Beam-footprint Detection for Non-cooperative Spaceborne/Airborne Bistatic SAR

Feifei Yan, Wenge Chang, and Xiangyang Li
College of Electronic Science and Engineering
National University of Defense Technology, Changsha, Hunan 410073, China

Abstract— In non-cooperative spaceborne/airborne bistatic synthetic aperture radar (SAR), the position of transmitter beam footprint should be detected in real-time to realize beam synchronization. Theoretical analysis shows that signal-to-noise ratio (SNR) of the reflected echoes from the observational area is too low to use the conventional detect method. According to the cross correlation between the echoes of adjacent pulse repetition frequency (PRF) and M-out-of-N (M/N) detection, a reflected echo detect method is proposed in this paper. This method can realize the accumulation of signal energy and enormously improve the performance of LFM detection. Therefore, it can be used for transmitter beam footprint detection in real-time. Simulation results are finally presented to validate the feasibility and efficiency of the proposed method. Finally, raw data of one monostatic SAR is equivalent to verify the efficiency of the proposed algorithm.

1. INTRODUCTION

Non-cooperative bistatic SAR, which using aircraft as receiver and spaceborne radar as illuminating of opportunity, has recently been an interesting research hotspot [1]. Non-cooperative radars with low system cost can achieve additional benefits like improving feature extraction and classification of targets, increasing surveillance for applications in conflict areas. Bistatic radar use separate antennas for transmission and reception, so the observations require accurate antenna pointing for both transmitter and receiver to achieve swath overlap. For the case of non-cooperative transmitter satellite, as there has no special synchronization link between the transmitter and receiver, the accurate position of transmitter beam footprint cannot be known in real-time [2]. So the sampling signal from the anticipative observational area should be analyzed in real-time to judge whether the transmitter beam footprint is coming. Then the synchronization mechanism of the receiver is working to realize beam synchronization.

The reflected echoes from the observational area can be seen as weak linear frequency modulation (LFM) signal detection. There are some classical methods for weak signal detection [3, 4]. Traditional methods include fast Fourier transform, filtering, and lock-in amplifier, etc.. When the SNR of reflected echoes is low, the detection performance will be poor. The fractional Fourier transform (FRFT) is very suitable to detect the LFM signals because of its unique properties. However, the computation cost is very high, and then the weak signal detection cannot be realized in real-time. In conclusion, few studies are reported on beam footprint detection for non-cooperative spaceborne/airborne bistatic SAR.

Based on cross correlation and M/N detection, a beam footprint detection method is proposed in this paper. Without long time noncoherent integration in azimuth dimension, the method can enormously improve the detection efficiency. Meanwhile, the constant false alarm rate (CFAR) and M/N detection methods are used for LFM signal detection. This paper is arranged as follows: Section 2 introduces cross correlation detection method. Simulation results and experimental data results are presented in Section 3 to verify the proposed method. Finally, some conclusions are given in Section 4.

2. BACKSCATTERING ECHO DETECTION

Since the observational area between the adjacent PRF is almost the same, so the adjacent backscattering echoes have high correlation. As noises between the adjacent PRF are irrelevant, there will be a peak value in the cross correlation result, and then CFAR detection for the scene raw data can be performed. To distinguish sample signal between LFM signal and other signals, noncoherent integration and M/N detection are performed in frequency domain. The proposed detection method can realize the accumulation of signal energy and enormously improve the performance of backscattering echo detection.

2.1. Cross Correlation

The backscattering echoes of the scene between the adjacent PRF are

$$\begin{cases} x_1(\tau,\eta) = s_r\left(\tau,\eta\right) + w_1 \\ x_2(\tau,\eta) = s_r\left(\tau,\eta + T\right) + w_2 \end{cases} \tag{1}$$

where $T = 1/\mathrm{PRF}$, $s_r(\tau,\eta)$ and $s_r(\tau,\eta+T)$ are the backscattering echoes between the adjacent PRF, respectively. w_1 and w_2 are white Gaussian noises between the adjacent PRF with zero mean and standard deviation σ^2, respectively.

The cross correlation result between the adjacent echoes is

$$R_{x_1x_2} = R_s + R_{sw_1} + R_{sw_2} + R_{w_1w_2} = R_s + R_w \tag{2}$$

R_w is the cross correlation result related to noise

$$R_s = R_{sw_1} + R_{sw_2} + R_{w_1w_2} = \frac{1}{N}\left[\sum s\left(n\right) w_1^*\left(n\right) + \sum s\left(n\right) w_2^*\left(n\right) + \sum w_1\left(n\right) w_2^*\left(n\right)\right] \tag{3}$$

For N large enough, according to the central limit theorems in probability theory, R_w is nearly white Gaussian noise with zero mean and standard deviation $(2E_s\sigma^2 + \sigma^4)/N$, where E_s is the energy summation of the signal. When the sample signal is only noise, the real and imaginary part of $R_{x_1x_2}(\tau)$ are independent, which are white Gaussian noise with zero mean and standard deviation σ^4/N. The PDFs are

$$P(x) = \begin{cases} \frac{x}{\sigma^4/N}\exp\left(-\frac{1}{2\cdot(\sigma^4/N)}x\right) & 0 \le x < \infty \\ 0 & x < 0 \end{cases} \tag{4}$$

In CFAR systems [5], the probability of false alarm is

$$P_{FA} = \int_{V_T}^{\infty} \left(X > TZ\left|H_0\right.\right) f_z\left(z\right) dx = E_z\left(p\left(X > TZ\left|H_0\right.\right)\right) \tag{5}$$

where Z is the mean clutter power, T is a scaling factor, $f_z(z)$ is the probability density function of Z.

Substituting $f_z(z)$ into (5), the P_{FA} is

$$P_{FA} = M_z\left(\frac{T}{2\sigma^2}\right) \tag{6}$$

where $M_z(\cdot)$ is the moment-generating function of Z. According to (6), when the false alarm probability P_{FA} is given, we can get the threshold V_T.

2.2. M/N Detection

The cross correlation result between the adjacent echoes cannot determine whether the received signal is LFM signal arisen from the spaceborne radar. As the signal bandwidth of the spaceborne radar can be getting from the direct path signal, then M/N detection is performed after noncoherent integration to distinguish the received signal between LFM signal and other signal in frequency domain.

After cross correlation, $R_s(\tau)$ is very narrow in time domain and has a symmetry distribution to the middle of $R_{x_1x_2}(\tau)$; meanwhile, $R_{sw_1}(\tau)$, $R_{sw_2}(\tau)$, $R_{w_1w_2}(\tau)$ distribute uniformity in time domain. When the cross correlation result $R_{x_1x_2}(\tau)$ is cut by rectangle window in the time domain, the amplitude of noncoherent integration result in frequency domain will be smooth, and then the performance of M/N detection can be easily improved.

The M/N detection can be written

$$\sum_{i=1}^{N} u(z_i - T) \underset{H_0}{\overset{H_1}{\gtrless}} M, \quad u(z) = \begin{cases} 1 & z \ge 0 \\ 0 & z < 0 \end{cases} \tag{7}$$

where N is the sample point in range dimension.

If $P_{d,cell}$ denotes the probability that any given pulse exceeds the threshold. Now let P_d, the double threshold probability of detection, be defined as the probability that signal is detected, i.e., the threshold is crossed M times within N looks, then from (7)

$$P_d = \sum_{m=M}^{N} \frac{N!}{m!(N-M)!} \left(P_{d,cell}\right)^m \left(1-P_{d,cell}\right)^{N-m} \tag{8}$$

The double threshold probability of false alarm is

$$P_{fa} = \sum_{m=M}^{N} \frac{N!}{m!(N-M)!} \left(P_{f,cell}\right)^m \left(1-P_{f,cell}\right)^{N-m} \tag{9}$$

As can be seen from (4), after cross correlation, w' is a white Gaussian noise with zero mean and standard deviation σ^4/N. When noise only is present, the standard deviation of noise after FFT is determined by the width W of the rectangle window. Then the real and imaginary part of noise is white Gaussian noise with zero mean and standard deviation $2W\sigma_p^2$.

$$\mathrm{real}\left(X(k)\right) \sim N\left(0, 2W\sigma_p^2\right), \quad \mathrm{imag}\left(X(k)\right) \sim N\left(0, 2W\sigma_p^2\right) \tag{10}$$

According to the probability theory [6], the PDFs of $z = |X(k)|^2$ are

$$P\left(z|H_0\right) = \begin{cases} \frac{z}{2W\sigma_p^2} \exp\left(-\frac{z}{2W\sigma_p^2}\right) & 0 \le z < \infty \\ 0 & z < 0 \end{cases} \tag{11}$$

Suppose the number of noncoherent integration is N_c, then the summation of noise energy is a central chi-square distribution with degrees of $2N_c$ freedom [6]. The PDFs are

$$p\left(x\left|2N_c, \sigma^2\right.\right) = \frac{1}{\left(2W\sigma^2\right)^{N_c}\Gamma\left(N_c\right)} (x)^{N_c-1} \exp\left(-\frac{x}{2W\sigma^2}\right), \quad x \ge 0 \tag{12}$$

Then the probability of false alarm $P_{f,cell}$ is

$$P_{f,cell} = \int_{V2}^{\infty} \frac{1}{\left(2W\sigma^2\right)^{N_c}\Gamma\left(N_c\right)} (x)^{N_c-1} \exp\left(-\frac{x}{2W\sigma^2}\right) dx \tag{13}$$

For a given false alarm probability P_{fa}, the threshold V_2 is computed as follows:

(1) The threshold M is set by the bandwidth of LFM signal.
(2) According to (9) and M, $P_{f,cell}$ can be obtained.
(3) According to (13), we can get the threshold V_2.

The scheme of detect method is shown in Figure 1.

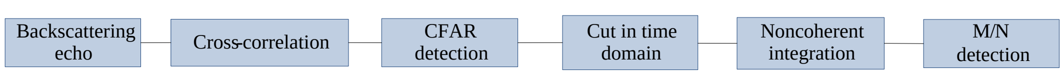


Figure 1: Scheme of backscattering echo detection.

3. SIMULATION AND VALIDATION

Suppose the transmitter and receiver is moving along parallel trajectories. Table 1 shows the simulation parameters.

The size of simulation scene is 2 km × 10 km, which is approaching the beam footprint width of receiver. When the beam footprint overlap between transmitter and receiver is set at 10%, the backscattering echoes of the simulation scene between the adjacent PRF are shown in Figure 2(a).

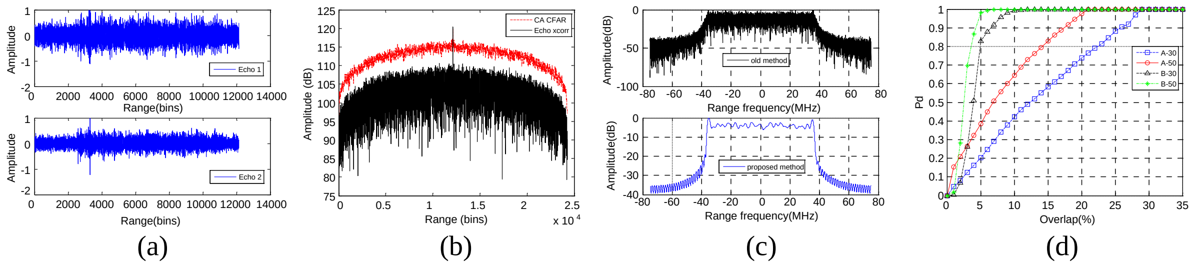
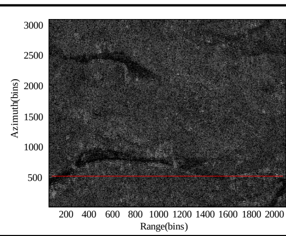
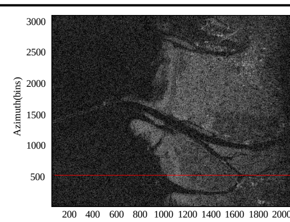
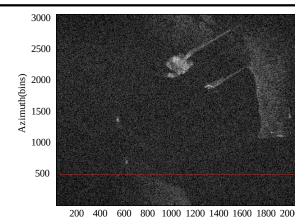


Figure 2: Detection performance, (a) adjacent echo, (b) cross correlation result, (c) power spectrum, (d) detection performance.

Table 1: Simulation parameter.

	Transmitter	Receiver
Height (km)	514	10
Velocity (m/s)	7600	100
Azimuth beam width (°)	0.33	2
Range beam width (°)	2.3	3
Incidence angle (°)	47	80
Bandwidth (MHz)	75	300
Wavelength (cm)	3.1	3.1
Antenna gain (dB)	45	28

Table 2: Detection probability of three different scenes.

Scene			
Detection probability	100%	95.77%	97.63%

The cross correlation result after CFAR detection is shown in Figure 2(b). The power spectrum is shown in Figure 2(c).

As can be seen from Figure 2(b), there is a peak value in the cross correlation result, and then the performance of CFAR detection can be enormously improved. Figure 2(c) shows the power spectrum of cross correlation result after noncoherent integration in frequency domain. The power spectrum without noncoherent integration is also presented in Figure 2(c). It is clearly seen that the power spectrum with noncoherent integration is obviously smooth than the power spectrum without noncoherent integration, which is suit for M/N detection. At the same time, the integration time is short, so the detection method can be realized in real-time.

The Monte-Carlo simulations are carried out to test the performance of the proposed detection method. The false alarm probability of M/N detection is set at 10^{-5}, the number of noncoherent integration is demonstrated using the various sizes (10 and 30). As can be seen from Figure 2(d), detection performance of the method with cross correlation (A) is superiority over the method without cross correlation (B); meanwhile, the detection performance is gradually improved with the increasing number of noncoherent integration. When the beam footprint overlap between the transmitter and receiver is over 10%, and the number of noncoherent integration exceeds 30, the backscattering echo can be stably detected by the proposed method.

Raw data of one monostatic SAR is used to test the propose detection method equivalently. From the simulation parameters in Table 1, theoretical analysis shows that the SNR of bistatic SAR is slightly higher than the monostatic SAR, then the raw data of monostatic SAR can be equivalently seen as the beam footprint overlap of bistatic SAR is 100%. Three kinds of scene echo are chosen to test the proposed method. The number of noncoherent integration is 30. The red line is the start noncoherent integration position in azimuth dimension.

Table 2 shows the detection probability of three different scenes. It can be seen that the detection probability of homogeneous scene is slightly higher than heterogeneous scene; meanwhile, as the the raw data of monostatic SAR can be equivalently seen as the beam footprint overlap of bistatic SAR is 100%, so the probability of detection is very high.

4. CONCLUSIONS

In this paper, an efficient transmitter beam detection method for non-cooperative bistatic SAR is presented. Based on cross correlation and M/N detection, the efficiency of scene raw data detection is greatly improved. Simulation results prove that the proposed detection method is much more efficient than conventional method. When the beam footprint overlap between the transmitter and receiver and the number of noncoherent integration exceed a certain number, the proposed detection method can achieve stably detect of backscattering echo. The efficient and performance of the proposed detection method is also equivalently validated by raw data of one monostatic SAR.

REFERENCES

1. Merrill, I. and T. Skolnik, *Radar Handbook*, Publishing House of Electronics Industry, Beijing, 2010.
2. Watterscheid, I., J. Klare, and A. R. Brenner, "Challenges of bistatic spaceborne/airborne SAR experiment," *European Conference on Synthetic Aperture Radar*, 673–678, Dresden, Germany, May 2006.
3. Zhang, S. S. and T. Zeng, "Dim target detection based on keystone transform," *Proceedings of IEEE International Radar Conference*, 889–894, Washington, DC, USA, May 2005.
4. Conte, E., A. Maio, and G. Ricci, "CFAR detection of distributed targets in non-Craussian disturbance," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 38, No. 2, 612–621, 2002.
5. Bisciglie, D. and R. Mauriziodi, "CFAR detection of extended objects in high resolution SAR images," *IEEE Trans. on Geoscience and Remote Sensing*, Vol. 43, No. 4, 833–843, 2005.
6. Kay, S. M., *Fundamentals of Statistical Signal Processing Volume IIDetection Theory*, Prentice Hall, New Jersey, 1998.