

Side-Scan Sonar SLAM Using Ping-Level Landmark Detection in Feature-Poor Seabed Environments

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Scan to see our recent RA-L paper!

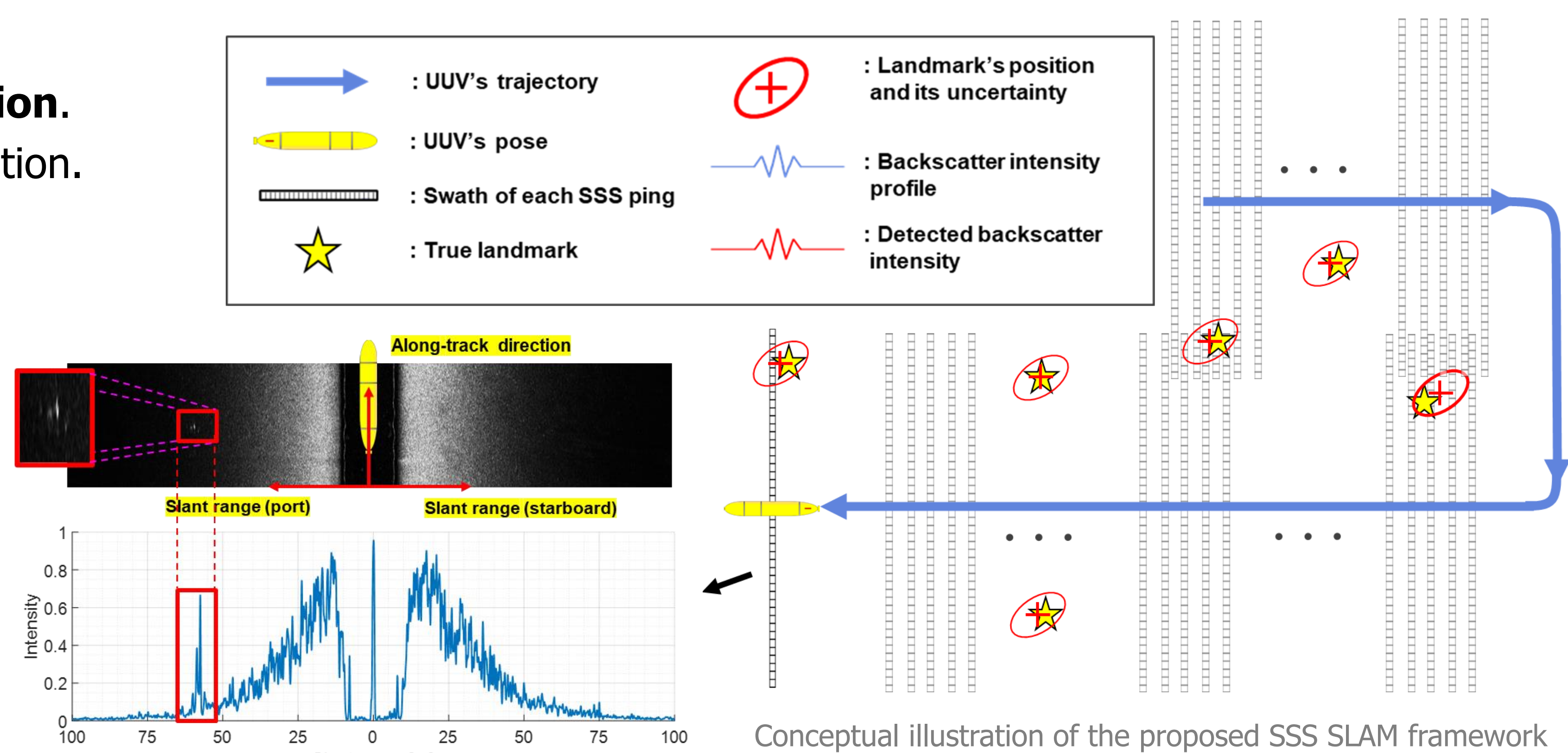
Key Contributions

Motivation

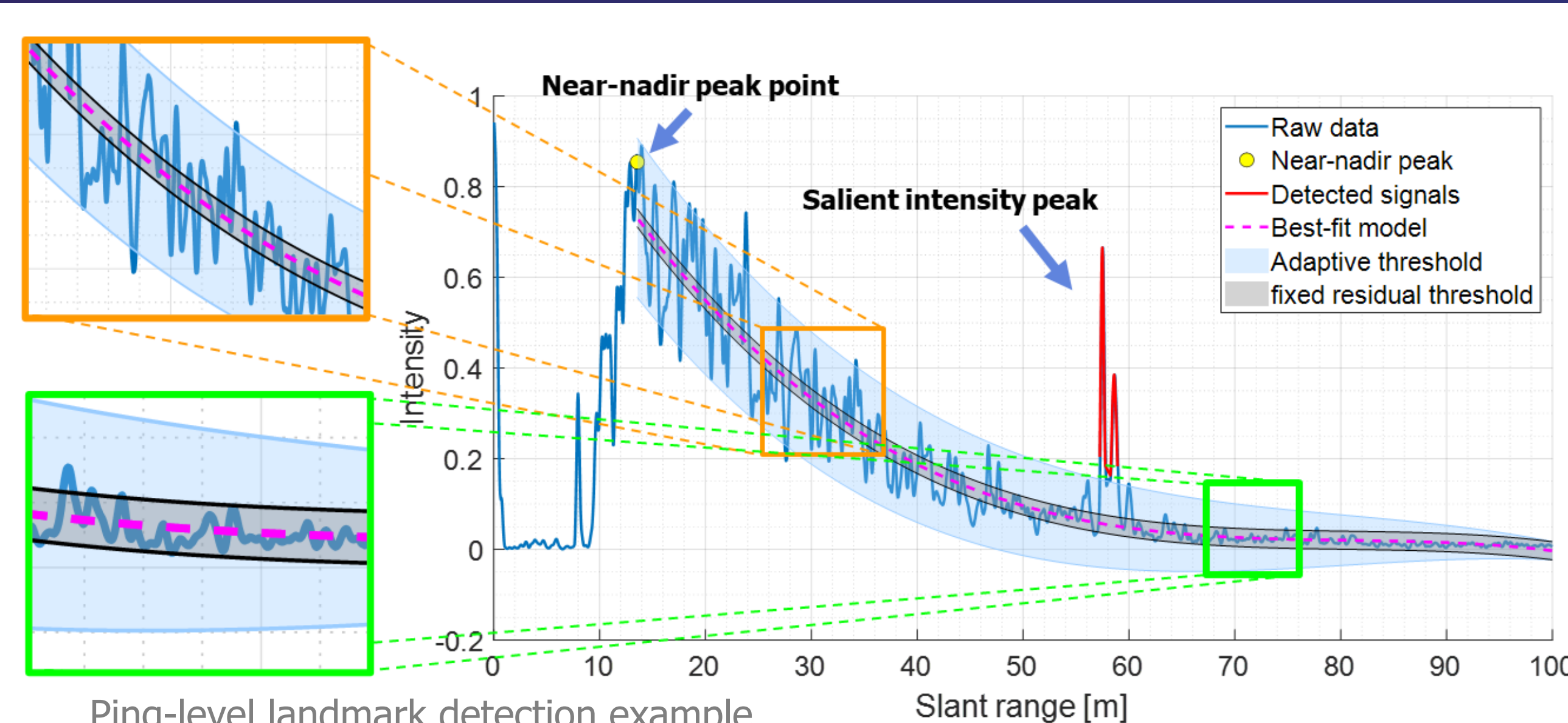
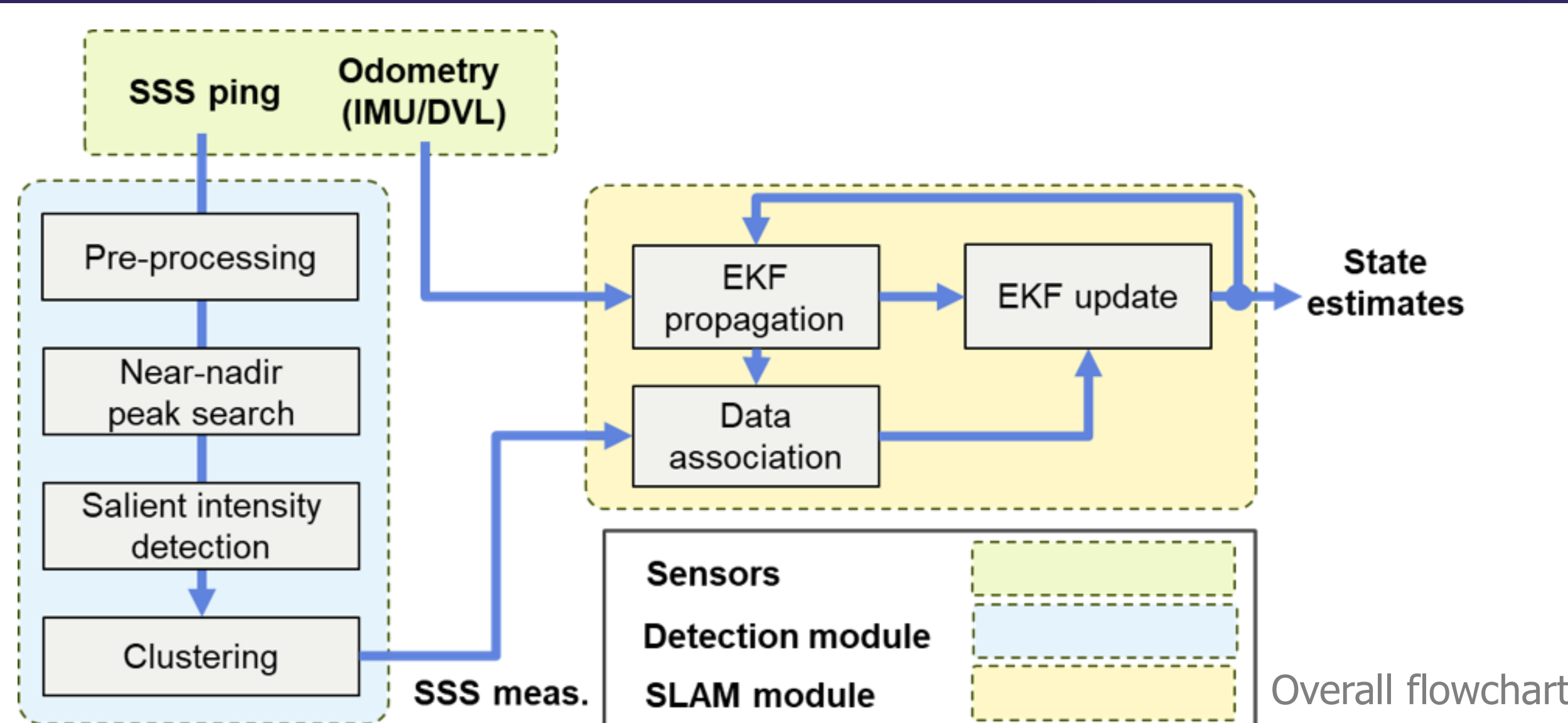
- Image-level SSS SLAM requires **slant-to-ground range projection**.
- Projection may induce **geometric distortion** under altitude variation.
- Feature-poor seabeds → **Unstable image-domain matching**

Our Approach & Contributions

- Ping-Level Landmark Detection**
Raw backscatter profile → Attenuation modeling → Salient peaks
- Direct Slant-Range EKF Update**
No ground-range projection
- Two Real-Sea Validations (~2 km each)**
Feature-poor seabed environments



Proposed SSS SLAM Method



SSS SLAM Formulation

$$\mathbf{x} = [\mathbf{x}_v^\top \quad \mathbf{x}_{l,1}^\top \quad \cdots \quad \mathbf{x}_{l,i}^\top \quad \cdots \quad \mathbf{x}_{l,n-1}^\top \quad \mathbf{x}_{l,n}^\top]^\top \quad \text{Full state vector}$$

$$\mathbf{x}_v = [x_v \quad y_v \quad z_v \quad \psi_v]^\top \quad \text{4-DOF Vehicle's pose} \quad \mathbf{x}_{l,i} = [x_{l,i} \quad y_{l,i} \quad z_{l,i}]^\top \quad \text{3D Landmark position}$$

$$\mathbf{z}_i = \begin{bmatrix} \rho_i \\ \alpha_i \end{bmatrix} = \begin{bmatrix} \sqrt{(x_{l,i} - x_v)^2 + (y_{l,i} - y_v)^2 + (z_{l,i} - z_v)^2} \\ \text{atan2}(y_{l,i} - y_v, x_{l,i} - x_v) - \psi_v \end{bmatrix} + \mathbf{v}$$

Measurement model using native slant-range and azimuth angle

Ping-Level Landmark Detection Method

Core idea: Salient intensity deviations → Landmark candidates

Detection pipeline:

- Gaussian filtering
- Near-nadir peak search (GSS) *Golden Section Search
- Cubic decay fitting by modified RANSAC w/ range-adaptive residual threshold

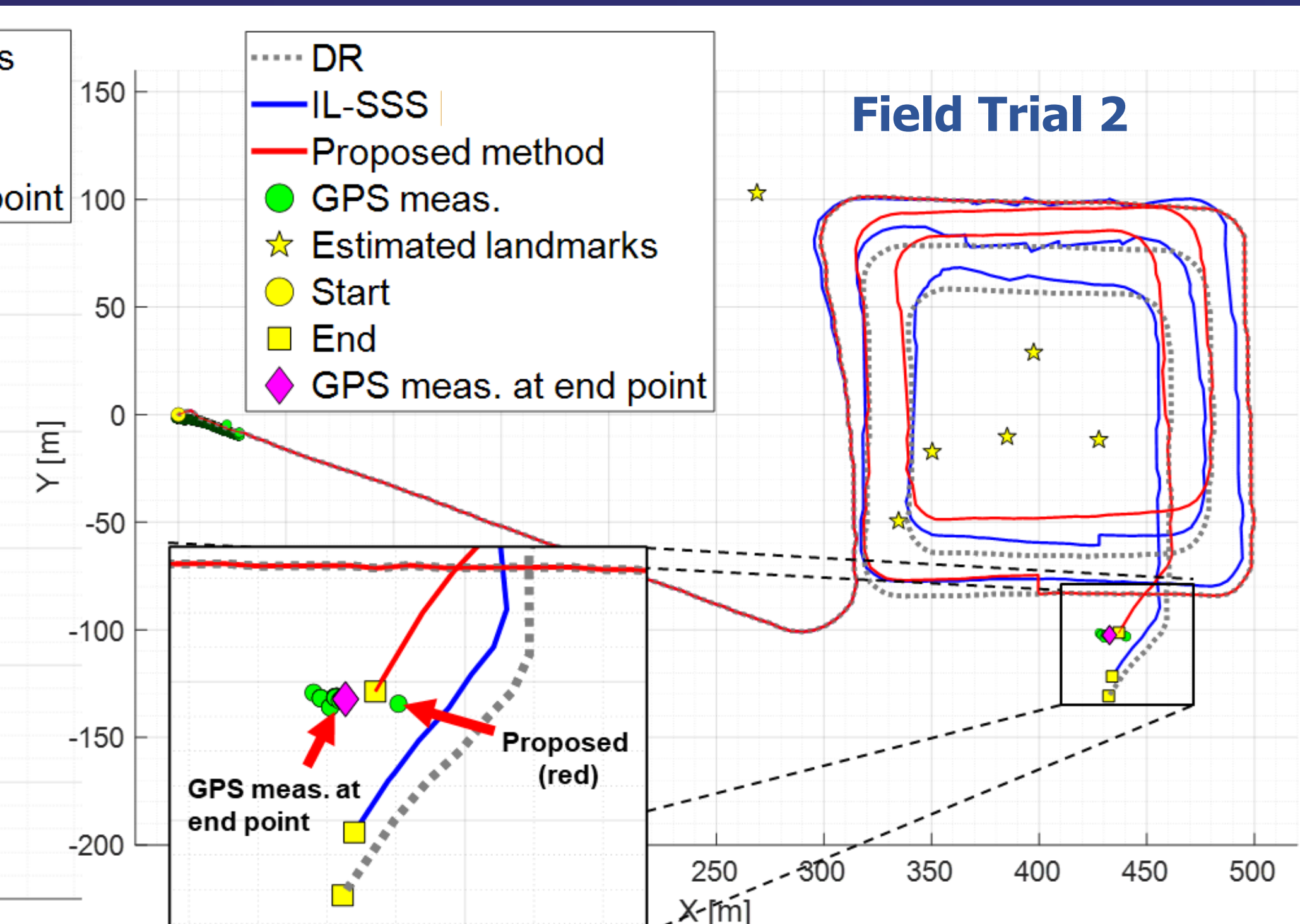
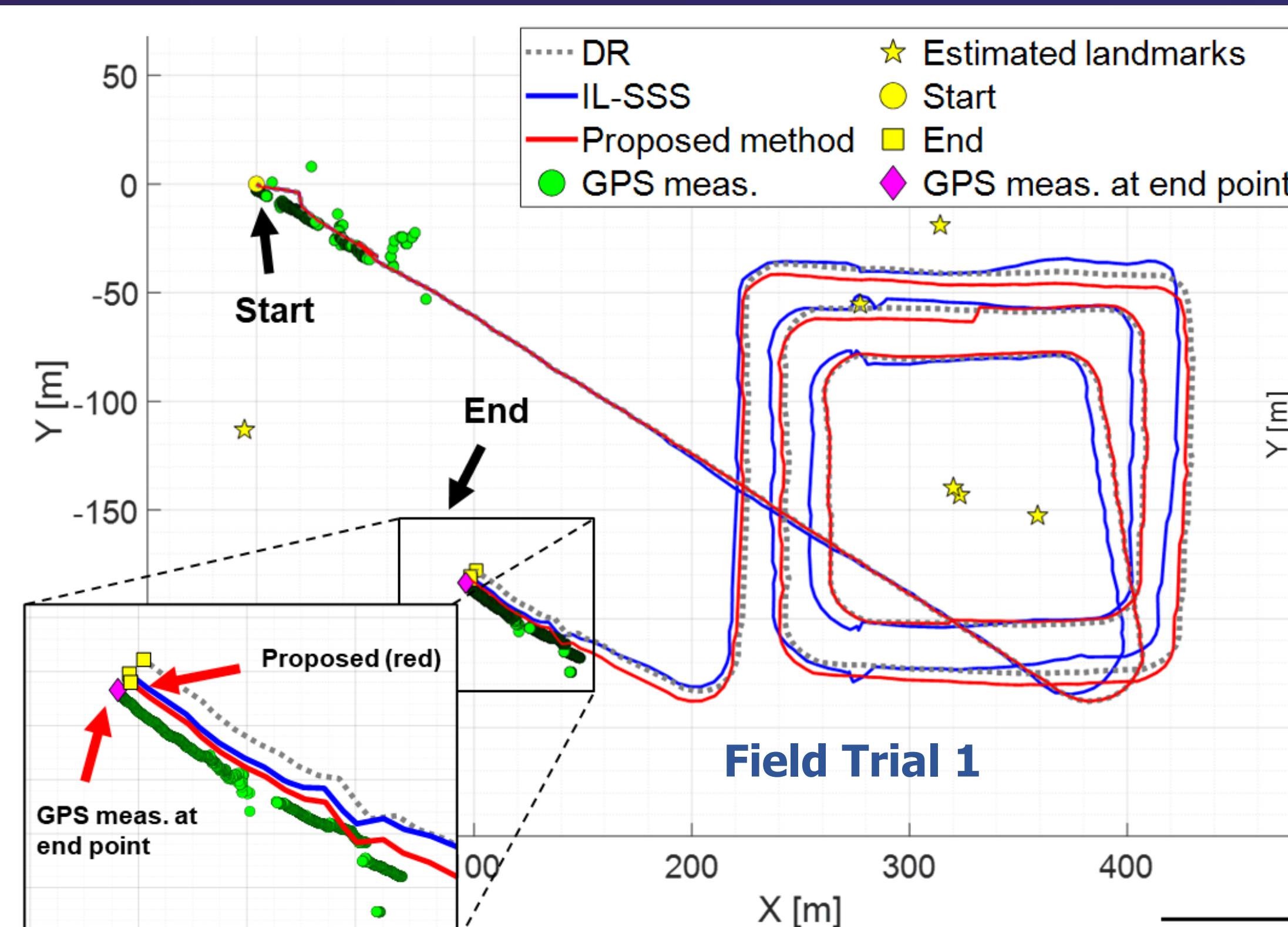
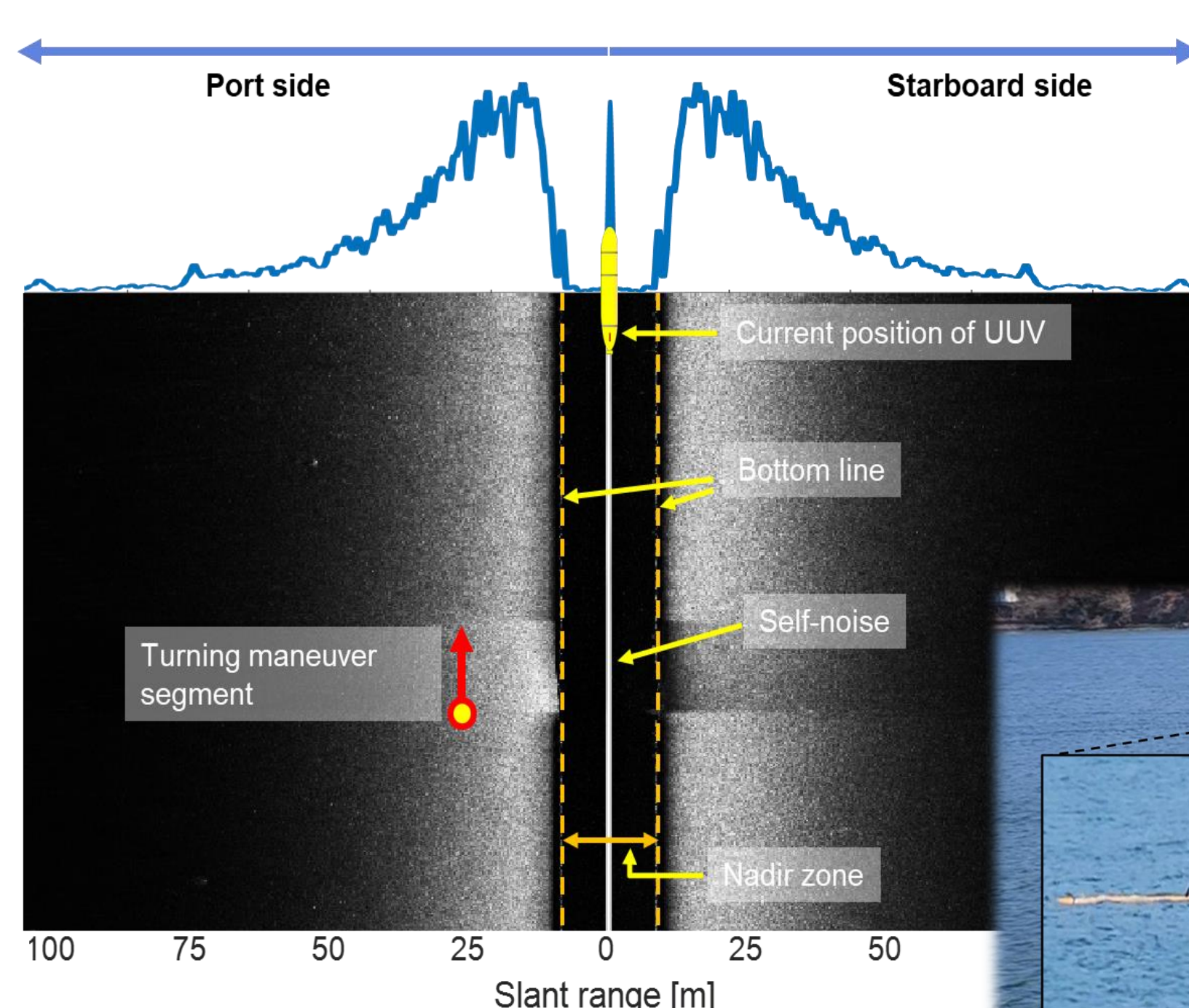
$$\epsilon(r) = \epsilon_t + w_t \frac{r_{\max} - r}{r_{\max}}$$

Weight Slant range
Residual thres. (fixed in original RANSAC)

Field Experiments in Real-Sea Environments

Experimental setup & Results

- IMU, DVL, SSS (455 kHz, 100 m swath per side)
- GPS (Reference available only at surfacing)
- Feature-poor seabed
- Homogeneous acoustic appearance
- Low-contrast intensity patterns



Baselines compared:

- DR based on DVL and IMU
- Image-level SSS SLAM (IL-SSS) (by Zhang & Folkesson, 2024)

Method	Field Trial 1 (L=2,243 m)		Field Trial 2 (L=2,012 m)	
	FPE [m]	FPE/L [%]	FPE [m]	FPE/L [%]
DR	7.39	0.33	28.36	1.41
IL-SSS	3.66	0.16	19.31	0.96
Proposed	2.75	0.12	4.47	0.22