Surface Water and Ocean Topography (SWOT) Mission

September 2023

Alejandro Bohe,

P. Dubois, B. Molero, B. Stiles

(on behalf of the JPL/CNES ADT team)

SWH measurements from KaRIn
+ « mitigation doppler »
+ noise from waves
+ wind retrieval status

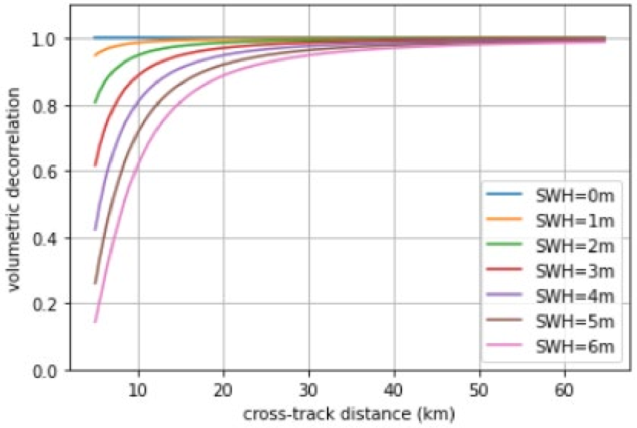
SWH from KaRIn : inversion method

- Waves introduce interferometric decorrelation. The effect increases with SWH.

- There are other sources of decorrelation :

  - Geometric/angular decorrelation only depends on the geometry of the acquisition and the PTR and antenna gains. It can be predicted.

  - Computing SNR decorrelation requires a measurement of SNR. This is estimated by measuring the power in the noise alone and substracting it from the total received power (noise+signal).



- Dividing the total measured coherence by those two contributions, one obtains a measurement of volumetric decorrelation, which can be inverted to measure the SWH.

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

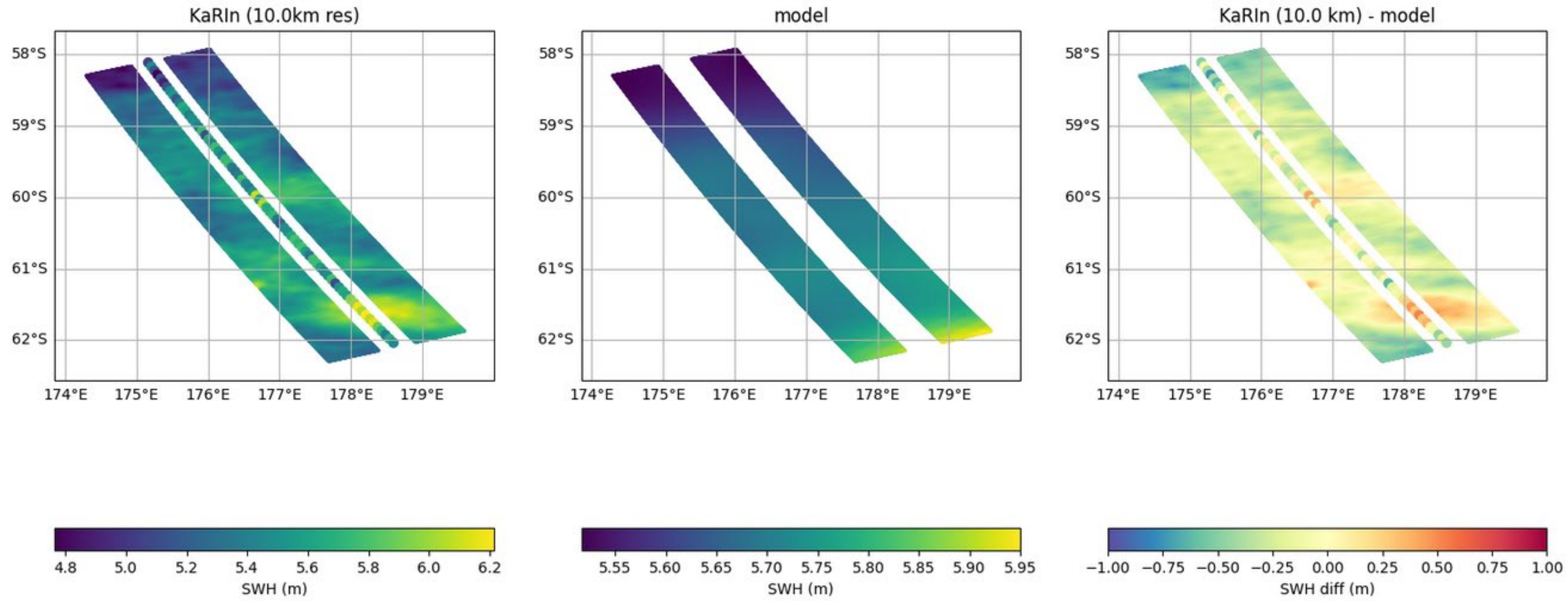
measure on data

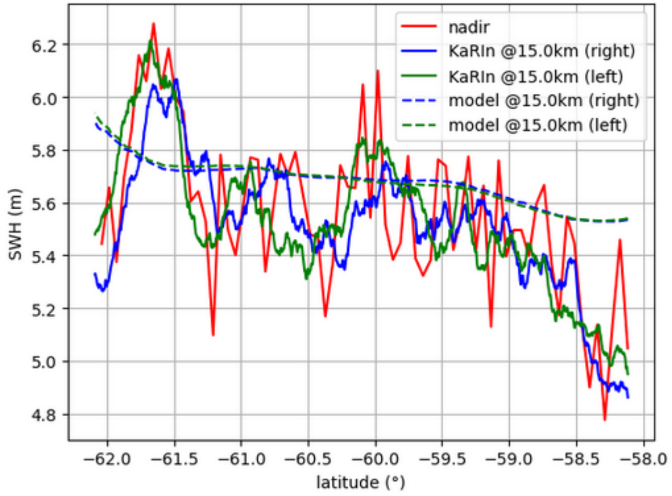
compute from system params and geometry

- Instrumental challenge : additional decorrelation is introduced by the hardware and needs to be calibrated with flight data.

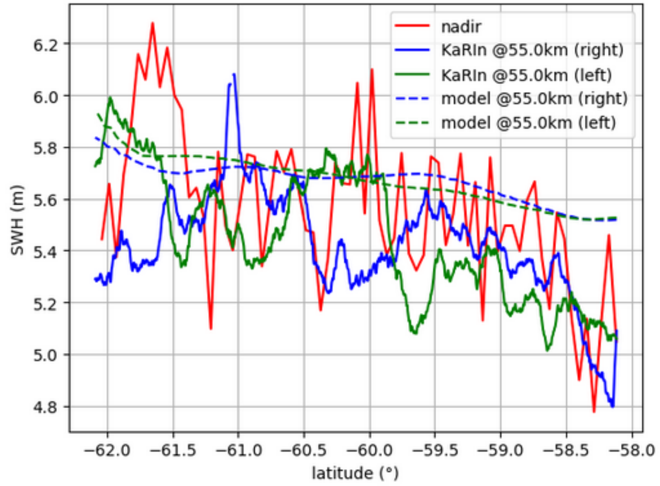
- Any additional decorrelation (e.g. from the atmosphere) would be interpreted as waves

2D SWH maps from KaRIn : a few examples



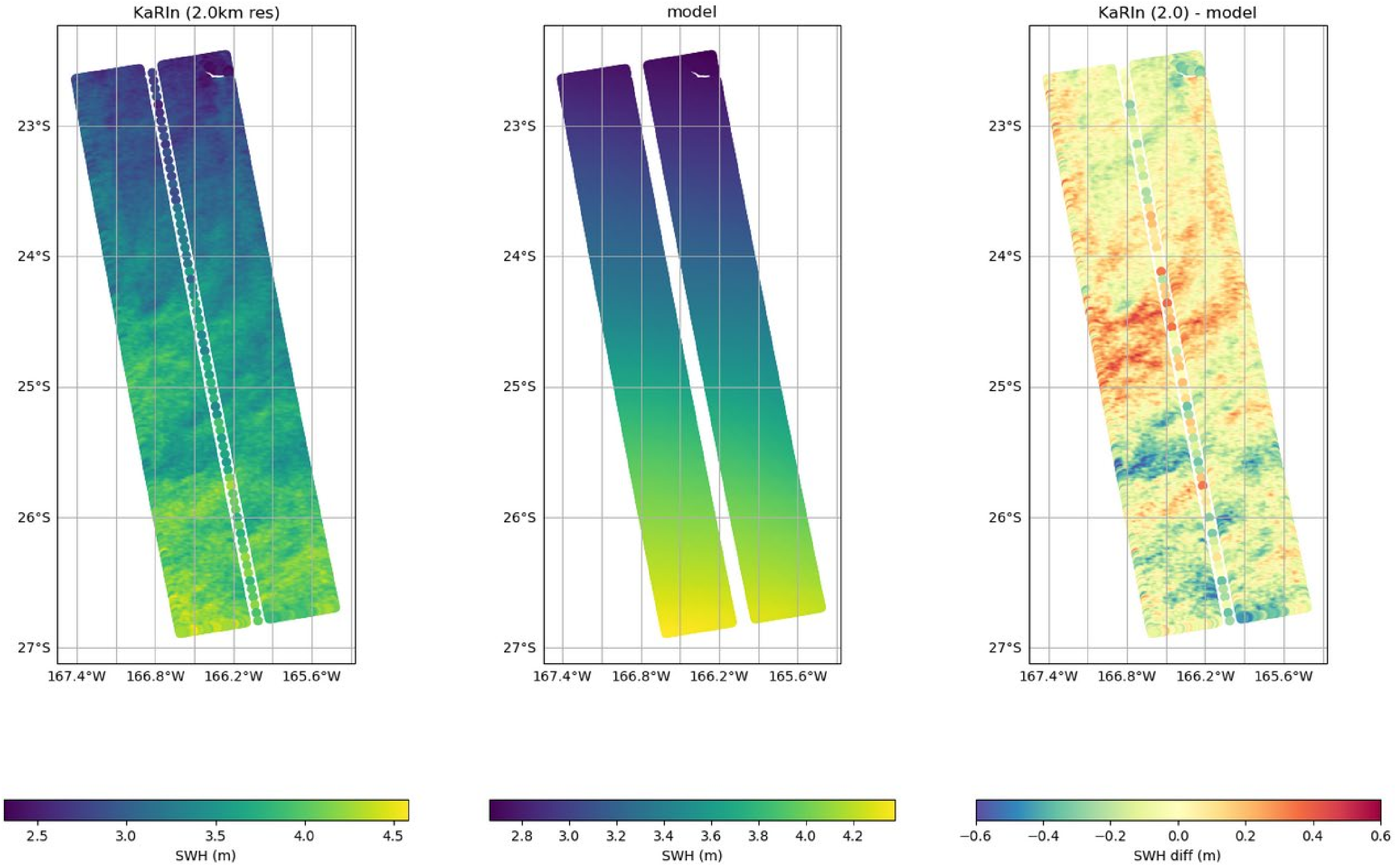


cycle 522
Pass 4



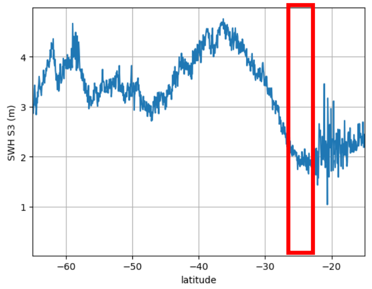
- High SWH region (5-6 m)
- The model misses some structures (at scales of tens of km) which are seen by KaRIn and the nadir. KaRIn reveals their actual shapes.
- Noise in KaRIn's measurements significantly smaller than in the nadir

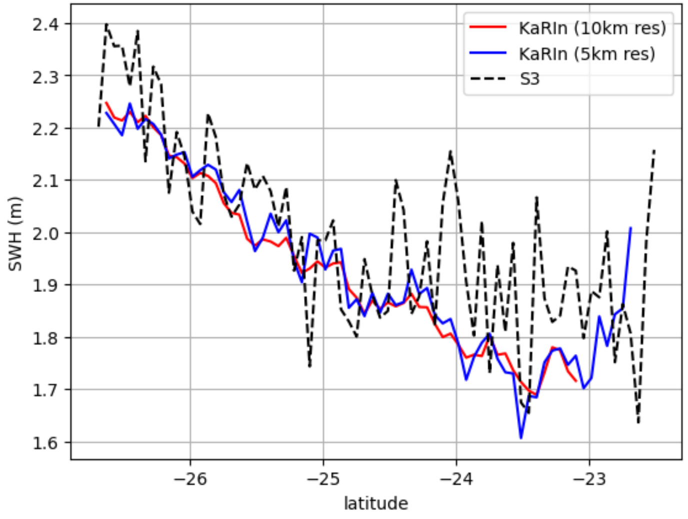
2D SWH maps from KaRIn : a few examples

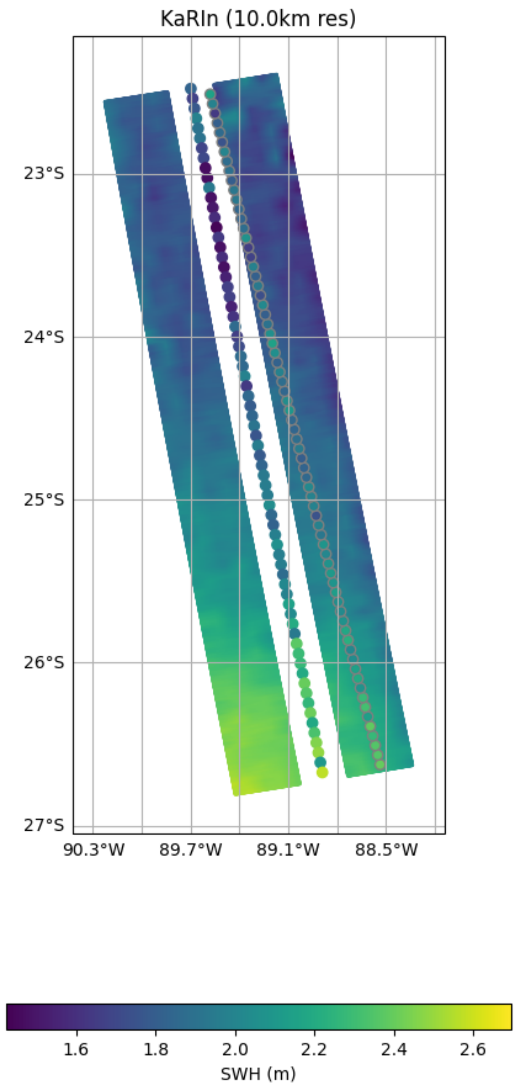


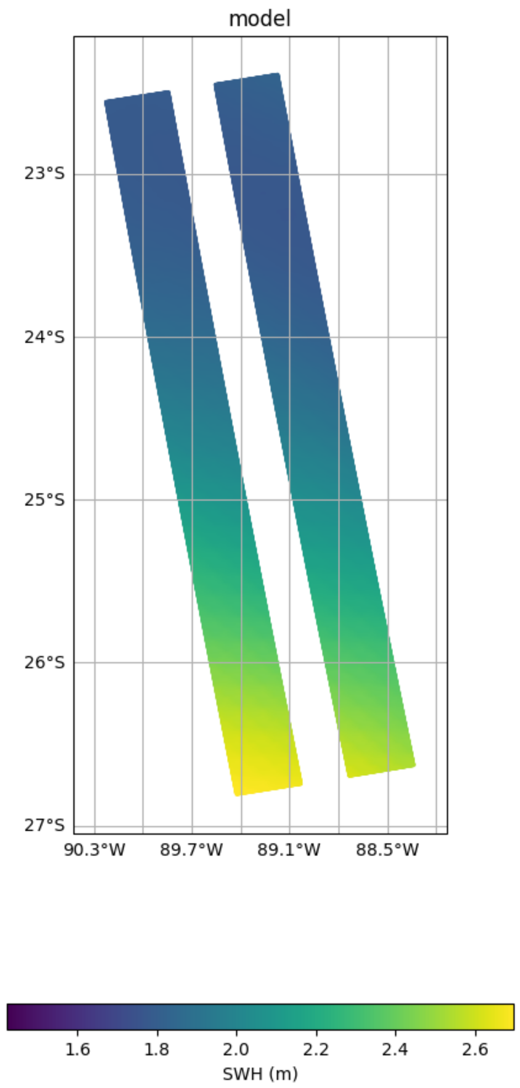
KaRin vs S3 comparison

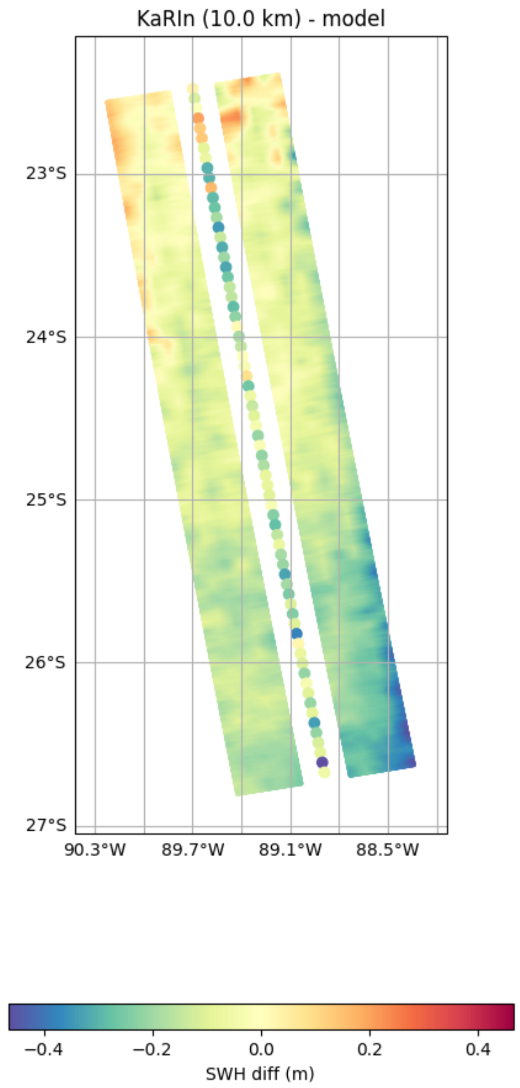
S3 crosses the left swath ~2h later





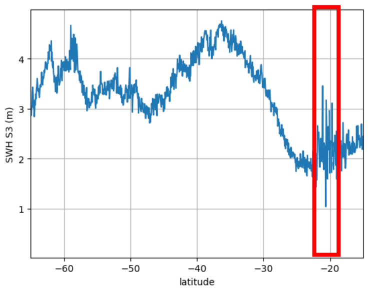


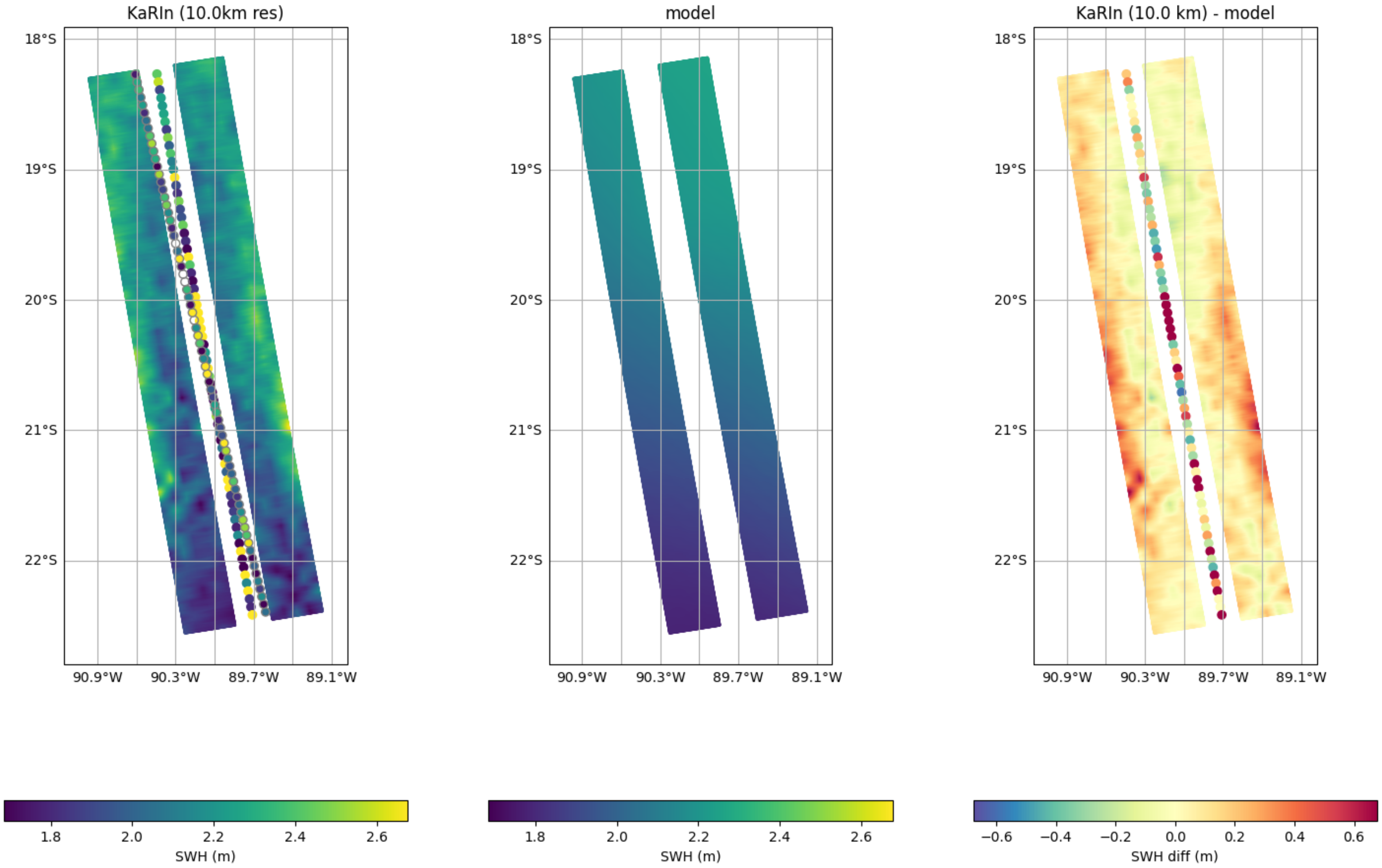


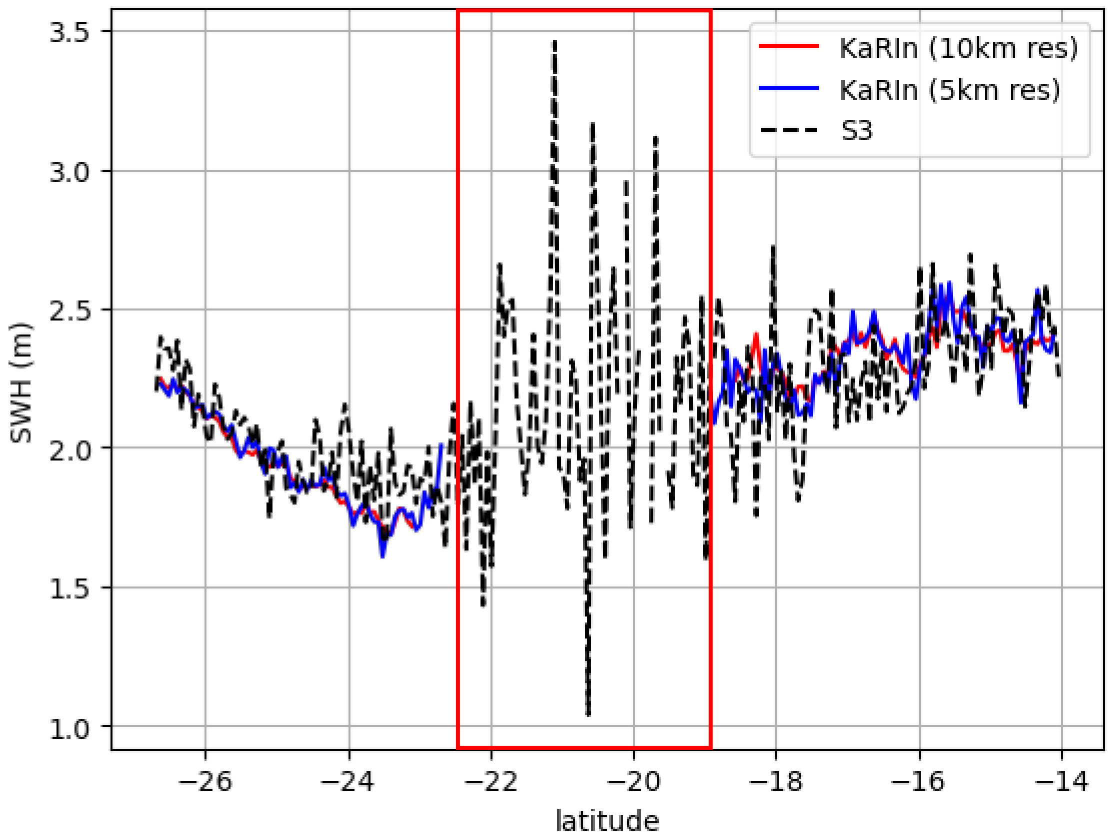


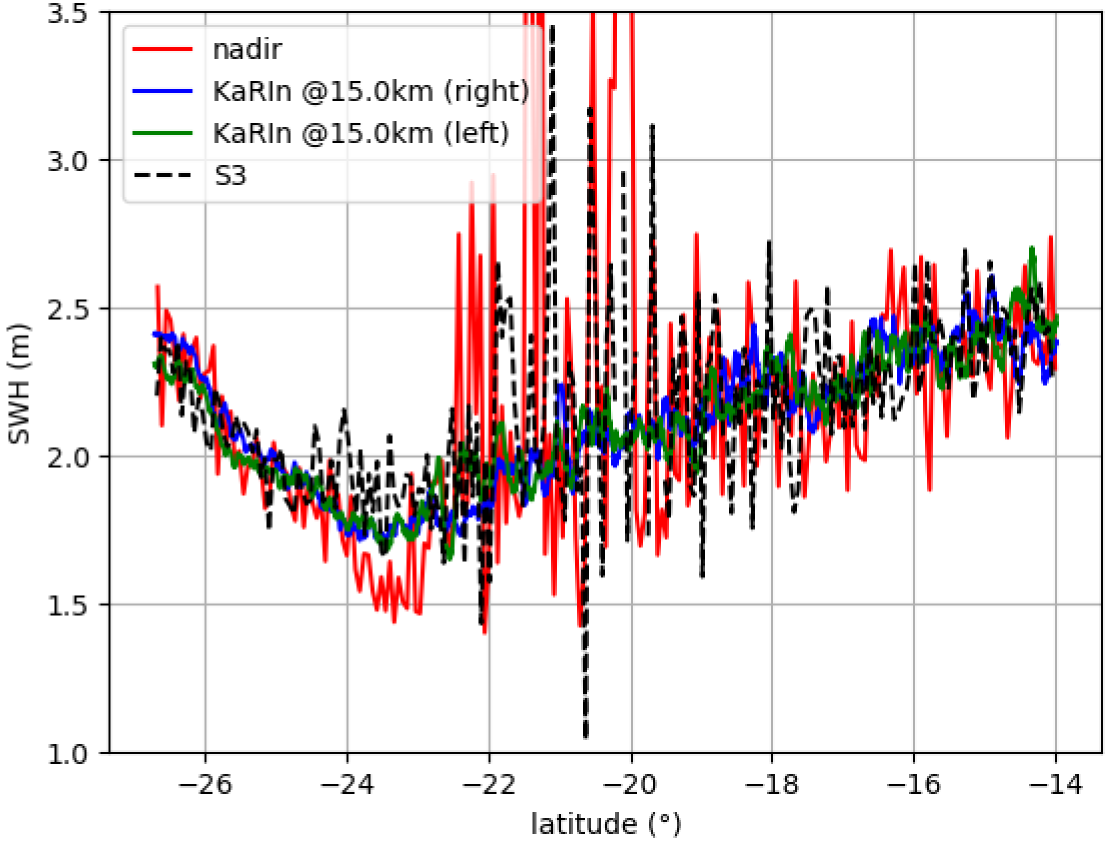
KaRin vs S3 comparison

S3 crosses the nadir gap









Sentinel3 crosses the gap between KaRIn's swaths just where the noise becomes very large for S3 (swell region).

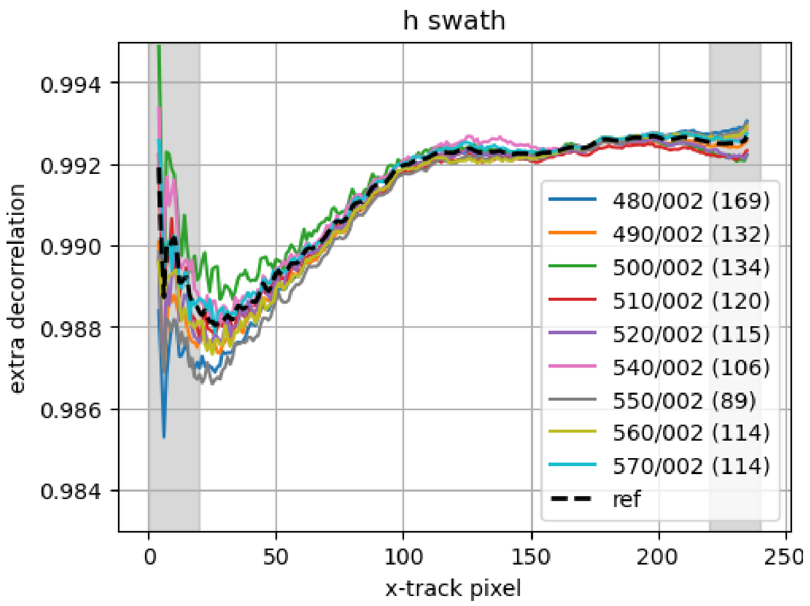
We cannot reinterpolate KaRIn's SWH on S3's track.

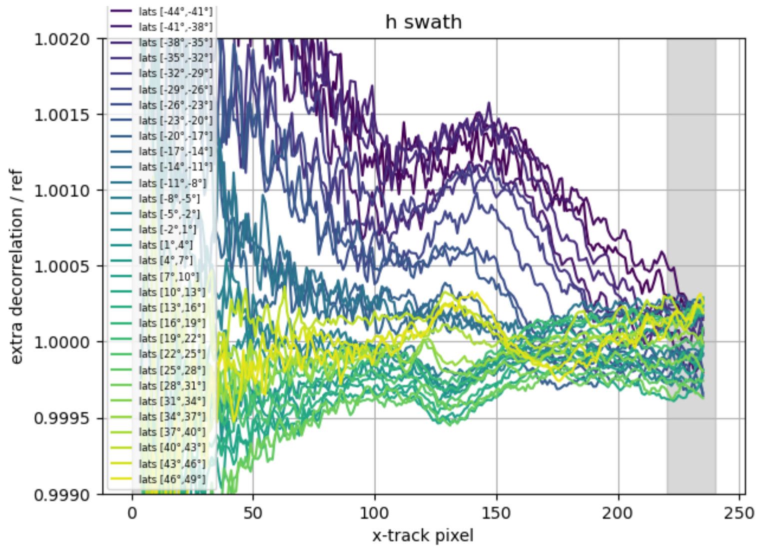
Instead, we compare the SWH measured at slightly different locations by

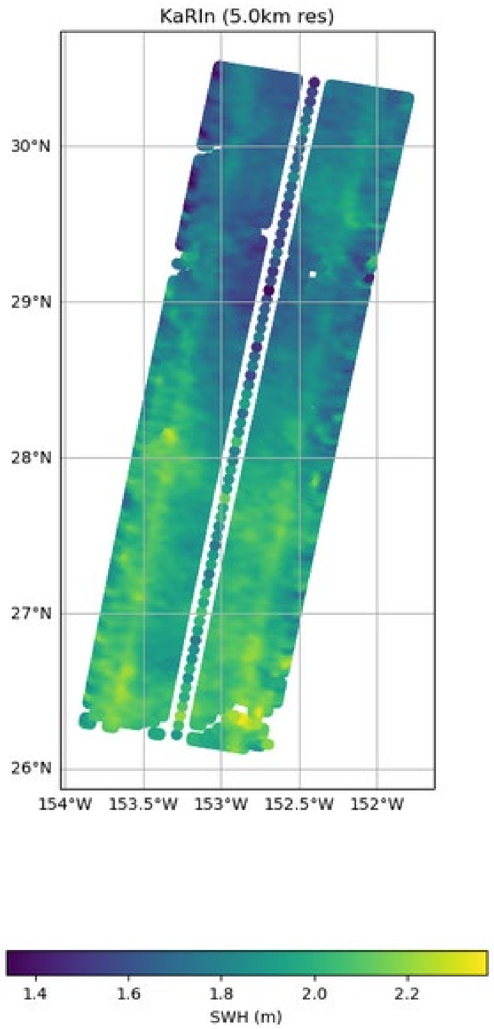
- S3
- POS-3C
- KaRIn at 15km left and right swath

The noise in POS-3C also blows up, so the swell is almost certainly still there despite the 2h offset. KaRIn's SWH noise remains much smaller

Calibration stability and variation along orbital circle

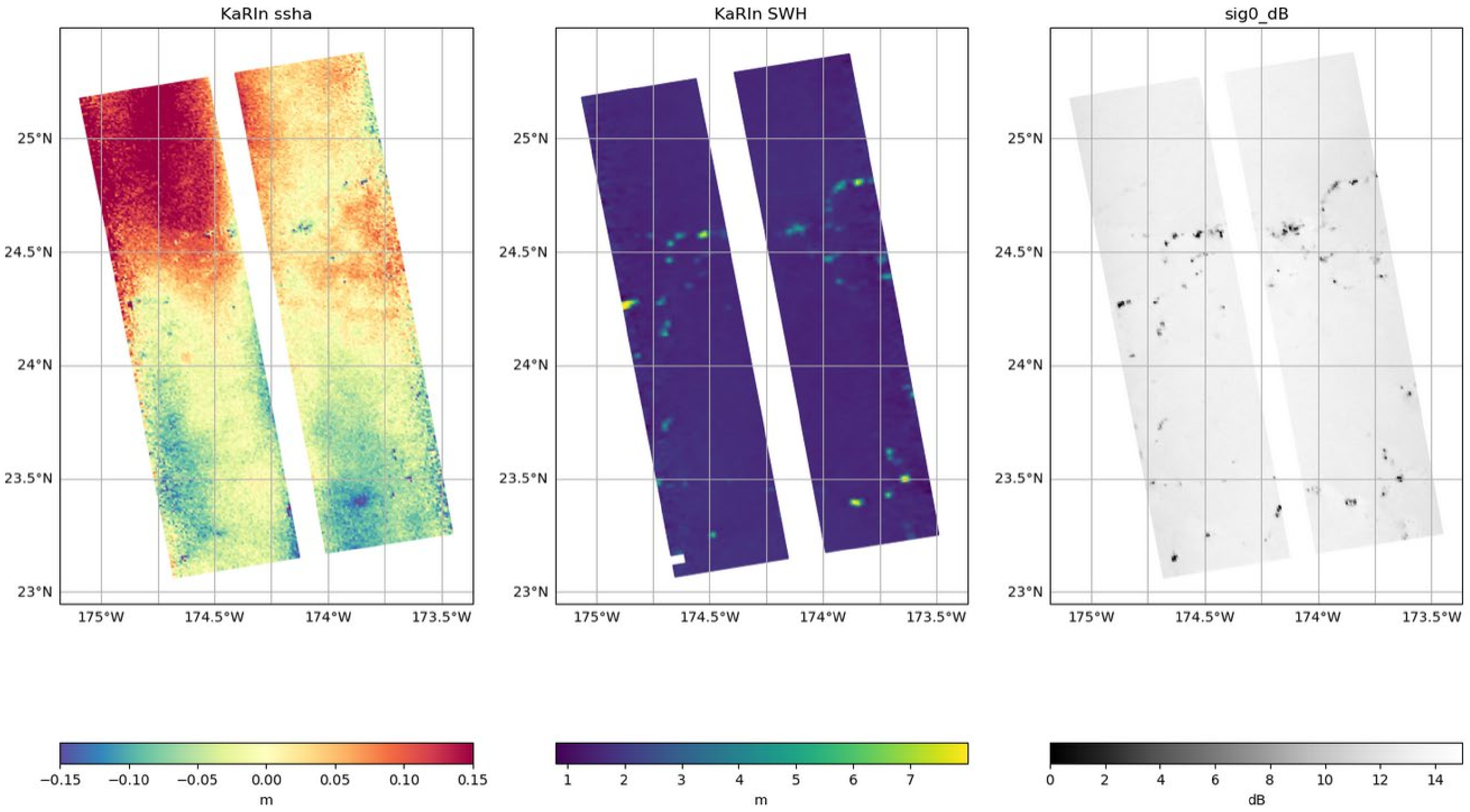




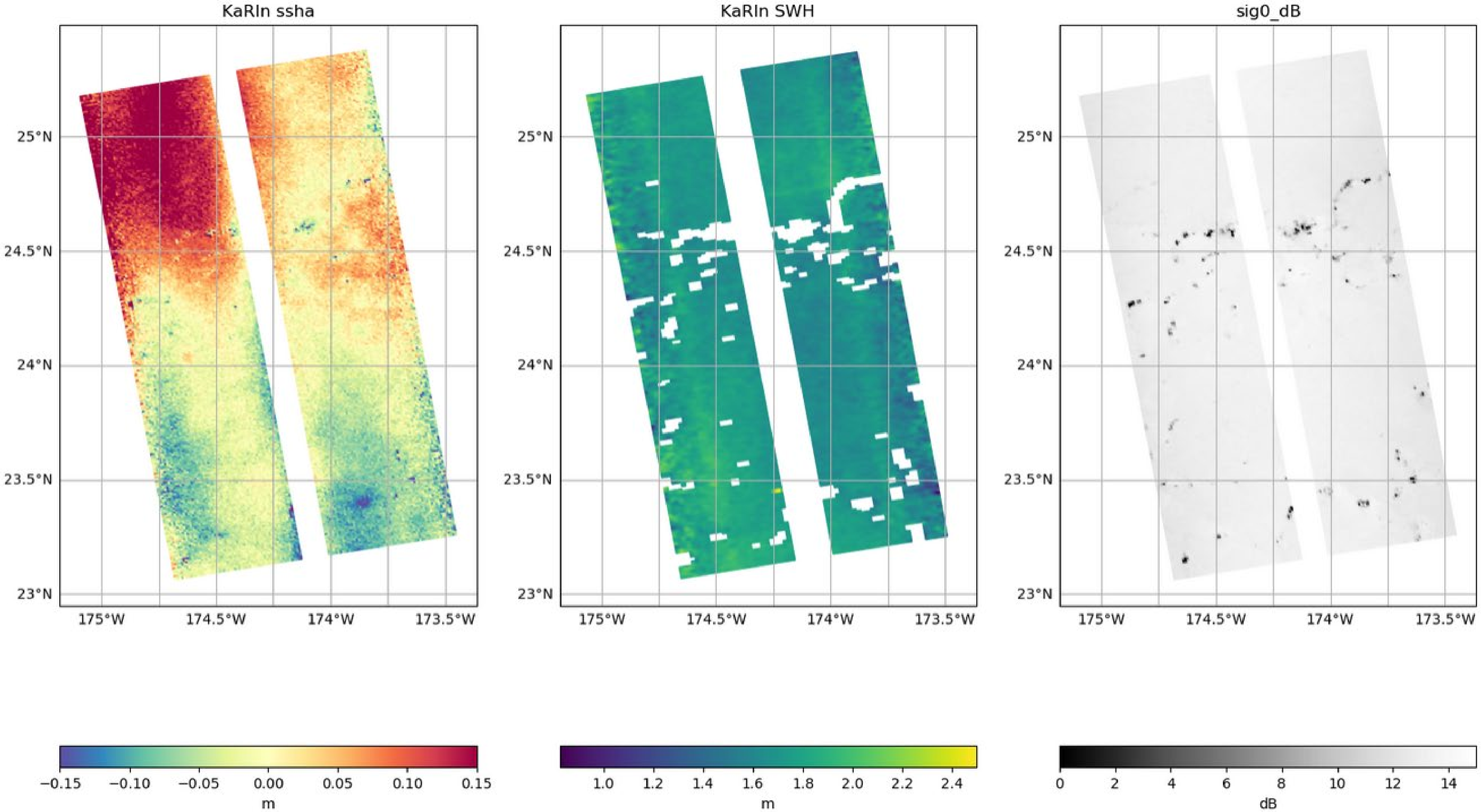


- The « average calibration per pass » remains stable over a timescale of weeks (no strong dependence on beta angle). The black line on the top left plot is what will be used in the « Fall » reprocessing?
- Small but non negligible variations of this instrumental decorrelation along the orbital cycle create latitude dependent artefacts in the retrieved fields.
- Neither the calibration of decorrelation nor this 2D inversion are in the official processing chain yet. All results shown here are from an offline processor which was run over a handful of passes.

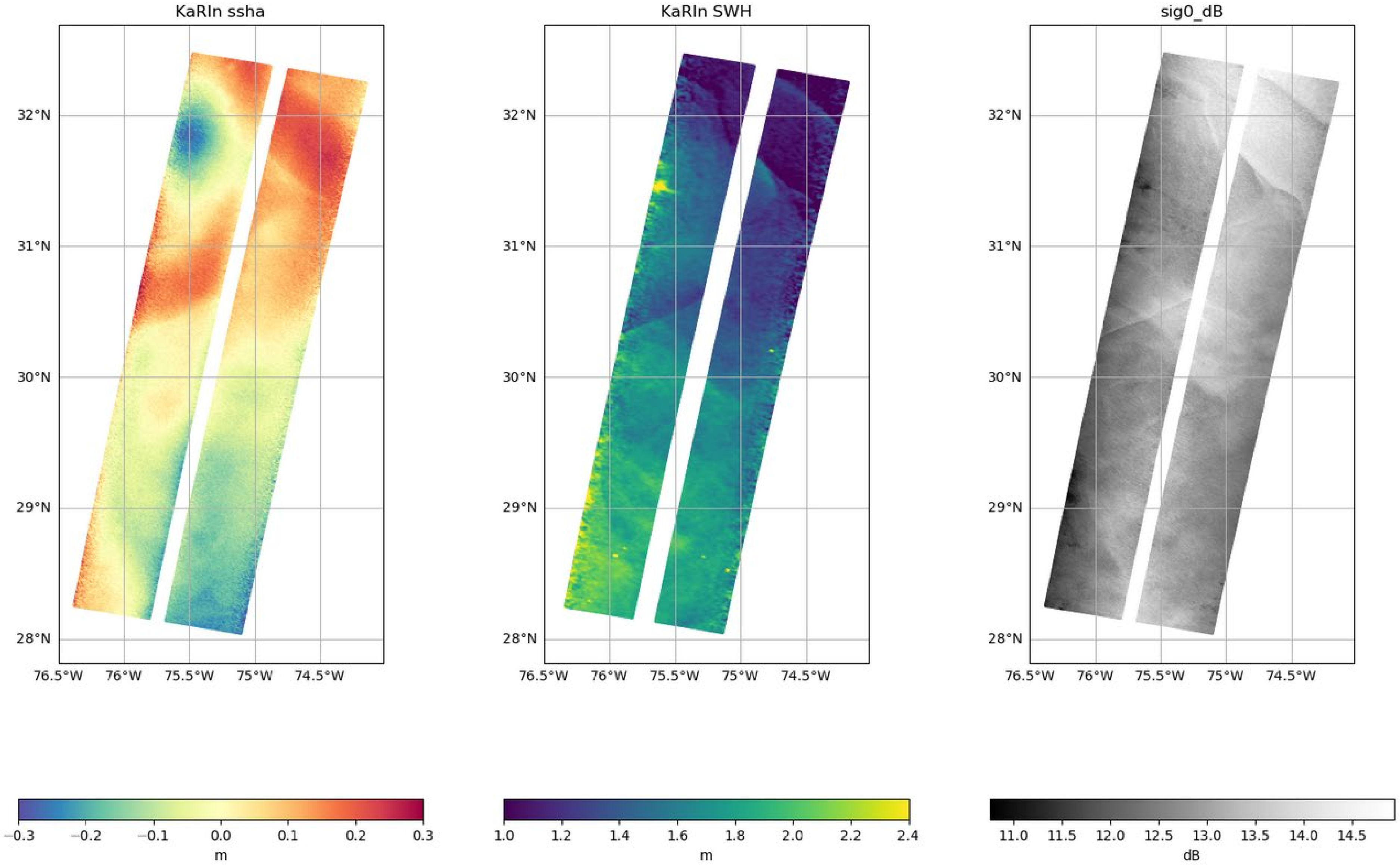
Wave retrieval and rain



Wave retrieval and rain



Correlated signal from surface vs correlated error ?



Summary

- Available in « Fall » reprocessing :
  - 2D SWH maps at 2km posting.
  - Calibration of instrumental effects in decorrelation, but needs to be refined (still contains latitude dependent effects leading to visible artefacts in the 2D fields)

- Preliminary analysis shows
  - Excellent consistency with completely independent nadir on SWOT
  - Excellent consistency with Sentinel 3 (only one Xover looked at so far)
  - 2D retrievals captured both along track and cross-track gradients make a lot of sense

- Validation is non trivial (models not sufficient at small scales). Disentangling actual SWH features from errors of geophysical origin (rain, probably other sources…) correlated with sig0 is one of the topics where we need input from the ST !

- Noise on SWH measurement hard to quantify, because not all the high frequency variations of SWH is noise. Wave groups induce local variations in statistics.

« mitigation doppler »

Mitigation/HR Doppler data variable

2 Doppler information in SWOT data product

- The OnBoard Doppler centroid: slope and intercept of a linear fit in across track direction, every 4km in along-track.
- 2-D Mitigation/ "High Resolution" Doppler image (L1B_LR_INTF): Doppler estimates on a 2x2km grid.

Note: Doppler are estimated using the pulse-pair method.

The Doppler captures everything that moves in the direction of the slant range during azimuth time:

$$\text{Measured Doppler} = \text{NonGeophysical Doppler} + \text{Geophysical Doppler}$$

NonGeophysical Doppler — originates from: The center of phase position in time + the ground projected antenna pattern shape.
It can be estimated using the POD, attitude reconstruction (L1B_LR_INTF data) and antenna pattern best knowledge (CAL data), by solving a geometric-based system of equations.

Geophysical Doppler — originates from: The surface motions: the surface currents and the waves orbital velocities
Note: SWOT's radial direction being almost vertical, the surface currents do NOT significantly impact the measured Dopplers.

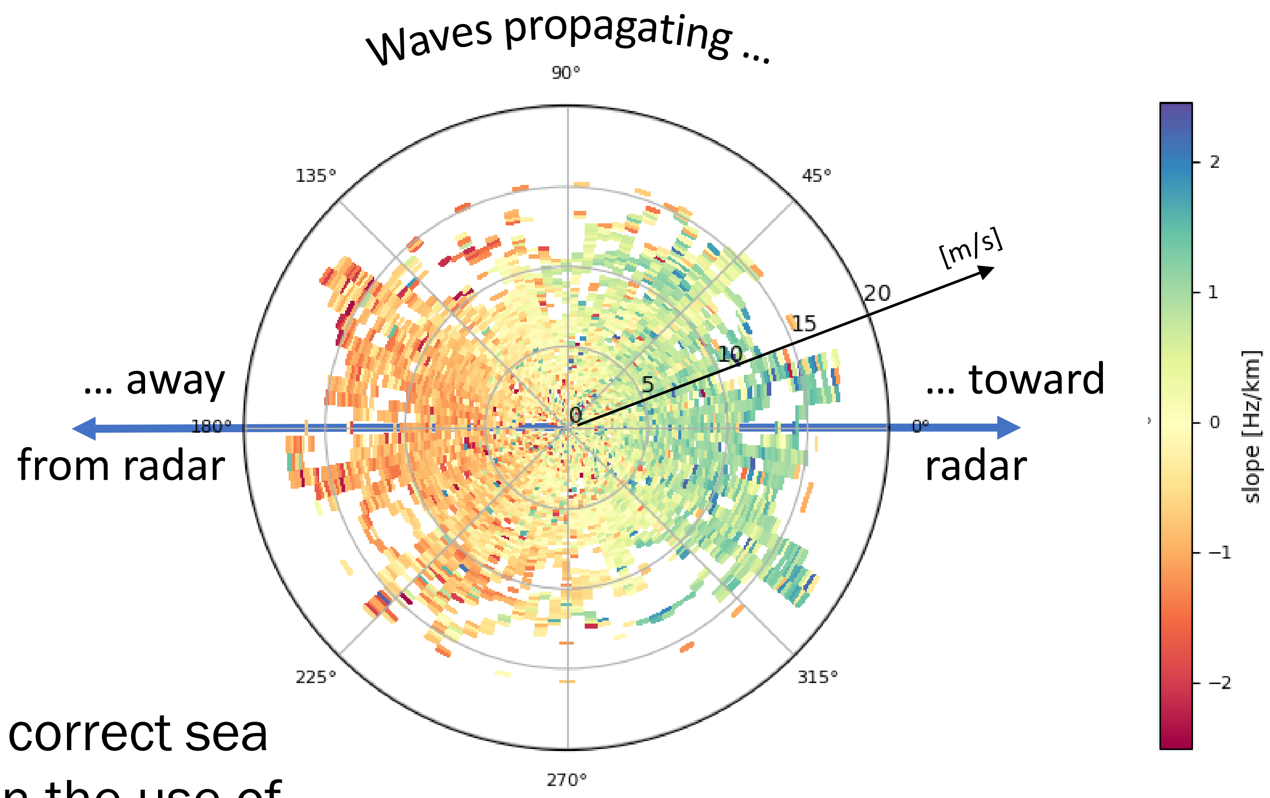
At last, $(\text{Measured Doppler} - \text{NonGeophysical Doppler})$ should contain sea state signature and should provide additional sea state information.

Mitigation/HR Doppler data variable

Methodology:

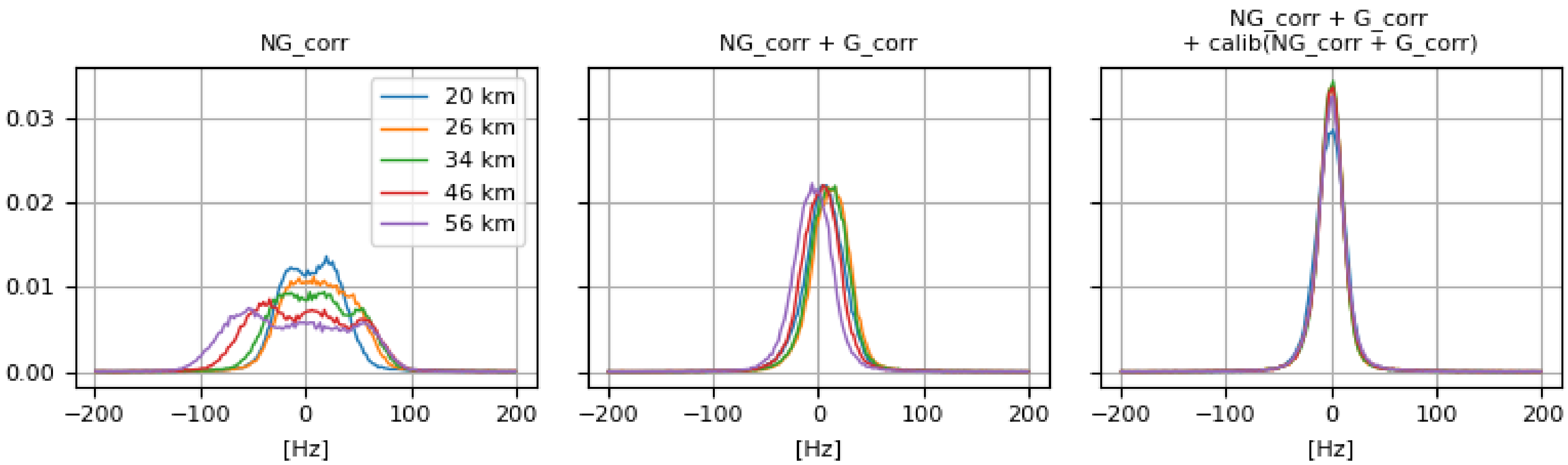
1. Correct measured Doppler from NonGeophysical Doppler
2. A theoretical Geophysical Doppler is computed for each pass, the mean of NG_corr + G_corr is removed
3. For each line (azimuth time), the slope of the corrected Mitigation Doppler across-track profile slope is estimated and reported in a table function of wind speed and wind direction (from ECMWF Model).

Results show a change of sign with the waves relative direction to radar, and the perpendicular directions producing no Doppler slope.
The magnitude of the Doppler is increasing with wind speed.



→ the mitigation Doppler data variable exhibits a correct sea state dependency. This is a promising first result in the use of Doppler to complete the characterization of sea state.

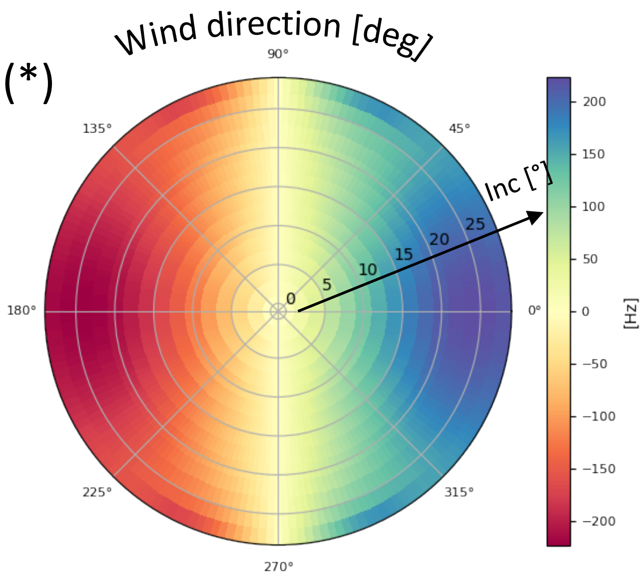
Mitigation/HR Doppler data variable



Methodology:

- NG_corr — Measured Doppler corrected from NonGeophysical Doppler.
- NG_corr + G_corr — Measured Doppler corrected from NonGeophysical Doppler and a Geophysical Doppler from a theoretical model (*) which is parametrized using wind speed and direction from ECMWF model
- NG_corr + G_corr + calib — for each pass, the residual mean of NG_corr + G_corr for each across track distance is removed.

(*)

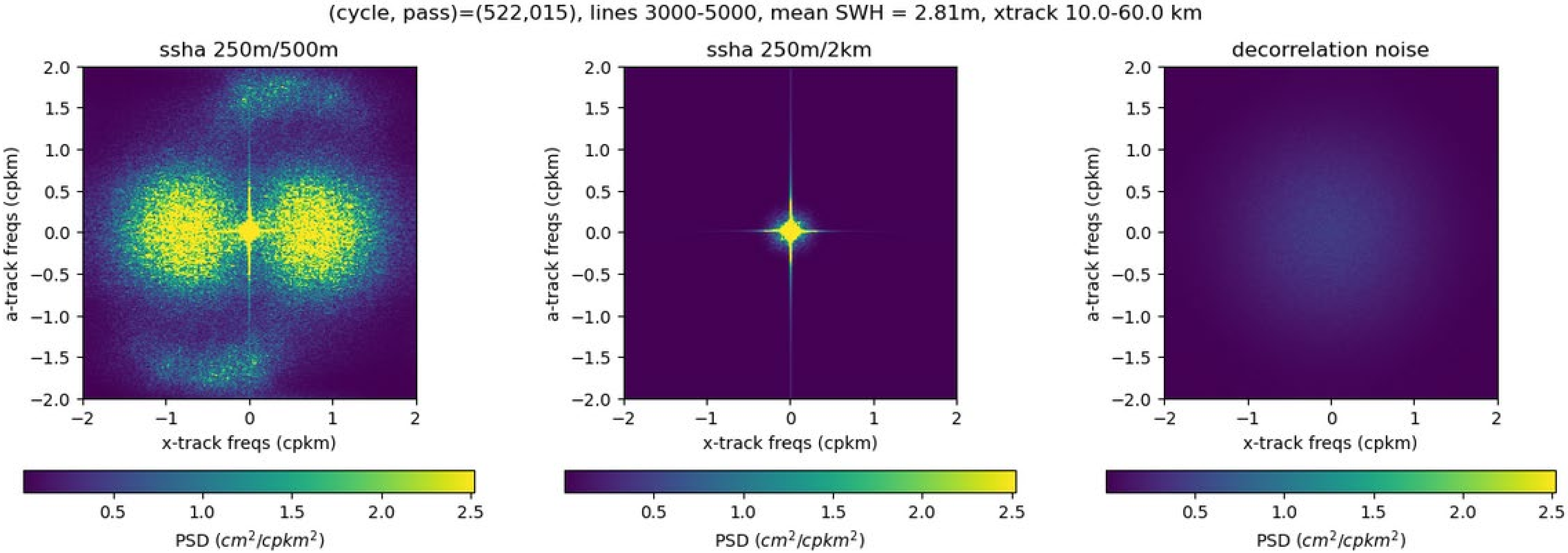


Model @10m/s

The results (right) show histograms with zero means, advocating that we can isolate a significant (in line with theory) Geophysical Doppler from the Mitigation Doppler.

Noise from waves

2D spectra : first example



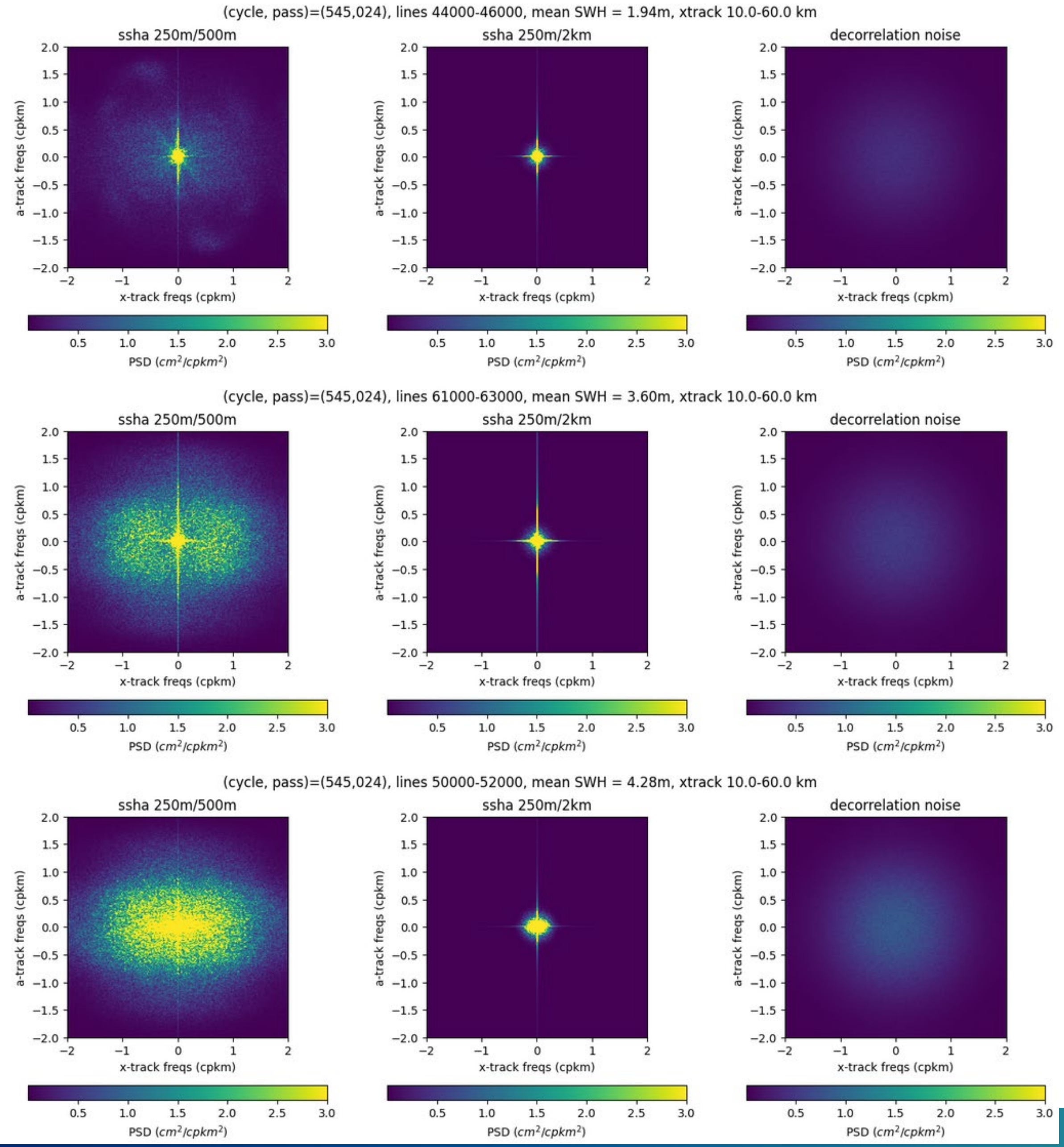
- The noise from waves has a non-trivial 2D structure.
- Rescaling of rms to different resolution is non trivial (and sea state dependent).
- A large amount of the non-linear noise from the waves is filtered out at 2km already.
- 1D spectrum is essentially an average line by line of these 2D spectra
- In this example, the non-linear contribution is much more significant than the one from decorrelation.

Impact of SWH

SWH ~2 m

SWH ~3.5 m

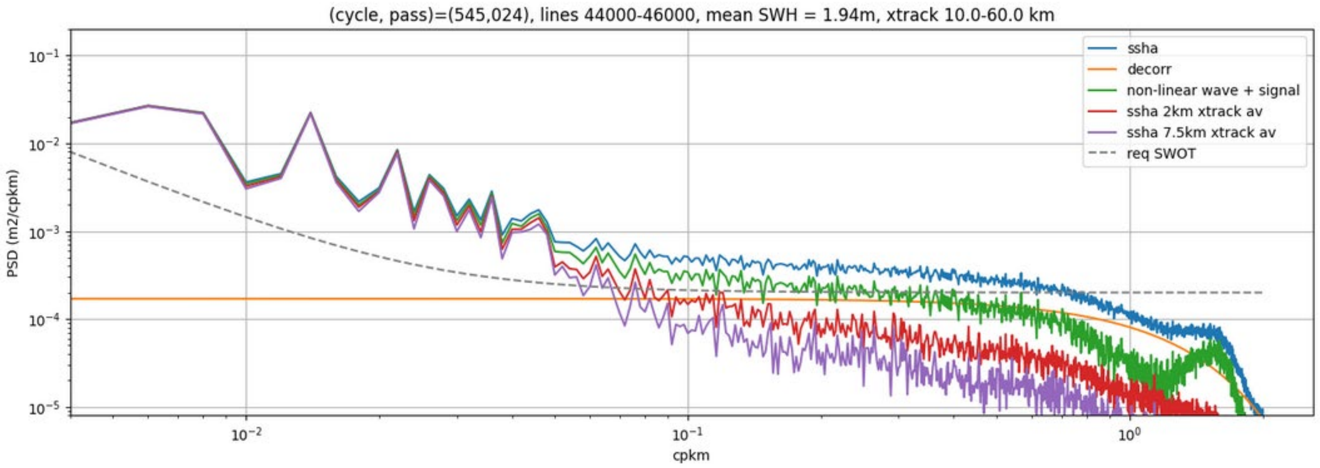
SWH ~4.3 m



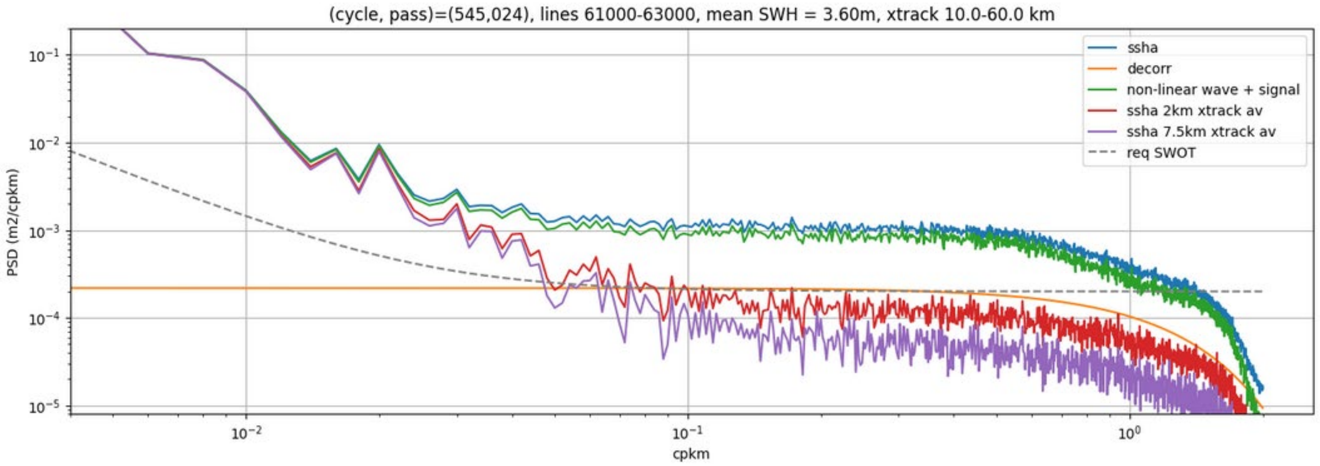
Impact of SWH

- As expected, the rms and the plateau of the 1D spectrum increase significantly with SWH for the 250m/500m resolution product.
- What looks in 1D like white noise dominating the signal up to wavelengths of tens of km is actually mostly high frequency 2D noise.
- Cross-track averaging significantly reduces these noise levels.
- Already at 2km resolution, the spectrum of the errors attributable to the waves is below the requirements (which apply to SWH<2m)

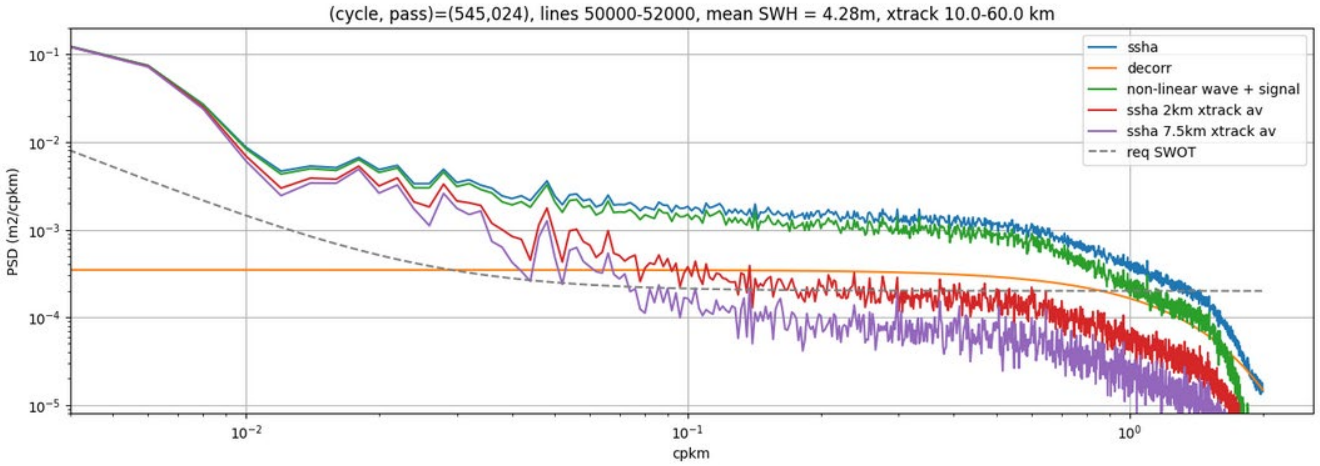
SWH ~2 m



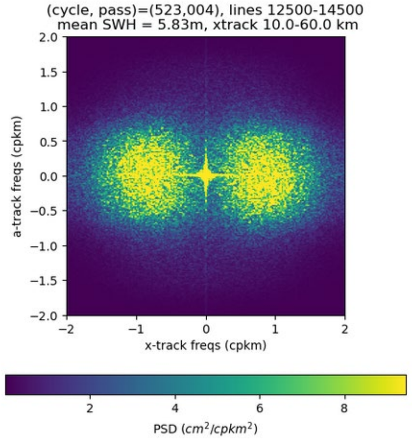
SWH ~3.5 m

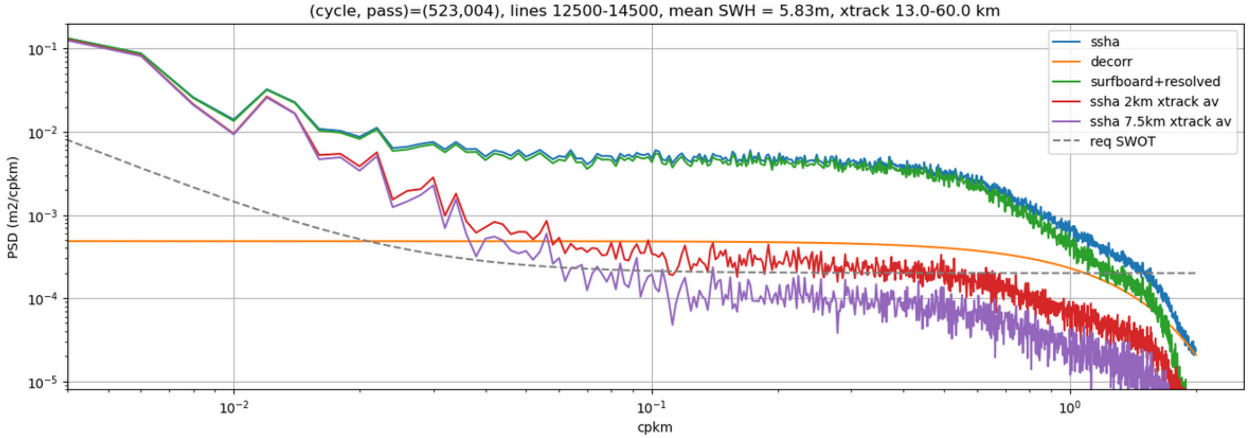


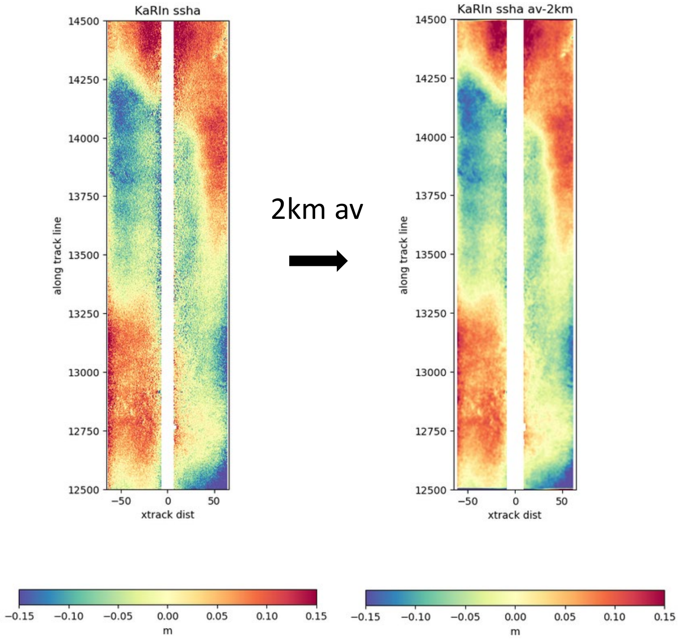
SWH ~4.3 m

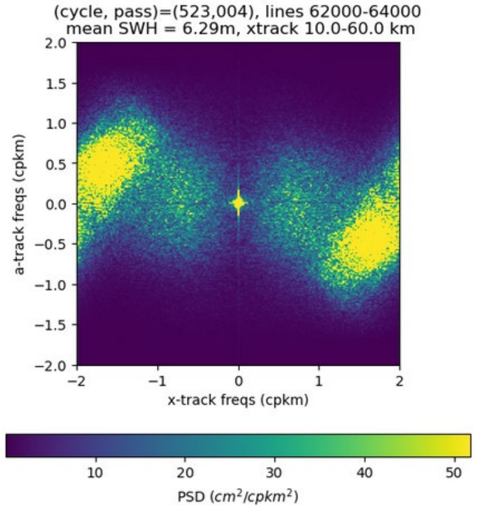


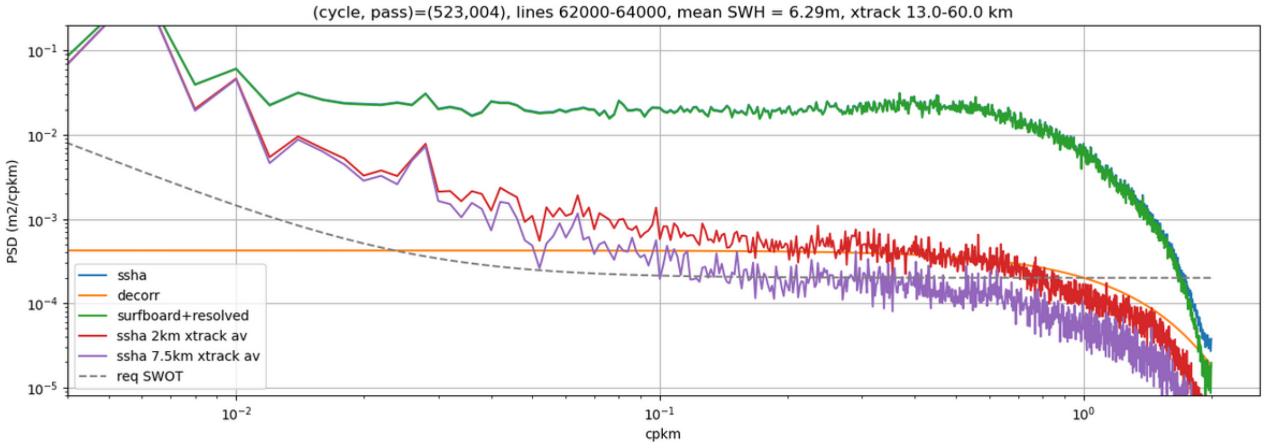
~ 6m waves

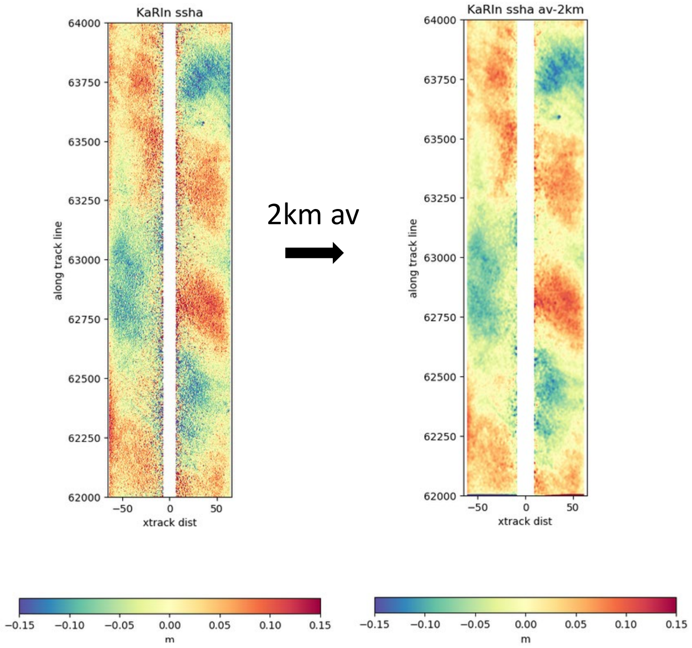






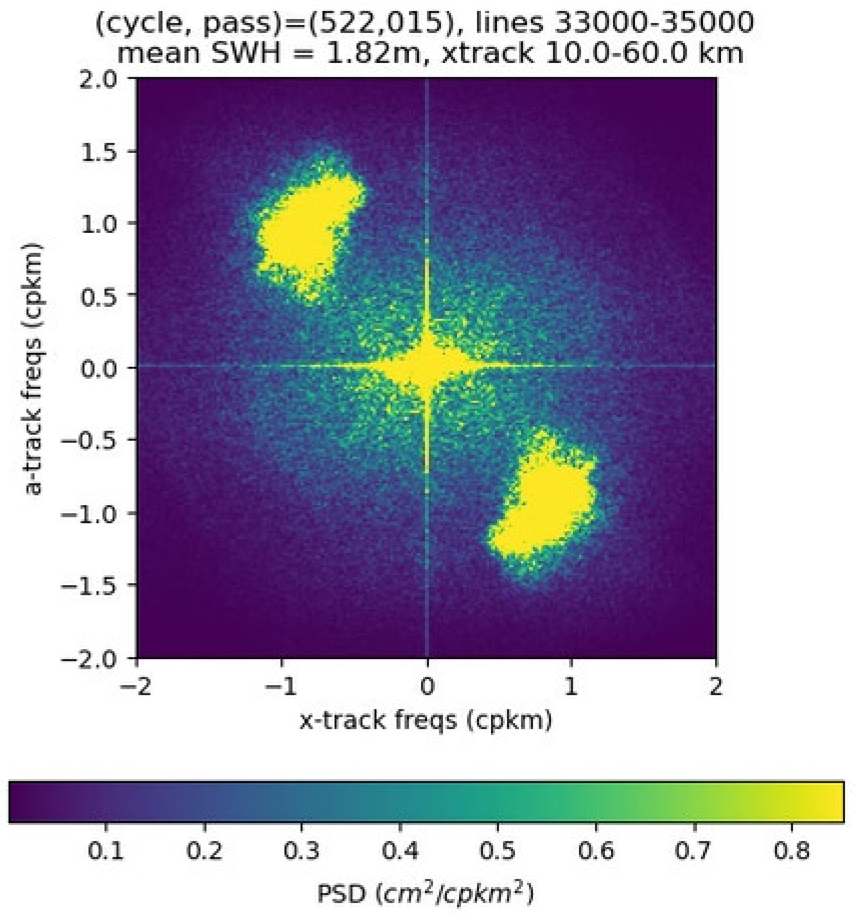


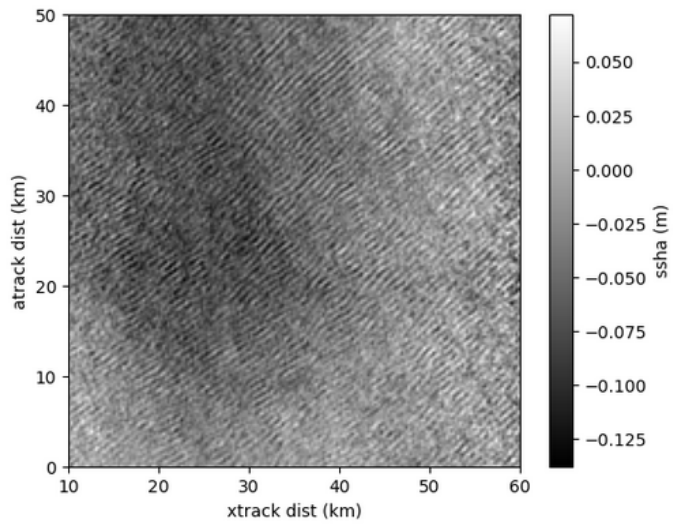




- RMS and 1D spectra level very large, but much smaller at 2km resolution
- The noise from waves is absolutely not covering the « signal » at ~10km

Resolved swell

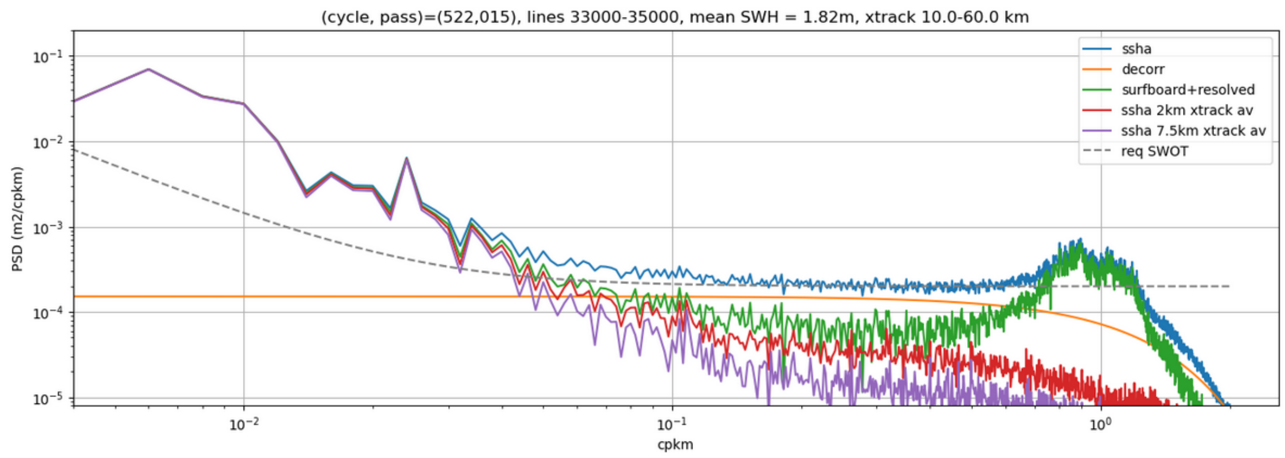




50km x 50km KaRIn snapshot

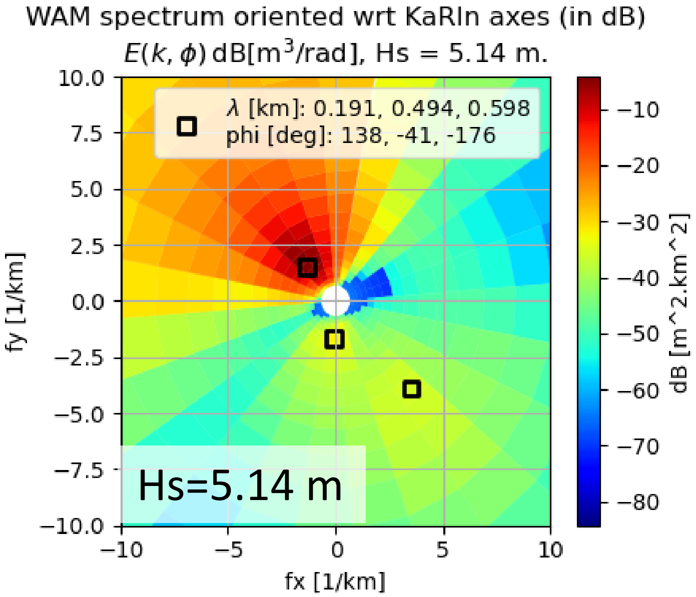
This is measured height, not power.

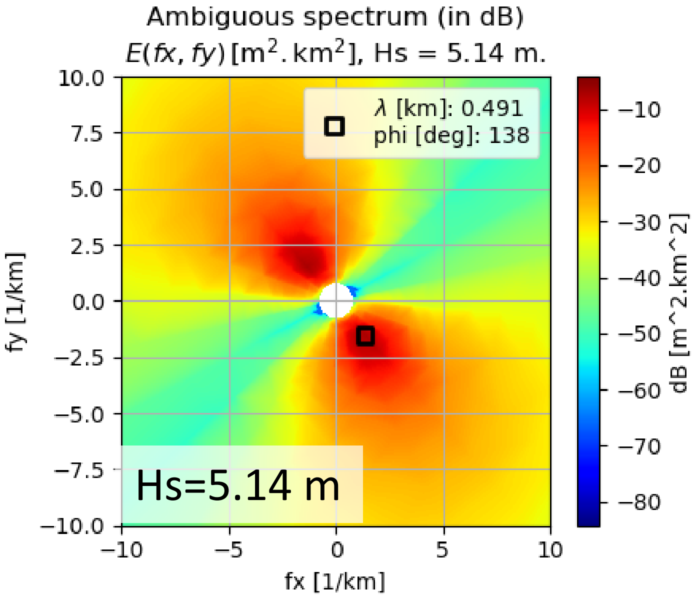
This is either large wavelength swell that is resolved (and attenuated) by KaRIn or lower frequency (higher amplitude) swell that aliases into the KaRIn band.



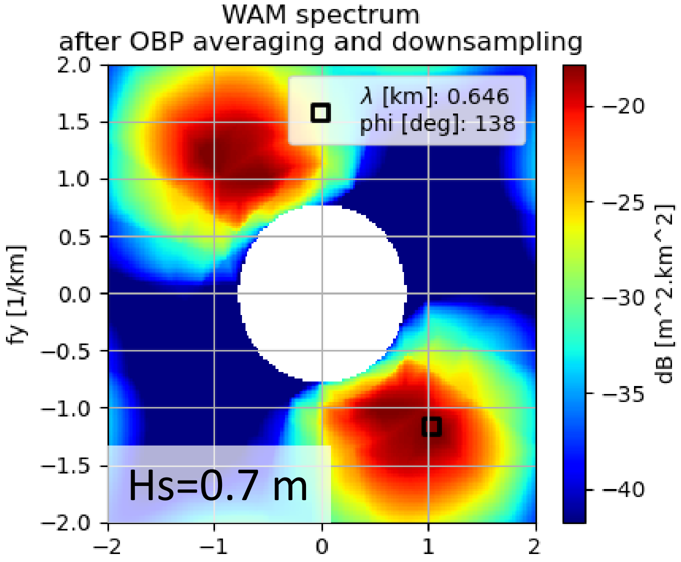
2D spectrum of heights: comparison to MFWAM (model)

Processing of MFWAM

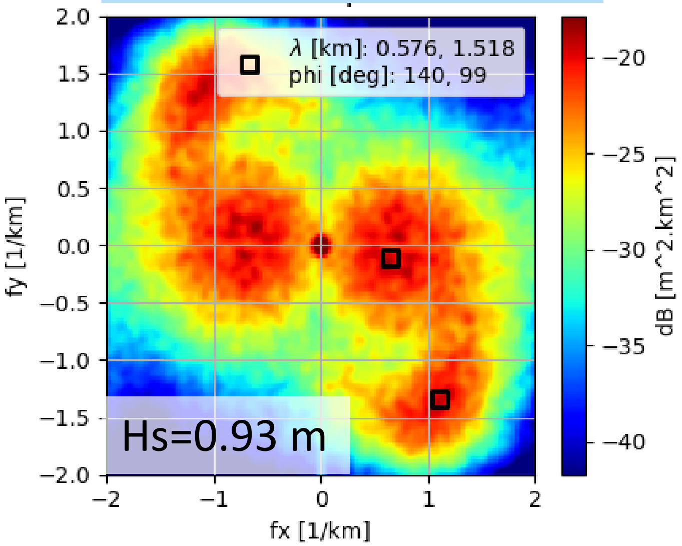




MFWAM

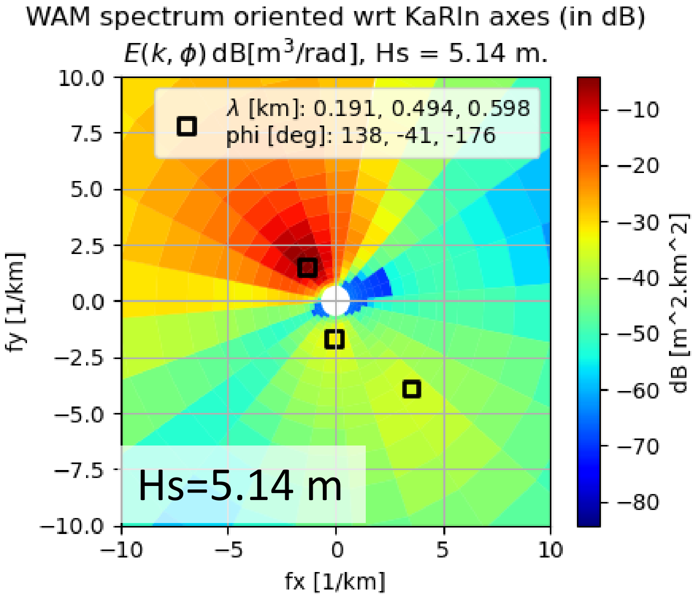


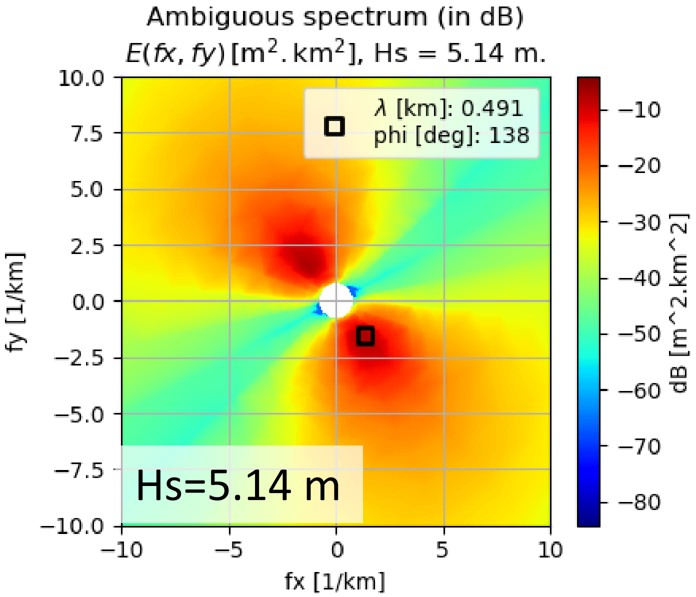
KaRIn SSH



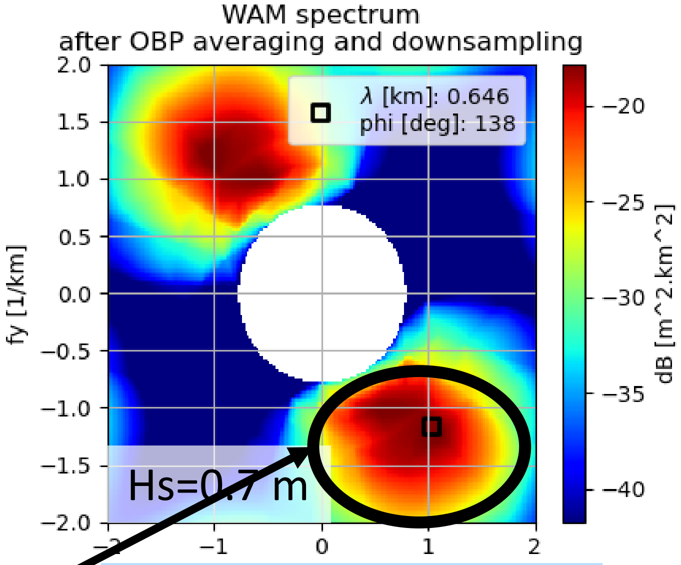
2D spectrum of heights: comparison to MFWAM (model)

Processing of MFWAM

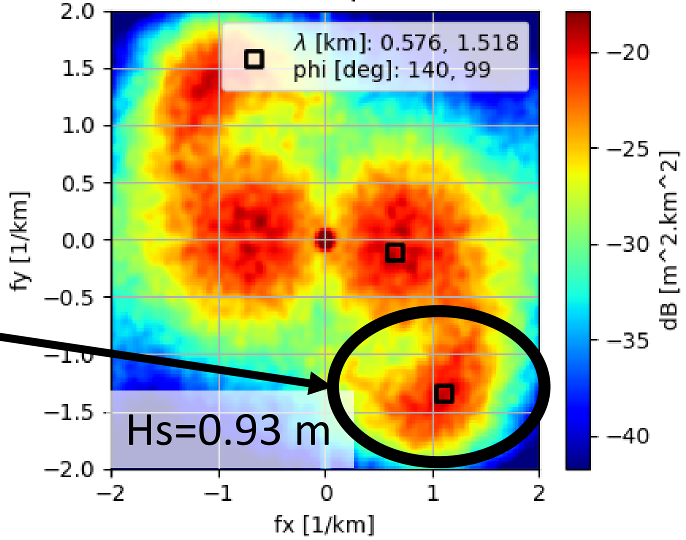




MFWAM



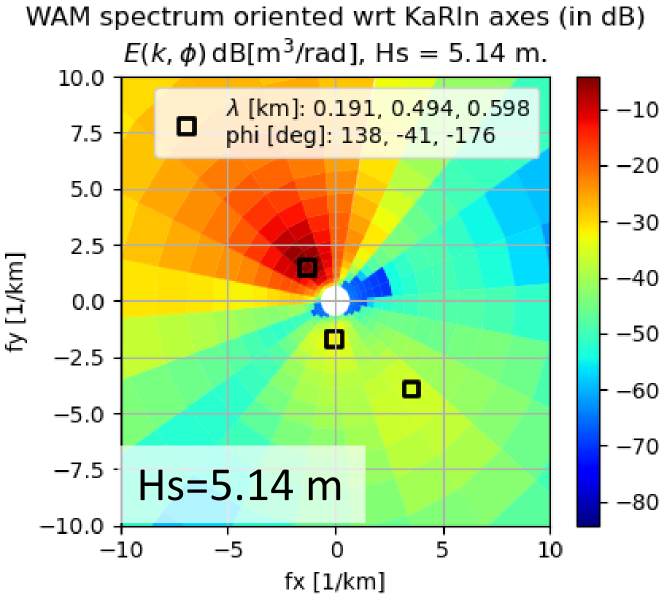
KaRIn SSH

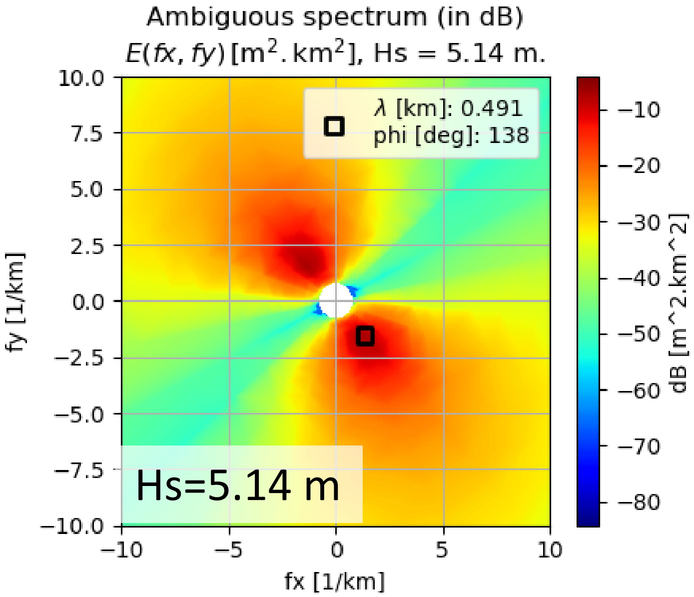


Swell component predicted by the model and seen (attenuated) by KaRIn (direction matches almost perfectly, energy of the partition has some differences in this example).

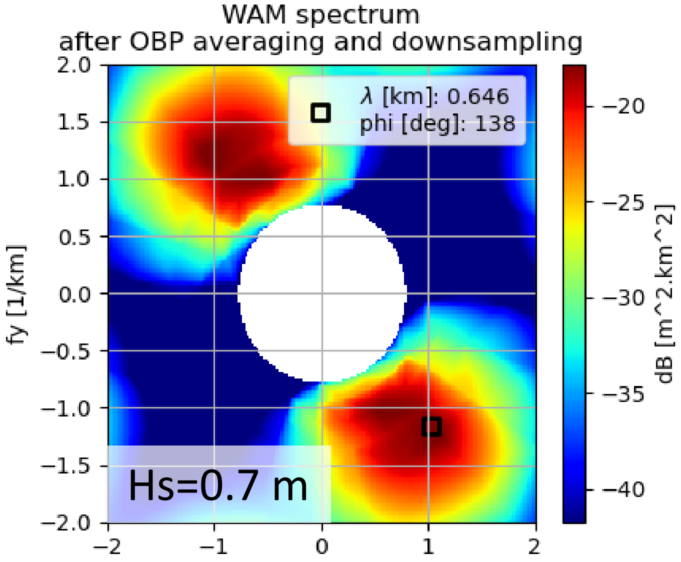
2D spectrum of heights: comparison to MFWAM (model)

Processing of MFWAM

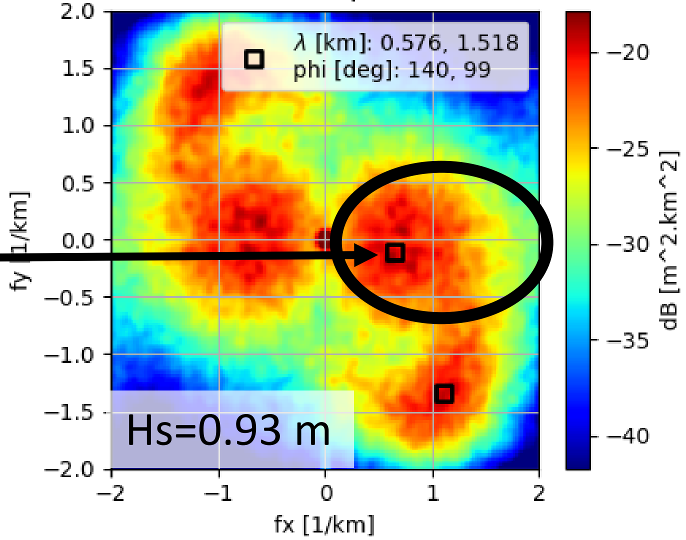




MFWAM



KaRIn SSH

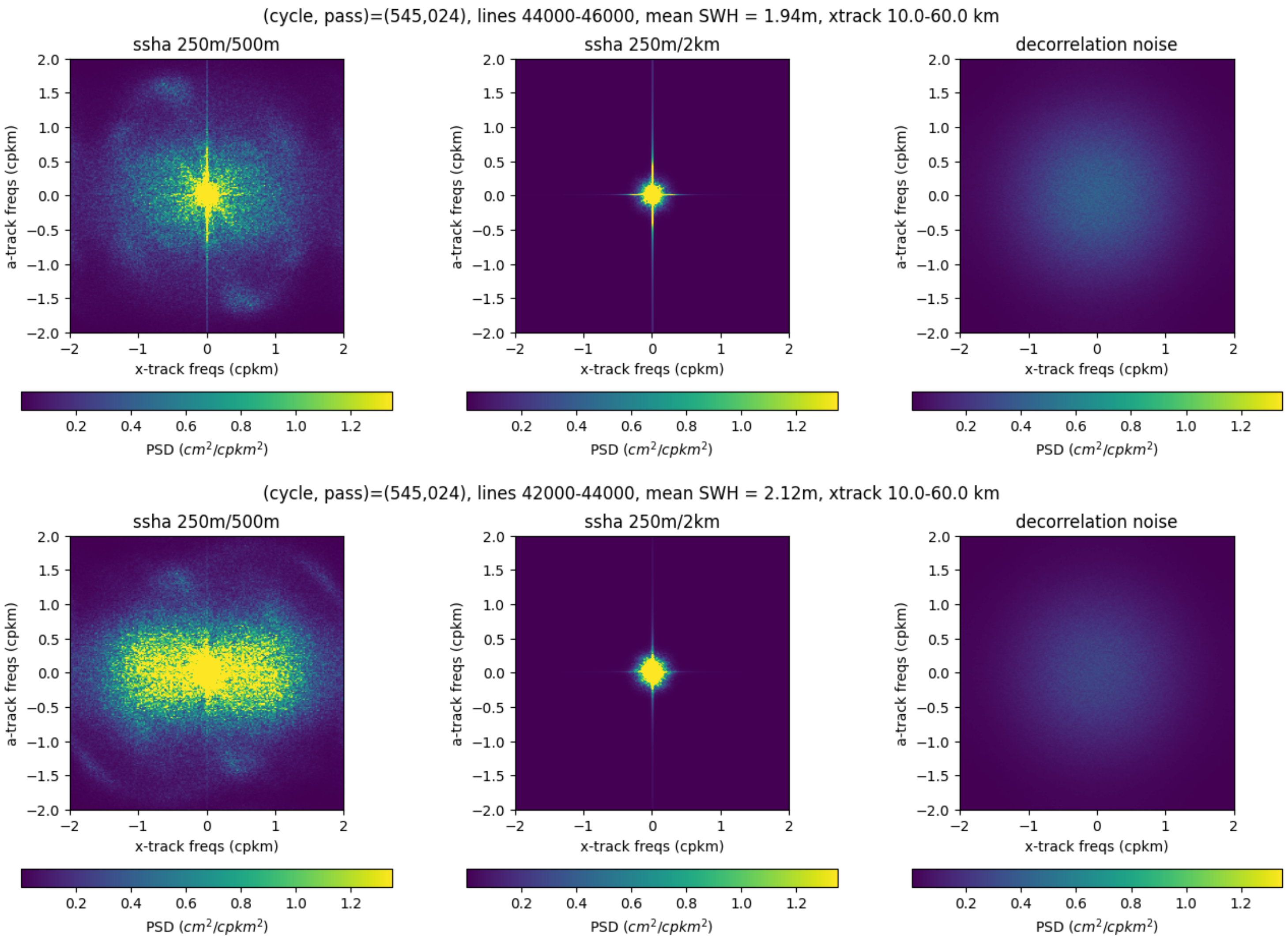


Additional energy in the KaRIn 2D spectrum not in the model (and almost certainly not in the true wave spectrum either). This is due to « non linear energy transfer » from the unresolved waves in KaRIn.

Impact of swell (not necessarily resolved!)

model T_{02} = 6.6s

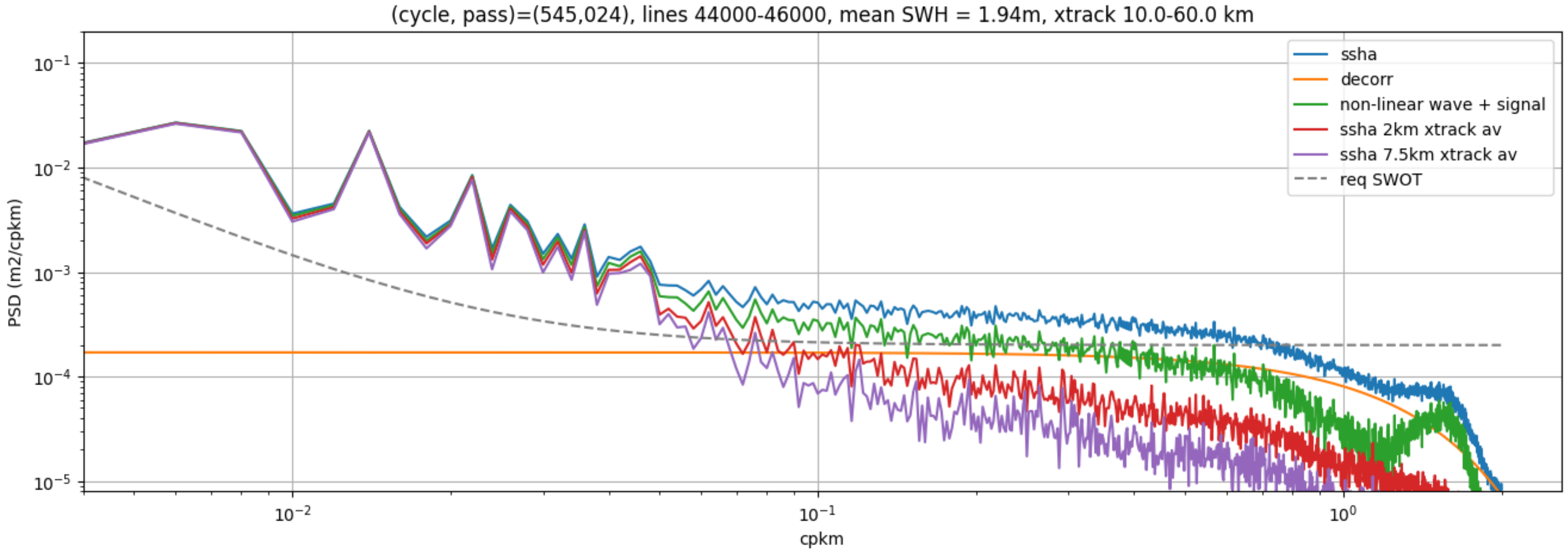
model T_{02} = 10.6s



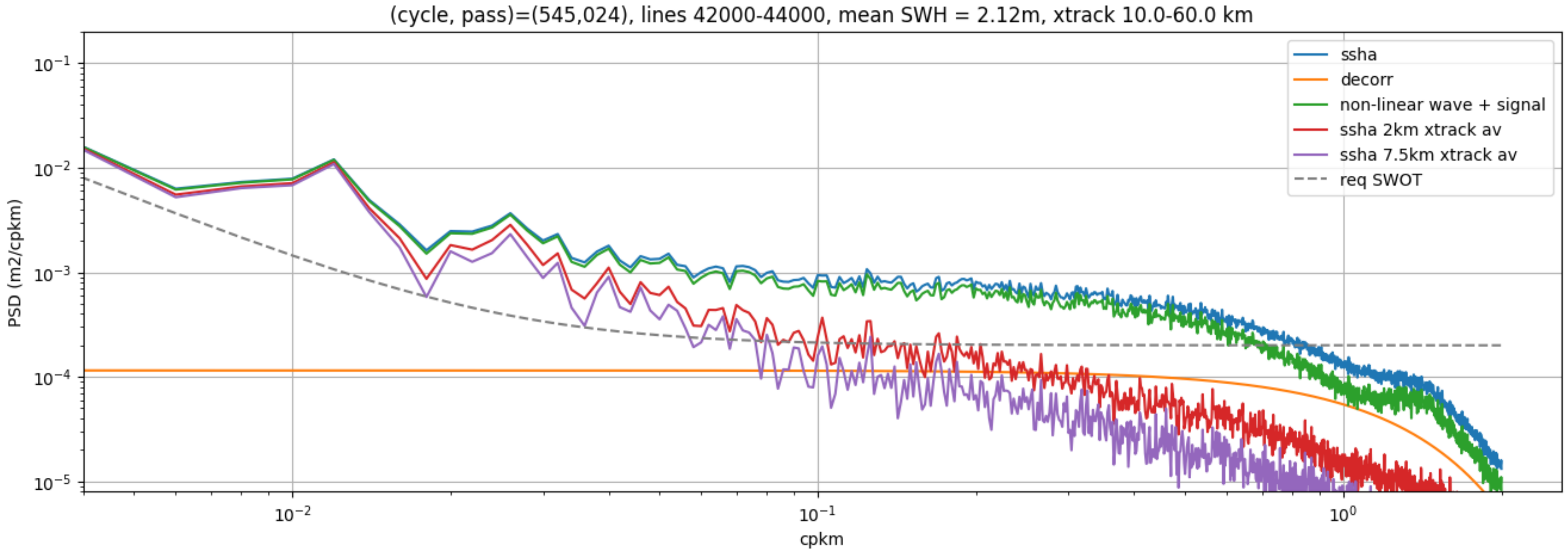
- The presence of swell increases the amount of « low frequency » energy contamination by the waves.
- Predicted in simulations (and analytical work)
- Magnitude of the effect depends on wave physics yet to be constrained

Impact of swell (not necessarily resolved!)

model T_{02} = 6.6s

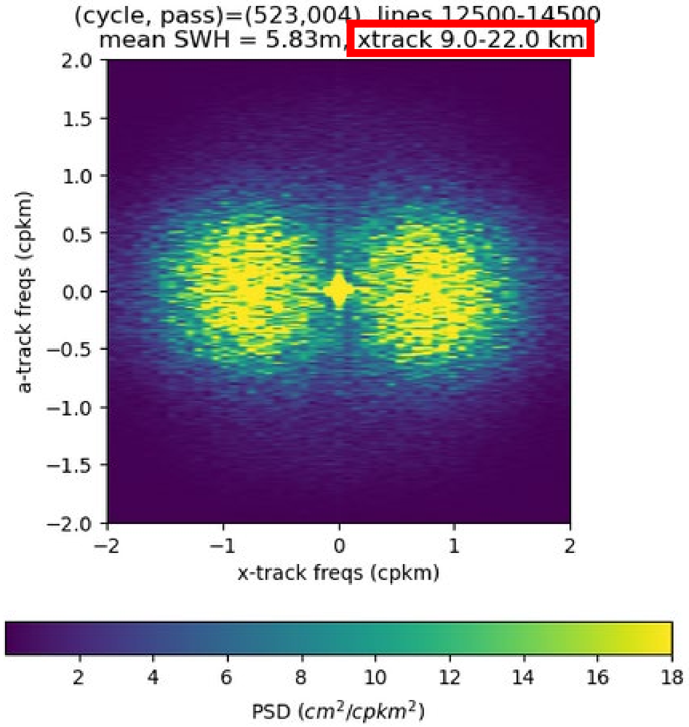


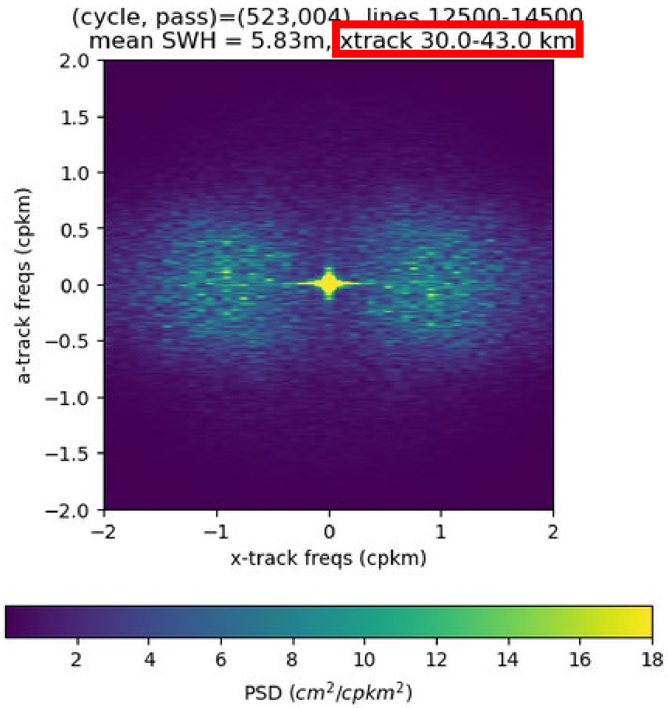
model T_{02} = 10.6s



Cross track dependence

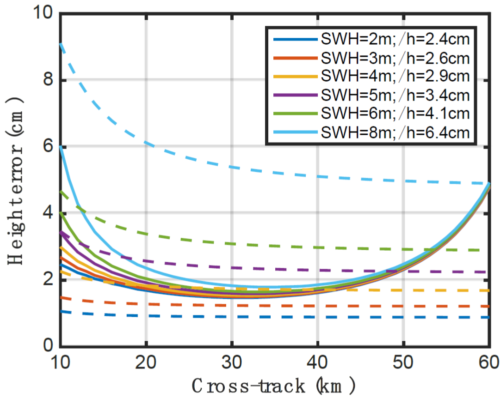
near swath





center of swath

As predicted both in simulations and in analytical work, the noise due to non-linear energy transfer from the waves increases in the near range. Again, the magnitude depends on wave physics, which the data will help constrain.



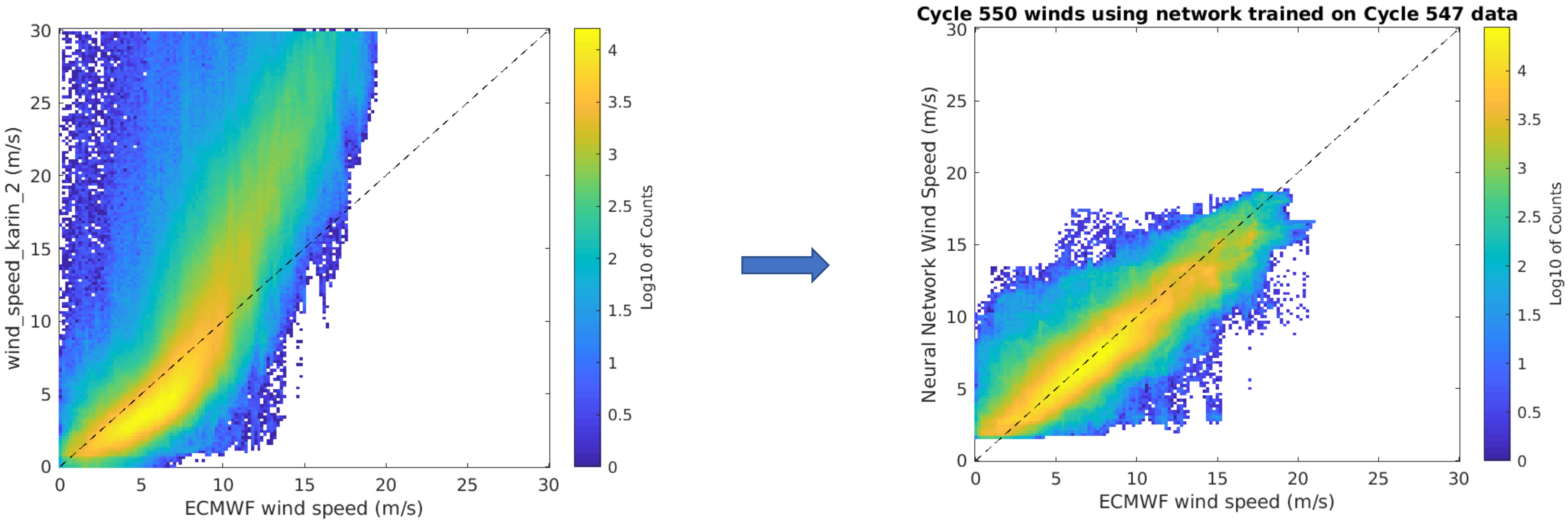
SWOT Wind Speed Retrieval Status

Bryan Stiles

Sept 19 2023

Synopsis

- Fit new GMF to fix speed dependent errors and incorporate variation in sigma-0 with SWH.
- Wind speed RMS difference from ECMWF is ~1.4 m/s which is similar to ocean wind scatterometer RMS differences from ECMWF
- Variation in wind speed bias with latitude is a few tenths of a m/s.



Wind retrieval algorithm for October Reprocessing

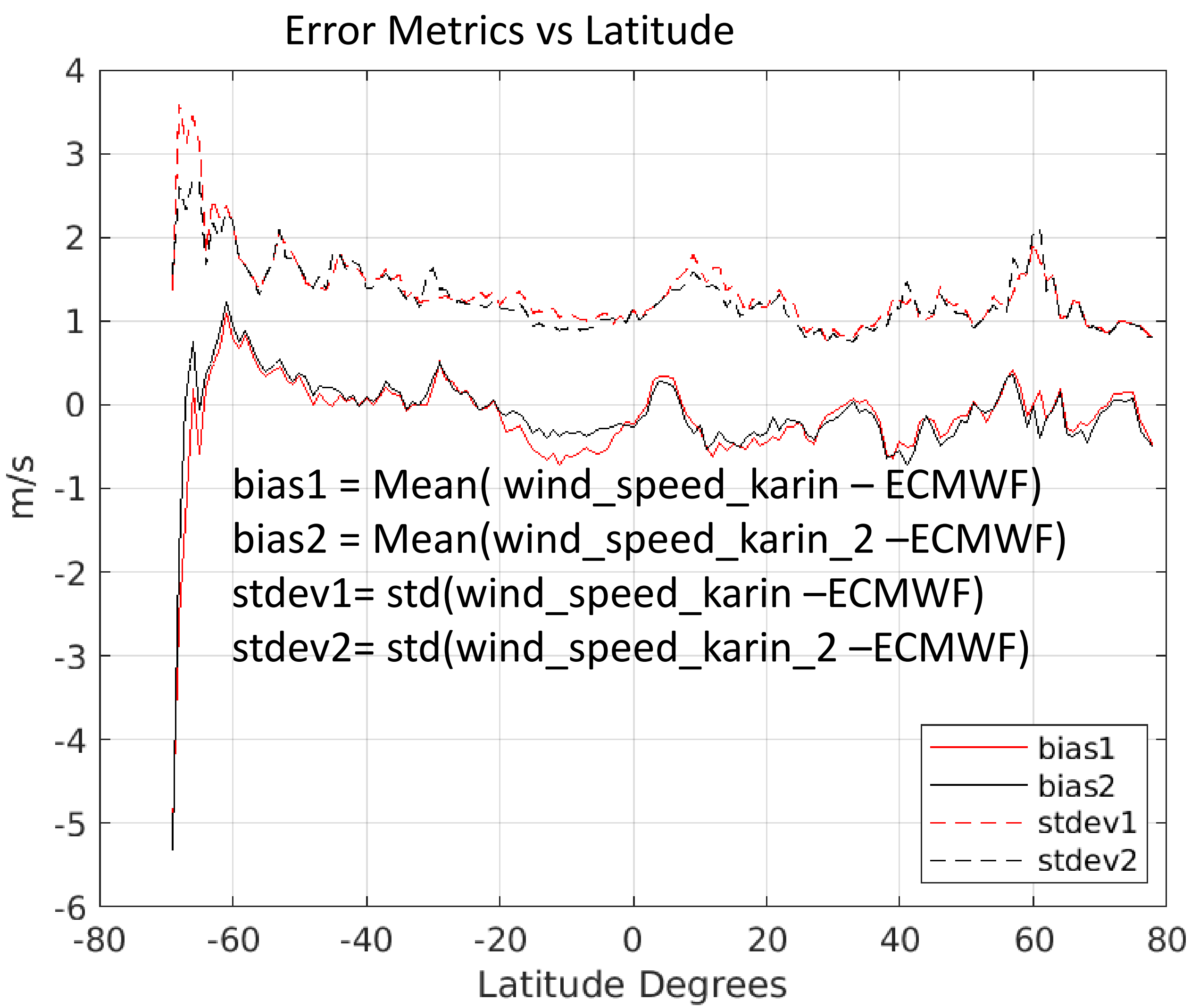
- Fit new GMF to fix speed dependent errors and incorporate variation in sigma-0 with SWH.
  - A direct mapping (sigma0, incidence angle, SWH) to wind speed is simpler to fit because it can use wind speed error rather than sigma-0 error in the training method.
  - Fitting the inverse mapping would require trading off a dB sigma-0 fit which is heavily weighted by high wind speed (large sigma-0 dB error) outliers or a linear sigma-0 fit which is heavily weighted by low wind speed (large sigma-0 linear scale errors) outliers.
- GMF Trained on SWOT 2-km data from June 10 through June 22 using SWOT sig0_karin_2 data, incidence angle, and model SWH as inputs and ECMWF wind speed as outputs.
- Validated on SWOT 2-km data from July 26 to July 28 over open ocean with ssh_karin_2_qual=GOOD.
  - wind_speed_karin: bias=-0.06 m/s and standard deviation = 1.41 m/s w.r.t ECMWF
  - wind_speed_karin_2: bias=-0.01 m/s and standard deviation = 1.36 m/s w.r.t. ECMWF
- Wind retrieval involves a simple table lookup and bilinear interpolation.
  - A small 0.1 dB bias between sig0_karin and sig0_karin_2 is accounted for prior to retrieving wind speed_karin.

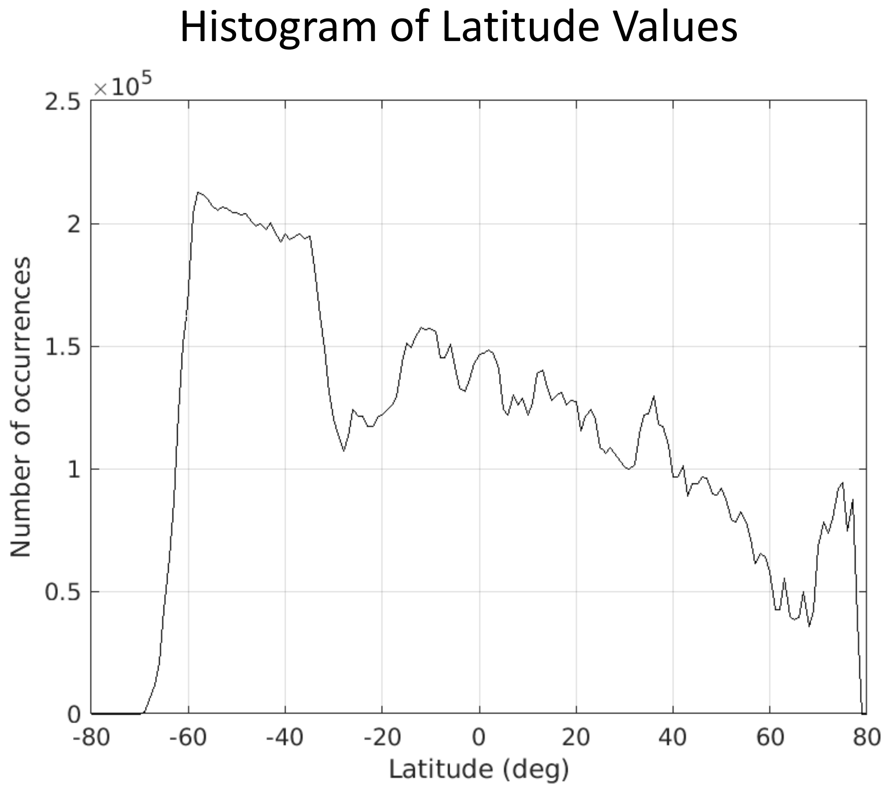
Comparison to ECMWF

- Bias and standard deviation with respect to ECMWF is computed as a function of:
  - Latitude
  - Significant Wave Height
  - Incidence angle
  - (KaRin Wind speed + ECMWF Wind speed)/2
    - Used instead of binning vs ECMWF speed to avoid statistical artifacts in the biases due to errors in ECMWF.

Comparison to ECMWF vs Latitude

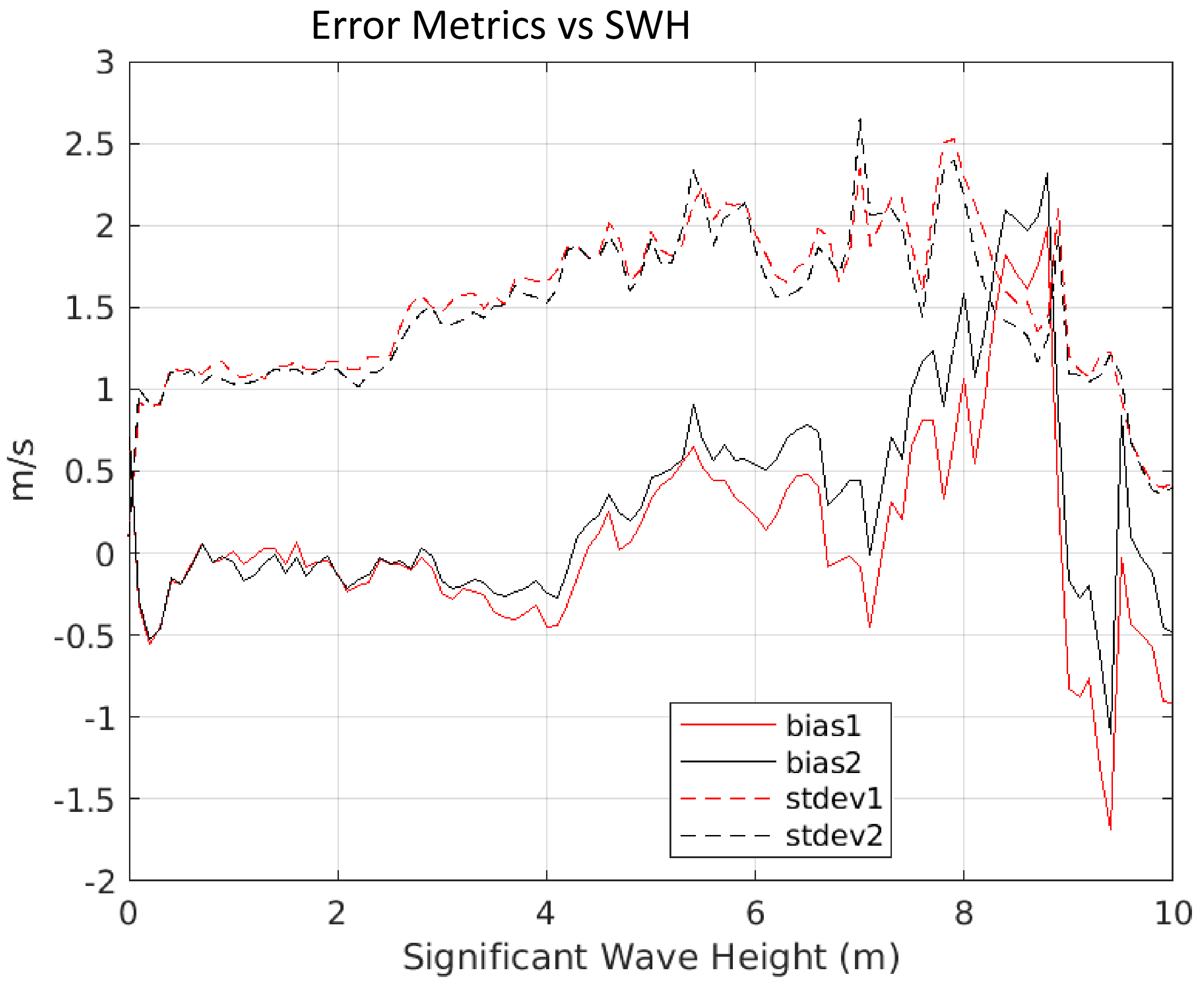
Very little variation in bias with latitude except in the extreme Southern latitudes, suspect unflagged sea ice

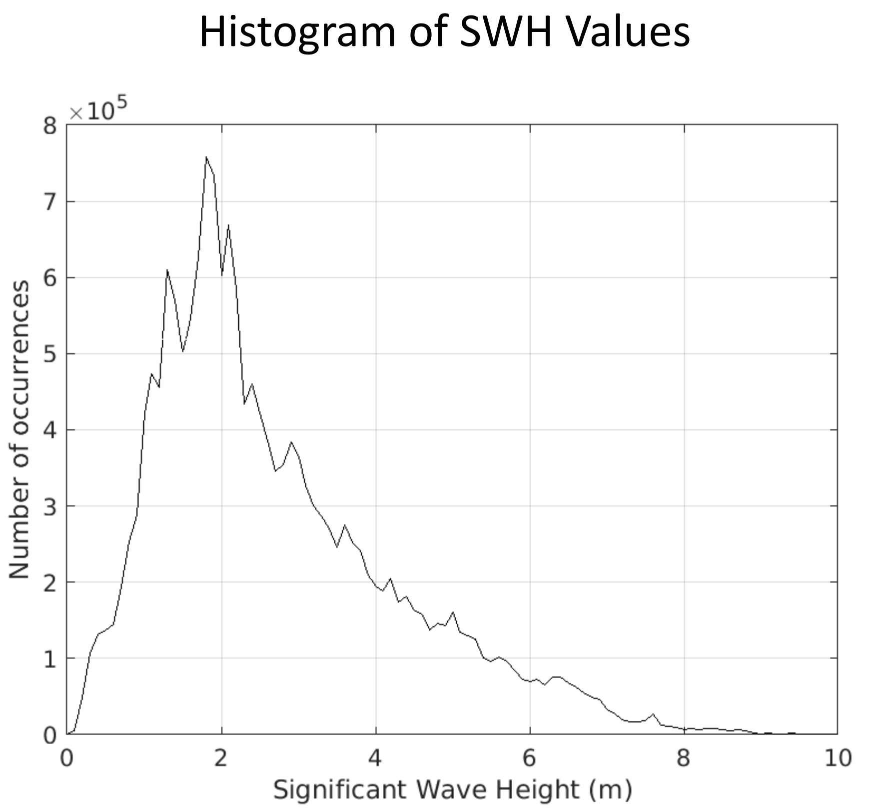




Comparison to ECMWF vs SWH

Largest errors at lowest and highest SWH where data including training data to fit the GMF is scarce

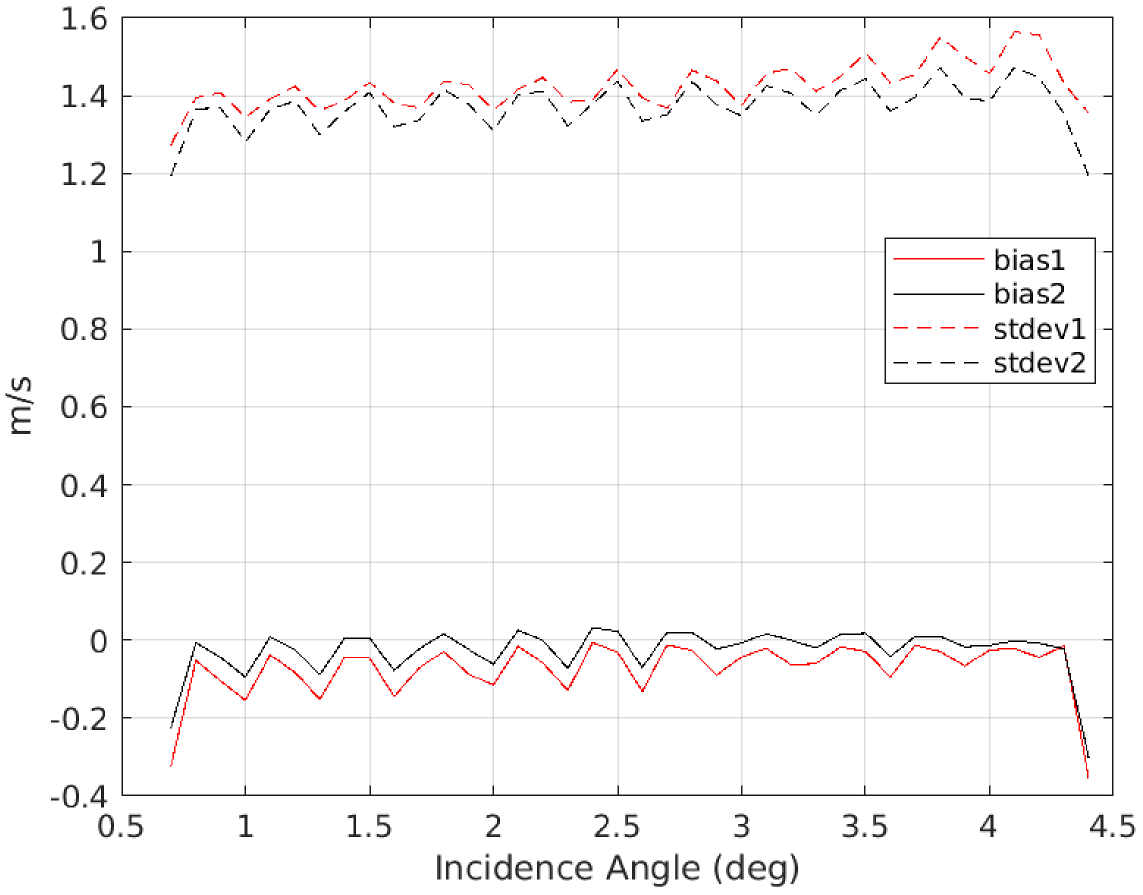




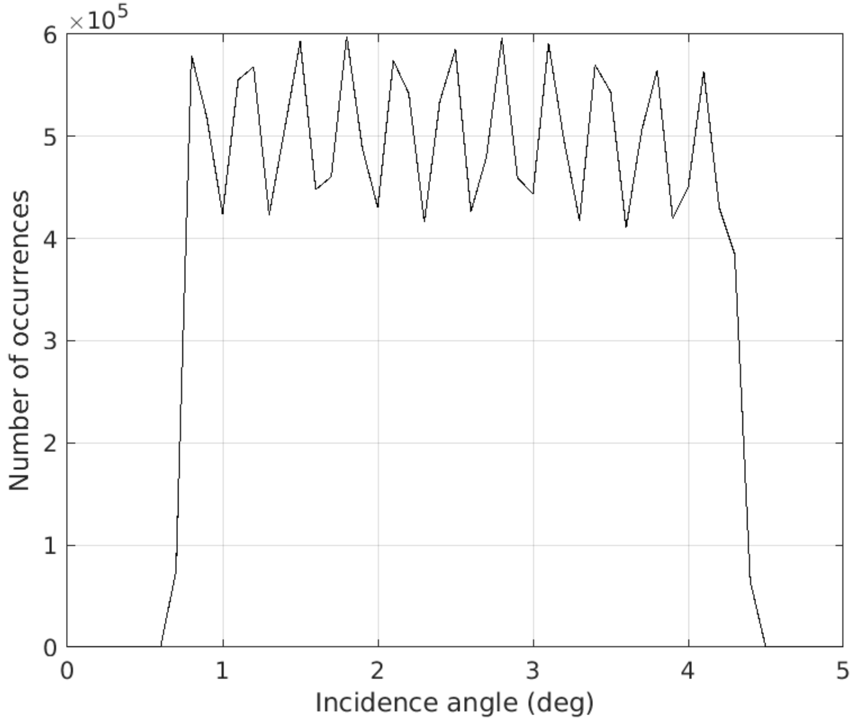
Comparison to ECMWF vs Incidence Angle

Ripples are due to quantization of incidence angle in the 2-km data and difference in altitude for different parts of the orbit

Error Metrics vs Incidence Angle

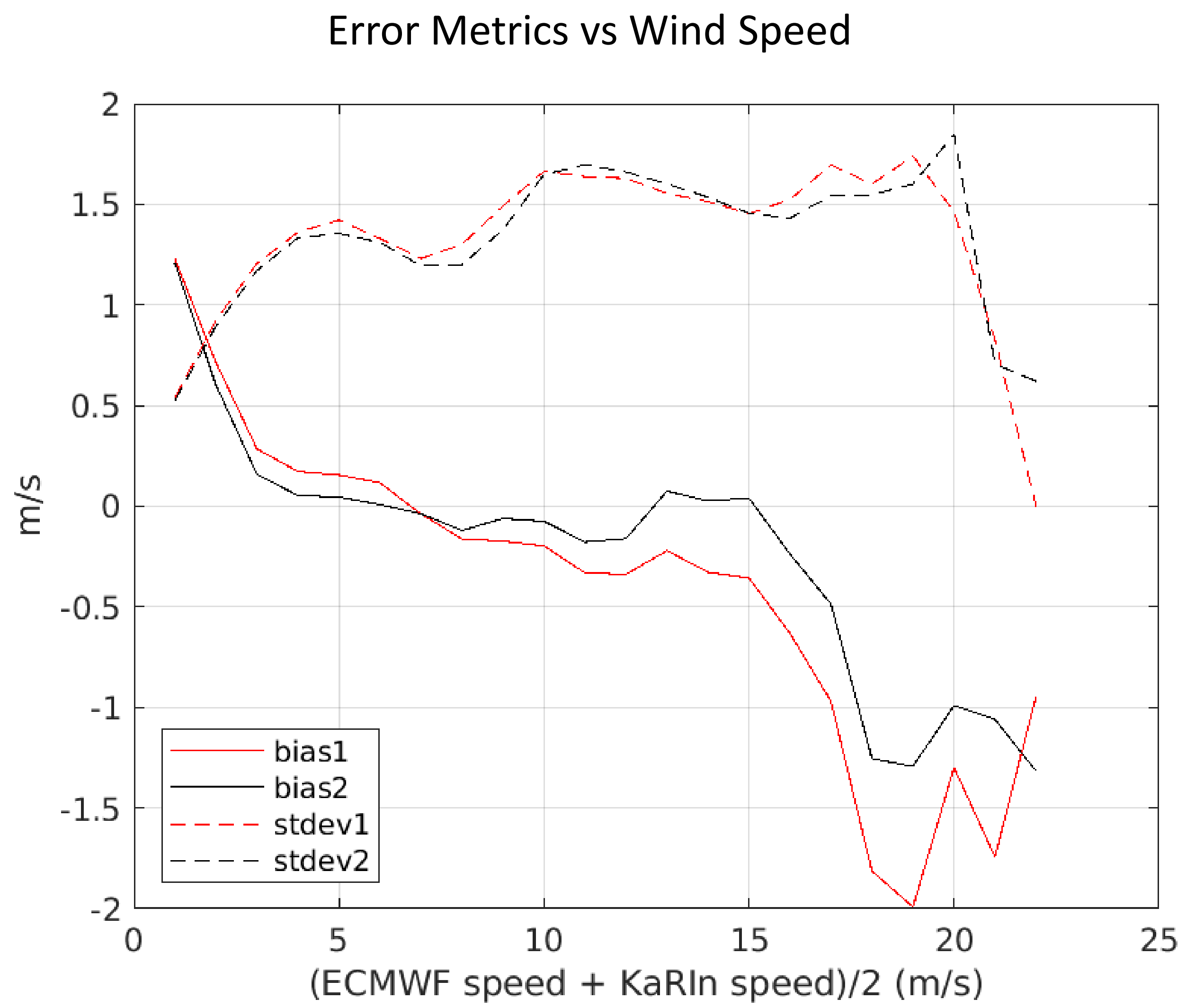


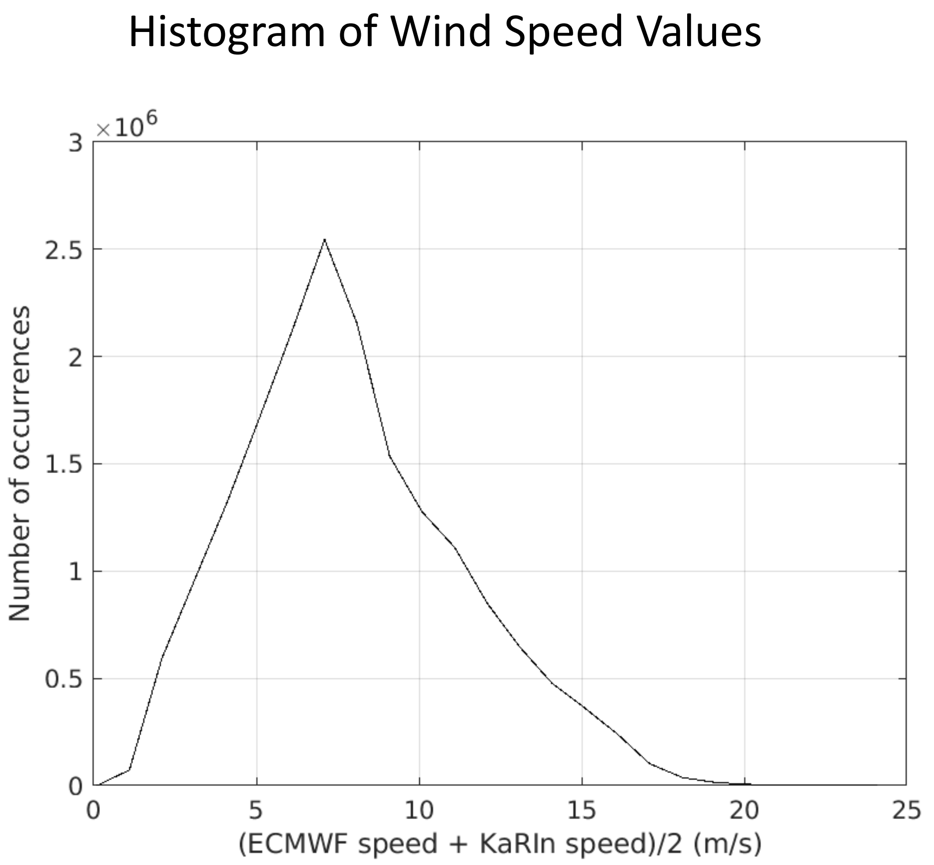
Histogram of Incidence Angle Values



Comparison to ECMWF vs Wind Speed

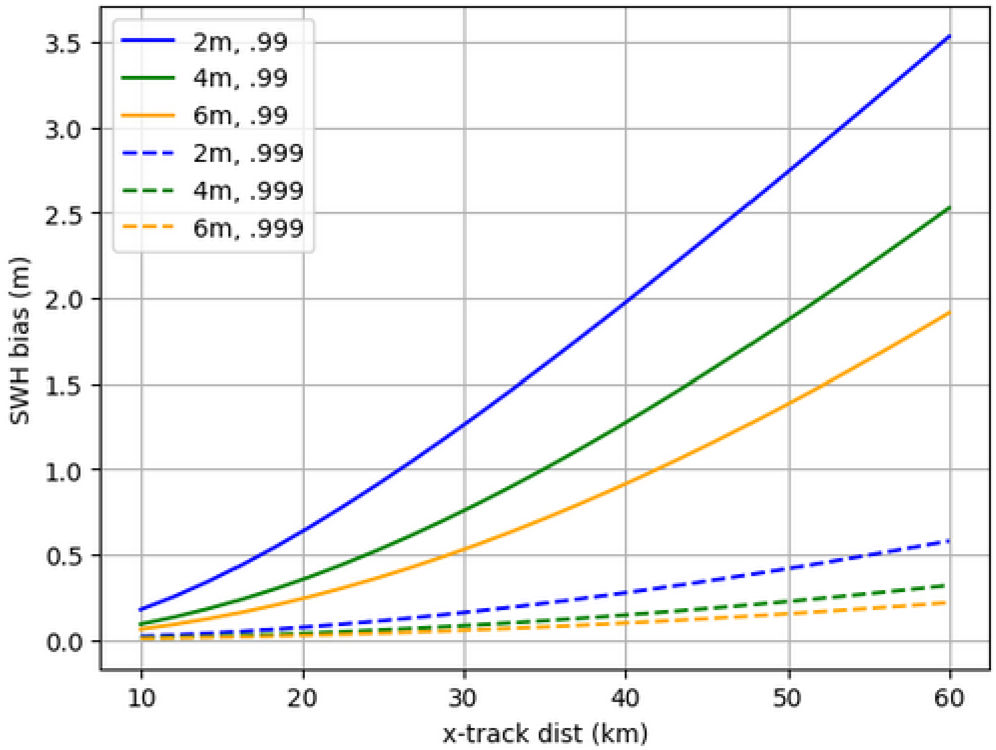
Largest errors at lowest and highest wind speeds where data including training data to fit the GMF is scarce





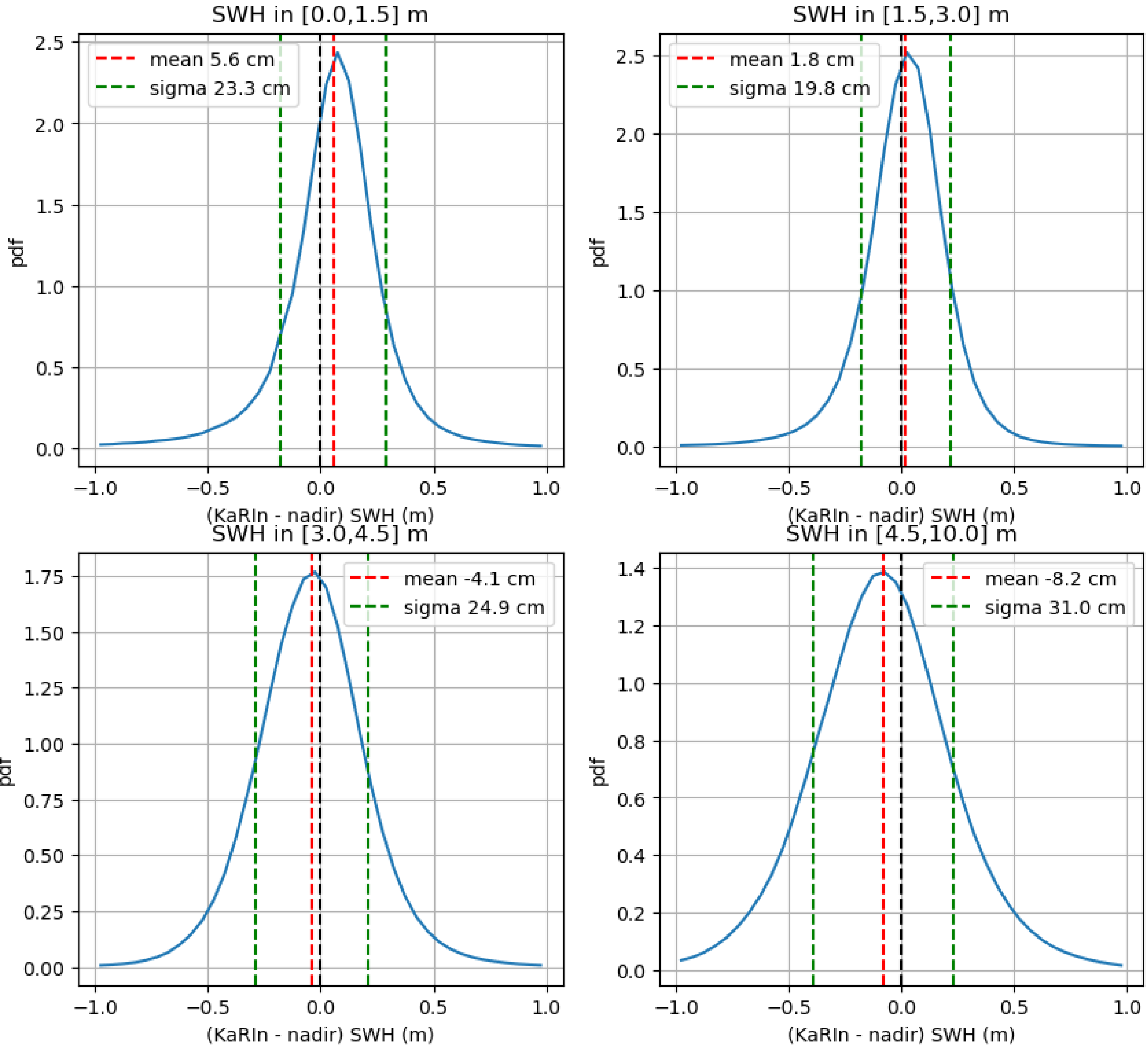
BACKUP

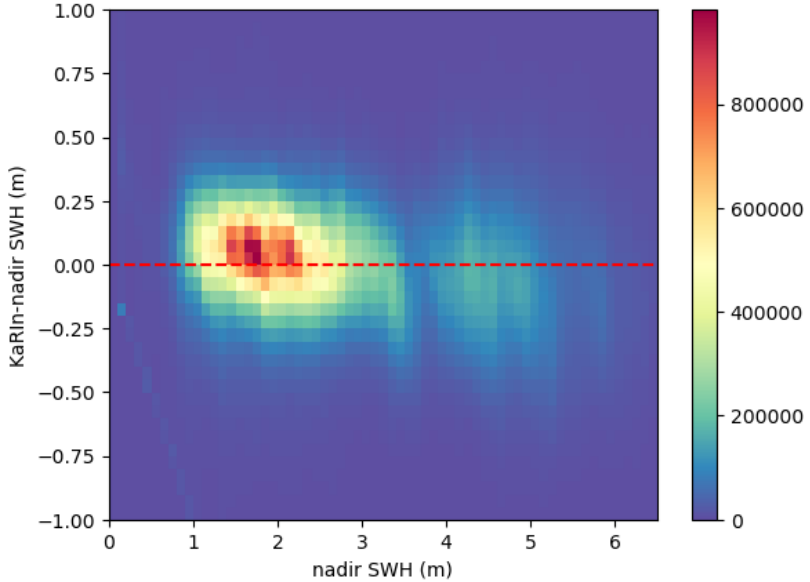
Calibration of instrumental decorrelation : required accuracy



- SWH bias as a function of true SWH (colors) assuming a non calibrated instrumental decorrelation of .99 (plain lines) or .999 (dashed)

- In the near range, an extra decorrelation of a few .001 is probably acceptable. In the far range, .999 alread gives several tens of cm of SWH bias.

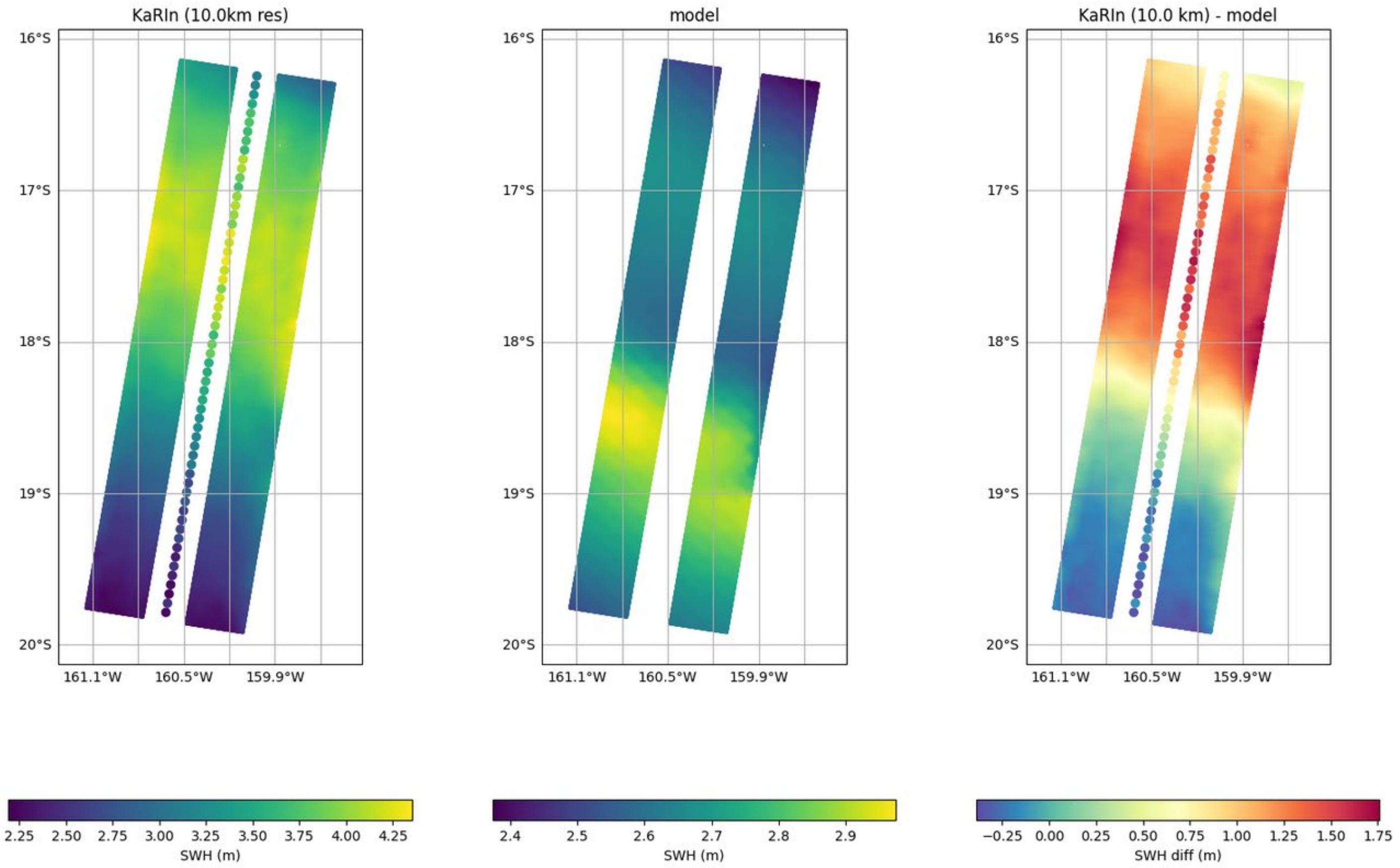


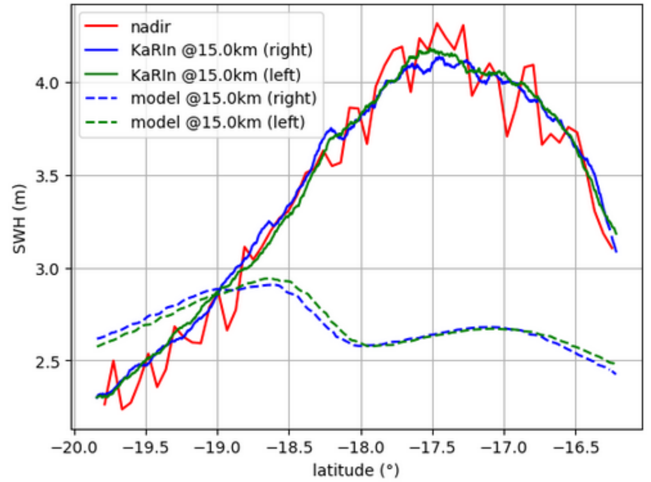


std likely still dominated by instrumental effects varying along orbital circle

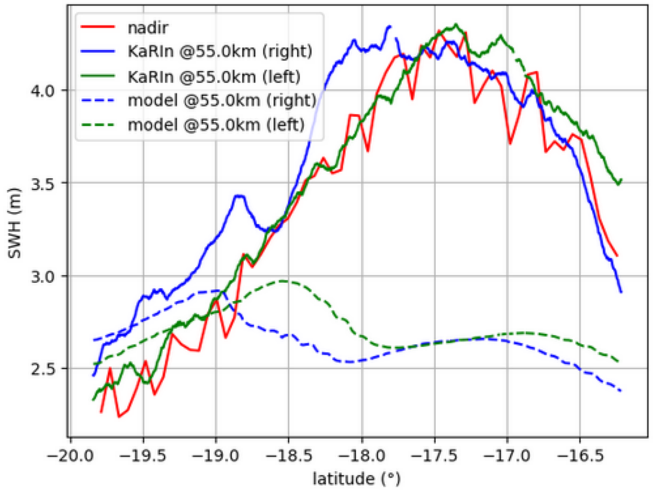
10-60 km, both swaths
2 km resolution

2D SWH maps from KaRIn : a few examples



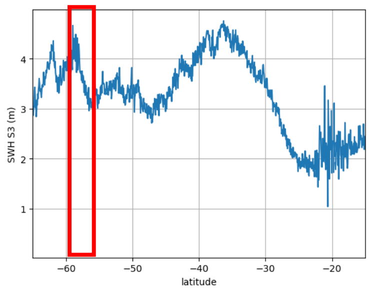


cycle 523
Pass 15

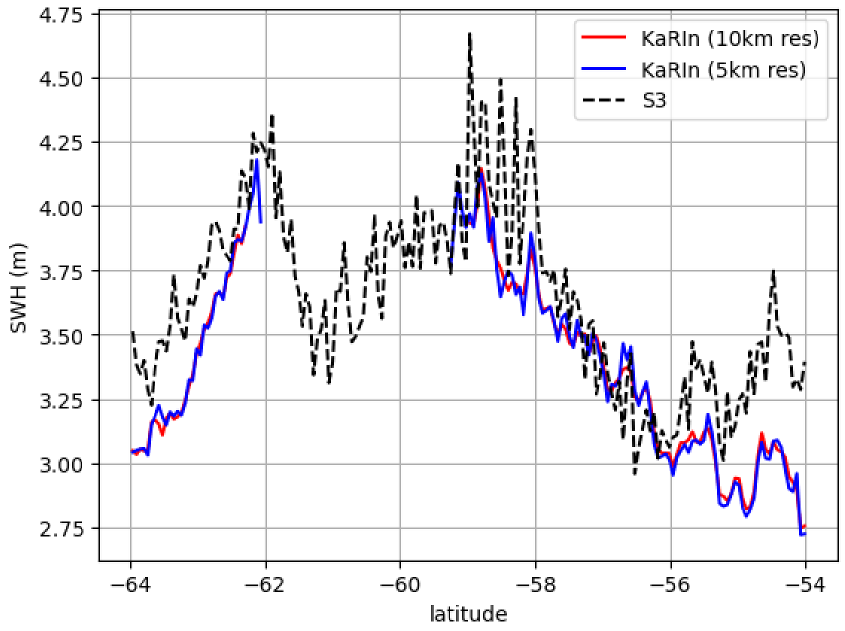


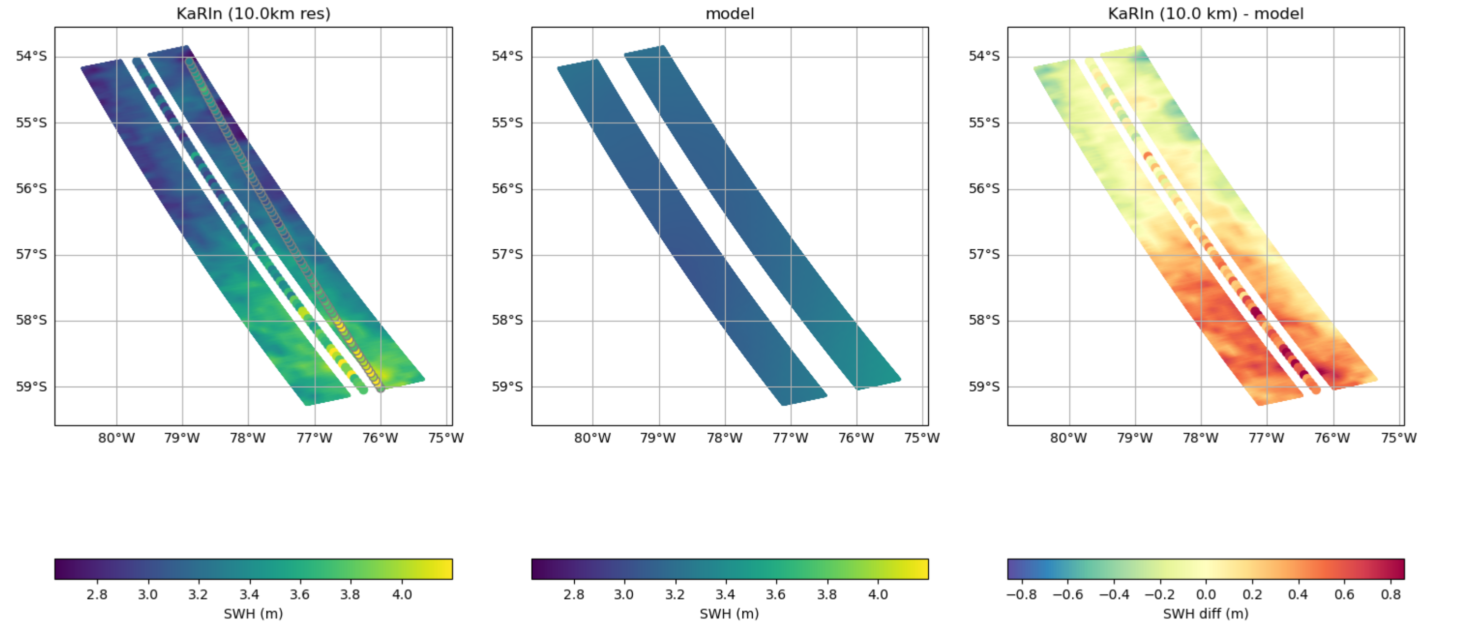
- Strong SWH feature predicted by the model but most likely with a largely underestimated amplitude and at the wrong position
- Excellent agreement between SWOT’s nadir and KaRIn

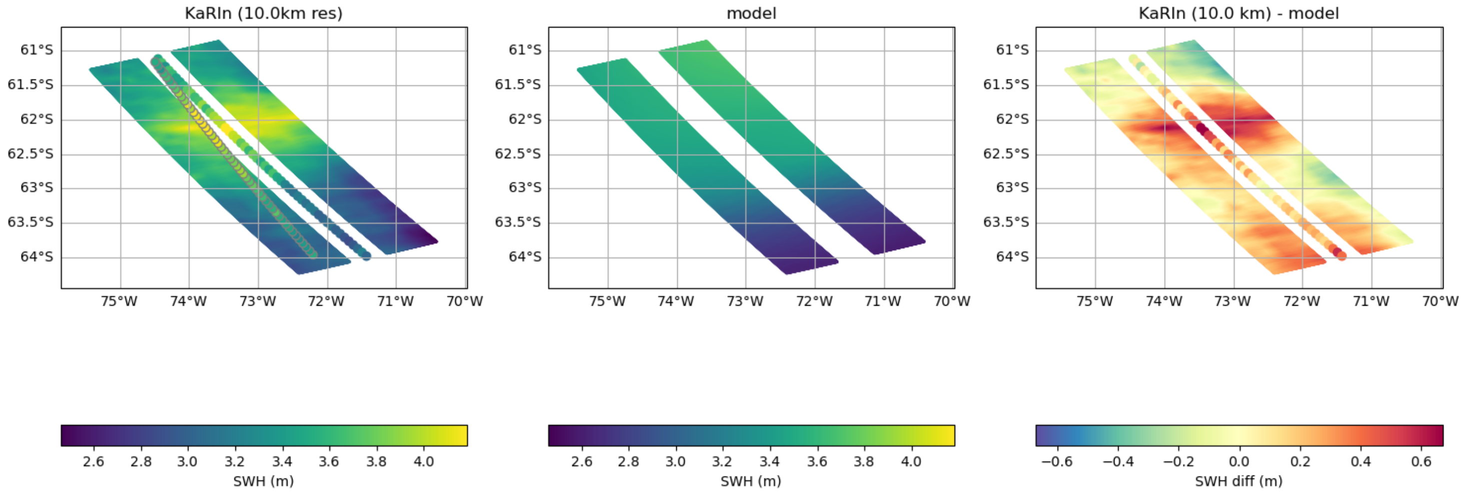
KaRin vs S3 comparison

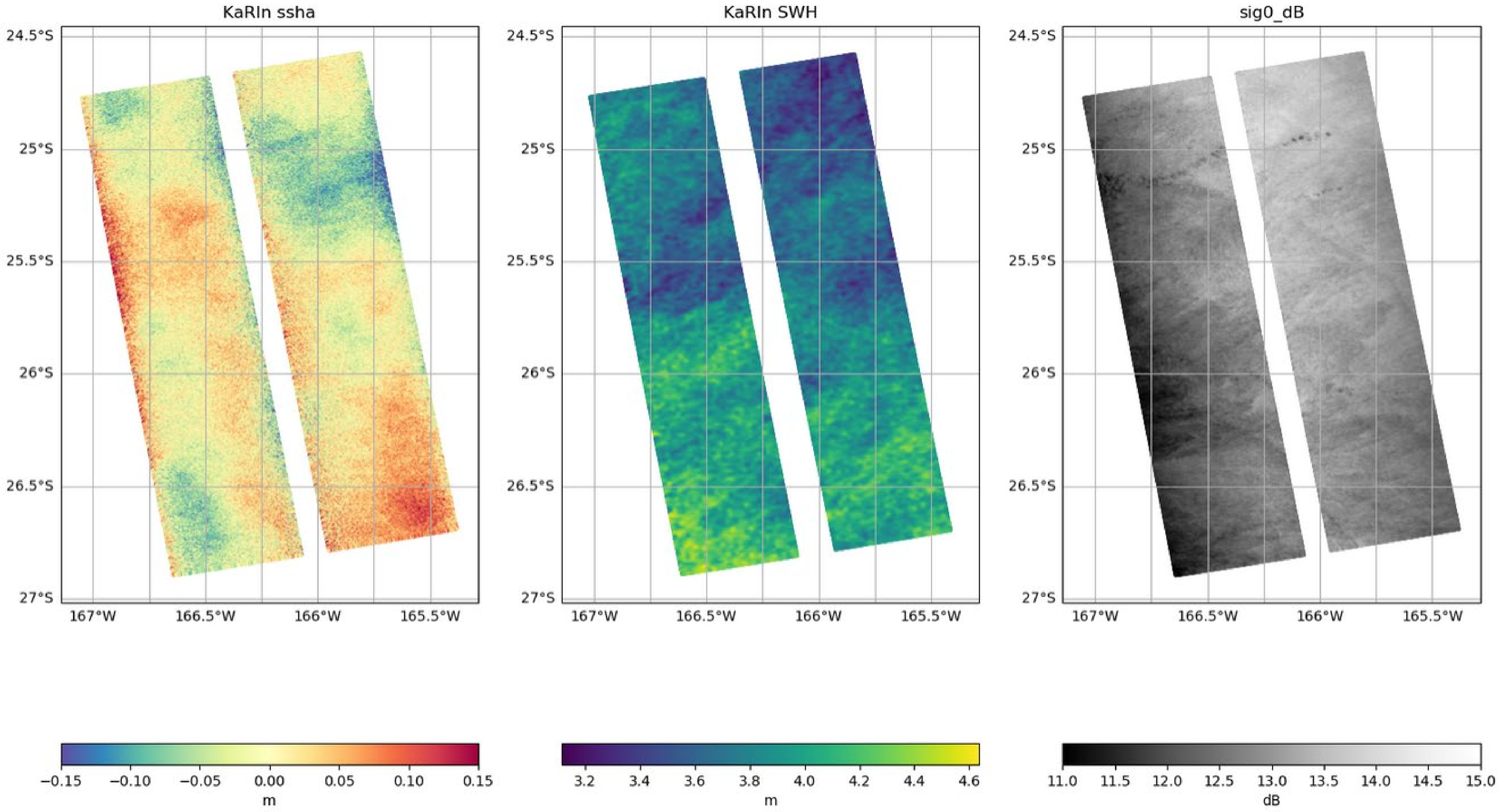


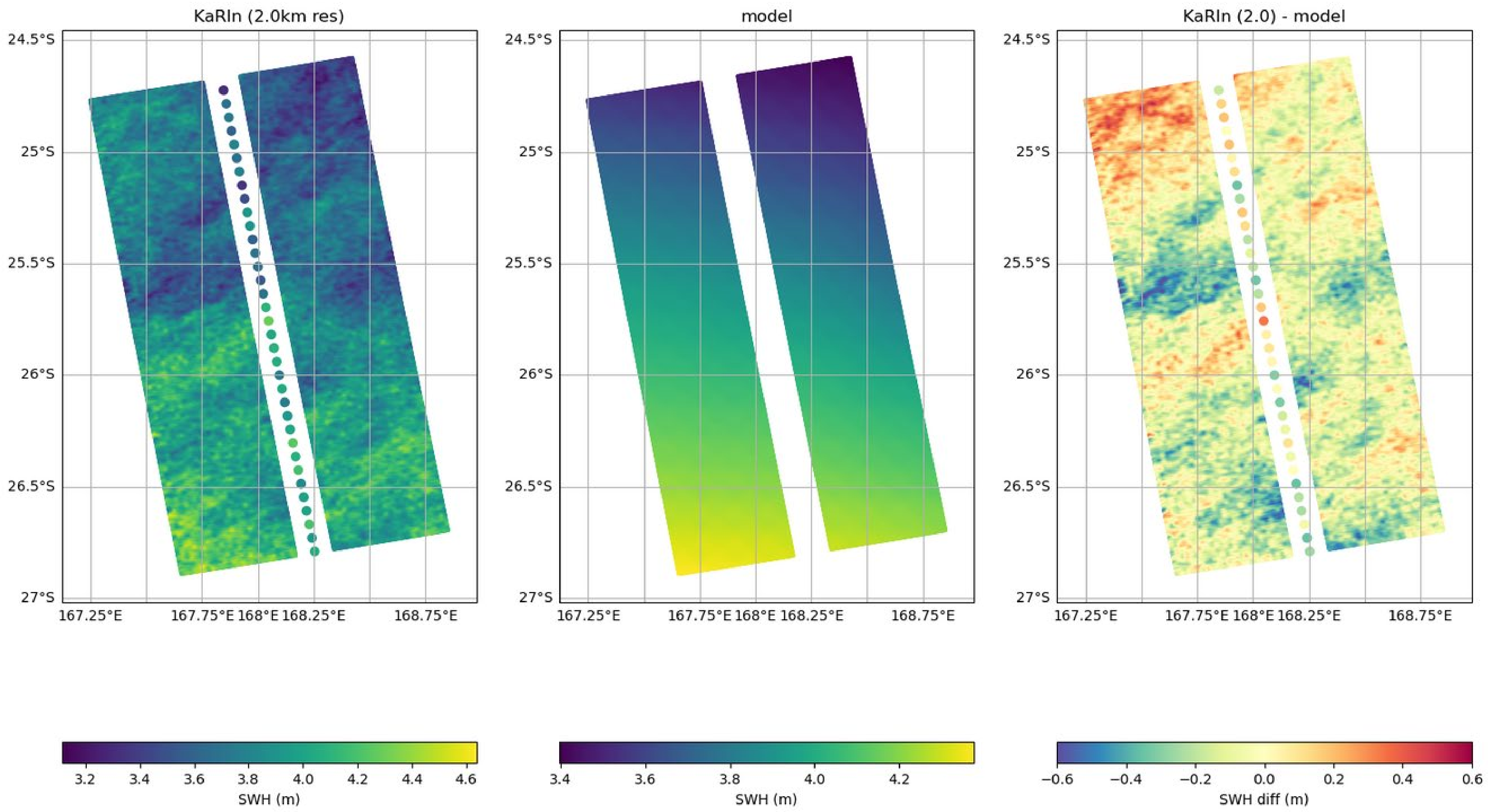
S3 crosses both swaths in the Southern ocean again

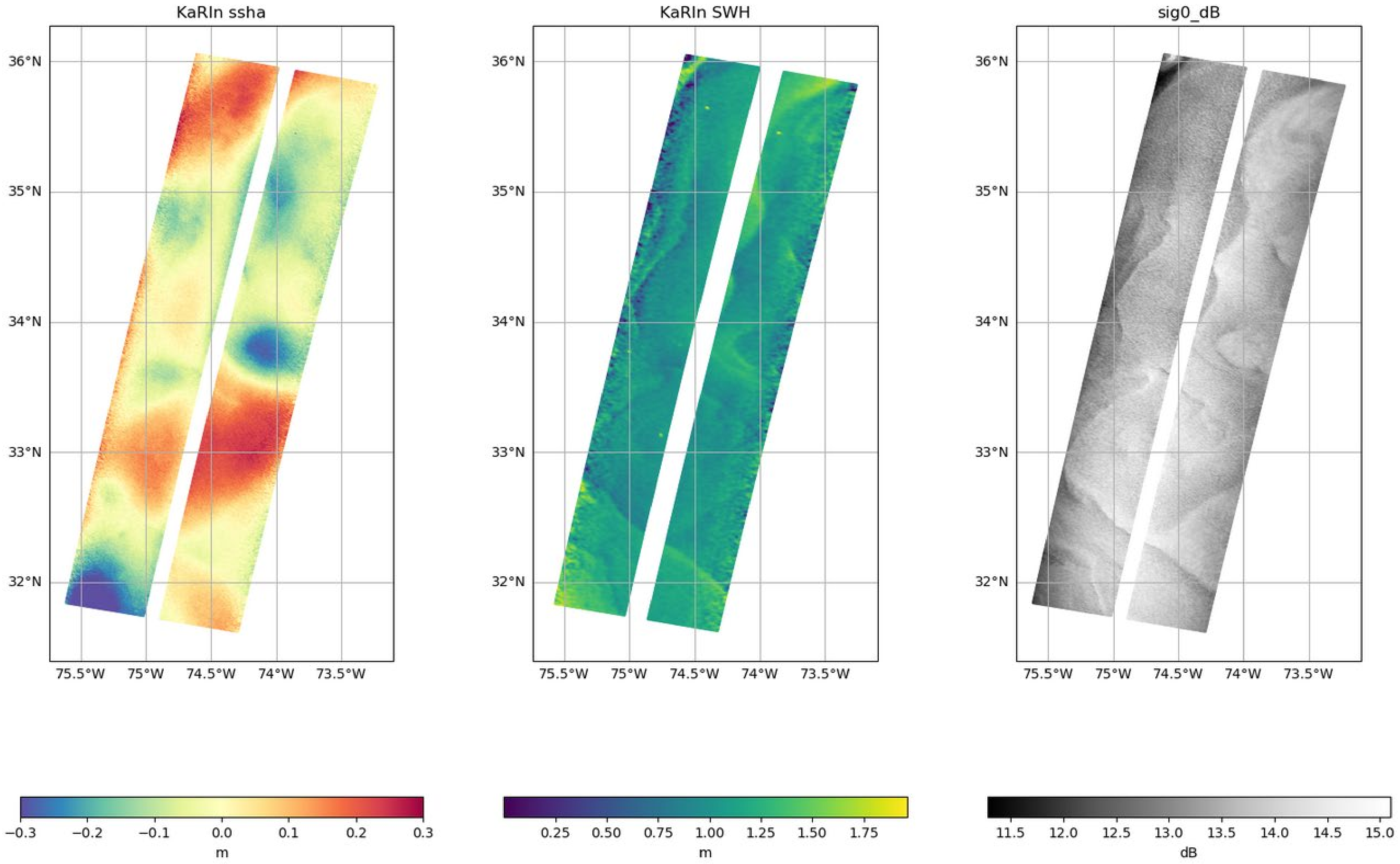







KaRIn ssha
KaRIn SWH
sig0_dB
24.5°S
25°S
25.5°S
26°S
26.5°S
27°S
167°W
166.5°W
166°W
165.5°W
−0.15 −0.10 −0.05 0.00 0.05 0.10 0.15
m
3.2 3.4 3.6 3.8 4.0 4.2 4.4 4.6
m
11.0 11.5 12.0 12.5 13.0 13.5 14.0 14.5 15.0
dB


KaRIn (2.0km res)
model
KaRIn (2.0) - model
24.5°S
25°S
25.5°S
26°S
26.5°S
27°S
167.25°E
167.75°E
168°E
168.25°E
168.75°E
3.2 3.4 3.6 3.8 4.0 4.2 4.4 4.6
SWH (m)
3.4 3.6 3.8 4.0 4.2
SWH (m)
−0.6 −0.4 −0.2 0.0 0.2 0.4 0.6
SWH diff (m)


KaRIn ssha
KaRIn SWH
sig0_dB
36°N
35°N
34°N
33°N
32°N
75.5°W
75°W
74.5°W
74°W
73.5°W
−0.3 −0.2 −0.1 0.0 0.1 0.2 0.3
m
0.25 0.50 0.75 1.00 1.25 1.50 1.75
m
11.5 12.0 12.5 13.0 13.5 14.0 14.5 15.0
dB