Improving KaRIn's SWH estimates

October 15th, 2025

SWOT Science Team meeting

Alejandro Bohe (CNES),

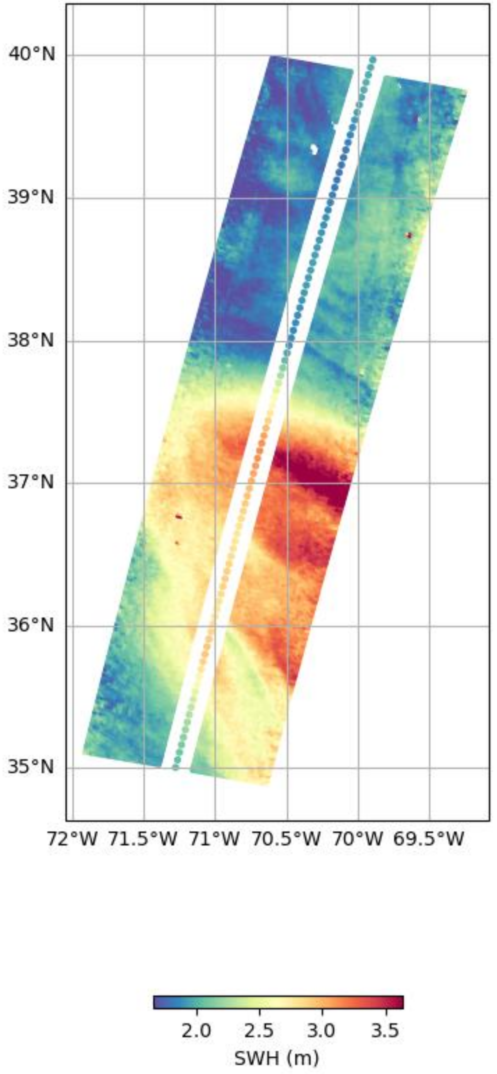
on behalf of the CNES/JPL algorithm team

Outline

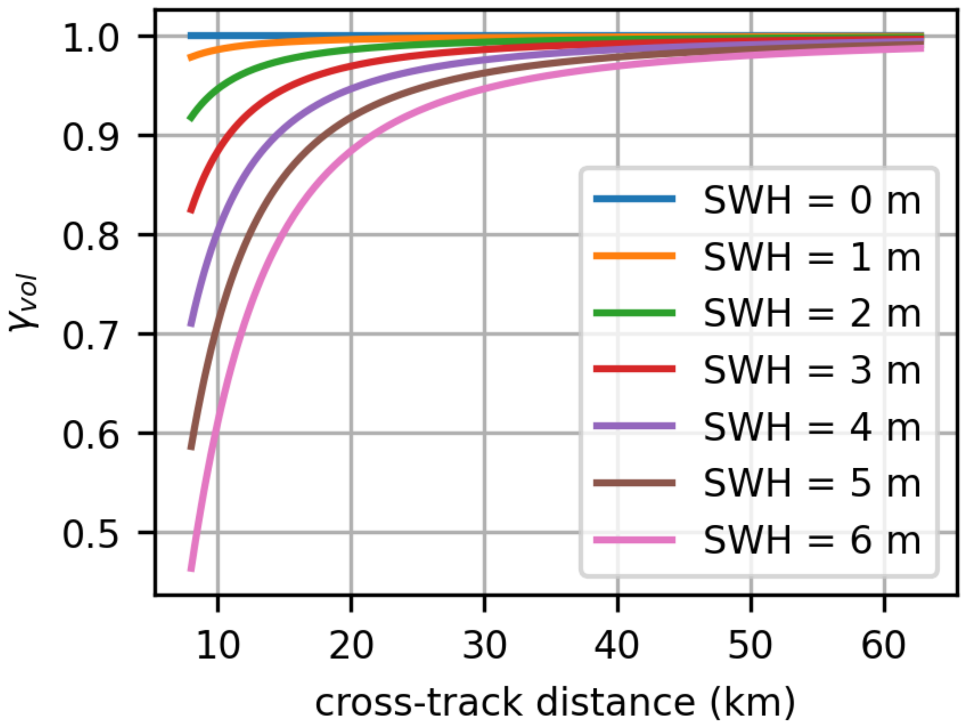
1. Reminder on inversion and sensitivity

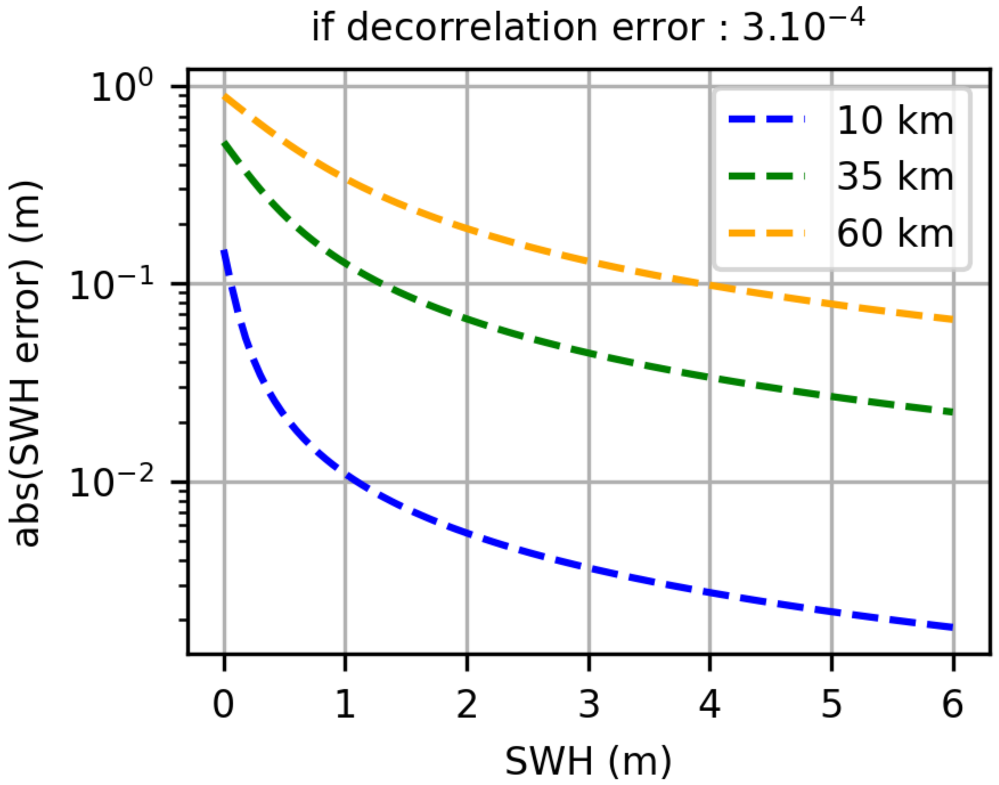
2. Summary of differences between product versions

3. Work towards improving current estimates



SWH from KaRIn : inversion sensitivity and required accuracy on γ





- The SWH inversion is most sensitive in the near range and for high SWH. **Most straightforward regimes for SWH measurements from KaRIn.**

- **In the far range, or for low values of SWH**, tiny errors in the decorrelation (e.g. 10^-3 chosen in the right plot) can lead to tens of cm of error on SWH. These are the **most challenging regimes for SWH measurements from KaRIn.**

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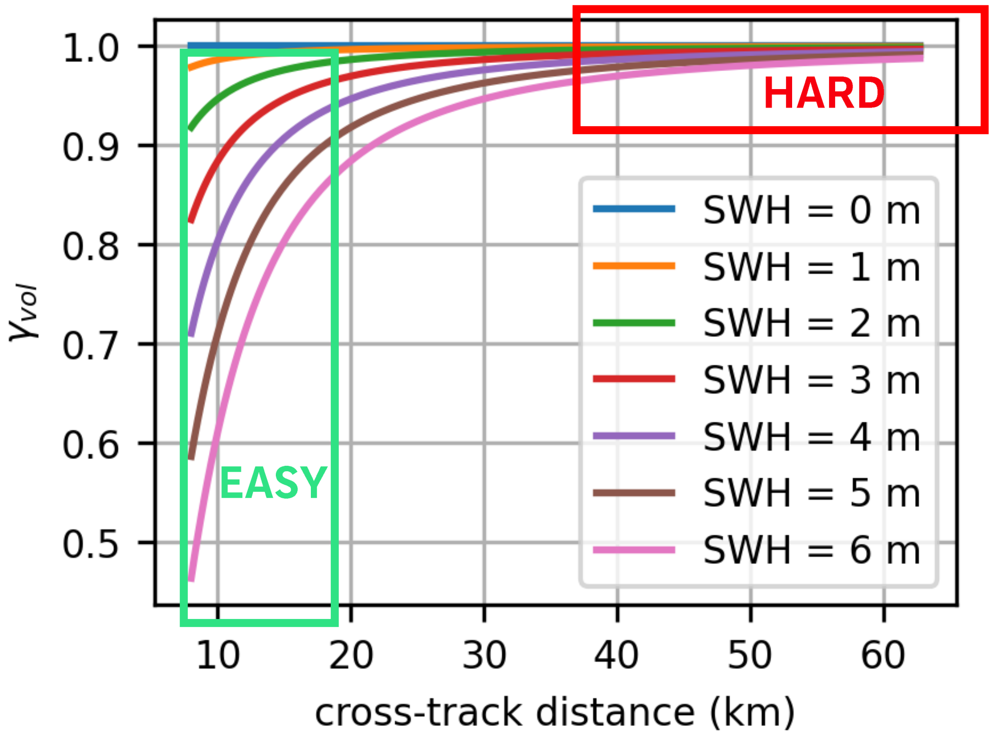

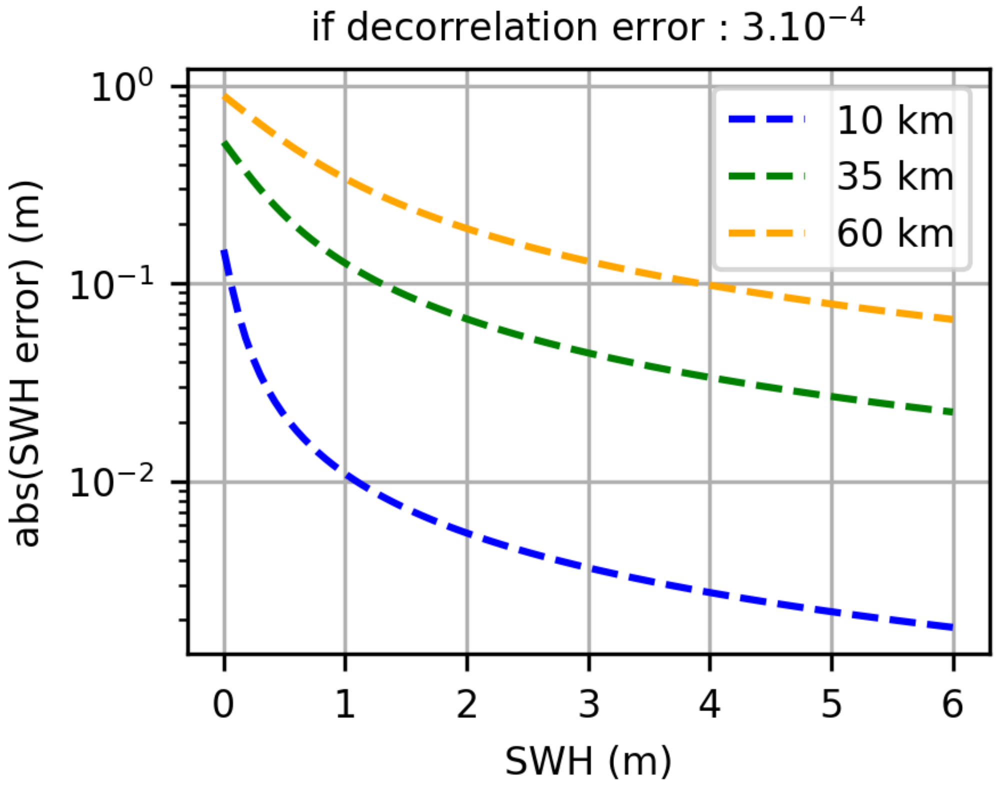

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SWH from KaRIn : inversion method (with static calibration)

- Measurement : total interferometric correlation. **Need to correct for instrumental sources of decorrelation** to obtain volumetric correlation.

- Instrumental corrections achieved with sufficient **accuracy (a few 10^{-4}) through**
    1. **careful modeling of dynamical instrumental effects** (using flight data)
    2. **empirical calibration** : corrects for yet to be understood effects and residual errors in the modelling of the effects that are understood.
       Note : this is a calibration of decorrelation, not SWH.

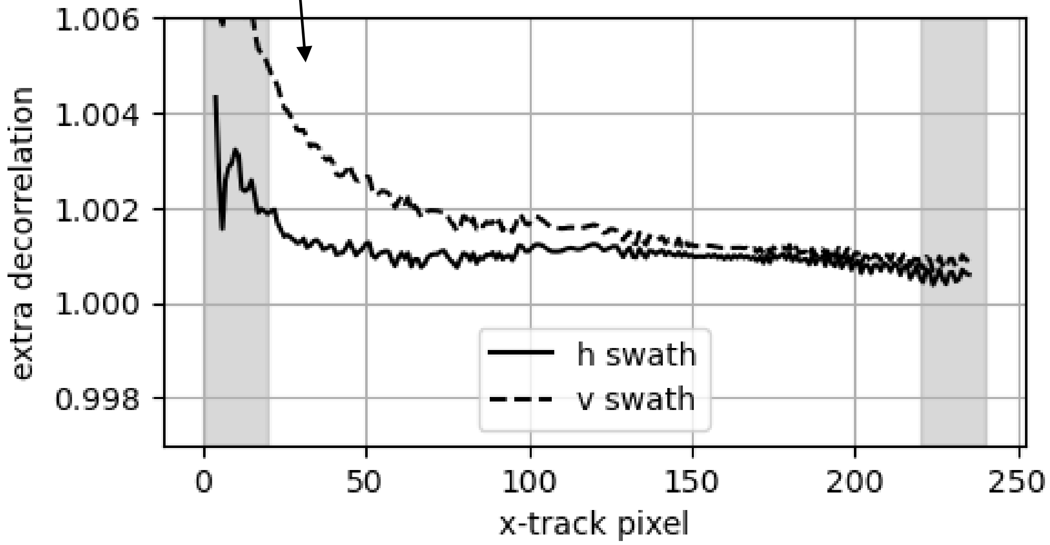
- **So far (including version D) : static calibration** used
  Derived using a few passes SWOT's nadir SWH measurements as (statistical) ground truth.

- With now more than 2 years of data, **we have observed that the effects caught by the empirical calibration vary in time**, creating time-dependent errors in SWH. Below, we present the work in progress to characterize these variations and correct for them.

$$\gamma = \gamma_{cal}\,\gamma_{SNR}\,\gamma_{geo}\,\gamma_{ang}\,\gamma_{vol}(SWH)$$

measure on data

compute from system params and geometry



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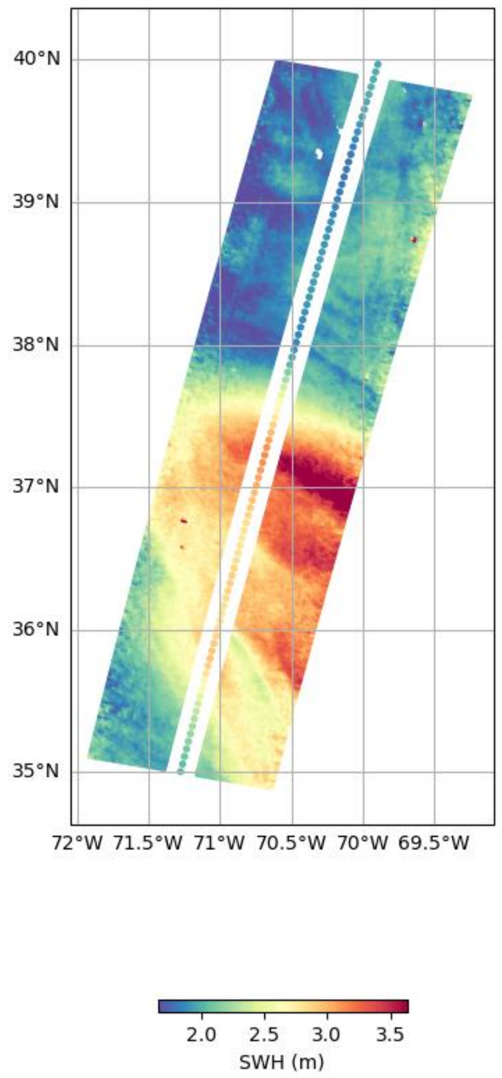


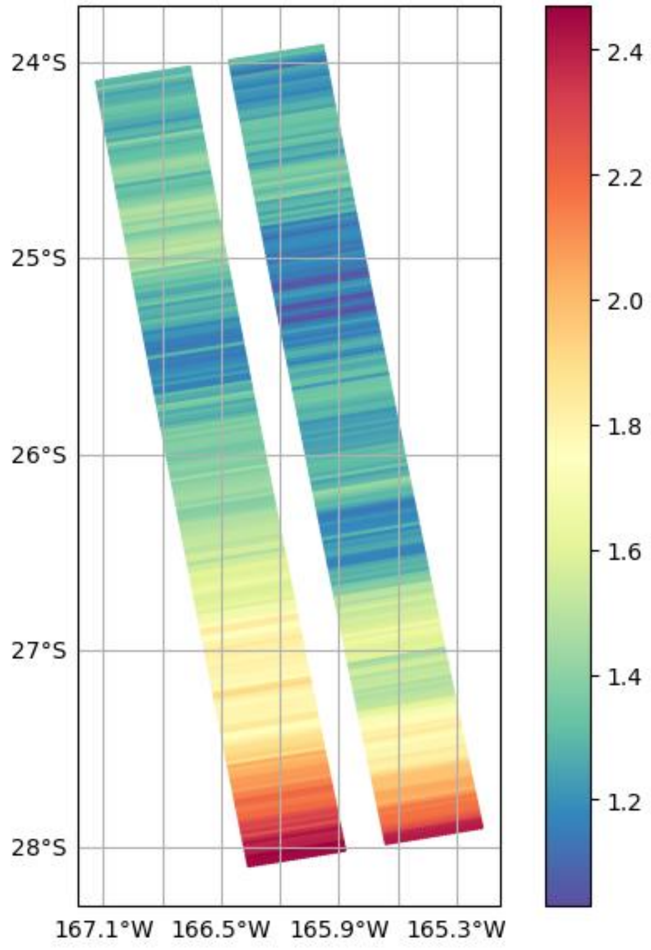
SWH product versions

KaRIn product versions denoted by CRID e.g (PIA0, PIA1, PIB0, PIC0, PGC0, PIC2, PID0, PGD0).

- second letter : I or G.
  - I = « forward processing » (typically less than 3 days after data is acquired)
  - G = global reprocessing (uses refined orbits etc…)
- **third letter + number = « algorithm version »**

KaRIn's SWH in PIA0, PIA1 and PIB0 (same algo in all three)

- Algorithm : no 2D inversion (1 value per swath, variation in along track only).
- Temporal coverage : CAL phase (=1day repeat phase = end of March 2023 -> July 2023) + first 6 cycles of SCIENCE phase.
- This version of the data should not be used anymore (this entire period is covered by data from PGC0 reprocessing, which will soon be superseded by the PGD0 version).



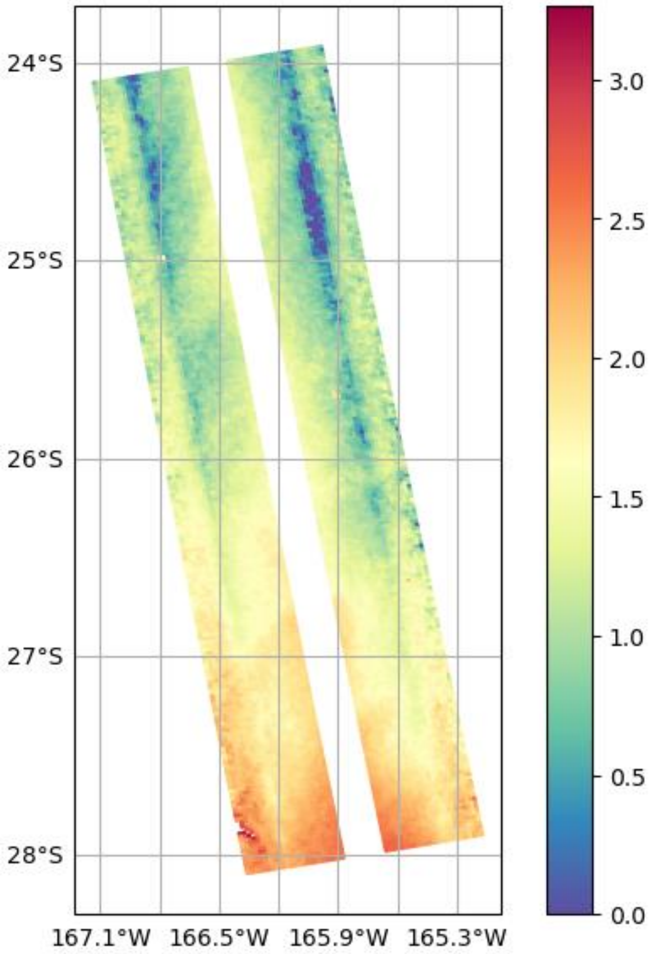
SWH product versions

KaRIn's SWH in PIC0 and PGC0 (same algo in both)

- Algorithm :
  - first 2D inversion
  - Several sources of instrumetal error, which vary dynamically, not accounted for. Expect significant errors dependent on latitude, cross-track distance, SWH itself (larger errors at low SWH). These errors have a component that varies over long timescales (beta) which cannot be corrected in post-processing

- Temporal coverage :
  - PIC0 : cycle 7 (Nov 2023) to cycle 22 (~Oct 2024)
  - PGC0 : CAL phase + cycles 1 to 9 of SCIENCE phase
    (beware, version changes not at the beginning of a cycle, please check CRID)

- I would suggest only using this version of the data if you need to work on data acquired before Oct 2024 AND you cannot wait for the upcoming PGD0 reprocessing



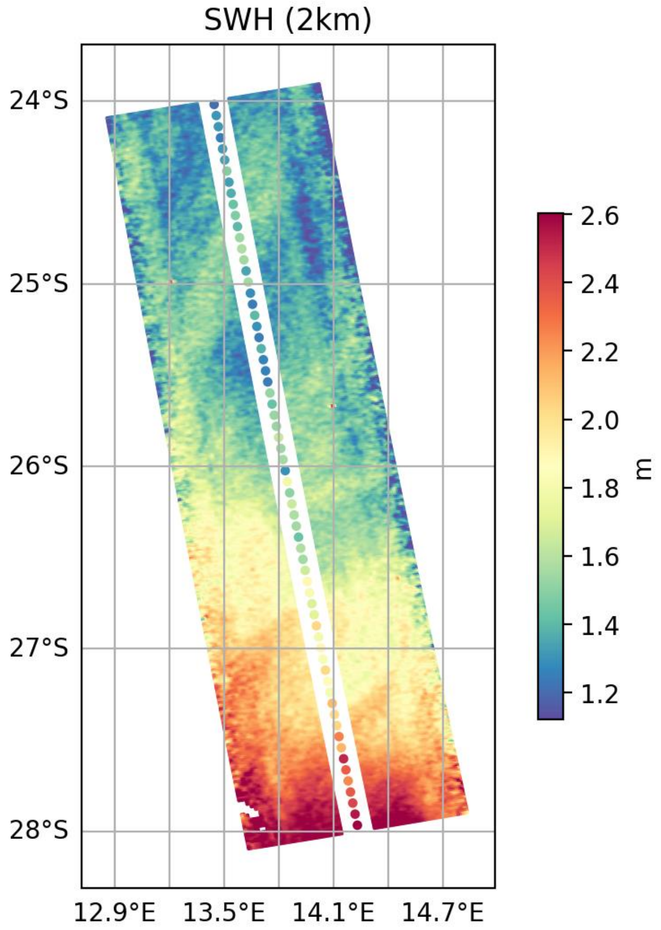
SWH product versions

KaRIn's SWH in : PIC2, PID0, PGD0 (same algo in all three)

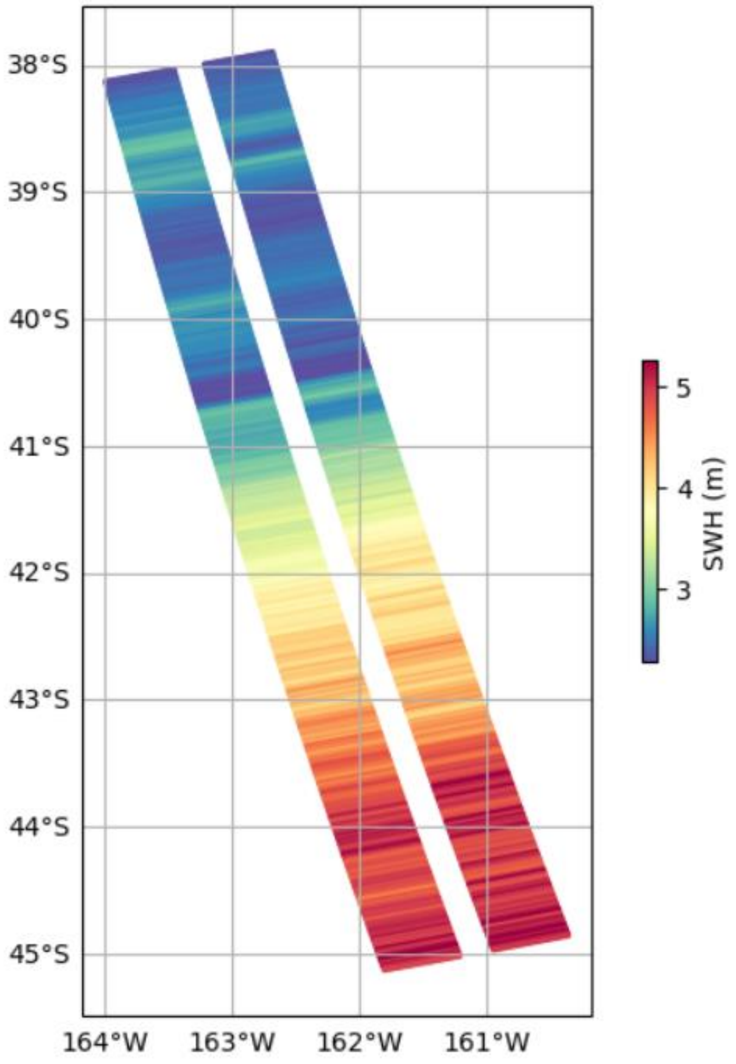
- Algorithm :
  - Improves on the PIC0 version by dynamically accouting for various sources of instrumental decorrelation.
  - Strong reduction of errors and their depence on latitude, cross-track distance, SWH and (to a lesser degree) beta angle. Some latitude dependent effects still visible (see blue along track stripe in plot on the right)
  - Algorithm matches what is described in Bohe et al (2025) https://ieeexplore.ieee.org/document/10947111

- Temporal coverage :
  - PIC2 : cycle 22 (~Oct 2024) to cycle 32 (May 2025)
  - PID0 : cycle 32 up to now
  - PGD0 : global reprocessing of the entire SWOT dataset from launch (not complete)

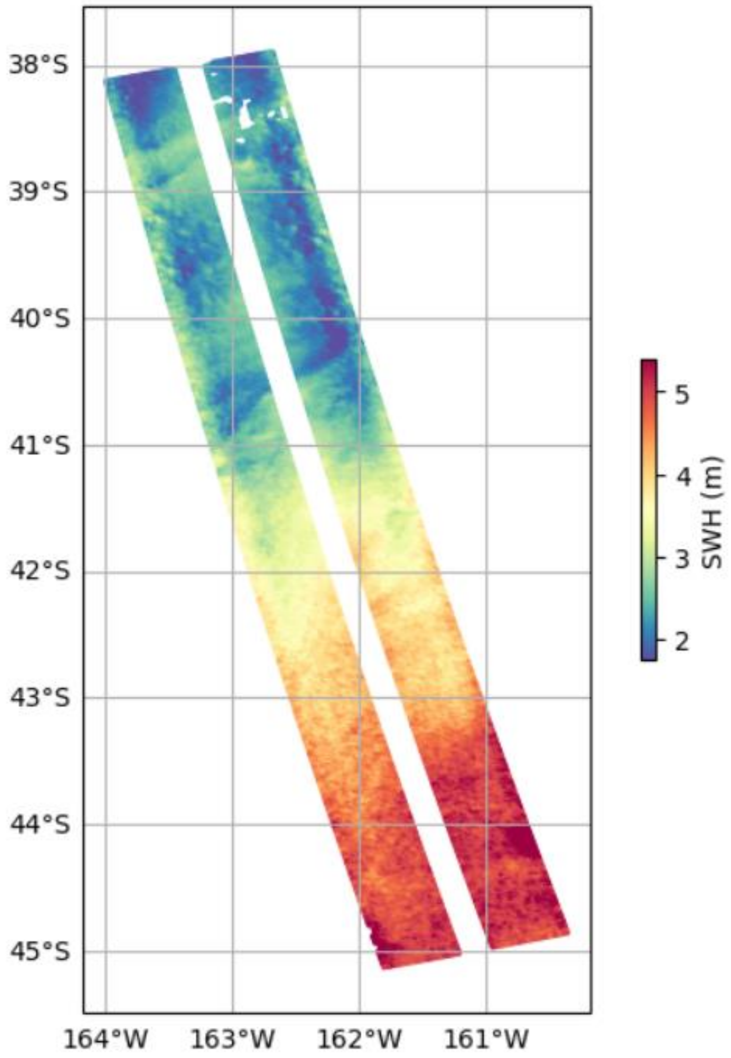
- As soon as PGD0 reprocessing is complete, use PGD0 or PID0 version of the data only



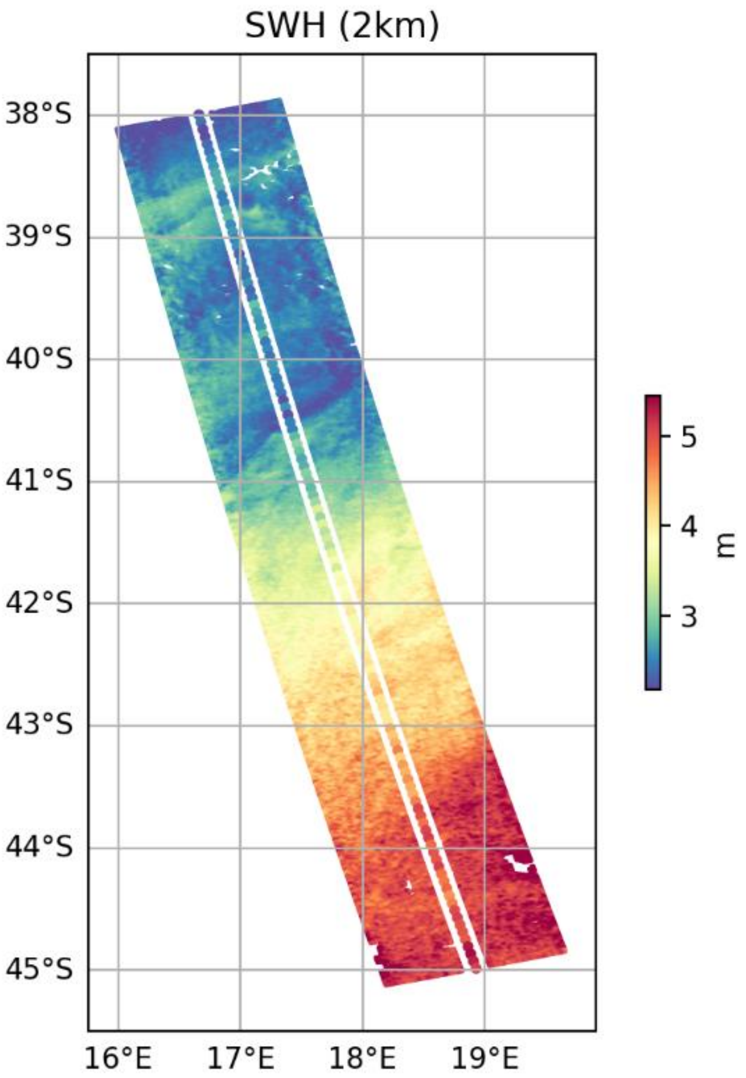
Product versions



Versions A and B



Version C



version D

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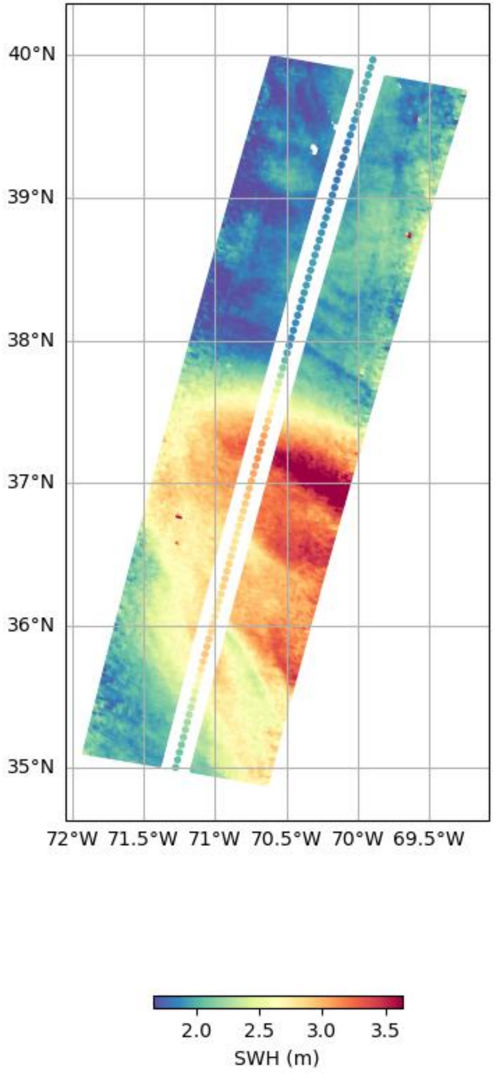


Work towards improving current estimates

1. Instrumental errors varying over long timescales (beta angle)

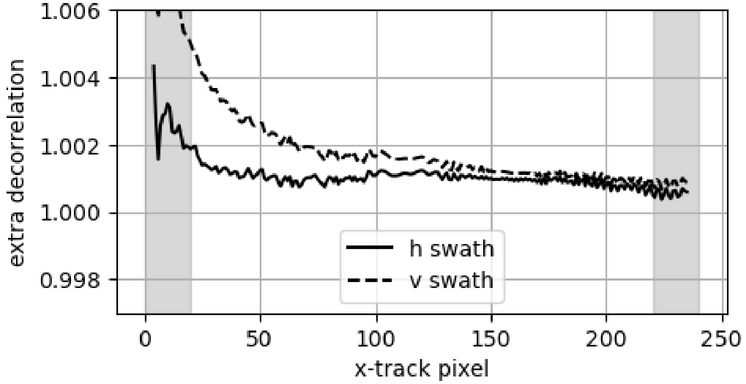
2. Instrumental errors varying over suborbital timescales

3. Errors in the presence of strong sigma0 surface gradients (in particular, coastal areas)

4. Rain corrupted measurements

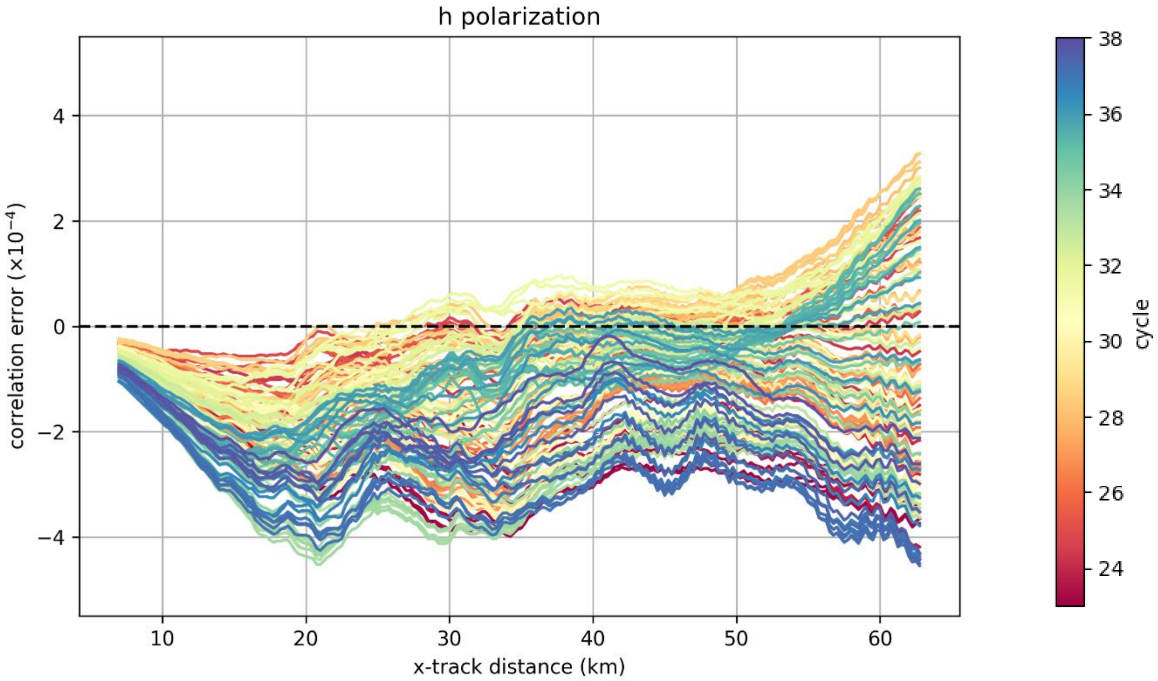
Instrumental errors varying over long timescales (beta angle)

- static calibration used in processing



- Starting from cycle 23 (start of PIC2), recompute a calibration 8 times per cycle (~ every2.5 days).

  Plot on the right is the difference with the static calibration shown above (i.e. by how much we should update the calibration used in the processing to make it optimal for each set of 2.5 days)



Instrumental errors varying over long timescales (beta angle)

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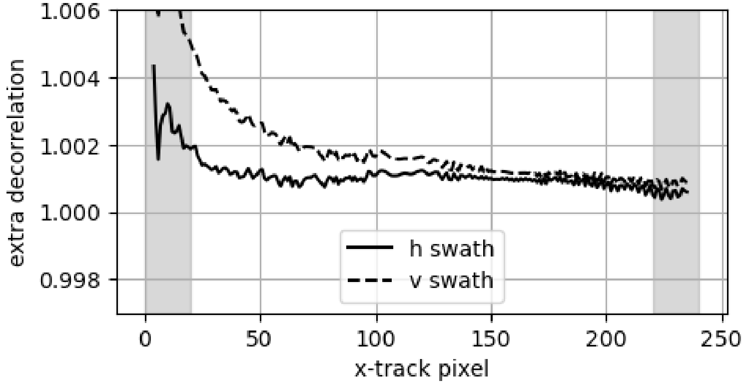

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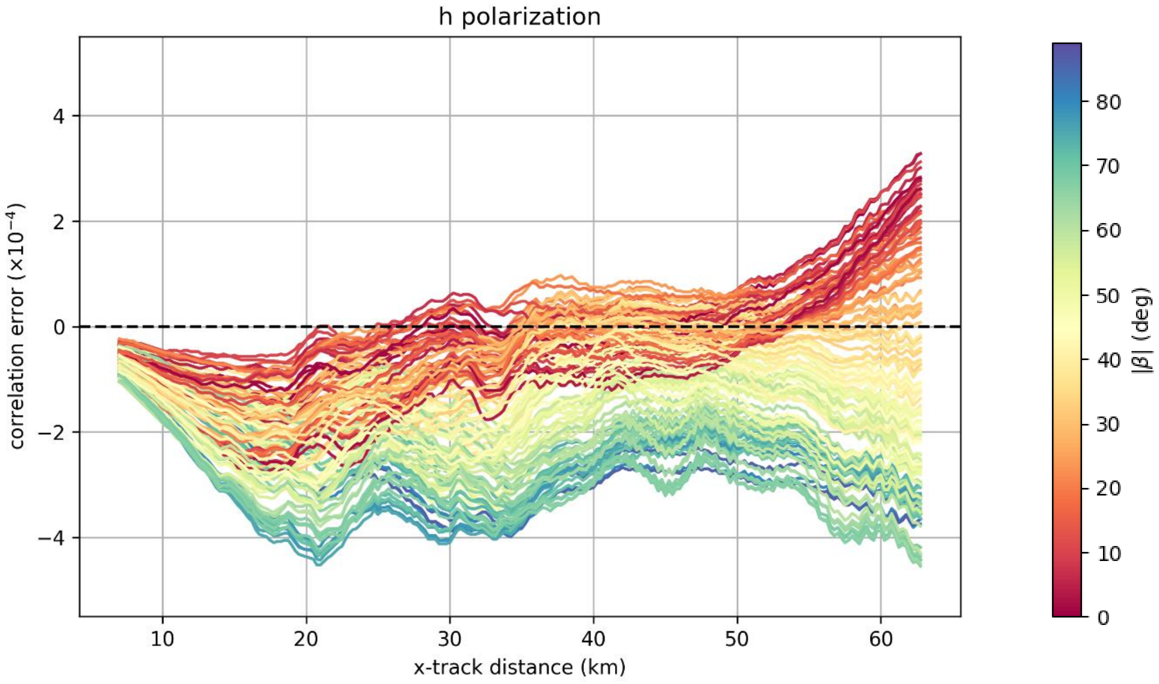

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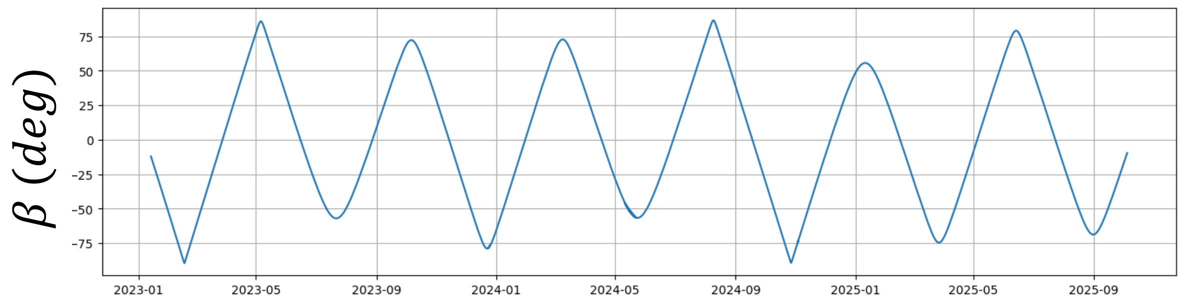

Angle between the vector from the Earth to the Sun and the plane containing the spacecraft orbit around the Earth. […]

cf User Handbook section 3.1.7 : ''The beta angle affects the solar illumination of the spacecraft and therefore influences the thermal environment of the SWOT spacecraft and its instruments. The beta angle may therefore be correlated with some systematic errors in the instruments.''

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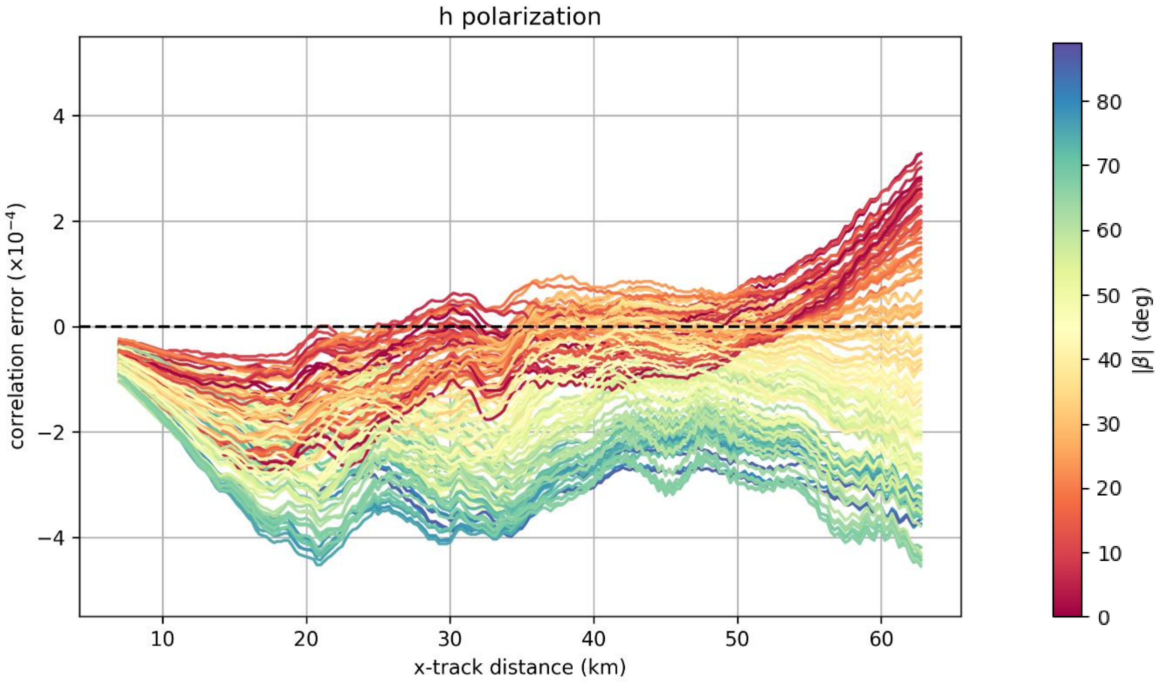
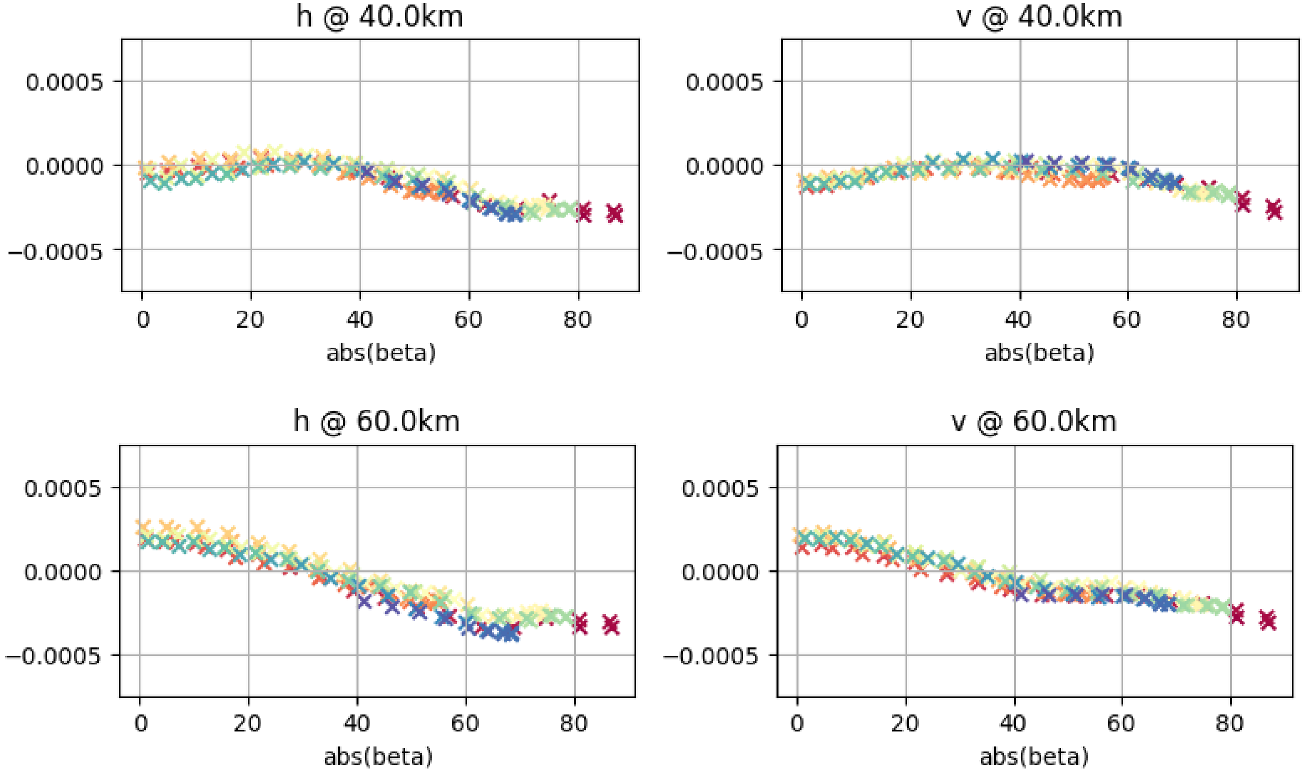
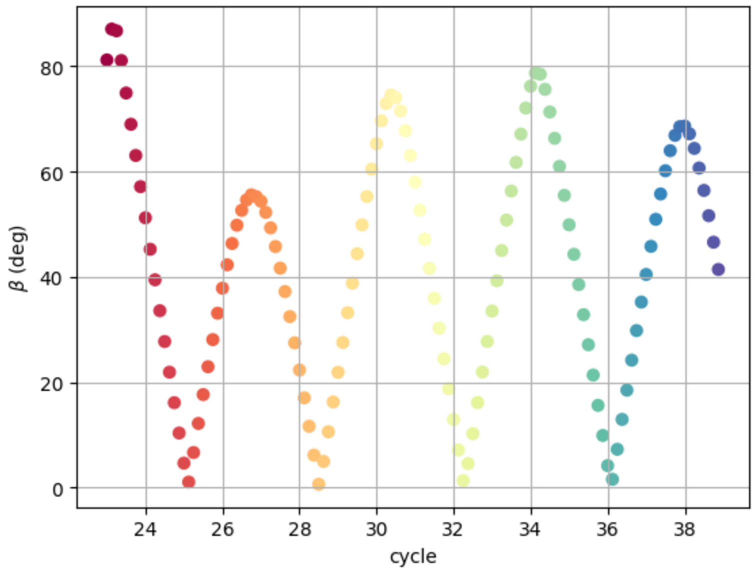


Instrumental errors varying over long timescales (beta angle)

Diff between optimal calibration for each 2.5-day period and the static one used in operational processing at fixed cross-track distances, shown as a function of absolute value of beta angle.





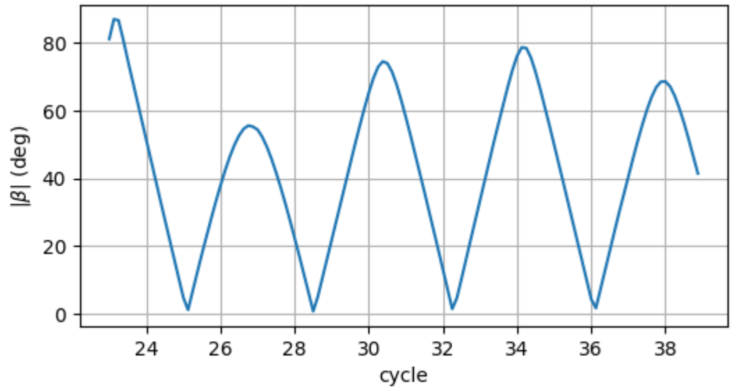
- Evolution predictible as a function of beta angle.
- **Easy to correct with a beta-dependent calibration.**

Likely to be corrected in future versions of the products.
Until then, correction and code to apply it provided here (see Bonus slides for more information) :
git clone https://framagit.org/alejandro.bohe/swot_karin_swh_gammavolcorr_update.git

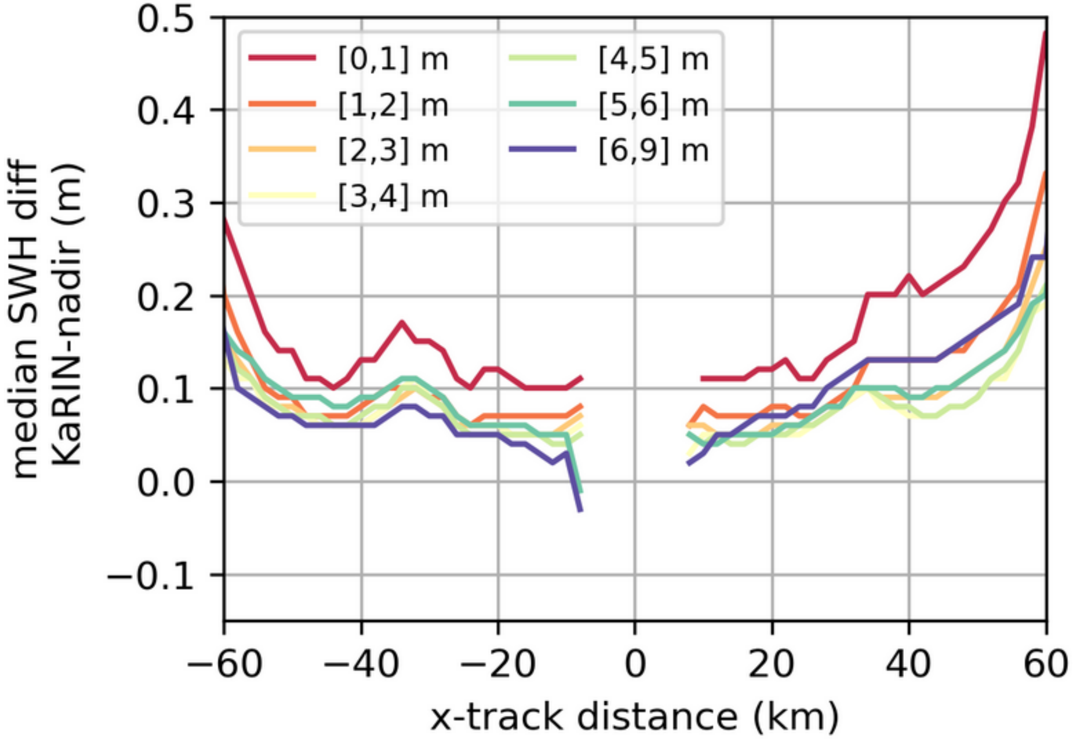
Instrumental errors varying over long timescales (beta angle)

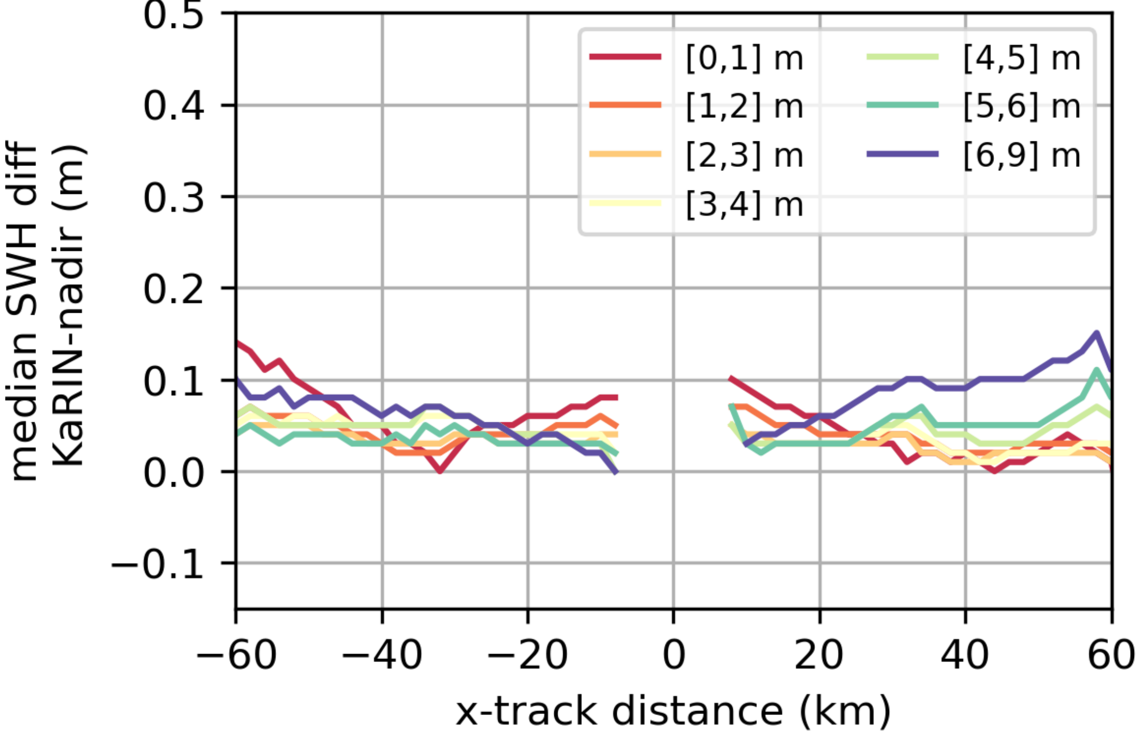
Slowly varying (~days-weeks) biases : small for most cycles, but can become large (several tens of cm) for extreme values of $|\beta|$.

Increase with across-track distance and SWH.



Cycle 22, Passes 410-576





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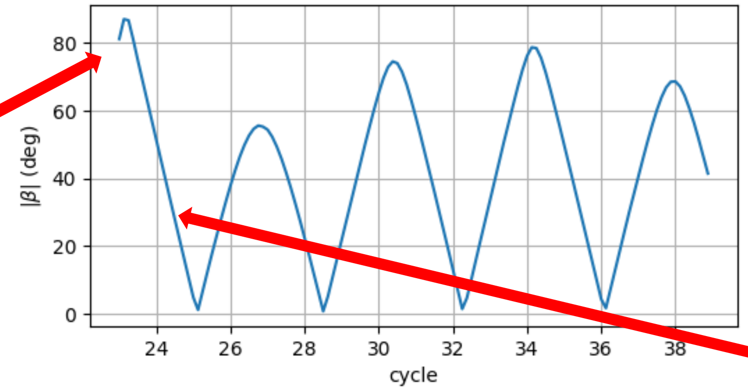

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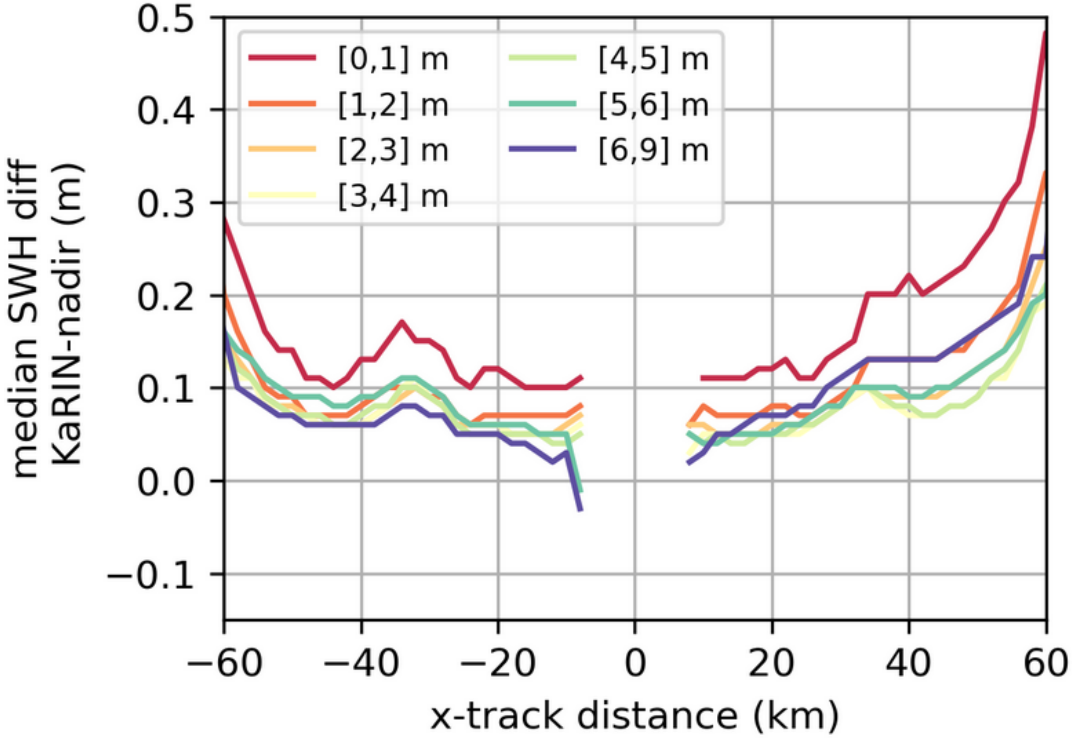

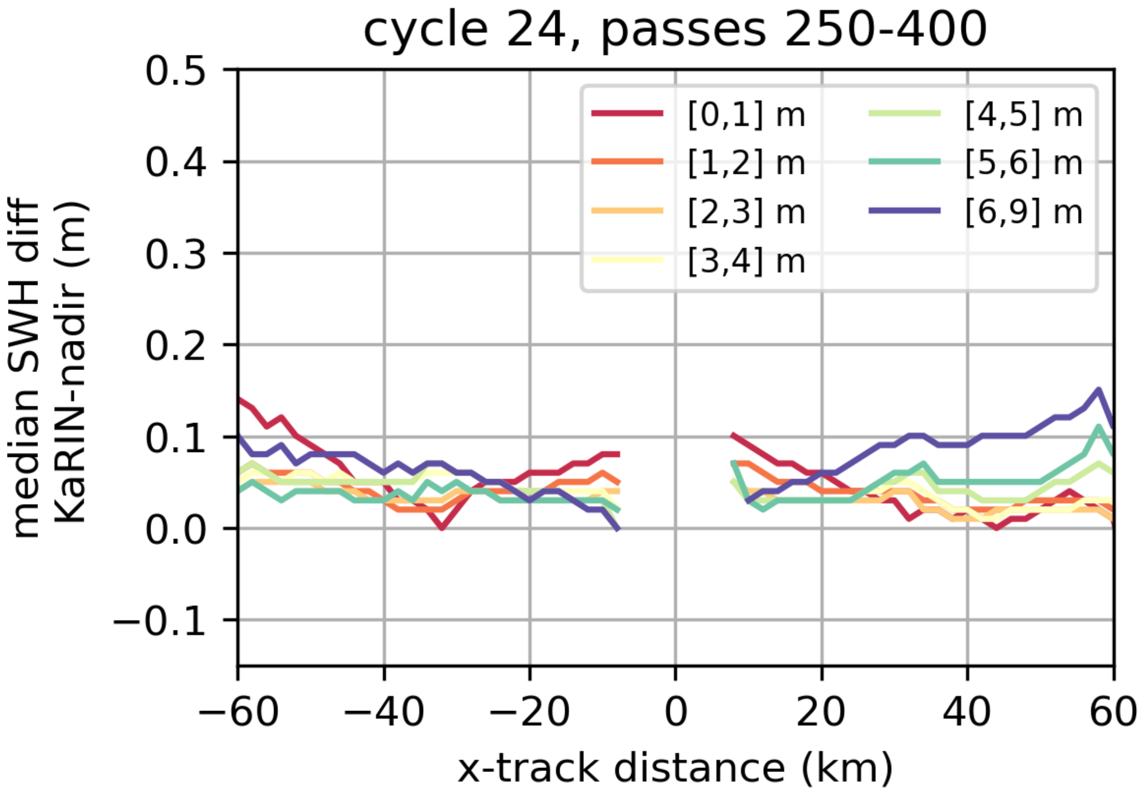

Work towards improving current estimates

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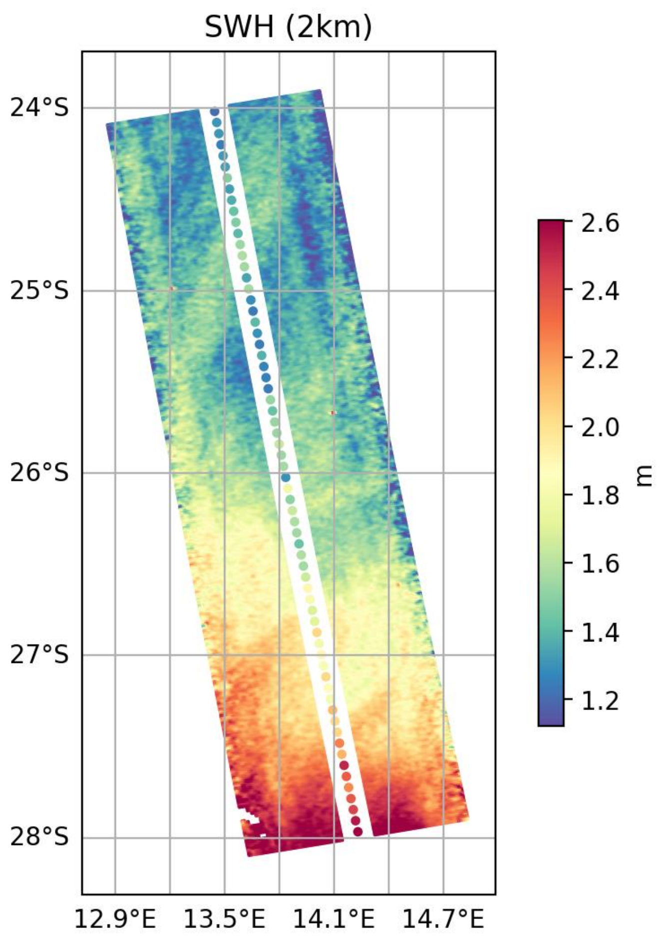
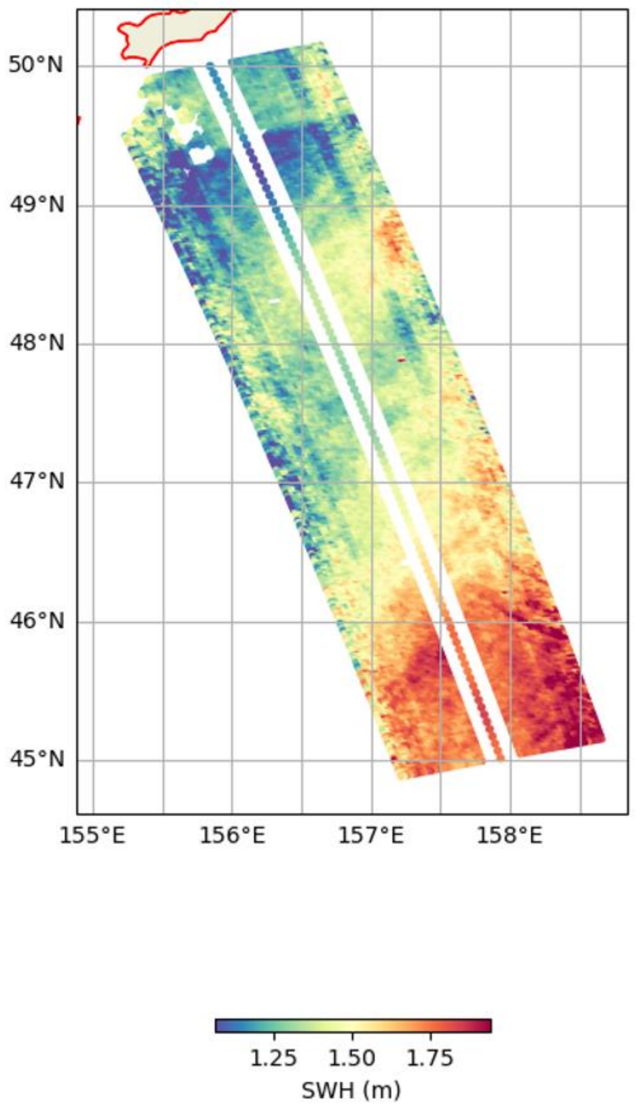
2. Instrumental errors varying over suborbital timescales

3. Errors in the presence of strong sigma0 surface gradients (in particular, coastal areas)

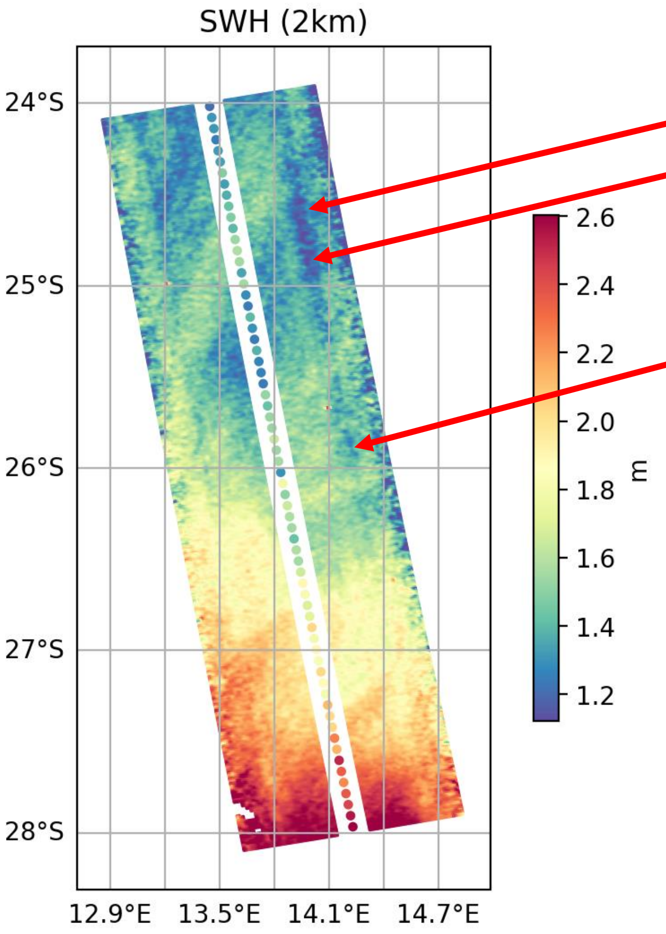
4. Rain corrupted measurements

Instrumental errors varying over suborbital timescales





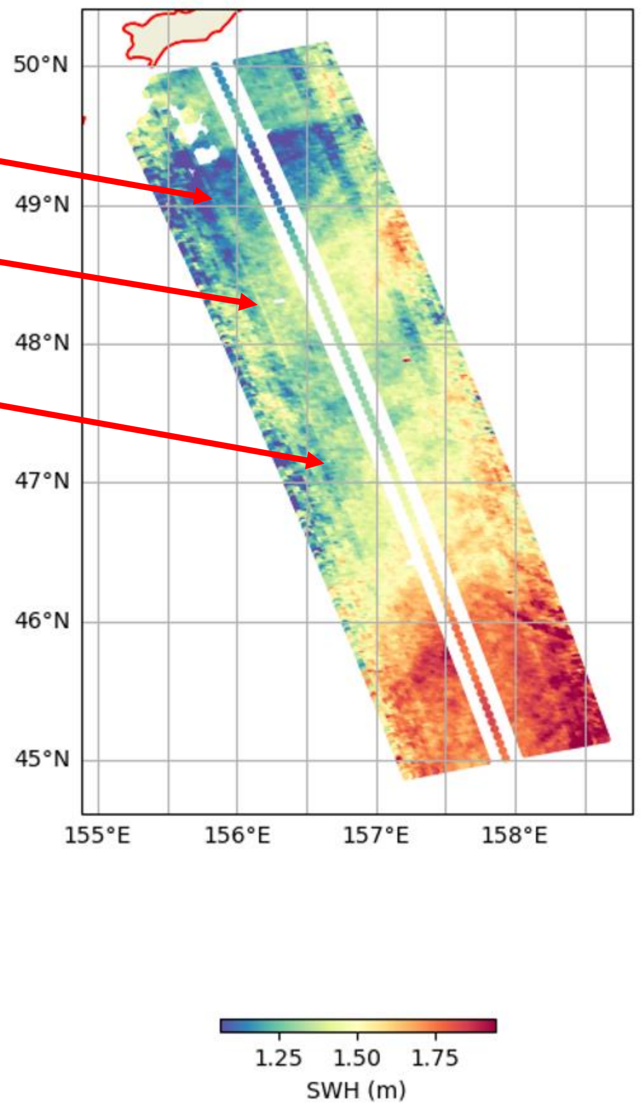
Instrumental errors varying over suborbital timescales



Along-track artefacts (likely coming from residual errors in the geometric correlation correction).

Latitude dependent (and ascending vs descending orbit)

As usual, magnitude of these errors increases at low SWH.



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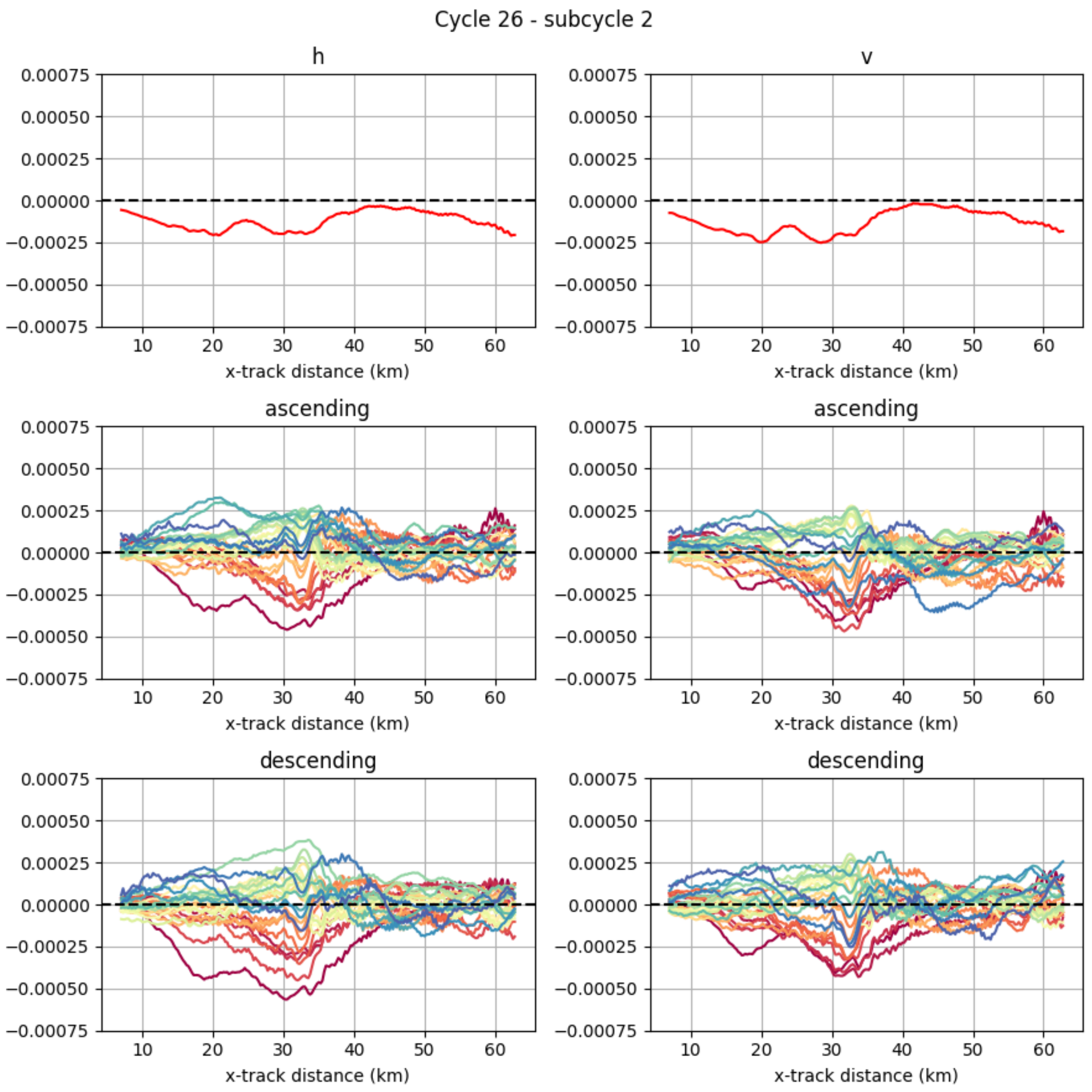
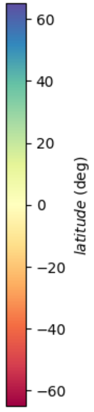


optimal calibration update for this specific 2.5 days interval (beta calibration)

Hypothetical additional optimal calibration update (for the same time period) **per band of latitude**



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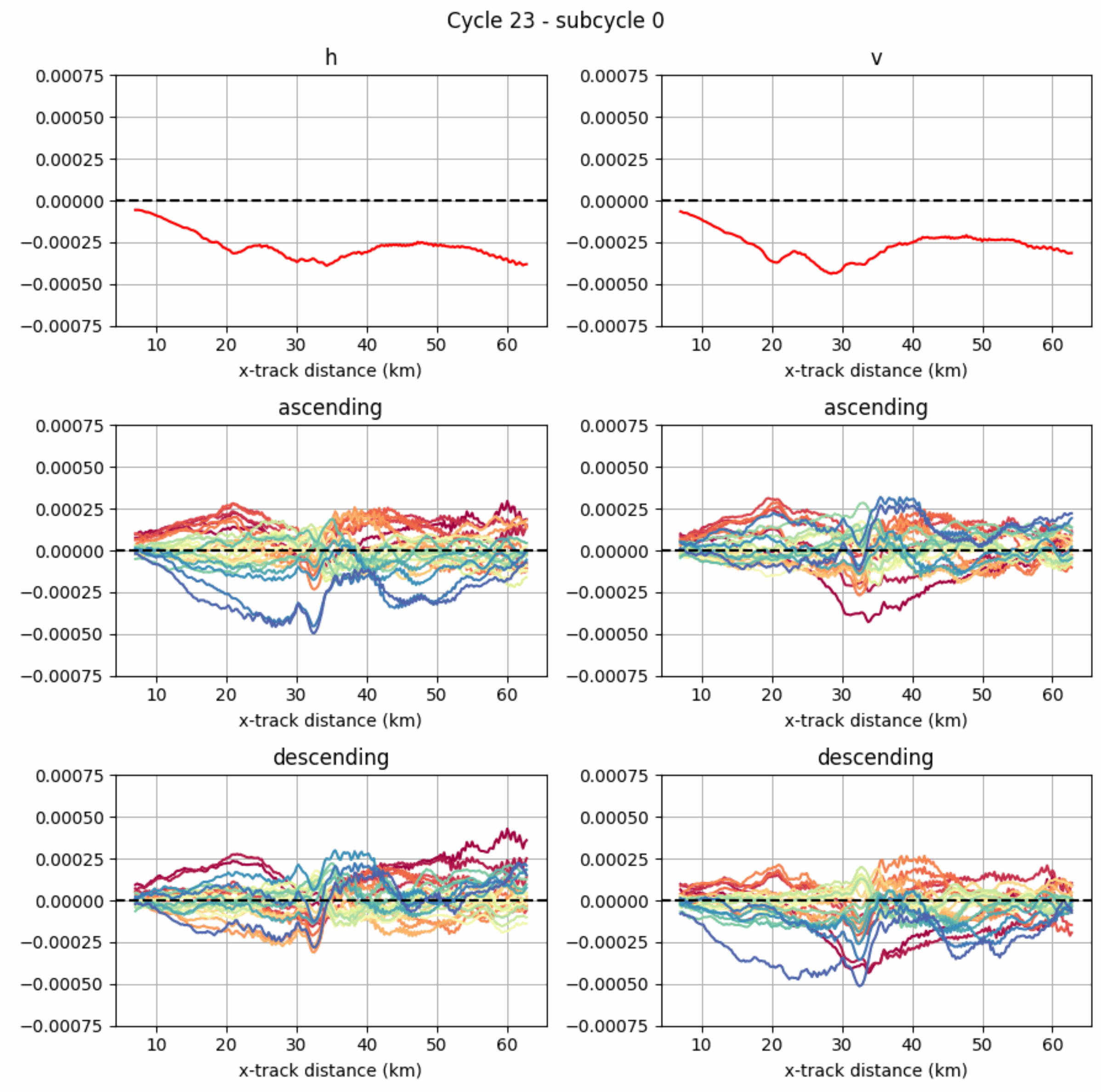

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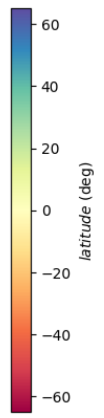

- **Dependence over long timescales involved (not beta).**
- **Possible dependence on surface (not just instrumental)**
- **Hard to capture empirically.**
- **Try to address it from first principles**

Work towards improving current estimates

1. Instrumental errors varying over long timescales (beta angle)

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3. Errors in the presence of strong sigma0 surface gradients (in particular, coastal areas)

4. Rain corrupted measurements

Errors in the presence of strong sigma0 surface gradients

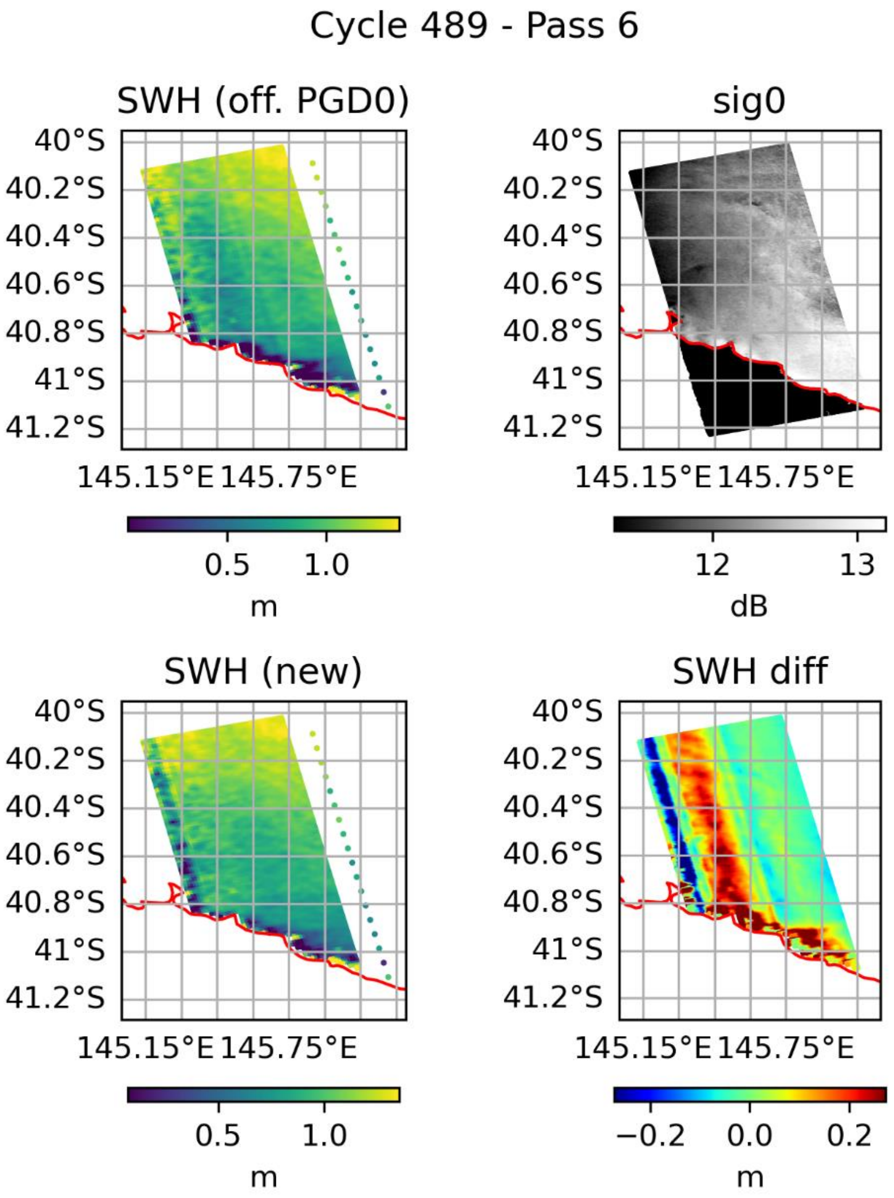
- The presence of (strong) across-track gradients of σ_0 at the surface induces changes in the geometric correlation (even in the absence of waves).

- Our **current processing assumes that σ_0 is uniform over the entire swath**, which can lead to SWH being underestimated when gradients are actually present.

- The **typical variations of sigma0 in the open ocean are small enough** for the error caused by ignoring them to be negligible.

- **At the coast, very strong contrast between water and land** (often more than 10dB) **leads to significant errors** (amplified by the fact that SWH is usually low close to the coast.

- **Current work** : experimental **algorithm** (computationnally expensive) **to account for sig0 variations** (using KaRIn's measurement of sig0) improves the behavior at the coast.



Errors in the presence of strong sigma0 surface gradients

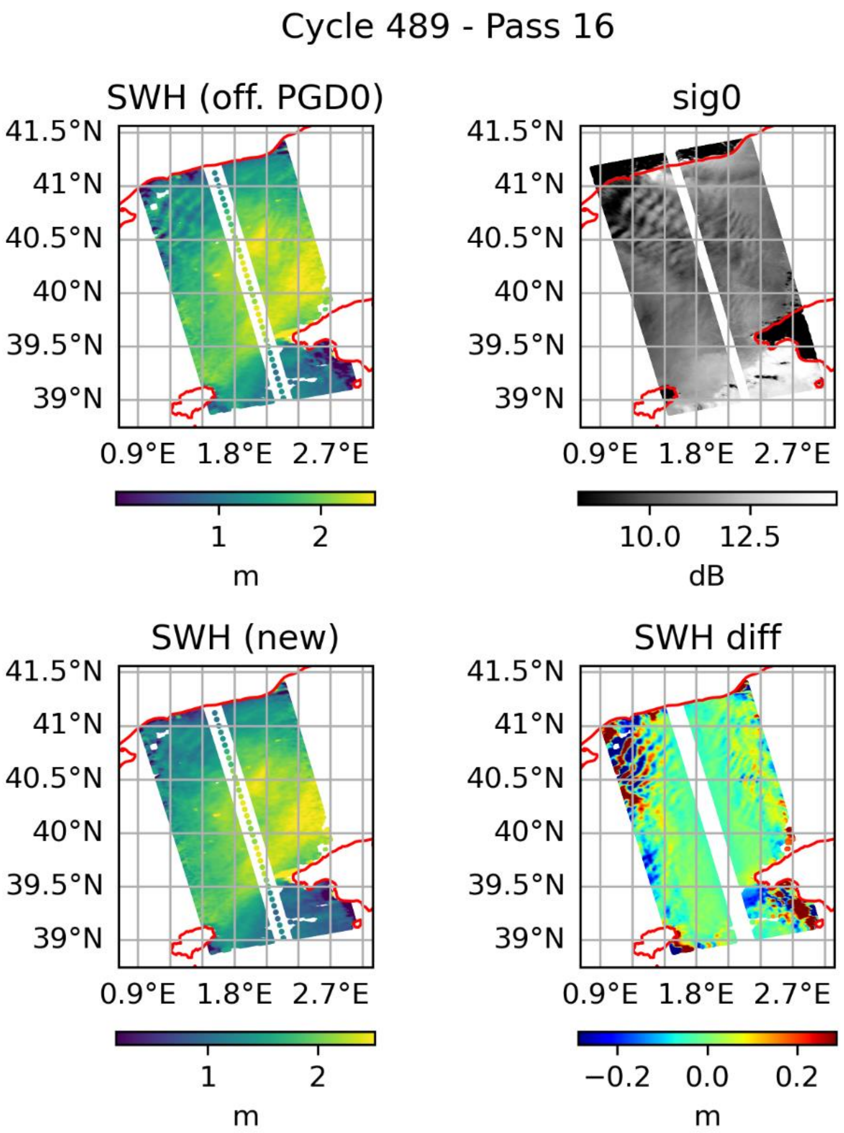
- Another example where large sig0 modulations come from the sea surface (not land/water contrast at coast).

  See P. Abjean's presentation for a much more detailed discussion of this case.

- Large spurious oscillations in SWH, where sig0 oscillates

- New SWH inversion algorithm accounting for measured sig0 in computation of geometric correlation drastically reduces these oscillations

- some (smaller amplitude) residual oscillations remain visible. Unclear whether they are residual error, or true geophysical patterns (SWH variations), or a mixture of both.



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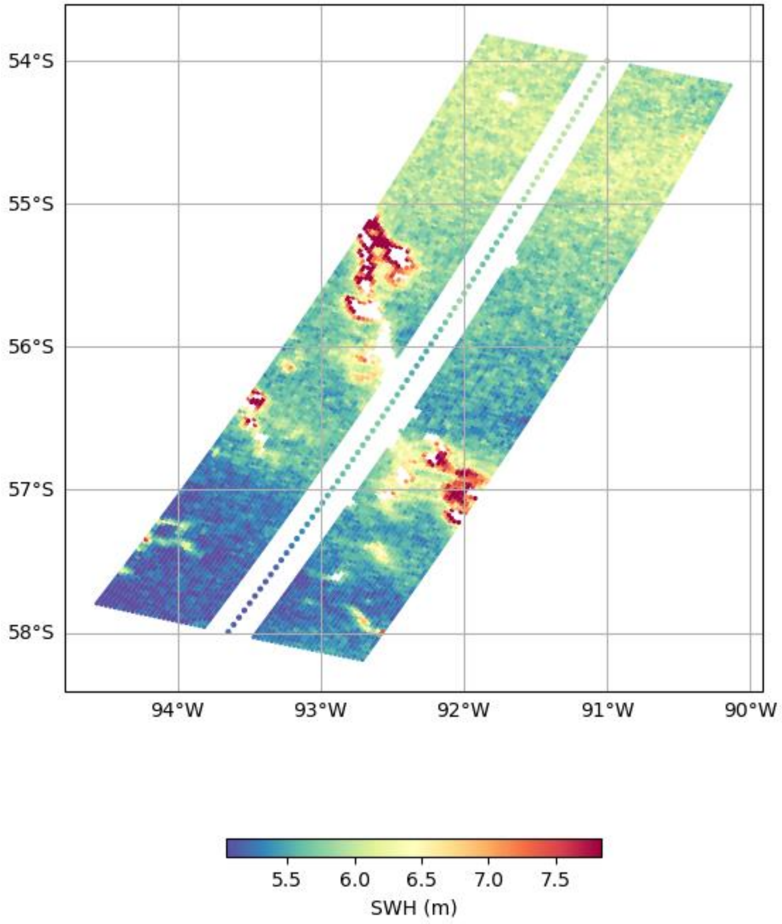
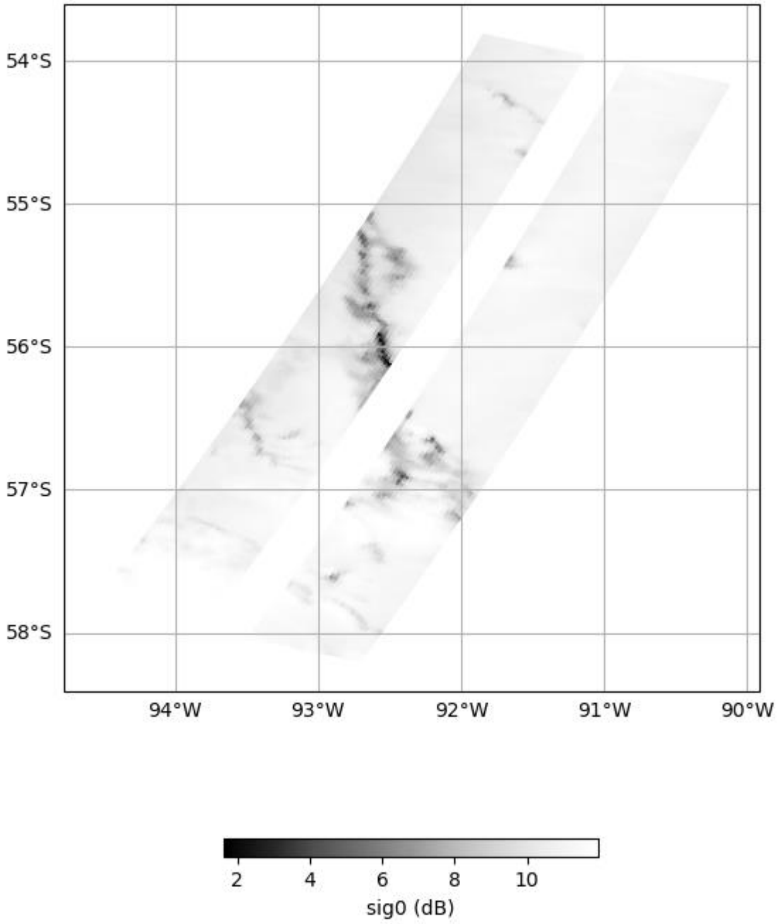




- Interferometric correlation very sensitive to rain. Leads to huge overestimates of SWH (by several meters)
- Hard to correct, hard to flag (work in progress, see M. Raynal's talk in this session)
- Current version of quality flag (swh_karin_qual) tends to correctly identify the center of the cells but misses the edges. Sometimes misses them entirely.

Conclusions

- KaRIn provides 2D maps of SWH, allowing to study small scale features of the wave fields.
- We continue to work on improving the SWH estimates from KaRIn.
  - identify/characterize/correct residual time-varying instrumental errors (beta angle, suborbital)
  - correct for effect of string sig0 gradients at the surface (most notably at coast)
  - flag rain-contaminated measurements

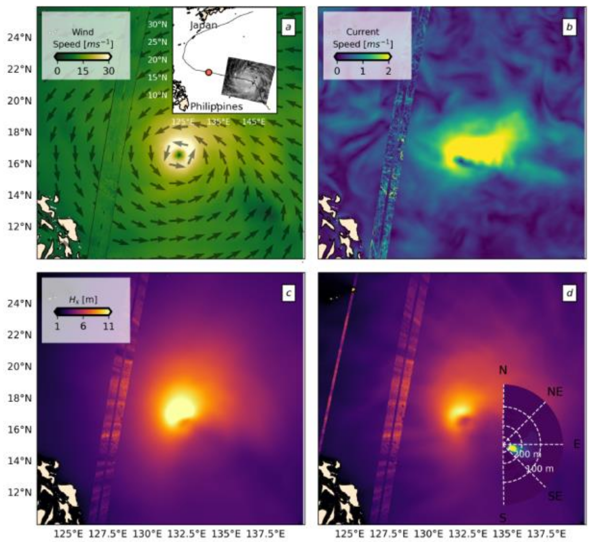


Figure 3. Panels (a)–(d) follow the same conventions as Fig 1, but show data for a SWOT pass over the far-field of Typhoon Mawar on 2023-05-27 at 06:41 UTC. The inset on panel (a) shows the TC's trajectory. The location of the TC during the SWOT pass is highlighted with a red circle and the closest Sentinel-3A image available is overlayed.

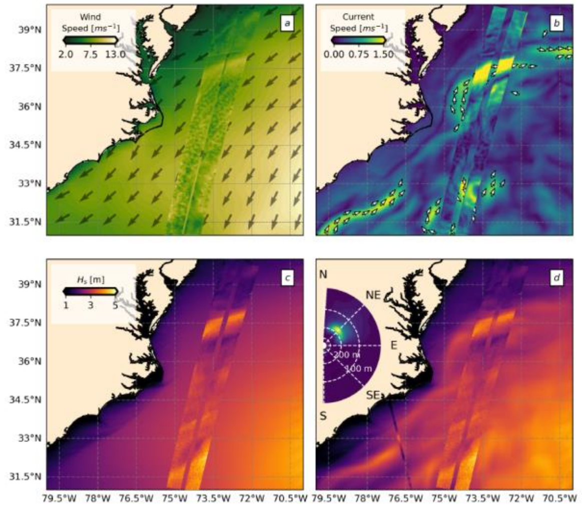
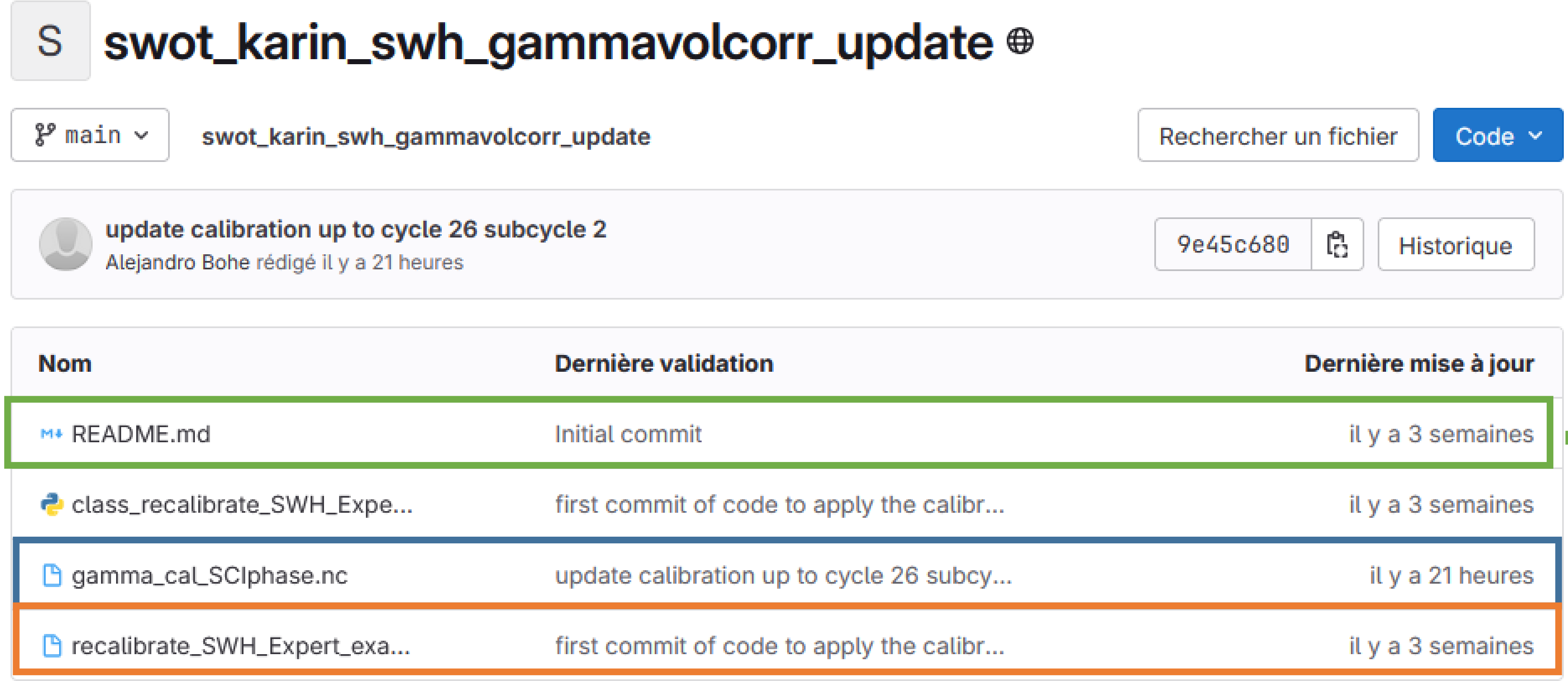


Figure 1. Wind, currents, and wave conditions in the Gulf Stream region during a SWOT pass on 2023-09-02 at 04:13 UTC. Panel (a) shows the wind speed and direction from the ERA-5 reanalysis. Wind speed from SWOT is overlayed. Panel (b) shows the current speed and direction (only for current faster than 0.7 ms^{-1}) from the HYCOM model. Geostrophic currents computed from SWOT's SSH observations are overlayed. Panels (c) and (d) show WW3 H_s snapshots from simulations performed with (CURR) and without (CTRL) current forcing respectively. H_s from SWOT is overlayed on (c) and (d). CFOSAT observations of H_s (thin line) and directional wave spectrum (inset) are shown on panel (d).

examples from Villas Bôas et al. 2025

beta dependent errors : code to apply the correction

For now, users can find tools to apply correction here :
git clone https://framagit.org/alejandro.bohe/swot_karin_swh_gammavolcorr_update.git



empty for now...

updated every 5-6 days

see next slide

beta dependent errors : code to apply the correction

```
[1]: import xarray as xr
     import numpy as np
     import matplotlib.pyplot as plt
```

```
[2]: calibration_path = './'
     import sys
     sys.path.append(calibration_path)
     import recalibrate_SWH_betatest

     calibration_file = calibration_path+'./gamma_cal_SCIphase.nc'
     updater = recalibrate_SWH_betatest.SWH_updater(calibration_file)
```

```
[3]: #%%time
     path_to_Expert_product = './SWOT_L2_LR_SSH_Expert_023_001_20241022T060534_20241022T065701_PIC2_01.nc'
     expert_ds = xr.open_dataset(path_to_Expert_product)
     # apply correction; returns an updated xarray dataset with a new variable "swh_karin_corrected"
     expert_ds = updater.correct_SWH(expert_ds)
```

SWOT primary … and secondary measurements

- **SWOT is primarily a topography mission !** **Surface height images are derived from the phase difference between the two KaRIn antennas.**

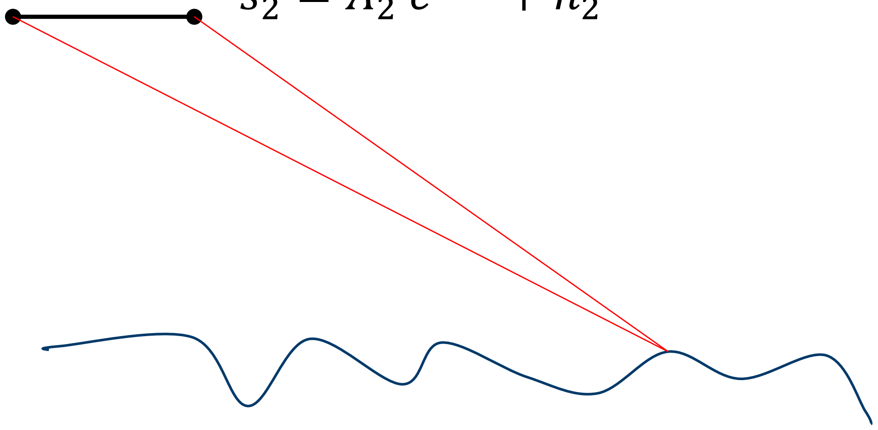
- This is « only » one of the four independent real combinations that can be formed using the two complex signals at each antenna.

- The **single-channel powers** can be **processed** (to remove instrumental contributions such as antenna gains) **to obtain NRCS images**, **from which we can infer wind speed** (other physical processes such as waves, currents or biological films also create sigma0 modulations, although they are in general sub dominant).

- **A fourth independent combination** of the complex received signals is the interferometric correlation (sometimes referred to as coherence).

$$s_1 = A_1\, e^{i\varphi_1} + n_1$$

$$s_2 = A_2\, e^{i\varphi_2} + n_2$$



$$arg < s_1\; s_2^* > = \varphi_2 - \varphi_1 \rightarrow height$$

$$< |s_1|^2 >, < |s_2|^2 > \rightarrow \sigma_0$$

$$\gamma = \frac{|< s_1 s_2^* >|}{\sqrt{< |s_1|^2 >< |s_2|^2 >}}$$