Università degli Studi di Napoli Federico II

Scuola Politecnica e delle Scienze di Base

Dipartimento di Ingegneria Elettrica e delle Tecnologie dell'Informazione

Università degli Studi di Napoli Federico II
Ph.D. Program in
Information Technology and Electrical Engineering
XXXV Cycle

Antenna-Based Techniques for Modern Radars

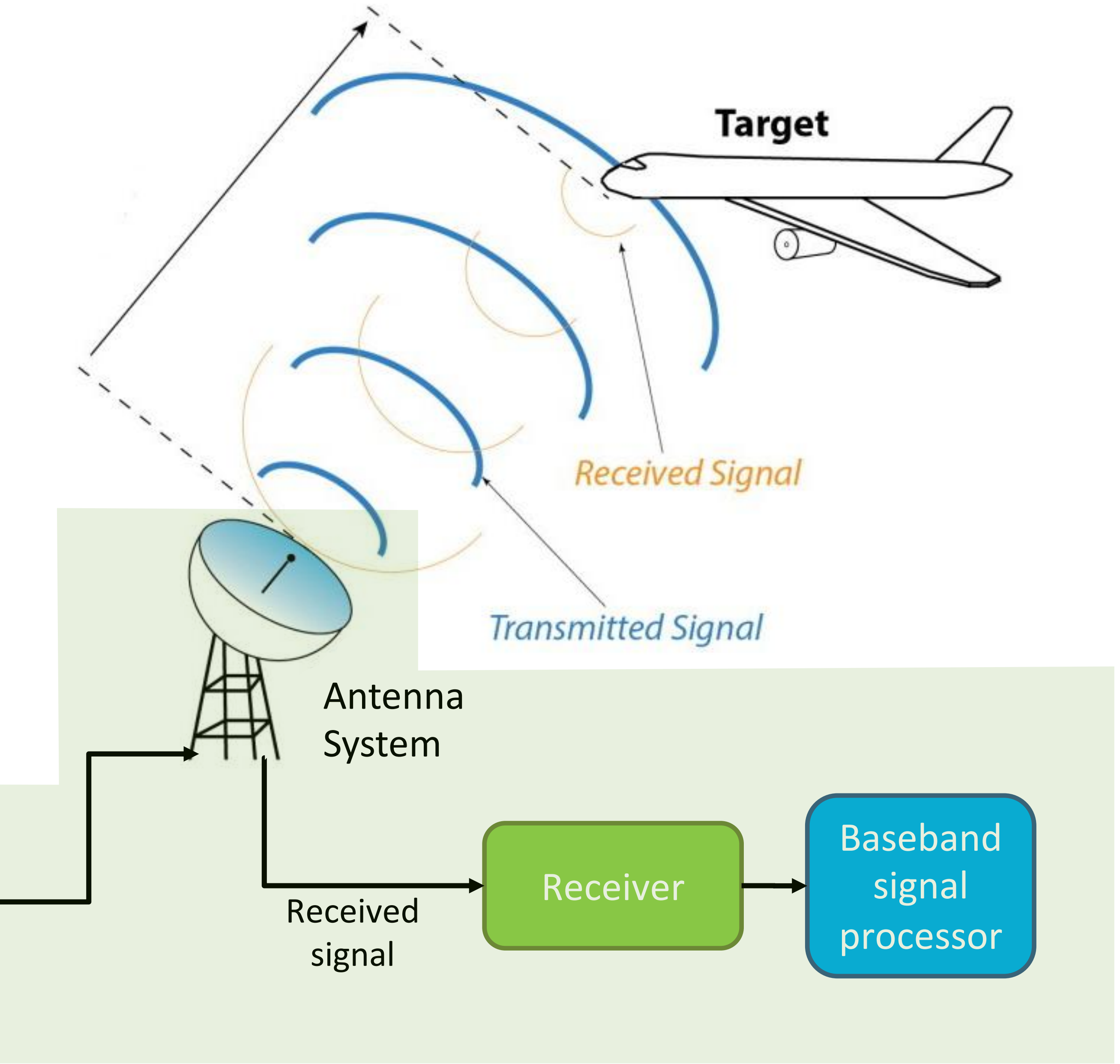
Massimo Rosamilia
(massimo.rosamilia@unina.it)

Supervisor: Prof. Antonio De Maio

GTTI PhD award for PhD Theses in the field of Communication Technologies

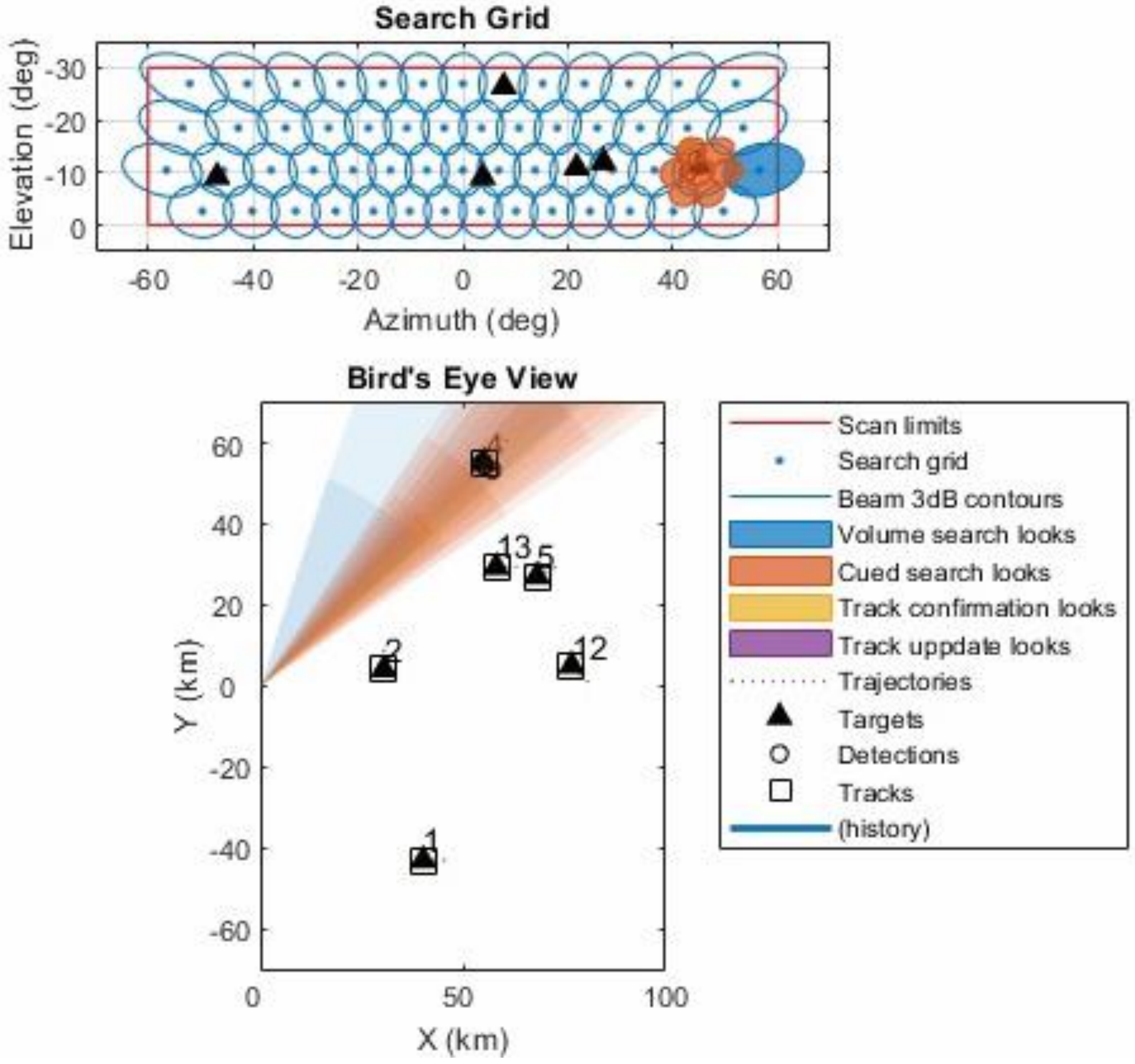
Introduction

Radar System



Modern Multichannel Array Radar Systems

- Surveillance at specific ranges
- Tracking with variable update rates
- 3-D target data measurements
- Manage many track simultaneously
- Ability to operate in clutter and jamming environments



Single-Pulse Simultaneous Target Detection and Angle Estimation [1/5]

Adaptive detection architecture

Accurate target localization (estimation)

Detection and estimation: two different signal processing tasks

Target parameter estimation only after target presence declaration!

DESIRED: **simultaneous** target detection and accurate angular estimation

Multichannel planar phased array radar system

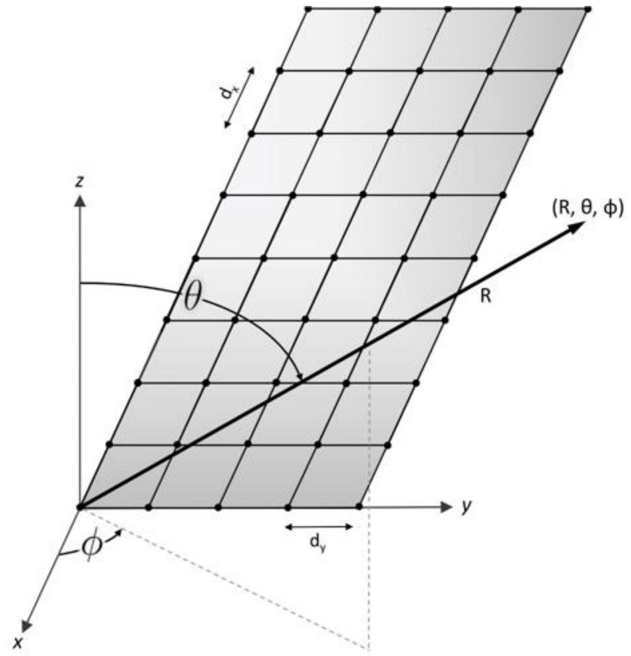
received data: $\boldsymbol{r} = a\boldsymbol{p}(u_0, v_0) + \boldsymbol{n}$

target backscattering and channel propagation effects

spatial steering vector

target DOA

Gaussian random noise



Planar array geometry

Array steering direction not usually aligned with target DOA → *Linearize the array manifold around the pointing direction* $(\bar{u}, \bar{v})$

$$\Delta u = u_0 - \bar{u} \quad \Delta v = v_0 - \bar{v}$$

unknown displacements

$$\boldsymbol{\Delta\theta} = \begin{bmatrix} \Delta u \\ \Delta v \end{bmatrix}$$

Linearized target steering vector

$$\boldsymbol{p}_a(\Delta u, \Delta v) = \boldsymbol{p}(\bar{u}, \bar{v}) + \left.\frac{\partial \boldsymbol{p}(u,v)}{\partial u}\right|_{\substack{u=\bar{u}\\ v=\bar{v}}} \Delta u + \left.\frac{\partial \boldsymbol{p}(u,v)}{\partial v}\right|_{\substack{u=\bar{u}\\ v=\bar{v}}} \Delta v = \boldsymbol{p} + \boldsymbol{H}\boldsymbol{\Delta\theta}$$

Target detection **problem**

$$\begin{cases} \mathcal{H}_0 : \begin{cases} \boldsymbol{r} = \boldsymbol{n} \\ \boldsymbol{r}_k = \boldsymbol{n}_k \quad k = 1, \dots, K \end{cases} \\ \mathcal{H}_1 : \begin{cases} \boldsymbol{r} = a\boldsymbol{p}_a(\Delta u, \Delta v) + \boldsymbol{n} \\ \boldsymbol{r}_k = \boldsymbol{n}_k \quad k = 1, \dots, K \end{cases} \end{cases}$$

Constraints
$|\Delta u| \leq \alpha$
$|\Delta v| \leq \beta$

Solution

Generalized Likelihood Ratio

$$\max_{\substack{|\Delta u| \leq \alpha \\ |\Delta v| \leq \beta}} \frac{(\bar{\boldsymbol{p}} + \bar{\boldsymbol{H}}\boldsymbol{\Delta\theta})^\dagger \bar{\boldsymbol{r}}\, \bar{\boldsymbol{r}}^\dagger (\bar{\boldsymbol{p}} + \bar{\boldsymbol{H}}\boldsymbol{\Delta\theta})}{(\bar{\boldsymbol{p}} + \bar{\boldsymbol{H}}\boldsymbol{\Delta\theta})^\dagger (\bar{\boldsymbol{p}} + \bar{\boldsymbol{H}}\boldsymbol{\Delta\theta})} = \boxed{\max_{\substack{|\Delta u| \leq \alpha \\ |\Delta v| \leq \beta}} \frac{N(\boldsymbol{\Delta\theta})}{D(\boldsymbol{\Delta\theta})}}$$

box constrained **fractional** quadratic optimization problem

Detect the target while simultaneously estimate its DOA

Single-Pulse Simultaneous Target Detection and Angle Estimation [4/5]

$$\max_{\substack{|\Delta u|\le\alpha \\ |\Delta v|\le\beta}} \frac{N(\boldsymbol{\Delta\theta})}{D(\boldsymbol{\Delta\theta})}$$

Dinkelbach's Optimization Algorithm

At each iteration

$$\boldsymbol{\Delta\theta}^\star = \underset{\substack{|\Delta u|\le\alpha \\ |\Delta v|\le\beta}}{\arg\max}\; N(\boldsymbol{\Delta\theta}) - q^+ D(\boldsymbol{\Delta\theta})$$

=> GLRT for Linearized Array Manifold with Dinkelbach Optimization

$$t_{\text{GLRT-LAM-DO}} = \frac{1}{1+\|\bar{\boldsymbol{r}}\|^2} \frac{\left|\bar{\boldsymbol{r}}^\dagger(\bar{\boldsymbol{p}} + \bar{\boldsymbol{H}}\widehat{\Delta}\boldsymbol{\theta}^\star_{DO})\right|^2}{\left\|\bar{\boldsymbol{p}} + \bar{\boldsymbol{H}}\widehat{\Delta}\boldsymbol{\theta}^\star_{DO}\right\|^2} \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} T$$

Coordinate Descent Algorithm

At each iteration

$$\Delta u^\star = \underset{|\Delta u|\le\alpha}{\arg\max} \frac{(\bar{\boldsymbol{p}}^{(n-1)}_{\Delta v} + \dot{\bar{\boldsymbol{p}}}_u\Delta u)^\dagger \bar{\boldsymbol{r}}\, \bar{\boldsymbol{r}}^\dagger (\bar{\boldsymbol{p}}^{(n-1)}_{\Delta v} + \dot{\bar{\boldsymbol{p}}}_u\Delta u)}{(\bar{\boldsymbol{p}}^{(n-1)}_{\Delta v} + \dot{\bar{\boldsymbol{p}}}_u\Delta u)^\dagger (\bar{\boldsymbol{p}}^{(n-1)}_{\Delta v} + \dot{\bar{\boldsymbol{p}}}_u\Delta u)}$$

$$\Delta v^\star = \underset{|\Delta v|\le\beta}{\arg\max} \frac{(\bar{\boldsymbol{p}}^{(n)}_{\Delta u} + \dot{\bar{\boldsymbol{p}}}_v\Delta v)^\dagger \bar{\boldsymbol{r}}\, \bar{\boldsymbol{r}}^\dagger (\bar{\boldsymbol{p}}^{(n)}_{\Delta u} + \dot{\bar{\boldsymbol{p}}}_v\Delta v)}{(\bar{\boldsymbol{p}}^{(n)}_{\Delta u} + \dot{\bar{\boldsymbol{p}}}_v\Delta v)^\dagger (\bar{\boldsymbol{p}}^{(n)}_{\Delta u} + \dot{\bar{\boldsymbol{p}}}_v\Delta v)}$$

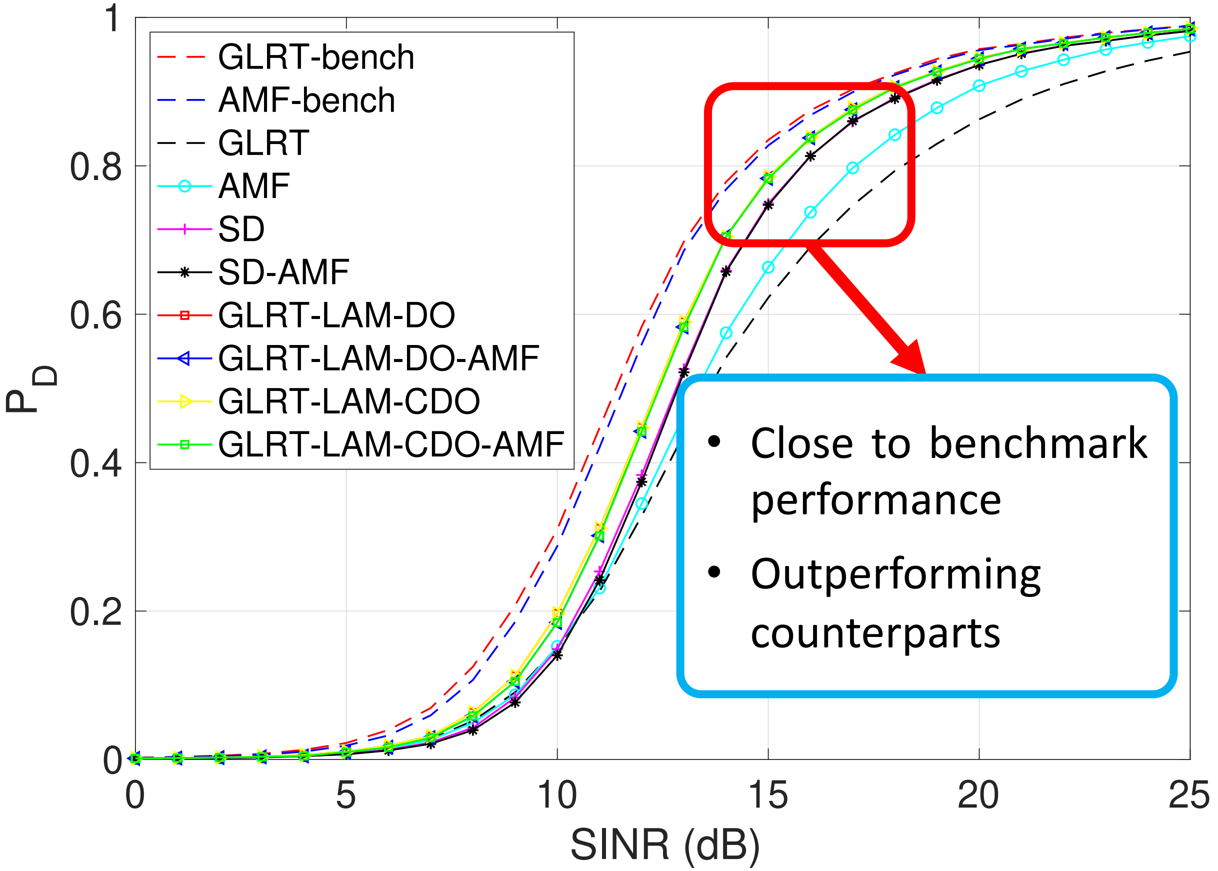
=> GLRT for Linearized Array Manifold with Coordinate Descent Optimization

$$t_{\text{GLRT-LAM-CDO}} = \frac{1}{1+\|\bar{\boldsymbol{r}}\|^2} \frac{\left|\bar{\boldsymbol{r}}^\dagger(\bar{\boldsymbol{p}} + \bar{\boldsymbol{H}}\widehat{\Delta}\boldsymbol{\theta}^\star_{CDO})\right|^2}{\left\|\bar{\boldsymbol{p}} + \bar{\boldsymbol{H}}\widehat{\Delta}\boldsymbol{\theta}^\star_{CDO}\right\|^2} \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} T$$

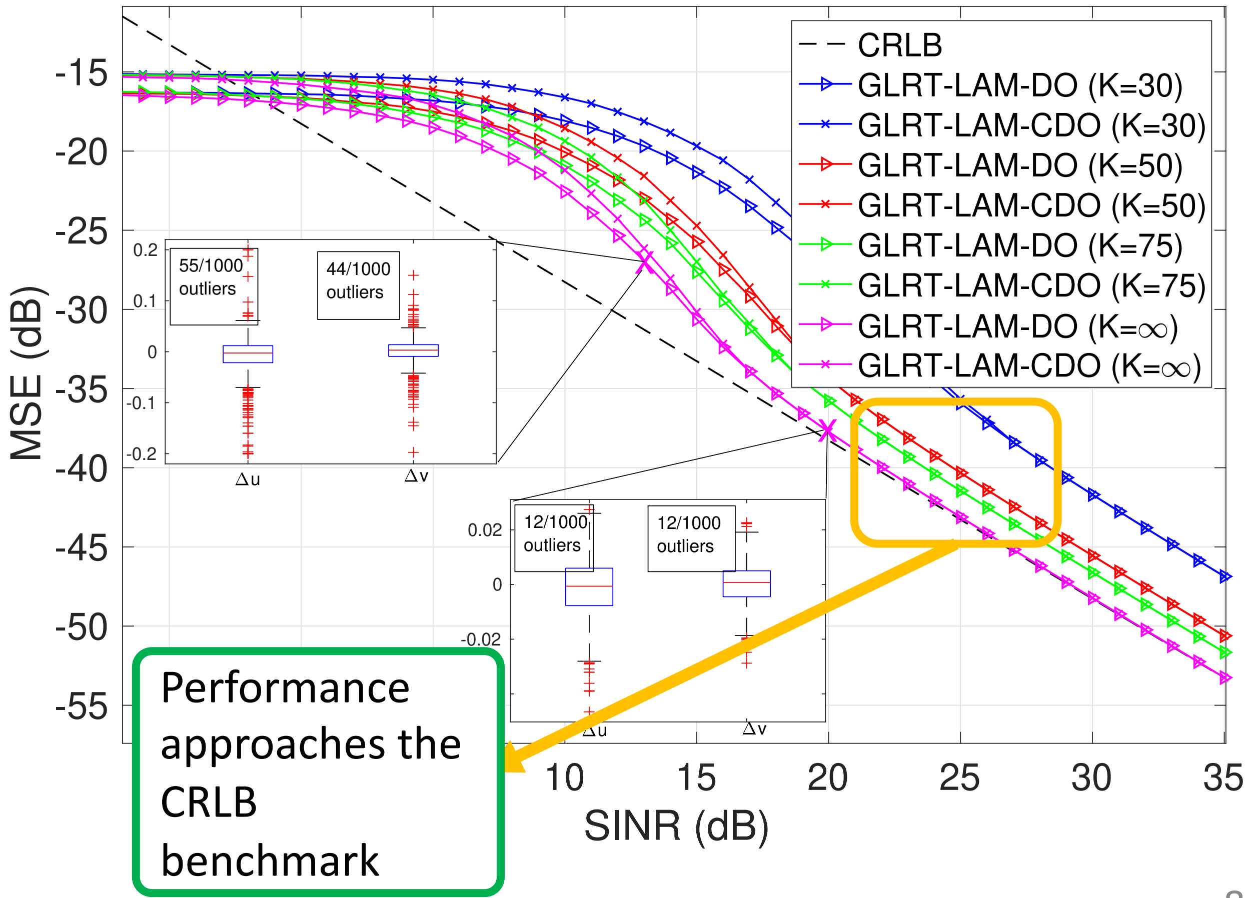
Single-Pulse Simultaneous Target Detection and Angle Estimation [5/5]

URA with 5x5 antennas, $\alpha = \beta = 0.2, (\Delta u, \Delta v) = (0.05, 0.05)$
1 narrow-band jammer at $(0.1, 0.1)$, with JNR = 30 dB and 1 wide-band jammer $(B_f = 0.3)$ at $(0.3, 0.3)$ with JNR2 = 40 dB

Detection Performance

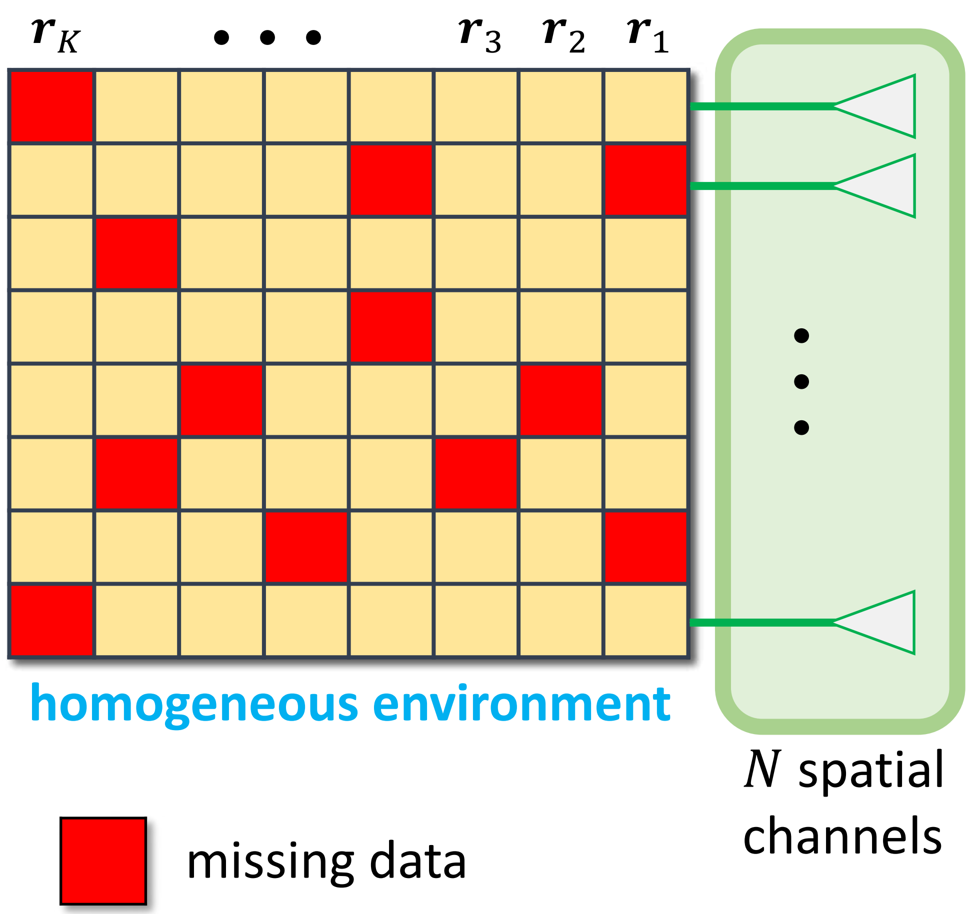


Estimation Performance



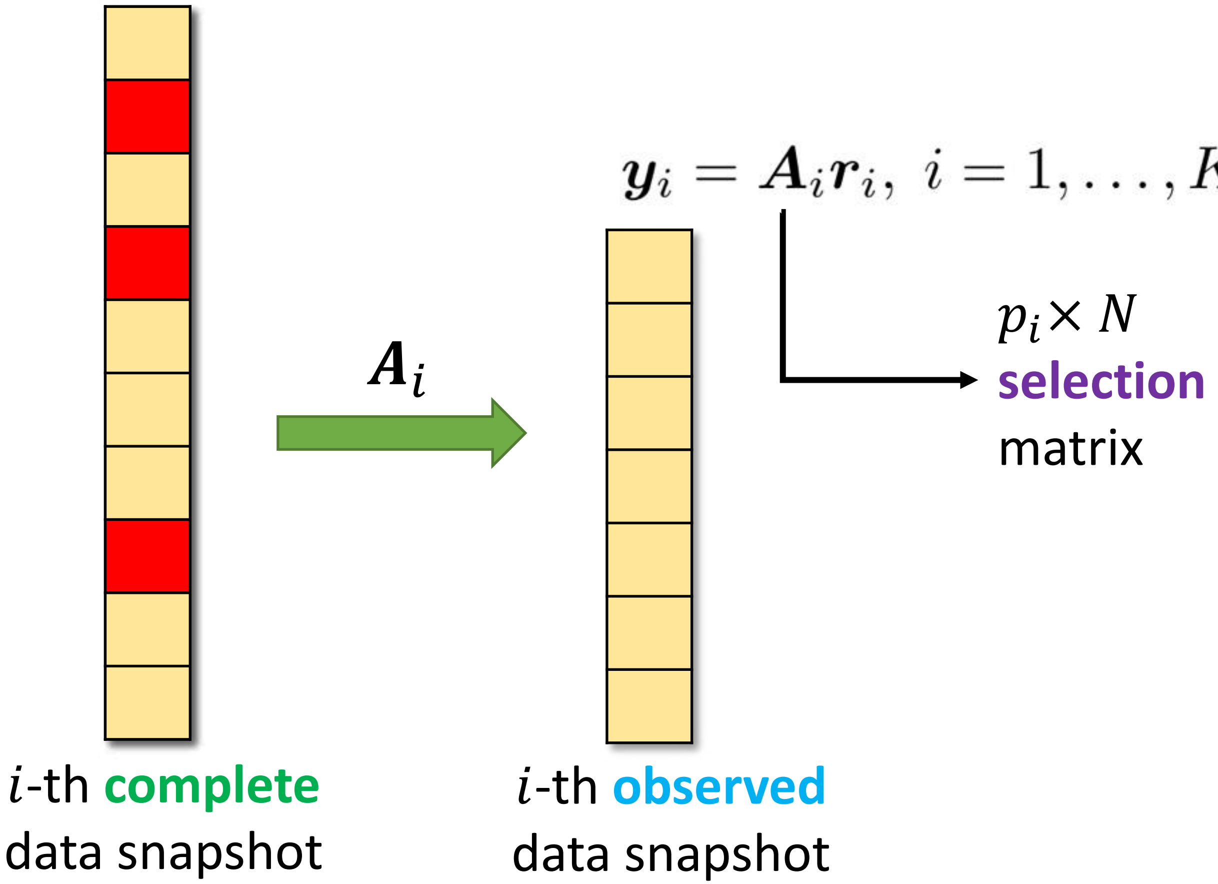
Structured Covariance Matrix Estimation with Missing-Data via EM

MOTIVATION



$$\boldsymbol{r}_i \sim CN(0, \boldsymbol{M}), \ \boldsymbol{M} \in \mathcal{C} \subseteq \mathbb{H}^N_{++}, \ i = 1, \ldots, K,$$

$$\boldsymbol{y}_i = \boldsymbol{A}_i \boldsymbol{r}_i, \ i = 1, \ldots, K,$$



PROBLEM FORMULATION

The **constrained maximum likelihood (ML) estimate** of the covariance matrix can be formulated as

$$\hat{\boldsymbol{M}}(\hat{\boldsymbol{\theta}}) = \underset{\boldsymbol{M}(\boldsymbol{\theta})\in\mathcal{C}}{\arg\max}\, \mathcal{L}_y(\boldsymbol{M}(\boldsymbol{\theta}) \mid \boldsymbol{Y}, \boldsymbol{A}_1, \dots, \boldsymbol{A}_K)$$

with

$\mathcal{L}_y(\boldsymbol{M}(\boldsymbol{\theta}) \mid \boldsymbol{Y}, \boldsymbol{A}_1, \dots, \boldsymbol{A}_K)$ the **observed data log-likelihood**

$\mathcal{C}$ the covariance matrix **uncertainty set**

$\boldsymbol{Y} = \{\boldsymbol{y}_1, \dots, \boldsymbol{y}_k\}$ the **observed data set**

$\boldsymbol{\theta} \in \mathbb{R}^{\mathrm{V}}$ the vector of the **unknown parameters** defining the underlining structure of $\boldsymbol{M}$.

Structured Covariance Matrix Estimation with Missing-Data via EM [3/5]

EXPECTATION MAXIMIZATION-BASED ESTIMATION PROCEDURE

Repeat until convergence

E-STEP

$$Q(\boldsymbol{\theta}, \boldsymbol{\theta}^{(h-1)})$$

M-STEP

$$\boldsymbol{\theta}^{(h)} = \underset{\boldsymbol{\theta}: \boldsymbol{M}(\boldsymbol{\theta}) \in \mathcal{C}}{\operatorname{argmax}} \; Q(\boldsymbol{\theta}, \boldsymbol{\theta}^{(h-1)}).$$

$h = h + 1$

$$Q(\boldsymbol{\theta}, \boldsymbol{\theta}^{(h-1)}) = -K[N \ln(\pi) + \ln(\det(\boldsymbol{M}(\boldsymbol{\theta}))) + \operatorname{tr}\{\boldsymbol{M}(\boldsymbol{\theta})^{-1} \boldsymbol{\Sigma}^{(h-1)}\}],$$

Solutions to the M-step devised in closed-form under the assumption of $\boldsymbol{M}$ belonging to a **specific** covariance matrix **uncertainty set**.

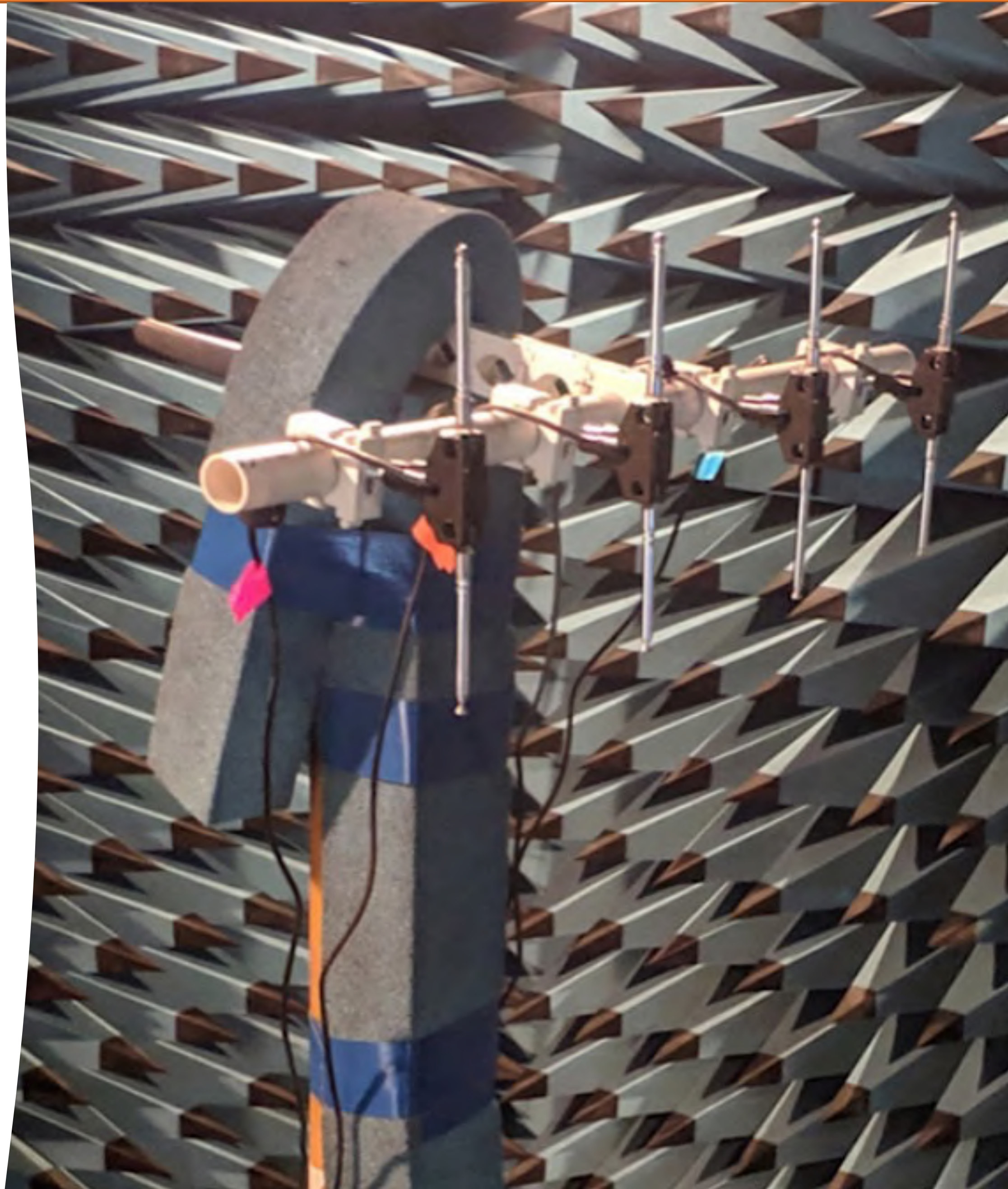
Structured Covariance Matrix Estimation with Missing-Data via EM [4/5]

EXPERIMENTAL ANALYSIS

Data **collected** in an **anechoic chamber** using:

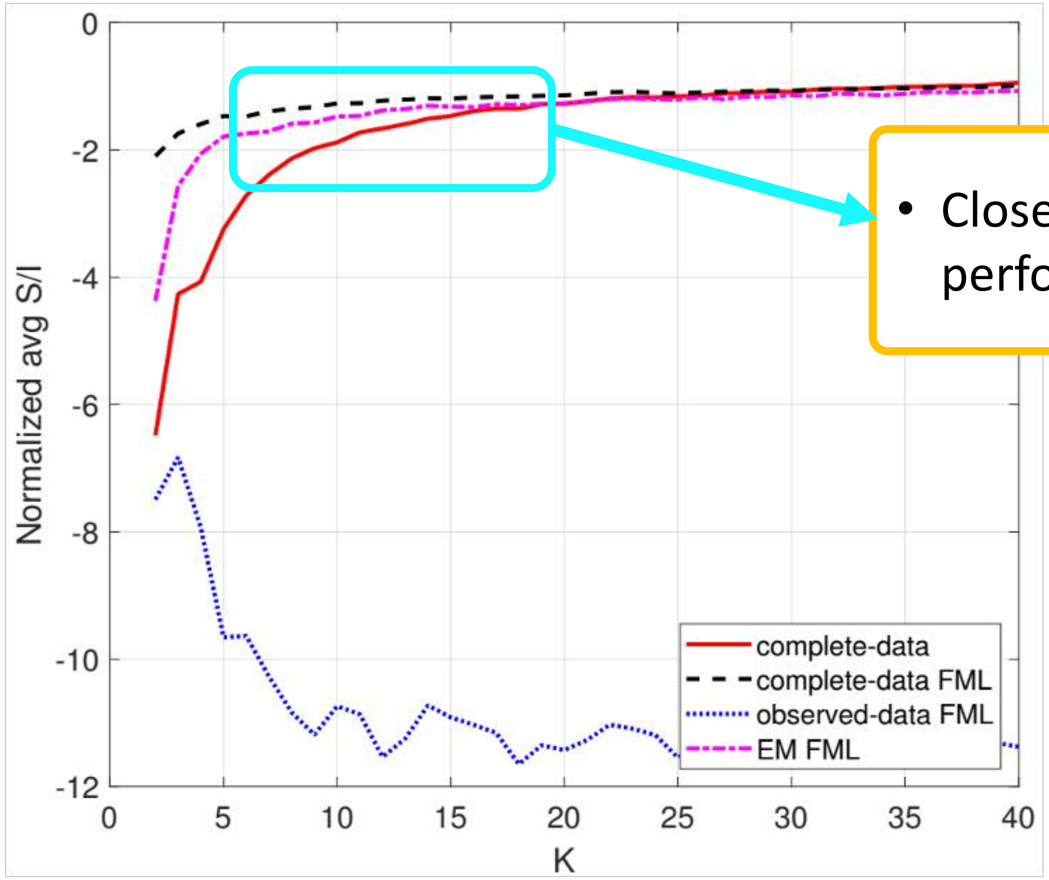
- **four-channels SDR coherent receiver**
- **SDR transmitters** to emulate the presence of unknown emitters
- a **Personal Computer** to perform digital signal processing operations;
- a **Uniform Linear Array** composed of four dipole antennas separated by $\lambda/2$

Missing data scenario emulated assuming probability of missing an observation $p_m = 0.3$



Structured Covariance Matrix Estimation with Missing-Data via EM [5/5]

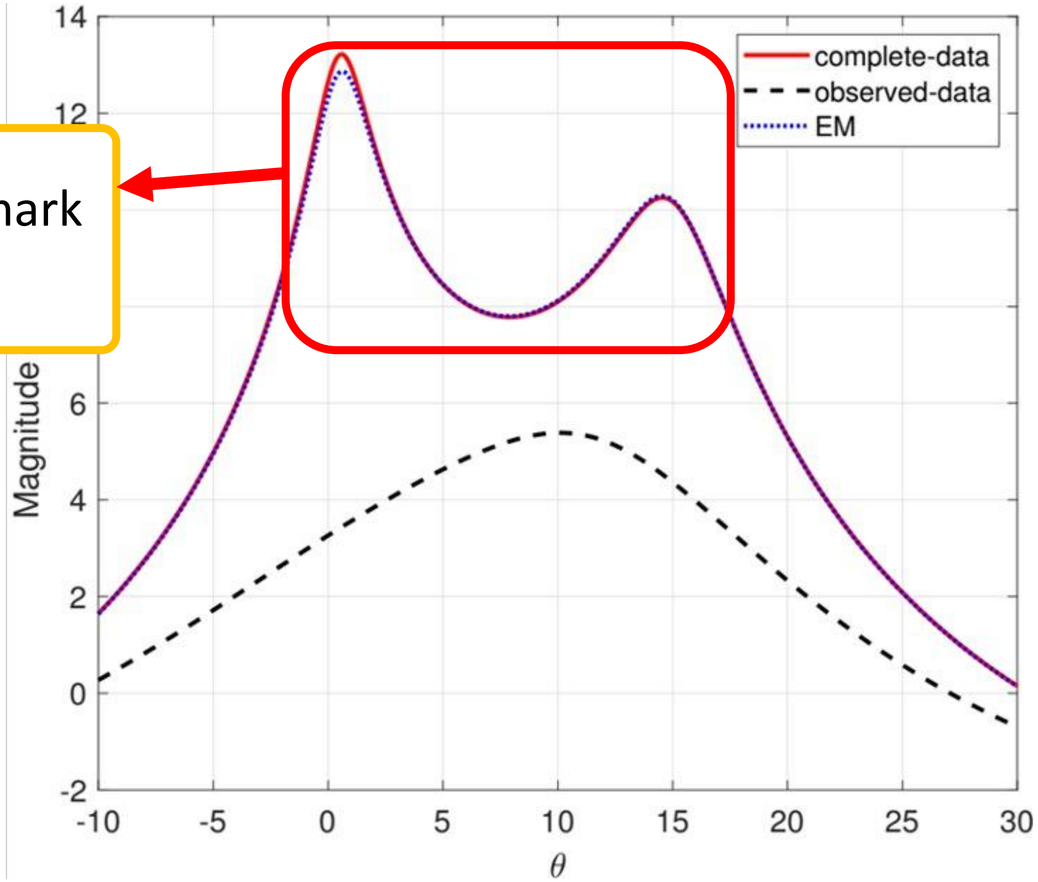
Adaptive Beamforming



SINR (estimated using $L = 500$ disjoint blocks, each composed of 40 snapshots) versus the number of snapshots.

- Close-to-benchmark performance

Detection of sources number



MUSIC Spatial Spectrum on a dataset of 250 samples.

TARGET DETECTION PROBLEM FORMULATION

ideal case (no missing-data)

$$\begin{cases} H_0 : \begin{cases} \boldsymbol{r} = \boldsymbol{n} \\ \boldsymbol{r}_i = \boldsymbol{n}_i, \quad i = 1, \ldots, K \end{cases} \\ H_1 : \begin{cases} \boldsymbol{r} = \alpha \boldsymbol{p} + \boldsymbol{n} \\ \boldsymbol{r}_i = \boldsymbol{n}_i, \quad i = 1, \ldots, K \end{cases} \end{cases}$$

$$\boldsymbol{z}_i = \boldsymbol{A}_i \boldsymbol{r}_i$$

missing-data

missing-data case

$$\begin{cases} H_0 : \begin{cases} \boldsymbol{z} = \boldsymbol{A}\boldsymbol{n} \\ \boldsymbol{z}_i = \boldsymbol{A}_i \boldsymbol{n}_i, \quad i = 1, \ldots, K \end{cases} \\ H_1 : \begin{cases} \boldsymbol{z} = \alpha \boldsymbol{A}\boldsymbol{p} + \boldsymbol{A}\boldsymbol{n} \\ \boldsymbol{z}_i = \boldsymbol{A}_i \boldsymbol{n}_i, \quad i = 1, \ldots, K \end{cases} \end{cases}$$

Adaptive Radar Detection in the Presence of Missing-Data [2/3]

H_0: estimation of $\boldsymbol{M}(\boldsymbol{\theta})$ → Computed by means of the previous EM estimation algorithm

H_1: estimation of $\boldsymbol{M}(\boldsymbol{\theta})$ and α → EM-based algorithm

E-step

$$Q\left(\alpha, \boldsymbol{\theta} | \alpha^{(h-1)}, \boldsymbol{\theta}^{(h-1)}\right) = -(K+1)\left[N \ln(\pi) + \ln(\det(\boldsymbol{M}(\boldsymbol{\theta})))\right]$$
$$-\mathrm{tr}\left\{\boldsymbol{M}(\boldsymbol{\theta})^{-1}[(\boldsymbol{\mu}^{(h-1)} - \alpha\boldsymbol{p})(\boldsymbol{\mu}^{(h-1)} - \alpha\boldsymbol{p})^{\dagger} + \boldsymbol{\Sigma}^{(h-1)}]\right\}$$

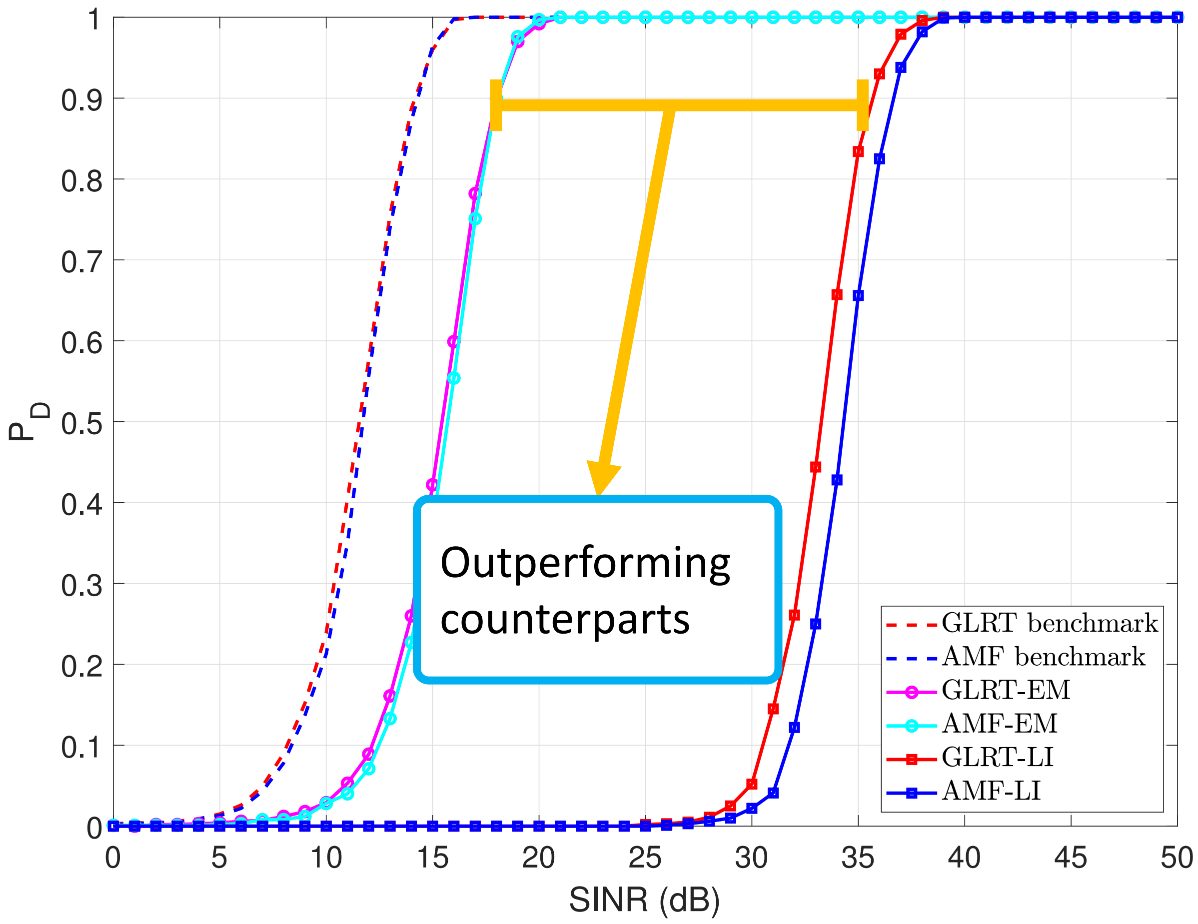
M-step

$$\left(\alpha^{(h)}, \boldsymbol{\theta}^{(h)}\right) = \underset{\alpha,\, \boldsymbol{\theta}: \boldsymbol{M}(\boldsymbol{\theta}) \in \mathscr{C}}{\mathrm{argmax}}\ Q\left(\alpha, \boldsymbol{\theta} | \alpha^{(h-1)}, \boldsymbol{\theta}^{(h-1)}\right)$$

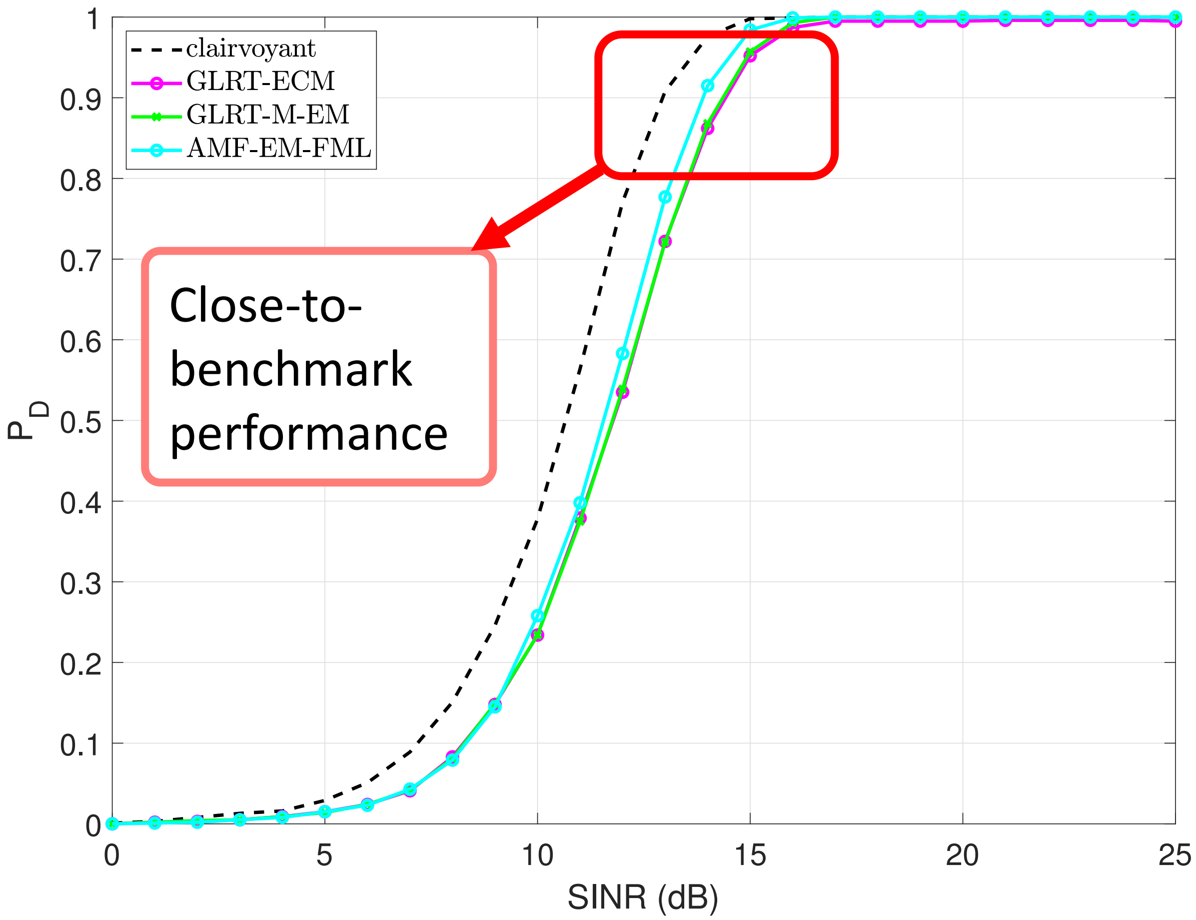
Devised in closed-form for some specific covariance matrix uncertainty set

Adaptive Radar Detection in the Presence of Missing-Data [3/3]

No specific covariance structure

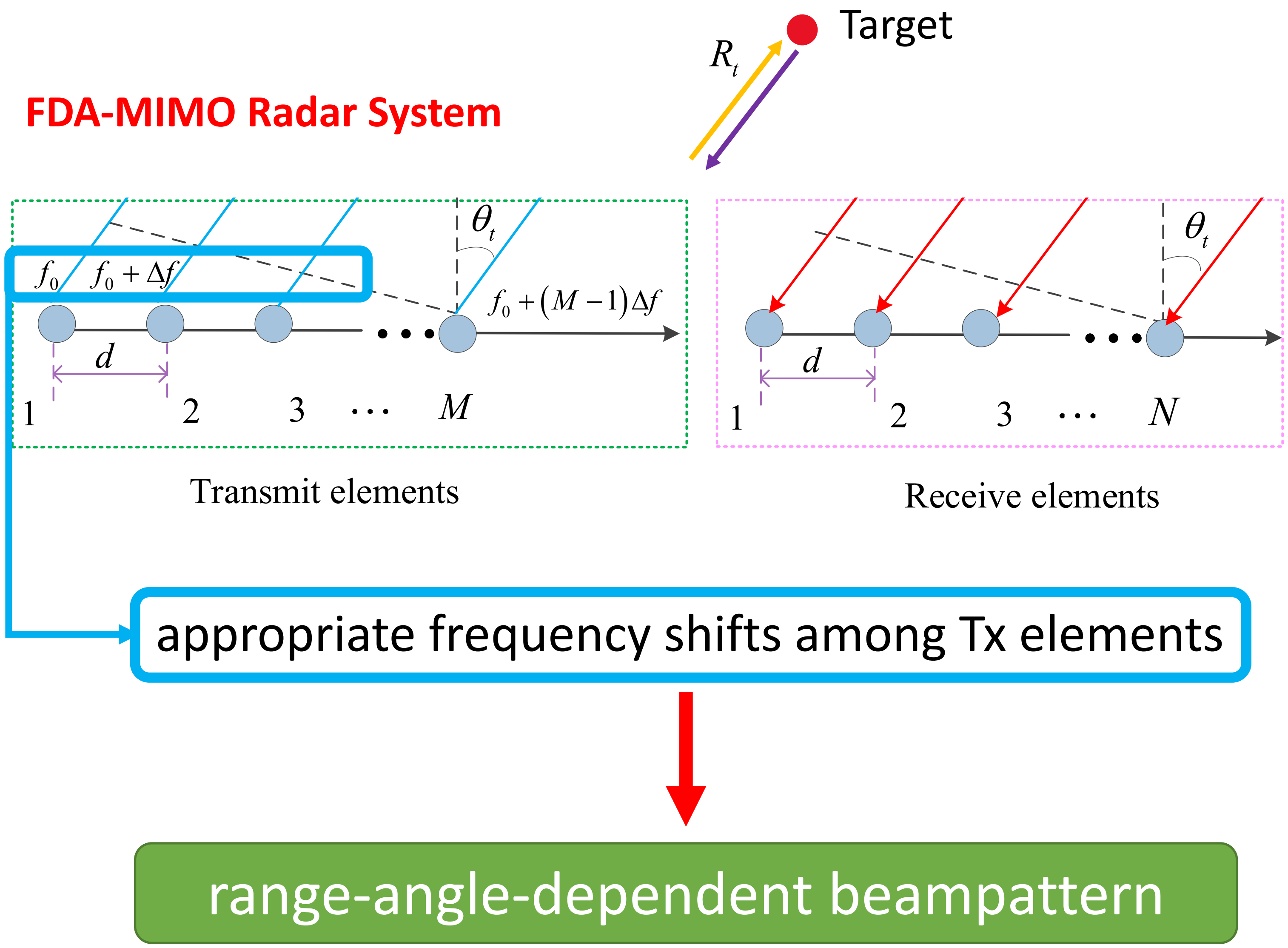


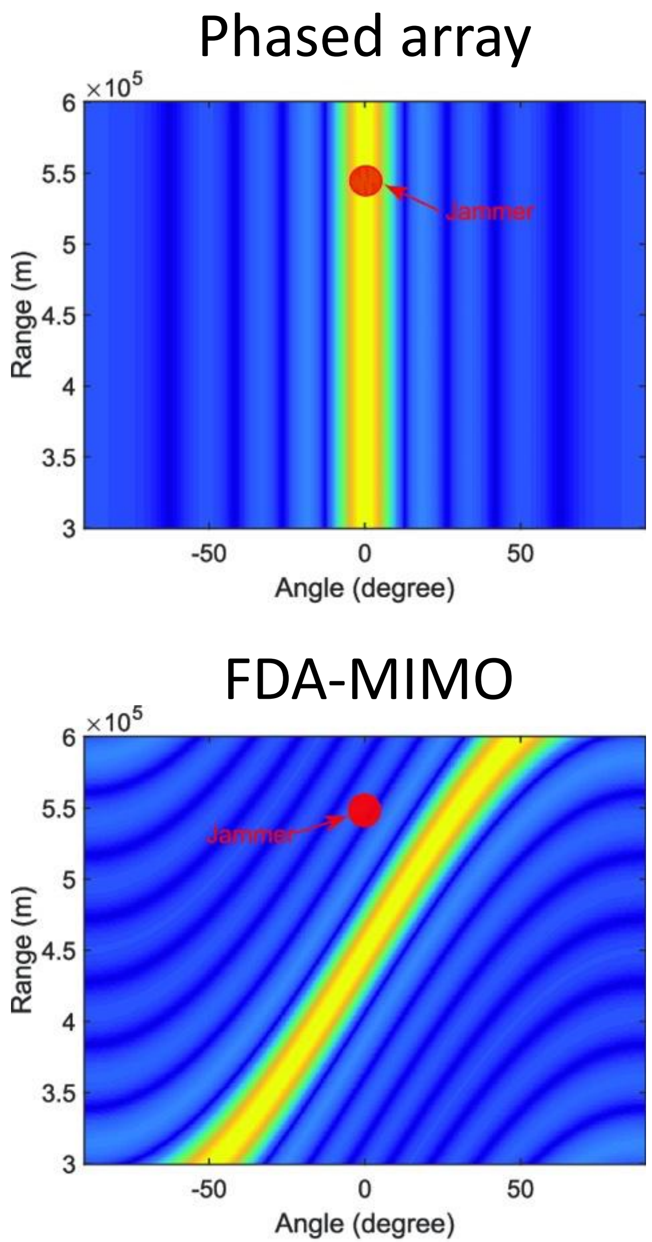
Structured covariance matrix with a lower bound on the white disturbance power level



Single-Snapshot Angle and Incremental Range Estimation for FDA-MIMO Radar

Single-Snapshot Angle and Incremental Range Estimation for FDA-MIMO Radar [1/4]

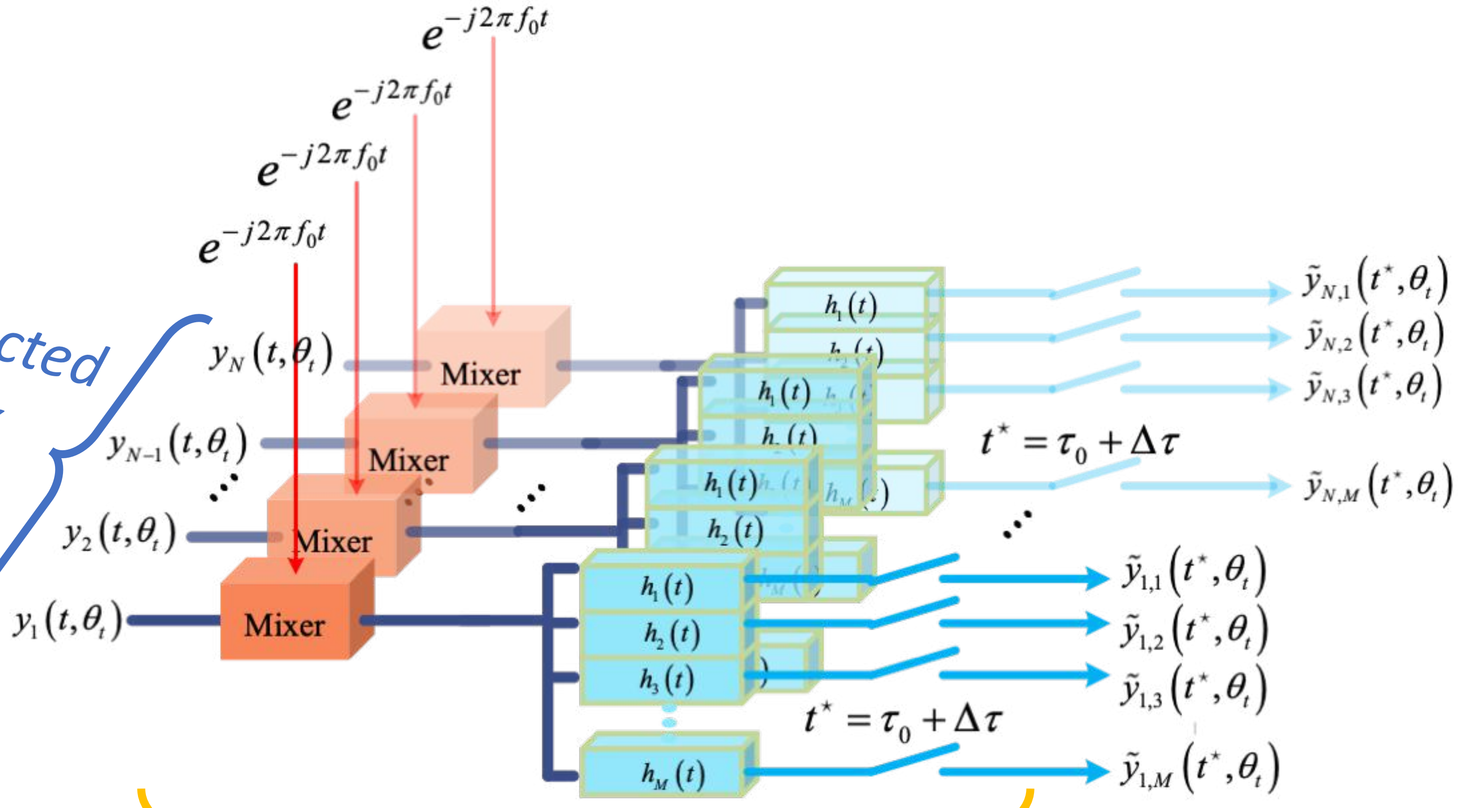




Single-Snapshot Angle and Incremental Range Estimation for FDA-MIMO Radar [2/4]

range-angle-dependent beampattern → Estimate target range and angle using a single data snapshot!

Data collected from Rx channels



Signal pre-processing

received signal

$$\boldsymbol{z} = \beta_1 \boldsymbol{s}(u, \delta) + \boldsymbol{n}$$

Target DOA

Target incremental range

Compute the ML estimate of u and δ

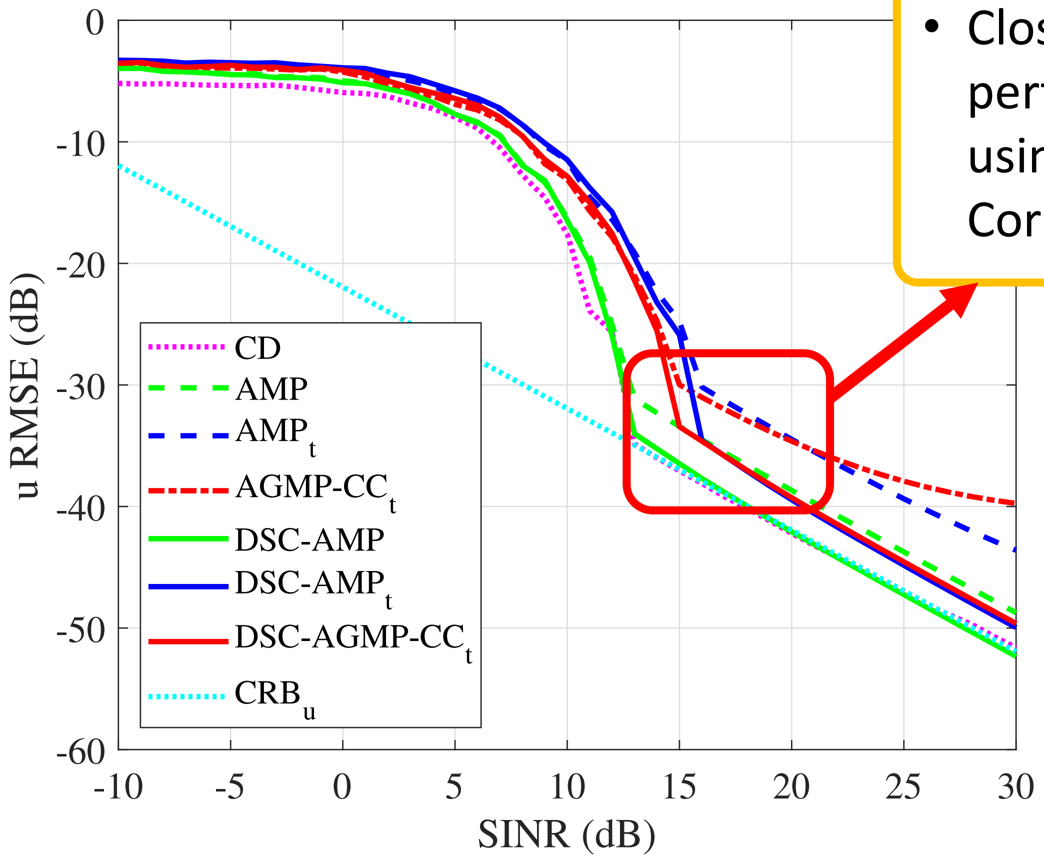
Solve

$$\max_{u\in[-1,1],\delta\in[-\frac{\Delta f}{B},\frac{\Delta f}{B}]} \frac{\left|\boldsymbol{s}^{\dagger}\left(u,\delta\right)\boldsymbol{Q}^{-1}\boldsymbol{z}\right|^{2}}{\boldsymbol{s}^{\dagger}\left(u,\delta\right)\boldsymbol{Q}^{-1}\boldsymbol{s}\left(u,\delta\right)}$$

1. CD-based method
2. Adaptive Monopulse Procedure
3. Adaptive Generalized Monopulse Procedure with Complex Correction

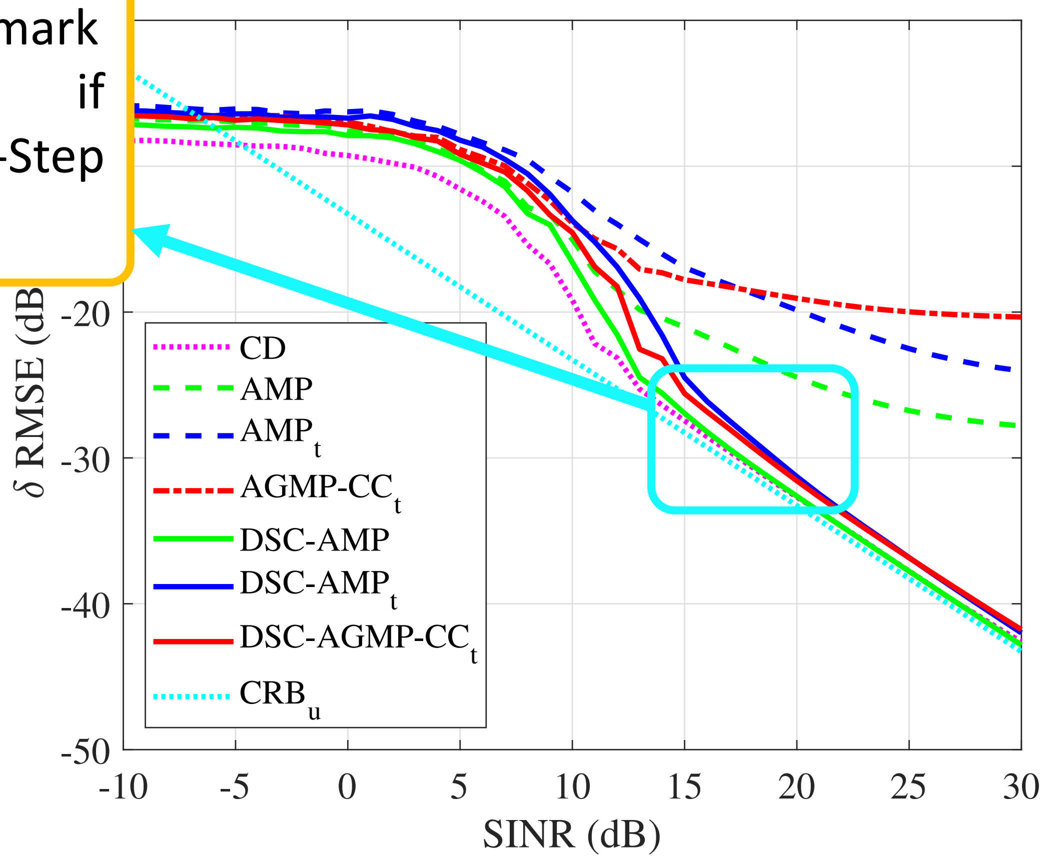
4 Tx and 10 Rx antennas, $B = 1$ MHz, $\Delta f = 0.5$ MHz
2 narrow-band jammers with JNR = 30 dB

RMSE – angle (u) estimation



- Close-to-benchmark performance if using a Double-Step Correction

RMSE – incr. range (δ) estimation



References

[J1]	A. Aubry, A. De Maio, S. Marano, and M. Rosamilia, “*Single-Pulse Simultaneous Target Detection and Angle Estimation in a Multichannel Phased Array Radar,*" IEEE Transactions on Signal Processing, IEEE TSP, published, 2020.
[J2]	L. Lan, M. Rosamilia, A. Aubry, A. De Maio, and G. Liao, “*Single-Snapshot Angle and Incremental Range Estimation for FDA-MIMO Radar,*” in IEEE Transactions on Aerospace and Electronic Systems, IEEE TAES, published, 2021.
[J3]	A. Aubry, A. De Maio, and M. Rosamilia, "*Reconfigurable Intelligent Surfaces for N-LOS Radar Surveillance*," in IEEE Transactions on Vehicular Technology, IEEE TVT, published, 2021.
[J4]	A. Aubry, A. De Maio, S. Marano, and M. Rosamilia, "*Structured Covariance Matrix Estimation with Missing-(complex) Data for Radar Applications via Expectation-Maximization,*" IEEE Transactions on Signal Processing, IEEE TSP, published, 2021.
[J5]	A. Aubry, V. Carotenuto, A. De Maio, M. Rosamilia, and S. Marano," *Adaptive Radar Detection in the Presence of Missing-Data*," IEEE Transactions on Aerospace and Electronic Systems, IEEE TAES, published, 2022.
[J6]	L. Lan, M. Rosamilia, A. Aubry, A. De Maio, G. Liao, and J. Xu, “*Adaptive Target Detection with Polarimetric FDA-MIMO Radar*,” IEEE Transactions on Aerospace and Electronic Systems, IEEE TAES, published, 2022.
[J7]	M. Rosamilia, A. Balleri, A. De Maio, A. Aubry, and V. Carotenuto, “*Radar Detection Performance Prediction using Measured UAVs RCS Data*”, IEEE Transactions on Aerospace and Electronic Systems, published, 2022.
[J8]	A. Aubry, A. De Maio, L. Lan, and M. Rosamilia, “*Adaptive Radar Detection and Bearing Estimation in the Presence of Unknown Mutual Coupling*”, IEEE Transactions on Signal Processing, IEEE TSP, published, 2023.

Thanks for the kind attention!