SEA STATE BIAS CORRECTION

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Outline

- **Sea State Bias**
  - Phenomenology
  - Nadir altimetry vs KaRIn
- **SSB correction : strategy @ launch**
  - From Sea State to Bias : Altika's empirical table
  - Sea State knowledge used as input
  - Expected residual error
- **Beyond launch**

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SEA STATE BIAS :

PHENOMENOLOGY

SEA STATE BIAS

- The presence of waves (even zero mean) on the ocean surface biases the topography measurement.

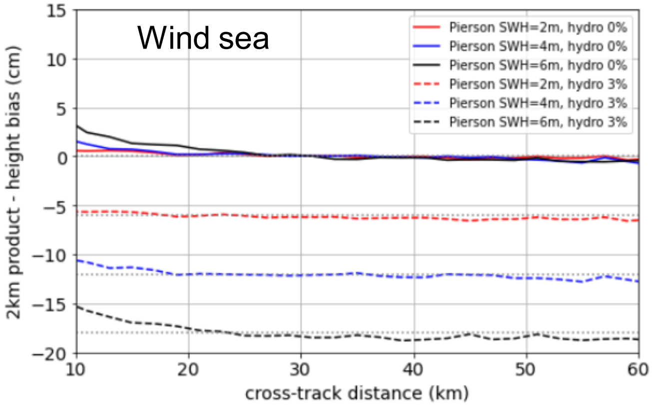
- (correlated) phenomena at play:
  - Height modulation
  - σ_0 tilt modulation : “wave portions facing the radar backscatter more than those facing away”
  - σ_0 hydrodynamical modulation : “troughs backscatter more than crests”
  - Surface motion : KaRIn is a SAR
  - Non gaussianities

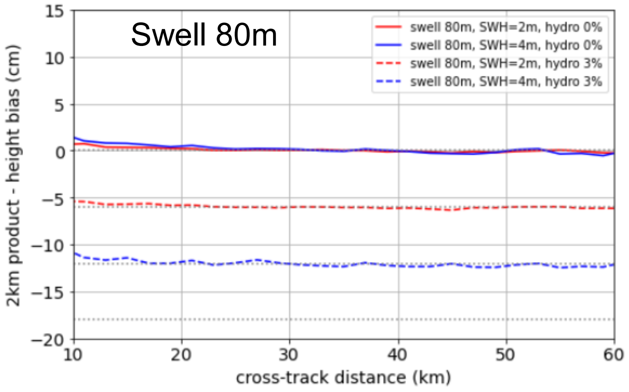
- Developing realistic models for some of these phenomena is an open problem

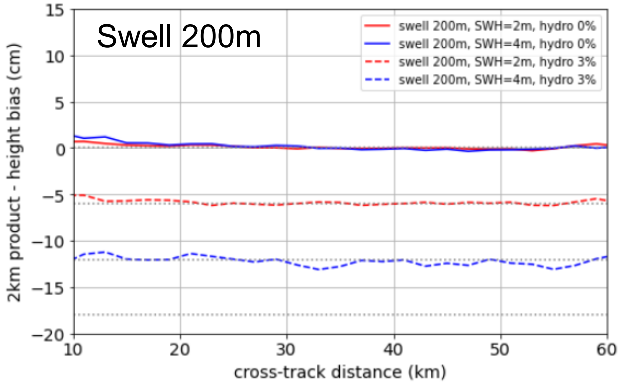
- SSB is a well-known issue in nadir altimetry and has to be corrected. Done empirically by minimizing variance at cross-overs.

Nadir vs interferometric SSB

- KaRIn's measurement is different from conventional nadir altimetry. The same sea state could a priori lead to different biases in both.
- We have investigated these potential differences both through simulations and by developing a theoretical model for SSB in KaRIn, within our physical description for the waves. We have found that
    - At leading order the biases are identical (determined by the amplitude of the hydrodynamical modulation and SWH). Known since paper by Peral et al.
    - KaRIn has some small additional bias which depend on SWH but also on the typical wavelength, orientation, and small scale roughness. This has some weak cross-track dependence







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SEA STATE BIAS CORRECTION :

STRATEGY @ LAUNCH

Baseline strategy @launch

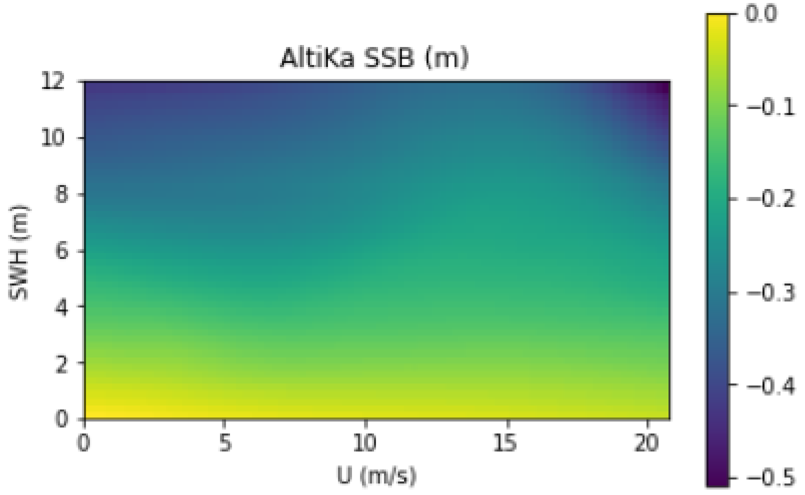
- Correcting for sea state bias requires

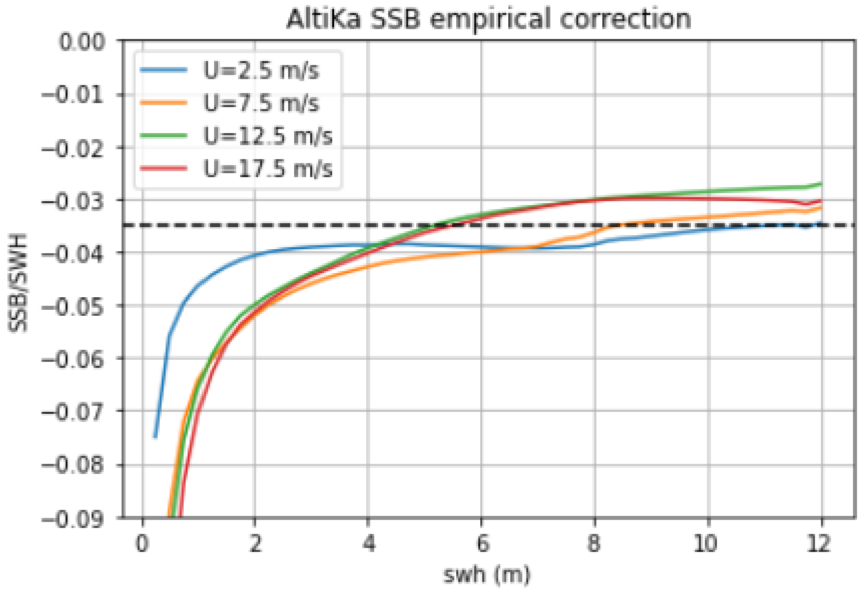
  1. a model for the bias on KaRIn's SSH measurement given a sea state

  2. knowledge about the sea state that SWOT is flying over

Baseline strategy @launch

- The model that we will use at launch for our SSB correction is a 2 parameter function SSB(wind speed, SWH) empirically derived using data from AltiKa.





Baseline strategy @launch

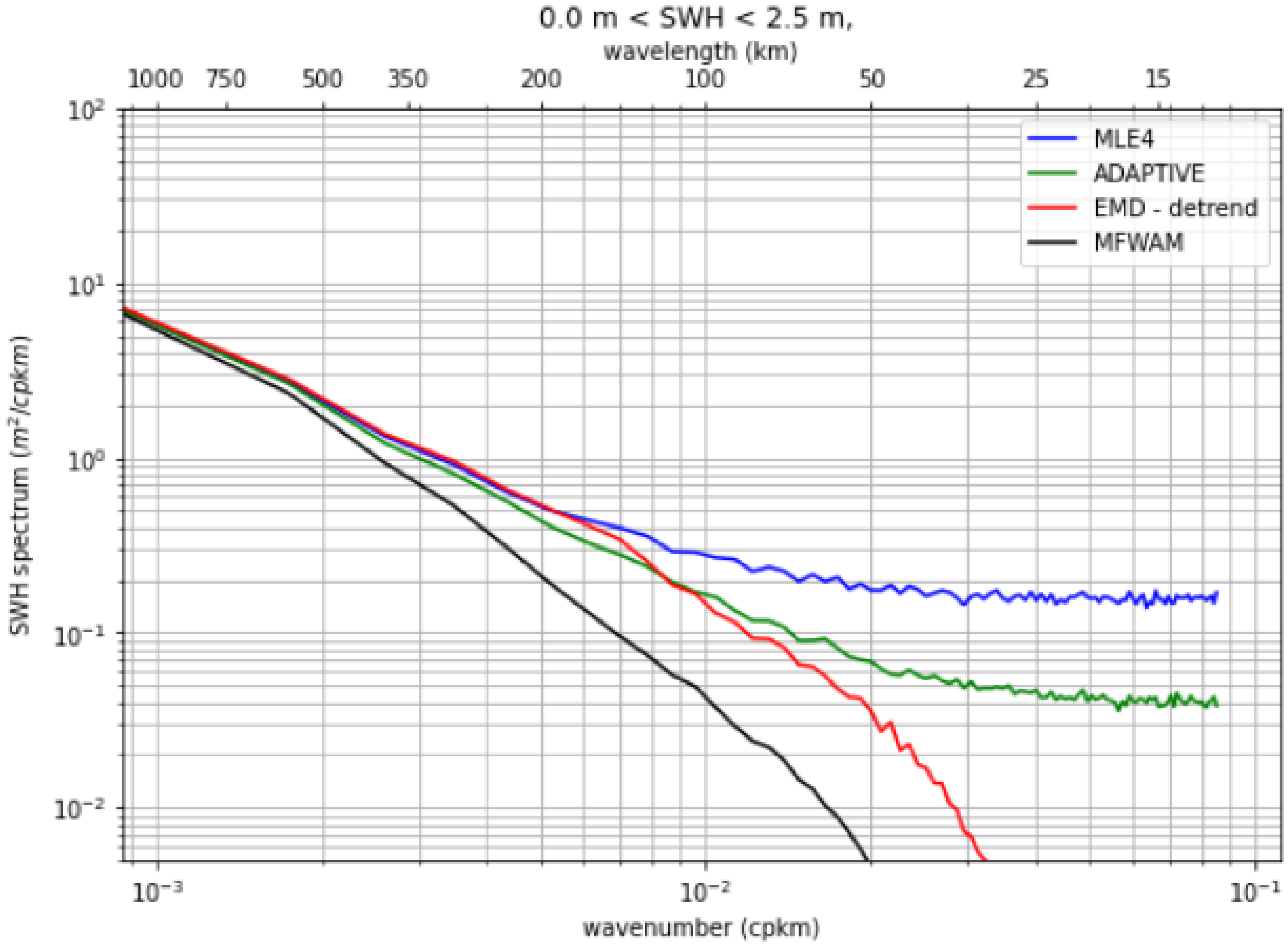
- The main parameter driving the SSB is SWH. Wind is a subleading order parameter. The strategy at launch is to use KaRIn's wind measurement.

- Guiding principle for SWH as an input to SBB @launch:
  - avoid relying at launch on KaRIn's SWH measurement which may require calibration
  - SWOT has a nadir altimeter whose SWH measurement is mature
  - Using a model-based SWH is also an option

➡ What is the SSB's contribution to the error budget given this strategy?

- First, focus on along track SWH variation
- Then, address cross-track variation

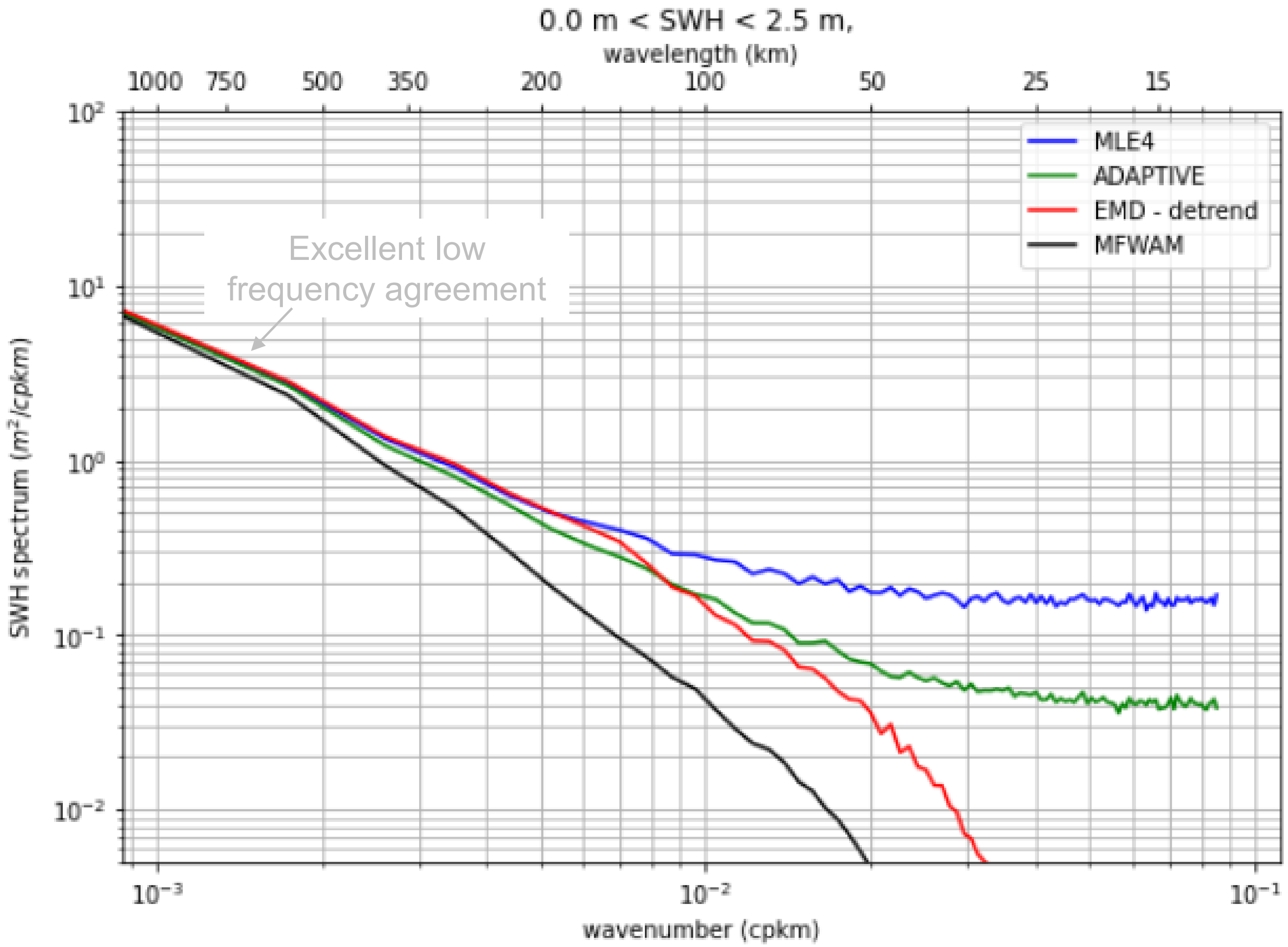
Along-track SWH spectrum



Mean SWH spectrum
Average over 1 month=3 cycles (november 2021)

Restricted to SWH<2.5m (to satisfy SWOT's requirements)

SWH spectrum



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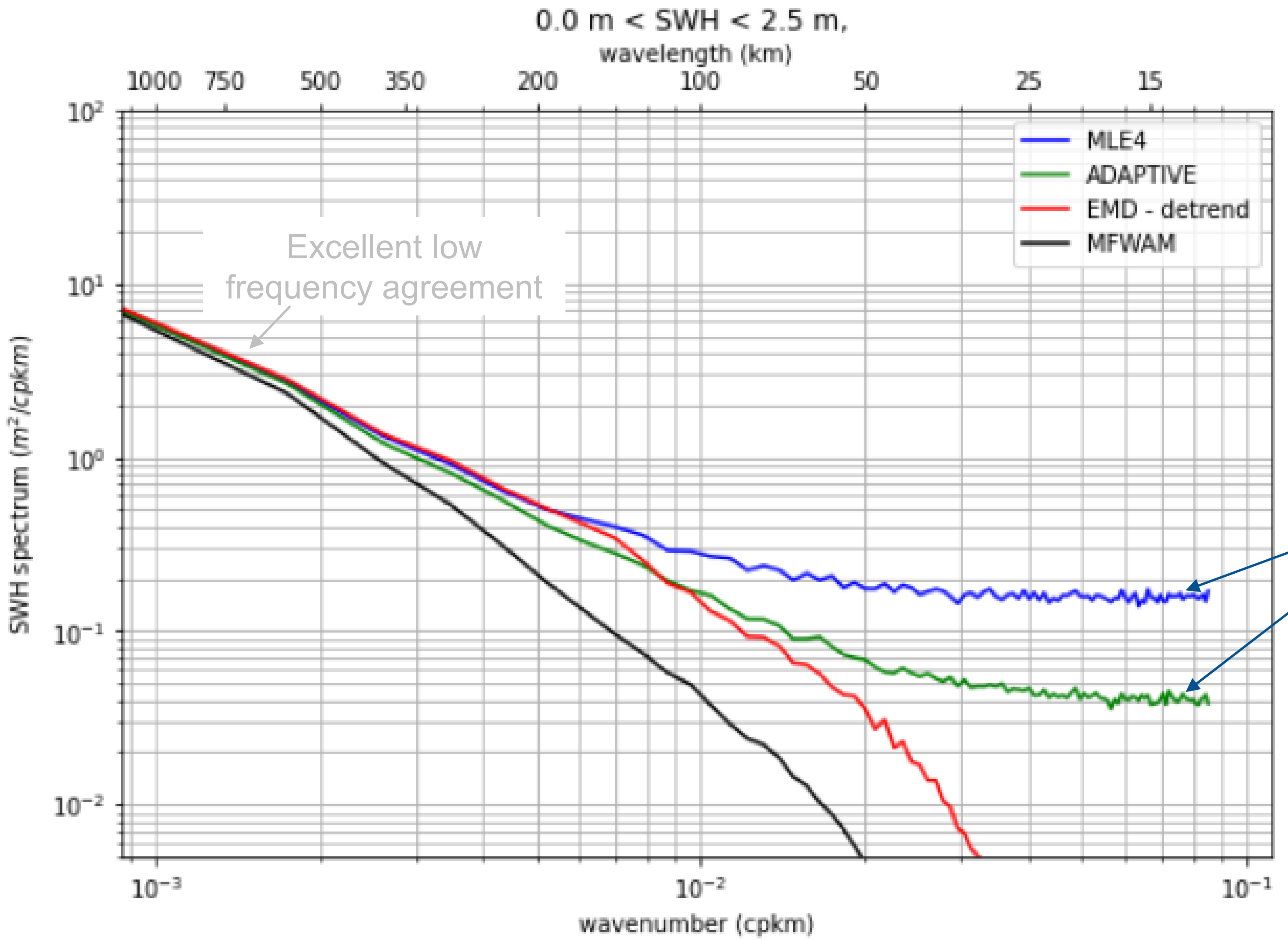
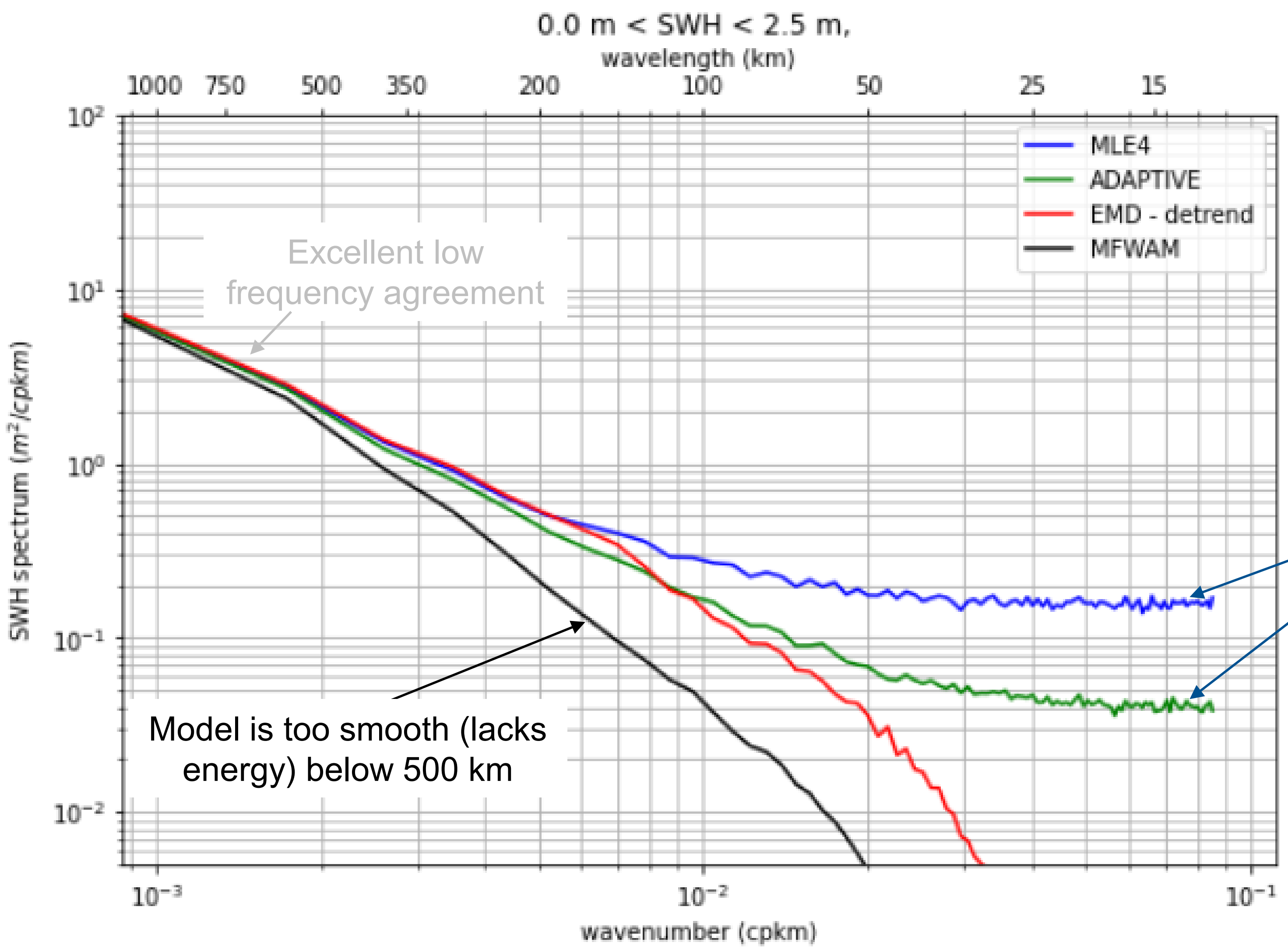


Mean SWH spectrum
Average over 1 month=3 cycles (november 2021)

Restricted to SWH<2.5m (to satisfy SWOT's requirements)

Noise plateau (lower for adaptive retracking). This is dominated by measurement noise and directly enters our SSB correction, increases our level of KaRIn SSH noise.

SWH spectrum



Mean SWH spectrum
Average over 1 month=3 cycles (november 2021)

Restricted to SWH<2.5m (to satisfy SWOT's requirements)

Noise plateau (lower for adaptive retracking). This is dominated by measurement noise and directly enters our SSB correction, increases our level of KaRIn SSH noise.

Residual error after SSB correction (various flavors)

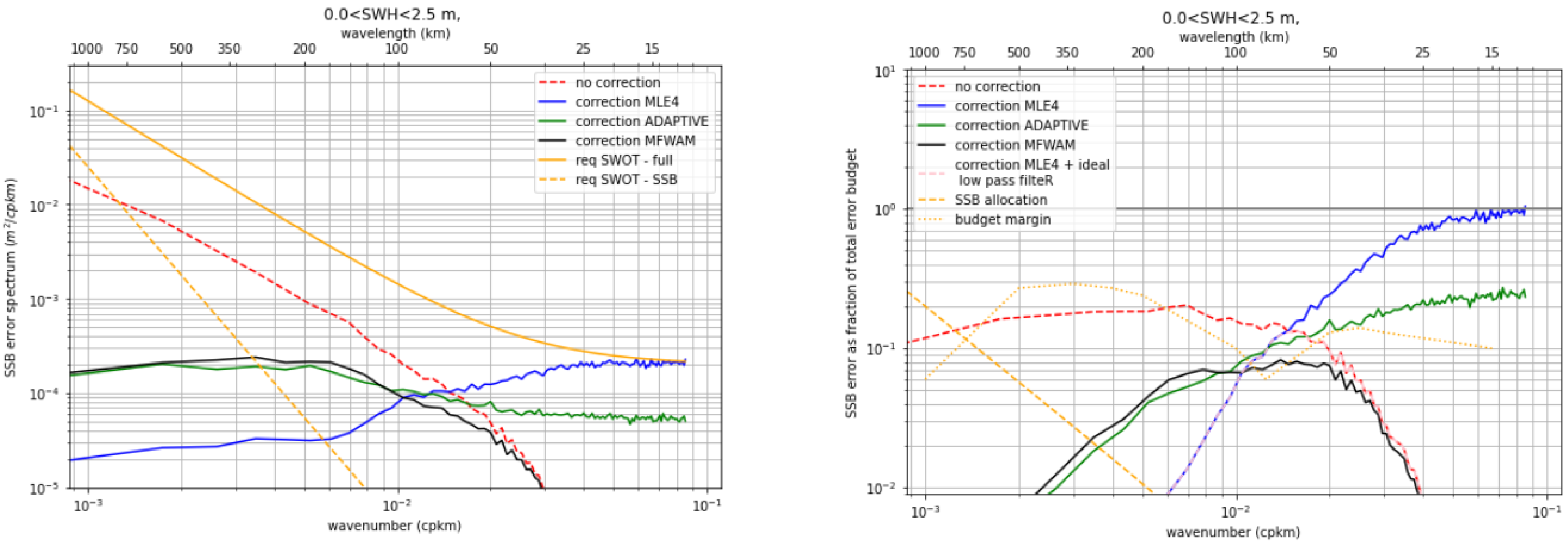
We take the EMD (L3) dataset as our proxy for the truth. In other words, we compute the residual error after correction using flavor XX of the SWH as

$$SSB_{\text{error}} = SSB_{model}(wind, SWH_{XX}) - SSB_{model}(wind, SWH_{EMD})$$

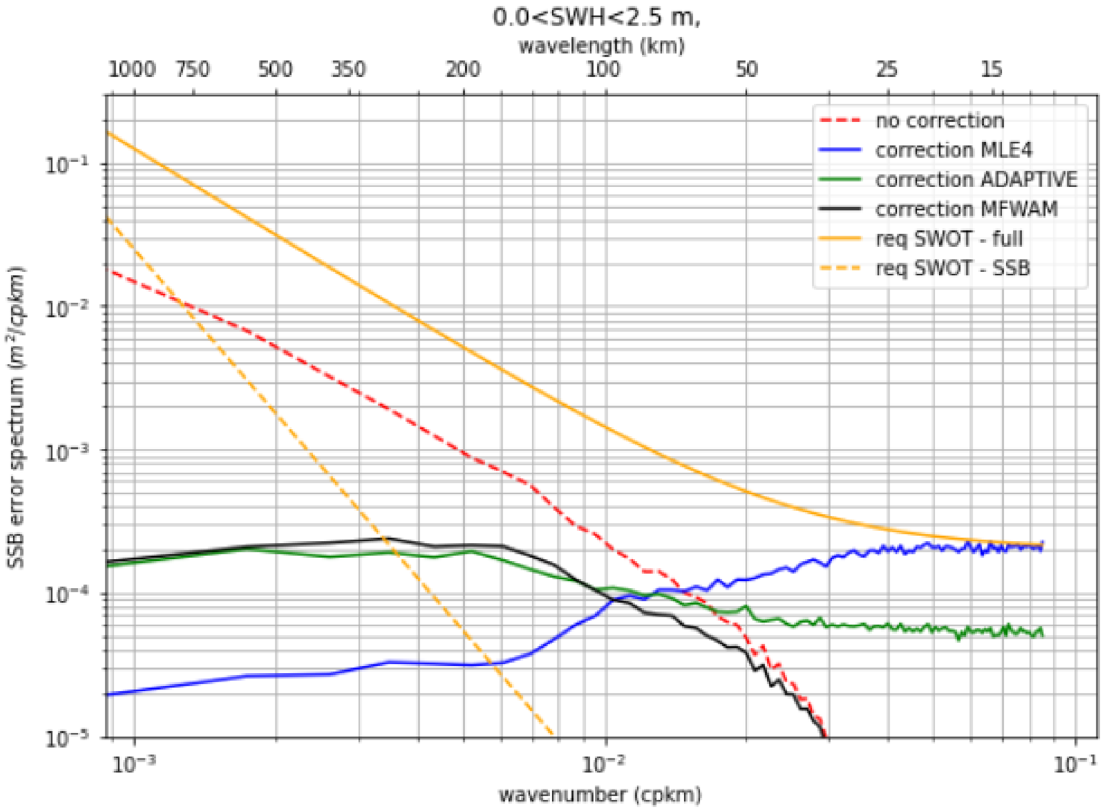
Our correction   Actual SSB in KaRIn (idealized)

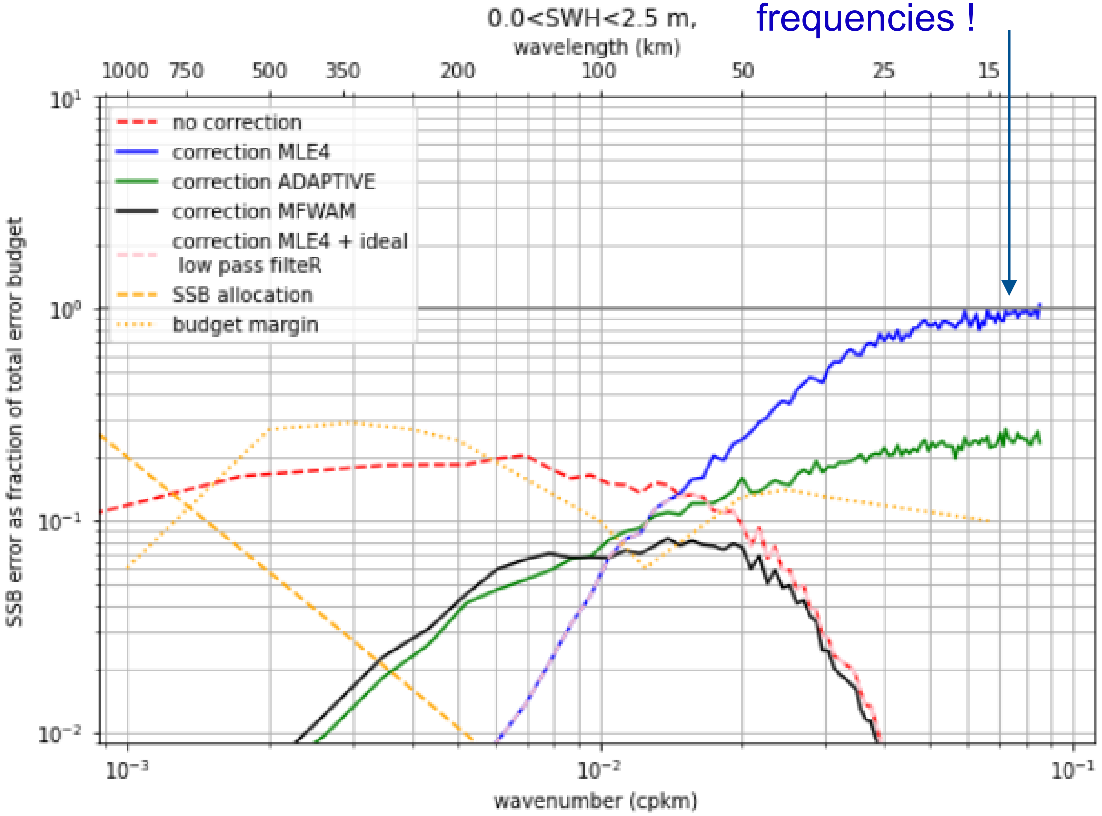
We compute this correction over all our data segments, then compute the average spectrum.

Residual error after SSB correction (various flavors)



Residual error after SSB correction (various flavors)

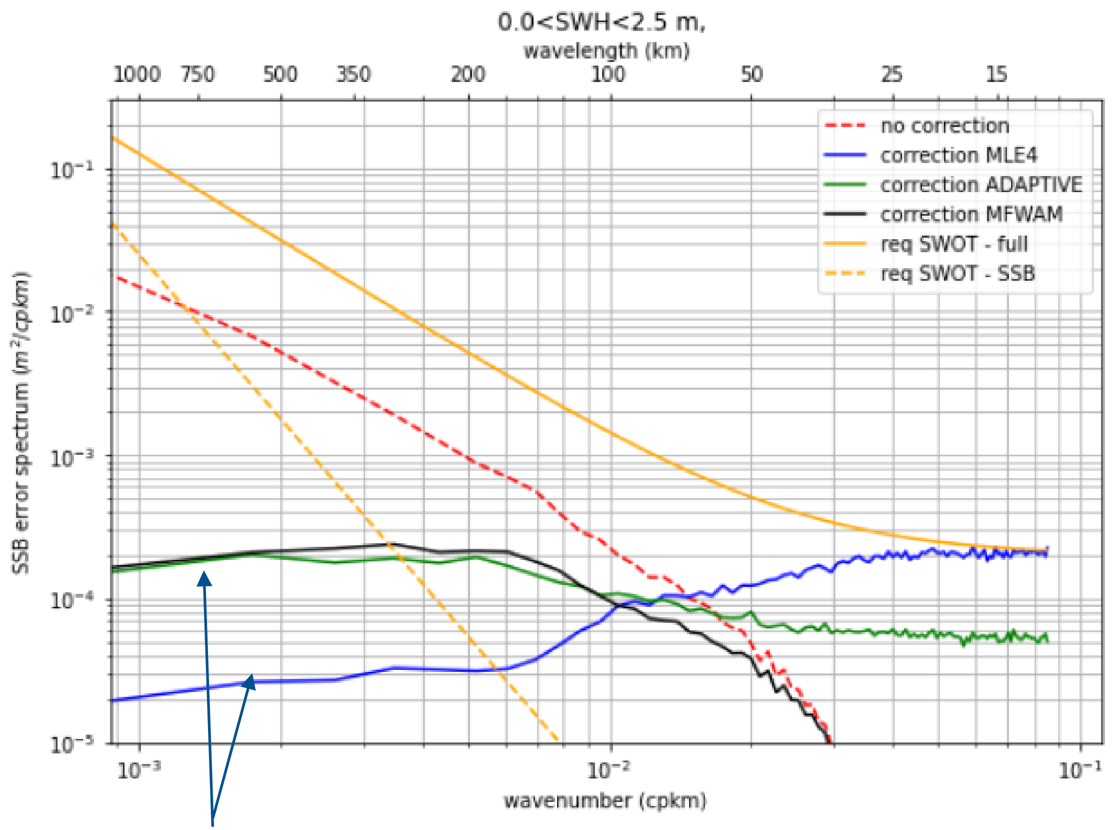


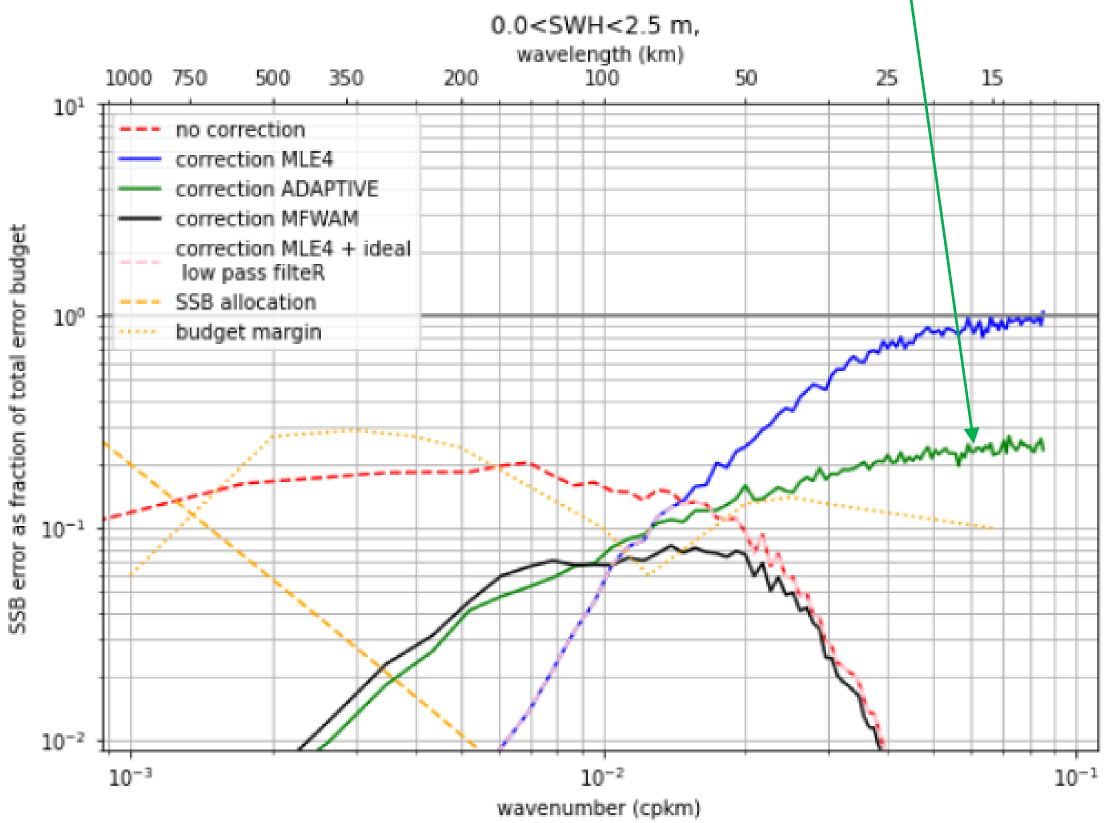


Measurement noise in MLE4. Eats up almost the entire eror budget at high frequencies !

Residual error after SSB correction (various flavors)

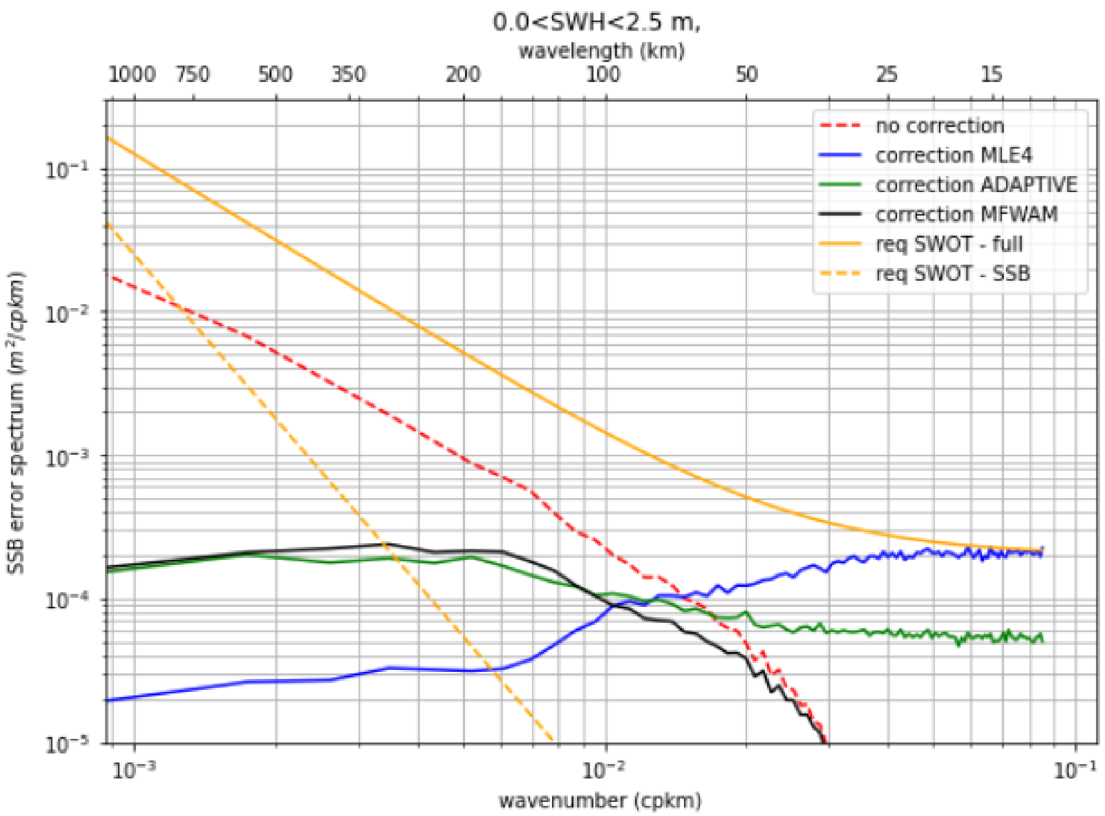
Better with adaptive, but still too large.

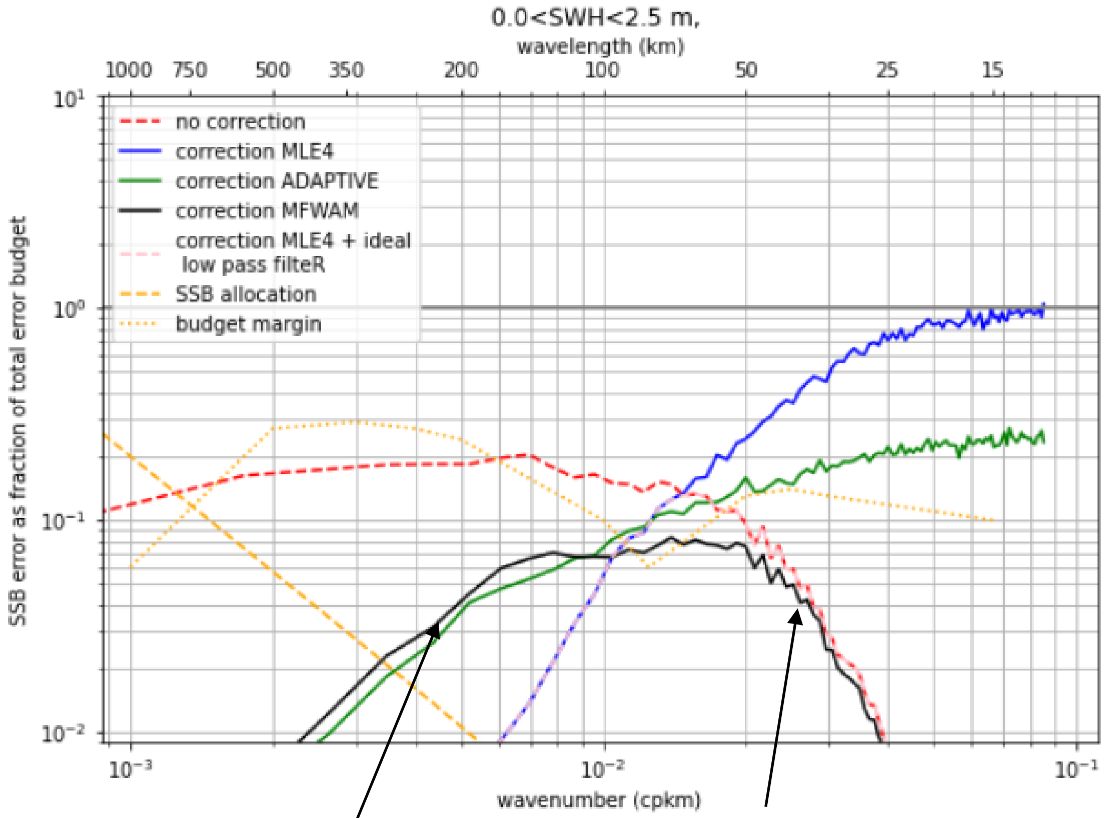




Difference here (adaptive worse) is almost certainly due to the fact that our proxy for the truth (EMD) is denoised MLE4.

Residual error after SSB correction (various flavors)

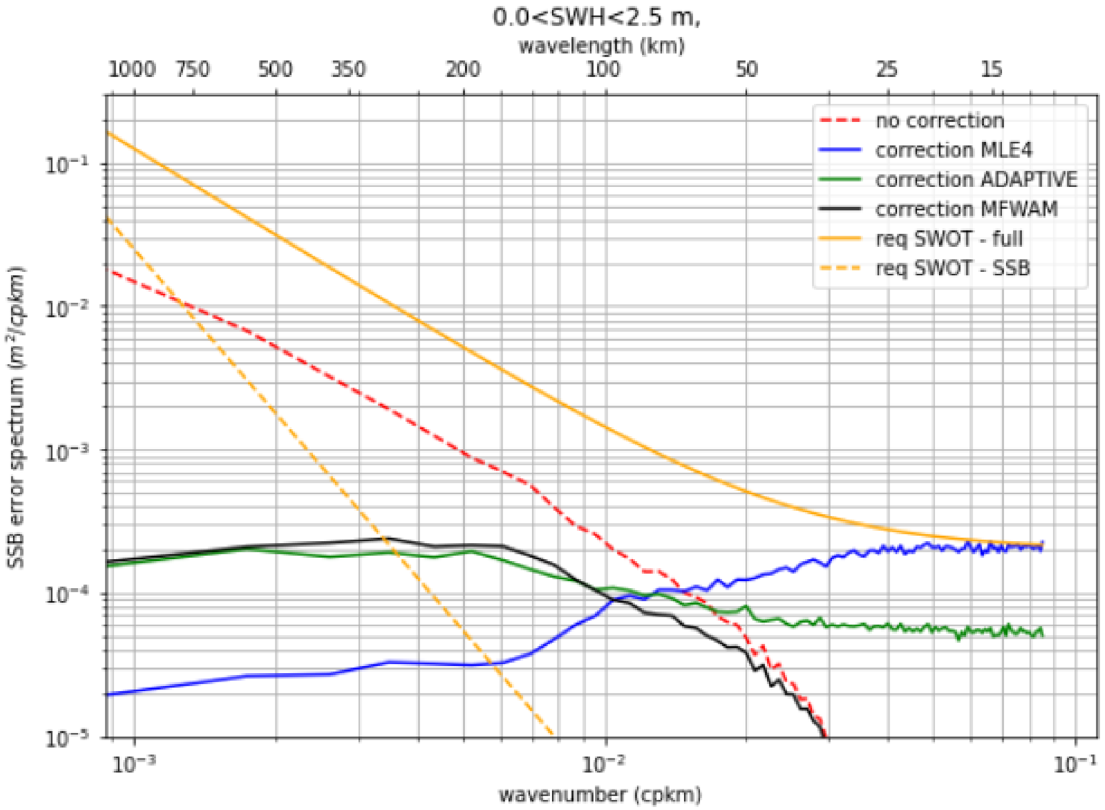


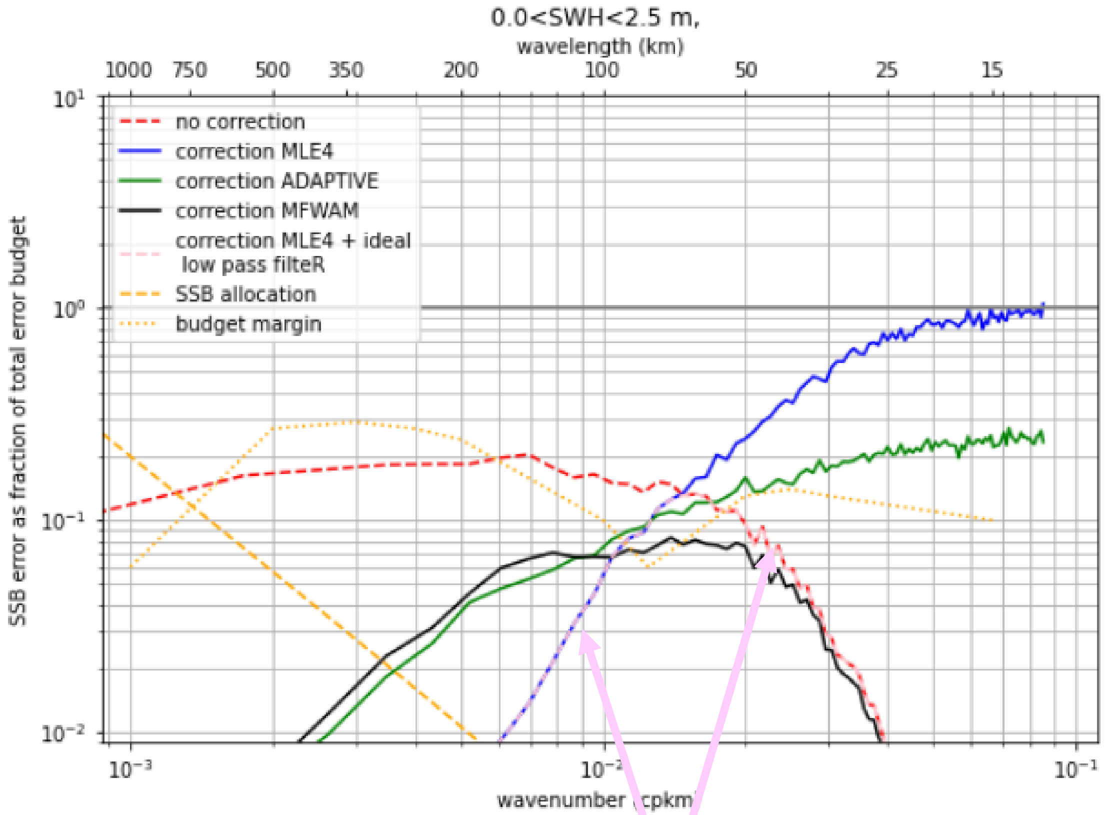


At large scales (>100 km), the model is good enough to keep the error below 10% of the total budget.

At short scales (<50-100 km), the model provides essentially no correction, but the actual error in the absence of correction is below 10%.

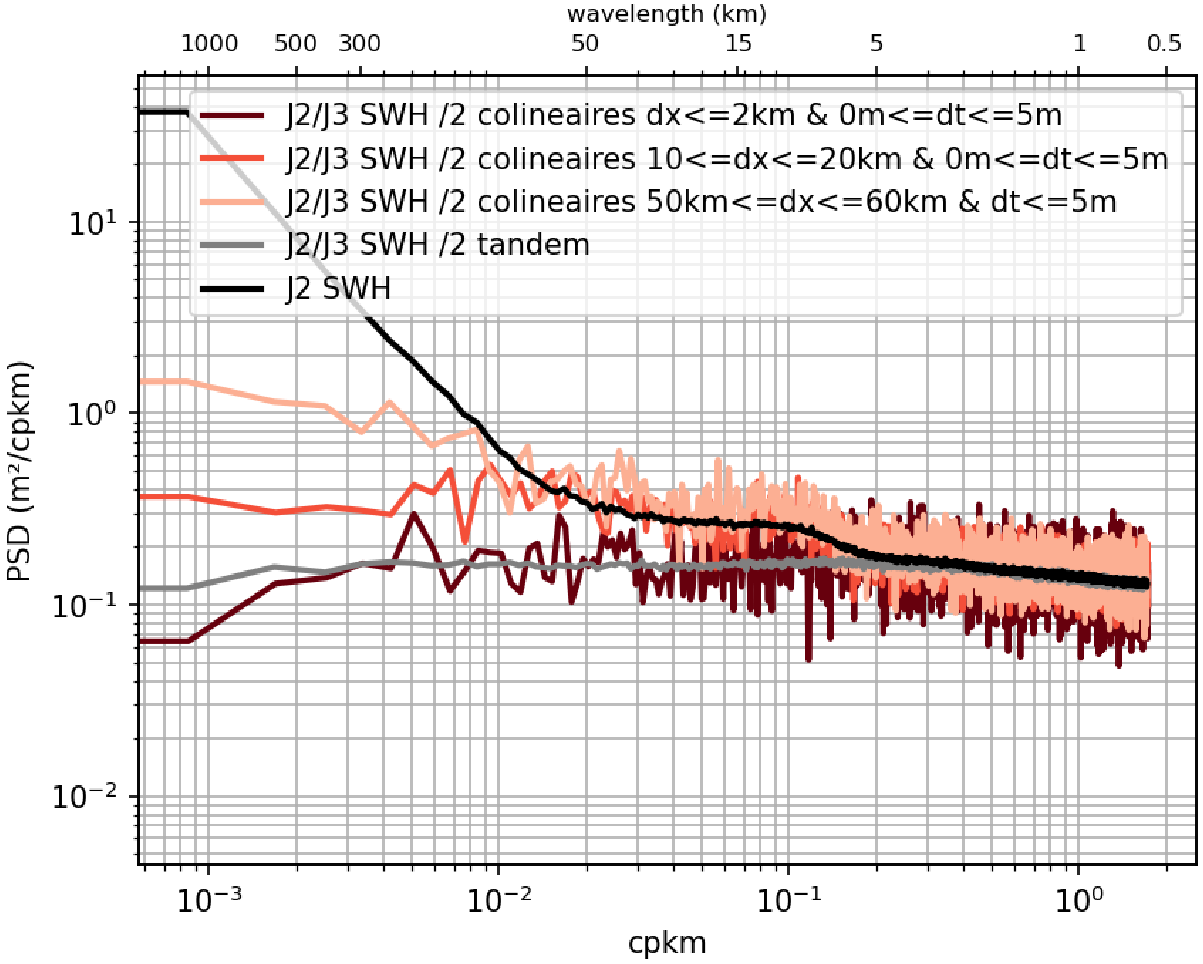
Residual error after SSB correction (various flavors)



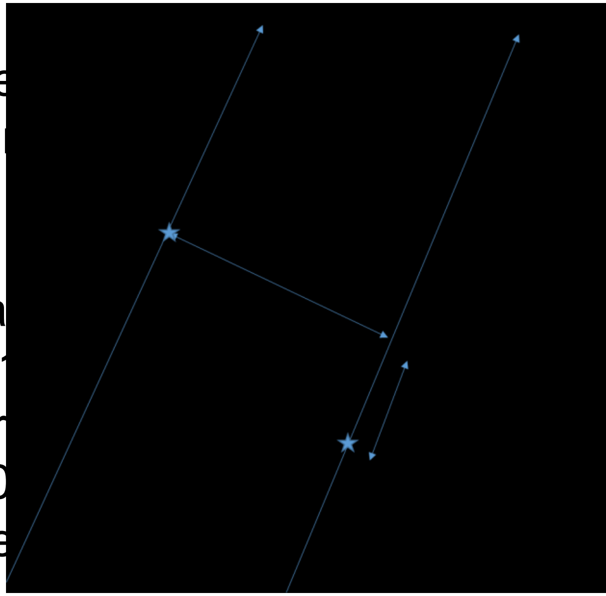


A MLE4 based correction could be built using a low pass filter. Correct the large scales using nadir data, but filter out the small scales which are noisy. Adjust cutoff so that what we gain by not introducing HF noise is more than what we loose by not correcting the small scales. Still up to ~15% of total error budget in the 50-100km region.

SSB and the cross-track dependence of SWH



- Studied cross-track depe of SWH using sets of pa J2/J3 orbits



- The SWH modulations a track scales larger than are largely correlated for track distances below 60 Using the SWH measure nadir is OK.

- Below 75km, they are almost completely uncorrelated but since this region is dominated by noise and we are not applying any correction there (low pass filter), not having a SWH measurement everywhere in the swath does not affect our performance.

Proposed strategy

- Baseline at launch
  - **Forward processing :**
    - SSB_cor_1 : use MLE4 from OGDR + low pass filter with ~75 km cutoff (and appropriate outlier rejection). Up to 15-20% of total budget in 50-100km region.
    - SSB_cor_2 : use model : likely ~10% of total error budget in 50-100km region. Might be more if phase of the model becomes incorrect at those scales.
  - **Re-processing :**
    - SSB_cor_1 : similar to forward but with ADAPTIVE from GDR and low pass filter with ~40 km cutoff. Should be below 10% of total error budget everywhere.
    - SSB_cor_2 : same as forward processing.

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BEYOND LAUNCH

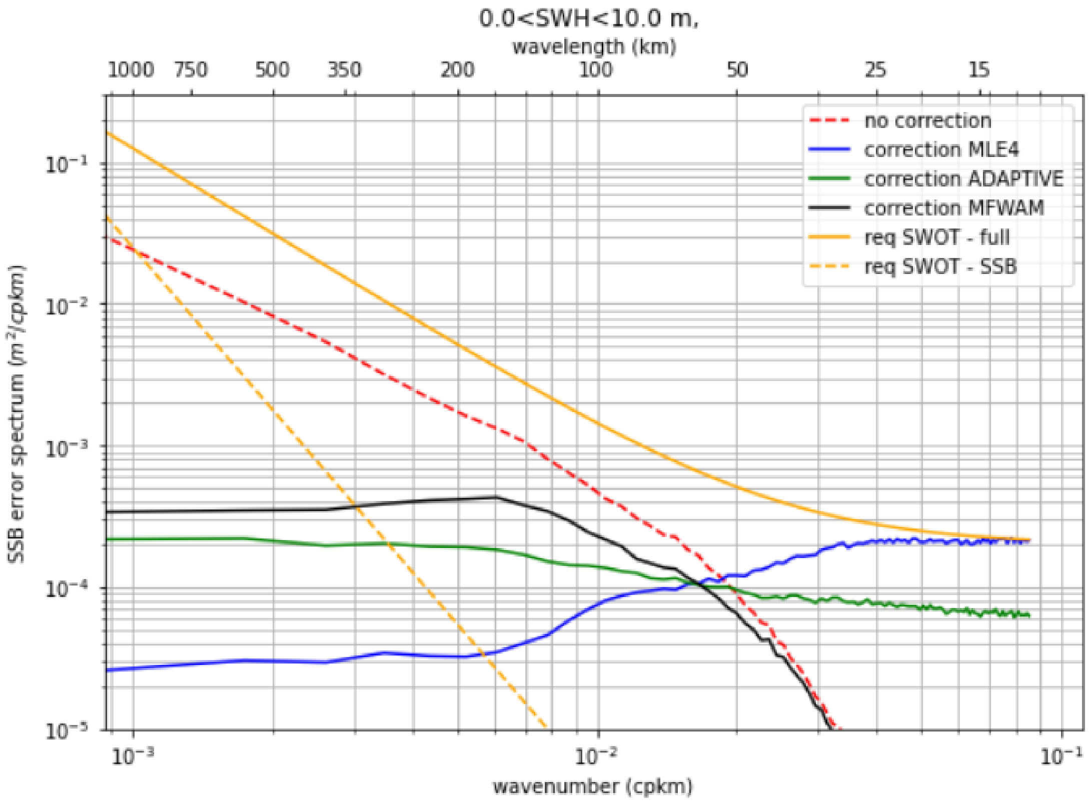
Proposed strategy

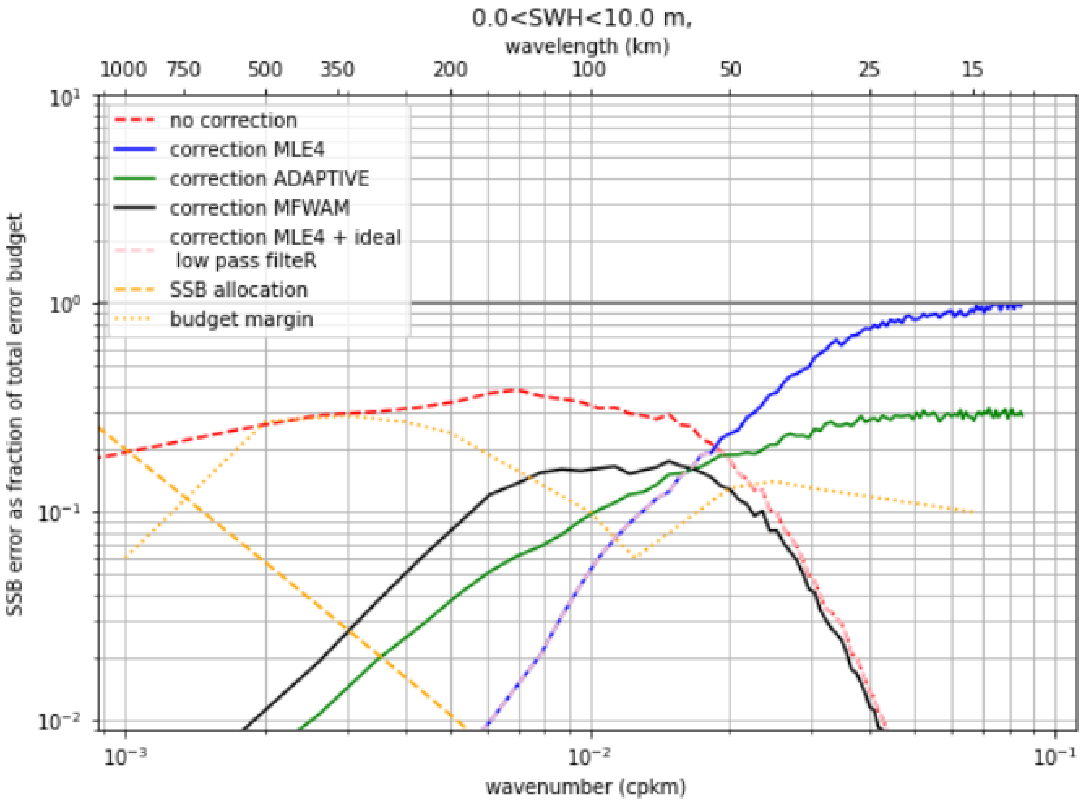
- Even with the choices described in the previous slides, our SSB correction will still represent a not insignificant source of error in particular in the 50-100km range.

- After launch, using flight data and additional studies, investigate more optimal strategies to bring the error down as much as possible
  - Possibly a mix of MLE4 (or adaptive if available) at large scales (>150km) + a model assimilating data from SWOT nadir at smaller scales.
  - Test corrections of the (small) cross-track dependent part of the bias : requires external data (model) for the typical wavelength and the orientation
  - Build an empirical KaRIn SSB table to replace the AltiKa table used at launch
  - Assuming SWH measurements from KaRIn can be successfully calibrated, consider using those as input for the SSB correction.
  - Explore ability to recover cross-track variation of SWH with KaRIn and therefore to improve SSB correction in far swath.

APPENDIX

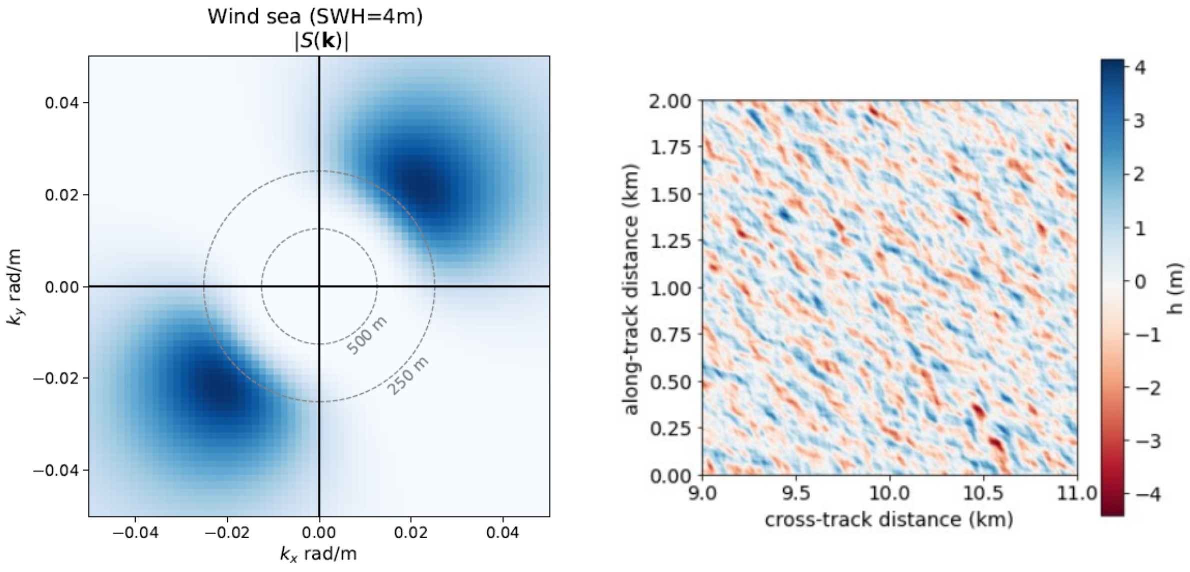
Results without restricting to low SWH

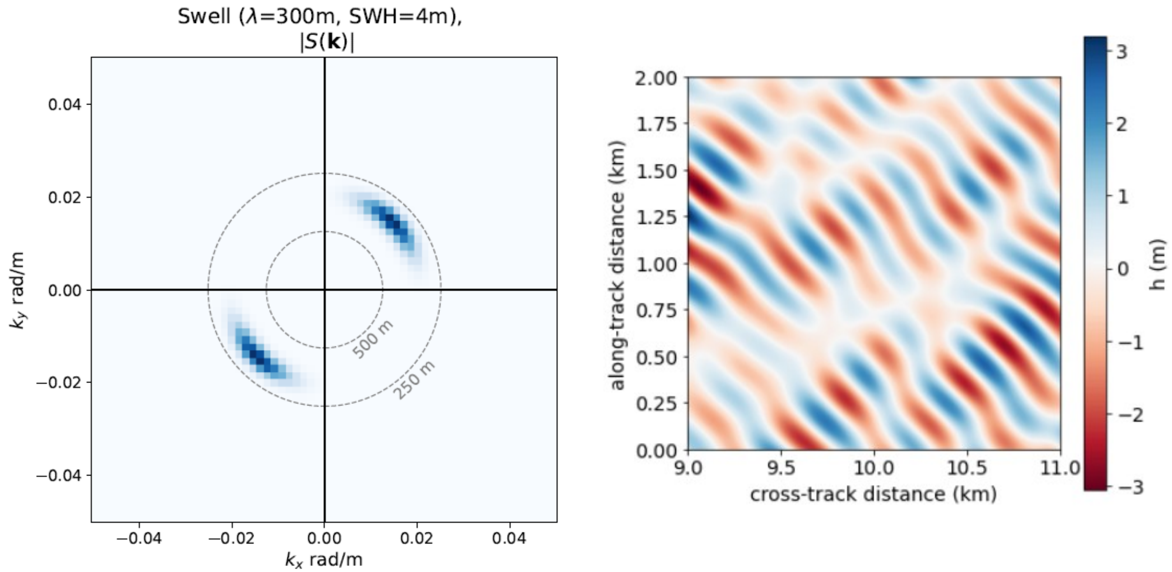




Wave spectrum

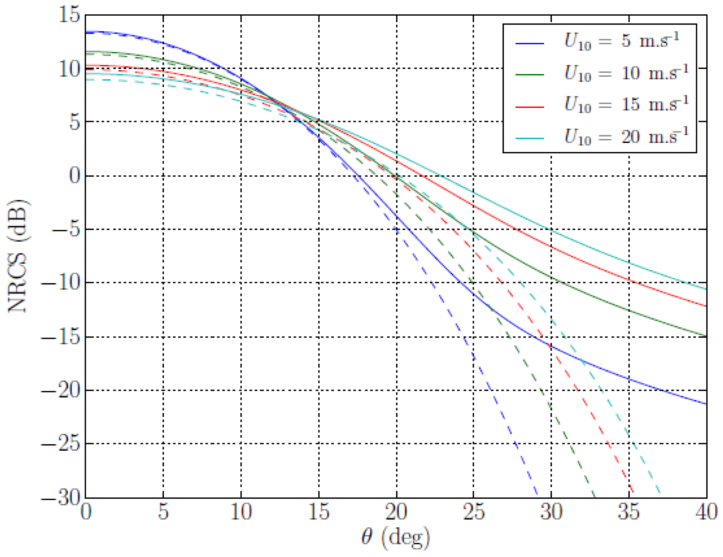
- The simplest (unrealistic) wave surface is uncorrelated waves (white spectrum).
- Realistic waves have spatial correlations described by their height spectrum





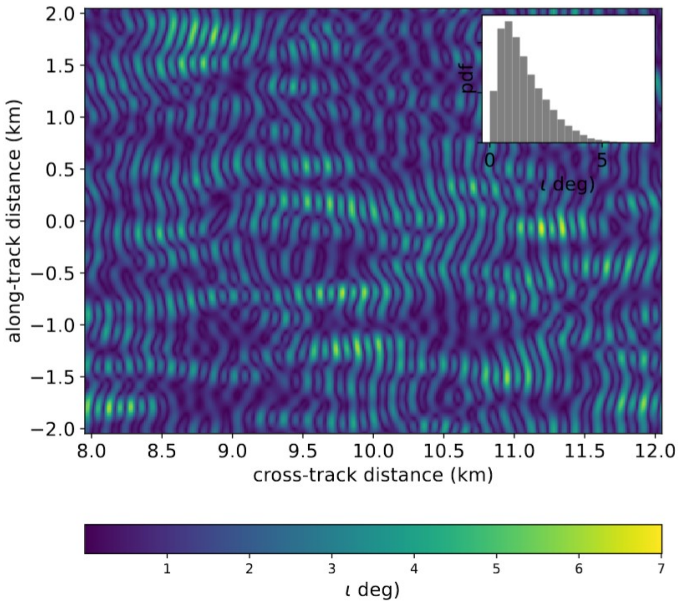
Backscatter modulation : tilt

- Portions of the surface facing the radar backscatter more than those facing away.
- Two scale approach : backscatter from any "facet" depends on the "short" (unresolved) waves and is described statistically.
- Various models (approximations) to describe the interaction between the EM waves from the radar and the rough surface : geometric optics, Kirchhoff…
- Results presented here assume a simple geometric optics model @Ka band. The short wave statistical information is encompassed into a single parameter, the mss.



(illustration Ku band)

Local incidence for a 200m swell with SWH=3m propagating in the cross-track direction



Basckatter : hydrodynamic modulation

- The troughs of the waves backscatter more than the crests. This is a source of Sea State Bias

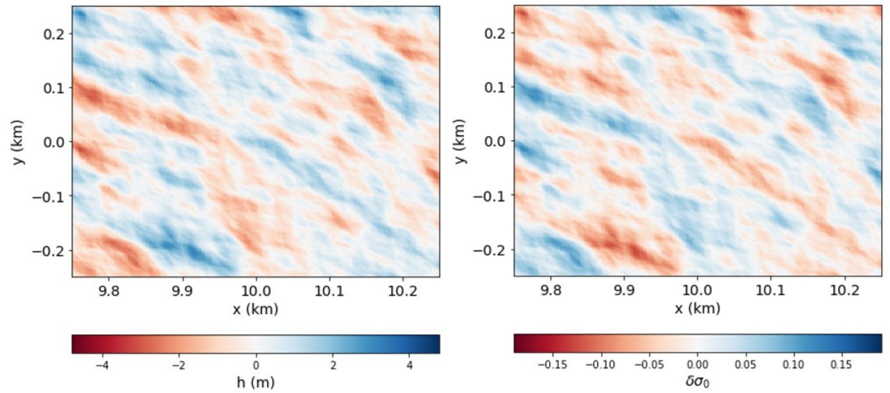
- This is due to the presence of more small scale roughness at the troughs, due to non-linear interactions between the waves. The large waves modulate the short wave spectrum.

- Deriving a complete physical model from first principles (i.e. that emerges from a formalism accounting for the non-linearities in wave propagation) for this modulation is still an open problem (things have been done to first order in non-linearity; using this is work in progress)

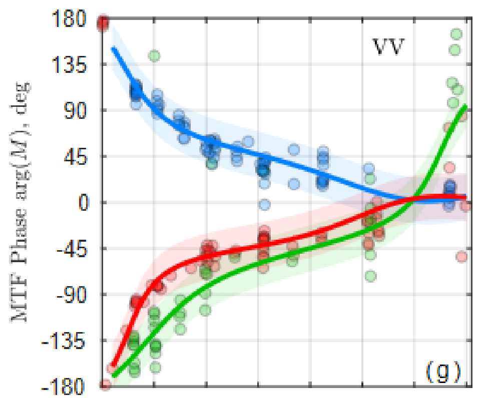
- A general formalism (assuming a linear relation between the Fourier components of the heights and backscatter modulations) is used in the literature. For each wavelength and direction of propagation, specify an amplitude and a phase.

- Results shown in this presentation assume the simplest possible model : the MTF is constant (same modulation for all wavelengths and directions) and the modulation is in phase with the heights. The amplitude is adjusted to match the SSB from nadir observations (~3% SWH). This is probably an overestimate of the amount of modulation since other effects must contribute to nadir SSB (skewness…)

- The code allows for the use of any MTF. Work in progress to build a more realistic one.



$$\delta\sigma_0 = -\beta \frac{h}{SWH}$$



Yurosky et al (2018)

MTF measurements

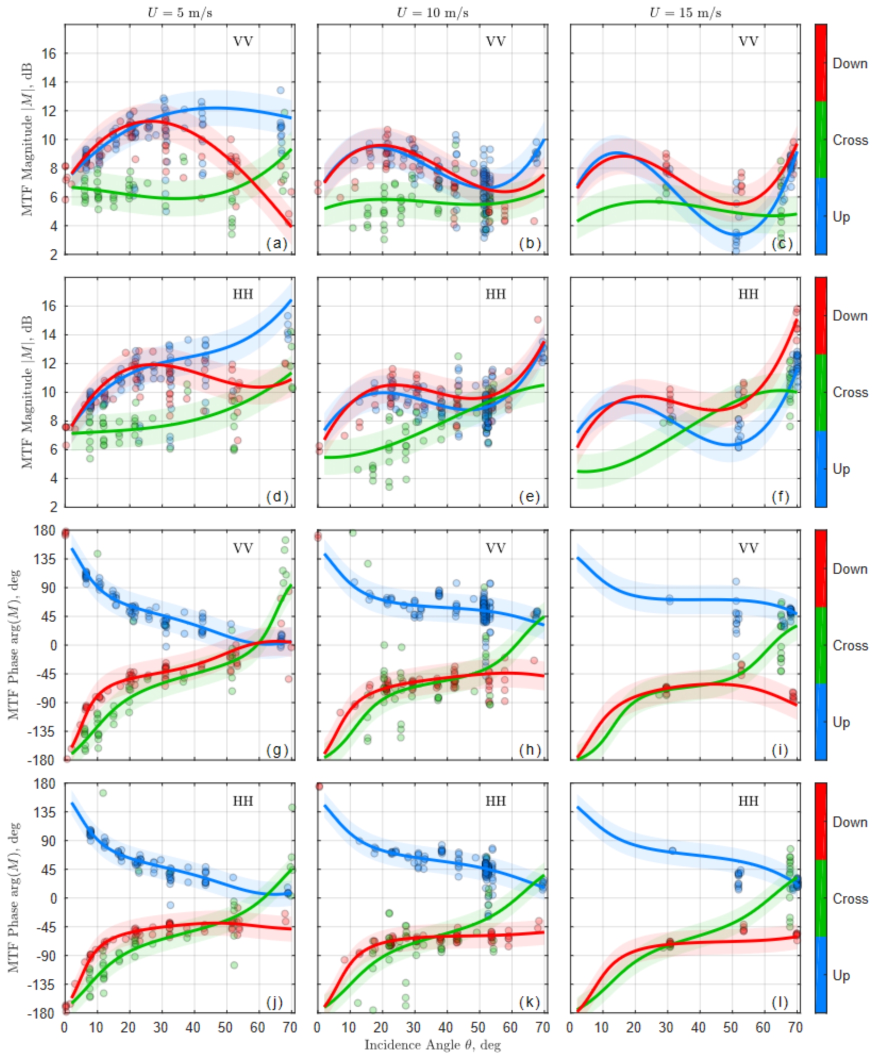
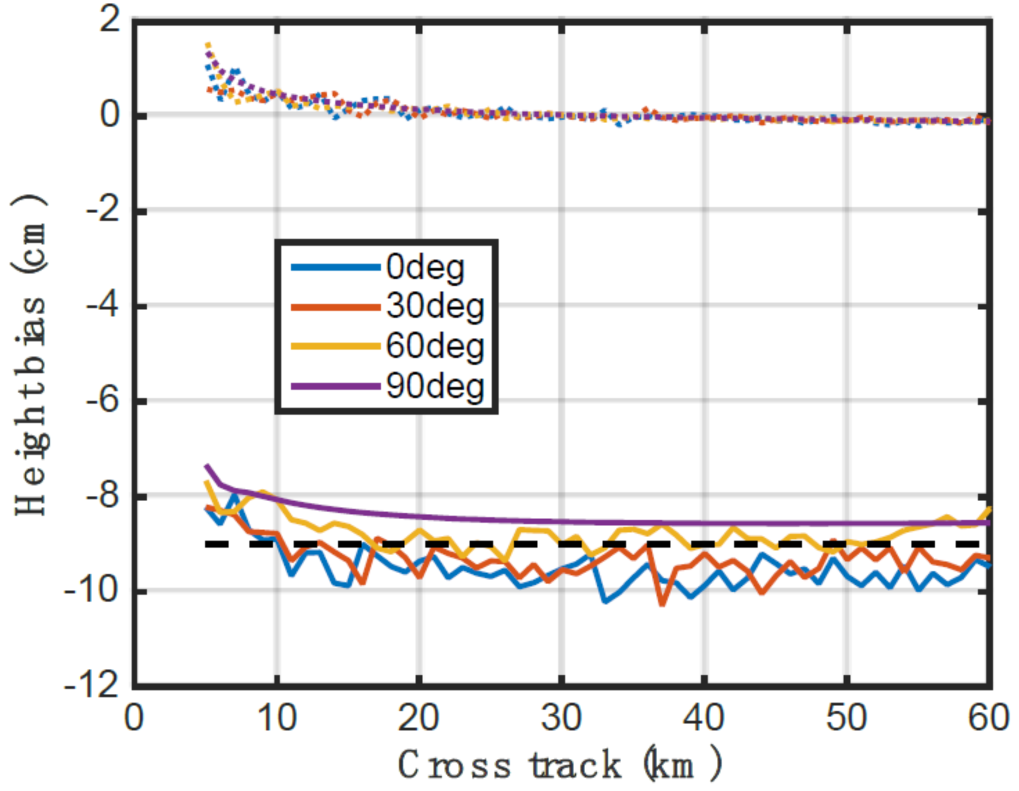
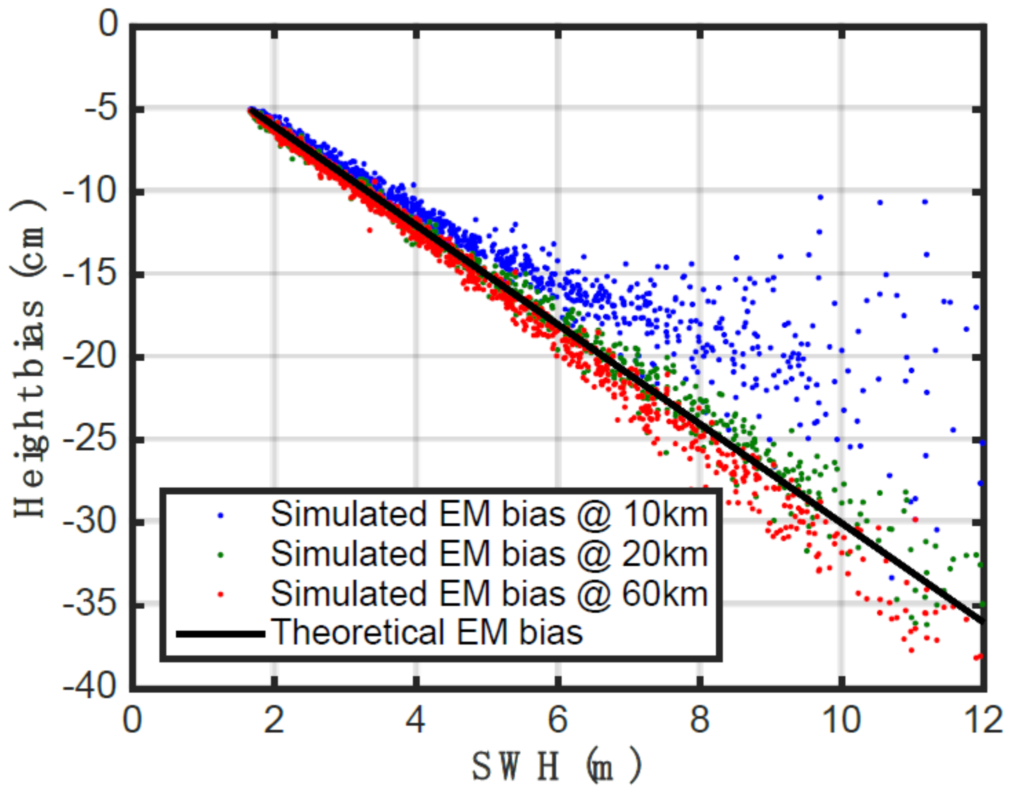


Fig. 9. Measured (circles) and fitted (lines) MTF averaged over resolved wave frequencies, $f_p < f < f_{cut}$. Measurements are binned in wind speed ($U \pm 2.5$ m/s) and azimuth ($\phi \pm 45°$). Confidence intervals (shading) correspond to root-mean-square error of the MTF fit (see Appendix C for details).

Non gaussianities

- Waves entirely characterized by their spectrum are Gaussian
- Real waves are not
- Adding e.g. skewness is far from trivial. Two approaches :
  - Either prescribe it “by hand” by using a skewed Gaussian distribution and making skewess a free parameter. But this simple 1D approach is only valid only for uncorrelated waves. Doing this for correlated (realistic) waves requires prescribing a tri-spectrum for which we have even less observations.
  - Either have it emerge from a model at least partially accounting for non-linearities (e.g. Choppy). But deriving a complete model is still an open problem.





Impact of Surface Waves on SWOT's Projected Ocean Accuracy

Eva Peral *, Ernesto Rodríguez and Daniel Esteban-Fernández

SWH from nadir : L3 level

- This is not an input to KaRIn's LR processing (and to be clear, I am not advocating that we should try to use it now)
- Difference wrt L2 product
  - **« Denoised » dataset**
    - Statistical rejection of outliers (flags not included in the L2 product)
    - Empirical denoising procedure applied (EMD, based on Quilfen & Chapron, 2021)
  - Inter-mission calibration
- State of the art SWH from altimetry (for 1D products; then L4 does 2D reconstruction). Here, we will use it as a proxy of the real (noise free) SWH from the ocean.
- This becomes increasingly less true at the shortest scales (<50km), see following slides. It is our best proxy right now, but investigations are in progress to try to quantify the residual noise (or the amount of real SWH content which has been smoothed out) at short scales.
- For JASON 3 (and other missions from altimetric constellation), distributed by Copernicus Marine Environment Monitoring Service (CMEMS).
- Note : the EMD procedure is applied to the MLE4 dataset from the L2 product

SWH from model

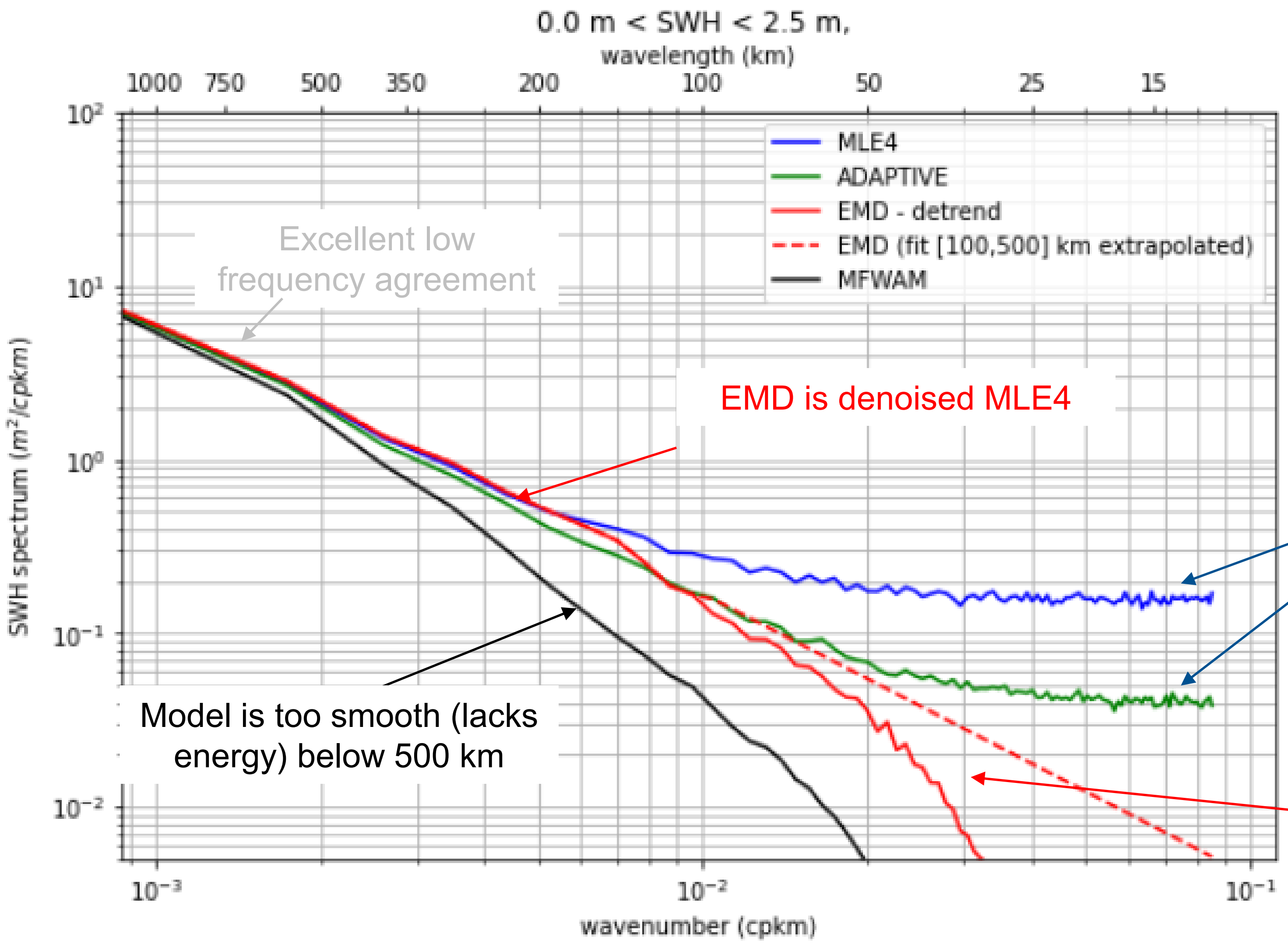
- Here,we use the MFWAM model (distributed by CMEMS), which provides SWH forecasts every 3h over a global 0,08° x 0,08° grid

- https://resources.marine.copernicus.eu/product-detail/GLOBAL_ANALYSIS_FORECAST_WAV_001_027/

- This is actually not exactly what we have at our disposal for KaRIn's LR processing (provided by GECO). While our model wave period and wave direction come from MFWAM, our model SWH comes from ECMWF. Differences are likely small, but to be checked.

- Additionally, GECO performs linear interpolation in time (whereas I am using simple nearest neighbour interpolation). Again, the effect is assumed to be small, but this still needs to be checked.

SWH spectrum



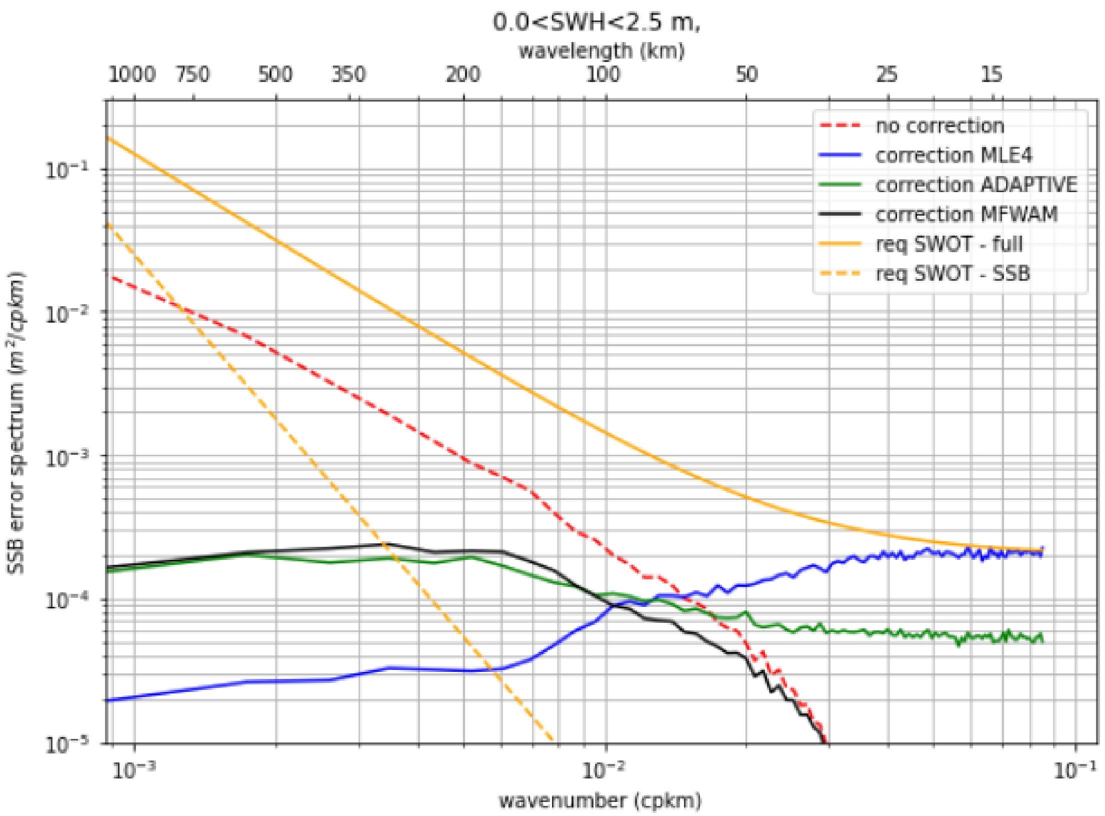
Mean SWH spectrum
Average over 1 month=3 cycles (november 2021)

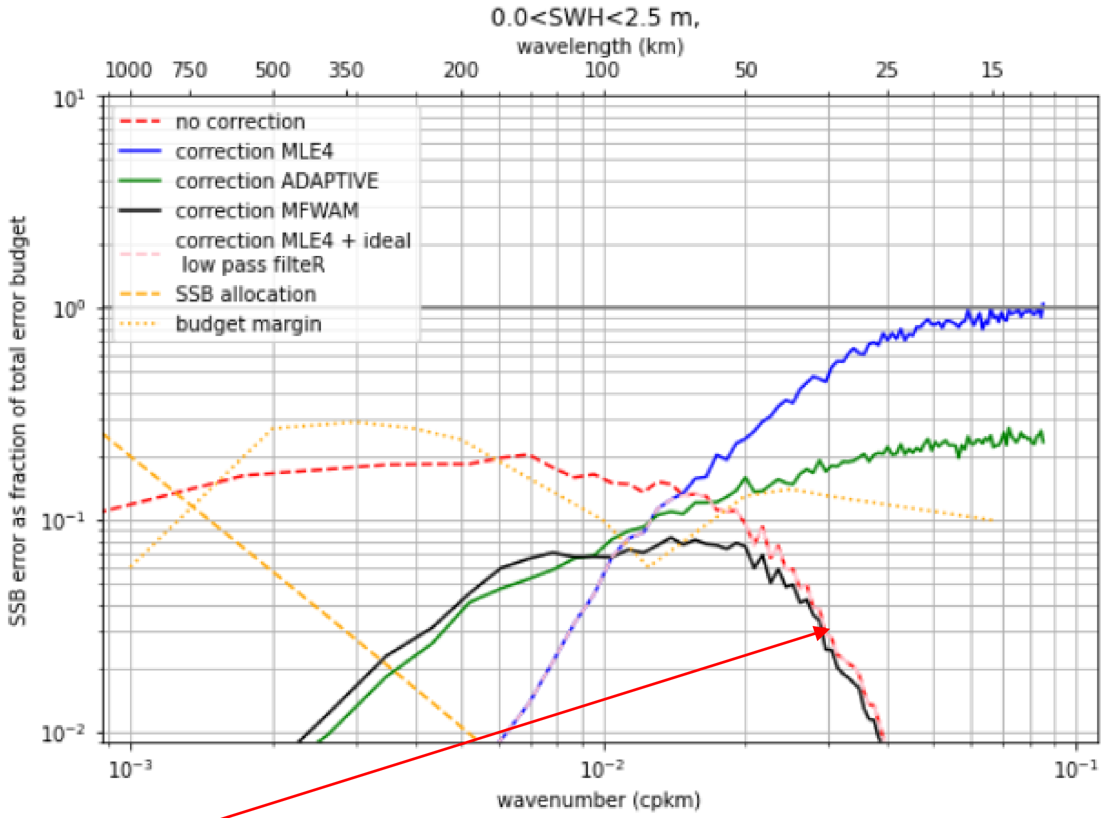
Restricted to SWH<2.5m (to satisfy SWOT's requirements)

Noise plateau (lower for adaptive retracking). This is dominated by measurement noise and directly enters our SSB correction, increases our level of KaRIn SSH noise.

EMD likely lacks energy at the shortest scales

Residual error after SSB correction (various flavors)

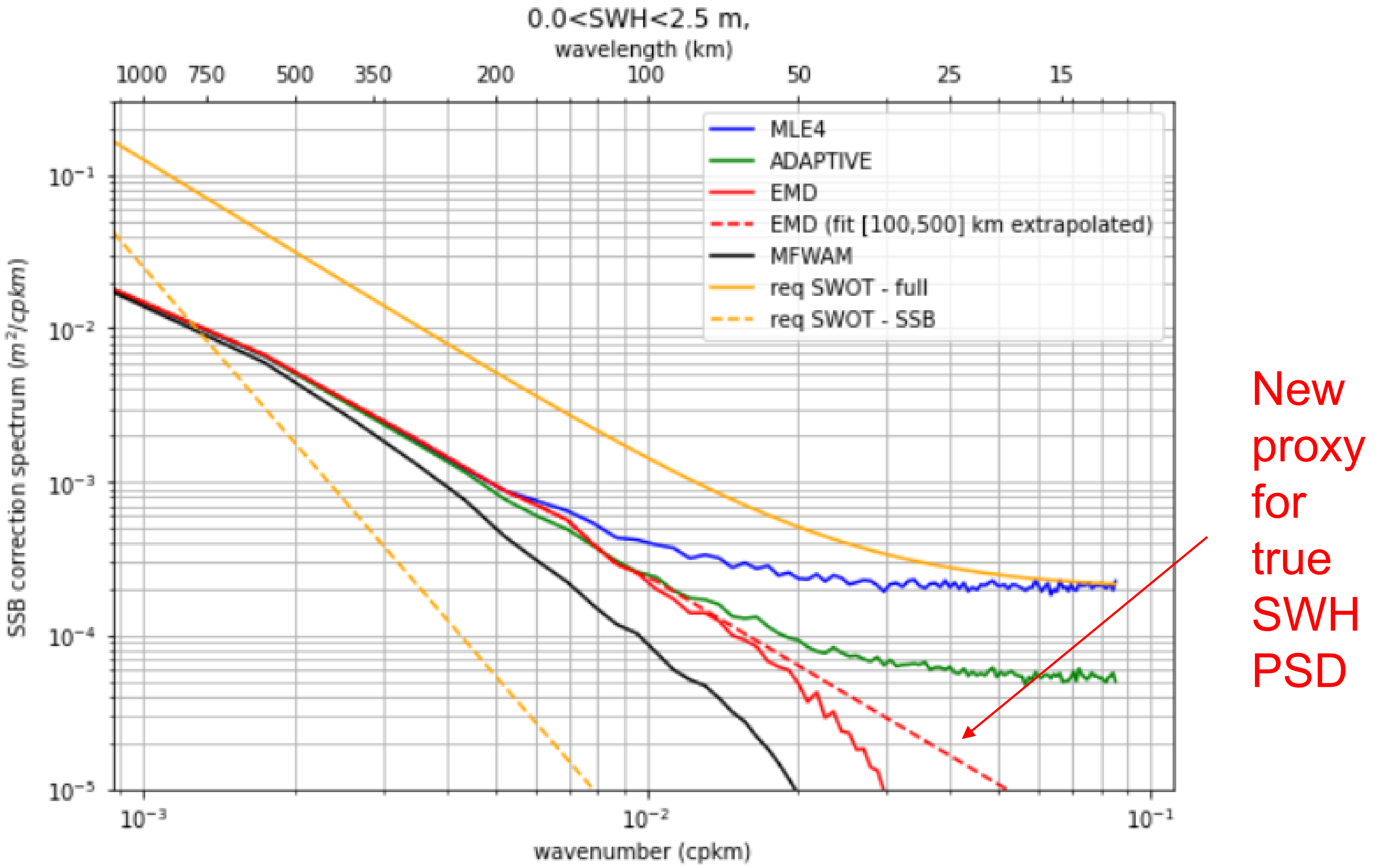




The error without correction drops fast at high frequencies, but this is an artifact of the energy drop in EMD. Note that this will (very slightly decrease the blue and green (but the black will follow the red)

Improved proxy for the high frequencies

Note : there is no guarantee that the SWH spectrum remains linear at high frequency and a steeper slope (broken power law) is possible. This linear extrapolation is at best an educated guess designed to make sure that the error does not blow up at high frequencies if we do not apply a correction there (either because we low pass filter our current correction, or because we decide to correct with the model which has almost no energy at these scales).



Improved proxy for the high frequencies

- At high frequencies (<50km), the EMD is probably not representative of the full SWH content. As a consequence, the error if we do not correct for SSB will be larger than what is shown in the previous slides.
- The error one would get by using the model for the correction (black curve) will also be larger (at high frequencies, it simply follows the « uncorrected SSB » error). Note : the high frequency noise introduced by the MLE4 and adaptive corrections (blue and green respectively) is also (very slightly) overestimated in the previous slides.
- In order to better estimate the actual high frequency error, we replace our previous proxy for the truth (EMD) by a new one : we linearly fit (in loglog) the EMD spectrum between 100 km and 500km and extrapolate below 100 km.
- This however only gives us a spectrum (which we take as a new proxy for the truth), instead of actual time series that can be substracted to the other ones (MLE4, adaptive, model…). We of course lost the phase information of each segment by just extrapolating the mean spectrum !
- As a result we cannot reproduce the computation described in slide 18 to obtain a PSD estimate of the error after correction (take the difference of the SWH time series XXX-EMD, then compute average spectrum of those differences).
- In order to obtain a best guess for the spectrum of the error after correction from the spectra of the correction and of the « truth » (extrapolated EMD spectrum), we need to make some simplifying assumptions (see next two slides)

Improved proxy for the high frequencies

- SWH from nadir measurements (XXX = MLE4 or ADAPTIVE):
  - **Assumption :**
    $SWH_{XXX} = SWH_{truth} + noise_{XXX}$
    where noise is not necessary white, but is independent from SWH_{truth}.
  - **Going to SSB, is approximately linear (~3.5%), so we have**
    $SSB_{XXX} = SSB_{truth} + Noise_{XXX}$
  - **As a result (statistical independence)**
    $PSD[SSB_{XXX}] = PSD[SSB_{truth}] + PSD[Noise_{XXX}]$
  - **The error after correction is**
    $error_{XXX} = SSB_{XXX} - SSB_{truth} = Noise_{XXX}$
    and its PSD is thefore
    $PSD[error_{XXX}] = PSD[SSB_{XXX}] - PSD[SSB_{truth}]$
  - **As stated previously, we use the extrapolated mean EMD spectrum as a proxy for $PSD[SSB_{truth}]$.**

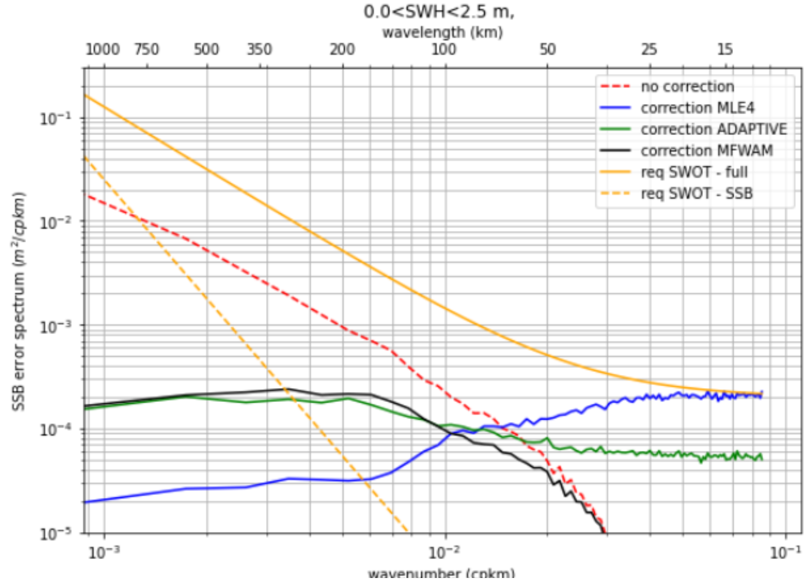
Improved proxy for the high frequencies

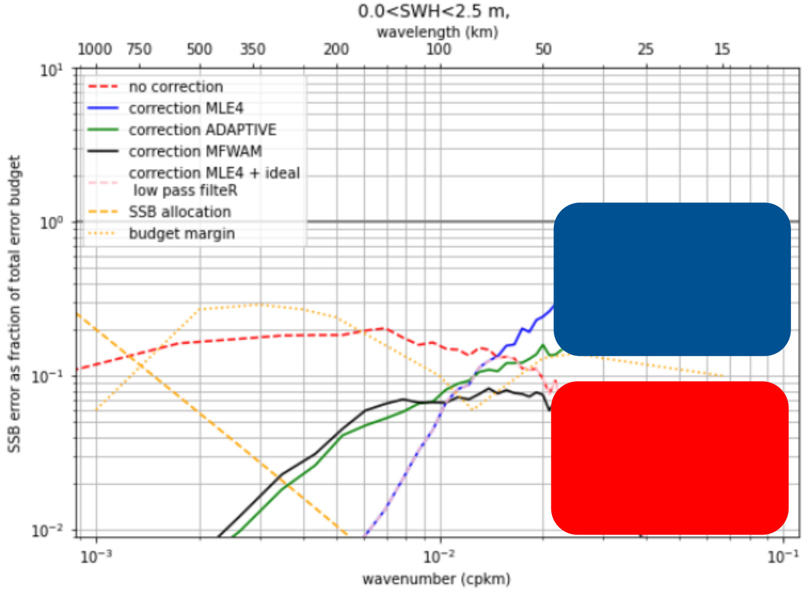
- SWH from model:

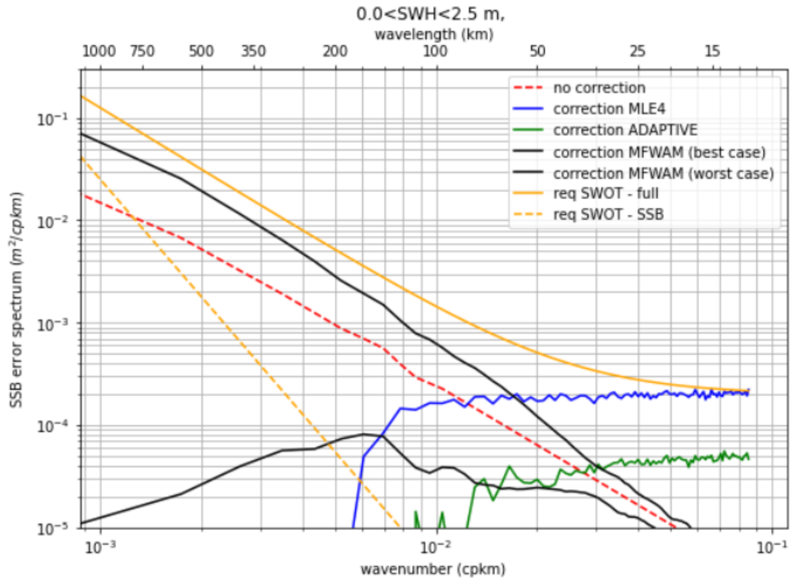
  - Assumption : does not contain measurement noise but is a smooth (filtered down) version of the truth. In the Fourier domain, for any segment $\widetilde{SWH}_{MFWAM}(k) = \widetilde{SWH}_{truth}(k)\widetilde{H}(k)$ where the filter $\widetilde{H}(k) = A(k)e^{i\phi(k)}$ rescales the amplitude of all modulations of waveumber k by the real quantity $A(k)$ and dephases them by $\phi(k)$. This is of course a very simplistic model and one could reasonably expect A and f to depend on geographical region, wind, SWH etc..
  - As a result, $PSD[SWH_{MFWAM}] = PSD[SWH_{truth}]A^2(k)$ and $A(k)$ can be determined from the MFWAM PSD shown before and the extrapolated EMD PSD which is our new proxy for the PSD for the true SWH.
  - Assuming a linear conversion between SWH and SSB,we get that the PSD for the residual error after correction is $PSD[SWH_{MFWAM} - SWH_{truth}] = |1 - Ae^{i\phi}|^2 PSD[SWH_{truth}]$
  - We however have no information about ϕ just from the PSDs. Best case : $\phi = 0$, i.e. the model is in phase with the truth and $PSD[SWH_{MFWAM} - SWH_{truth}] = |1 - A|^2 PSD[SWH_{truth}]$. Worst case : $\phi = \pi$ i.e. model exactly out of phase with the truth and $PSD[SWH_{MFWAM} - SWH_{truth}] = |1 + A|^2 PSD[SWH_{truth}]$. (in the case where both have the same level of energy (A=1) then the PSD of the residual error after correction is 4 times as large as the PSD of the residul error without correction in that worst case)

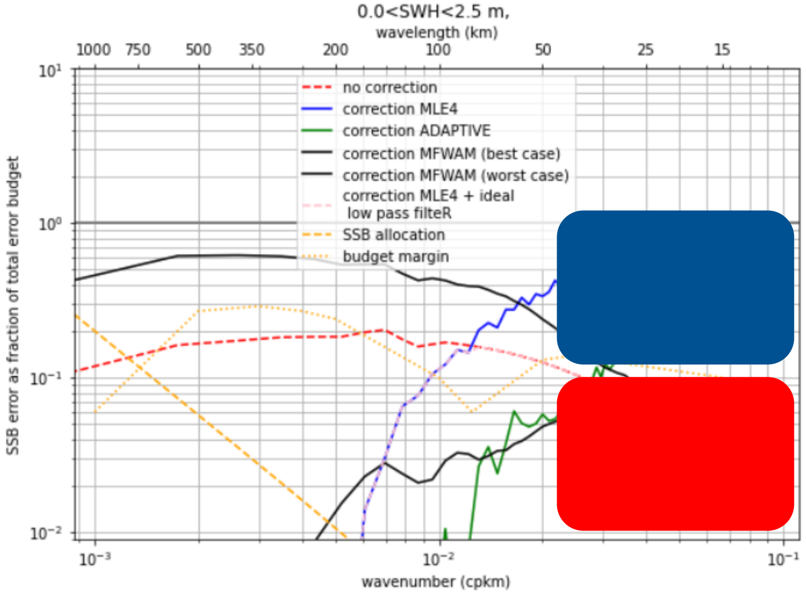
Improved proxy for the high frequencies

same as slide 19



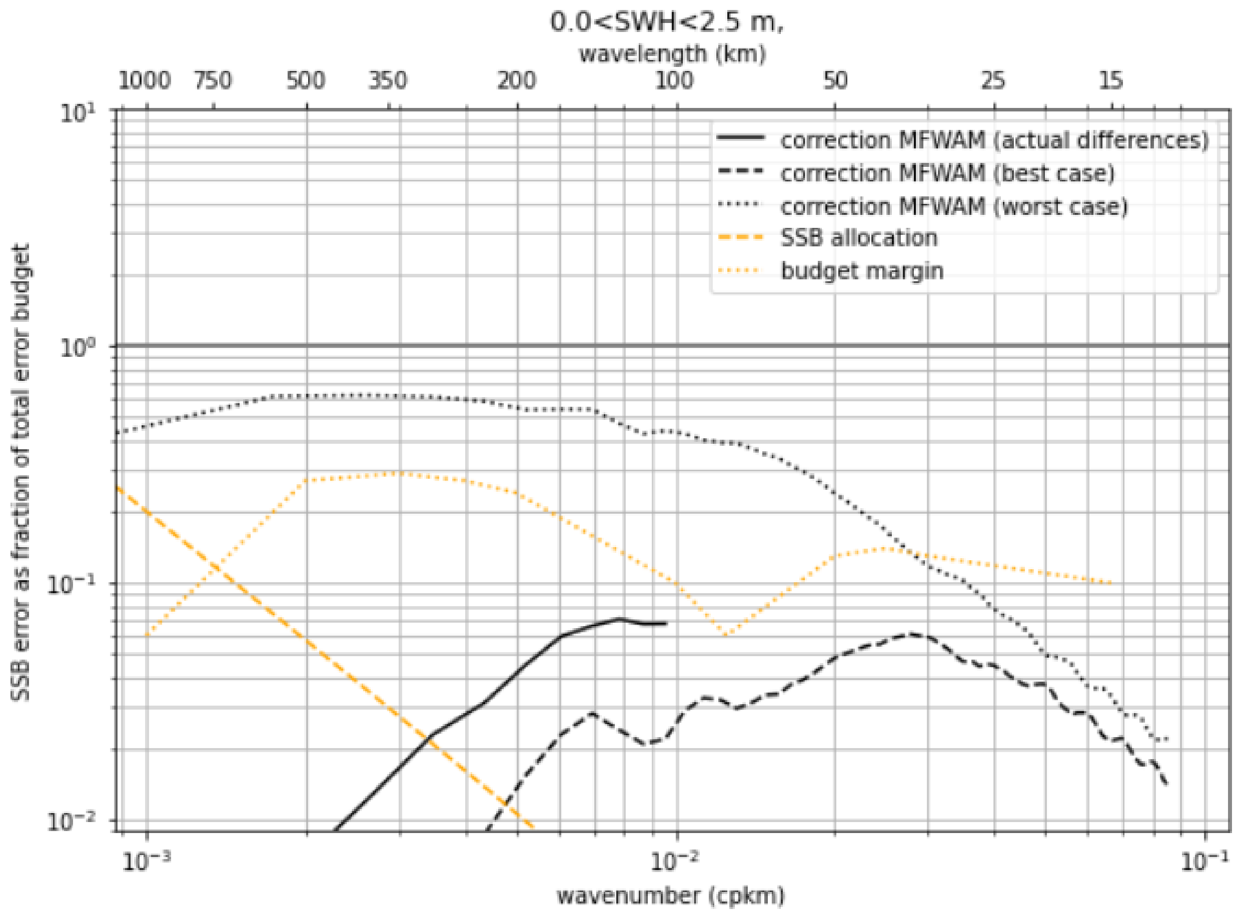






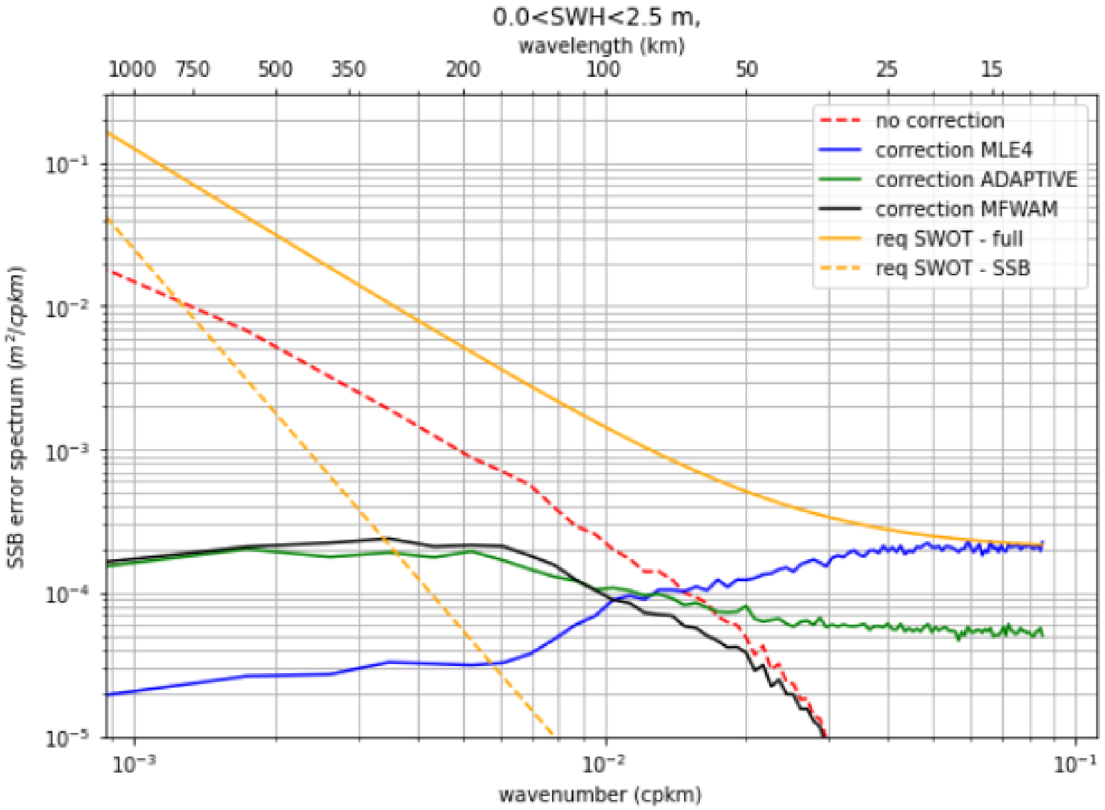
HF linear extrapolation of EMD

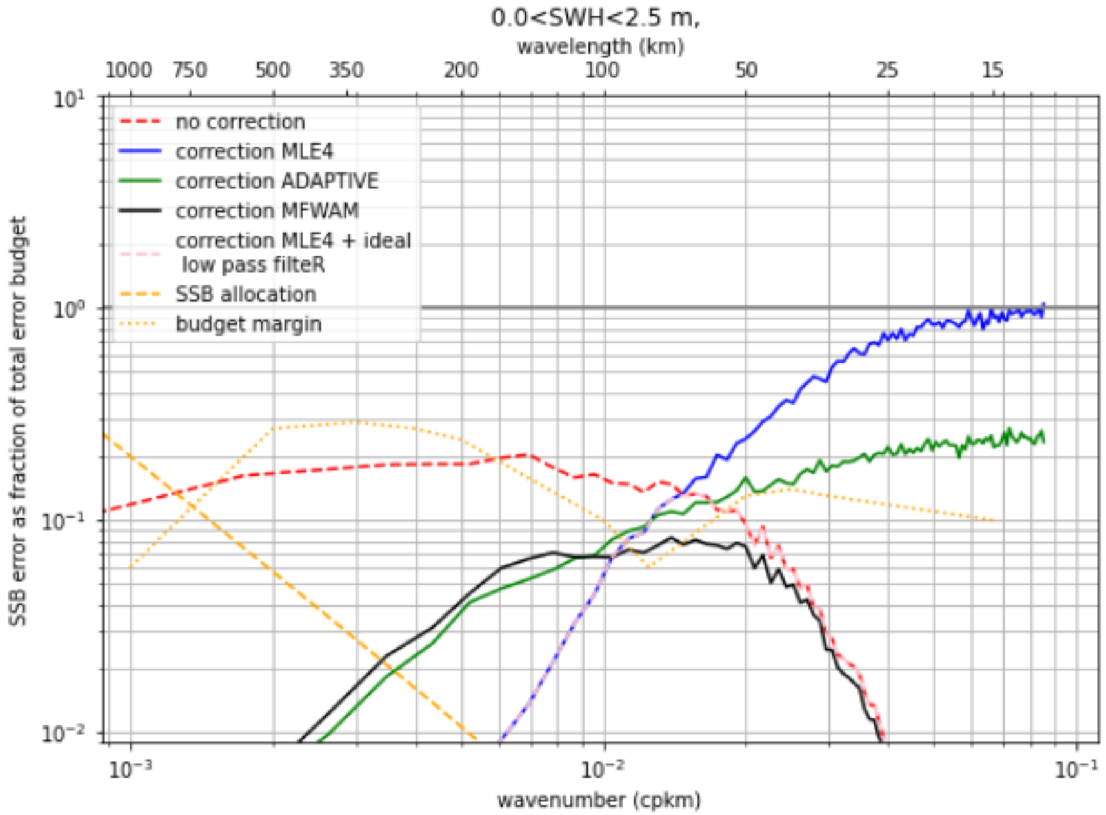
Improved proxy for the high frequencies



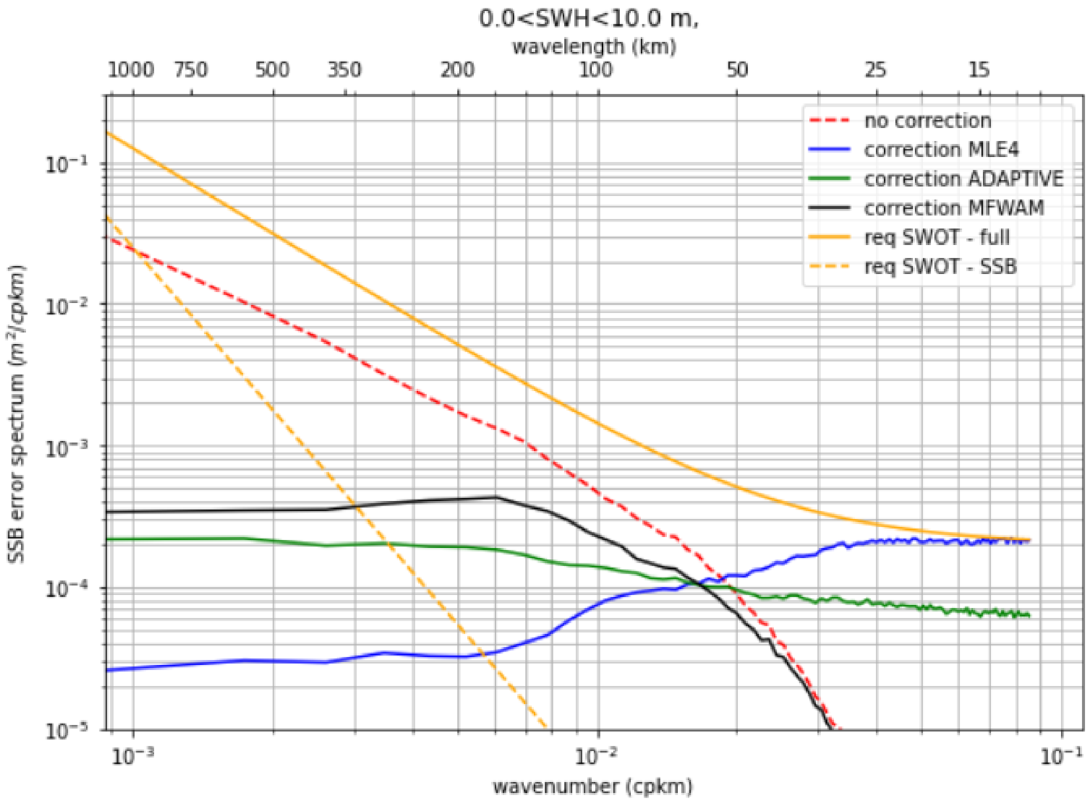
Above 100 km where we trust the EMD time series and can use them to properly compute the PSD of the residual SSB error assuming a model based correction, the PSD is closer to the best case. The model correctly captures the phase information. This may become increasingly false at higer frequencies (harder for the model to place perturbations correctly) but it matters less since the energy in the model is much lower anyway?

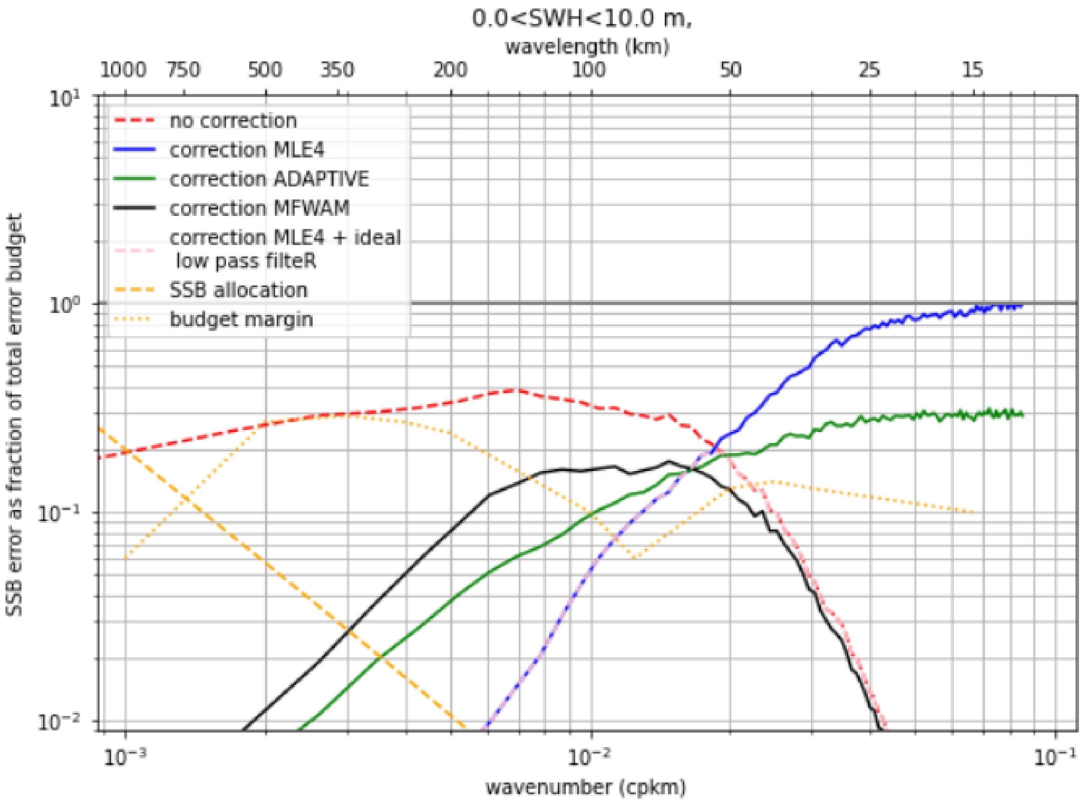
Residual error after SSB correction (various flavors)





Results without restricting to low SWH





SWH measurement principle

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

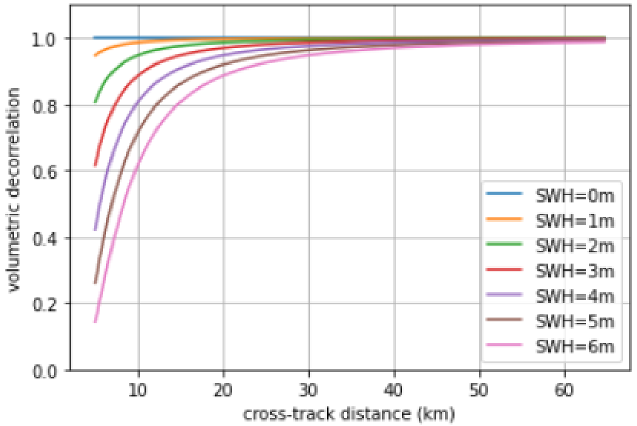
- There are other sources of decorrelation : $\gamma_{total} = \gamma_{SNR}\gamma_{geo,ang}\gamma_{vol}(SWH)$

  - Geometric decorrelation only depends on the geometry of the acquisition and the range PTR. 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).

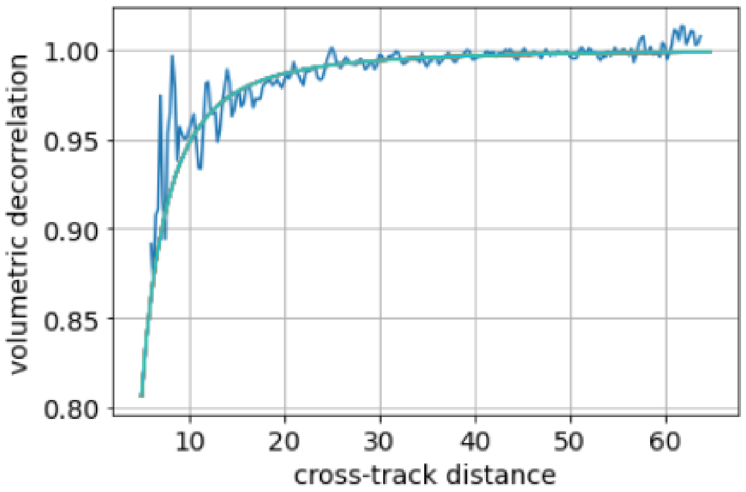
- Dividing the total measured coherence by those two contribitions, one obtains a measurement of volumetric decorrelation, which can be inverted to measure the SWH.

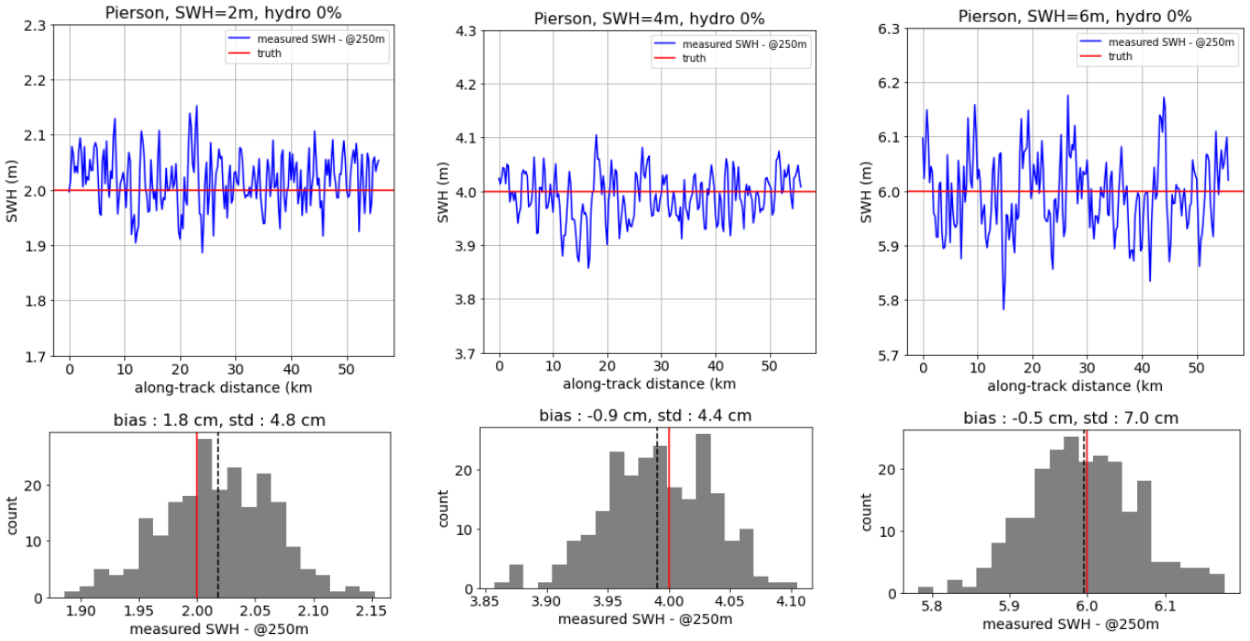
- Instrumental challenge : additional decorrelation may be introduced by the actual hardware and may need to be calibrated with flight data.

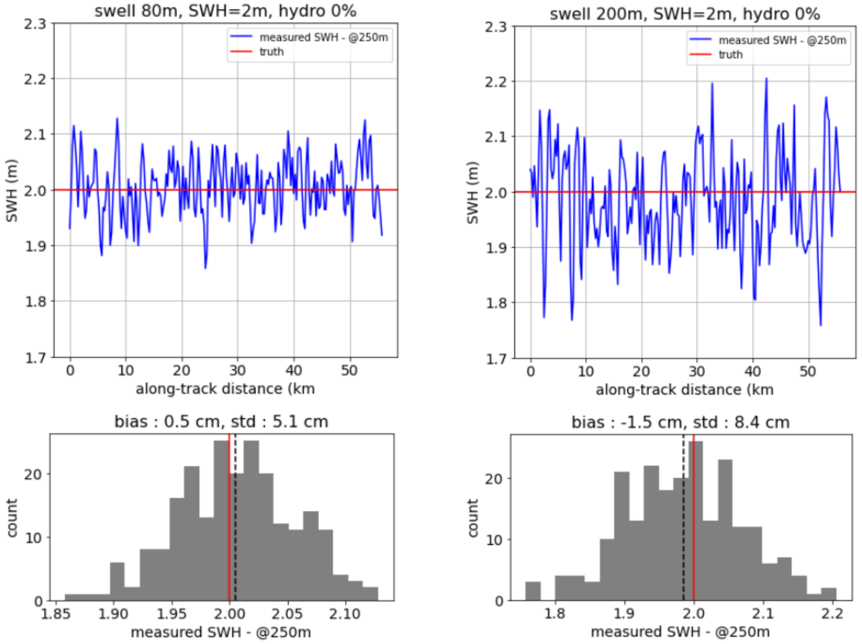


SWH measurement : baseline algorithm

- One estimation per azimuth line (cross-track fit)
  = one value every 250 m in along track.
- Then averaged @2km in the WindWave product.
- Performance shown here for the 250m product



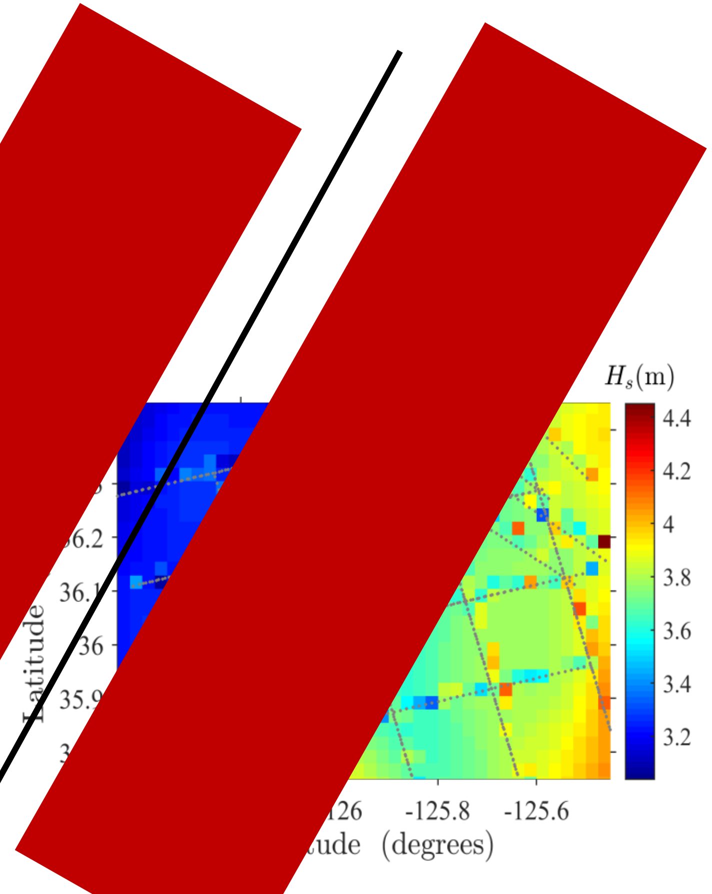




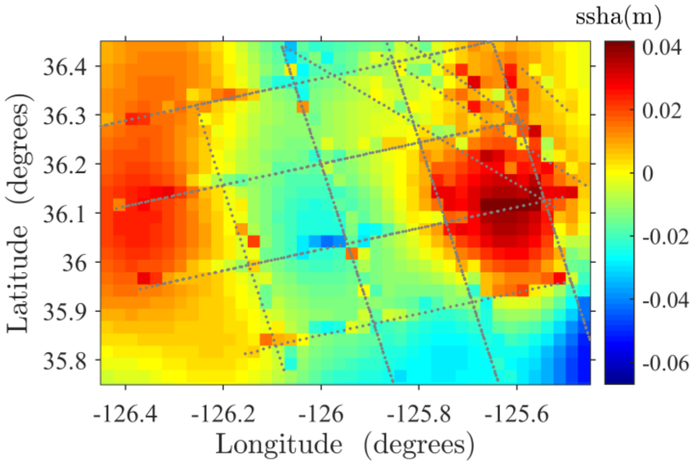
SWH variation at small scales : modulation by currents

- The analysis presented before shows that on average, our current SSB strategy is sufficient to meet the requirements.

- Currents sometimes create SWH modulations at the scale of a few tens of km.



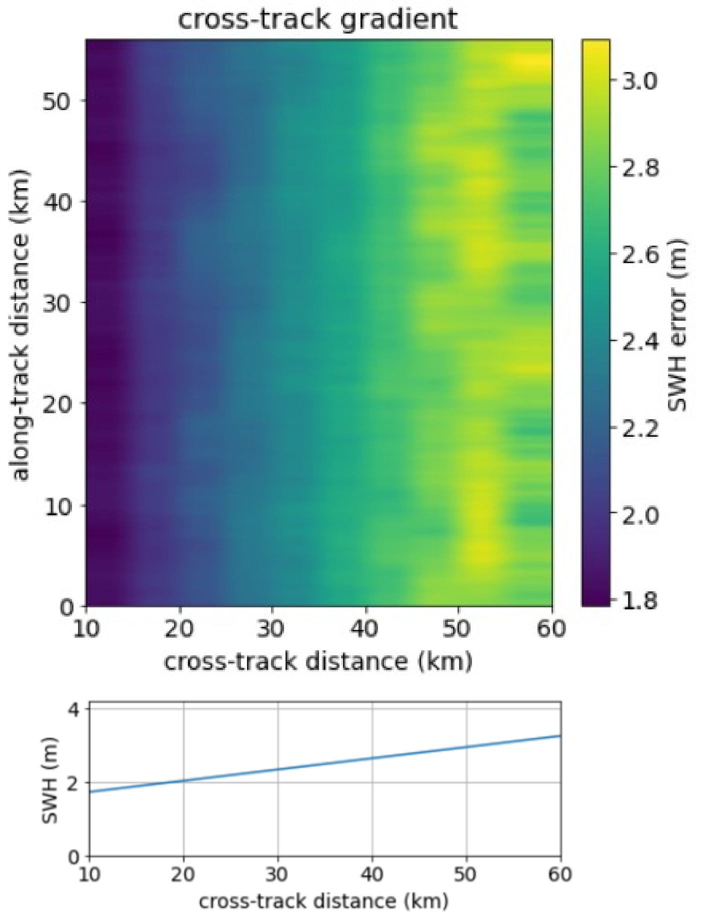
SWOT footprint (50km swath off nadir)



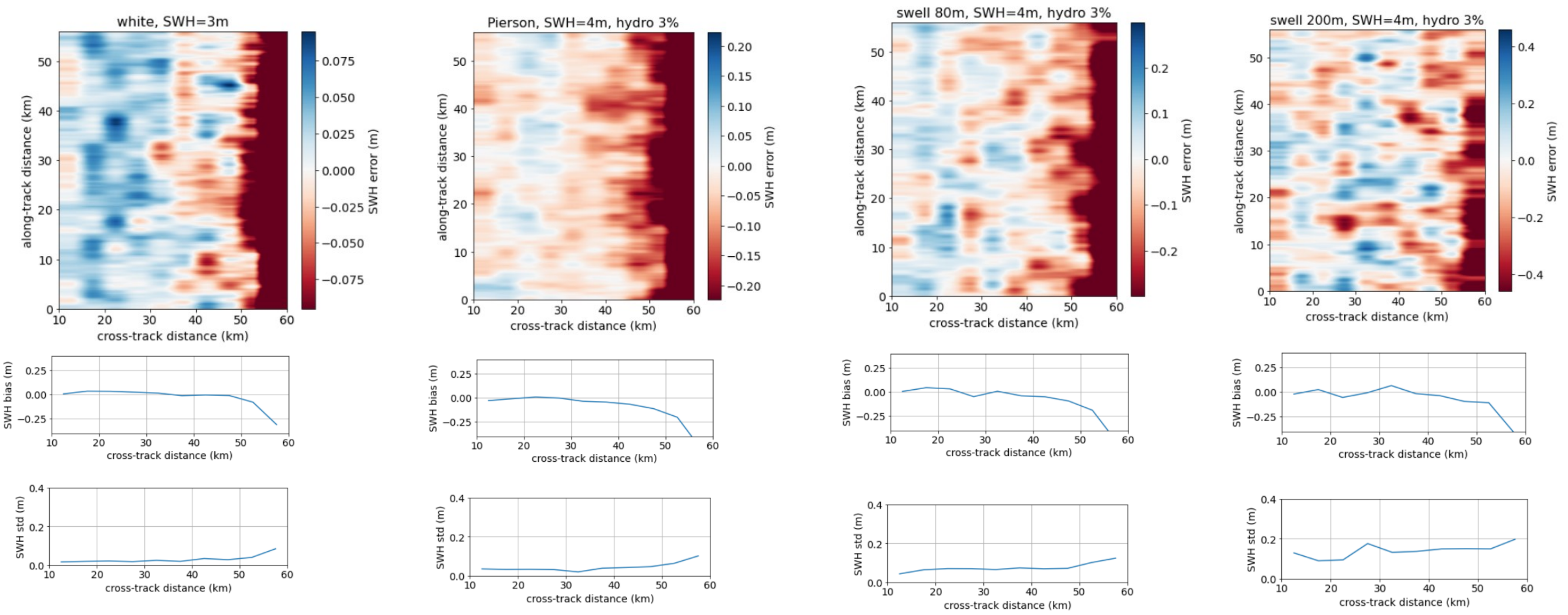
- Illustration on the left : lidar data (courtesy Luc Lenain) at California CalVal site. Gradients (over ~40km)
    - SSH ~ 6 cm
    - SWH ~ 50 cm -> SSB error ~1.5 cm

SWH measurement : beyond the baseline algorithm

- Capturing the cross-track dependence of SWH is not necessary to meet SWOT's requirement, so it is has not been at the top of the priority list before launch.
- Post launch, once instrumental effects on the decorrelation are under control, several alternative algorithms will be tested.
- We have started exploring their performance (preliminary results)
- Algorithm shown here : average measured volumetric decorrelation inside 5x5km boxes and perform one SWH inversion per box.



Wavelength increases (and spectrum becomes narrower)



Variance increase due to SWH modulation by groups of waves ?

Towards a SSB correction based on KaRIn's local SWH

- Another motivation for having a SWH measurement at several cross-track positions is to apply a Sea State Bias correction which accounts for these local modulations by wave groups.

- This can be tested with simulations since wave groups are naturally formed in realizations of swell spectra.

- Even with this extremely preliminary algorithm (5x5km inversion), some level of spectral reduction is achieved.