. Different from the second one, this term is introduced by the target radial velocity. It can bring the Doppler spectrum shift from its original position, and the corresponding value is $f_\mathrm{D} = 2v_\mathrm{r}/\lambda$, which will lead to the target shift in the azimuth direction ultimately. The fourth exponential term is a linear term about range fast time, also introduced by the target radial velocity. For range dechirped raw data, since it is imaged in the range frequency domain, this term can lead to range shift. As for pulse SAR, the influence of this item can be neglected, but for FMCW SAR, the influence is considerable. It is clear in the following analysis. The fifth exponential term includes range signal, reflecting the target range position, in which $v_\mathrm{r}t_m\hat{t}$ is a couple between range and azimuth, and will defocus the image if not compensated. The last exponential term includes residual video phase (RVP) item, which can be negligible, or otherwise corrected in FMCW SAR [6]. In the above analysis, we know that the third exponential term can result in the Doppler spectrum shift and the azimuth shift consequently. Compute the azimuth shift

$$\Delta x = R_0\frac{v_\mathrm{r}}{v} = \frac{R_0\lambda}{2v}f_\mathrm{D} = \frac{L}{v}\frac{D}{2}f_\mathrm{D} = \rho_\mathrm{a}f_\mathrm{D}T_\mathrm{a}, \tag{8}$$

where f_D is the Doppler spectrum shift of the moving target, L is the length of data support band ($L \approx R_0\theta_\mathrm{3dB}$, θ_3dB represents 3 dB antenna beam width), D is the azimuth antenna aperture, ρ_a is the azimuth resolution, and T_a is the synthetic aperture time. If Δx is larger than $L/2$, it will generate ambiguities. The ambiguous value is [2]

$$\Delta x' = \left(\left(\Delta x + \frac{L}{2}\right) \bmod L\right) - \frac{L}{2}, \tag{9}$$

and this is mainly due to the ambiguity of pulse repetition frequency (PRF).

For the fourth exponential term, the corresponding range shift is

$$\Delta R = \frac{2v_\mathrm{r}}{\lambda}\frac{c}{2\gamma} = \frac{f_c v_\mathrm{r}}{\gamma} = \frac{c}{2B}\frac{f_c}{c}v_\mathrm{r}T_\mathrm{p} = \rho_\mathrm{r}\frac{f_\mathrm{D}}{\mathrm{PRF}}, \tag{10}$$

in which B is the transmitted signal band width, ρ_r is the range resolution, and PRF is the reciprocal of half pulse width. The range shift is a particular characteristic of the FMCW radar and it is not present in conventional pulse SAR systems because of their narrow pulse width. Furthermore, the sign of ΔR depends on the sign of v_r and γ. For upslope and downslope modulation, the range shift is toward the opposite direction, and high-speed moving target detection using triangular modulation FMCW is just based on this phenomenon.

4 Principle of moving target detection using triangular modulation FMCW

For triangular modulation FMCW signal, the upslope and downslope can be imaged, respectively. After correcting the Doppler frequency shift induced by the continuous motion and the time difference between the upslope and downslope images, stationary targets and slow moving targets are imaged in the same way, but for the moving targets with partial or complete Doppler spectrum ambiguities, namely the high-speed moving targets, there exists a phase error due to the ambiguities. Then, if we subtract one image from the other, also called DPCA processing, the stationary targets (clutter) and slow moving targets will be eliminated completely. For the targets with ambiguities, there will be a residual (when the Doppler spectrum ambiguity number of moving targets is odd, it is both the phase error and the range shift that make the cancellation incomplete. When the Doppler spectrum ambiguity number of moving targets is even, it is mainly the range shift that makes the cancellation incomplete). Through comparison with a presetting threshold, we can make a decision. When the moving target is judged, according to the above analysis, it is imaged with opposite shift in range direction for triangular modulation FMCW signal. By extracting the moving target image, and carrying through the correlation processing operation, we can estimate the range shift value, denoted as ΔR, and further evaluate the moving target radial velocity

$$v_r = \frac{\gamma}{f_c} \Delta R. \tag{11}$$

According to the computed radial velocity, we can locate the moving target to its real position. When there are more than one high-speed moving targets, it needs to repeat the above processing several times, and compute the moving targets' radial velocity, respectively. Substituting the result into Eq. (8), the azimuth shift without ambiguities can be acquired, thus the moving target can be located to its real position. Furthermore, according to the estimated parameters, we can also realize accurate imaging of moving targets. Since the reference function used in range and azimuth compression is matched for stationary targets and mismatched for moving targets, there inevitably exists a defocus phenomenon for moving targets. Another point is that there is no exact discrimination for slow or high-speed moving targets, and here we treat a moving target as a high-speed one in case its radial velocity can lead to the Doppler spectrum ambiguities.

5 Processing block diagram of moving target detection using triangular modulation FMCW

The processing block diagram of high-speed moving target detection using triangular modulation FMCW is shown in Fig. 3. First, the received SAR raw data are divided into two parts along the range direction, extracting the upslope and downslope raw data, respectively. For the FMCW SAR system, with dechirp-on-receive techniques, narrow swath and long sweep period, the extraction operation is simple; just segment the raw data recording time. Second, transform both the upslope and donwslope raw data to the azimuth frequency domain, compensate the Doppler frequency shift induced by the platform's continuous motion while radar transmitting and receiving signals, and correct for the range cell migration, which is equivalent to eliminating the couple between the range and azimuth. After this, the signals are transformed to range frequency domain. For the range de-chirped data, this step also realizes range compression. Next, multiply the two-dimensional frequency domain signals with the azimuth reference function, followed by an IFFT operation, and then we can get the upslope and downslope FMCW SAR images, respectively. We now have completed the whole image processing and next proceed to moving target detection. Observe Fig. 1, there is a time interval of $T_p/2$ between the upslope and downslope FMCW SAR images. The moving target detection processing first compensates the time deviation, equivalent to image registration, and then subtracts one image from the other. Since the stationary targets and slow moving targets are imaged in the same way, and there is a phase error for the high-speed moving targets, the stationary targets and slow moving targets will be eliminated and high-speed moving targets remain. The high-speed moving targets can be detected through amplitude comparison. For the detected high-speed moving targets, extract its images, and carry through correlation processing to estimate the range shift. Further,

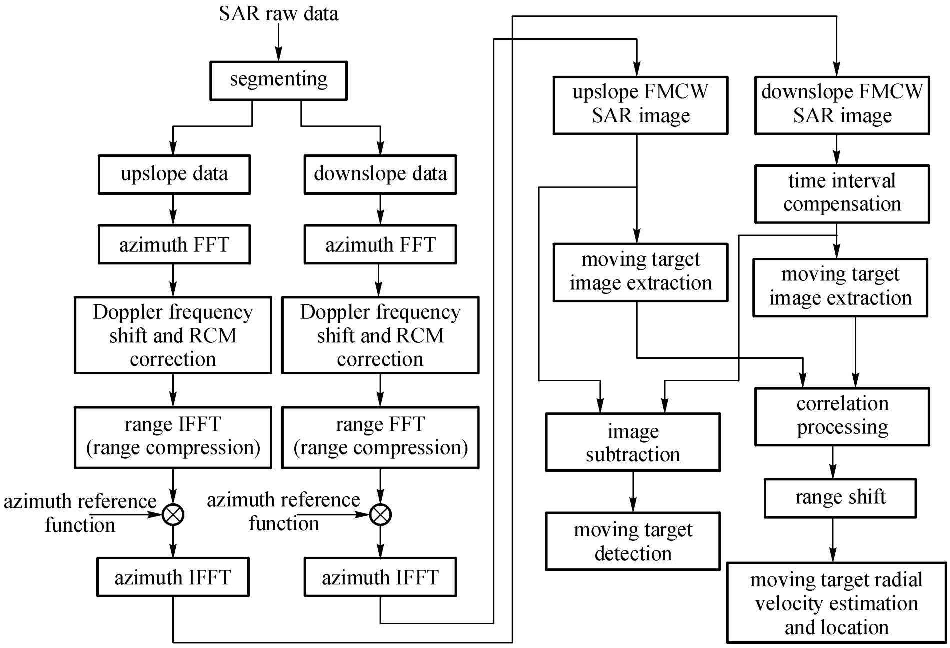

Fig. 3 Processing block diagram of moving target detection using triangular modulation FMCW

substitute the range shift into Eq. (11) to obtain the targets' radial velocity, and substitute the radial velocity into Eq. (8) to complete the location of moving targets.

6 Simulation data processing and analysis

6.1 Simulation parameters

In order to demonstrate the analysis and the performance of the proposed approach, we carry out a simulation with the parameters listed in Table 1.

Table 1 System parameters

parameter	value
carrier frequency/GHz	10
platform velocity/($\mathrm{m \cdot s^{-1}}$)	33
swath width/m	150
synthetic aperture length/m	90
sampling frequency/MHz	1.3
signal band width/MHz	130
pulse repetition interval/ms	1
modulation form	triangular
azimuth beam width/(°)	8.6
reference range/m	600

6.2 Moving target detection result and analysis

Suppose the scene is a two-dimensional plane; put a moving target at the scene center and the origin of azimuth slow time, and other four stationary targets at the up-down, left-right symmetrical positions for a total of five targets. According to the parameters listed in Table 1, the upper limit of the radial velocity without Doppler spectrum ambiguities is 5.025 m/s. Considering the expanding of the Doppler spectrum, the lower limit for the velocity to be detected is slightly less than this value. Next, we will simulate moving targets in the case of different radial velocities. Figure 4 shows the imaging result of the moving target with radial velocity -2 m/s, in which Fig. 4(a) is the upslope FMCW SAR image. The radial velocity of the moving target causes the Doppler spectrum shift from the zero Doppler frequency, and correspondingly an azimuth shift $\Delta x = R_0 v_\mathrm{r}/v = 36.3636$ m. Since this value is less than one-half of the synthetic aperture length, there is no ambiguity for the azimuth shift. Figure 4(b) is an image after the upslope and downslope FMCW SAR images cancellation. The stationary targets are eliminated completely after time interval compensation. For the moving target, although there is a range shift, it is very small ($\Delta R = f_c v_\mathrm{r}/\gamma = 0.0769$ m). When the two images are subtracted, the moving target is cancelled at the same time, making it undetected.

Figure 5 shows the imaging result of the moving target with radial velocity -6 m/s, and Fig. 5(a) is the upslope FMCW SAR image. Also, the moving target is imaged shift in azimuth, and the corresponding value is $\Delta x = R_0 v_\mathrm{r}/v = 109.0909$ m. On the other hand, the radial velocity makes the image defocused in range and the target energy migrates through several range bins. The maximum range migration is $\delta R = v_\mathrm{r} T_\mathrm{a} = 16.3636$ m, which will occupy fifteen range bins. Figure 5(b) is the result after DPCA processing. The stationary moving targets are cancelled completely after compensating the time interval between upslope and downslope FMCW SAR images, but for the moving target, since the radial velocity of the moving target causes partial Doppler spectrum ambiguities in this case, only the Doppler spectrum without ambiguities can be cancelled. For the Doppler spectrum with ambiguities, there still exists a phase error, which makes the moving target unable to be canceled, and further to be detected. In Fig. 5(a), the image of the moving target consists of two parts, one coming from the Doppler spectrum without ambiguities, and the other from the Doppler spectrum with ambiguities. When the upslope and downslope FMCW SAR images are subtracted, the image coming from the Doppler spectrum with ambiguities will remain. For the detected moving target, extract its image in the upslope and downslope FMCW SAR images, respectively, carry through correlation processing to estimate the range shift, and further derive the radial velocity. In this case, the estimated radial velocity is -7.5 m/s, deviated from the ideal value. This is because only part of the moving target's energy is preserved for range shift estimation, which produces a larger estimated error.

Figure 6 shows the imaging result of the moving target with radial velocity -13 m/s, in which Fig. 6(a) is the upslope FMCW SAR image. In this case, the range imaging defocus much severely, and the maximum range walk is $\delta R = v_\mathrm{r} T_\mathrm{a} = 35.4545$ m, which will occupy thirty-one range bins. Figure 6(b) is the result of subtraction of the upslope and downslope FMCW SAR images. Since the radial velocity of the moving target causes complete Doppler spectrum ambiguities, the information of the moving target can be preserved. The same as the previous processing, the estimated radial velocity is -12.6562 m/s, which is close to the ideal value.

7 Conclusions

This paper studies the method of high-speed ground moving target detection using triangular modulation FMCW, and proposes a new approach for high-speed ground moving target detection and location using single channel SAR, which is applicable to the case with Doppler spectrum ambiguities. Simulation data processing verifies the analysis and the performance of the proposed approach.

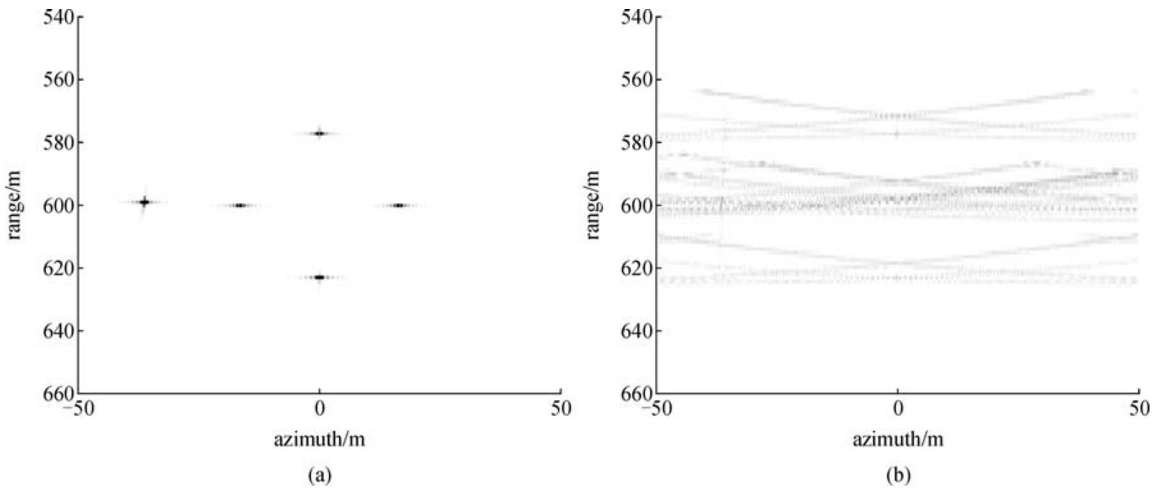

Fig. 4 Imaging result of moving target with radial velocity –2 m/s. (a) Upslope FMCW SAR image; (b) result after cancellation

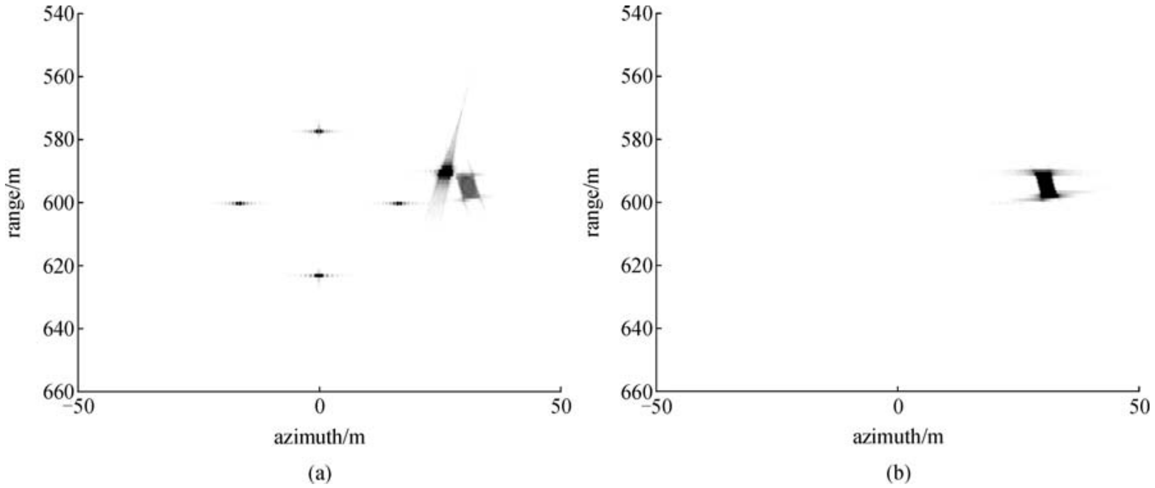

Fig. 5 Imaging result of moving target with radial velocity –6 m/s. (a) Upslope FMCW SAR image; (b) result after cancellation

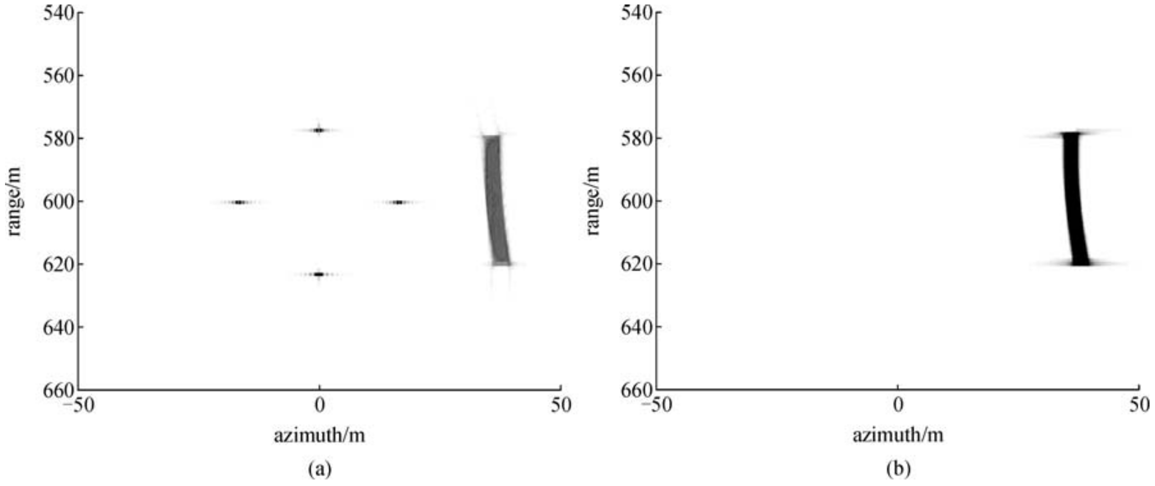

Fig. 6 Imaging result of moving target with radial velocity –13 m/s. (a) Upslope FMCW SAR image; (b) result after cancellation

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