

Polar Cluster-Based Target Tracking for Maritime Radar Applications

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Introduction

This work evaluates a polar-domain clustering algorithm and its impact on extended-object multi-target tracking (MTT) algorithms. A Random Matrix Model (RMM) incorporating radar intensity improves estimation of target centroid and extent. Performance is validated on real-world X-band radar data within selected Regions of Interest (ROI) and different distances from the sensor, where objects have different point cloud spatial densities.

Extended Objects

Extended objects generate multiple detections, forming point clouds rather than single measurements (Fig 1).

- **Clustering algorithms:** provide a cost-effective way to group spatially and temporally consistent detections.
- **RMM framework:** the cluster centroid provides the target position, while the scatter matrix describes its extent and orientation.

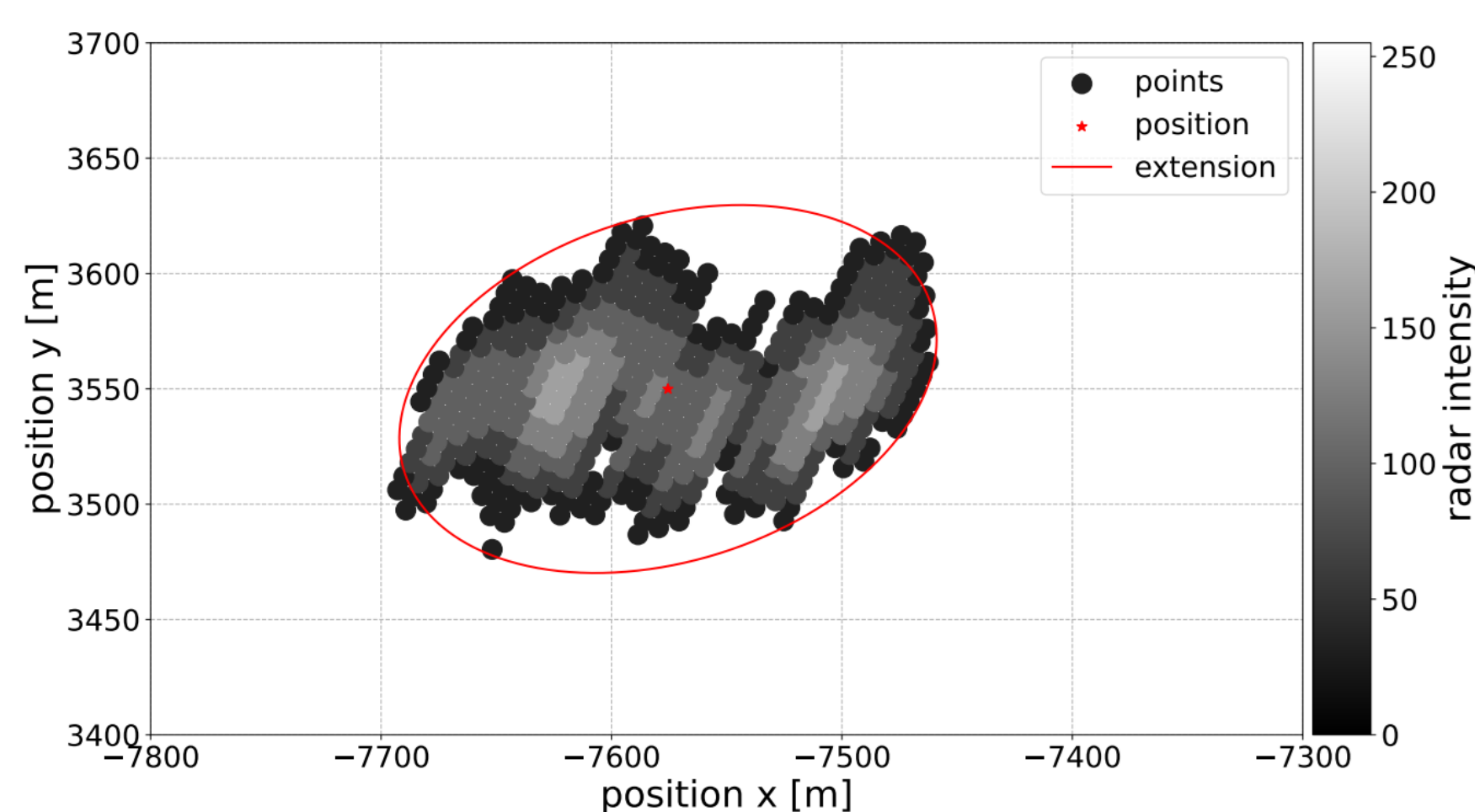


Fig. 1: Example for X-band radar detections for a large vessel with the intensity information and an ellipse approximation where the sensor is located in the origin

Clustering

- **Cartesian domain:** range-dependence behaviour of cluster spatial density.
- **Polar domain:** requires definition of distance for density clustering algorithms.
- **Reconstruction of polar coordinates:** points are mapped to the lateral surface of a cylinder (Fig 2). The distance between two points on the lateral surface (i.e., geodesic) can then be estimated similar to Euclidean distance ($R = \sigma_r / \sigma_\phi$):

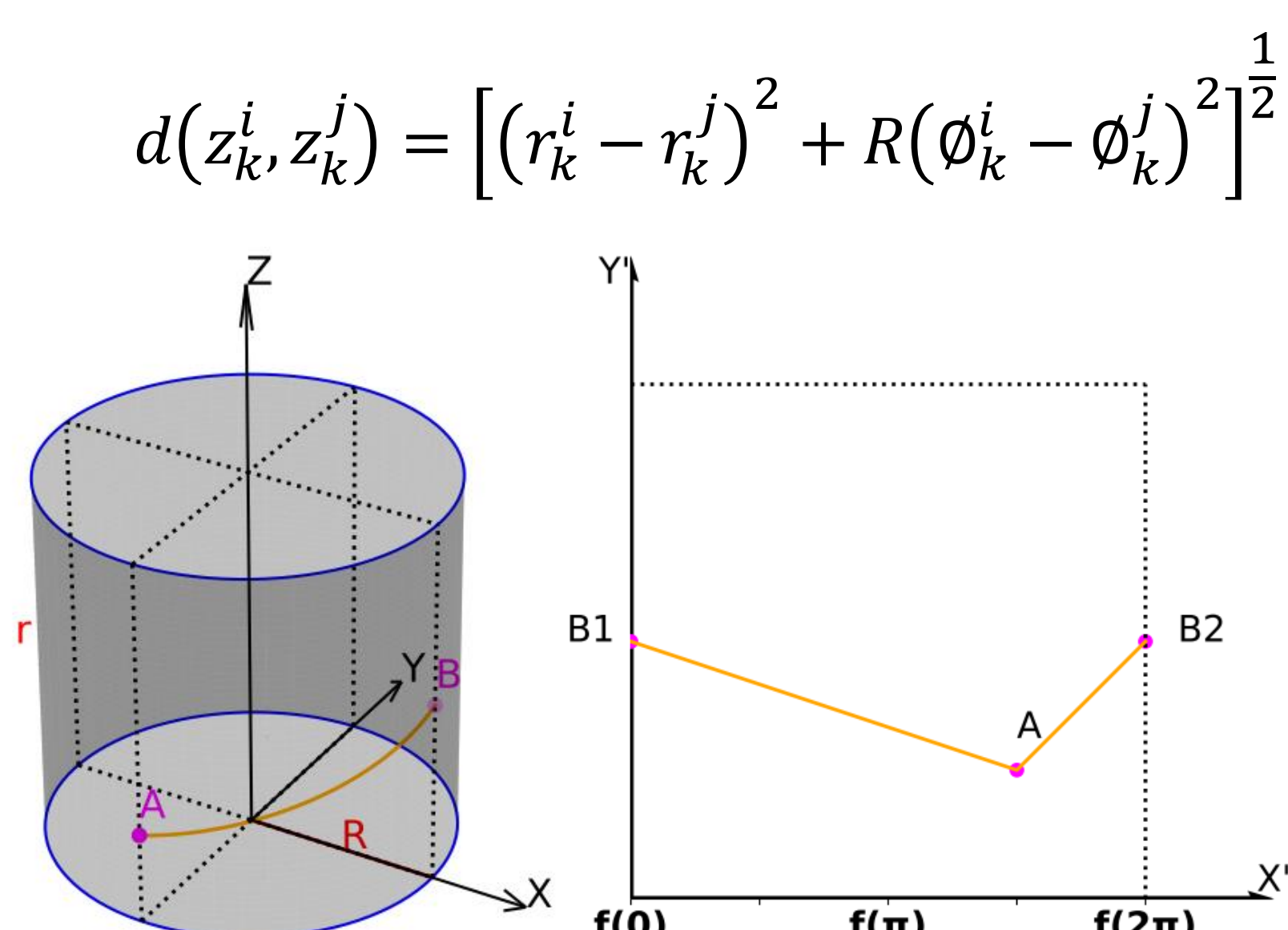


Fig. 2: Reconstruction of polar coordinates on the rectangular plane (X' , Y') using cylindrical coordinates, adapted from [10].

Multi-Target Tracking

RMM for kinematic state (Gaussian distribution) and extend estimator (Inverse Wishart distribution). For the hypothesis generation and data association step, the MTT formulations:

- Sequential Probability Ratio Test (SPRT) tracker
- Multi-instance Integrated Probabilistic Data Association (IPDA)
- Joint IPDA (JIPDA)
- Cluster-based modified version of Gaussian Inverse Wishart Probability Hypothesis Density (CB-GIW-PHD) filter.

Numerical stability

- **Large number of measurements:** numerical imbalance of the Wishart distribution, we define a normalized cluster likelihood via the ratio:

$$\Lambda(Z_j) = \frac{1}{P_G} \frac{p(\bar{z}_j|H_1)p(\bar{Z}_j|H_1)}{\lambda_c p(\bar{z}_j|H_0)}$$

where P_G is the gating probability, \bar{z}_j is the cluster centroid, \bar{Z}_j is the cluster spread matrix, and λ_c is the clutter density.

- **Floating-point underflow:** log-domain calculations using Log-Sum-Exp (LSE) identity:

$$\ln \sum_i \exp(x_i) = M + \ln \sum_i \exp(x_i - M)$$

where $M = \max(x_i)$.

Results

Evaluation with GOSPA (Fig. 3) and the T-GOSPA metrics for ID switching information (Table 1) using real-world manually labelled marine datasets. Two scenarios were selected:

- distances up to 5 km (near-field), with similar performance for both clustering domains.
- distances higher than 20 km (far-field).

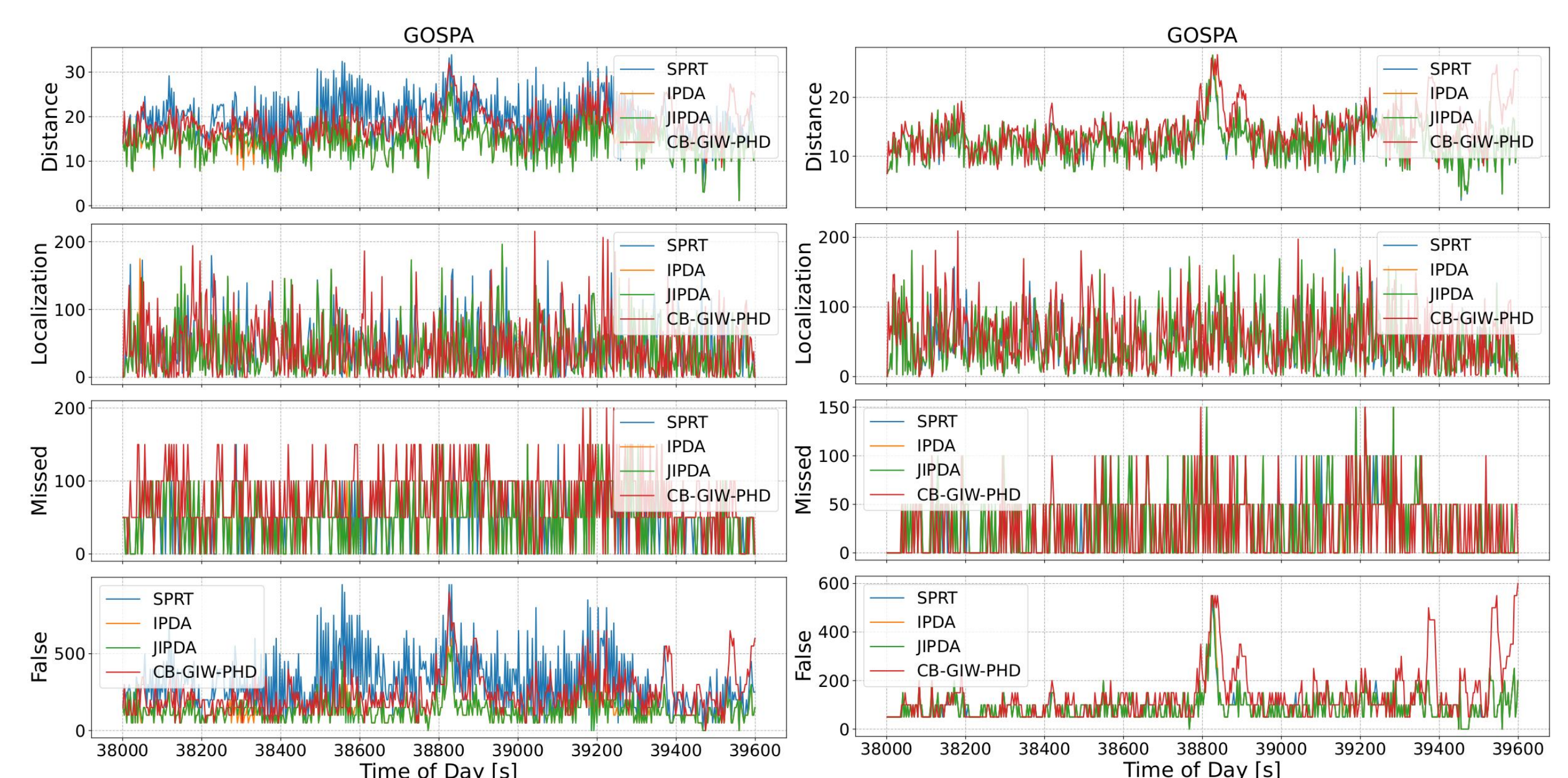


Fig. 3: GOSPA metrics for the far-field scenario. On the left the results for clustering in Cartesian domain. On the right the results for clustering in polar domain.

TABLE I: T-GOSPA Track Switching Cost

Scenario	Case	SPRT	P-IPDA	P-JIPDA	CB-GIW-PHD
Near Field	Cartesian	40.0	44.3	44.3	28.1
	Polar	38.4	40.8	40.8	24.7
Far Field	Cartesian	53.3	24.2	23.7	22.6
	Polar	20.9	21.5	20.9	10.6

Conclusions

- The proposed clustering method tackles the issues inherent to the polar data, especially the variance of point cloud spatial density w.r.t. the distance to the sensor, impacting the most sensitive hyper-parameter in density-based clustering algorithms such as DBSCAN.
- The effectiveness of this method was assessed in four different MTT frameworks with different levels of complexity. Their performance corroborate the robustness assumption of polar-domain clustering.