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Comparative Analysis of Target Localization Accuracy in Radar PPI Images Using Geometric Enclosures

Bounding boxes vs. convex hulls vs. concave hulls: which shape finds a ship's true centre?

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HIGHLIGHTS

What Did This Study Find?

1

Best Accuracy

The concave hull method reaches a 58–70 m average localization error when fusing radar with AIS data.

2

Beats Bounding Boxes

Up to 12.7% more accurate than the simple bounding-box method.

3

Beats Convex Hulls

Up to 2.1% more accurate than the convex hull method.

4

Why It Works

Concave hulls keep the natural dents and gaps in a ship's echo — caused by clutter, noise, and structure — instead of smoothing them away.

Why Is It Hard to Pin Down a Ship's Position?

Irregular Echoes

Sea clutter, multipath reflections, and limited resolution give ships oddly shaped, non-convex blobs on the radar screen — not neat, simple dots.

Azimuth Bias

Antenna misalignment and small timing mismatches rotate the whole radar picture by a fixed 0°–5° compared to true AIS positions.

The gap in prior work: most studies pick one enclosure shape (usually a bounding box or convex hull) without comparing it against the alternatives on the same real data.

This paper asks a simple question: does the shape of the enclosure around an echo actually change how well we can locate the ship?

RELATED WORK

Building on a Growing Body of Hull-Based Research

Nemirko & Dulá — nearest-convex-hull classifier	0.23% error, beating SVM and k-NN
Külcü — earlier ASV radar tracking framework	98.7% true positives, 59% fewer false positives
Xu et al. — VTS collision-risk pipeline	Lower speed/heading variance on Yangtze River data
Guo et al. — convex-hull feature adaptation (CFA)	State-of-the-art on DOTA and SKU110K-R datasets
Liang et al. — DeepHullNet (Transformers)	5–8% more accurate, 100× faster hull computation
Shi et al. — FB-ICHC concave hull detector	20% higher detection rate, 49% faster

The gap: no earlier study directly compares bounding boxes, convex hulls, and concave hulls for ship localization on the same real X-band PPI + AIS dataset. This paper fills that gap.

CONTRIBUTION

The First Controlled, Head-to-Head Comparison

Fair, direct comparison

Bounding box, convex hull, and concave hull are tested on the exact same echoes, under the same optimal azimuth correction.

Real-world validation

Every result is checked against real, synchronized AIS ground-truth positions — not simulated data.

Lightweight by design

No deep learning or heavy detectors are needed — just colour thresholding and classic geometry, fast enough for onboard use.

Practical payoff

Concave hulls cut localization error by up to 12.7%, offering an easy upgrade path for existing VTS and ASV systems.

Source: Section 1 (Külcü 2026)

The DLR Baltic Sea Radar + AIS Dataset

X-band marine radar, ~10 m resolution, with synchronized AIS

- AIS records give ground-truth position (East/North), course, speed, and heading for each of 4 vessels, at every one of 781 time steps.
- Vessel 1 is the "own-ship" carrying the radar — it appears stationary at the centre of the display.
- Vessel 3 was excluded from the analysis — it leaves the radar's 3 NM range after step 80 and is visible in only 10% of frames.
- Vessels 2 and 4 (the two vessels studied in detail) move on clearly different, fast-changing paths — good stress tests for localization accuracy.

781 synchronized radar scans

3 NM radar range (~5,556 m)

11.82 m real-world size of 1 pixel

Source: Sections 2.1.1–2.1.2, Figs. 1–3 (Külcü 2026)

Fixing the Rotation Between Radar and AIS

The whole radar picture is rotated a little compared to true AIS positions. The fix: test many rotation angles and keep the one that minimizes error.

θ (°)	0.0	1.0	2.0	3.0	4.0	4.5	5.0
Vessel 2 (px)	12.54	10.56	8.31	6.28	5.99	6.63	7.65
Vessel 4 (px)	15.71	14.74	13.34	9.48	6.10	5.18	5.27
Total (px)	28.25	25.30	21.65	15.76	12.09	**11.81**	12.92

θ = 4.5° gives the clear minimum — a combined error of just 11.81 pixels (about 140 m). This single, fixed correction is then applied to every measurement in the rest of the study.

Source: Table 1, Section 2.2 (Külcü 2026)

From Yellow Pixels to Clean Target Clusters

1. Colour Threshold

Convert the image to HSV and isolate the bright yellow used for radar echoes.

→

2. Clean the Mask

One round of morphological closing and dilation joins small gaps without changing the overall shape.

→

3. Extract Contours

Find each echo's outer boundary; drop any shape smaller than 16 pixels as noise.

Why keep it this simple?

No CFAR detectors or trained neural networks are used. Colour thresholding plus basic morphology is fast enough to run in real time on embedded VTS/ASV hardware, and different ships' echoes almost never merge at this resolution and sea state — so each contour reliably represents one vessel.

Three Ways to Enclose an Echo and Find Its Centre

Bounding Box

$O(n)$

The smallest upright rectangle around all echo pixels. Centre = midpoint of the rectangle. Fast, but empty corners pull the centre away from the true position.

Convex Hull

$O(n \log n)$

The smallest "rubber band" polygon around the points. Centre = centre of mass (shoelace formula). Tighter than a box, but still smooths over real dents.

Concave Hull ($\alpha = 0.1$)

$O(n \log n)$

An alpha-shape that hugs the true, dented outline of the echo. Centre = centre of mass of the actual visible pixels — closest to the real ship centre.

Source: Sections 2.4–2.6, Algorithms 1–3 (Külcü 2026)

Baseline: Localization with Bounding Boxes

Error is measured as the distance (in metres) between the estimated centre and the true AIS position, across hundreds of radar frames.

Target	N	Mean (m)	Median (m)	Min (m)	Max (m)	Std. Dev. (m)
Target 2	697	80.51	76.18	18.81	173.74	35.39
Target 4	665	59.37	60.66	5.95	120.45	27.40

The weak point: empty corners inside the rectangle systematically pull the estimated centre away from the ship — especially for Target 2, which manoeuvres more and has a less regular echo.

Source: Table 2, Section 3.1 (Külcü 2026)

Improvement: Localization with Convex Hulls

The convex hull follows the outer shape of the echo more closely than a rectangle — does this help?

Target	N	Mean (m)	Median (m)	Min (m)	Max (m)	Std. Dev. (m)
Target 2	696	71.85	70.37	11.90	164.82	36.26
Target 4	649	59.18	60.66	10.57	128.14	30.96

Yes — a clear gain: Target 2's mean error drops by 10.8% versus the bounding box. But convexity still forces the hull to fill in real dents and gaps in the echo, which limits how much further it can improve.

Source: Table 3, Section 3.2 (Külcü 2026)

Best Result: Localization with Concave Hulls

The concave hull is allowed to follow the real, dented shape of the echo — does keeping those dents pay off?

Target	N	Mean (m)	Median (m)	Min (m)	Max (m)	Std. Dev. (m)
Target 2	696	70.32	69.17	11.59	161.09	35.89
Target 4	653	58.44	59.46	11.23	127.17	29.16

The winner overall: 12.7% better than the bounding box and 2.1% better than the convex hull for Target 2; 1.6% and 1.3% better, respectively, for Target 4 — the lowest mean error of all three methods, for both vessels.

Source: Table 4, Section 3.3 (Külcü 2026)

Does the Concave Hull Setting (α) Matter?

The concave hull needs one setting, α, that controls how tightly it hugs the echo. A sensitivity test checked four values:

α value	Target 2 (m)	Target 4 (m)
0.02 (too tight)	71.81 ± 36.12	59.33 ± 29.45
0.05	70.58 ± 36.01	58.31 ± 29.34
0.1 (used in study)	**70.32 ± 35.89**	**58.44 ± 29.16**
0.2 (too loose)	72.19 ± 37.44	59.87 ± 30.28

Good news: the method is robust. Values between 0.05 and 0.1 give almost identical, best results. Going too small (0.02) overfits to noise; going too large (0.2) starts to behave like a convex hull and loses its concavity advantage. There is no need for delicate, per-frame tuning.

Source: Table 5, Section 3.4 (Külcü 2026)

Seeing the Difference on a Real Echo

(a) Bounding Box

Encloses the echo in the smallest upright rectangle. Simple and fast, but the empty corners clearly bias the centre estimate for a tilted, elongated echo.

(b) Convex Hull

Wraps tightly around the outer points, cutting most of the corner bias. But it still fills in any real notch or gap in the echo's shape.

(c) Concave Hull

Follows the echo's true, irregular boundary — including dents from clutter or shadowing — giving a centroid closest to the real vessel centre.

In the paper's figures, red/blue marks the enclosure and centroid on real yellow radar echoes — the concave hull (c) visibly hugs the echo tightest of the three.

CONCLUSION

Shape Choice Really Does Matter

- Concave hulls give the most accurate ship position of the three methods tested: 70.32 m average error for Target 2, 58.44 m for Target 4.
- That's an improvement of up to 12.7% over bounding boxes and 2.1% over convex hulls — using only classic geometry, no deep learning.
- The fixed 4.5° azimuth correction is a simple, one-time calibration step that keeps radar and AIS positions properly aligned throughout.
- Future work: automatically adapt the concave hull setting per frame, add machine learning on top, and extend the method to dense, multi-vessel traffic scenes.

REFERENCE

Source

Külcü, S. (2026).
Comparative Analysis of Target Localization Accuracy in Radar PPI Images Using Geometric Enclosures.
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Dataset: DLR real-world marine radar repository (Baltic Sea) — https://doi.org/10.26090/rwmr

This presentation is an academic summary of the research paper above. For the full reference list (19 citations), please see the original article.

Thank You