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Knowledge-based wideband radar target detection in the heterogeneous environment

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ABSTRACT

In this paper, we address wideband radar target detection in the heterogeneous environment. Firstly, a linear model of the wideband radar target return with the steering vector dispersion is established. Secondly, the heterogeneous clutter is modeled as a two-dimensional wide-sense stationary (WSS) process with inverse complex Wishart distributed random covariance matrices in the time-space and frequency domain. Then, several generalized likelihood ratio test (GLRT) based detectors are designed, some of which integrate the prior knowledge of the clutter covariance matrix with the Bayesian approach, while the others are with the heuristic approach. Finally, the performance of the detectors is evaluated by simulations, and the results show that the detectors based on the Bayesian approach outperform the other detectors.

1. Introduction

By virtue of the high range resolution, the wideband radars play an increasingly important role in many military and civil applications, e.g., synthetic aperture radar (SAR), inverse synthetic aperture radar (ISAR), and radar target recognition in past decades [1]. Recently, wideband radar target detection in clutter has received significant interest [2–15], in which clutter is regarded as the radar echo of natural objects. Usually, clutter contains a mass of scatterers and its power in a range cell decreases as the radar signal bandwidth increases. For artificial targets, the target return primarily comes from several isolated scattering centers; therefore, the return power of each range cell does not always decrease with the radar signal bandwidth when the corresponding scattering centers are resolved in different range cells. Based on the above analysis, increasing the radar signal bandwidth can improve the signal to clutter ratio (SCR, which is defined as the signal power in a range cell versus the clutter power in a range cell), and the detection performance of the wideband radar is better than that of the narrowband radar in clutter environment.

Although increasing the radar bandwidth improves the detection performance in clutter environment, wideband radar target detection in clutter encounters several unique challenges. 1) A large bandwidth leads to the range cell to be smaller, and there are only a small number of clutter scattering centers in one range cell. In this case, the central limit theorem cannot hold any more, and then the Gaussian distribution fails to describe the wideband radar high-resolution clutter [2–10]; 2) The physical size of the target of interest is usually larger than the range resolution of the wideband radar, and such kind of target is referred to as range spread target or distributed target. To sufficiently utilize the energy of the target return, the return of the scattering centers distributed in different range cells should be integrated effectively in the absence of the prior information about the number, the positions and the amplitudes of the scattering centers [14]; 3) For the array and multi-pulse radar, the envelope migration across array elements and pulses usually surpasses the size of the range cell, so the subspace signal model of the narrowband radar is no longer suitable [15–18,43].

In order to handle the non-Gaussian and high spiky properties of the clutter caused by the high range resolution, the compound Gaussian (CG) or sphere invariant random process (SIRP) models are developed to characterize the wideband radar clutter. Besides the reasonable physical interpretation, it has been verified empirically that the CG and SIRP models match the real wideband radar clutter well. Adaptive range spread target detection in CG or SIRP clutter environment has been addressed in [2–13], where the

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range spread target return signal is modeled as a group of vectors in the same rank-1 subspace but with different amplitudes. The covariance matrix of the clutter is estimated from the secondary data which only contains the clutter, and the detectors based on the generalized likelihood ratio test (GLRT) are designed. These detectors are designed for the multiple elements array or multiple pulses, and can be described uniformly as generalized match filtering in each range cell, followed by directly noncoherent integration across the range cells covered by the target. However, most of the existing work on adaptive range spread target detection focuses on the effect of the target return spread in several range cells caused by large bandwidth, while ignoring the range migration of the envelope across array elements or during multiple pulses.

The traditional adaptive detectors presume that the secondary data, which is free of target signals, is sufficient to estimate the clutter covariance matrix. However, this assumption does not always hold, especially for the wideband radar in the heterogeneous environment. Recently, the so-called knowledge aided (KA), knowledge based (KB) or cognitive radar (CR) signal processing is proposed to improve the detection performance of the radar in heterogeneous clutter background by utilizing the prior knowledge of the environment [2,19–33]. The prior knowledge can be classified into two classes according to its origins. One comes from the remote sensing information of the area of interest, such as the digital elevation model (DEM) data, the land use and land cover (LULC) data, or SAR images; and the other comes from the history data, such as the clutter map.

In this paper, we address the problem of the wideband radar target detection in the heterogeneous clutter. The contributions of this paper are as follows. 1) A standard linear model is derived to describe the wideband radar target with range migration; 2) A time-space and frequency two-dimensional correlation model with a random covariance matrix is established to characterize the heterogeneous clutter of multi-channels and multi-pulses wideband radar; 3) By making full use of the prior knowledge of the environment, we design the wideband radar target detectors based on the Bayesian approach. In most existing papers on range spread target detection, the range migration is ignored under the wideband assumption due to the processing difficulty [10]. However, the omitting of the range migration will cause severe detection performance deterioration [43].

The rest of this paper is organized as follows. Section 2 establishes the wideband radar target model, and the time-space and frequency two-dimensional correlated wideband radar clutter model. In Section 3, the optimal detector based on the wideband radar and the clutter model with the known clutter covariance matrix is derived. In Section 4, several wideband radar target detectors integrating prior knowledge of the clutter with different approaches are proposed. The performance of the proposed wideband radar detectors are evaluated by Monte–Carlo simulations in Section 5. Section 6 gives the conclusions of this paper.

2. Signal model and detection problem formulations

2.1. The signal model of the wideband radar target

The radar range resolution depends inversely on the bandwidth of the transmitted signals, i.e., $\Delta r = c/2B_W$, where c is the propagation velocity of the electromagnetic wave and B_W is the bandwidth of the transmitted signal. Consider that the radar receiver contains K_s array elements, and there are K_t pulses during a coherent processing interval (CPI). Denote the high range resolution profile (HRRP) of the target produced by the first pulse and received by the first array element as $g(t)$. Then the received baseband of the signal from the k_tth$(k_t = 1, \ldots, K_t)$ pulse of the k_sth$(k_s = 1, \ldots, K_s)$ array element can be expressed as [15],

$$s_{k_t k_s}(t) = g\left(t - \frac{2v(k_t-1)T_r}{c} - \frac{(k_s-1)d\sin\theta}{c}\right) \times \exp\left(-j2\pi\left(\frac{2v(k_t-1)T_r}{\lambda_c} + \frac{(k_s-1)d\sin\theta}{\lambda_c}\right)\right) \tag{1}$$

where v and θ are the radial velocity and the incident angle of the target, respectively, λ_c is the wavelength of the radar carrier frequency, d is the distance between two adjacent array elements and T_r is the pulse repetition interval (PRI). The first factor of the right hand side (R.H.S.) of (1) denotes the translation of the target return envelope across array and pulses, and is referred to as the range walk or range migration [15–18]. For the narrowband radar with low range resolution, the size of the range cell is much larger than the translation of the target return envelope, and the range migration can be ignored. For wideband high-resolution radar considered in this paper, however, the size of the range cell is usually smaller than the translation of the target signal envelope. For example, when the carrier frequency is 10 GHz, the bandwidth of the transmit signal is 400 MHz, the pulse repetition frequency is 250 Hz, the CPI is 128 ms, the array aperture is 1.5 m, the radial velocity of the target is 50 m/s, and the angle between the target and the baseline of the radar is 60°, then the range migration during the CPI is 6.4 m and more than 17 range cells, and the envelope range difference across the aperture is 0.75 m and equivalent to 2 range cells. As a result, the target signal of each range cell cannot be represented as the product of the amplitude and the steering vector. To overcome this inconvenience, we transform the target signal into the frequency domain (the Fourier dual domain of time delay or radial range) by taking the Fourier transform to the received baseband signal model in (1),

$$\begin{aligned} S_{k_t k_s}(f) &= \underbrace{G(f)\exp\left(-j2\pi\left(\frac{2v(k_t-1)T_r}{\lambda_c} + \frac{(k_s-1)d\sin\theta}{\lambda_c}\right)\right)}_{\tilde{G}(f)} \\ &\quad \times \exp\left(-j2\pi\left(\frac{2v(k_t-1)T_r}{c} + \frac{(k_s-1)d\sin\theta}{c}\right)f\right) \\ &= \tilde{G}(f)\exp\left(-j2\pi\left(\frac{2v(k_t-1)T_r}{c} + \frac{(k_s-1)d\sin\theta}{c}\right)f\right) \end{aligned} \tag{2}$$

where $G(f)$ is the Fourier transform of the high-resolution target return envelope, i.e., the frequency response of the target. Assume that the target return is sampled uniformly by N points in the frequency domain, and then the discrete version of the signal model in the frequency domain can be represented compactly as,

$$\mathbf{S}(n) = b_n \mathbf{p}_n, n = 0, \ldots, N-1 \tag{3}$$

where $\mathbf{S}(n)$ is an $M \times 1$ column vector with $M = K_t K_s$ for $n = 0, \ldots, N-1$, $b_n = \tilde{G}(nB_W/N)$ and the time-space steering vector of the target $\mathbf{p}_n$ is,

$$\mathbf{p}_n = \mathbf{q}_{1n} \otimes \mathbf{q}_{2n} \tag{4}$$

where "$\otimes$" denotes the Kronecker product, $\mathbf{q}_{1n} = [\exp(j\omega_n 0) \quad \exp(j\omega_n 1) \quad \cdots \quad \exp(j\omega_n K_t - 1)]^T$ with $\omega_n = \frac{4\pi v T_r}{c}(f_c + \frac{B_W}{N}n)$ and the superscript "T" denoting transpose, and $\mathbf{q}_{2n} = [\exp(j\varpi_n 0) \quad \exp(j\varpi_n 1) \quad \cdots \quad \exp(j\varpi_n K_s - 1)]^T$with $\varpi_n = \frac{2\pi d\sin\theta}{c}(f_c + \frac{B_W}{N}n)$. Note that the length of $\mathbf{p}_n$ is M.

Generally, the steering vector is used when the signal satisfies the narrowband assumption and abandoned for wideband radars, due to the range migration between pulses and array elements. Compared with the existing literature on range spread or distributed target detection [2–13], the main difference of the signal