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Performance analysis of space–time-adaptive monopulse

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Abstract

The two-dimensional monopulse estimation scheme is extended to space- and time-adaptive processing (STAP) for arbitrary sum and difference beams and arbitrary subarrays in space and time. This includes the case of time samples at the pulse repetition frequency (PRF, slow time STAP) as well as time samples at Nyquist frequency according to the receiving bandwidth (typically samples from range cell to range cell, fast time STAP), or both. We then show how the distribution of the monopulse estimates, which was developed in a previous paper, can be extended to this generalised monopulse. The meaning of the distributional assumptions for the signal (fixed target, Rayleigh target) is explained for the different types of space–time data. The application of these distributions as a performance measure is then demonstrated by comparison with the Cramér–Rao bound for different scenarios, different types of beamforming (narrowband or broadband beam forming), and different types of subarray configurations, like the generalised sidelobe canceller, which can be interpreted as a special subarray configuration.

Keywords: Phased array radar; Direction finding; STAP; Monopulse; Broadband beamforming; Cramér–Rao bound

1. Introduction

Monopulse is an established technique for phased array radars for precision angle estimation. The underlying principle of the monopulse technique is to estimate the direction of the target by extrapolation from a measured value of the sum beam and its derivative, called difference beam. To counter external interference sources, these beams can be formed with nulls in the interference direction. With this adaptive beamforming, the classical monopulse technique is no more effective because the beams are distorted due to the adaptation and this may lead to angle errors. This has been recognised early and new techniques based on the maximum-likelihood (ML) estimator have been developed [1,4,15]. Although these techniques have a clear link to the optimum angle estimator, they have the disadvantage that they lead to non-linear formulas and do not have the convenient linear structure of the monopulse estimator. The requirement for preserving low sidelobes is not accounted for in these approaches. This topic was addressed in [34]. In [14] monopulse estimates using subarray outputs were considered; however, only for the special case of overlapping subarrays which is inconvenient for large phased arrays. Farina et al. [8] derive a monopulse procedure directly from the measured array scan pattern. The angle errors with adapted monopulse can also be reduced by adding suitable constraints for the required adapted difference beam [6,25,26]. The problem is that all additional constraints consume degrees of freedom and reduce the output signal-to-noise ratio.

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Recognising this fact, Paine included the performance criterion into the design of the monopulse procedure. In [22], a minimum variance-adaptive monopulse estimator was developed which adaptively chooses the optimum difference weight (applied at subarray level).

All these techniques were designed for linear antennas. For planar antennas, the techniques are usually applied independently to azimuth and elevation estimates. However, this does not correspond to the real situation. Depending on the jammer location the azimuth and elevation difference beams and hence the estimates are highly correlated. The two-dimensional ML angle estimation was described in [9]. In [18] a two-dimensional general monopulse technique was derived from the adaptive sum beam ML estimator. This approach has been generalised to arbitrary subarrays and arbitrary sum and difference beam weightings in [20]. This includes the case of low sidelobe weightings.

Interference characterised in space and time has to be countered by adaptive filtering (beamforming) in space and time. The extension of the adaptive monopulse to space–time adaptive processing (STAP) was given in [6,25,26]. The error problem with the adaptively distorted beams was solved via additional constraints in time and space. Different processing structures and performance studies were conducted in [25,26]. New ML-based (non-linear) estimation schemes for simultaneous STAP angle and Doppler estimation were introduced in [32,33]. The minimum variance estimator of [22] has been extended to space–time adaptivity in [23]. However, all these techniques are limited to isolated azimuth or elevation estimates and ignore the correlation between the two components.

An important aspect of all these techniques is the performance and this has mostly been established by simulation. The distribution of the angle estimates is not only of interest for performance assessment for different target and jamming scenarios and for optimising the antenna configuration (subarray shapes, sum and difference beam shapes), but also very useful as a priori information for tracking algorithms [3]. Often the Cramér–Rao bound is used, but this is an asymptotic measure which refers to some optimum unbiased estimator. For the study of the influence of different antenna configurations, it is important to determine the statistics of the estimation procedure that is really implemented. The statistical distribution of the monopulse ratio has been given in the classical paper by Kanter [12], and has been refined and extended in [2,24,30]. All these results were developed for linear arrays and were applied to planar arrays assuming uncorrelated azimuth and elevation estimates which, as mentioned above, does not correspond to reality. In [21], the distribution of the adaptive 2D-monopulse procedure of [20] was calculated including given correlations for planar arrays.

In this paper, we extend the two-dimensional monopulse estimation scheme of [20] to STAP. This includes the case of time samples at the pulse repetition frequency (PRF), called *slow time STAP*, as well as time samples at Nyquist frequency according to the receiving bandwidth (typically samples from range cell to range cell), called *fast time STAP*, or both. We then show how the distribution of the monopulse estimates given in [21] can be extended to this generalised higher-dimensional monopulse. The meaning of the distributional assumptions for the signal (fixed target, Rayleigh target) has to be explained for the augmented data vectors. The usefulness of these performance measures is then demonstrated by showing the performance in comparison with the Cramér–Rao bound for different scenarios, different types of beamforming (narrowband phase shifting only or beam forming with subarray time delays), and different types of subarray configurations. In particular, we show the performance for a generalised sidelobe canceller (GSLC), which can be interpreted as a special subarray configuration.

2. Signal model and adaptive array processing

2.1. Signals sampled in space and time

Suppose we have an array with N elements at the positions (x_i, y_i, z_i), $i = 1..N$. Let the direction of a plane wave impinging on the array be described by the unit direction vector $\boldsymbol{\kappa}$ ($\|\boldsymbol{\kappa}\| = 1$) in the (x, y, z)-coordinate system. A monochromatic plane wave (elementary wave) with amplitude b from direction $\boldsymbol{\kappa}_0 = (u_0, v_0, w_0)^{\mathrm{T}}$ at frequency f at the position $\mathbf{r}_i = (x_i, y_i, z_i)^{\mathrm{T}}$ is written as $s_i = b\mathrm{e}^{\mathrm{j}2\pi f t}\mathrm{e}^{\mathrm{j}2\pi f \mathbf{r}_i^{\mathrm{T}}\boldsymbol{\kappa}_0/c}$, where c is the velocity of light. For the most