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Difference beam aided target detection in monopulse radar

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Abstract The classical detection step in a monopulse radar system is based on the sum beam only, the performance of which is not optimal when target is not at the beam center. Target detection aided by the difference beam can improve the performance at this case. However, the existing difference beam aided target detectors have the problem of performance deterioration at the beam center, which has limited their application in real systems. To solve this problem, two detectors are proposed in this paper. Assuming the monopulse ratio is known, a generalized likelihood ratio test (GLRT) detector is derived, which can be used when targeting information on target direction is available. A practical dual-stage detector is proposed for the case that the monopulse ratio is unknown. Simulation results show that performances of the proposed detectors are superior to that of the classical detector.

1. Introduction

Monopulse is a widely used technique to provide accurate angle measurements in the tracking radar.[1] A monopulse system for estimating one angle typically consists of two identical antennas, either separated by some distance (phase monopulse) or at the same phase center but with a squint angle (amplitude monopulse), whose outputs are summed up to produce a sum beam Σ and are subtracted to yield the difference beam Δ. The angular information θ is contained in the monopulse ratio $\gamma = \Delta(\theta)/\Sigma(\theta)$ provided that the function $\theta \rightarrow \gamma(\theta)$ is invertible.[2–4]

The open literature[5–8] has revealed a separate analysis of detection and estimation. The detection step has been performed with the sum beam only, while the difference beam is used only for angle estimation. In Refs.[9–12], angle estimation conditioned on the detection has been studied, however, the detections in them are performed with the sum beam only, too. The classical sum beam detector is optimal provided the boresight is close to the true target direction, since amplitude of the difference beam is approximately zero there. However, amplitude of the difference beam is comparable to that of the sum beam near the sum beam half-power point. Thus it is possible to utilize the difference beam to improve the detection performance.

Armstrong and Griffiths[13] firstly proposed the idea of using difference beam at the detection step. Two realizations of this idea were presented. One of them is to use different linear

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combinations of the sum and difference beams as the test statistics. It was shown that certain combinations can give a detection gain relative to the sum beam only detection. The other one is based on the complex indicated angle. Constant false-alarm rate (CFAR) performance has been achieved without using adjacent cells as references. However, the CFAR loss of this method is comparatively high. Chaumette et al.[14,15] applied optimal detection theory to this problem. They treated the difference aided detection as a composite hypothesis testing problem and obtained the generalized likelihood ratio test (GLRT) under some approximation, which is referred to as the Power-Mosca detector-estimator solution. The Power-Mosca detector is similar to the linear combination method in Ref.[13] It combines the sum and difference beam with equal weights irrespective of the deviation angle. As a result, the performance is improved at the beam edge but deteriorated at the beam center.

In this paper, we use the monopulse ratio as the weight of the difference beam and take weighted sum of the sum and difference beams as the test statistic to get performance improved at the beam edge while keeping the performance at the beam center. For the cases that the monopulse ratio is known or unknown, two practical difference beam aided detectors are proposed. The performances of the two detectors are studied via Monte Carlo simulations.

2. Signal model

Firstly we take the phase monopulse as an example to show the angle estimation process in monopulse systems. In the case of phase monopulse with two antennas separated by a distance L as shown in Fig. 1, the phase difference φ between the two antennas is

$$\varphi = \frac{2\pi}{\lambda} L \sin\theta \tag{1}$$

where λ is the wavelength and θ the deviation angle from boresight. Let E_1 and E_2 denote the two monopulse antenna outputs. The sum and difference beam have the form (ignoring receiver noise):

$$\begin{cases} \Sigma = E_1 + E_2 = 2E_1\cos(\varphi/2)\exp(\mathrm{j}\cdot\varphi/2) \\ \Delta = E_2 - E_1 = 2\mathrm{j}E_1\sin(\varphi/2)\exp(\mathrm{j}\cdot\varphi/2) \end{cases} \tag{2}$$

Therefore the monopulse ratio γ takes the form

$$\gamma = \Delta/\Sigma = \mathrm{j}\cdot\tan(\varphi/2) = \mathrm{j}\cdot\tan\left(\frac{\pi}{\lambda}L\sin\theta\right) \tag{3}$$

which is a fairly linear function in the neighborhood of the look direction (i.e., θ is small). The angle θ can then be calculated using the monopulse ratio γ. Typical sum and difference beam patterns are shown in Fig. 2. Readers could refer to Ref.[2] for detail.

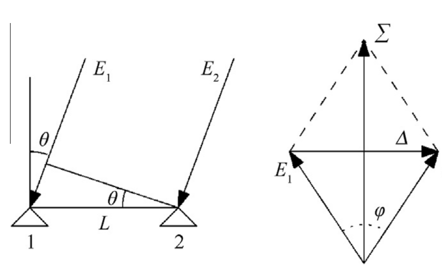

Fig. 1 Pictorial description of phase monopulse.

In practical monopulse systems, the receiver noise is present, and the received signal can be modeled as two parallel sequences $\{x_i\}$ (sum beam), $\{y_i\}$ (difference beam) of complex-valued voltage samples representing amplitude and phase of the N pulse returns from a target.[8] The radar target is considered to be a point target whose return signal is assumed to be non-fluctuating from pulse to pulse. Jamming is assumed to be absent so that the target signal competes only against receiver thermal noise. To unify the phase and amplitude monopulses, the imaginary unit j in γ (which exists only in phase monopulse) is dismissed and γ is real. The signal model under the null hypothesis (noise only) H_0 and the alternate hypothesis (signal plus noise) H_1 is

$$\begin{aligned} &H_0 : \boldsymbol{x} = \boldsymbol{u},\ \boldsymbol{y} = \boldsymbol{v} \\ &H_1 : \boldsymbol{x} = \boldsymbol{a} + \boldsymbol{u},\ \boldsymbol{y} = \gamma\boldsymbol{a} + \boldsymbol{v} \end{aligned} \tag{4}$$

where $\boldsymbol{x}\triangleq\{x_i\}$, $\boldsymbol{y}\triangleq\{y_i\}$, $\boldsymbol{a}\triangleq\{a_i\}$, $\boldsymbol{u}\triangleq\{u_i\}$, $\boldsymbol{v}\triangleq\{v_i\}$ are $N\times 1$ column vectors and γ is the monopulse ratio, which is considered constant over the N pulses (Because the range between target and radar is long, the effect of target's movement within N pulses on its DOA can be neglected); $a_i\triangleq a_{\mathrm{I}i} + \mathrm{j}a_{\mathrm{Q}i}$ is the complex amplitude of the i th pulse return from direction γ, which is unknown; $\{u_i\}$ and $\{v_i\}$ are the stationary complex Gaussian noise processes with zero means and variance σ^2 associated with observables $\{x_i\}$ and $\{y_i\}$, respectively (The unbalance of the sum and difference channels' noise levels can be adjusted at the initialization stage of the monopulse radar); Independence between and among the Gaussian processes $\{u_i\}$, $\{v_i\}$ is assumed.

Under this signal model, the classical sum beam detector can be formulated as

$$||\boldsymbol{x}||^2 > T \tag{5}$$

where $||\boldsymbol{x}||^2\triangleq\sum_{i=1}^{N}|x_i|^2$ and T is the detection threshold. The sum beam detector Eq. (5) is referred to as the Classical detector in the remainder of this paper. The Power-Mosca detector proposed in Ref.[15] has the form

$$||\boldsymbol{x}||^2 + ||\boldsymbol{y}||^2 > T \tag{6}$$

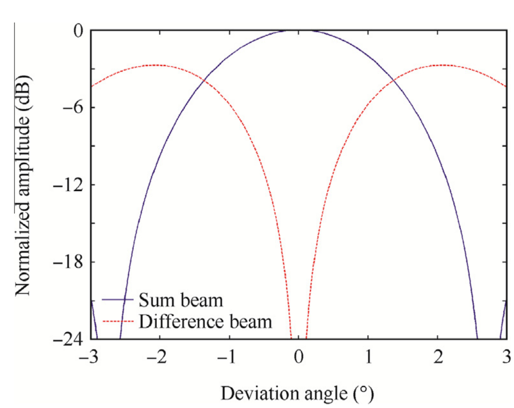

Fig. 2 Typical sum and difference beam patterns of monopulse.