RADAR Signal Processing for Target Range, Doppler and DoA Estimation

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Abstract *Radar target detection is a two dimensional search problem. The radar signal processor has to simultaneously estimate target's range and velocity by processing the received echo signal. Direction of Arrival (DoA) of the target is an other parameter to be estimated for which Linear and Planar arrays are being used and processing is done in a separate processor. In this paper, a radar signal processing algorithm is presented for the estimation of target parameters (range & Doppler shift). The RSP algorithm is demonstrated through computer simulation. Target's direction of arrival estimation (DoA) is discussed. A comparison of different DoA estimation algorithms is presented based on their computational complexities and performance. The presented Radar signal processing algorithm and the comparison of DoA algorithms may be useful for radar and antenna system designers in realizing the physical systems.*

Keywords: *Radar Signal processing; Target detection; Range estimation; Doppler shift; Array processing, Direction of Arrival (DoA) estimation.*

1. Introduction

Radars are being used for different surveillance modes since six decades [1]. Different applications of radar are presented in [2-3]. But as accuracy and computational cost is a trade-off, different architectures and signal processing techniques are being employed [4-5]. A Radar has RF, Analog, Digital circuits and processing units.

Radar parameter estimation using 2L shape array is presented with computation details in [6]. In [7], many FPGA architectures and timing diagrams are discussed. VHF radar application for Space awareness system is discussed in [8]. VHF radar is very much helpful in long-range applications. In [9] the FFT structures and other details of processor are presented without giving computations involved.

In this paper, we have presented a radar signal processor for the estimation of Range and Doppler shift. Some beamforming algorithms used for target Direction of Arrival (DOA) estimation are discussed and a performance comparison of these algorithms is presented based on their computational complexities.

The organization of this paper is as follows. Section 2 gives the System details. Section 3 includes DOA estimation characteristics. Conclusion is presented in Section 4.

2. RADAR System Description

2.1 System Simulation Design

The Radar system consists of transmitter and receiver. For monostatic radar, same antenna is used for transmitter and receiver. Many array configurations are used for beam forming and direction of arrival estimation [10]. In pulse Doppler radar, a train of pulses is transmitted. The reflected pulses get the range and Doppler shift induced in them from the target. Figure 1 shows the overall radar simulation block diagram

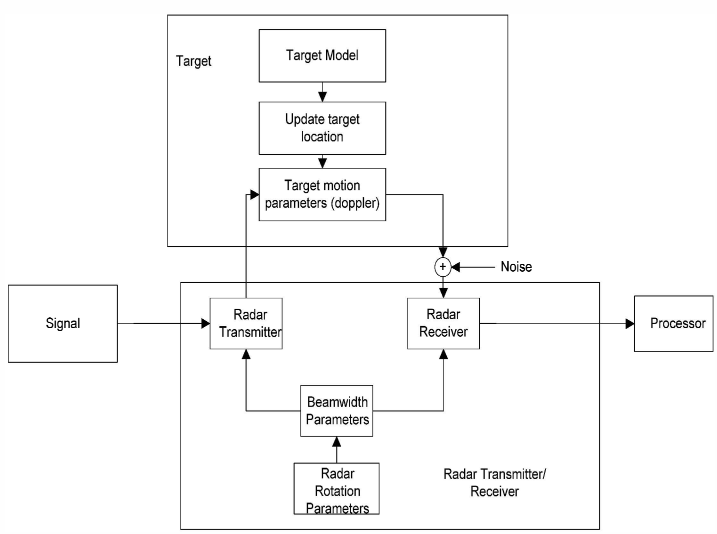

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Figure 1 Radar Simulation Block Diagram

The reflected pulse train is received through the Radar antenna, and it is demodulated and processed for Range, Doppler and DOA estimation.

2.2 Radar Signal Processing Algorithm for Pulse Doppler Radar

Pulses being received are collected in such a way that one batch is processed at a time. Figure 2 shows a stack constructed of N received pulses

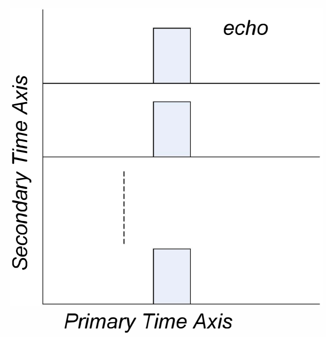

Figure 2: Received echo pulses

The Radar signal processing algorithm (Range / Doppler Processor) [12] is summarized in Figure 3

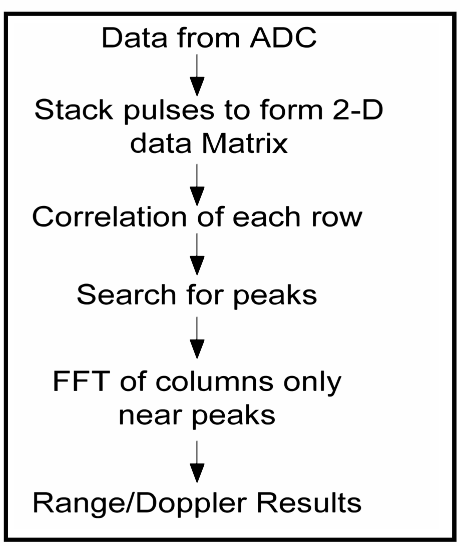

Figure 3: Summary of RSP ALGO

Peaks corresponding to targets are achieved after thresholding in the Range/Doppler space. Figure 4 shows detection of 2 targets using the above stated algorithm.

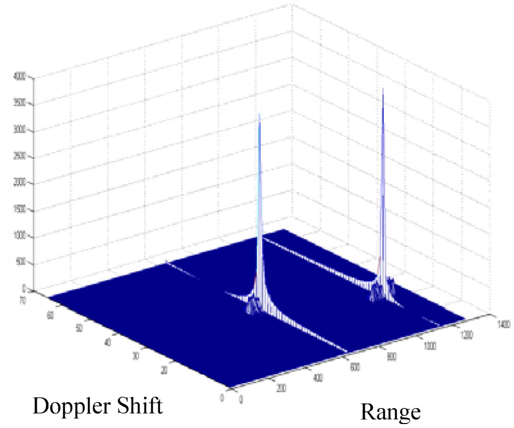

Figure 4: Two targets detected through RSP Algorithm simulation

3. Estimation of DOA

Multiple antennas are helpful when using phase difference for estimation of direction of a target. For DOA estimation in one dimension, uniform linear array is enough as shown in Figure 5.

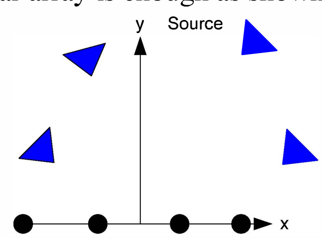

Figure 5: ULA with omni-directional sensors to estimate Azimuth position

For both, azimuth and elevation angle estimation, a 2 dimensional array is required. [13-15] gives DOA estimation using Amplitude modulation of the main beam during antenna scan. Rectangular array is shown in Figure 6 below

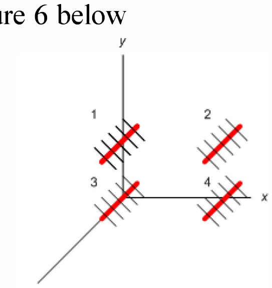

Figure 6: Rectangular Array with Yagiudda antennas

After batch collection and range/Doppler processing, DOA estimation is done in separate processors. Figure 7 shows the processing stages

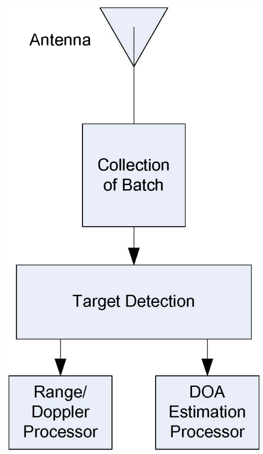

Figure 7: Complete Block Diagram

Beam-forming has been widely used for DOA estimation. Beam-forming techniques can be divided into spectral estimation techniques and subspace based methods [16, 18]. DOA estimation using Beam-forming techniques can be classified in the following shown in Figure 8

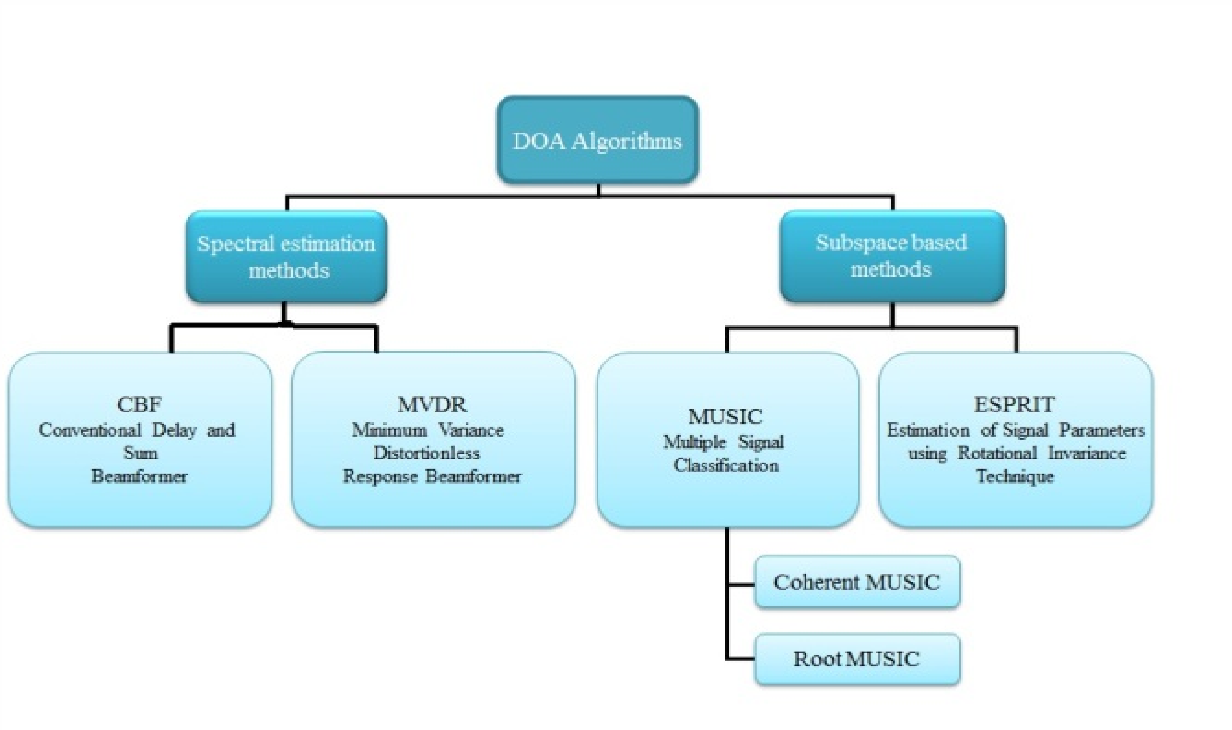

Figure 8: DOA Estimation techniques

The received signal at the ULA is formed as given in [19] and represented in eq (1)

$$\mathbf{x}(n) = \mathbf{A}(\phi)\mathbf{s}(n) + \mathbf{n}(n) \qquad (1)$$

Here, $\mathbf{A}(\phi)$ $(N \times M)$ is the steering matrix where N is the number of sensors and M is the number of sources. $\mathbf{s}(n)$ is the signals vector and $\mathbf{n}(n)$ is additive white Gaussian noise. The number of snapshots of the signals are K, $n=1,2,3,\ldots,K$. It is also assumed that the signal and noise both are zero mean, noise variance at each of the sensors is σ^2. The sample correlation matrix is given by Eq. (2)

$$\hat{\mathbf{R}} = \frac{1}{K}\sum_{n=1}^{K}\mathbf{x}(n)\mathbf{x}^H(n) \qquad (N \times N) \qquad (2)$$

The mathematical details of DOA estimation techniques can be found in [19]. The summaries of these techniques are given below in Figures 9, 10 and 11.

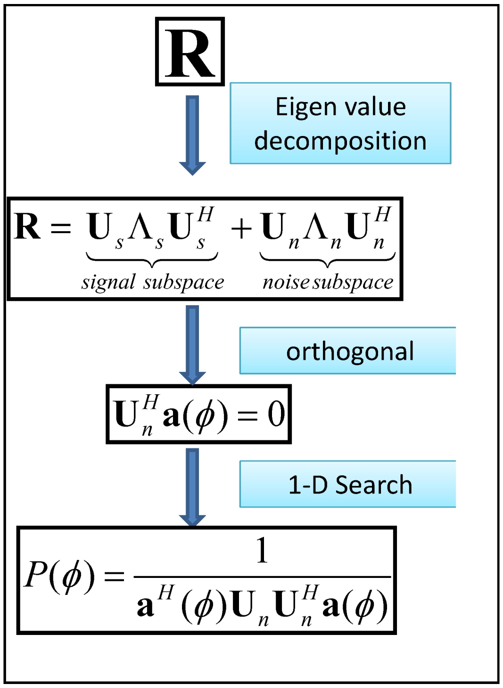

Figure 9: MUSIC Algo

Eigenvalue decomposition is required in MUSIC algorithm which takes a lot of time.

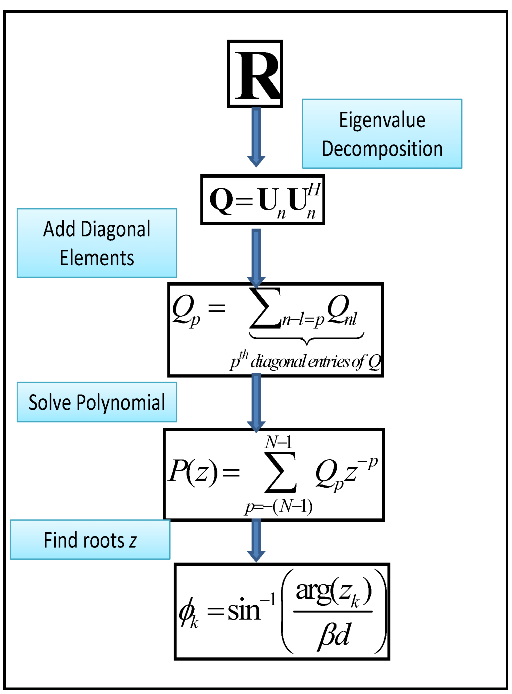

Figure 10: Root MUSIC Algorithm

The roots give the DOAs in root MUSIC.

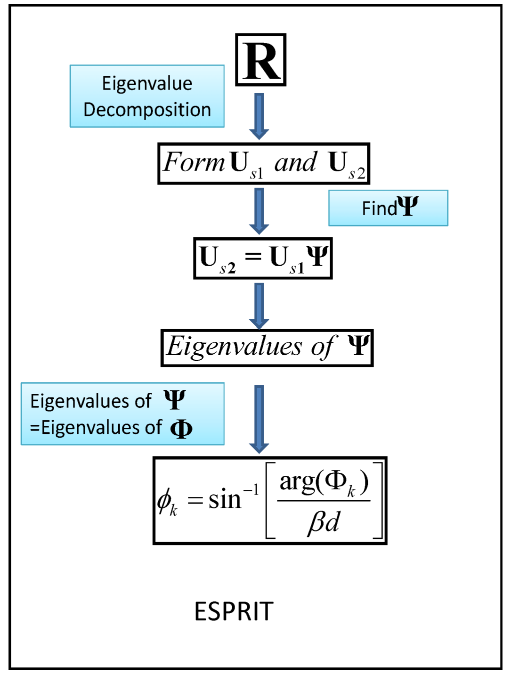

Figure 11: ESPRIT Algorithm for DOA Estimation

ESPRIT has much higher resolution than MUSIC and root-MUSIC.

3.1 Computational Complexity and Performance Comparison of DoA Estimation algorithms

The following table (Table-1) shows the number of multiplications, divisions and additions required for each of the DoA algorithm [16]. The following symbols are used

N = number of sensors in the array

M = number of signals (targets)

K = number of samples

L = number of angles to scan

The computations of MUSIC and ESPRIT are much higher than that of CBF and MVDR.

Method	Equations Involved	Multiplications	Additions	Divisions
Correlation Matrix	$\mathbf{R}_{N\times N} = \frac{1}{K}\sum_{n=1}^{K}\mathbf{x}(n)_{N\times 1}\mathbf{x}^{H}(n)_{1\times N}$	$K\left(\frac{N^2}{2}+\frac{N}{2}\right)$	$(K-1)N^2$	N^2
CBF	$P(\phi)_{1\times 1} = \mathbf{a}^{H}(\phi)_{1\times N}\mathbf{R}_{N\times N}\mathbf{a}(\phi)_{N\times 1}$	$L(N^2+N)$	$L(N^2-1)$	–
MVDR	$\mathbf{R}^{-1}_{N\times N}$ (Gauss Jordan Inversion) [7]	$\frac{N^3}{3}+\frac{N^2}{2}+\frac{N}{6}$	$\frac{N^3}{3}+\frac{N^2}{2}+\frac{N}{6}$	$\frac{N^2}{2}+\frac{N}{2}$
	$P(\phi)_{1\times 1} = \frac{1}{\mathbf{a}^{H}(\phi)_{1\times N}\hat{\mathbf{R}}^{-1}_{N\times N}\mathbf{a}(\phi)_{N\times 1}}$	$L(N^2+N)$	$L(N^2-1)$	L
MUSIC	$\mathbf{R}_{N\times N} = \mathbf{U}_{N\times N}\Lambda_{N\times N}\mathbf{U}^{H}{}_{N\times N}$ [8], [9]	$\frac{16}{5}N^3$	$\frac{44}{5}N^3$	–
	$\mathbf{Q}_{N\times N} = \mathbf{U}_{n[N\times(N-M)]}\mathbf{U}^{H}_{n\,[(N-M)\times N]}$	$\frac{(N-M)N^2}{2}+\frac{(N-M)N}{2}$	$\frac{(N-M)N^2}{2}-\frac{N^2}{2}+\frac{(N-M)N}{2}-\frac{N}{2}$	–
	$P(\phi)_{1\times 1} = \frac{1}{\mathbf{a}^{H}(\phi)_{1\times N}\mathbf{Q}_{N\times N}\mathbf{a}(\phi)_{N\times 1}}$	$L(N^2+N)$	$L(N^2-1)$	L
ESPRIT	$\mathbf{R}_{N\times N} = \mathbf{U}_{N\times N}\Lambda_{N\times N}\mathbf{U}^{H}{}_{N\times N}$	$\frac{16}{5}N^3$	$\frac{44}{5}N^3$	
	$\mathbf{A}_{M\times M} = \mathbf{U}^{H}_{s1[M\times(N-1)]}\mathbf{U}_{s1[(N-1)\times M]}$	$\frac{(N-M)(N-1)^2}{2}+\frac{(N-M)(N-1)}{2}$	$\frac{(N-M)(N-1)^2}{2}-\frac{(N-1)^2}{2}+\frac{(N-M)(N-1)}{2}-\frac{(N-1)}{2}$	
	$\mathbf{B}_{M\times M} = \mathbf{A}^{-1}_{M\times M}$ (Gauss Jordan Inversion) [7]	$\frac{N^3}{3}+\frac{N^2}{2}+\frac{N}{6}$	$\frac{N^3}{3}+\frac{N^2}{2}+\frac{N}{6}$	$\frac{N^2}{2}+\frac{N}{2}$
	$\mathbf{C}_{M\times M} = \mathbf{U}^{H}_{s1[M\times(N-1)]}\mathbf{U}_{s2[(N-1)\times M]}$	$\frac{(N-M)^2(N-1)}{2}+\frac{(N-M)(N-1)}{2}$	$\frac{(N-M)^2(N-1)}{2}-\frac{(N-M)^2}{2}+\frac{(N-M)(N-1)}{2}-\frac{(N-M)}{2}$	
	$\Psi_{M\times M} = \mathbf{B}_{M\times M}\mathbf{C}_{M\times M}$	$(N-M)^3$	$(N-M)^3-(N-M)^2$	

Table 1: Table of Computational Complexities

The comparison of performance of the DoA algorithms [20] is given in table below

Algorithm	Resolution	Complexity	General Remarks
CBF	Poor	Simple Implementation, 1-D search	Resolution depends on main lobe
MVDR	Good	Inverse of **R**, 1-D search	Poor performance in low SNR
MUSIC	Very Good	Eigen value Decomposition, 1-D search	Also estimates number of sources
ESPRIT	Excellent	Eigen value Decomposition	Array needs doublets

Table 2: Comparison of performance of DoA Algorithms

4. Conclusions

We have discussed Radar target detection as a signal parameter estimation problem. A Radar Signal processing Algorithm for pulse Doppler Radar is discussed in detail for target detection and estimation of its parameters i.e. range and Doppler shift. The RSP algorithm is demonstrated through computer simulation for the detection, ranging and Doppler localization of targets. Estimation of Direction of Arrival (DoA) of the target is then discussed. Some DoA estimation algorithms are considered and their computational complexities are presented. A comparison of the performance of these algorithms is also made. This comparison will be helpful for physical system realization. A radar system designer can choose a particular DoA algorithm by considering its computational complexity and performance.

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