Coastal Case Study for Leveraging the Potential of Sentinel-6 MF FF-SAR Altimetry for Significant Wave Height

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Motivation

- The coastal zone with of less than 5 km from the coast is challenging for satellite altimetry due to strongly reflective targets

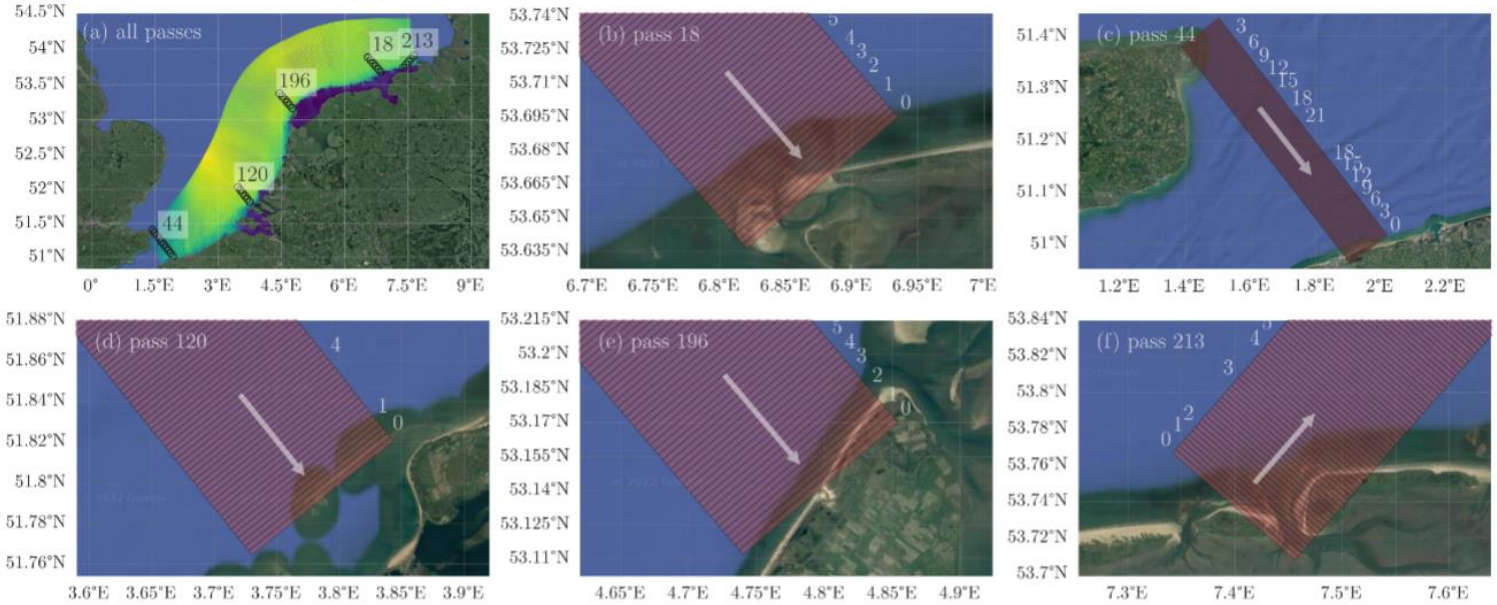
- FF-SAR altimetry provides a theoretical along-track resolution of up to ~0.5 m
- Sentinel-6 MF (S6-MF) has only minor grating lobes in its along-track point target response (PTR, as compared to S3/CS2)

„What do we gain from FF-SAR altimetry for S6-MF for SWH in the coastal zone?“

Data

S6-MF data

- Passes 44, 120, 196, 18, 213; cycles 5 to 42 (year 2021)
- nearest distance-to-coast of up to 31 km (coastline = first contact with land (Wadden islands, sand bank))
- baseline F06



High-resolution SWAN-Kuststrook wave model

Operational wave model from the Deltares RWsOS North Sea forecasting system

resolution (latitude/longitude): 50-1400 m / 35-2600 m

Methods: Altimetry Data Processing

Datasets

Name	L1b: proc. type	L1b: posting rate [Hz]	L2: retracker
FFSAR-60	FF-SAR	60	CORALv2
FFSAR-140	FF-SAR	140	CORALv2
UFSAR-20	UF-SAR	20	CORALv2
PDAP-HR	UF-SAR	20	SAMOSA-based

Processed starting from Level-1a

Baseline EUMETSAT L2

L1b processing (starting from Level-1a)

- FF-SAR processor from Kleinherenbrink et al. 2020 + extension to S6-MF
- Total illumination times: FF-SAR: 2.1 s, UF-SAR: 2.4 s
- UF-SAR: Generated using FF-SAR processor (coherent integration over burst repetition interval)

L2 processing

- coastal retracker CORALv2 (Schlembach at al. 2022)
- α_p-LUT for UF-SAR from baseline F06, FF-SAR: from ESA S6 L2 GPP project (zero-Doppler fit, T=2.1 s)

- Reduction of FFSAR-140 and FFSAR-60 estimates by linear averaging → 20-Hz estimates
- Outlier removal with (scaled MAD) median filter (Alvera-Azcárate et al. 2012)

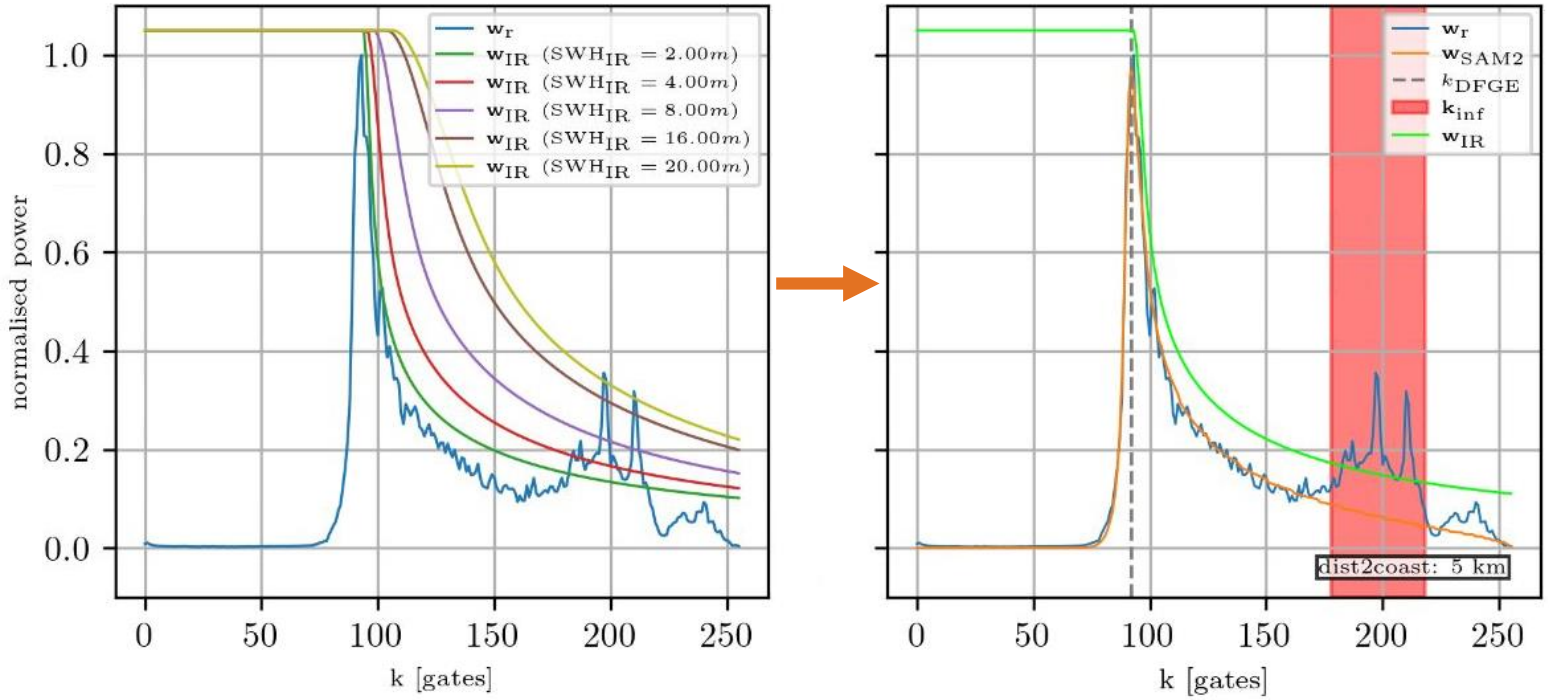
Methods: CORALv2 Coastal Retracker

Schlembach F., Passaro M., Dettmering D., Bidlot J., Seitz F.: **Interference-sensitive coastal SAR altimetry retracking strategy for measuring significant wave height**. Remote Sensing of Environment, 274, 112968, 10.1016/j.rse.2022.112968, 2022

Adaptive Interference Masking (AIM)

→ senses and masks interference within the trailing edge

Generation of a single-look SAMOSA model $\mathbf{w}_{\mathrm{SAM2}}$ to produce the interference reference waveform $\mathbf{w}_{\mathrm{IR}}(\mathrm{SWH}_{\mathrm{IR}})$



detected interference gates

$$\mathbf{k}_{\mathrm{inf}} = \mathrm{True}(\mathbf{w}_{\mathrm{r}} > \mathbf{w}_{\mathrm{IR}})$$

→ AIM detects interference gates and excludes them from fitting procedure → **quality** of SWH estimate is improved.

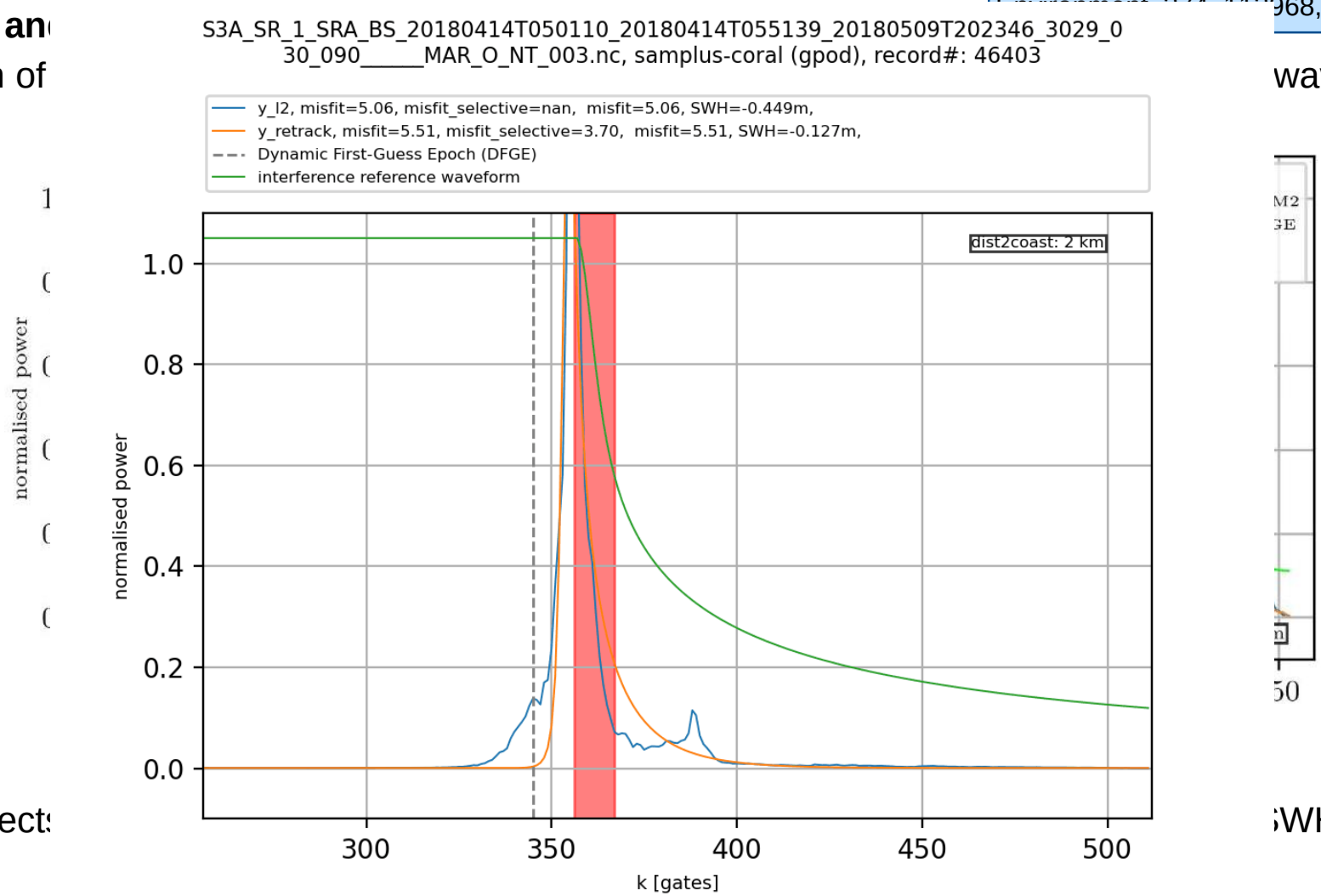
Methods: CORALv2 Coastal Retracker

Schlembach F., Passaro M., Dettmering D., Bidlot J., Seitz F.: **Interference-sensitive coastal SAR altimetry retracking strategy for measuring significant wave height**. Remote Sensing of Environment, 274, 112968, 10.1016/j.rse.2022.112968, 2022

Adaptive Interference Masking (AIM)

→ **senses an**

Generation of



waveform $\mathbf{w}_{\mathrm{IR}}(\mathrm{SWH}_{\mathrm{IR}})$

detected interference gates

$$\mathbf{k}_{\mathrm{inf}} = \mathrm{True}(\mathbf{w}_{\mathrm{r}} > \mathbf{w}_{\mathrm{IR}})$$

→ AIM detects

SWH estimate is improved.

Methods

Evaluation

Comparison with the SWAN-Kuststrook wave model

- Pearson correlation coefficient
- median offset
- percentage of cycles with high correlation (PCHC) of >= 0.8 : ratio between # of highly correlated cycles and # of all cycles

Quantity and Precision

- Number of valid records → quality flag
- L2 noise → absolute deviation from consecutive records

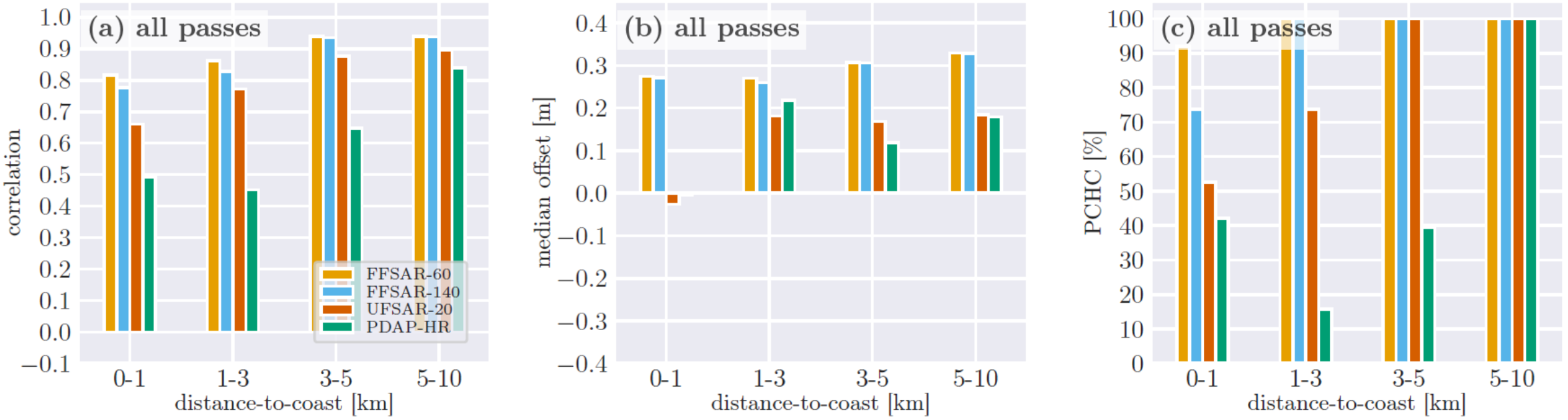
Coastal SWH variation

between coastal estimates between 1-3 km and 5-7 km off the coast and the offshore SWH values

$$\Delta_{\text{2-30/6-30}} = (1 - \frac{\text{median}(\text{SWH}_{\text{1-3/5-7}})}{\text{median}(\text{SWH}_{\text{29-31}})}) \cdot 100$$

Results: Comparison with SWAN-Kuststrook Wave Model

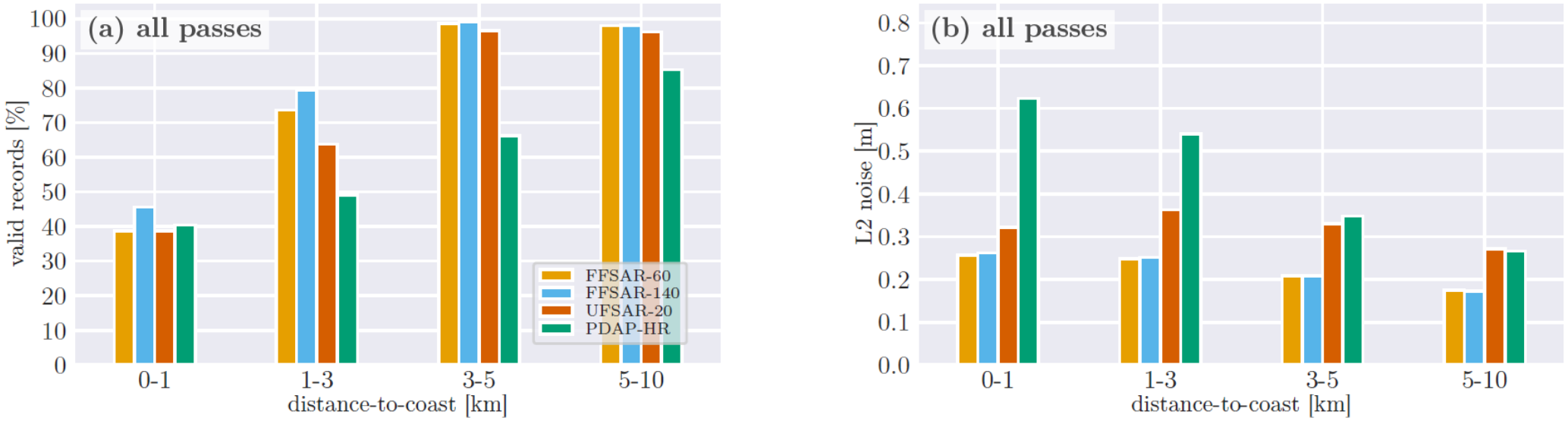
Statistical Analysis: correlation, median offset, PCHC



→ high correlations up to 1-3 km band in all passes with 100% of PCHC

Results: Comparison with SWAN-Kuststrook Wave Model

Number of valid records (quantity) and L2 noise (precision)

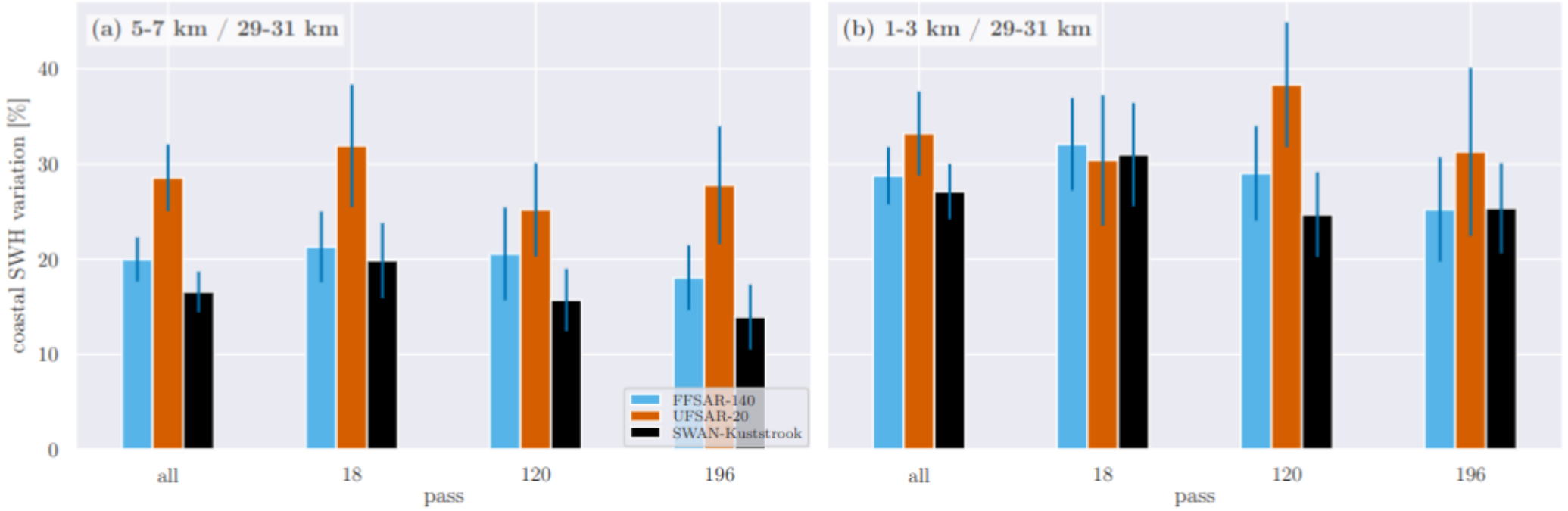


→ high number of valid records of >70% up to 1 km from the coast

→ lower L2 noise for FFSAR-140 vs UFSAR-20 in the 1-3 km band: 25 cm vs 36 cm (>30%)

Results: Coastal SWH Variation

- global mean attenuation of SWH towards the coastline from **>3 km** from offshore at 30 km amounts to 22%, with strong regional variations (Passaro et al. 2021)



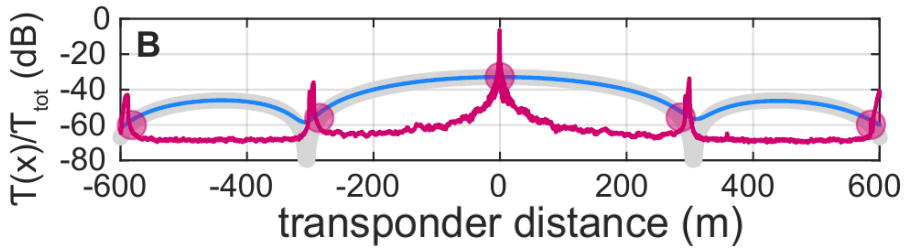
→ coastal SWH variations of up to 1 km from the coast

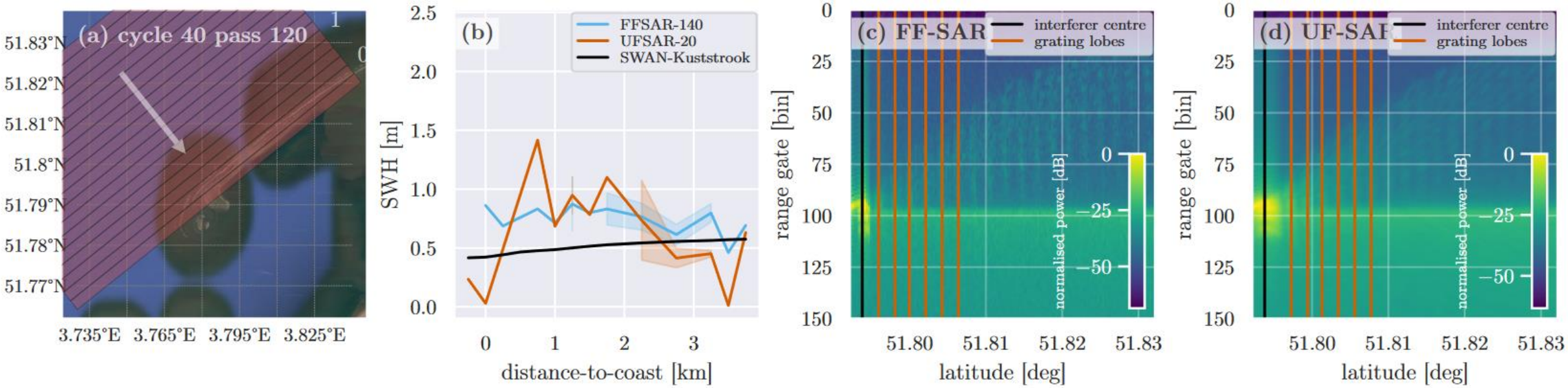
Results: Increase in SWH

In some cases, the SWH increases in the last 1-2 km
due to strongly reflective targets in the along-track direction

Here, pass 120 with the strongly reflective sandbank (300 m in width)

Along-track PTR (Ehlers et al. 2022):





→ the grating lobes at multiples of ~300 m from the along-track PTR can be recognised

Conclusion

- Robust HR SWH estimates of up to 1 km from the coast: FF-SAR + S6-MF + CORALv2 coastal retracker + Outlier rejection
- **FF-SAR outperforms UF-SAR** in terms of correlation, PCHC, quantity and precision
- The coastal SWH variations can estimated more accurately for up to 1 km off the coast with **FF-SAR**

- To be submitted soon

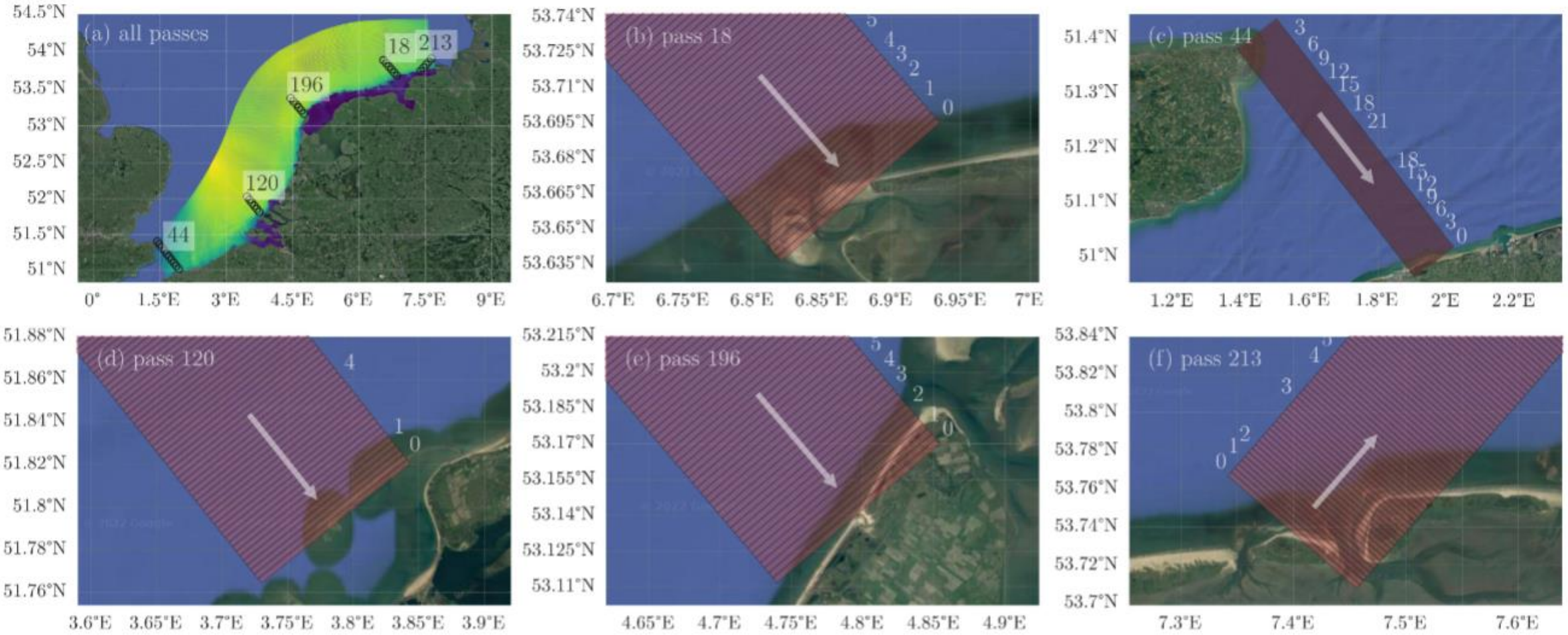
Schlembach, Florian, Frithjof Ehlers, Marcel Kleinherenbrink, Passaro Marcello, Dettmering Denise, Seitz Florian, und Slobbe Cornelis. **„Coastal Case Study for Exploiting Sentinel-6 MF Fully-Focused SAR Altimetry for Significant Wave Height“** *in prep.*

References

- Egido, Alejandro, Salvatore Dinardo, and Christopher Ray. 2020. ‘The Case for Increasing the Posting Rate in Delay/Doppler Altimeters’. *Advances in Space Research*, March. https://doi.org/10.1016/j.asr.2020.03.014.
- Ehlers, Frithjof, Florian Schlembach, Marcel Kleinherenbrink, and Cornelis Slobbe. 2022. ‘Validity Assessment of SAMOSA Retracking for Fully-Focused SAR Altimeter Waveforms, in Review’. *Advances in Space Research*.
- Passaro, Marcello, Mark A. Hemer, Graham D. Quartly, Christian Schwatke, Denise Dettmering, and Florian Seitz. 2021. ‘Global Coastal Attenuation of Wind-Waves Observed with Radar Altimetry’. *Nature Communications* 12 (1): 3812. https://doi.org/10.1038/s41467-021-23982-4.
- Schlembach, Florian, Marcello Passaro, Denise Dettmering, Jean Bidlot, and Florian Seitz. 2022. ‘Interference-Sensitive Coastal SAR Altimetry Retracking Strategy for Measuring Significant Wave Height’. *Remote Sensing of Environment* 274: 112968. https://doi.org/10.1016/j.rse.2022.112968.

Spare Slides

Data


(a) all passes
18
213
196
120
44
(b) pass 18
(c) pass 44
(d) pass 120
(e) pass 196
(f) pass 213

Data

High-resolution SWAN-Kuststrook wave model

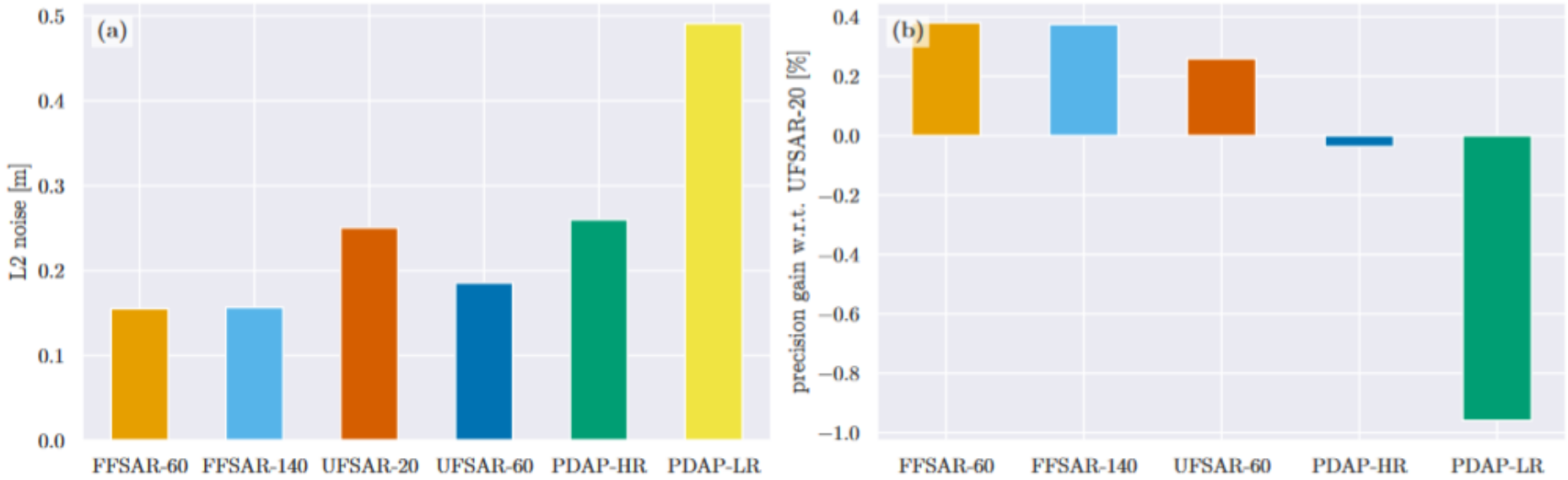
- Operational wave model from the Deltares RWsOS North Sea forecasting system
- Model domain: Dutch Coast and parts of the German Coast of the North Sea
- SWAN offshore wave boundary conditions from ECMWF-WAM
- Water level/current fields from WAQUA-ZUNO
- Wind fields from HIRLAM
- Bathymetry data from a combination of EMODnet (deeper parts) and Baseline (near the coast)
- resolution (latitude/longitude): 50-1400 m / 35-2600 m

Data: Increasing the posting rates for UF-SAR-processed altimetry data

Egido et al. 2020 have suggested UF-SAR waveforms with >20-Hz (40 or 80-Hz):

- Process UF-SAR waveforms at posting rates of >20-Hz, e.g. 60-Hz
- E.g. retrack the 60-Hz waveforms individually
- Average the 60-Hz estimates and form 20-Hz rates

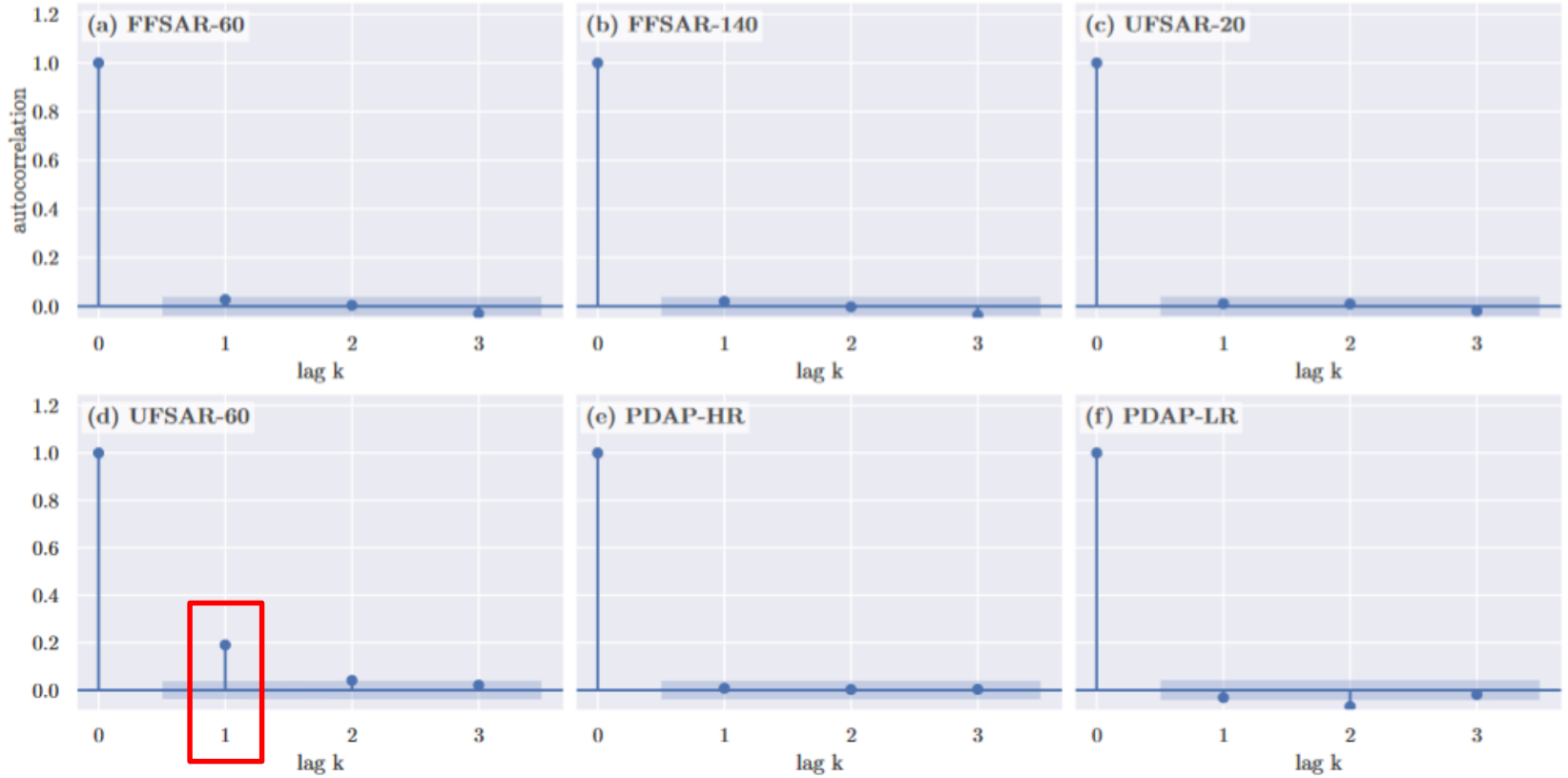
→ a gain in precision of the L2 estimates could be observed of ~25% for UFSAR-60 vs. UFSAR-20:



BUT…

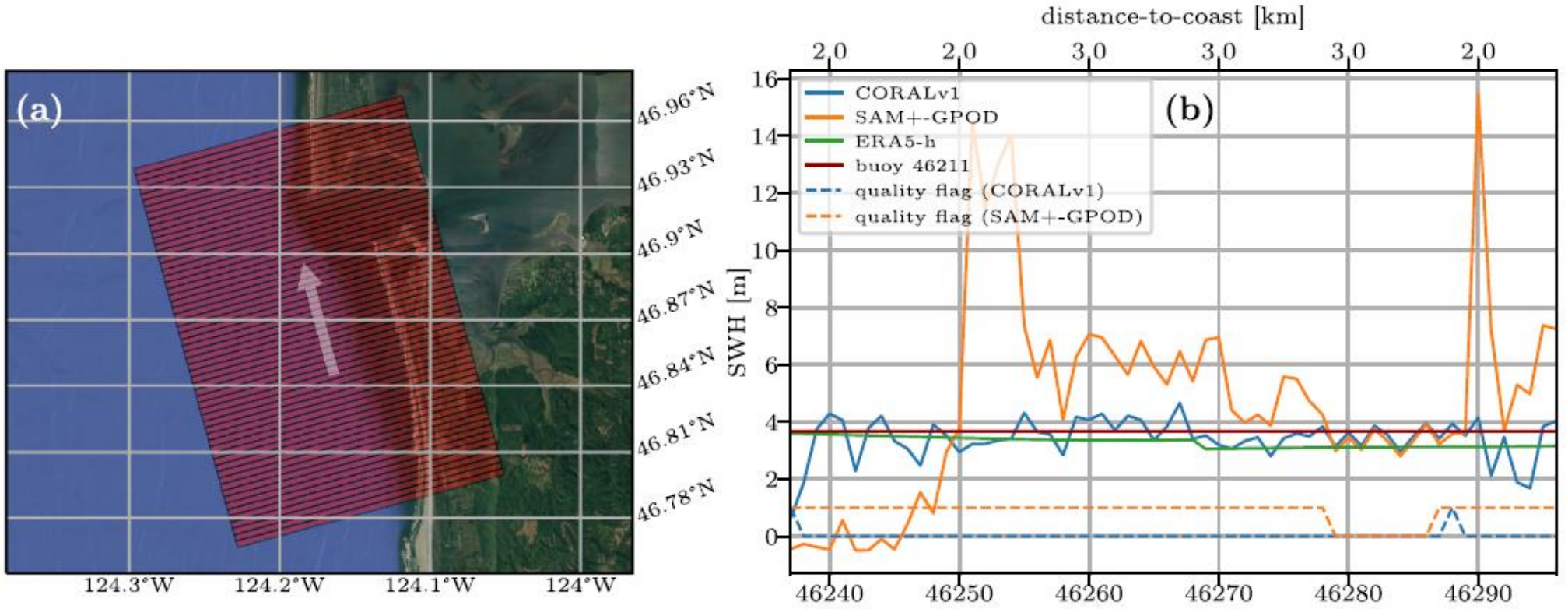
Data: Increasing the posting rates for UF-SAR-processed altimetry data

…a correlation between the averaged 20-Hz L2 estimates is introduced:
autocorrelation of detrended SWH open ocean segments (that show an expected variability)



CORALv2 Coastal Retracker

Retracking waveforms with strong coastal interference by CORALv2 in comparison with SAMOSA+



→ **quantity** of the SWH estimates is increased significantly

CORALv2: AIM (cont‘d)

CORALv2 improves the quality flag by using the **selective misfit**
→ excluding of interference gates $\mathbf{k}_{\mathrm{inf}}$ from the misfit calculation

$$\mathrm{misfit}_{\mathrm{selective}} = 100 * \sqrt{\frac{1}{N}\sum_{i}^{N}(w_{r,i} - w_{\mathrm{SAM2},i})^2}$$

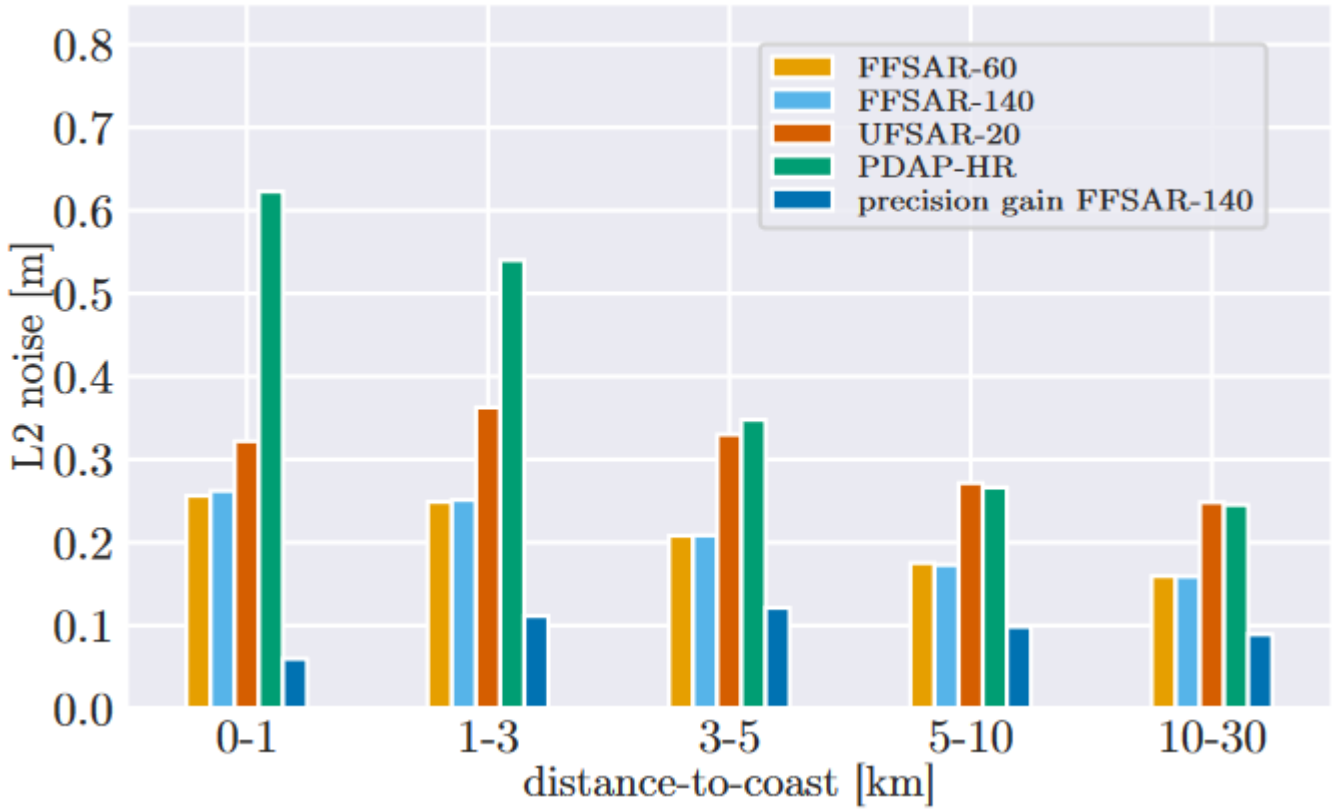
$$i \notin \mathbf{k}_{\mathrm{inf}} = \mathrm{True}(\mathbf{w}_{\mathrm{r}} > \mathbf{w}_{\mathrm{IR}})$$

$$q_{\mathrm{CORALv1}} = \mathrm{misfit}_{\mathrm{selective}} > 4$$

→ AIM better determines the goodness of the fit and recovers strongly interfered waveforms → **quantity** of records ↗

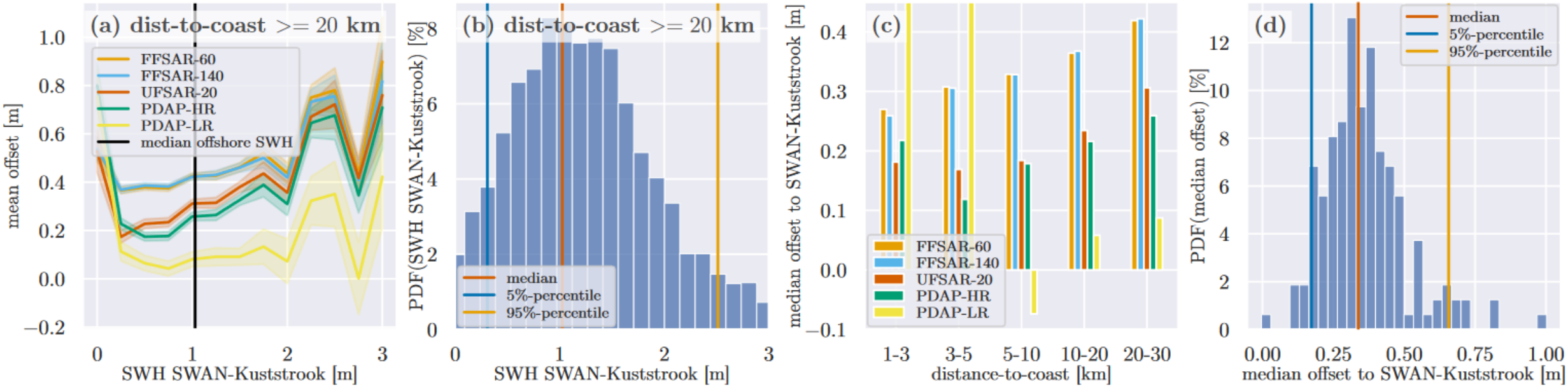
Results: L2 noise

From offshore towards the coast



Results: Comparison with SWAN-Kuststrook wave model

Statistical Analysis: offset analysis

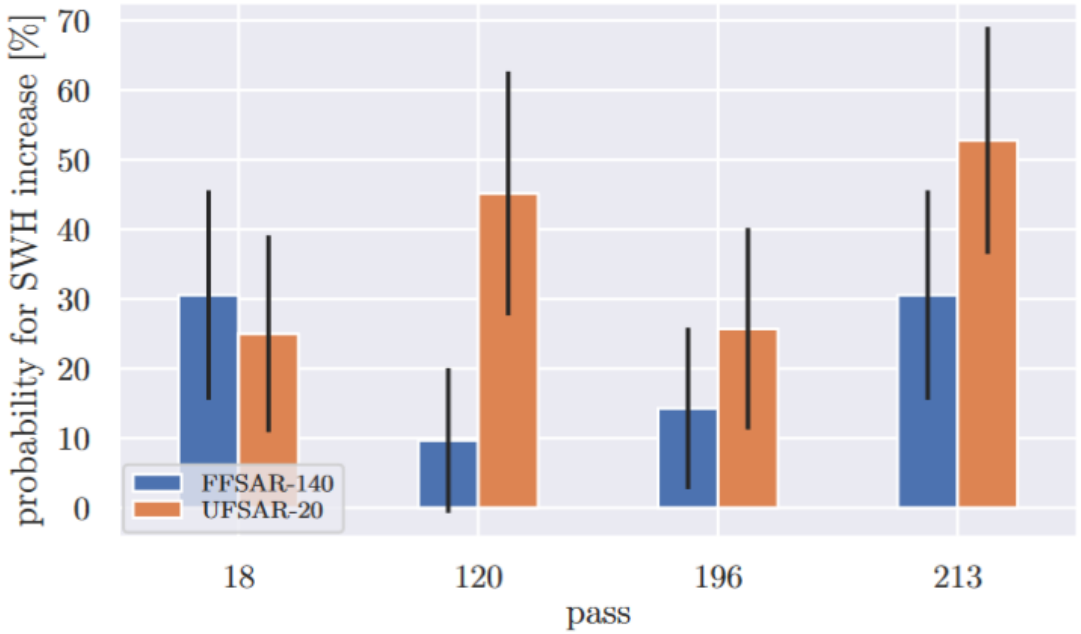


Results: Increase in SWH

In some cases, the SWH increases in the last 1-2 km
Probability of occurence of an increase in SWH
determined based on this (empirical) criterion (per overpass)

$$\max(\mathrm{SWH}_{0\text{-}3}) > \max(\mathrm{SWH}_{3\text{-}5} + n_{\mathrm{L2}}))$$

n_L2: L2 noise with 0.2 m/0.3 m for FF-SAR/UF-SAR



Results: Coastal SWH Variation

Mean offset with respect to the SWAN-Kuststrook wave model