RiwiSAR-SWH: A data-driven method for estimating significant wave height using Sentinel-3 SAR altimetry

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Significant Wave Height (SWH)

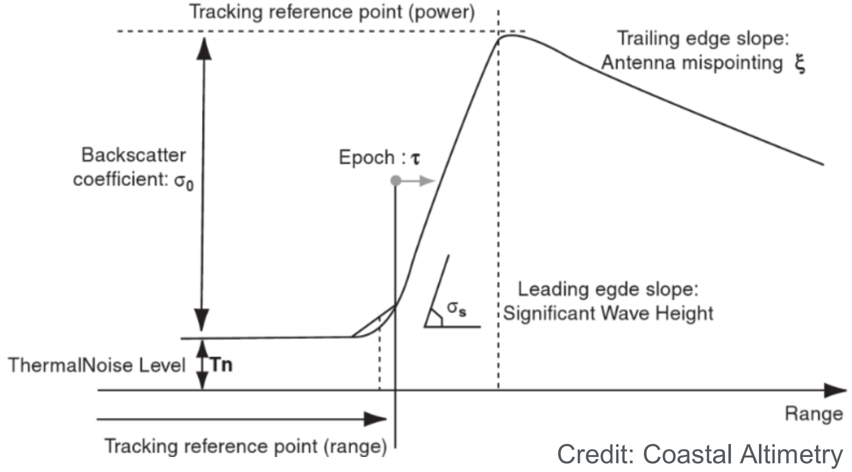
- **Definition:**
  - The mean of the highest third of the waves
  - Four times the standard deviation of the surface elevation

- **Importance：**
  - Monitoring water surfaces
  - Weather/hazard forecasting

- **Challenges:**
  - Lack of in-situ measurement
  - Inland waveforms and the final kilometers to coastlines are difficult for satellite altimetry

Estimation of SWH

- **Conventional Satellite Altimetry:**
  - Brown model[1]
  - $\text{SWH} = 2 \cdot c \cdot \sigma_s = 2 \cdot c \cdot \sqrt{\sigma_c^2 - \sigma_p^2}$
  - Many well-known empirical retrackers



Credit: Coastal Altimetry [2]

- **Synthetic-Aperture Radar (SAR) measurements:**
  - Improve along-track resolution from 1.6 km into 300 m
  - Closed-form expression[3] is complex
  - No well-known empirical retracker

$$P_{k,\ell} = K B_{k,\ell} \sqrt{g_l} \Big[(1 + T_{k,\ell} k_{\text{off}}) f_0(g_\ell \kappa) + T_{k,\ell} g_l \sigma_s^2 f_1(g_\ell \kappa) + \lambda_s \frac{g_l^3 \sigma_s^3}{6} \left(3 f_1(g_\ell \kappa) + f_3(g_\ell \kappa)\right) \Big] \quad (36)$$

with

$$K = \frac{\lambda_0^2 N_b^2 L_x L_y}{4\pi h^4} \sqrt{2\pi} A_g^2 \sigma_g^2, \qquad \sigma_s = \frac{\sigma_z}{L_z} \quad (37)$$

$$k_{\text{off}} = \frac{\langle z \rangle - z_{\text{EM}}}{L_z} \qquad \kappa = k + k_{\text{off}} \quad (38)$$

$$g_\ell = \left[\sigma_g^2 + \left(2\sigma_g \ell L_x^2 / L_y^2\right)^2 + \sigma_s^2 \right]^{-1/2} \quad (39)$$

$$f_n(\xi) = \int_0^\infty dv (v^2 - \xi)^n e^{-(v^2 - \xi)^2/2}. \quad (40)$$

[1] Brown, G. (1977). The average impulse response of a rough surface and its applications. IEEE Transactions on Antennas and Propagation, 25 , 67-74.
[2] Vignudelli, Stefano, et al., eds. Coastal altimetry. Springer Science & Business Media, 2011.
[3] Ray, Chris, et al. "SAR altimeter backscattered waveform model." IEEE Transactions on Geoscience and Remote Sensing 53.2 (2014): 911-919.

Is it possible to estimate SWH using simple features of SAR waveforms?

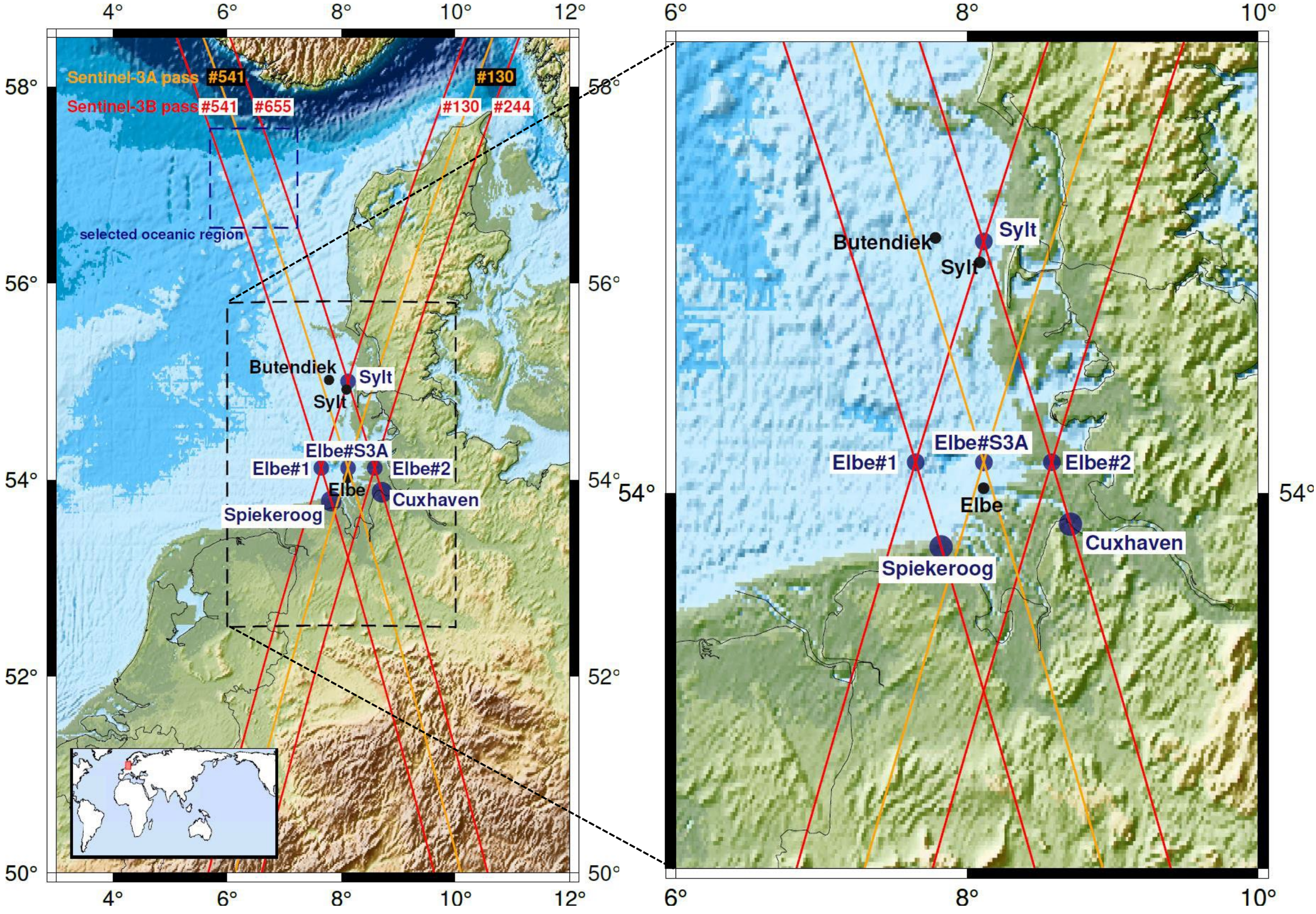
→ Data-driven

Case study

- **1 oceanic region:**
  - Standard waveform
  - SAMOSA+[1] has good performance
  - Derive the model

- **4 virtual stations nearshore**
  - Influence of waveform types
  - Validate against in-situ buoys

- **2 virtual stations on the coastlines**
  - Influence of waveform types
  - Influence of offshore distance
  - Validate against in-situ buoys



[2] Gou, J., & Tourian, M. J. (2022)

[1] Dinardo, S., Fenoglio-Marc, L., Buchhaupt, C., Becker, M., Scharroo, R., Joana Fernandes, M., & Benveniste, J. (2018). Coastal SAR and PLRM altimetry in German Bight and West Baltic Sea. Advances in Space Research, 62 , 1371-1404. The CryoSat Satellite Altimetry Mission: Eight Years of Scientic Exploitation.
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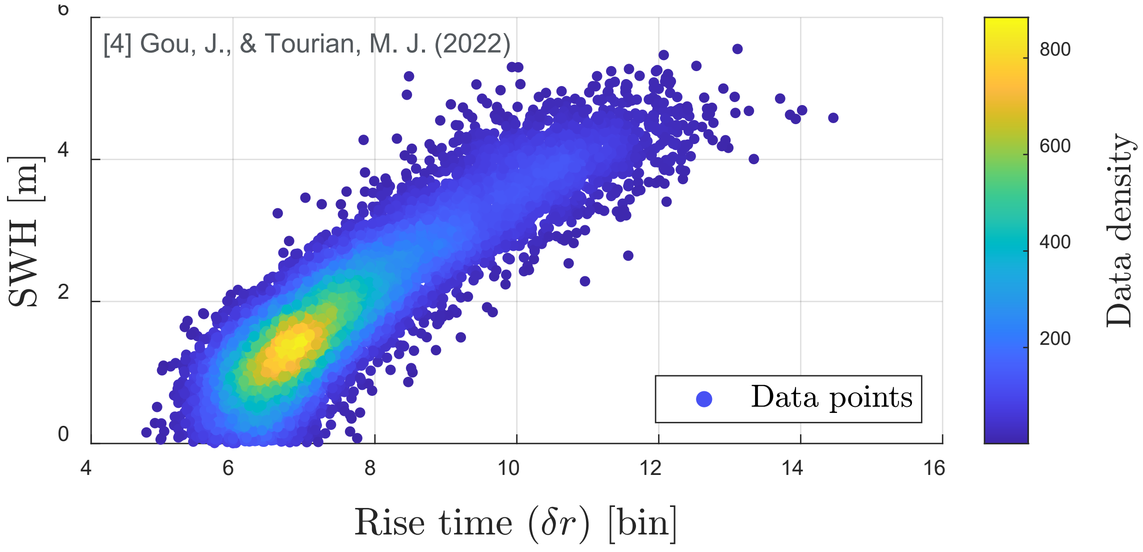
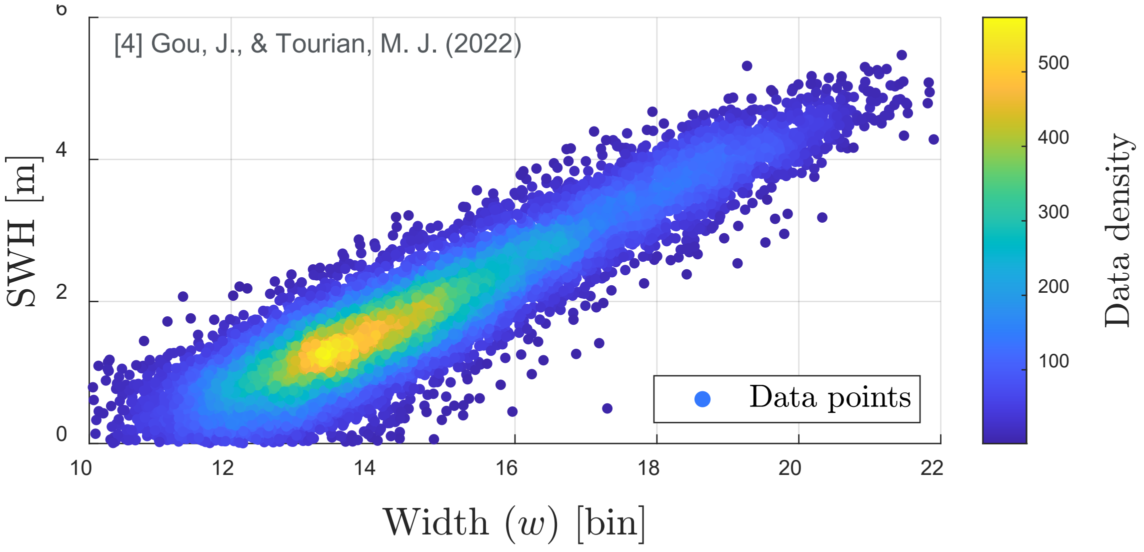
Idea: Data-driven

- **Extract two essential features based on the oceanic region:**
  - The **rise time ($\boldsymbol{\delta r}$)** based on the 4-β model: $y(t) = \beta_1' + \beta_2' P\left(\frac{t-\beta_3'}{\beta_4'}\right)$ (modified from the 5-β retracker[1,2])
  - The width ($\boldsymbol{w}$) from the OCOG[3] retracker
  - Opposite non-linear behaviors





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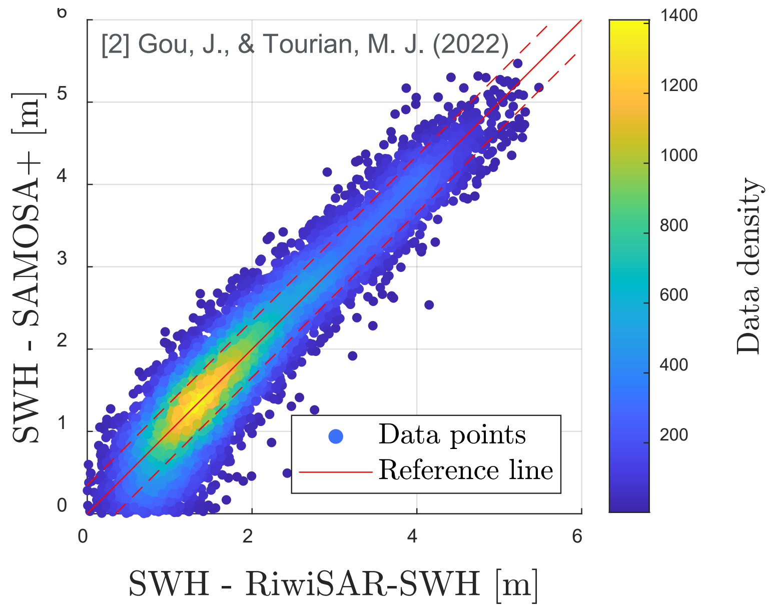
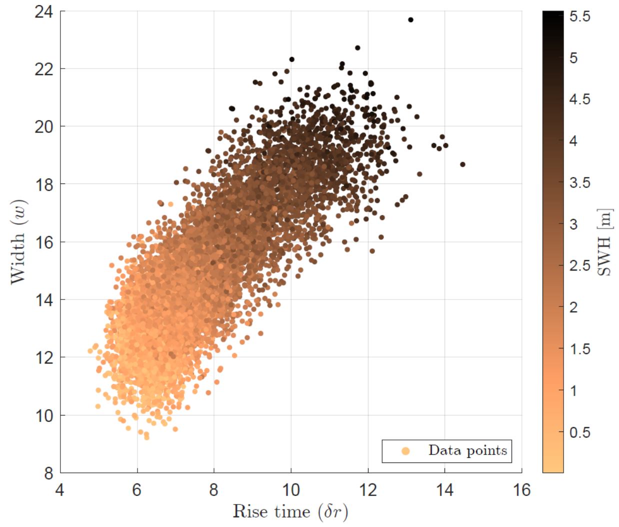
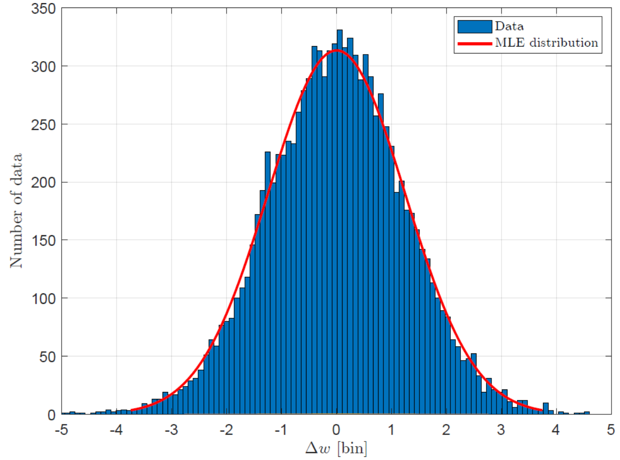
Idea: Data-driven

- SWH estimated by **SAMOSA+[1] as the reference**
- $SWH = 0.39 \cdot \delta r + 0.29 \cdot w - 0.47$
  → Rise time width model for SAR SWH (RiwiSAR-SWH)
- High similarity over the oceanic region:
  - Pearson correlation: 0.95
  - RMSE: 0.34 m
- In the coastal zones:
  - The trailing edge is contaminated
    → Width cannot be estimated correctly
  - However, δr is independent on the trailing edge
    → Estimate width from δr
    → $w = 1.24 \cdot \delta r + 5.26$







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Validation with the focus on the coastal zones

Validation – Evaluation metrics

- Interested in both **median performance** and **individual performance**

- Median performance:
  - $\mathrm{RMSE_m} = \sqrt{\frac{\sum_{n=1}^{N}\left(\mathrm{SWH}_{\mathrm{median},\,n} - \mathrm{SWH}_{\mathrm{buoy},\,n}\right)^2}{N}}$, where N is the number of observed days

- Individual performance:
  - $\mathrm{RMSE_i} = \sqrt{\frac{\sum_{n=1}^{N}\sum_{m=1}^{M_n}\left(\mathrm{SWH}_{\mathrm{m},n} - \mathrm{SWH}_{\mathrm{buoy},n}\right)^2}{\sum_{n=1}^{N} M_n}}$, where M_n is the number of total observations on the n^{th} day
  - Valid Ratio: $\mathrm{VR} = \frac{\mathrm{Num_{valid}}}{\mathrm{Num_{all}}}$

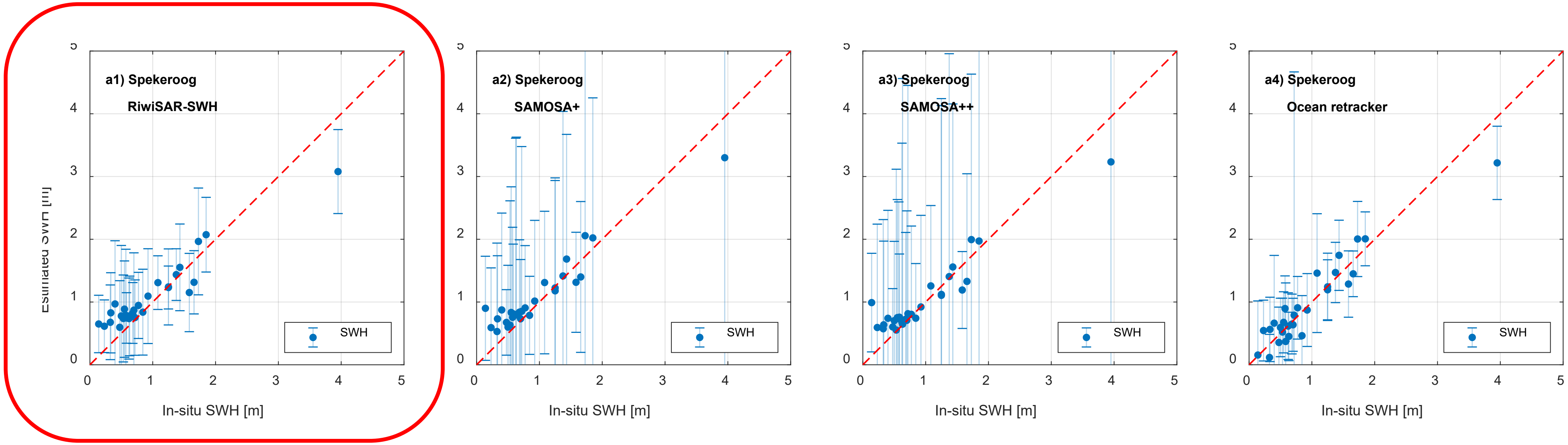
- Compared to SAMOSA+[1], SAMOSA++[2] and the ocean retracker[3]

[1] Dinardo, S., Fenoglio-Marc, L., Buchhaupt, C., Becker, M., Scharroo, R., Joana Fernandes, M., & Benveniste, J. (2018). Coastal SAR and PLRM altimetry in German Bight and West Baltic Sea. Advances in Space Research, 62 , 1371-1404. The CryoSat Satellite Altimetry Mission: Eight Years of Scientic Exploitation.
[2] Dinardo, S., Fenoglio-Marc, L., Becker, M., Scharroo, R., Fernandes, M. J., Staneva, J., Grayek, S., Benveniste, J., 2021. A RIP-based SAR retracker and its application in North East Atlantic with Sentinel-3. Adv. Space Res. 68, 892–929.
[3] ESA, 2021. SAMOSA Project: CCN Final Project Report V1.3. URL: http://www.satoc.eu/projects/samosa/index.html.

Validation – Spiekeroog

- **Relatively homogenous environment**
- Comparable median estimates
- Outperform other candidates by:
  - Individual measurements
  - Number of valid estimates

Method	$RMSE_m$ [m]	$RMSE_i$ [m]	Valid ratio
RiwiSAR-SWH	0.31	0.77	96%
SAMOSA+	0.28	1.92	85%
SAMOSA++	0.28	2.45	84%
Ocean	0.24	0.95	82%



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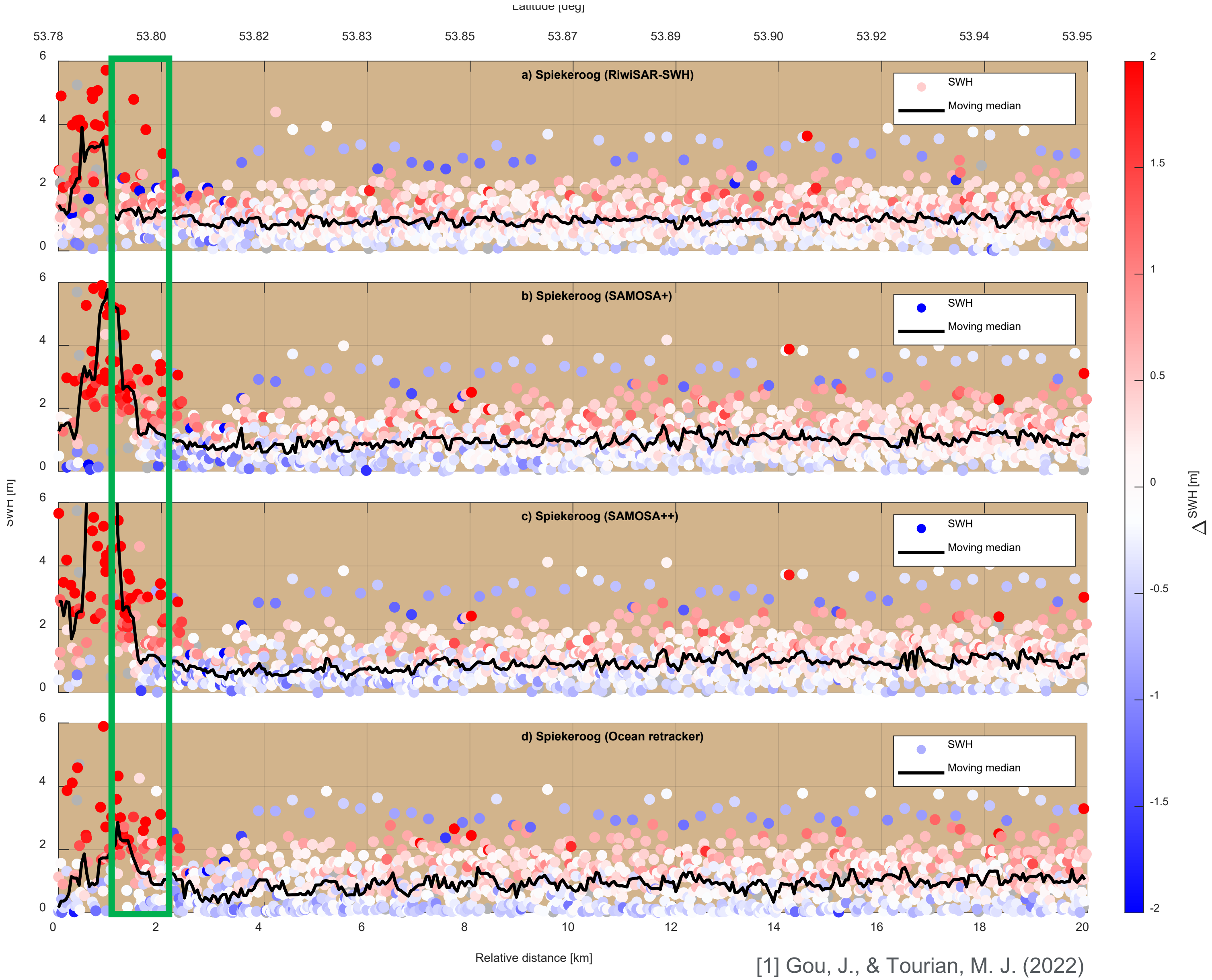
Validation – Spiekeroog

- Individual estimates w.r.t. distance
  - Black line: Moving median
  - $\Delta SWH = SWH_{estimation} - SWH_{buoy}$
- Better performance close to the coastlines:
  - RiwiSAR-SWH: ca. 1 km offshore
  - Others: More than 1.8 km
  - **40% improvements**



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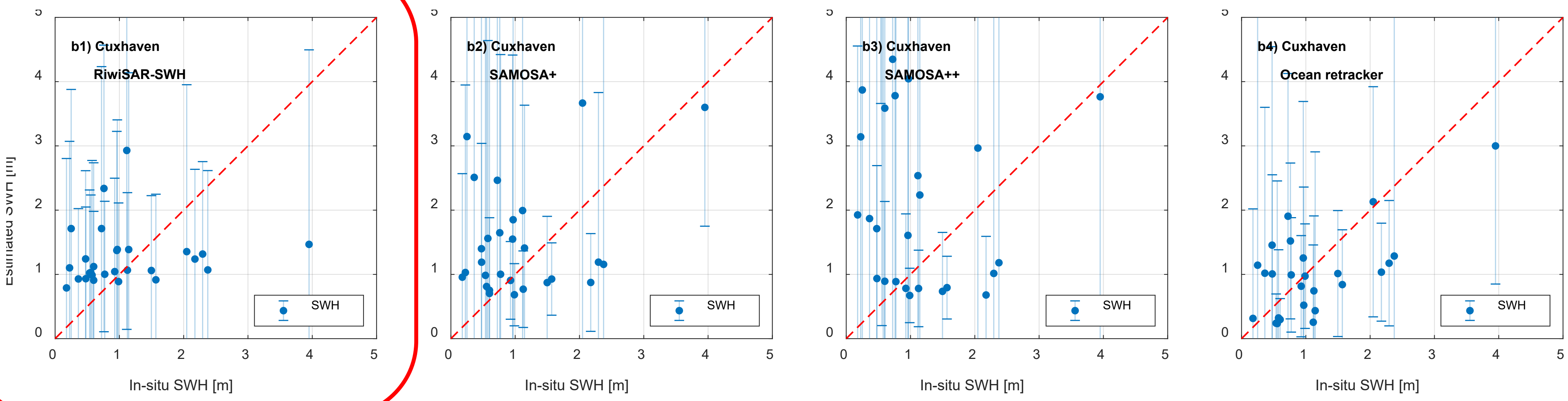
Validation – Cuxhaven

- **Extreme complicated environment**
- Acceptable median estimates
  - RMSE_m under 1m
  - Outperforms SAMOSA+ and SAMOSA++
- Significantly better individual estimates
  - Both RMSE_i and VR

Method	RMSE_m [m]	RMSE_i [m]	Valid ratio
RiwiSAR-SWH	0.91	1.90	57%
SAMOSA+	1.05	4.69	51%
SAMOSA++	2.70	5.98	53%
Ocean	0.68	2.26	51%



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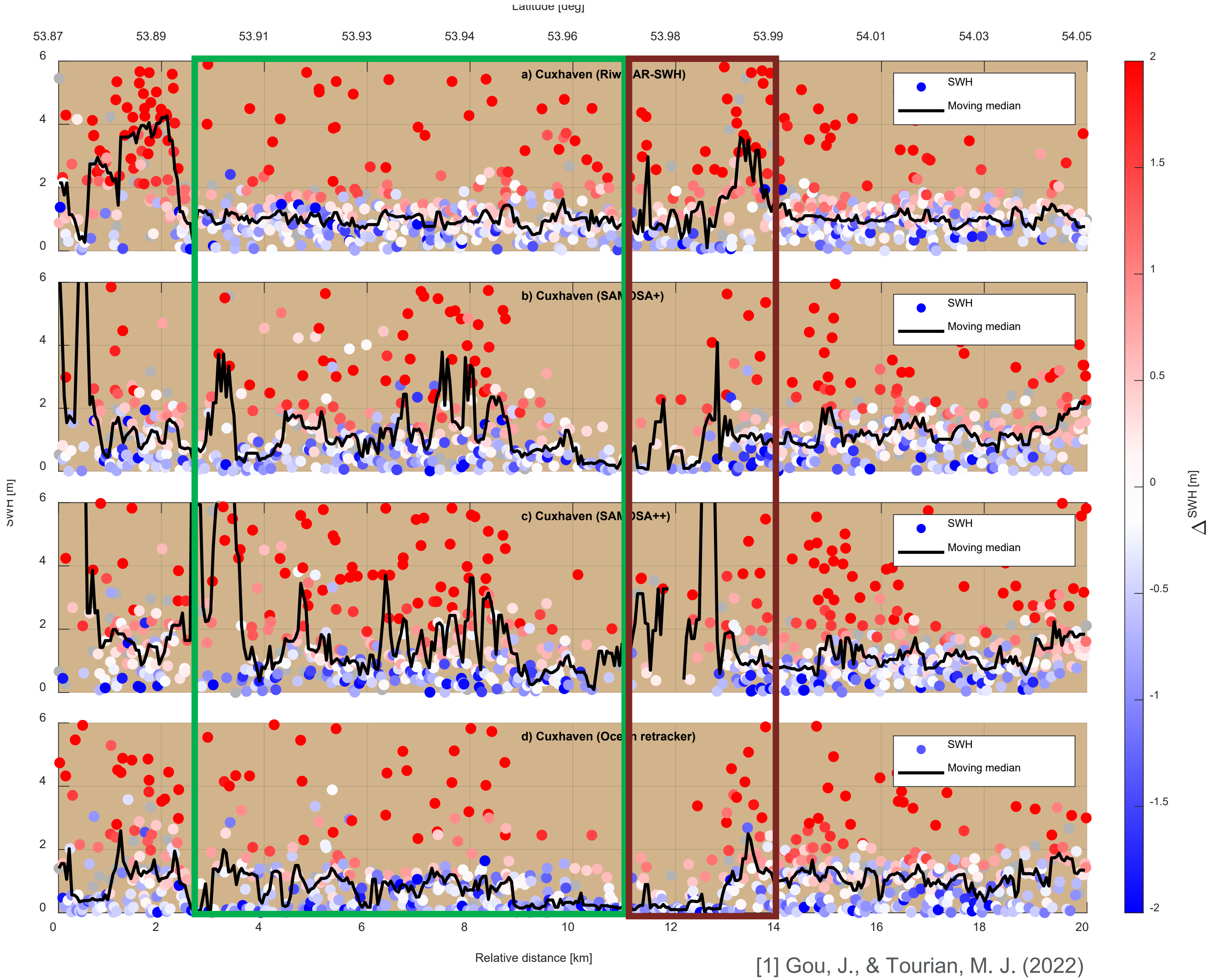
Validation – Cuxhaven

- Individual estimates w.r.t. distance
  - Black line: Moving median
  - $\Delta SWH = SWH_{estimation} - SWH_{buoy}$
- Better performance close to the coastlines:
  - RiwiSAR-SWH: ca. 1.1 km offshore
  - Others: Failed
- 11 km to 14 km: A big island
  - RiwiSAR-SWH can provide reliable estimates right after the island



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Conclusion

Conclusion

- Data-driven model: RiwiSAR-SWH
  - Provide reliable SWH estimates **without** considering the **complicated physical model**

- Better performance in the **coastal zones**
  - Better RMSE_i (asses both precision and accuracy)
  - Robust against **non-standard** waveforms
  - Provide reliable SWH estimates starting from around **1 km offshore** → more than 40% improvements

- Applicable for globally for all types of SAR waveforms
  - With necessary readjustments of the model
  - Potential application for inland altimetry

Conclusion

- For more information, please check our publication on *Advances in Space research*: https://doi.org/10.1016/j.asr.2021.12.019

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Thanks for your attention!

Looking forward to further discussion

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