# Uncertainty assessment of SWOT's systematic errors calibration algorithm

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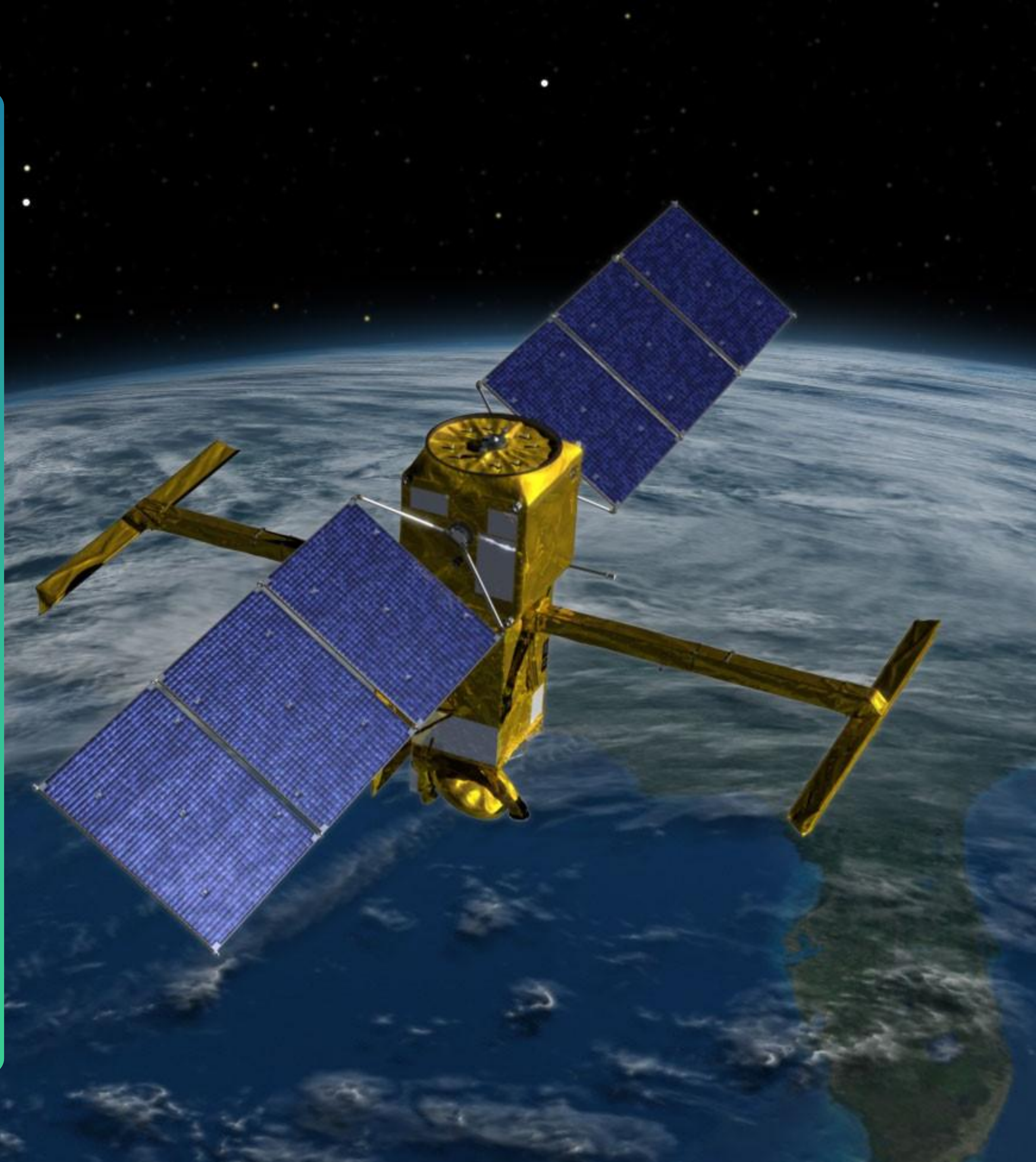
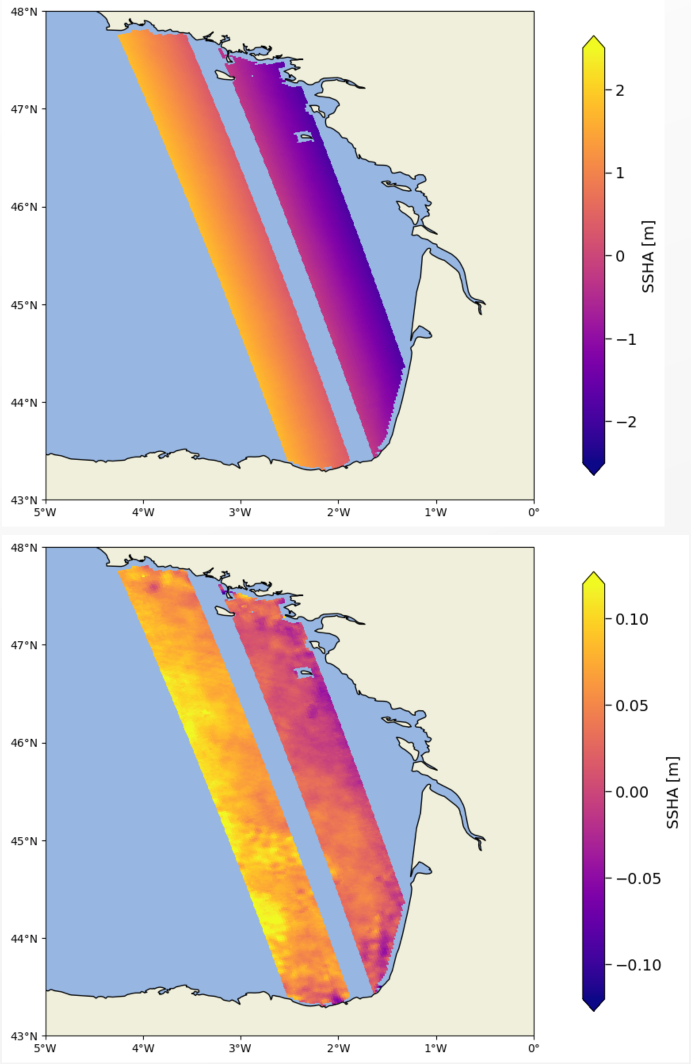


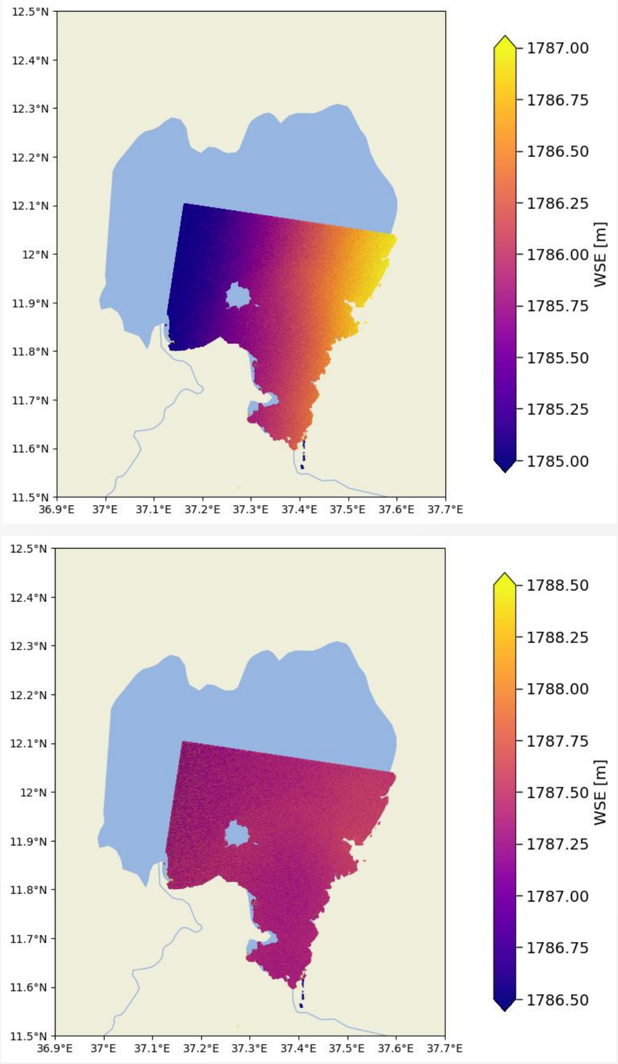
# Why is cross-calibration needed?

- **Without XCal:** signal of interest completely drowned by systematic errors
- Four main sources of error:
  - ⟶ Imperfect roll angle knowledge
  - ⟶ Interferometric phase error
  - ⟶ Baseline dilation
  - ⟶ Range timing bias
- **With XCal:** systematic errors corrected, finer topography appears
- Systematic errors typically exhibit wavelengths > 1000 km
  - ⟶ Can be filtered out on ocean
  - ⟶ XCal crucial for inland waters

Systematic error calibration over the Bay of Biscay




Systematic error calibration over Lake Tana (Ethiopia)



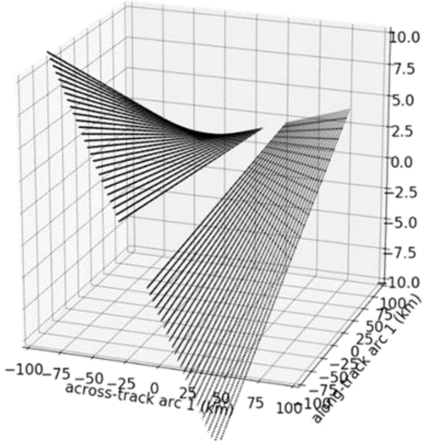

Adapted from Ubelmann *et al.*, 2024

# Cross-track error signatures

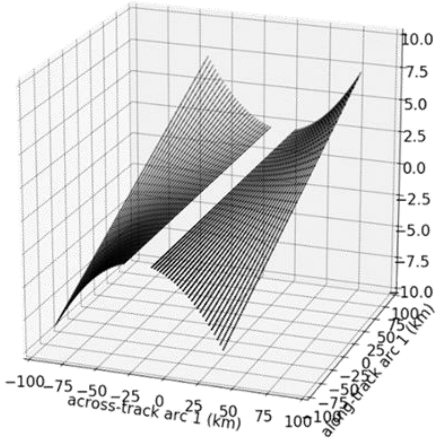
- Systematic errors exhibit distinct cross-track signatures
- **The linear cross-track term significantly outweighs the others**

- The L2 XCal algorithm estimates systematic errors using **only SWOT data** as input
  → Independent of other altimetry missions
  → Notably exploits SSH mismatches at **KaRIn-KaRIn crossovers over the ocean**

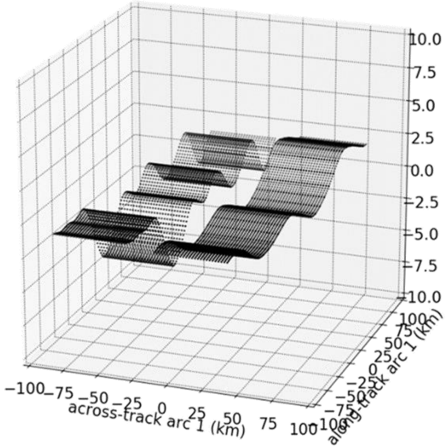
Roll & phase errors → **Linear cross-track topography**




Baseline dilation → **Quadratic cross-track topography**




Range timing bias → **Left-right offset**



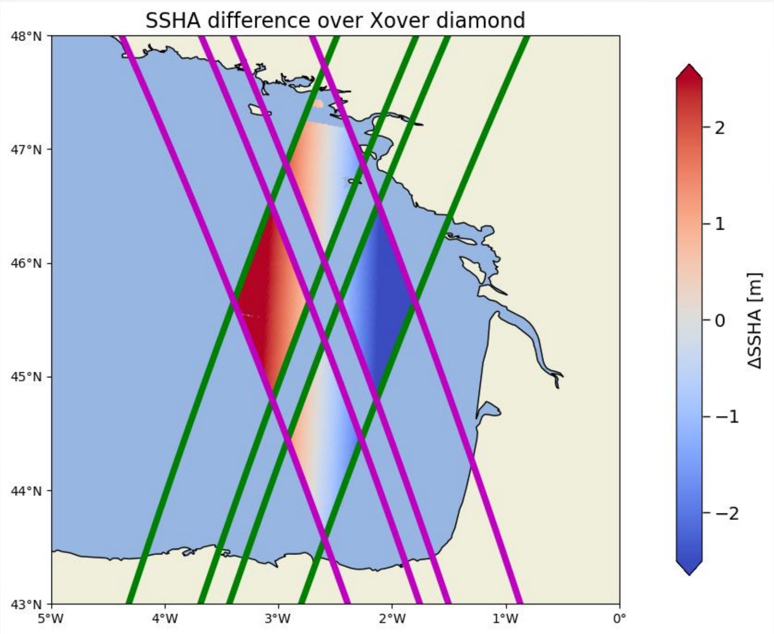

Dibarboure *et al.*, 2022

# How to compute the XCal height correction?

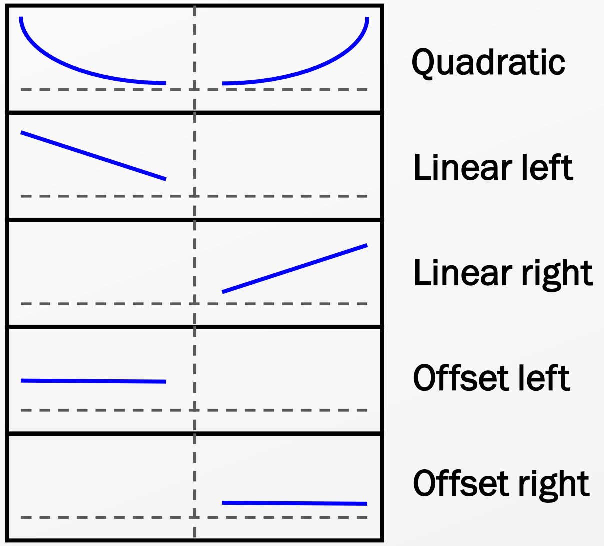
The L2 XCal algorithm operates in two main steps

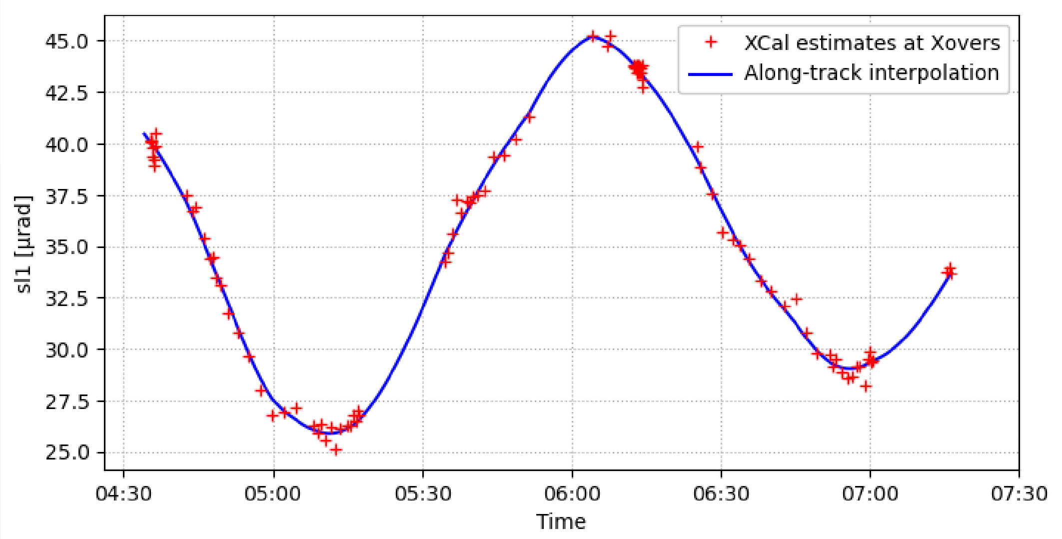
1) Parameter estimation from SSH difference at crossovers

2) Along-track interpolation to produce a continuous correction in time
   - ⟶ Harmonic fit at orbital frequency
   - ⟶ Gaussian filtering of residuals (for roll error only)




Estimated parameters for each pass



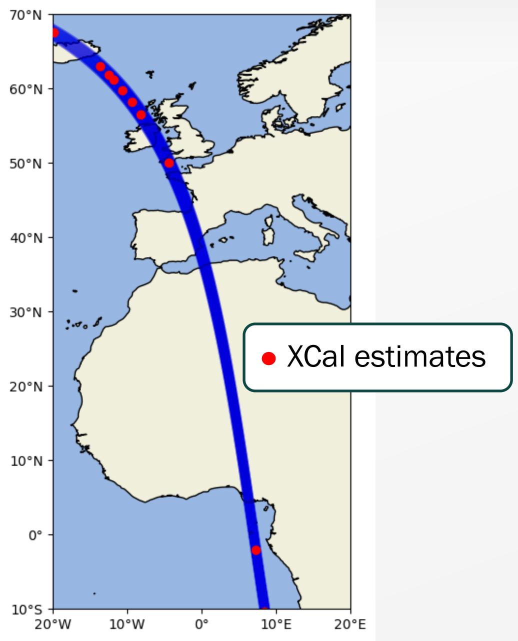
# Limitations for inland waters

- No Xovers available on land
  ⟶ Inland XCal height correction relies on distant oceanic estimates

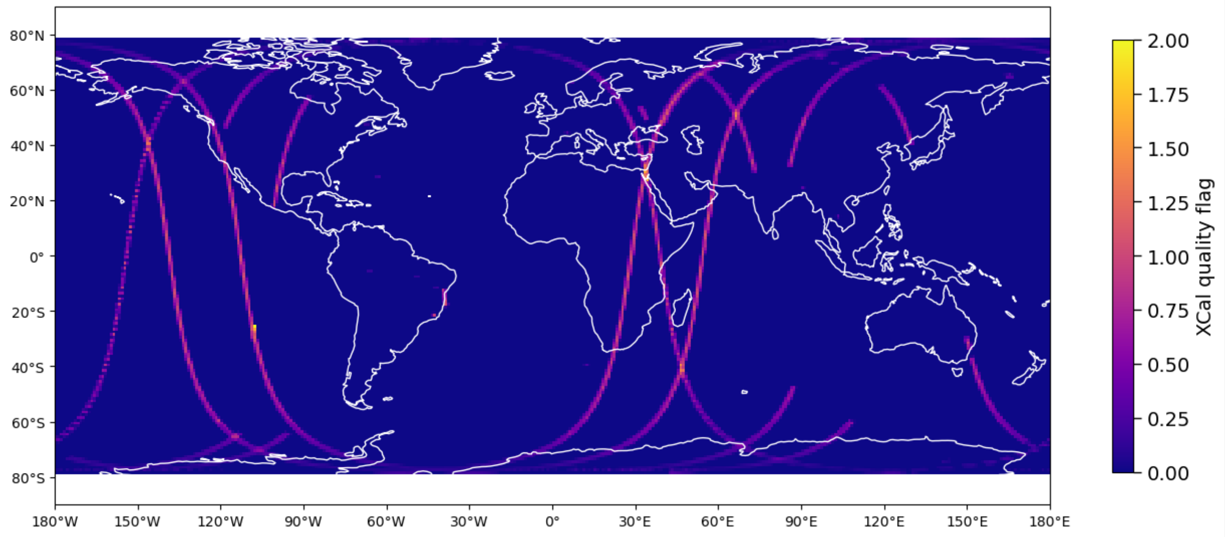
- L2 XCal quality information currently conveyed through a 3-state flag based on two main criteria:
  ⟶ Distance between successive Xovers
  ⟶ # of Xovers in a given time window

- How to systematically provide users with a reliable XCal quality assessment?
  ⟶ Construction of an uncertainty field for the XCal height correction
  ⟶ Enables users to select data more accurately according to their needs

⟶ No Xover available between the English Channel and the Gulf of Guinea

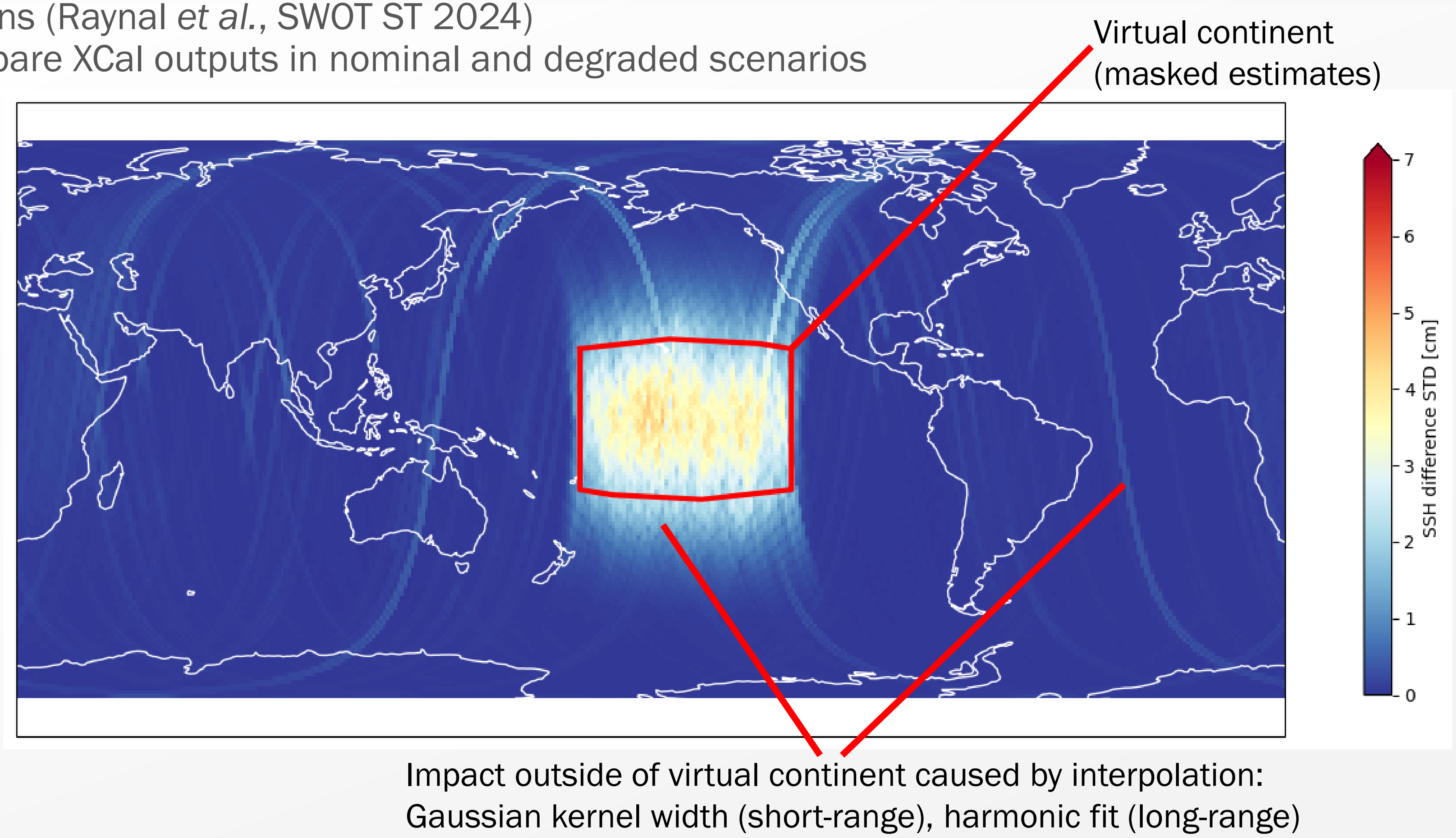



XCal quality flag mean value over SWOT cycle 38
⟶ Mostly missing data are flagged



# The virtual continent experiment

- Artificially mask large areas in the open ocean to simulate inland conditions (Raynal *et al.*, SWOT ST 2024)
  → Compare XCal outputs in nominal and degraded scenarios



# Estimating XCal uncertainty

- How to estimate XCal uncertainty using the virtual continent?

$$\eta = \eta^* + \varepsilon + \xi$$

Observed topography (systematic errors corrected) → $\eta$

True topography (unknown) → $\eta^*$

Other (random) errors (unknown) → $\varepsilon$

**XCal errors** (what we are interested in) → $\xi$

- True topography and random errors are realized identically with and without fake continent:

$$\eta_{\text{degraded}} - \eta_{\text{nominal}} = \xi_{\text{degraded}} - \xi_{\text{nominal}}$$

→ Access to XCal errors through topography

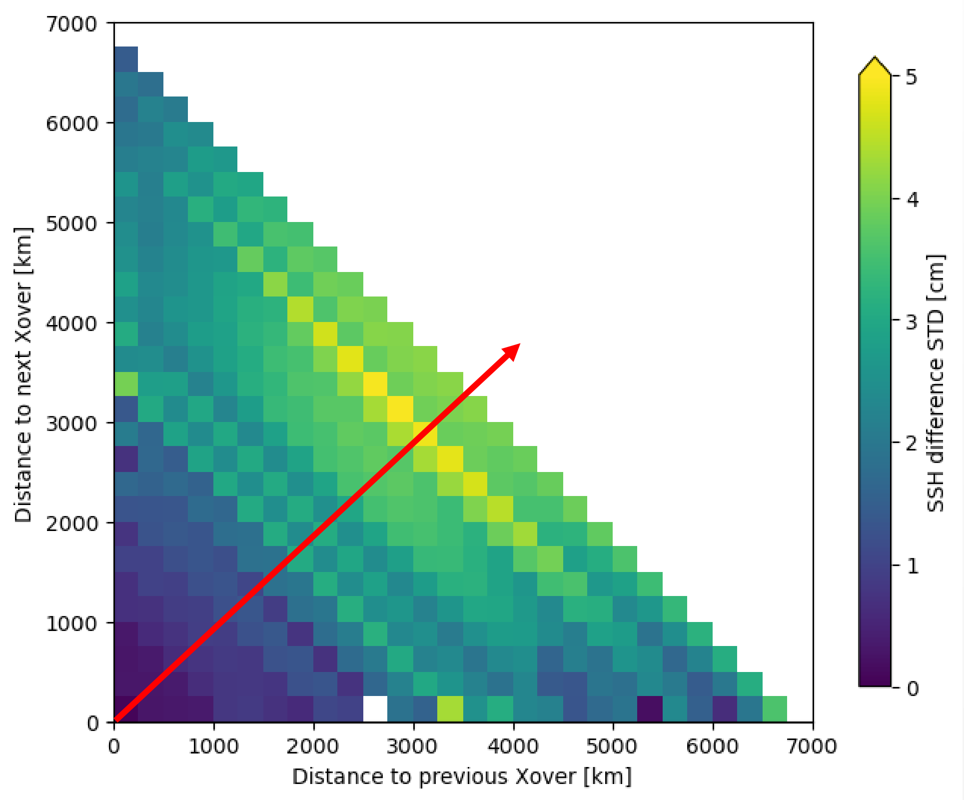
- If XCal errors have zero mean, we can show that

$$\text{STD}(\xi_{\text{degraded}}) - \text{STD}(\xi_{\text{nominal}}) \leq \text{STD}(\eta_{\text{degraded}} - \eta_{\text{nominal}})$$

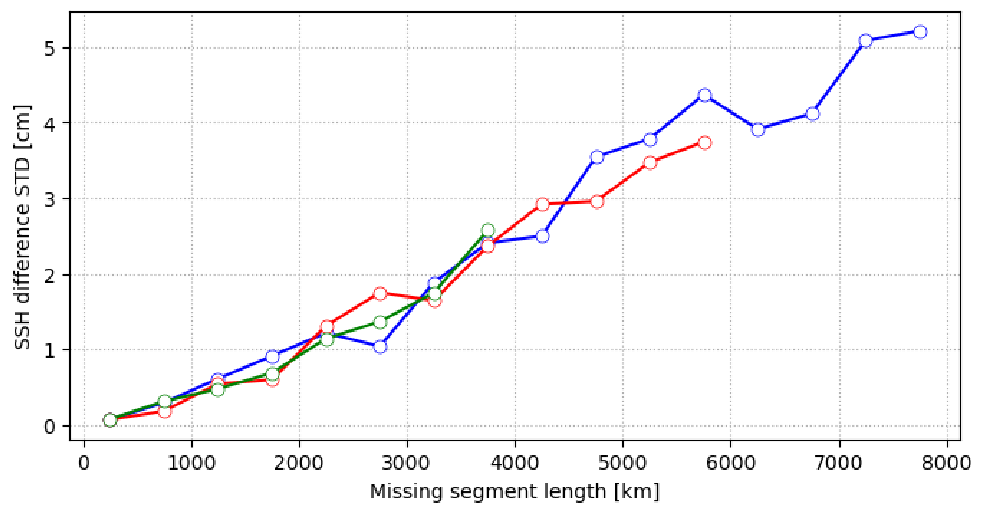
**Upper bound for the supplemental XCal error between Xover estimates**

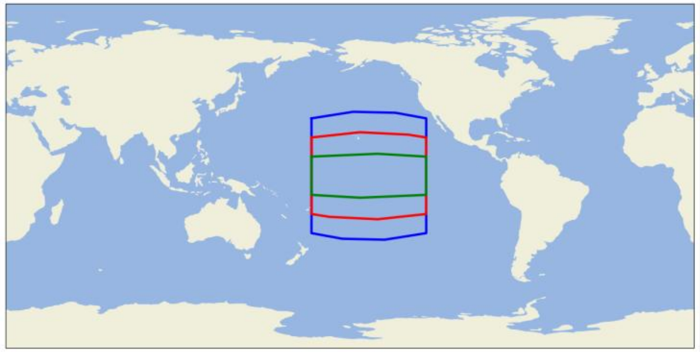
# Virtual continent – results

Standard deviation of SSH differences over the virtual continent versus distance to previous/next XCal estimate **(upper bound for the uncertainty increase between Xovers)**




→ STD at the middle of missing segments grows linearly with segment length

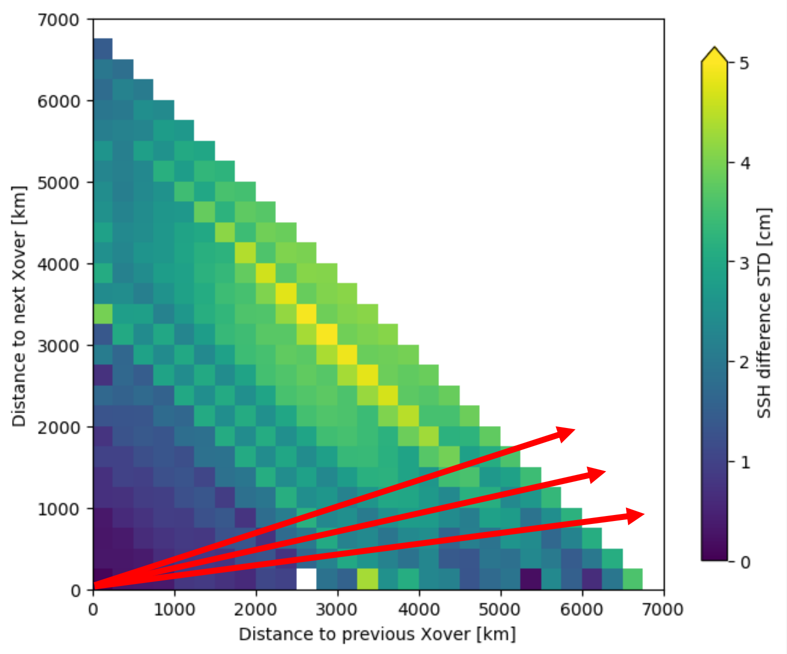


Consistent behavior across virtual continents of various sizes

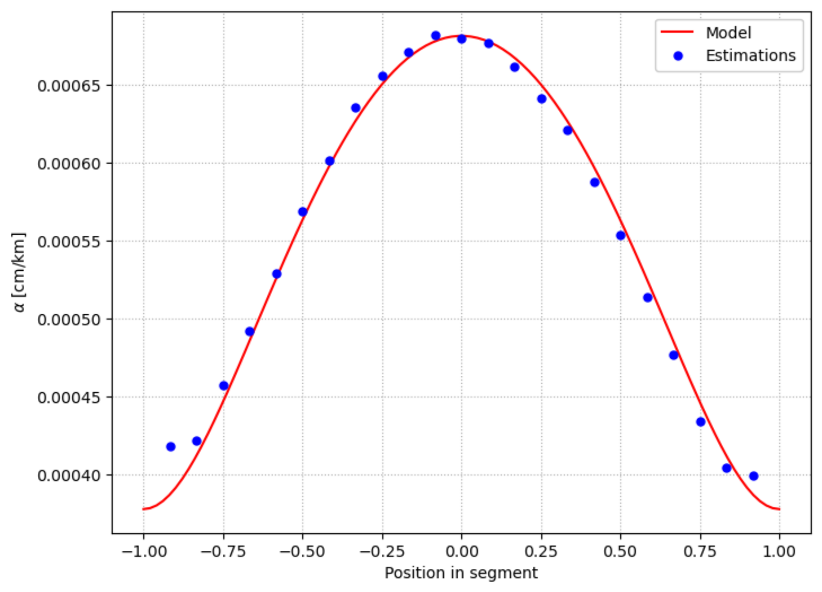
# Model for XCal uncertainty estimation

- Uncertainty model constructed from two parameters:
  - ⟶ Length of segment without estimate
  - ⟶ Position within said segment

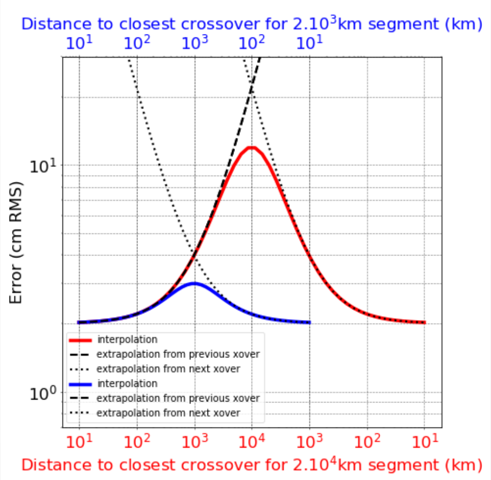



→ Fit a linear model versus segment length for each position:

$$\mathrm{STD}(\Delta\eta) = \alpha(p)L$$




Results reminiscent of pre-launch simulations

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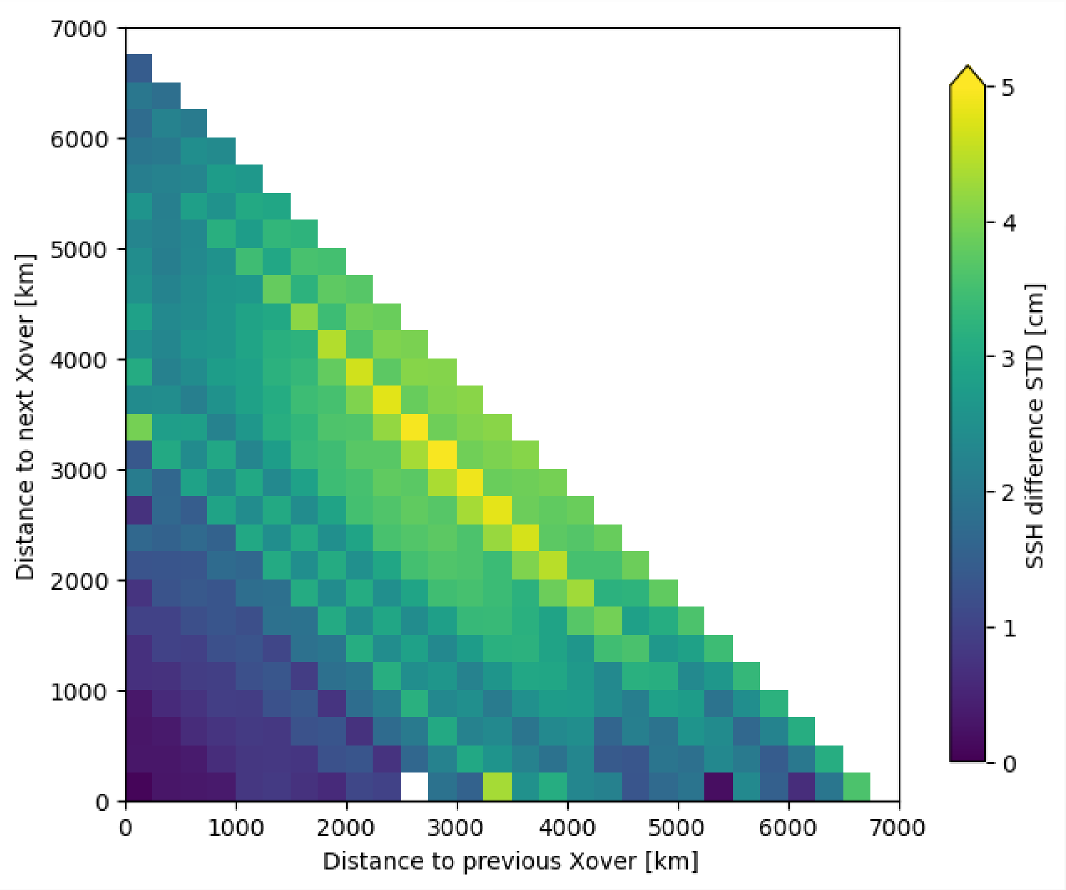
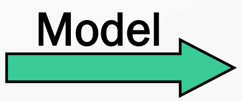
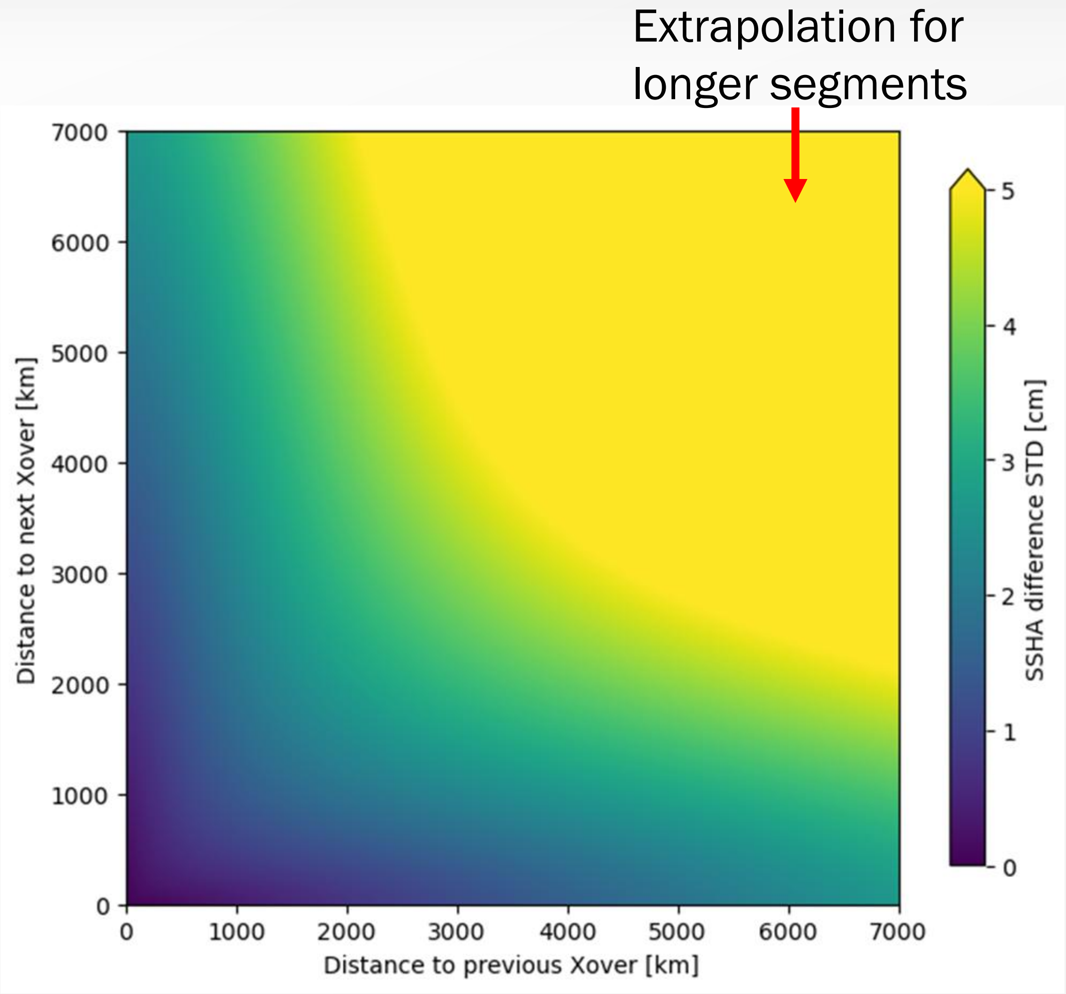
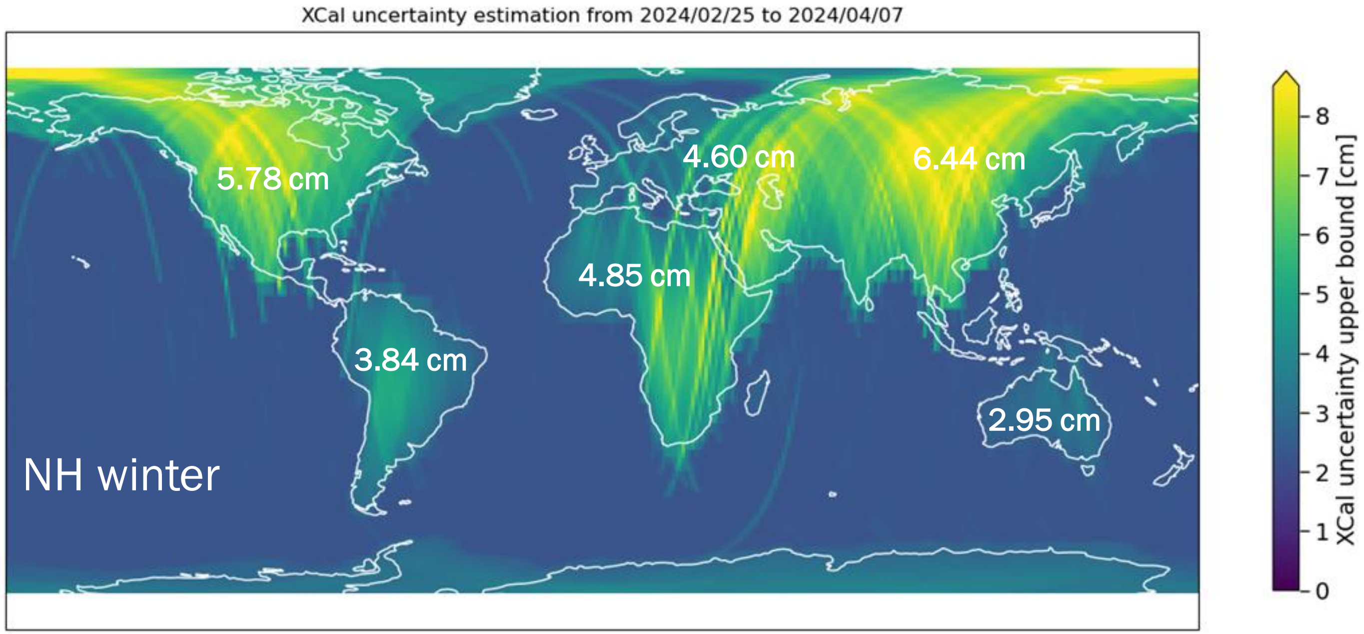
# Model for XCal uncertainty estimation

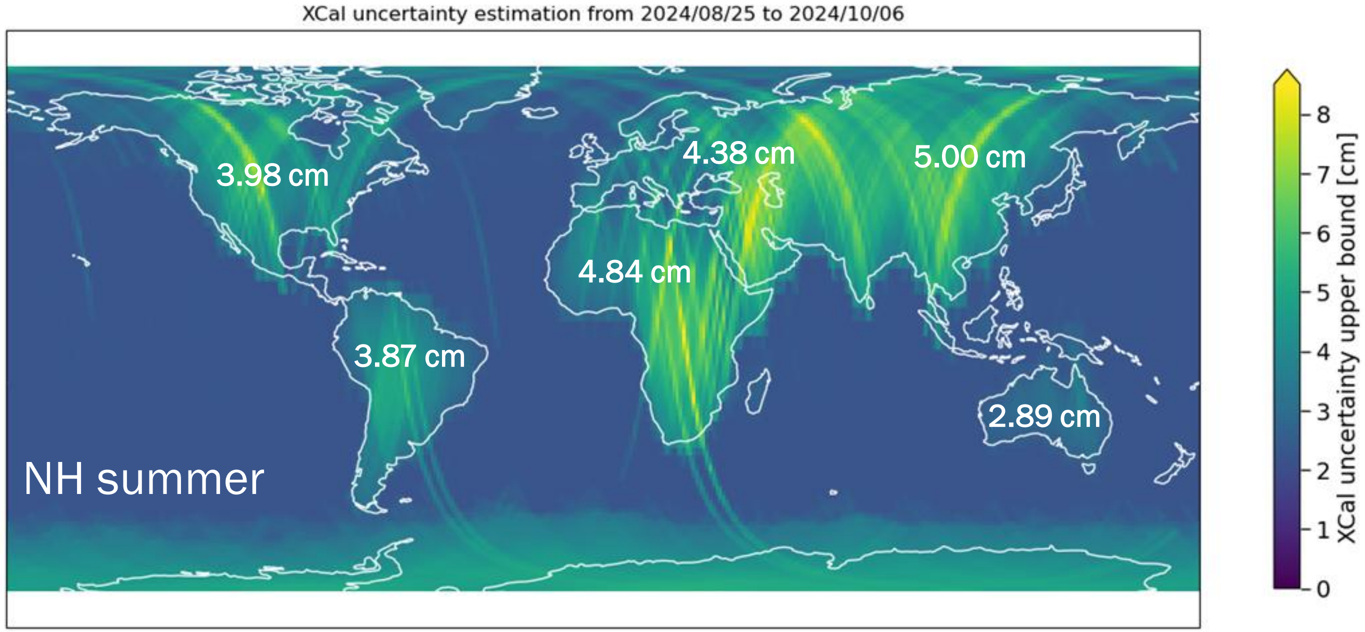


# Cartographies




- Model applied to actual SWOT data

$$u_{\mathrm{XCal}} = \sqrt{5\ \mathrm{cm}^2 + \alpha^2 L^2}$$

Floor value to account for the residual uncertainty over the ocean (Raynal *et al.*, SWOT ST 2024)

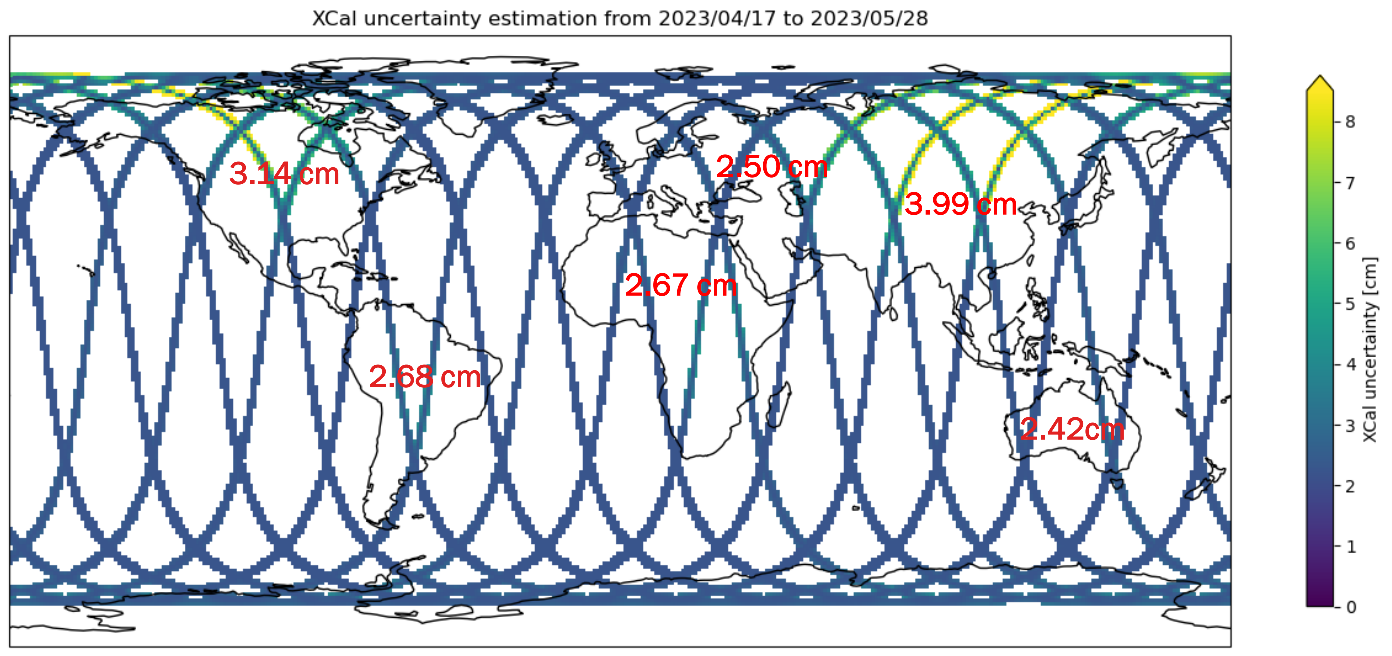
- XCal uncertainty estimated for ocean and inland waters alike
- Uncertainty **upper bound** mostly below requirements (7.4 cm of residual error)
- Clear impact of missing Xovers at high latitude
  → Particularly crucial for hydrological targets in Asia and North America

# CalVal orbit: L3 cross-calibration

- L2 XCal algorithm unfit for the CalVal (1-day repeat) orbit due to the scarcity of Xovers
  → L3 XCal to be used on hydrological targets (takes input from other altimetry missions)
  → **L2 & L3 algorithms are independent from one another**

- Optimal interpolation scheme developed to further improve interpolation and provide users with an uncertainty value

L3 XCal uncertainty estimation during the CalVal phase

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SWOT KaRIn Calibration Algorithm: principle, updates and analysis of the absorption of geophysical corrections residues such as tide and sea state bias

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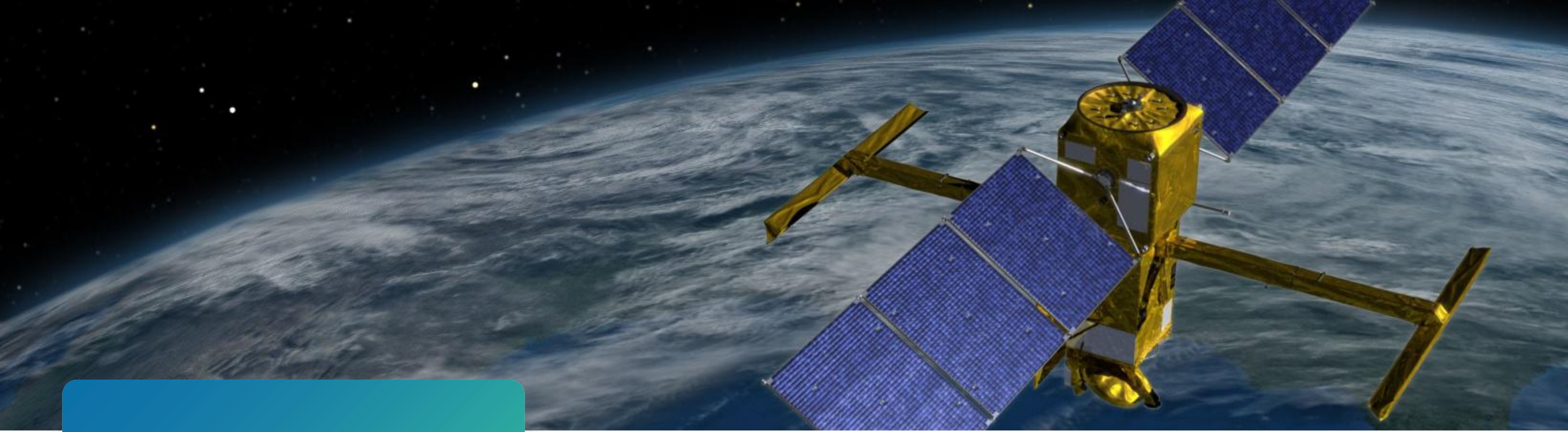
# Conclusion and future prospects

- The L2 XCal algorithm produces a correction for SWOT's systematic errors based on estimates at Xovers followed by harmonic and Gaussian interpolation
⟶ XCal height correction inland relies on estimates produced over the open ocean
⟶ Challenging to assess XCal quality

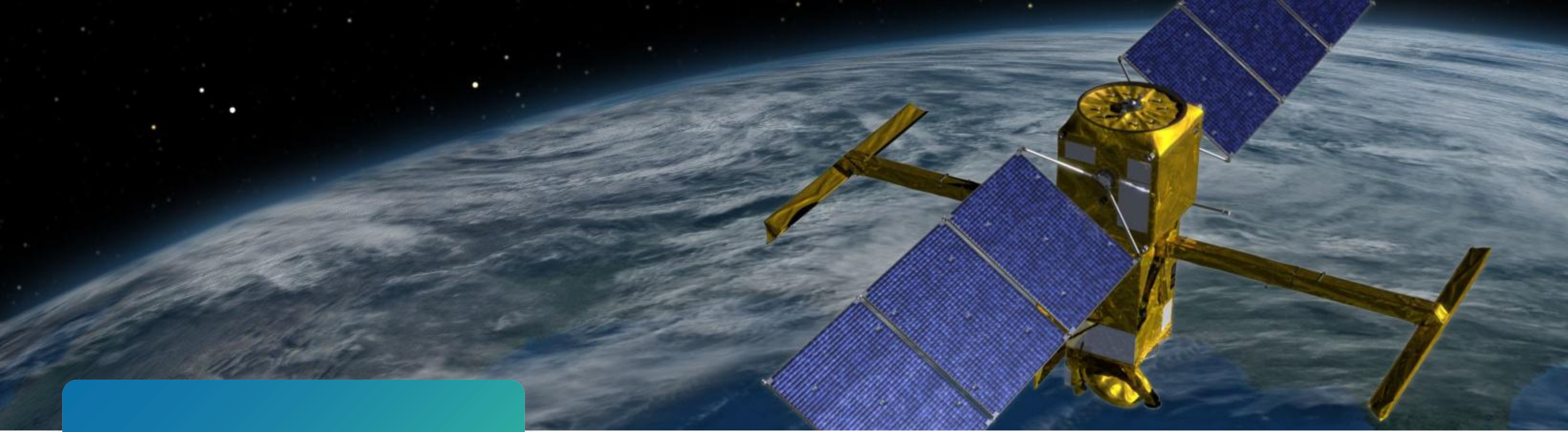
- Need for an accurate and reliable metric for XCal quality
⟶ Construction of an uncertainty field using the virtual continent experiment

- The STD of topography differences between degraded and nominal XCal runs provides an **upper bound** for the supplemental error between Xover estimates
⟶ Grows linearly with missing segment length
⟶ Data-driven model depending on the distances to the previous and next Xovers

- Some remaining challenges
⟶ Refine XCal uncertainty estimation at Xovers
⟶ How to deal with long missing segments (e.g., missing passes)?
⟶ Construct model with other input variables besides distances to nearest Xovers

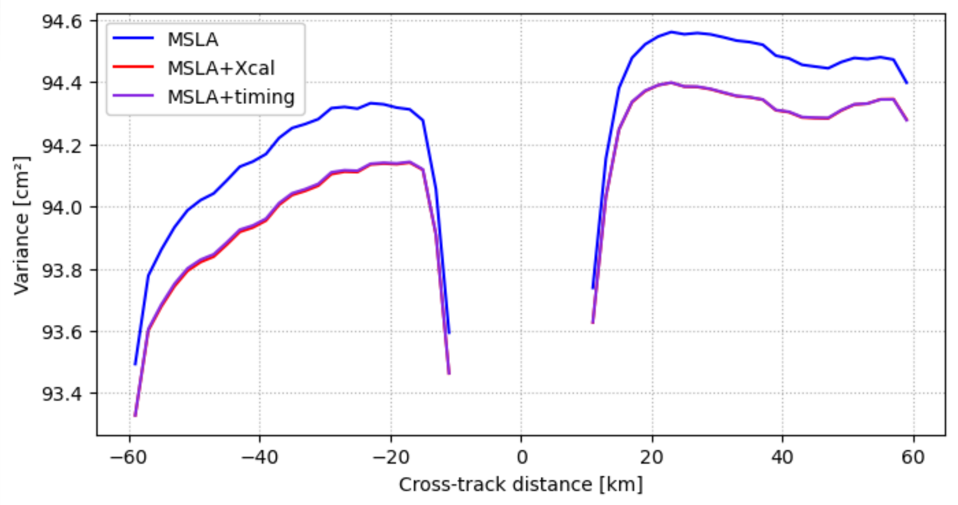


# *Thank you for your attention!*



# Back-up

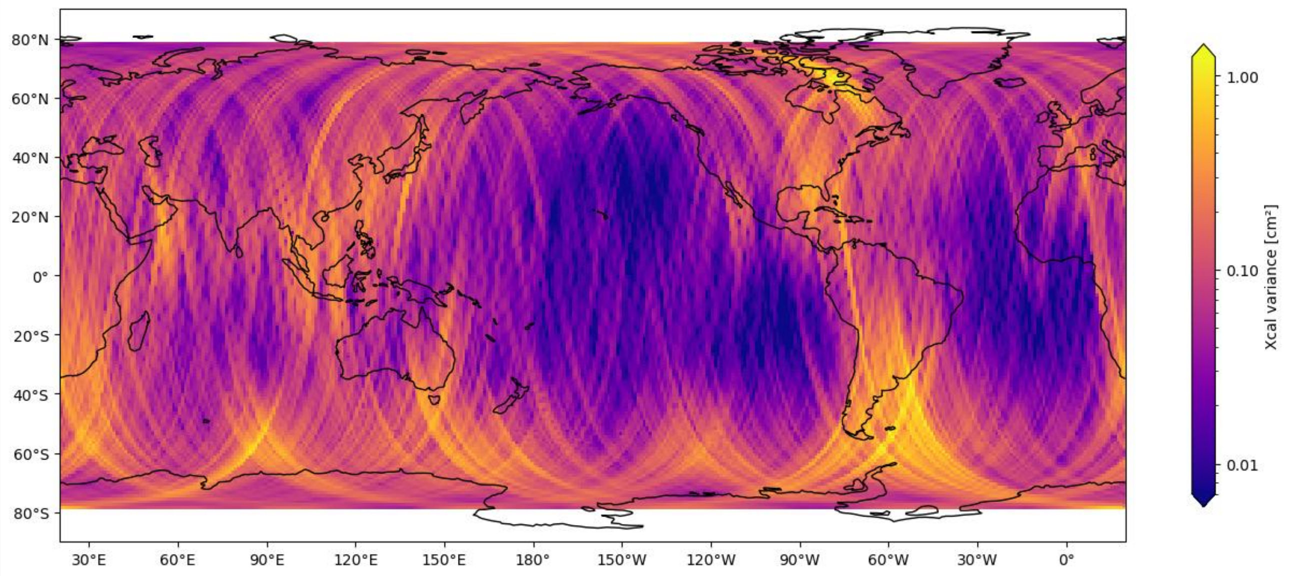
# Leakage from ocean variability




- XCal run generated with MSLA as input
  → resulting height correction strictly zero ideally

→ ~0.2 cm² of ocean variance absorbed globally

→ Almost entirely due to the timing correction




→ Height correction variance
(visualize ocean signal projected inland)

→ ≤ 0.1 cm² in the open ocean

→ Can reach 1 cm² at high latitudes or around coastal/highly dynamic areas