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Study of detection performance of passive bistatic radars based on FM broadcast*

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Abstract: The passive bistatic radar based on the FM broadcast has inherent superiority with respect to its survivability. In this article, the ambiguity function (AF) and the cross ambiguity function (CAF) of the FM radio signal are analyzed and illustrated. The Kolmogorov Smirnov (K-S) test verifies that the amplitude probability density function of the CAF side lobes is exponential; the distribution of the target is also deduced. Finally, the detection performance of the passive radar is studied, and the result shows that this new type bistatic radar has favorable detection capability.

Keywords: Bistatic radar, Ambiguity function, Cross ambiguity function, Probability density function (PDF).

1. Introduction

Passive radar utilizes transmitters of opportunity to detect targets[1] and estimate their parameters, and the transmitters of opportunity can be other radars, satellites, and civil illuminators (such as communication systems, FM or television broadcast stations), which are already present in the environment. H. D. Griffiths[2] used a television-based bistatic radar to detect airplanes; the Manastash Ridge Radar[3] was developed by the University of Washington to study the density irregularities in the ionosphere. Passive radars are developed owing to survivability considerations, and are undetectable by electronic reconnaissance equipments since these do not transmit electromagnetic radiation. Since these contain no transmitter, passive radars are simple, less expensive, and have good electromagnetic compatibility. The configuration of a typical passive bistatic radar is illustrated in Fig.1, where the illuminator of opportunity is stationary; commonly, there are two receiving beams formed by an antenna array or two antennas; the corresponding receivers are: RX_1, which receives the transmitted direct signal, and RX_2, which receives the signals reflected by moving targets. The distance from the transmitter to the receiver is the baseline distance L; the distance from the transmitter to the target is denoted by R_t, and the distance from the target to the receiver is denoted by R_r. In this article, the illuminator is an FM broadcast transmitter; the bandwidth of the FM signal is less than 200 kHz.

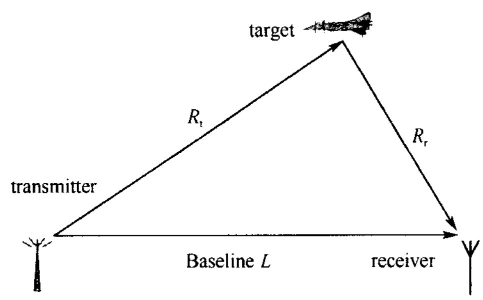

Fig.1 The configuration of a passive bistatic radar

2. The cross ambiguity function of the FM signal

2.1 The received signals

The FM Radio broadcast uses voice or music signals to modulate the carrier frequency; the transmitted signal is represented in complex notation as

$$s(t)=\exp(\theta(t))=\exp(2\pi f_0 t+2\pi\Delta f\int_0^t A(u)\mathrm{d}u) \quad 0\leqslant t\leqslant T \tag{1}$$

where, $\theta(t)$ is the phase of the transmitted signal, $A(u)$ is the modulation signal, and Δf is the maximum frequency variation. The direct signal received by RX_1 is

$$x(t)=a\cdot s(t-\tau_L)+w_1(t),\quad 0\leqslant t-\tau_L\leqslant T \tag{2}$$

where, a is the amplitude of the signal, τ_L is the propagation time from the transmitter to the receiver RX_1, and $w_1(t)$ is the channel noise. The echo signal received by RX_2 is

$$y(t)=b_1\cdot s(t-\tau_2)+b_2\cdot s(t-\tau_t)\cdot \exp[j(2\pi f_d t+\theta_t)]+w_2(t) \quad 0\leqslant t-\tau_2\leqslant T \tag{3}$$

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where, $b_1 \cdot s(t-\tau_2)$ is the direct signal with amplitude b_1 and time delay τ_2 (when RX_1 and RX_2 are co-located, $\tau_2 = \tau_L$), $b_2 \cdot s(t-\tau_t)\exp[j(2\pi f_d t + \theta_t)]$ is the target echo with amplitude b_2, time delay τ_t, Doppler frequency f_d, and phase shift θ_t, and $w_2(t)$ is the channel noise.

2.2 The ambiguity function of the FM signal

The ability of a radar to detect targets among clutter and noise and the ability to determine the parameters of these targets mainly depend on the radar waveforms. AF is a powerful tool for determining the kind of waveform of the illuminator suitable for radar implementation. The AF of the radar transmitter signal denotes the range, the Doppler resolution, and the clutter rejection capability of the radar. The output of the matched filter to a delayed Doppler shifted version of the transmitter signal can be expressed as

$$\chi_s(\tau,f) = \int_{t=0}^{T} s(t)s^*(t-\tau)\exp(-j2\pi ft)\mathrm{d}t \qquad (4)$$

where τ is the time delay, f is the Doppler shift, T is the integration time, and $s^*(t-\tau)$ is the conjugation of $s(t-\tau)$. The AF [4] is defined as

$$A_s(\tau,f) = |\chi_s(\tau,f)|^2 \qquad (5)$$

The AF of the FM signal is shown in Fig.2, where it is an obvious single peak surrounded by small side lobes. From Fig.2, it is found that the FM signal is ideal for radar applications.

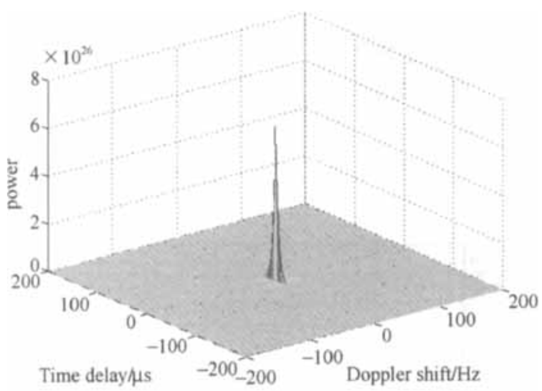

Fig.2 AF of the FM signal (the integration time is 1s)

2.3 The cross ambiguity function of the FM signal

The cross correlation of $y(t)$ and $x(t)$ is defined as

$$\chi_{yx}(\tau,f) = \int_{t=\tau_L}^{T+\tau_L} y(t)x^*(t-\tau)\exp(-j2\pi ft)\mathrm{d}t \qquad (6)$$

The CAF of $y(t)$ and $x(t)$ is defined as

$$A_{yx}(\tau,f) = |\chi_{yx}(\tau,f)|^2 \qquad (7)$$

The CAF is a useful tool for estimating the time delay and the Doppler shift of moving targets. The CAF of a period sampled FM signal is shown in Fig.3, where the strongest peak ($\tau = 0$, $f = 0$) corresponds to the direct signal received by RX_2, and the small peak corresponds to the echo of an airplane, the delay time of which is defined as the time difference of arrival (*TDOA*) as shown in Fig.1,

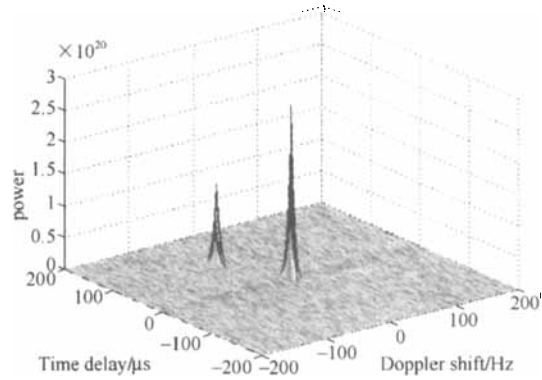

Fig.3 CAF of the FM signal (the integration time is 1s)

$$TDOA = \tau_t - \tau_L = (R_t + R_r - L)/c \qquad (8)$$

where, c is the velocity of light.

3. The probability distribution of the CAF side lobes

3.1 Theoretic analysis

The self correlation of $s(t)$ is defined as $r_s(\tau) = E\{s(t)s^*(t-\tau)\}$, where, E denotes the statistical expectation, and $r_s(0) = 1$. When $\tau > \tau_s$, $r_s(\tau) = 0$, where, τ_s is the self correlation time of $s(t)$. Commonly, $s(t)$, $w_1(t)$ and $w_2(t)$ are independent of each other; when no target is present, the following is obtained:

$$E\{\chi_{yx}(\tau,f)\} = E\left\{\int_{t=\tau_L}^{T+\tau_L} y(t)x^*(t-\tau)\exp(-j2\pi ft)\mathrm{d}t\right\} =$$

$$a \cdot b_1 E\left\{\int_{t=\tau_L}^{T+\tau_L} s(t-\tau_L)s^*(t-\tau_L-\tau)\exp(-j2\pi ft)\mathrm{d}t\right\} =$$

$$a \cdot b_1 E\left\{\int_{t=\tau_L}^{T+\tau_L} \exp[j\theta'(t,\tau,f)\mathrm{d}t\right\} =$$

$$a \cdot b_1 \int_{t=\tau_L}^{T+\tau_L} r_s(\tau)\exp(-j2\pi ft)\mathrm{d}t =$$