Front. Electr. Electron. Eng. China (2006) 4: 410–415
DOI 10.1007/s11460-006-0079-z

RESEARCH ARTICLE

LI Yan-ping, XING Meng-dao, BAO Zheng

DBS imaging and GMTI in a wideband airborne mechanic scanning radar

Abstract A principle for choosing the coherent integration number and an improved Doppler beam sharpening (DBS) imaging algorithm for mechanic scanning radar are presented in this paper. By compensating the range migration in wideband airborne mechanic scanning radar, the proposed DBS imaging algorithm can efficiently improve the resolution of a DBS image. In addition, based on the characteristic that the echo from the moving target will be modulated by the antenna pattern, a novel method used to locate the moving target is also presented, which begins with the sub-aperture moving target detection followed by the sliding window detection. Proper location can be achieved by using this method. Finally, the results on real radar data are provided to demonstrate the effectiveness of these proposed methods.

Keywords DBS, range migration correction, moving target indication, moving targets location, radar imaging

1 Introduction

When the antenna of the airborne radar is scanning on a large scale, the DBS technique can be used to obtain the non-focus image of the observed scene with relatively low computation burden. In modern war, it is not only required to obtain the synthetic aperture radar (SAR) image of the surveillance area and to look at the interesting fixed target from the image, but it is also required to have the ability of detection and location of the moving target. The most important breakthrough in Joint STARS [1] is that it has combined the SAR mode with the GMTI mode in the radar system, namely, the fixed targets of the enemy are imaged in SAR mode, and the moving targets of the enemy are detected and located in the GMTI mode. With the cooperation of the SAR mode and GMTI mode, the moving targets in the battlefield can be tracked and monitored. The famous radar of this kind in the USA is the Lynx radar system, which provides both the SAR mode and the mechanic scanning GMTI mode [2] with a single channel. Since the Lynx radar is light-weight, it has been mounted on the I-Gnat unmanned aerial vehicle. It has been proved that this system can provide good images and show high performance even in the bad weather.

Moving target detection and imaging in SAR [3] have been gaining importance abroad. In this paper, it has been pointed out that the resolution of the DBS image will be degraded in the mechanic scanning mode if the coherent integration number is not properly chosen or the range migration is not considered. Based on the analysis of the signal model of the static target, we present a principle for choosing the coherent integration number and an improved DBS imaging algorithm in order to improve the quality of the DBS image. On the other hand, most of the moving target detection and location methods available are applicable only when the system has multiple channels and the coherent integration time is long enough. In the case of mechanic scanning mode with only one channel, the coherent integration time will be very short. We can use the sharpened beam to locate the static clutter, but since the moving target will introduce an unknown Doppler due to its motion, it is hard to locate the moving target. Based on the characteristic that the echo from the moving target will be modulated by the antenna pattern, a novel method used to locate the moving target is presented, which begins with the sub-aperture moving target detection and followed by the sliding window detection. Proper location can be achieved by using this method. In the end the positions of the moving targets are labeled on the DBS image.

The remainder of the paper is organized as follows: the following section presents an improved DBS imaging algorithm in detail. Section 3 describes the moving target location method in mechanic scanning mode. The results of the experiments are given in Sect. 4. Conclusions are drawn in Sect. 5.

Translated from *Journal of Xidian University (Nature Science)*, 2006, 33(1): 116–120 (in Chinese)

LI Yan-ping(✉), XING Meng-dao, BAO Zheng
Key Laboratory of Radar Signal Processing, Xidian University, Xi'an 710071, China
E-mail: maplelyp@163.com

2 DBS imaging in mechanic scanning mode

2.1 The geometry and the theory of DBS technique

DBS is one of the SAR modes. Using this technique, the real beam of the antenna can be divided into many narrow sub-beams [4]. Since the target-to-antenna velocity in line of sight direction is different at the center of each sub-beam, the Doppler of each sub-beam is different. If we design a set of narrow-band filter and make sure that the center and the bandwidth of each filter correspond to the center and the width of the sub-beam, the Doppler can be filtered in the frequency domain by these narrow-band filters; thus the azimuth resolution can be improved effectively.

Let us refer to Fig. 1 in which the geometry of the static target in the scanning mode is shown: v_a is the velocity of the craft, $\Delta\theta$ is the beam width, θ is the angle between the cross-track direction and the direction of the beam. φ is the pitch angle, R_0 is the target-to-radar distance. t is the time spent by the craft flying from O to o_1, if the target-to-radar distance at time t can be denoted as R_t, we obtain

$$R_t \approx R_0 - v_a \sin\theta\cos\varphi t + \frac{v_a^2(1-\sin^2\theta\cos^2\varphi)}{2R_0}t^2 \tag{1}$$

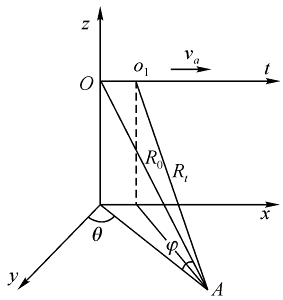

Fig. 1 The geometry of the static target in the scanning mode

From Eq. (1) we obtain the Doppler center of the signal as follows:

$$f_{dc} = \frac{2v_a \sin\theta\cos\varphi}{\lambda} \tag{2}$$

For mechanic scanning radar, the spectrum width of the echo in a processing cycle is

$$\Delta f_d = \frac{2v_a \cos\theta\cos\varphi}{\lambda}\phi \tag{3}$$

where ϕ is the range of the azimuth angle covered by the radar beam in a processing cycle, $\hat{\theta}$ is the scanning speed of the antenna, T_s is the coherent integration time. We have

$$\phi = \Delta\theta + \hat{\theta}T_s \tag{4}$$

2.2 The principle for choosing the coherent integration number

Since fast Fourier transformation (FFT) is used in DBS technique to achieve non-focus SAR imaging (using the first-order term of the phase), the coherent integration time cannot be increased arbitrarily. Only when the non-focus condition is satisfied, can the coherent integration be achieved by FFT.

From Eq. (1) the echo of the point target can be expressed as

$$s(t) \approx \exp\left\{-\mathrm{j}\frac{4\pi}{\lambda}[R_0 - v_a \sin\theta\cos\varphi t + \frac{v_a^2(1-\sin^2\theta\cos^2\varphi)}{2R_0}t^2]\right\}$$
$$t \in [-\frac{T_s}{2}, \frac{T_s}{2}] \tag{5}$$

In order to integrate the signal, we should make sure that the second-order term in $s(t)$ be smaller than $\pi/2$, that is

$$\frac{4\pi}{\lambda}\frac{v_a^2(1-\sin^2\theta\cos^2\varphi)}{2R_0}(\frac{T_s}{2})^2 \leqslant \frac{\pi}{2} \tag{6}$$

If the coherent integration number is N_a, the pulse repetition frequency is f_{pr}, then we have

$$N_a \leqslant \frac{f_{pr}}{v_a}\sqrt{\frac{\lambda R_0}{1-\sin^2\theta\cos^2\varphi}} \tag{7}$$

The Eq. (7) should be satisfied when we choose the coherent integration number N_a. When N_a equals the maximal value, the angle resolution can be expressed as follow

$$\delta\theta = \frac{\lambda f_{pr}}{2N_a v_a \cos\theta\cos\varphi} = \frac{1}{2\cos\theta\cos\varphi}\sqrt{\frac{\lambda(1-\sin^2\theta\cos^2\varphi)}{R_0}} \tag{8}$$

The ground resolution at the distance R_0 can be written as:

$$\delta R_a = R_0\delta\theta = \frac{\sqrt{\lambda R_0(1-\sin^2\theta\cos^2\varphi)}}{2\cos\theta\cos\varphi} \tag{9}$$

We denote the sharpen ratio as

$$\beta = \frac{\Delta\theta}{\delta\theta} = 2\cos\theta\cos\varphi\,\Delta\theta\sqrt{\frac{R_0}{\lambda(1-\sin^2\theta\cos^2\varphi)}} \tag{10}$$

Equation (8) states that the angle resolution can be improved if we increase the coherent integration number. But if the Eq. (7) is not satisfied, coherent integration cannot be properly achieved. On the contrary, the resolution will be degraded. So Eqs. (7)–(10) can be considered as the principle for choosing the coherent integration number.

2.3 Range migration compensation

The target-to-radar distance will change between the pulses when the craft is moving along the track. The range migration phenomenon will occur if the difference of the target-to-radar distance is beyond a range resolution cell. From Eq. (1) we obtain the result that the range migration phenomenon will not occur only when

$$\frac{v_a \sin\theta \cos\varphi \, N_a}{f_{\mathrm{pr}}} < \frac{\mathrm{c}}{2B} \tag{11}$$

where c is the light speed, B is the band-width of the transmitted signal. When Eq. (11) is not satisfied, the range migration should be corrected. We take a real radar system for example. This system, whose antenna rotates at the speed of 18 deg/s and scans from –18 deg to 18 deg without stop, operates in the mechanic scanning mode. The velocity of the carrier is 110 m/s. If we choose N_a as the max value in Eq. (8), the range walk value will be 3.8 m when the scanning angle is 10 deg, thus beyond the range resolution 3 m. This range migration phenomenon is not considered in the conventional DBS imaging algorithm; as a result, the final image quality will be impaired. In this paper we propose an improved DBS imaging algorithm incorporating the range migration correction.

The scanning angle θ, as well as the range walk ratio $R_{\mathrm{WR}} = v\sin\theta\cos\varphi$, will change with the mechanic antenna scanning. Since the coherent integration time is very short, we can compensate the range migration with the range walk ratio at the middle time of the processing cycle.

For the data after dechirp and residual video phase (RVP) term removal in the range direction, it can be written as [5]

$$s_{rd}(n,\hat{t}) = A\,\mathrm{rect}\left[\frac{\hat{t} - \frac{2R_{\mathrm{ref}}}{\mathrm{c}}}{T_p}\right] \mathrm{e}^{-\mathrm{j}\frac{4\pi\gamma}{\mathrm{c}}(\hat{t} + \frac{f_{\mathrm{c}}}{\gamma} - \frac{2R_{\mathrm{ref}}}{\mathrm{c}})R_{\Delta}} \tag{12}$$

where f_{c} is the carrier frequency, T_{p} is the pulse width, γ is the chirp-rate, $\hat{t}$ is the fast time (with respect to the reference range), A is the amplitude, R_t is the target-to-radar distance, R_{ref} is the reference distance, $R_{\Delta} = R_t - R_{\mathrm{ref}}$, the range walk value δR can be expressed as

$$\delta R = \frac{\lambda f_{\mathrm{dc}} k}{2 f_{\mathrm{pr}}} \tag{13}$$

where f_{dc} is the Doppler center during the coherent integration time, k represents the kth coherent integration pulse. Now we can compensate the range migration by multiplying a linear phase term in the frequency domain. Since $f = -2\gamma\,\delta R/\mathrm{c}$, we get the range walk compensation function as

$$RM_{\mathrm{ref}}(f) = \exp(-\mathrm{j}2\pi\gamma \frac{2\delta R}{\mathrm{c}} \hat{t}) \tag{14}$$

Multiplying Eq. (12) with the walk compensation function, and followed by transformation of the signal to the frequency domain by FFT, we get

$$S_d(n,\hat{t}) = AT_p \mathrm{sinc}\left[T_p(f + 2\frac{\gamma}{\mathrm{c}}(R_0 - R_{\mathrm{ref}}))\right] \mathrm{e}^{-\mathrm{j}\frac{4\pi}{\mathrm{c}} f_{\mathrm{c}} R_{\Delta}} \tag{15}$$

where R_0 is the target-to-radar distance when the scanning angle is θ. Equation (15) states that the range walk has been compensated.

3 Moving target location in mechanic scanning mode

3.1 The geometry of the moving target

Let us refer to Fig. 2 in which the geometry of the moving target in the scanning mode is shown. The original coordinate of the radar is $(0,0,R_0\sin\varphi)$, the coordinate of the moving target that the beam illuminated in the line of sight direction is $(R_0\cos\varphi\sin\theta, R_0\cos\varphi\sin\theta, 0)$. v_x and a_x are the velocity and acceleration in the azimuth direction on the ground, respectively. v_y and a_y are the velocity and acceleration in the range direction on the ground, respectively. The moving target moves to position A_1 after time t, and now the target-to-radar distance can be expressed as

$$\begin{aligned} R_t \approx\ & R_0 - [(v_a - v_x)\sin\theta\cos\varphi + v_y\cos\theta\cos\varphi]\,t \\ & + \frac{1}{2R_0}[(v_a - v_x)^2 + v_y{}^2 - ((v_a - v_x)\cos\varphi\sin\theta \\ & + v_y\cos\varphi\cos\theta)^2 + a_x R_0\cos\varphi\sin\theta \\ & - a_y R_0\cos\varphi\cos\theta]\,t^2 \end{aligned} \tag{16}$$

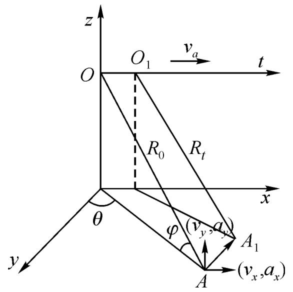

Fig. 2 The geometry of the moving target in the scanning mode

The Doppler center of the moving target is

$$f_{\mathrm{center}} = \frac{2v_a\sin\theta\cos\varphi}{\lambda} - \frac{2v_x\sin\theta\cos\varphi}{\lambda} + \frac{2v_y\cos\theta\cos\varphi}{\lambda} \tag{17}$$

where the first term is introduced by the motion of the radar, the second term and the third term is introduced by the motion of the moving target.

3.2 Moving target location

Most of the moving target detection and location methods available are applicable only when the system has multiple channels and the coherent integration time is long enough. In the case of mechanic scanning mode with only one channel, the coherent integration time will be very short. We can use the sharpened beam to locate the static clutter, but since the moving target will introduce an unknown Doppler due to its own motion, it is hard to locate the moving target with only one antenna.

In this paper, we propose a moving target locating method that is applicable for the mechanic scanning radar with only one antenna. Firstly, moving target detection should be implemented in the sub-aperture, and by this way, the position of the moving target can be determined crudely. Then we extract the data around the position of the moving target in the range bin that contains the moving target, followed by sliding window detection in order to determine the exact position of the moving target.

For the radar system with only one antenna, space and time adaptive processing (STAP) is not applicable for main-lobe clutter suppression. Based on the characteristic that the Doppler of the moving target is different from that of the static target, we can only detect the moving target in the side-lobe. It is known that the pulse repetition frequency of the SAR is always higher than the main-lobe bandwidth of the static target. The moving target will fall into the clutter area if the Doppler introduced by its own motion is not high enough. Then the moving target will be buried by the main-lobe clutter if the amplitude of the signal is relatively lower. On the other hand, if the velocity of the moving target is very fast, velocity blur phenomenon will occur due to the too large Doppler introduced by the moving target. If the spectrum of the moving target is required to separate from that of the static target, and also the velocity blur phenomenon is required to be avoided, then Doppler center introduced by the motion of the moving target should satisfy that

$$\frac{\Delta f_d}{2} < f_{\text{tc}} = -\frac{2v_x \sin\theta\cos\varphi}{\lambda} + \frac{2v_y \cos\theta\cos\varphi}{\lambda} < f_{\text{pr}} - \frac{\Delta f_d}{2} \tag{18}$$

In order to decrease the minimum detectable velocity, we can decrease the velocity of the craft, the beam-width or the rotation speed of the antenna, so as to make the clutter spectrum narrower. In order to increase the maximum detectable velocity, we hope the pulse repetition frequency will be far higher than Δf_d. But range blur will occur in the case of high pulse repetition frequency, thus limiting the width of the strip observed.

The mechanic antenna often scans continuously. Let us take the case that the antenna scans in the same direction as the craft moving as an example: the beam dwell time of the moving target can be written as

$$t_A = \frac{\Delta\theta}{\left(\frac{v_a\cos\theta}{R_0\cos\varphi} + \hat{\theta}\right)} \tag{19}$$

Equation (19) states that, in the case that the antenna scans in the same direction as the craft moving, the beam dwell time of the moving target will be shorter than that in the case that the radar does not move (in this case the dwell time is $t_c = \Delta\theta / \hat{\theta}$). From Eq. (19) we obtain the number of the pulse that the radar will receive from the moving target.

$$M_t = t_A f_{\text{pr}} = \frac{R_0 \cos\varphi\,\Delta\theta f_{\text{pr}}}{(v_a\cos\theta + R_0\cos\varphi\hat{\theta})} \tag{20}$$

After range compression and range walk correction, we suppose that the echo of the moving target is in the *n*th range bin and contains M_t pulses. We then separate the M_t pulses as four sub-apertures, as illustrated in Fig. 3. It is obvious that the moving target is in the line of sight direction of the radar beam at the $M_t/2$ pulse. If we detect the moving target in the sub-apertures, we can discover the moving target in the four sub-apertures in the *n*th range bin, and we will not discover the moving target before the first sub-aperture or after the fourth sub-aperture. Based on the aforementioned reason, we denote that the moving target is in the line of sight direction of the radar beam at the joint between the second sub-aperture and the third sub-aperture. Then we can determine the cursory position of the moving target.

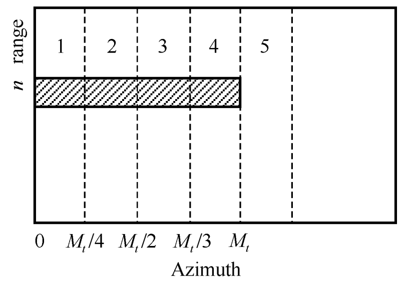

Fig. 3 Moving target location cursorily by sub-aperture detection

But in the actual case, we do not know the position of the moving target before the moving target detection. So we cannot equally divide the signal of the moving target into several sub-apertures, and the case will occur as illustrated in Fig. 4. In this case, if the amplitudes of the signal of the moving target in the first and the fifth sub-aperture are great enough, we will discover the moving target in these five sub-apertures, then we can denote that the moving target is in the line of sight direction of the radar beam in the middle of the third sub-aperture. Then we also can determine the cursory position of the moving target.

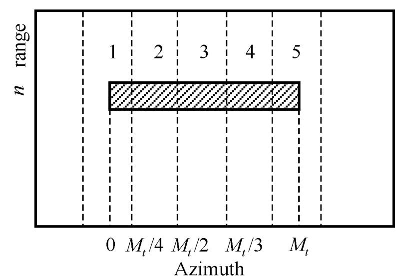

Fig. 4 Actual case of moving target location by sub-aperture detection

If the length of the sub-apertures is equal as illustrated in Fig. 3, there is no location error. For the case as illustrated in Fig. 4, the maximum location error is

$$\Delta R_{\max} = \frac{\Delta\theta}{4} R_t \tag{21}$$

where $\Delta\theta$ is the beam-width, R_t is the target-to-radar distance. Equation (21) denotes the location error in the case of four sub-apertures. If we divide the signal of the moving target into N sub-apertures, the maximum location error is then

$$\Delta R_{\max} = \frac{\Delta\theta}{N} R_t \tag{22}$$

Equation (22) states that the more the sub-aperture is divided, the less the location error will be. But as the number of the sub-apertures is increasing, the coherent integration pulse will decrease, and also the amplitude of the signal will reduce in each sub-aperture. As a result, the moving target will not be detected if the amplitude of the moving target signal in each sub-aperture is too low.

After the sub-aperture detection, we can determine the cursory position of the moving target. The continuous scanning mode of the antenna is similar to the stepped walk scanning mode. But the difference is that the echo from the moving target will be modulated by the antenna pattern in the continuous scanning mode. That means the amplitude of the moving target is not constant. If the moving target is in the line of sight direction of the radar beam, the amplitude of the moving target approaches the greatest value. If the moving target deviates the line of sight direction of the radar beam, the amplitude of the moving target will decrease. Based on this characteristic, we can determine the position of the moving target more exactly. Firstly, we detect the moving target in the sub-aperture and obtain the cursory position of the moving target. Secondly, we select the data around the cursory position of the moving target. Thirdly, we determine the exact position by sliding window detection. We consider that the moving target is in the line of sight direction of the radar beam if the amplitude of the moving target approaches the greatest value (we can get the maximum position of the amplitude by second-order curve fit). Then we can determine the exact position of the moving target.

In the proposed algorithm, sub-aperture moving target detection is required, followed by the sliding window detection. Since the computation burden of the sliding window detection is great, the reason why we do not implement sliding window detection directly is that the computation burden will be greatly decreased if we first implement sub-aperture moving target detection to obtain the cursory position of the moving target.

Figure 5 is the diagram of the DBS imaging algorithm and moving target detection.

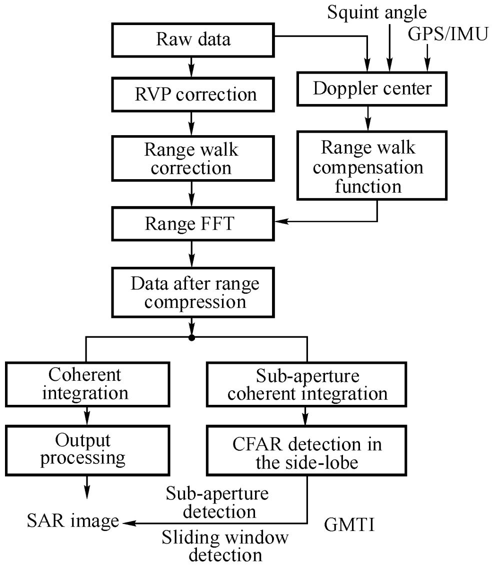

Fig. 5 Block diagram of DBS imaging and moving target detection and location

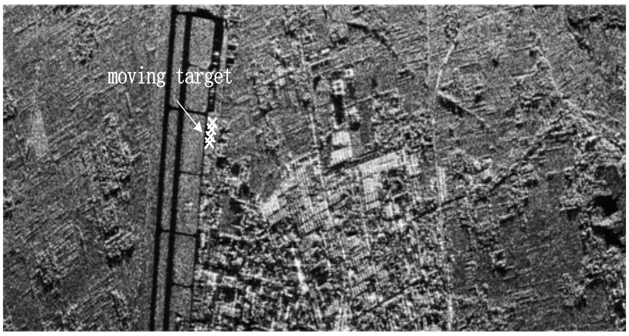

Fig. 6 DBS imaging (resolution 3 m × 14 m) and moving target location

4 Experiments

Figure 6 provides the result on the real data (the resolution is 3 m × 14 m). The antenna scans a cycle using 4 s and scans from −18 deg to 18 deg. It can be seen that, after range migration correction, the DBS image is in focus even when the scanning angle is high. There is a moving target that is illuminated during the time when the antenna scans for four cycles. We determine the exact position of the moving target in each cycle by the sub-aperture detection and sliding window detection. We label the position of the moving target determined in the DBS image as illustrated in Fig. 6. It is obvious that the moving target is moving along the airport road.

5 Conclusions

Based on the analysis of the characteristic of DBS imaging, it is pointed out that the final DBS image quality will be degraded if we choose the coherent integration number inaccurately or the range migration phenomenon is not considered. In this paper, a principle for choosing the coherent integration number and an improved DBS imaging algorithm for mechanic scanning radar are presented. By compensating the range migration in wideband airborne mechanic scanning radar, the proposed DBS imaging algorithm can efficiently improve the resolution of a DBS image. In addition, most of the moving target detection and location methods available are applicable only when the system has multiple channels and the coherent integration time is long enough. Based on the characteristic that the echo from the moving target will be modulated by the antenna pattern, a novel method used to locate the moving target is also presented, which begins with the sub-aperture moving target detection followed by the sliding window detection. Proper location can be achieved by using this method.

References

1. Entzminger J. N., Fowler C. A. Jr., Kenneally W. J., Joint STARS and GMTI: past, present and future, IEEE Trans. on AES, 1999, 35(2): 748–761
2. Tsunoda S. I., Pace F., Stence J. et al, Lynx: a high-resolution synthetic aperture radar, SPIE Aerosense, Orlando, 1999: 1–8
3. Pettersson M. I., Detection of moving targets in wideband SAR, IEEE Trans. on AES, 2004, 40(3): 780–796
4. Zhou Yin-qing, Doppler beam sharpening technique for airborne pulse Doppler radar, Acta Aeronauticaet Astronautica Sinica, 1988, 9(12): 574–581 (in Chinese)
5. Carrara W. G., Goodman R. S., Majewski R. M., Spotlight synthetic aperture radar: signal processing algorithms, Boston: Artech House, 1995: 458–459
6. Wang Tong, Bao Zheng, Liao Gui-sheng, Adaptive ST-MTI processing for airborne radars, Journal of Xidian University, 2000, 27(5): 537–541 (in Chinese)