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Research Article

Weak Target Detection Method of Passive Bistatic Radar Based on Probability Histogram

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Passive bistatic radar (PBR) has attracted widespread attention for its capabilities in dealing with the threat of electronic countermeasure, stealth technology, and antiradiation missile. However, passive detection methods are limited by unknown characteristics of the uncooperative illuminators, and conventional radar signal processing algorithms cannot be conducted accurately, especially when the carrier frequency of the transmitting signal is agile and the signal-to-noise ratio (SNR) in the scattered wave of target is low. To address the above problems, this paper presents a novel weak target detection method based on probability histogram, which is then tested by a field experiment. Preliminary results indicate the feasibility of the proposed method in weak target detection.

1. Introduction

In recent years, passive bistatic radar (PBR) has become an emerging technology owing to its covert detection and lower cost compared to active radar systems. Therefore, many kinds of illuminators are exploited as transmitter, such as FM radio[1–3], television[4], satellites[5, 6], cellular phone downlink[7, 8], WIFI[9, 10], digital video broadcasting, and digital audio broadcasting[11–13]. However, these researches mainly focus on civil illuminators. The probing distance is always close due to the limited transmitting power and the ambiguity function of the transmitting signal usually has high side lobes or undesired peaks, which can degrade the detection performance significantly.

Compared with the aforementioned transmitters, a dedicated radar usually has a higher power and a better range resolution[14–17]. At present, with the rapid development of the radar technology, frequency agile and phased array radar has attracted much attention because of its advantages of anti-jamming and high detection probability. The use of frequency agile phased array radar as transmitter can extend the range of available illuminators of opportunity, while it also poses many challenges in PBR signal processing. Due to frequency agility, the coherency between pulses is disrupted and beam scanning flexibility makes the space synchronization become difficult for PBR system. Therefore, long-time integration algorithms are hardly conducted and weak target detection becomes difficult[18–22]. To improve the performance of weak target detection, some complex signal processing methods must be employed, which increase the complexity of the PBR system.

To the best of authors' knowledge, researches into the PBR system using frequency agile phased array radar as the uncooperative transmitter are rarely documented. In this paper, a novel weak target detection method based on probability histogram is proposed for PBR to detect target in low SNR, in which a frequency agile phased array radar is utilized as the uncooperative transmitter. To be specific, an experimental study is conducted to detect weak target in different azimuth and range. The experimental results verify the excellent performance of the proposed method in weak target detection.

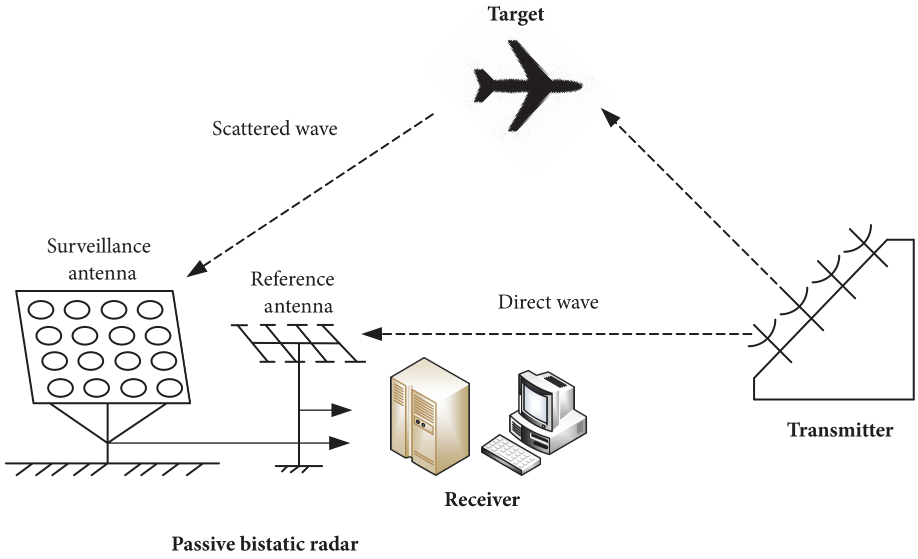


Figure 1: Geometry of PBR system.

2. Problem Statement

2.1. Unknown Parameters of Uncooperative Transmitter. PBR refers to the bistatic radar that exploits uncooperative illuminators of opportunity as the transmitter. The geometry of PBR is shown in Figure 1. It consists of a surveillance antenna, a reference antenna, and a receiver. The reference antenna points to the exploited transmitter to receive direct wave, and the surveillance antenna is directed to the target to receive scattered wave of target. In PBR signal processing, the parameters of transmitting signal in the direct wave must be extracted firstly; then the reference signal is reconstructed and cross-correlated with target signal in the scattered wave to achieve target detection.

The reference signal is a copy of transmitting signal and can be reconstructed with the pulse width and bandwidth of the transmitting signal in the direct wave. The pulse repetition interval (PRI) and time of arrival (TOA) are used for time-frequency synchronization in PBR signal processing. However, the instantaneous parameters of the uncooperative transmitter are unknown, and conventional radar signal processing cannot be conducted accurately to some extent.

2.2. Frequency Agility and Beam Scanning Flexibility. In the PBR system, a frequency agile phased array radar is selected as the uncooperative illuminators of opportunity. The frequency agility technology can improve the ability of anti-jamming and the capability of target detection. The phased array antenna can provide flexibility of beam scanning, which makes it competent for the task of searching and tracking different targets. The beam scanning in the task of searching and tracking is illustrated in Figure 2.

However, the frequency agility technology destroys the coherency between the received pulses in the scattered wave; long-time integration algorithms are hardly applicable in PBR signal processing. Furthermore, the ability of rapidly changing beam scanning makes it impossible for PBR to predict the next beam position. These problems bring difficulties in weak target detection and space synchronization

3. Signal Processing Method

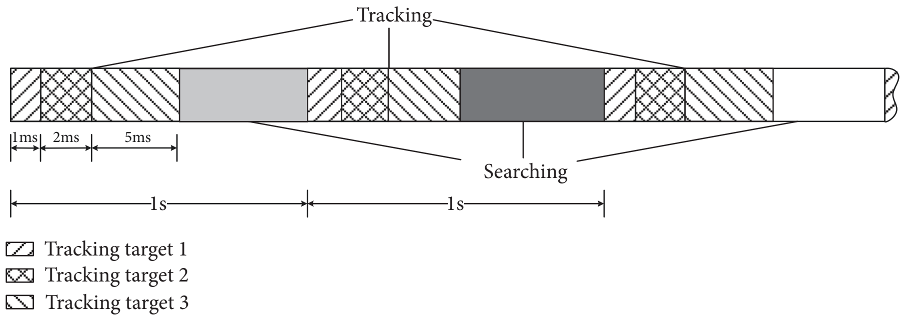
3.1. Signal Model of PBR. In order to overcome the aforementioned problems, a signal processing method is proposed in this paper. The signal model and signal processing procedure are described below. To realize space synchronization and increase detectable probability in PBR signal processing, the digital beamforming method is adopted to form multiple beams simultaneously to cover the observation area. The schematic of simultaneous multi-beamforming method is shown in Figure 3.

In addition, the observation area is divided into azimuth-range unit, which is shown in Figure 4. Each azimuth-range unit stands for the azimuth and range parameter of the detected targets.

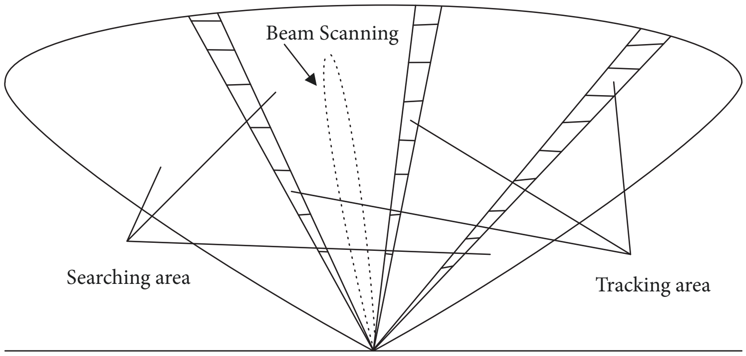
Herein, a linear array antenna of L isotropic sensors spaced half-wave length apart is adopted. As Figure 3 shows, the simultaneous multi-beamforming method is utilized to form multiple beams and the beam weight vector of the ith azimuth unit is given by

$$W_i = [w_{0i}, w_{1i}, \cdots w_{li} \cdots, w_{(L-1)i}] \tag{1}$$

where $w_{li=}e^{-j\pi l \sin(\theta_i)}$ is the beamforming weight coefficient of the ith azimuth unit and the lth array sensor.



(a) Task assignment of searching and tracking



(b) Flexibility of beam scanning

Figure 2: The illustration of beam scanning in the task of searching and tracking.

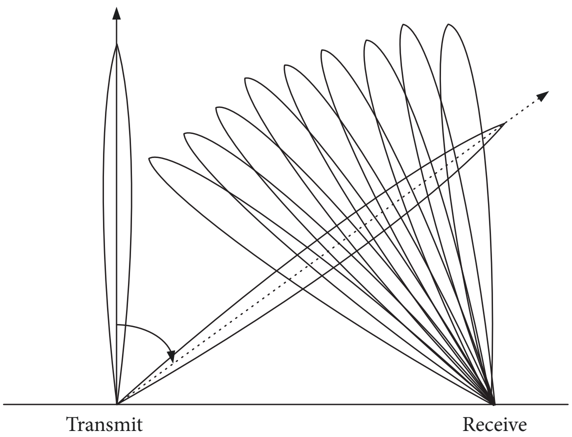


Figure 3: The schematic of simultaneous multi-beamforming method.

Suppose that the exploited radar transmits a linear frequency modulated (LFM) signal. The directly transmitting signal can be written as

$$P(\hat{t}, t_n) = rect\left(\frac{\hat{t}}{T_p}\right)\exp\left(j\pi\frac{B}{T_p}\hat{t}^2 + j2\pi f_n\hat{t}\right) \quad (2)$$

where $\hat{t}, t_n$ denote the fast and slow time, respectively, T_p and B are the pulse width and bandwidth, and f_n is the *nth* agile carrier frequency of the transmitting signal.

Assume there is a moving target with the radial the velocity v_0 and the initial radial range r_0. In the observation time, the target's bistatic range walk can be given as

$$r(t) = r_0 + v_0 t, \quad t \in \left[-\frac{T}{2}, \frac{T}{2}\right] \quad (3)$$

Then, the target signal in the scattered wave can be expressed as

$$s(\hat{t}, t_n) = A(t_n)\, P\left(\hat{t} - \frac{r(t_n)}{c}, t_n\right) \quad (4)$$

where $A(t_n)$ denotes the amplitude of scattered target signal and c is the speed of light.

Then, multiply the scattered target signal with the beam weight vector to acquire the target signal of *ith* azimuth unit and *jth* range unit.

$$s_{ij}(\hat{t}, t_n) = W_i s_j(\hat{t}, t_n) + n(\hat{t}, t_n) \quad (5)$$

where $n(\hat{t}, t_n)$ is the Gaussian white noise and is not related to the target signal.

Pulse compression is performed by the matched filtering method, and the reference signal is retrieved from the

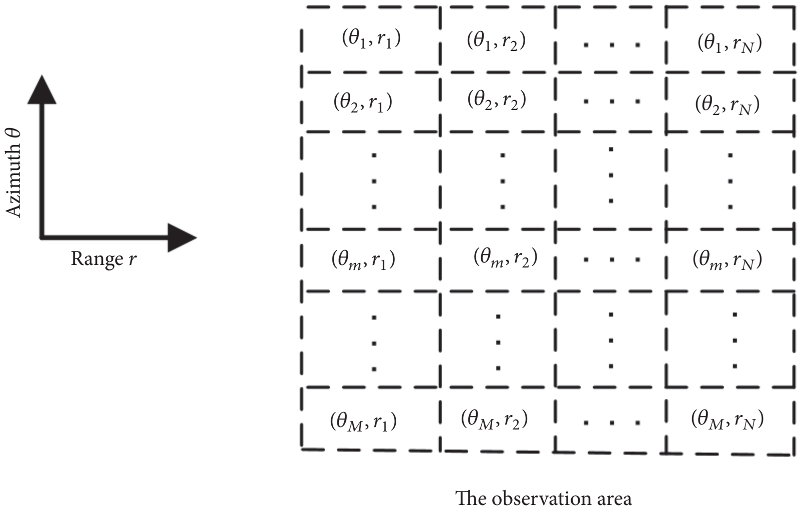


FIGURE 4: The azimuth-range units divided in observation area.

transmitting signal in the direct wave of the uncooperative transmitter, which is expressed as

$$h(t) = rect\left(\frac{t}{T_p}\right)\exp\left(j\pi\frac{B}{T_p}t^2\right) \tag{6}$$

Substitute (5) and (6) into (7) to obtain the target signal model of different azimuth-range unit.

$$s_{pc}(\hat{t}, t_n) = s_{ij}(\hat{t}, t_n) * \operatorname{conj}(h(\hat{t})) = BTA_{ij} \cdot \operatorname{sinc}\left(\pi B\left(\hat{t} - \frac{r(t_n)}{c}\right)\right)\exp\left(-j2\pi f_n\frac{r(t_n)}{c}\right) \tag{7}$$

where $(*)$ and (conj) denote the convolution and conjugate operation.

In the process of the constant false alarm rate (CFAR) detection during the observation time, if the position exceeds the detection threshold, the corresponding azimuth-range unit is set as 1 and recorded in the buffer.

$$\begin{gathered} d = 1, \\ s.t.\ s_{pc}(t) \geq T_h(t) = CFAR\left(s_{pc}(t)\right), \quad t \in \left[-\frac{T}{2}, \frac{T}{2}\right] \end{gathered} \tag{8}$$

and the whole detection results with different azimuth-range unit are represented in the probability histogram.

$$\begin{gathered} D_{ij} = histogram\left(sum\left(d_{ij}\right)\right), \\ i \in [1, \ldots, M], \ j \in [1, \ldots, N] \end{gathered} \tag{9}$$

Define that the total target detection times are Ω in the observation time, the detection times of target signal in the same azimuth-range unit are $\Omega_{ij} = sum(d_{ij})$, and then the detection ratio in probability histogram can be expressed as

$$\xi_{ij} = \frac{\Omega_{ij}}{\Omega} \geq \varepsilon \tag{10}$$

It is worth noting that the position of noise appears randomly, whereas the target signal is detected regularly. If the detection ratio ξ_{ij} is significantly higher than a given threshold ε, then it is regarded that there exists a target in observation area. The corresponding azimuth-range unit is the measured parameters of the target. As a result, we can effectively perform weak target detection of PBR based on the proposed method.

3.2. Signal Processing Procedure

3.2. Signal Processing Procedure. In this section, the signal processing flow is shown in Figure 5, and the main procedure of the signal processing method is described in detail.

(i) Parameters Extraction. The direct wave of the uncooperative radar transmitter is received by the reference antenna. The pulse width, bandwidth, and carrier frequency of the transmitting signal are matched and updated with the known parameters template through the minimum Euclidean distance criterion of cluster analysis algorithm. PRI and TOA are measured by the segment autocorrelation method, which is mentioned in [17].

(ii) Digital Mixing and Filtering. The scattered wave is received by surveillance antenna, and the baseband signal is obtained by digital mixing in quadrature demodulator with the obtained carrier frequency of the transmitting signal.

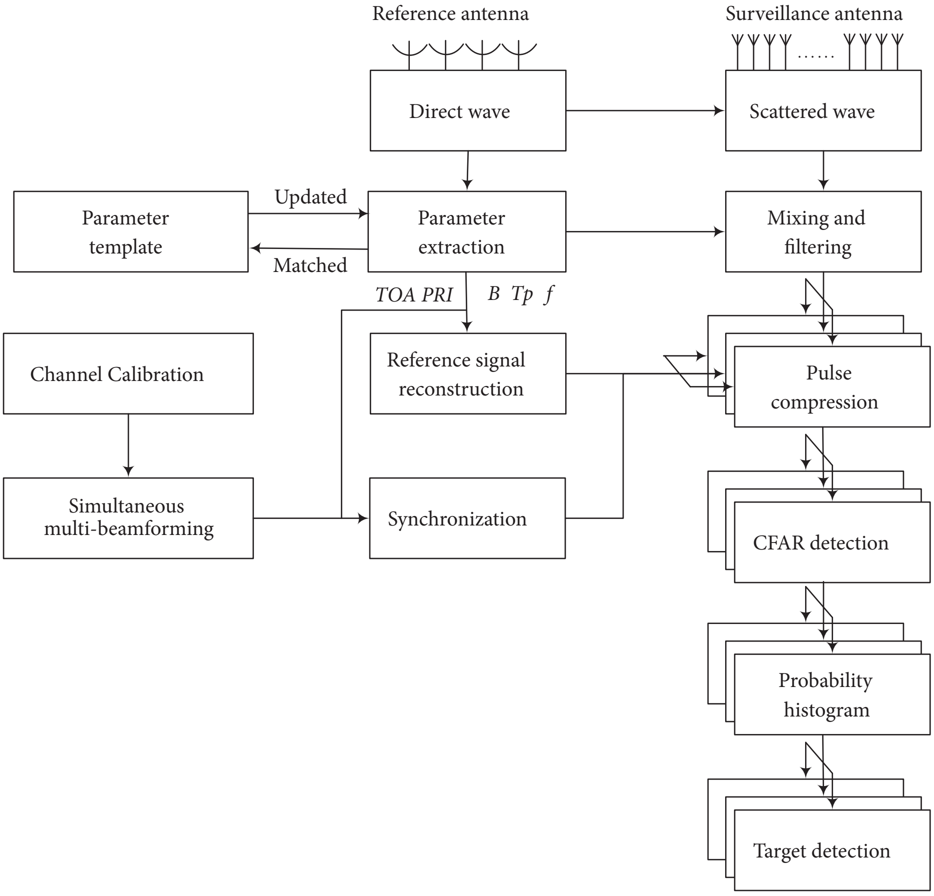


Figure 5: The flow of the proposed signal processing method.

Then, the low pass filtering is then used to eliminate noise interference.

(iii) Time-Frequency and Space Synchronization. Time-frequency synchronization is done by using the extracted parameters of the transmitting signal[23]. To implement surveillance antenna with equally strong beams, the amplitude and phase of all channels must be corrected with the given coefficients. To realize space synchronization, simultaneous multi-beamforming method is used to form multiple beams to cover the observation area[24]. Thus, the receiving data of the array sensor domain are transformed into the azimuth-range domain with the corresponding beam weight vector.

(iv) Reference Signal Reconstruction and Pulse Compression. With the extracted parameters of the transmitting signal in the direct wave, the reference signal is reconstructed, and then pulse compression is done by cross-correlating the reference signal with the received target signal in the scattered wave.

(v) Target Detection Based on Probability Histogram. CFAR detection is performed with all the received waves in the observation time. In the target detection process, when the detection ratio exceeds the given detection ratio threshold, the corresponding azimuth-range unit is recorded. Then, the probability histogram with different azimuth units is plotted.

4. Results and Discussion

4.1. Experimental Scenario and Parameters Setting. In order to verify the performance of the proposed signal processing method, an experimental study of PBR utilizing a frequency agile phased array radar as the uncooperative transmitter is presented. A uniform linear array of eight isotropic sensors with half-wavelength spacing is used as the surveillance antenna. The field experiment is conducted to detect aircraft from different azimuth and range. The basic scenario of field experiment is shown in Figure 6.

In the field experiment, the baseline length between the transmitter and the receiver is 10 km. The carrier frequency of the transmitting signal is randomly changing between 300 MHz and 310 MHz, and the bandwidth is changed depending on the task of searching or tracking of the uncooperative transmitter. The array antenna of PBR uses

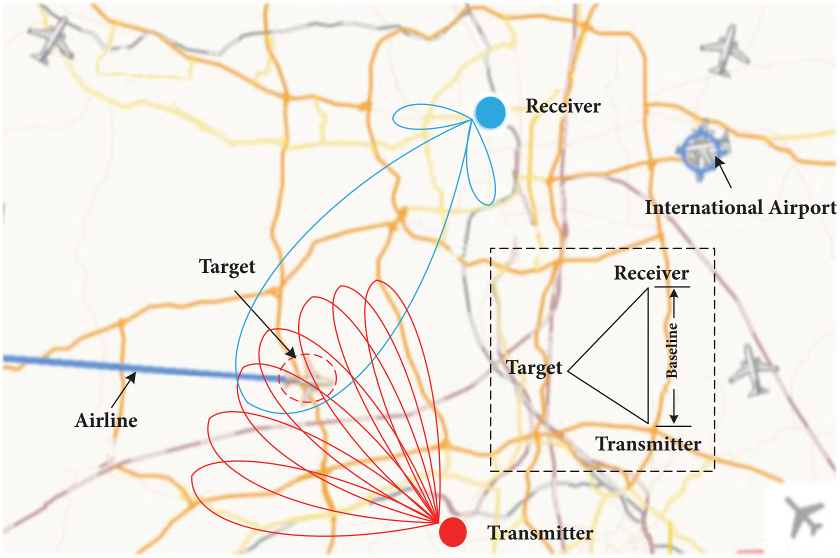


Figure 6: The basic scenario of the field experiment.

Table 1: Parameters of field experiment.

	Parameter	Value
Transmitter	Carrier frequency/MHz	300-310
	Bandwidth/MHz	0.5/2.25
	Pulse width/us	20/100
	Pulse repetition interval/ms	1.5/5
Passive bistatic radar	Bandpass sampling rate/MHz	5
	Range coverage/km	15-200
	Azimuth coverage	-45°-45°
	False alarm probability	$1e^{-5}$
	Detection ratio threshold	50%
	Array antenna sensors	8
	Polarization	Horizontal
Target	RCS/dB	10
	The observation time/min	1

eight sensors to form seven beams simultaneously to cover the observation area. The azimuth coverage is $-45^{\circ}-45^{\circ}$and the range coverage is 15 km − 200km. Particularly, the false alarm probability of the PBR system is set relatively large to ensure that weak targets could be detected. In the target detection process, if the detection ratio in the probability histogram is higher than 50%, the detection result is effective. More detailed parameters of the field experiment are listed in Table 1.

4.2. Experimental Results and Analysis. The latest measurement results of the field experiment are analysed as follows. In Figure 7, the direct wave of the exploited transmitter and the scattered wave of target are received together by the surveillance antenna. Figure 8 depicts the results after pulse compression and CFAR detection, in which the red line represents the detection threshold.

As shown in Figure 7, the amplitude of transmitting signal in the direct wave is extremely high, whereas the amplitude of target signal in the scattered wave is almost submerged in the noise. In Figure 8, after pulse compression, the peak of direct wave is very high and the peak of the scattered wave is relatively low. In the process of CFAR detection, the peak of target signal in the scattered wave can be detected successfully. However, there are three noise interference that also exceed the detection threshold, which can cause a wrong detection result.

In order to improve the weak target detection performance of PBR, the proposed signal processing method based

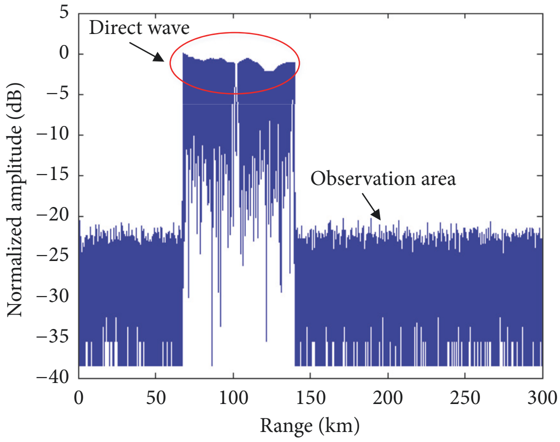


Figure 7: The received signal in the surveillance channel.

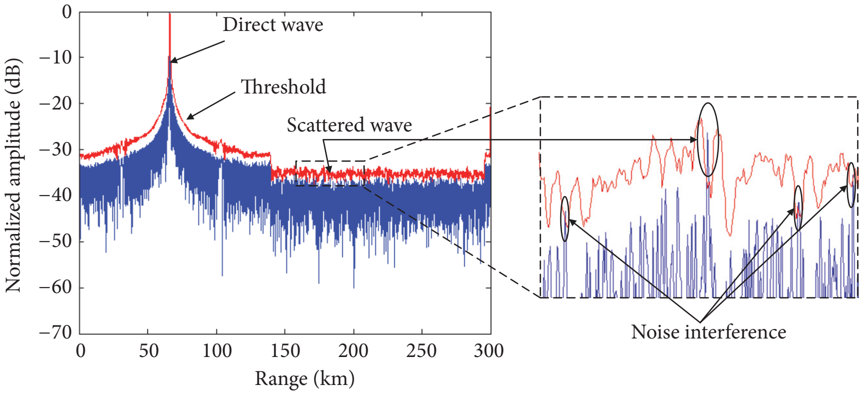


Figure 8: Pulse compression and CFAR detection with the received signal.

on probability histogram is carried out. The surveillance antenna is pointed to the airline to detect aircraft in the observation area. In the observation time, we extract part of the data of the received scattered wave and perform target detection 256 times. The detection results in the probability histogram of different azimuth and range are shown in Figure 9.

From the detection results in the probability histogram mentioned in Figure 9, there is one position in the azimuth unit of $\theta = 0^\circ$ that can be clearly detected and the detection ratio is significantly higher than 50%. Therefore, we can confirm that the aircraft is detected, the azimuth is 0°, and the range is 155 km.

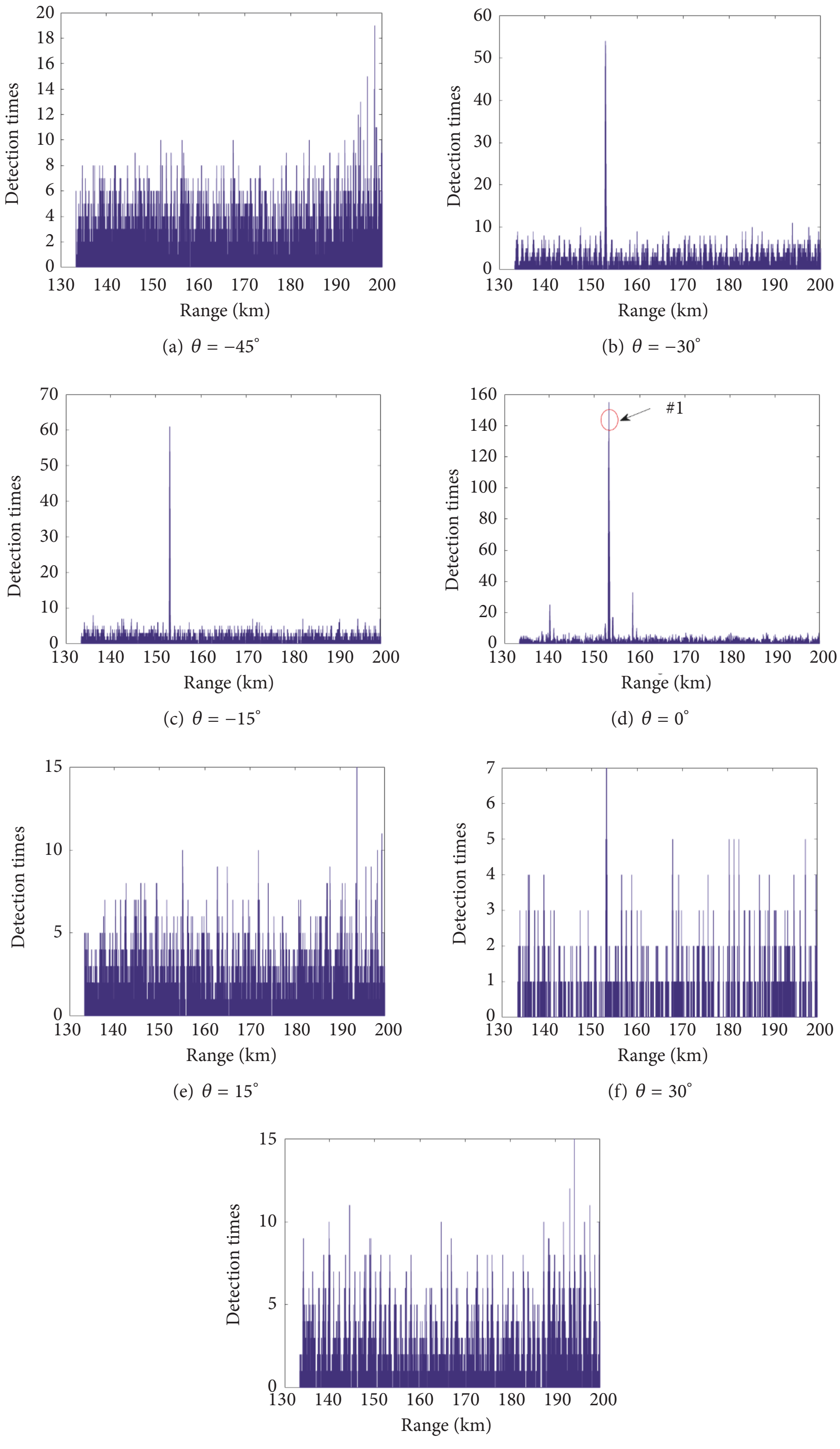
Furthermore, the proposed method is also effective in multiple target detection. Figure 10 illustrates the detection results in the probability histogram of azimuth $\theta = -30^\circ$, in which the surveillance antenna is directed to two airlines in another observation time. Obviously, two targets are detected and located in the range of 142 km and 157 km, respectively.

5. Conclusions

In this paper, an experimental study on PBR using a frequency agile phased array radar as the uncooperative transmitter is presented, and the experimental results provide the proof that the proposed method can effectively solve the problems encountered in weak target detection of PBR. In addition, the proposed method has a low complexity and can be a viable solution for PBR system engineering. Since the presented PBR system works in VHF band, the performance of target detection may be affected by multipath interference, especially in low angle measurement. In order to improve the accuracy of target detection and localisation, anti-multipath techniques should be taken into consideration in future works.

Data Availability

No data were used to support this study.



(a) $\theta = -45^{\circ}$ (b) $\theta = -30^{\circ}$

(c) $\theta = -15^{\circ}$ (d) $\theta = 0^{\circ}$

(e) $\theta = 15^{\circ}$ (f) $\theta = 30^{\circ}$

(g) $\theta = 45^{\circ}$

FIGURE 9: The detection result of one target in probability histogram.

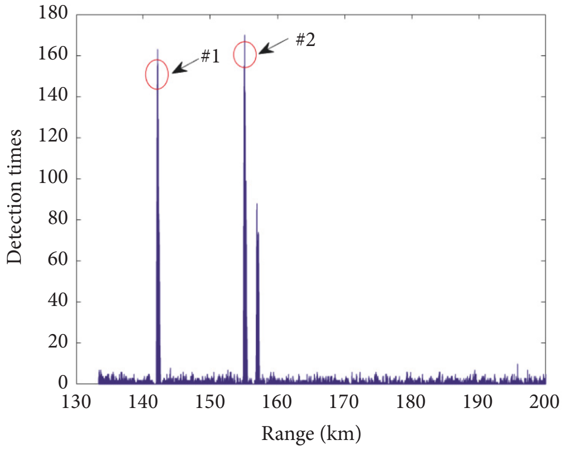


Figure 10: The detection result of two targets in probability histogram.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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