Sea State Bias : current work towards improving the model

October 15th, 2025

SWOT Science Team meeting

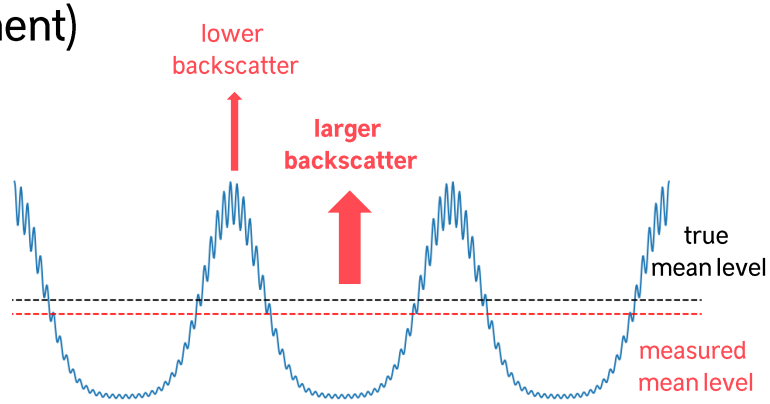
Alejandro Bohe (CNES),

on behalf of the CNES/JPL algorithm team

Sea State Bias (SSB) : brief introduction

- **Negative bias (a few percent of SWH)** in the measured height **in the presence of waves**

- Well known effect in conventional altimetry (but KaRIn is a different type of instrument)

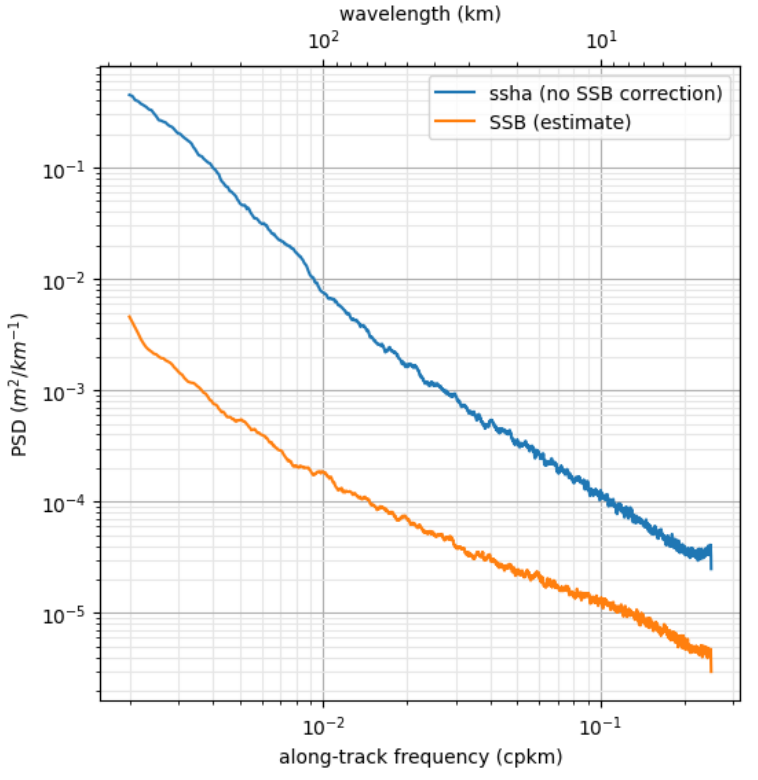


- **Theoretical models :**
  - Provide very valuable insight on the physical origin

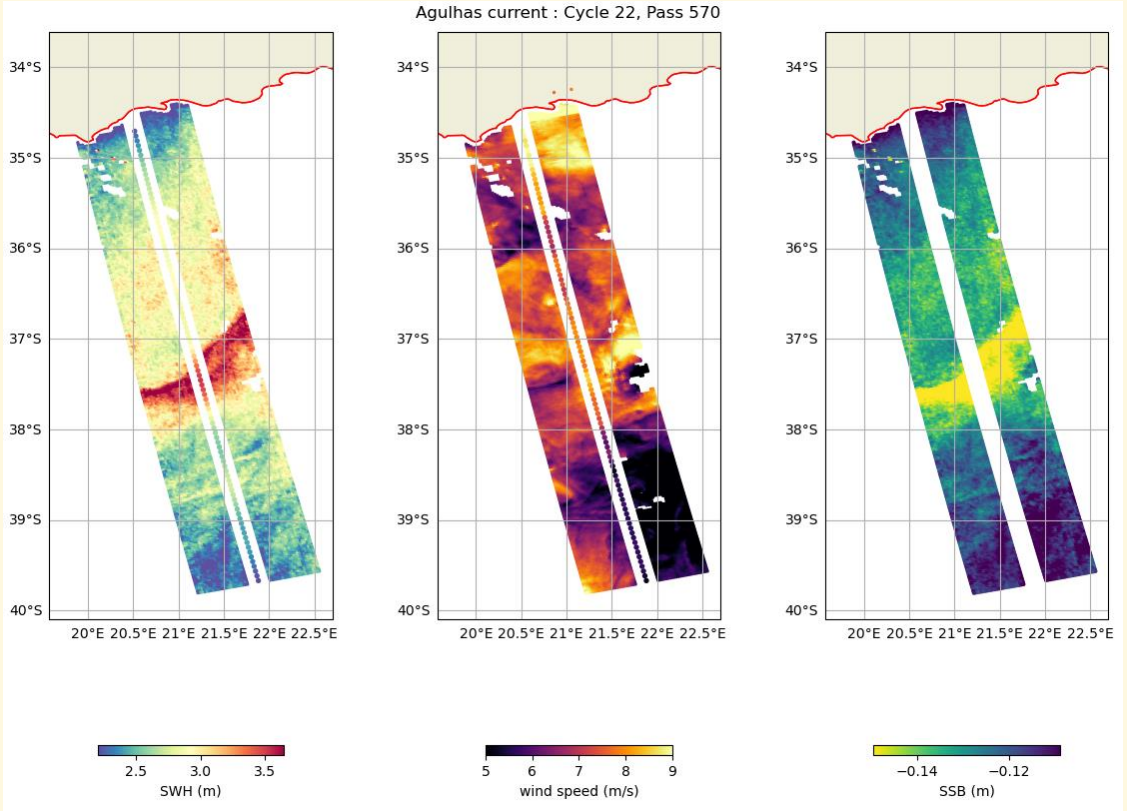
    Very schematically, non-linear interactions between waves lead to
    - wave crests which take up less space (elevation skewness) than troughs
    - wave crests which are pointier than troughs (elevation/slope correlation)
    - wave crests which are rougher than troughs (modulation of short waves by long ones)
  - Allow to account for instrument geometry/processing
  - So far not accurate enough to be used for correction of operational products.

- **Empirical approaches :**
  - Designed to remove the observed statistical dependence of height measurements on a handful of sea state parameters (SWH, wind speed…).
  - Used operationally in nadir altimetry, and in KaRIn since launch
  - Drawbacks :
    - can absorb other sources of error if they happen to be goegraphically correlated with sea state
    - require a priori knowledge of the relevant sea state parameters

SSB : typical amplitude and local illustration



Magnitude of the SSB error (even when uncorrected) is well below the ssha signal on average



Locally, strong patterns in the SWH field (here due to wave-current interactions) can lead to large amplitude SSB variations.

SSB : model vs sea state inputs

Correcting for Sea State Bias (SSB) requires both

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

SSB(SWH, U_{10}, ...?)

+

knowledge
about the **sea state** that SWOT is flying over

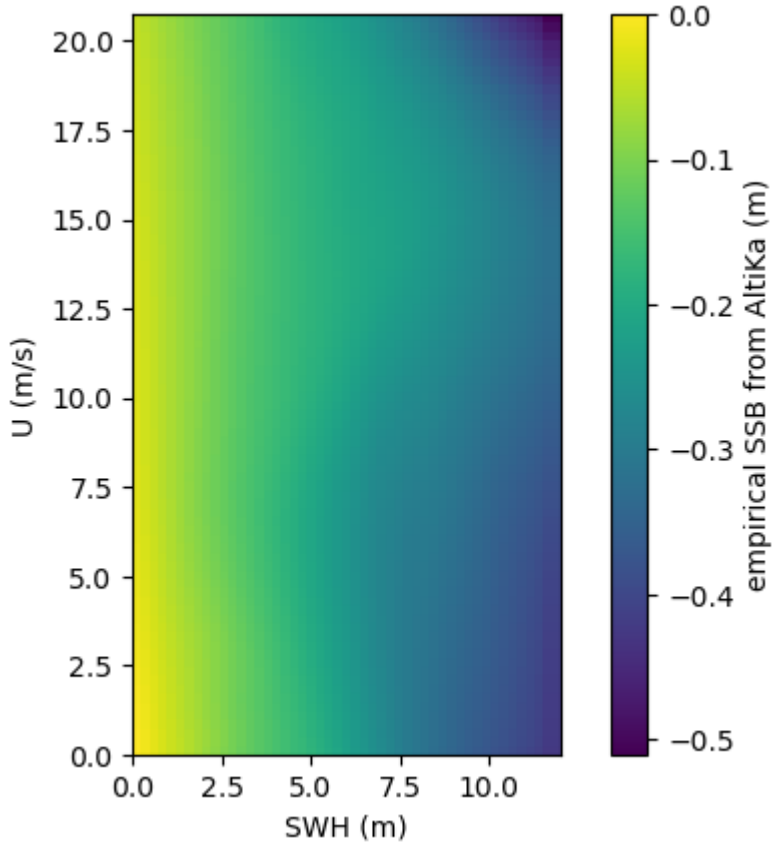
SWH ? U_{10} ?
wave spectrum ?

this talk

next presentation
by B. Molero

SSB : model used for KaRIn's SSB correction

- **Since launch**, the model used for SSB correction of KaRIn's height mesurement is an **empirical table built from AltiKa data** (Ka band nadir altimeter).
- Depends on two sea state parameters : **SWH and wind speed**. To first order : proportional to SWH.
- Empirical tables absorb (by design) the mean dependence of the ssha with the sea state parameters used to build the table.
- KaRIn uses SAR interferometry to measure the topographhy, which is very different from conventional nadir altimetry (AltiKa)



→ Now that we have accumulated more than 2 years of data, investigate the performance of this model, and if necessary, work towards an improved model.

Work in progress to improve the SSB model for KaRIn

1. Empirical approach : build a table directly from KaRIn's data
2. Theoretical approach : model KaRIn's SSB from first principles (wave physics and instrument)
3. Complementary way to probe properties of wave scattering in Ka-band : HR data

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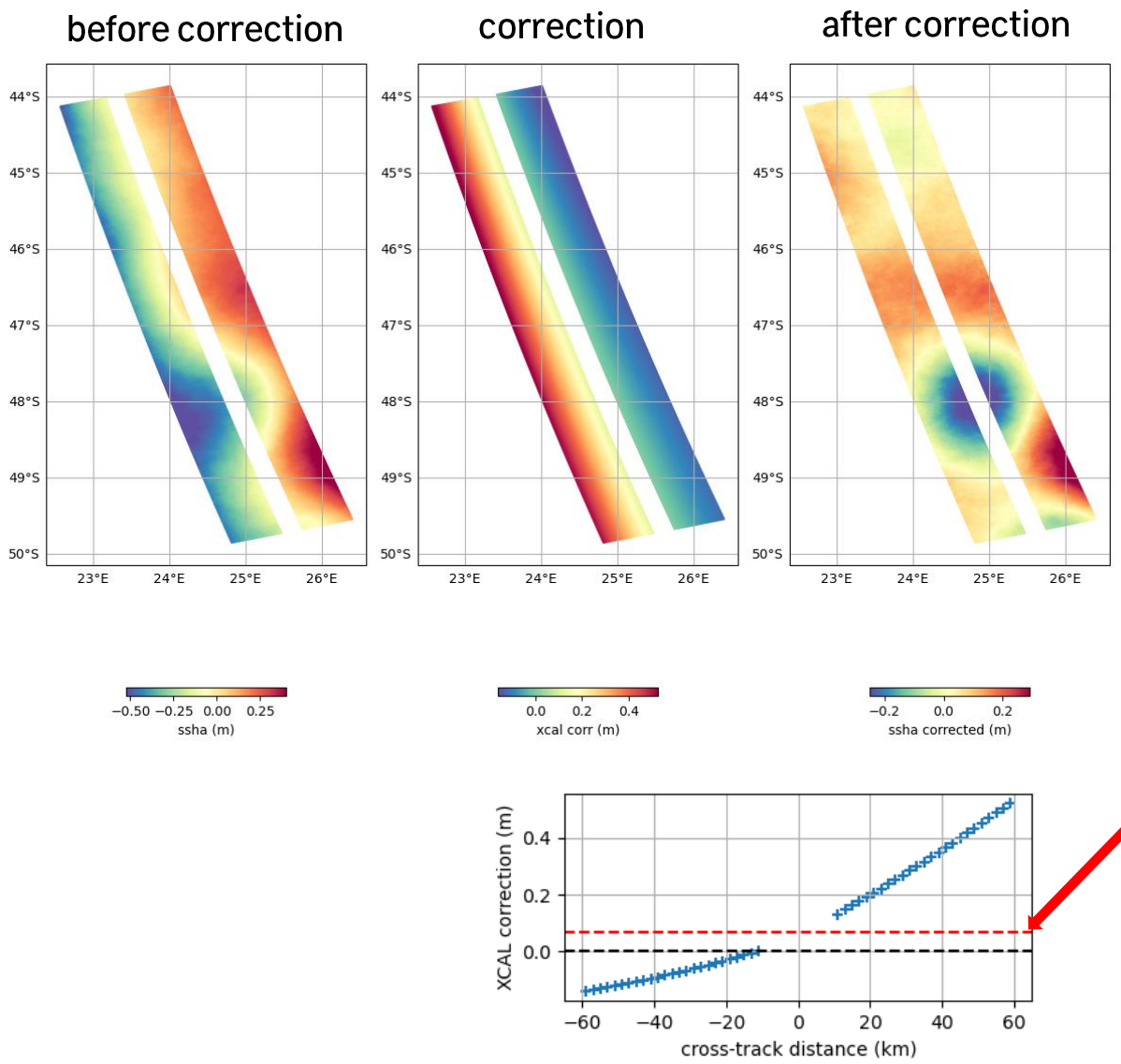
XCAL correction : minimal refresher

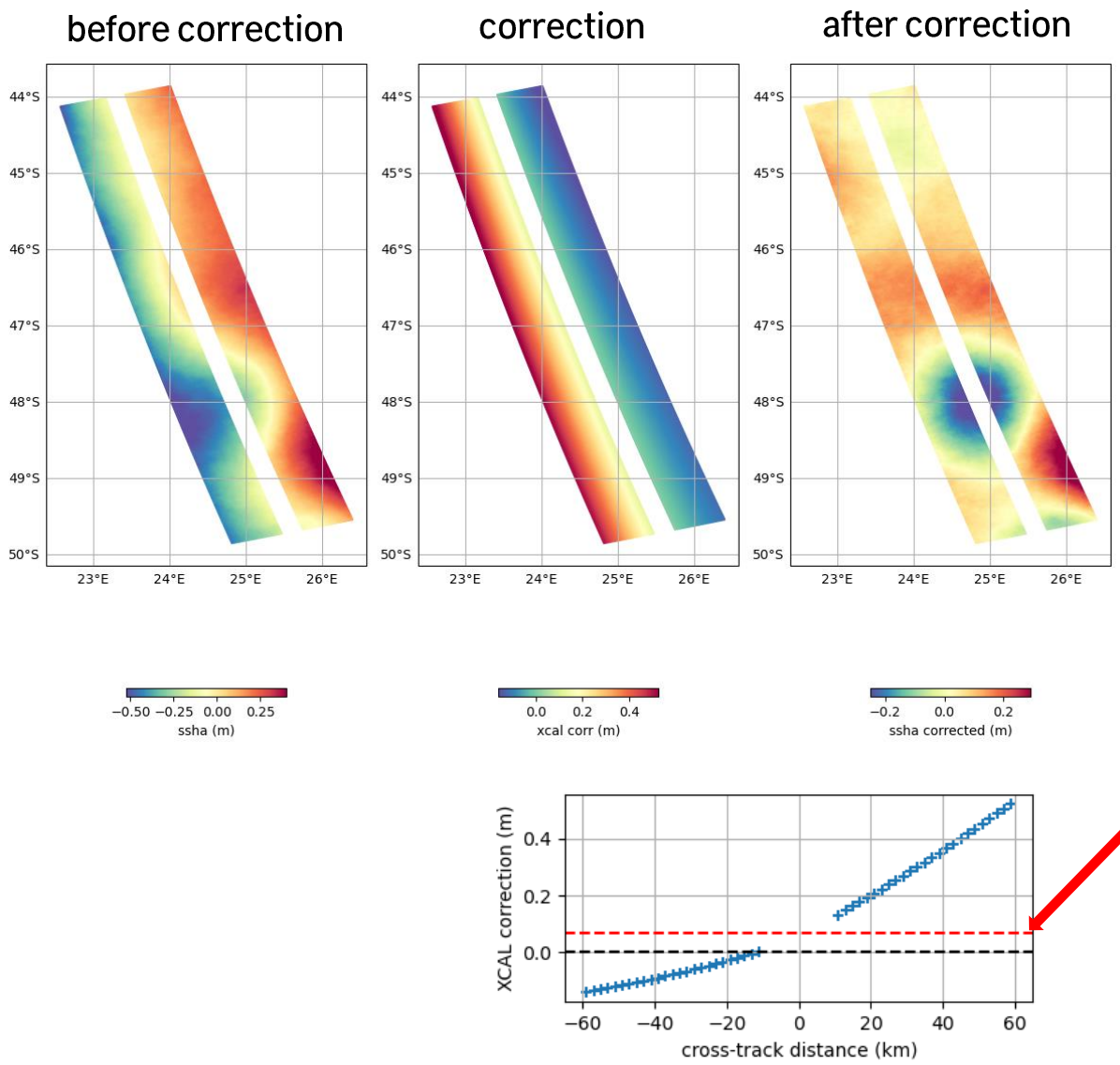


- The **cross-over calibration** (XCAL) aims at correcting for **« systematic » errors** affecting KaRIn's measurement **which have nothing to do with SSB.**
- It is a **low frequency correction** (error themselves are dominated by large scales)
- Timing part of the XCAL correction is designed to match the large scales of KaRIn onto a reference surface (e.g. SWOT nadir, DUACS)

Schematically :

$$XCAL_{corr} = (ssha_{KaRIn}^{uncorr} - ssha_{ref})_{LF}$$

XCAL correction : minimal refresher



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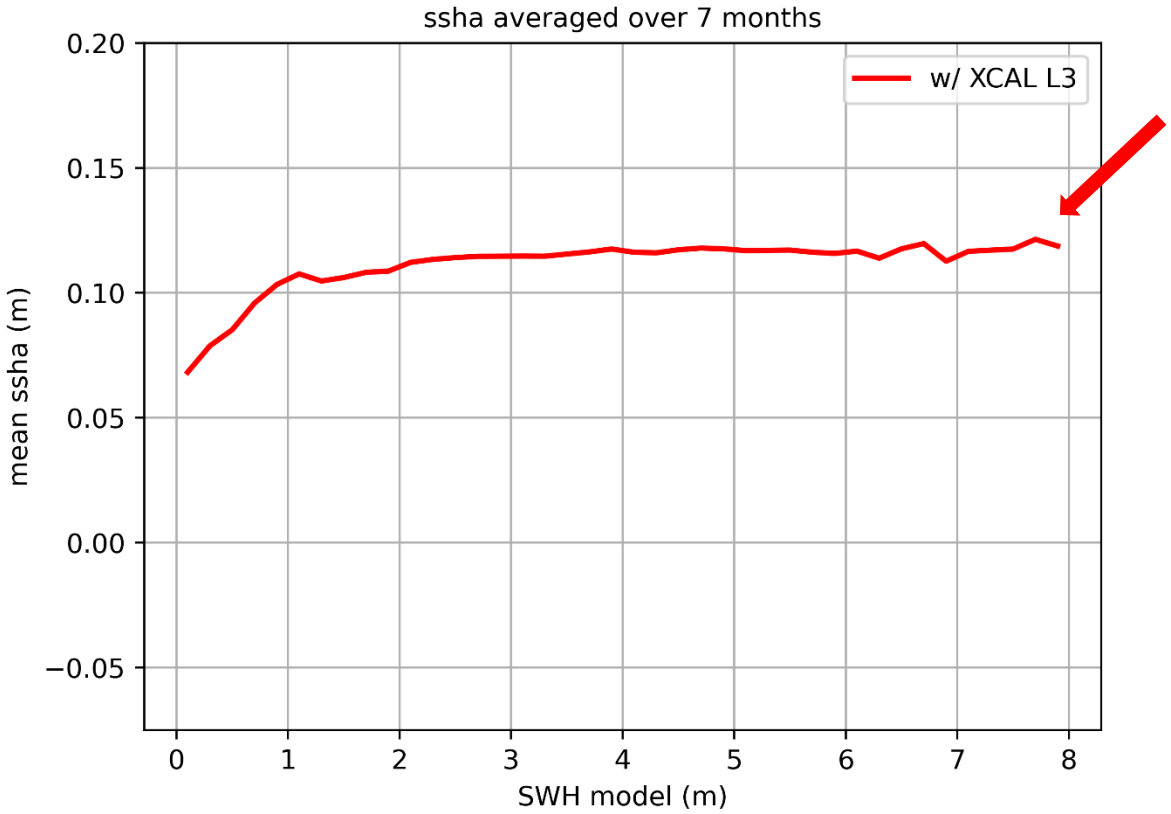
Schematically :

$$XCAL_{corr} = (ssha_{KaRIn}^{uncorr} - ssha_{ref})_{LF}$$

Are there residual dependences on sea state in KaRIn's data ?

Simplest « direct » method :

- use SWH as only descriptor of sea state relevant for SSB
- investigate **dependance of mean of ssha (after SSB correction)** over several months, **per bin of (model) SWH**



- Here, the level 3 XCAL correction has been used. Reference ssha is from DUACS, and cutoff scale for timing correction is ~1000km.
- Absolute level not relevant here (depends e.g. on reference period for MSS computation)
- No residual SWH dependence (except in low SWH regime)
- Tempting to conclude that the current SSB correction is performing well. But…

(work led by E. Cadier (CLS))

Are there residual dependences on sea state in KaRIn's data ?

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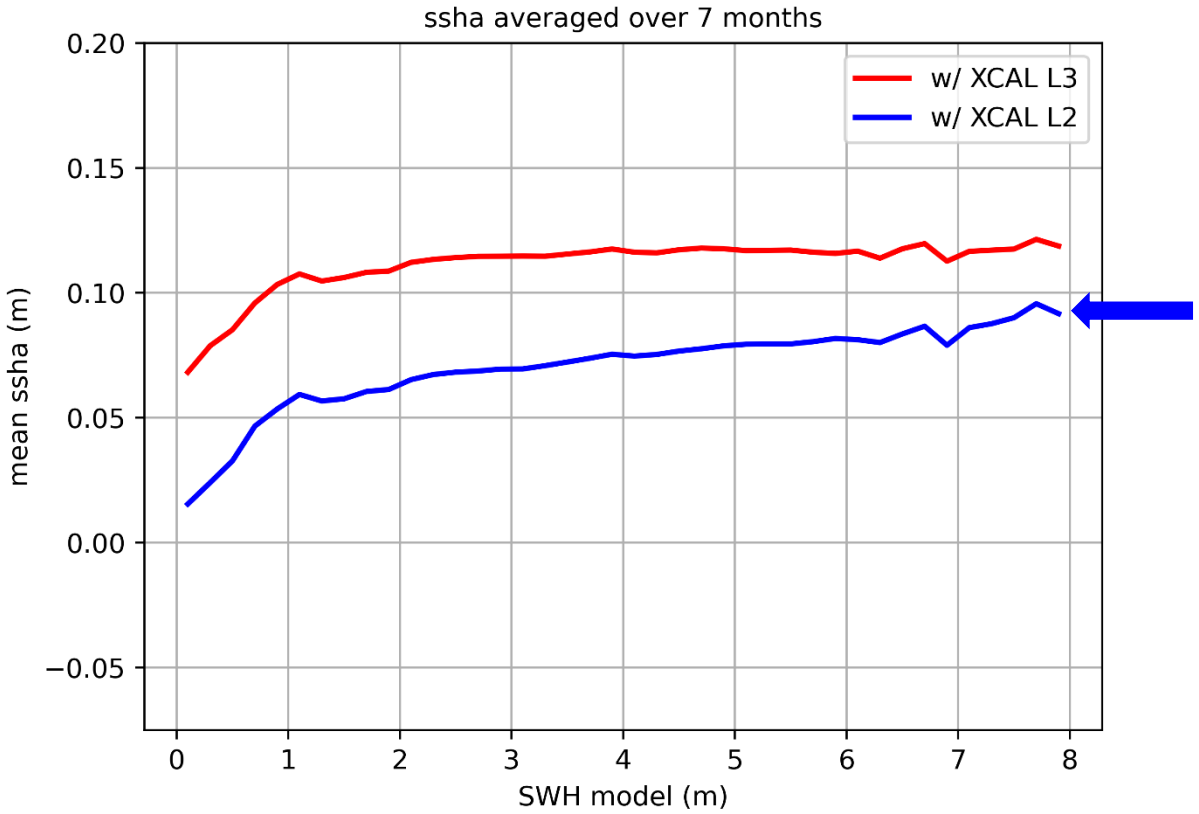

- Here, the level 2 XCAL correction has been used. Reference ssha is from SWOT's nadir, and cutoff scale for timing correction is ~10000km.
- Absolute level not relevant here (depends on reference period for MSS computation and POS4C's range bias)
- Dependence on SWH starts appearing

Are there residual dependences on sea state in KaRIn's data ?

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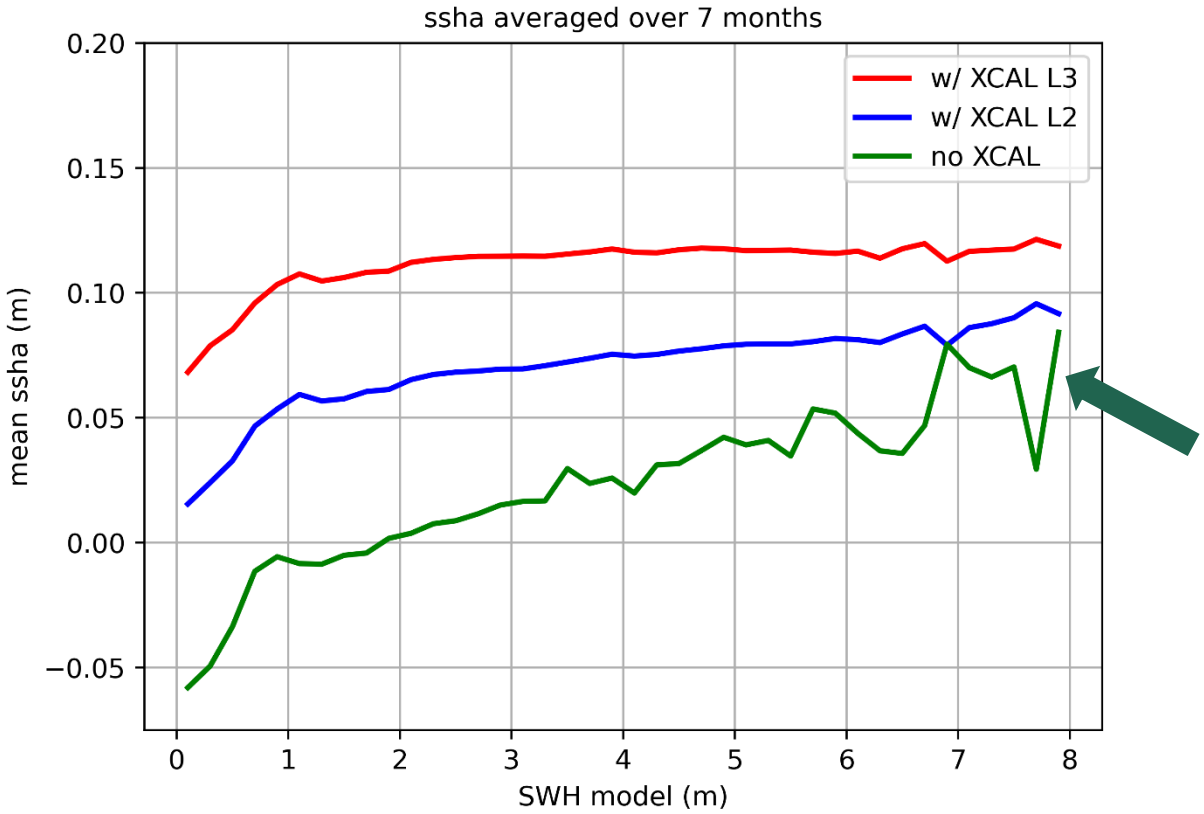

- Here, no XCAL correction has been used.
- Absolute level not relevant here (depends on reference period for MSS computation and KaRIn's mean timing error)
- **Even stronger dependence on SWH**

Are there residual dependences on sea state in KaRIn's data ?

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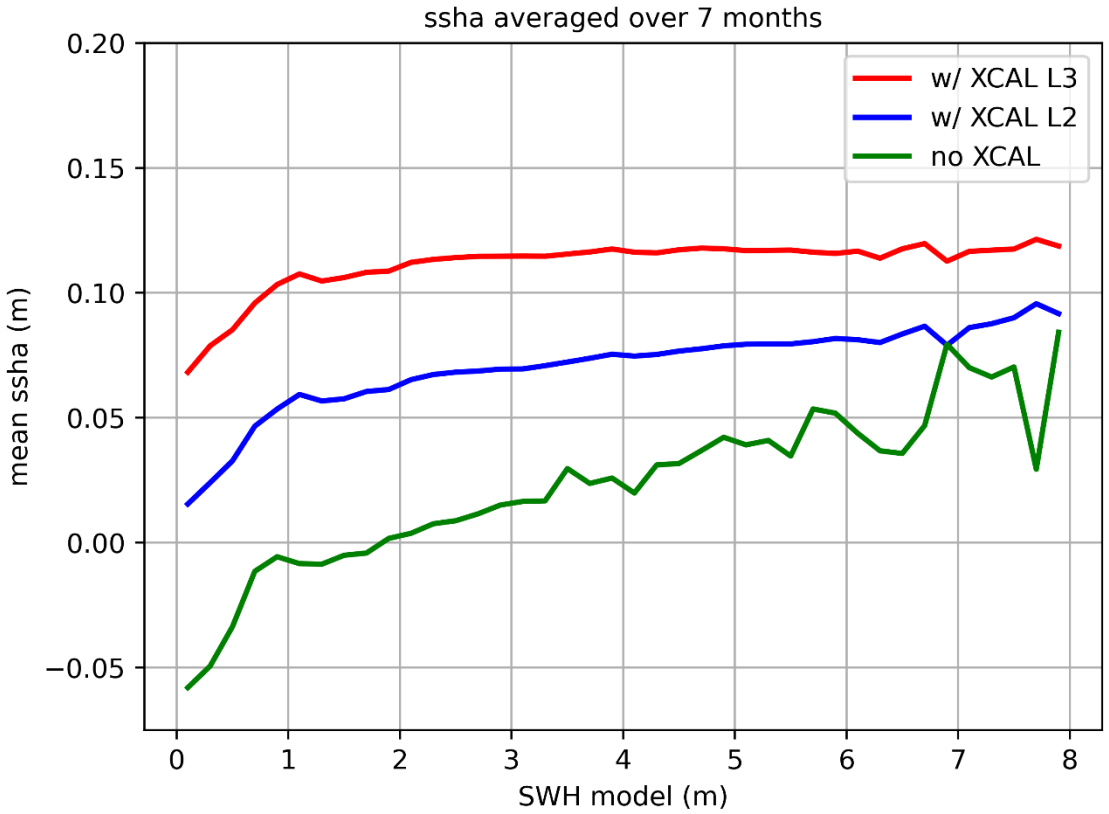

Also tempting to conclude that the current SSB correction is not optimal, but that the XCAL (at least the L3) in practice acts as a SSB correction, and gets us rid of SSB error.

This is also incorrect. The XCAL only affects the lower frequencies, so **at scales <1000km, the residual SSB error cannot be corrected by the XCAL.**

Are there residual dependences on sea state in KaRIn's data ?

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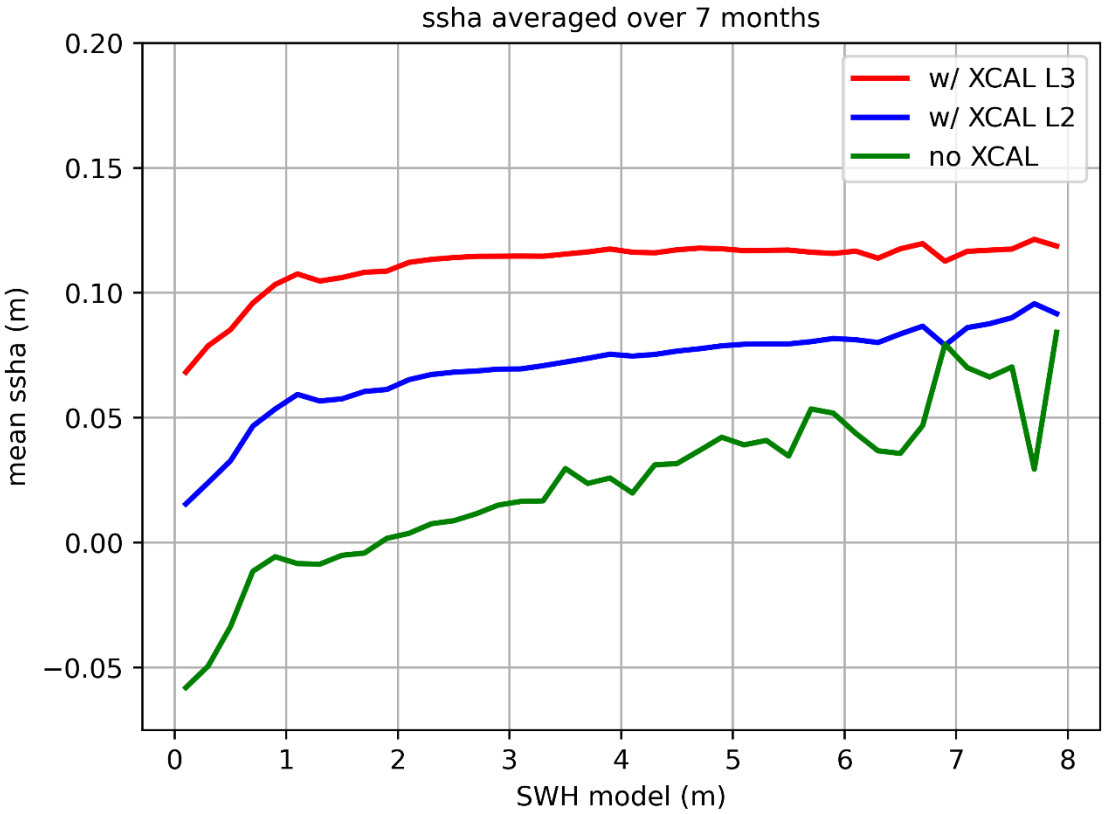

- The XCAL prevents us from identifying the SSB error from such a simple method.
- But without an XCAL correction to get rid of most of the low frequency noise from KaRIn's systematic errors, hard to beat down the noise (OK in 1D, but hard to study joint dependence with other parameters such as wind speed, etc…)

→ **Need to design a XCAL correction dedicated to the SSB.**

Are there residual dependences on sea state in KaRIn's data ?

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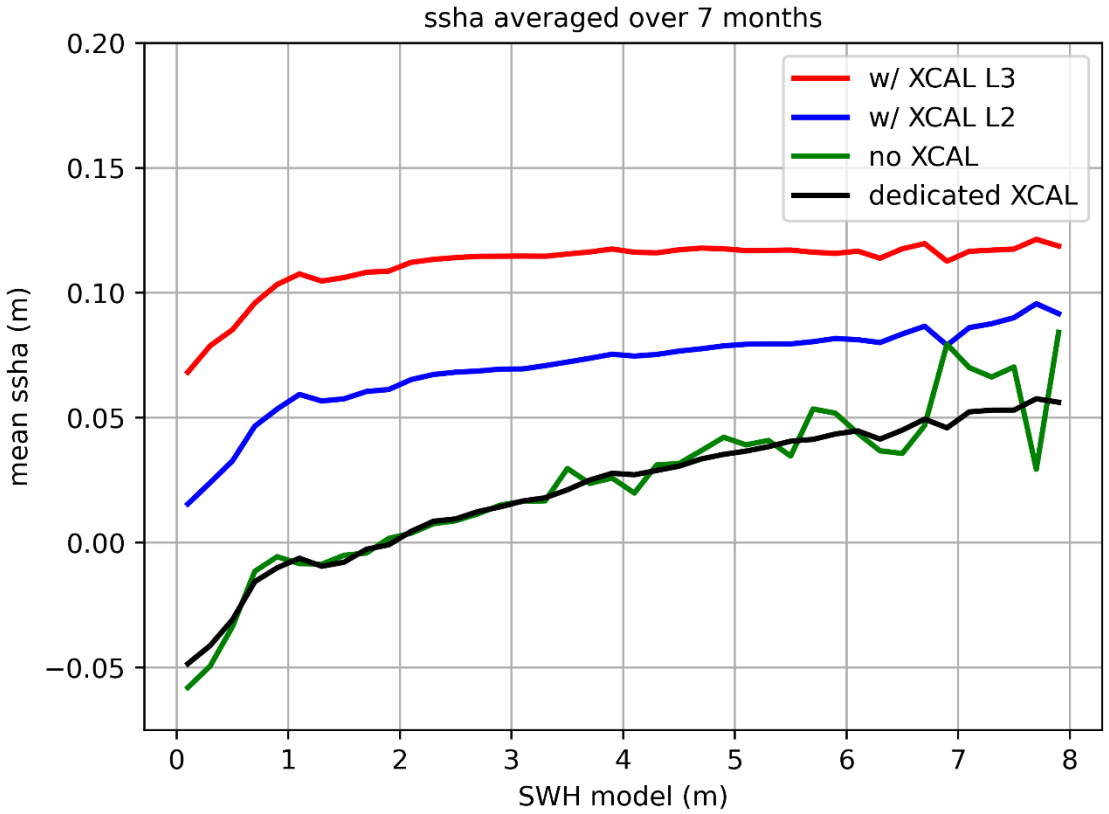

- **Challenge** : **design an XCAL correction that absorbs enough of the systematic errors** (roll in particular) to allow for empirical methods based on massive averaging to provide clean results **while interacting with the SSB as little as possible.**

- Basic idea = disable the timing correction

- Drawback : if timing error happens to be correlated with SWH (e.g for some reason it tends to be larger over Southern ocean, where SWH tends to be larger), then this introduces an SWH dependence in this plot which is not SSB.

- Other possible drawbacks : possible ssha/swh correlations through regional MSL trends not accounted for here, or topography anomalies at the scale of months

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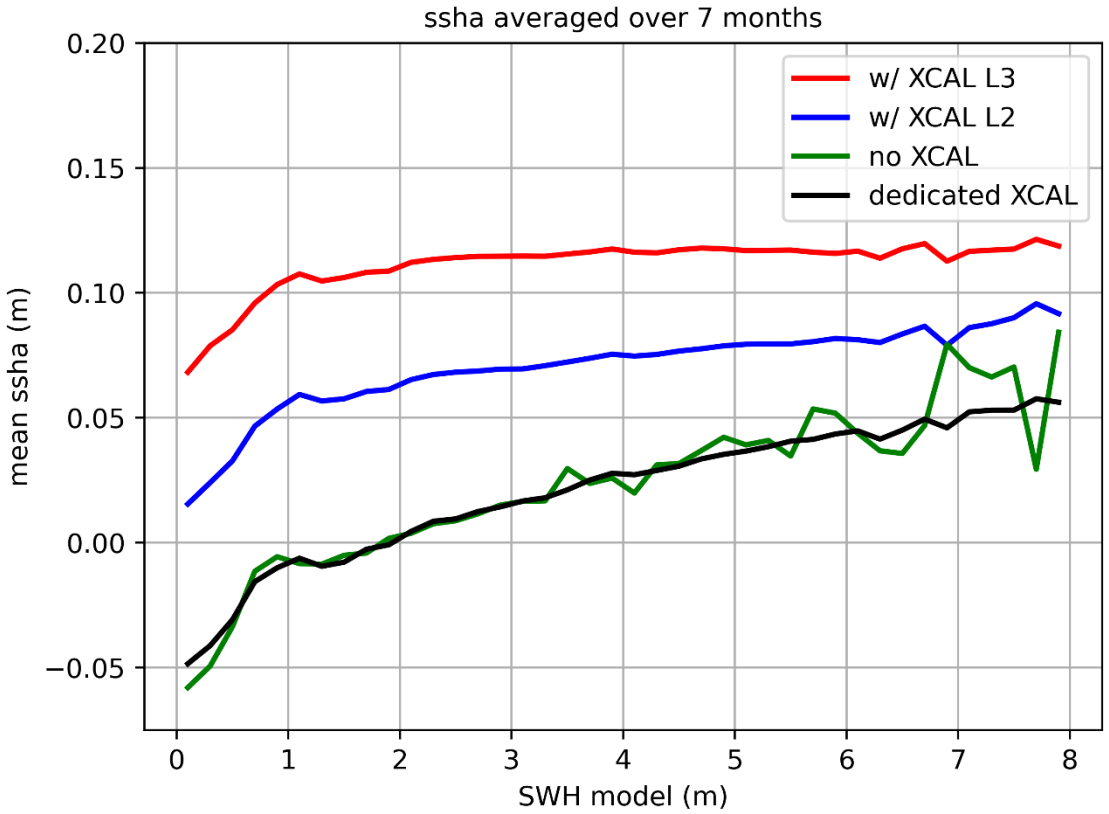
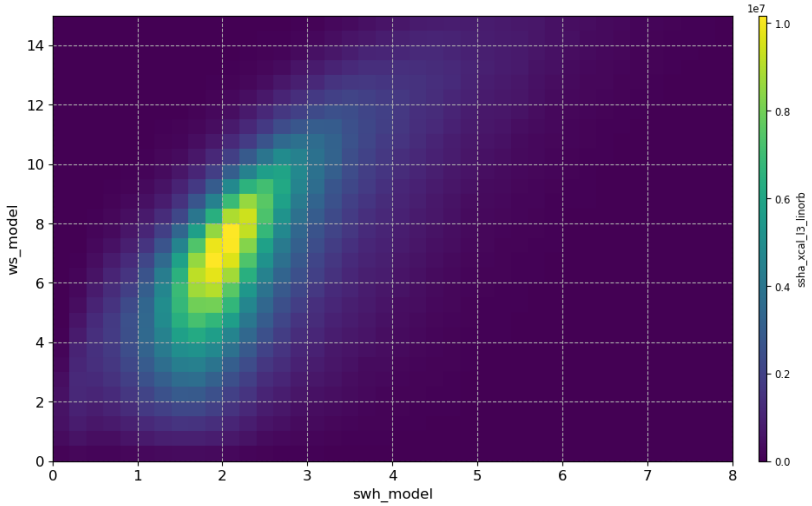


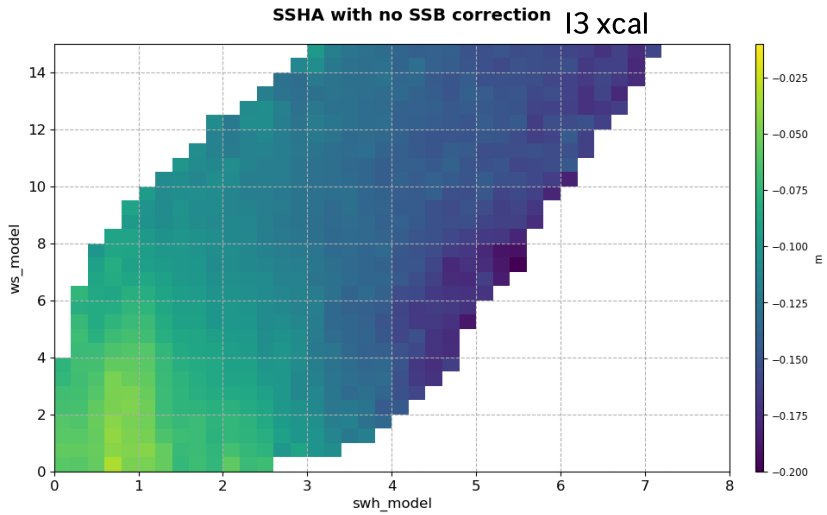
- **The current SSB correction seems to overcorrect : its dependence on SWH is too steep**

Work in progress : 2D empirical table

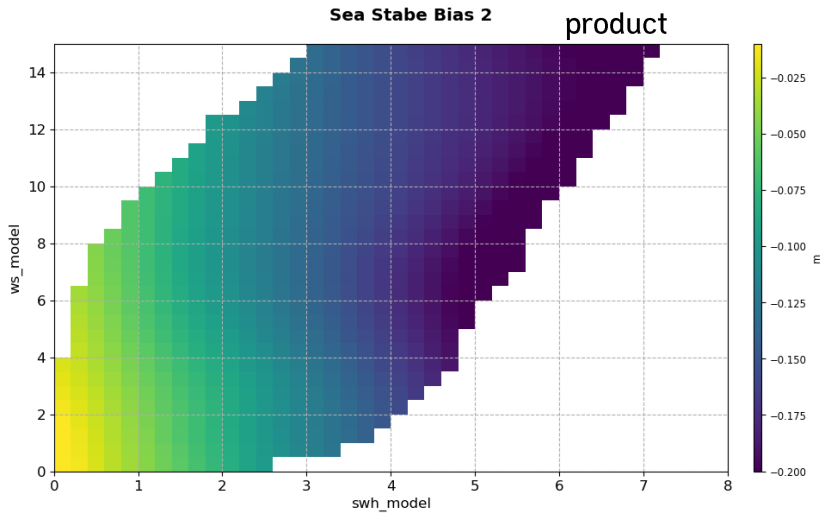
Versus SWH and Wind-Speed :



Corrected with lin_orb l3 xcal

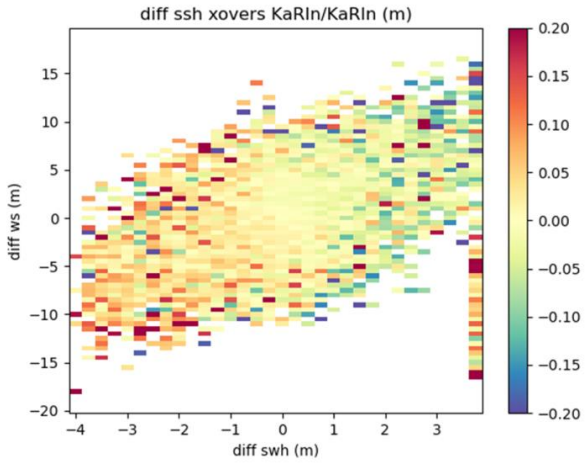


== AltiKa table in Karin product



Next steps :

- use all available data
- compare with independent methods (exploit KaRIN/KaRIn cross-overs)
- understand why differences with current (AltiKa based) correction
- should we use additional sea state/geometrical parameters ?



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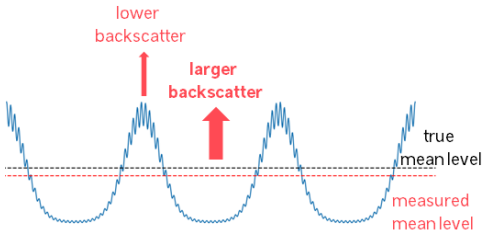
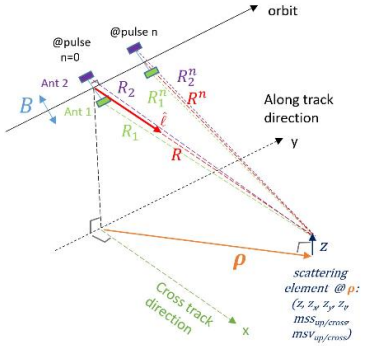
Theoretical SSB : understanding what SSB should look like for KaRIn

- Results shown here part of **Samuel Osina's PhD work** at Ifremer. → Go see his poster for more details !

- **Requires** :
  - accurate **representation of wave physics** : Lagrangian weakly non-linear approximation at 1st order used here. First step before moving on to 2nd order (work in progress)
  - full description of **acquisition geometry and SAR interferometric processing of the data**, to identify contributions specific to KaRIn

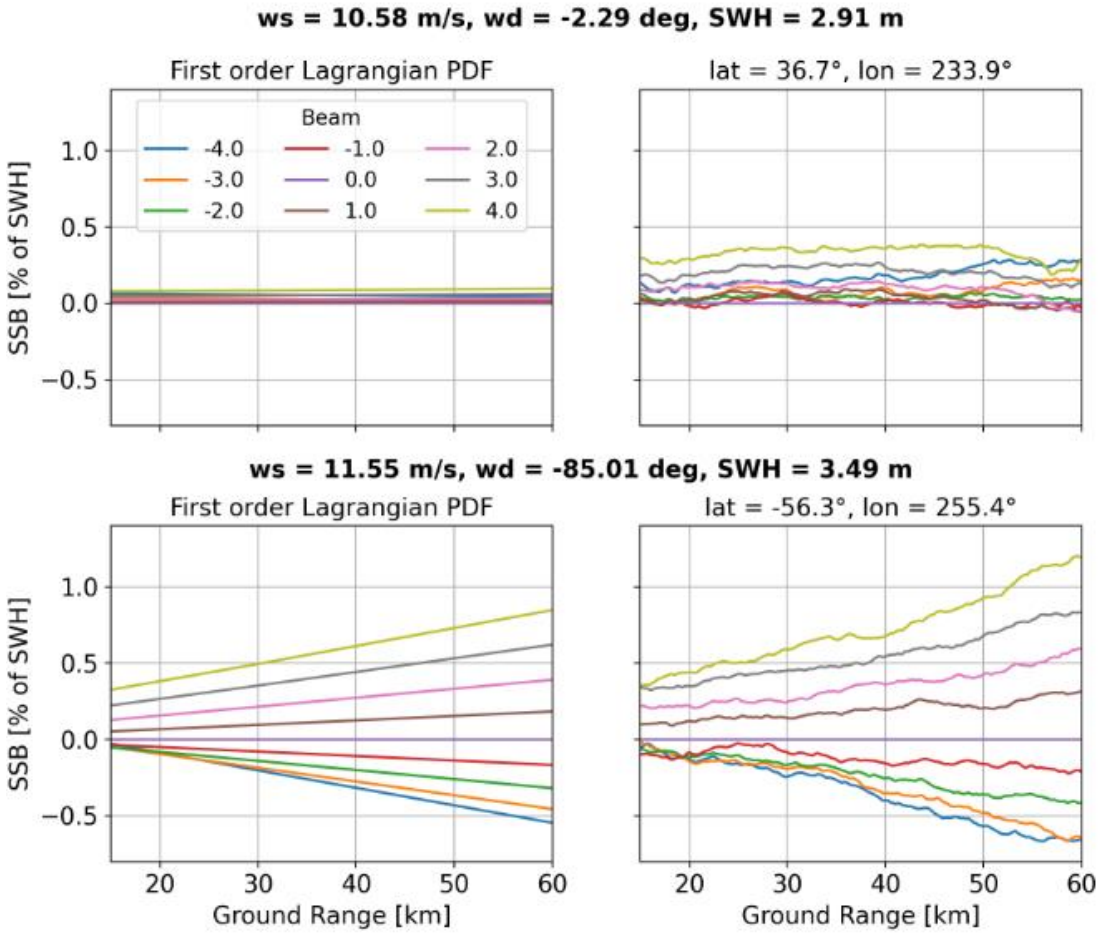




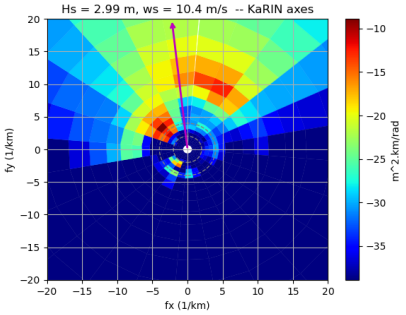
- **Goal** :
  - **long term** : **provide a model for SSB correction of operational products**. Not achievable with 1st order perturbation theory (wave self interactions not sufficiently represented), so numerical values shown in next slides not to be compared with e.g. table from AltiKa
  - **short term** : **shed light on potential SSB contributions specific to KaRIn** (e.g. surface motion, wave spectrum directionality, dependence on across-track distance) **to inform empirical approaches**.

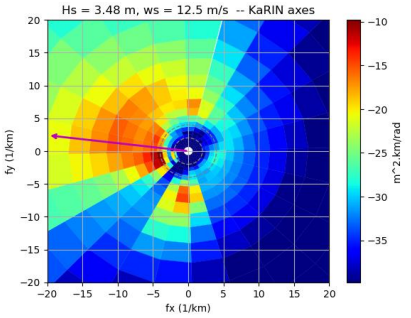
Theoretical SSB : (partial) validation against data

- Focus on height bias between the various Doppler beams and the central beam (no need for an absolute truth)
- Broken symmetry between beam for across-track propagation and across-track dependence well catured by the model
- The model allows us to understand why these features arise



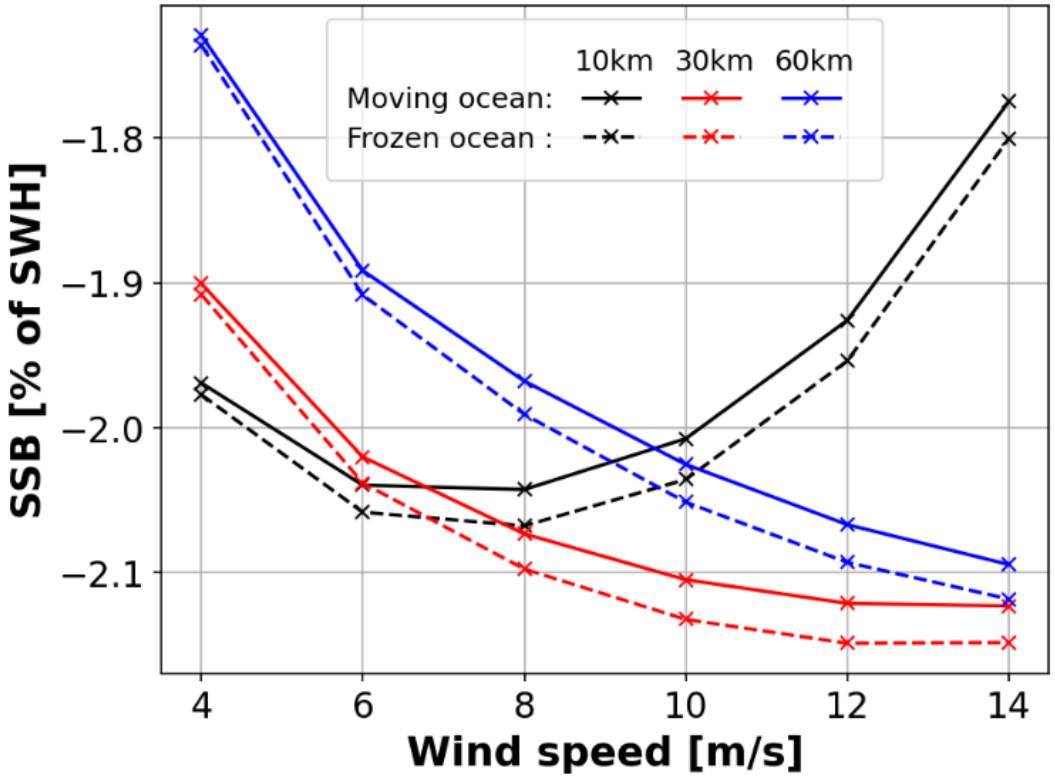
along-track propagating waves



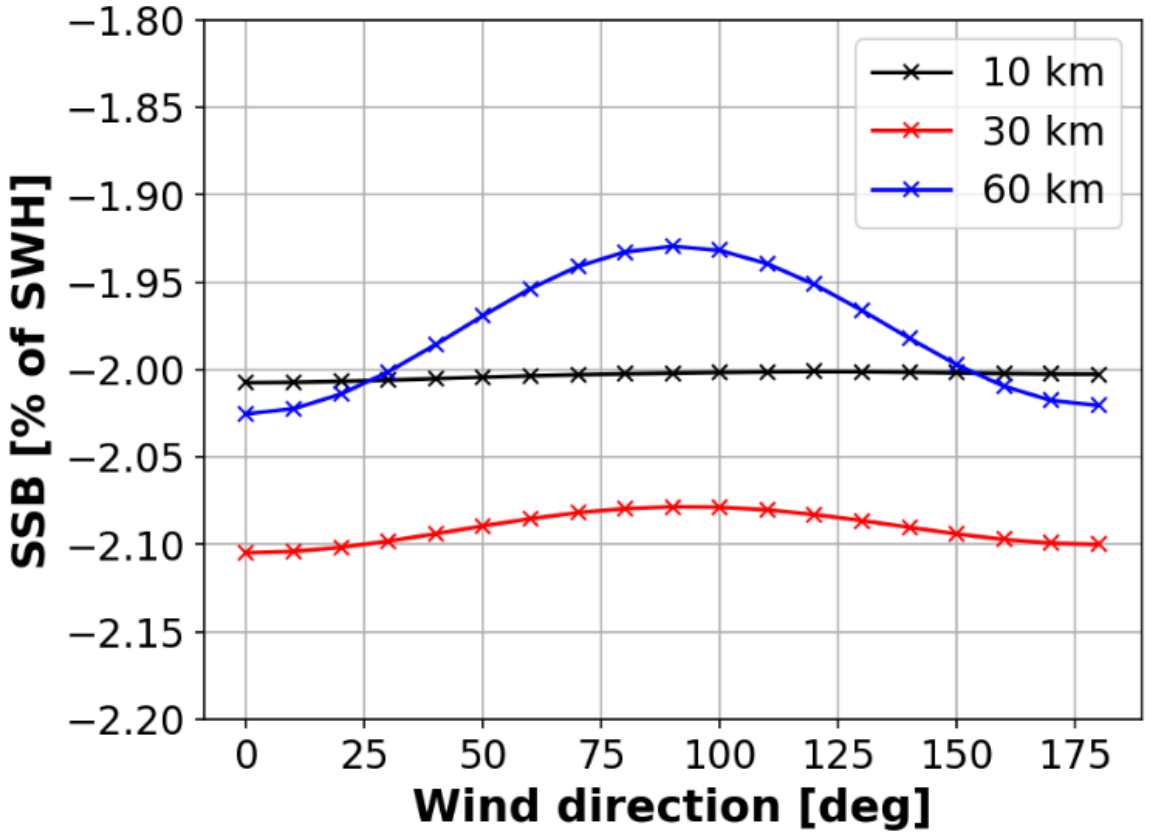


across-track propagating waves

Theoretical SSB : quicklook at some results



surface motion effects subdominant after beam-combine
non-trivial across-track dependence



very mild dependence on directionality of waves

Please see Samuel's poster for many more details !

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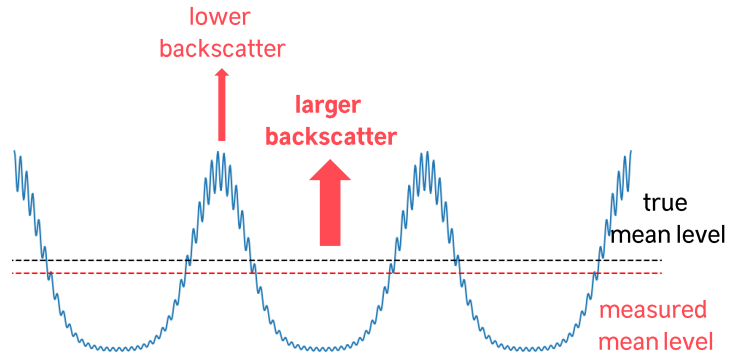
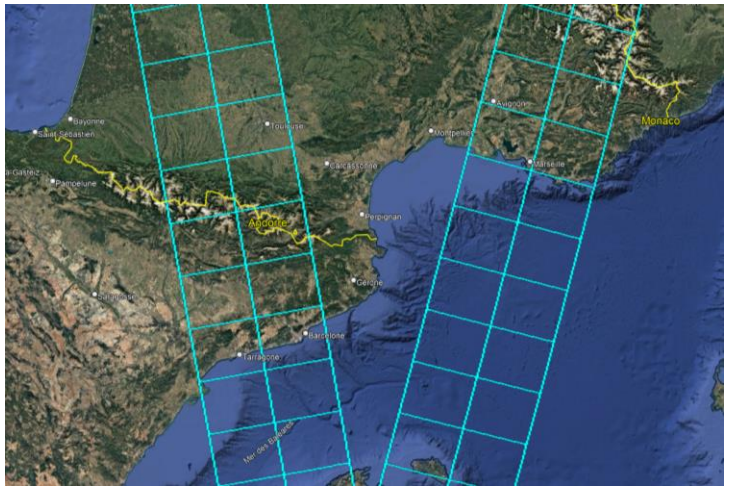
Probing properties of wave scattering in Ka-band using HR data

HR data (Pixel Cloud) :

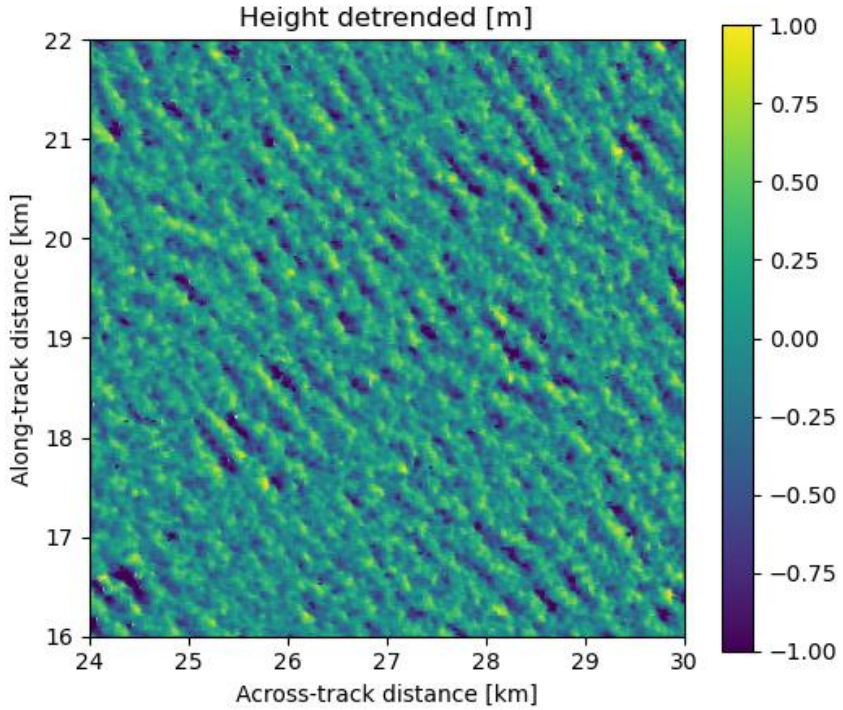
- Tiles of ~60km
- Spatial maps of height and backscatter
- Posting : 60m near-range →10m far range
- Swells (~100m+) are resolved

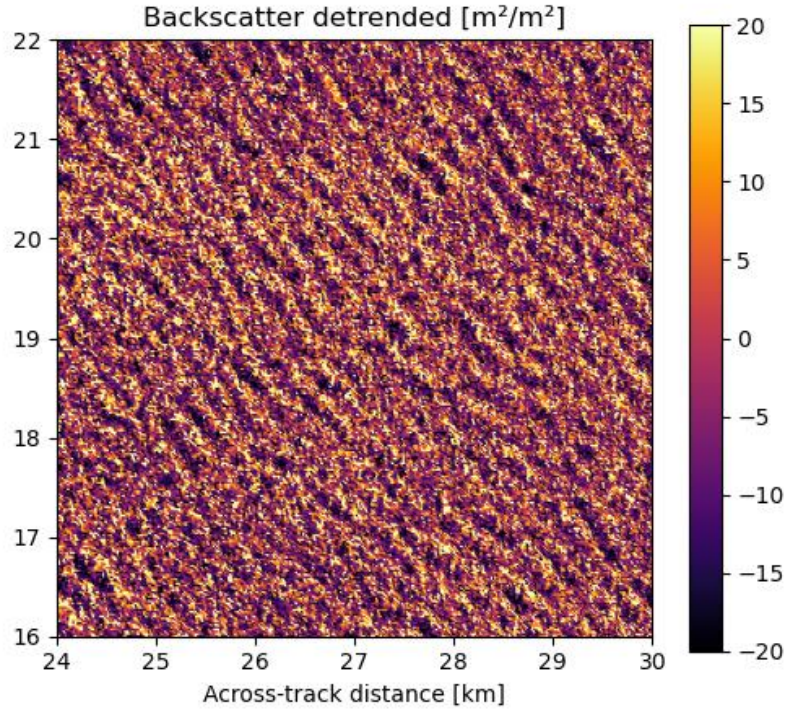
Unique opportunity to study the backscatter modulation along the wave profile, a crucial ingredient of SSB.





SWOT_L2_HR_PIXC_493_024_221R

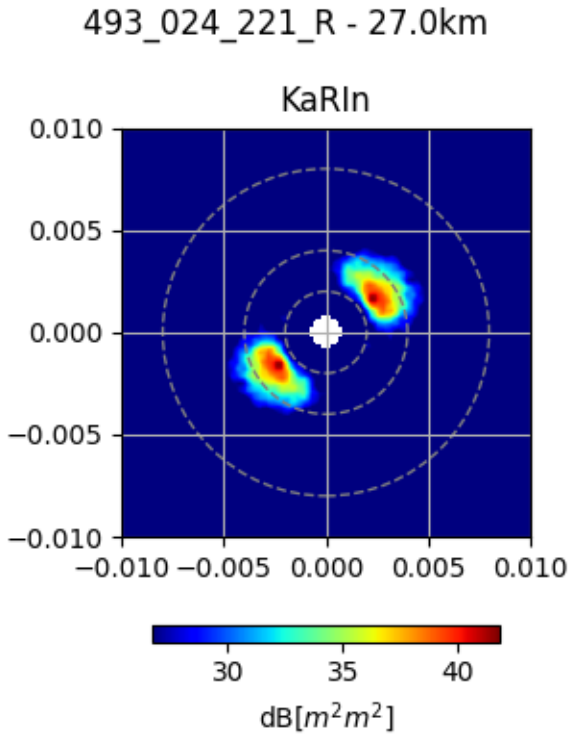


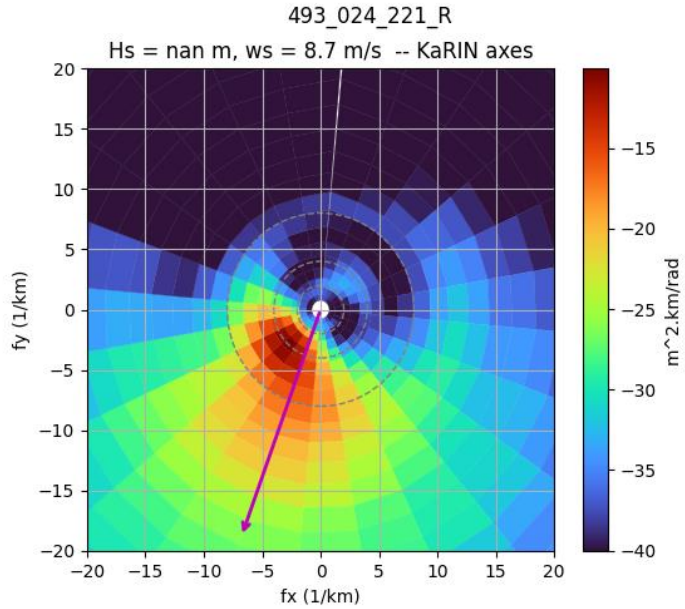


Probing properties of wave scattering in Ka-band using HR data

But the waves are heavily distorted by the measurement technique (range bunching, velocity bunching, azimuth cutoff, grid distorsion from radial velocity…)

Height spectrum from KaRIn's measurement





Height spectrum from buoy (ground truth)

These distorsions need to be carefully understood and modelled to interpret the HR data measurements in terms of what is really happening at the surface.

(work led by L. Yu (CNES))

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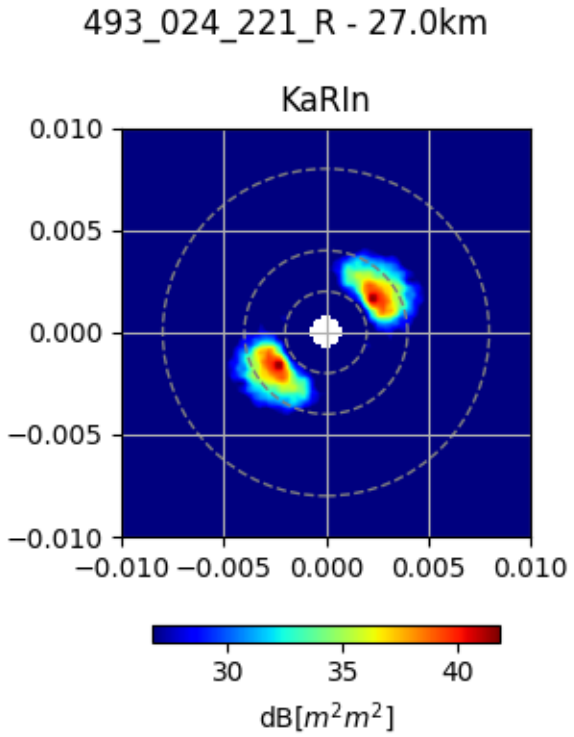

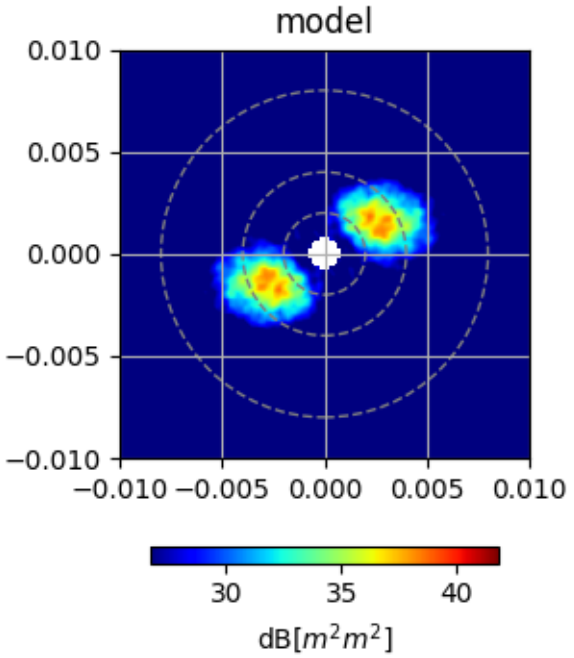

Height spectrum from buoy (ground truth) + model of instrumental distorsions

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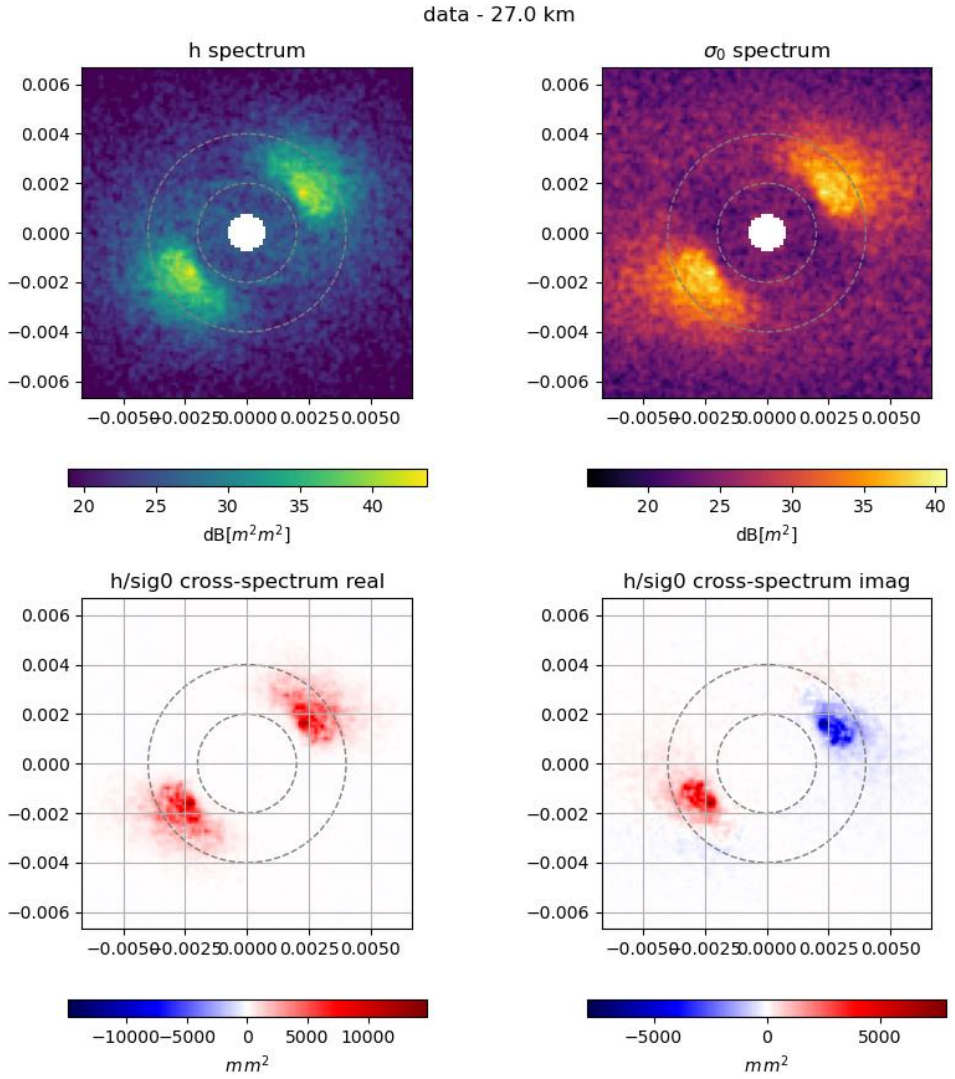
(work led by L. Yu (CNES))

Probing properties of wave scattering in Ka-band using HR data

$\widehat{H}$



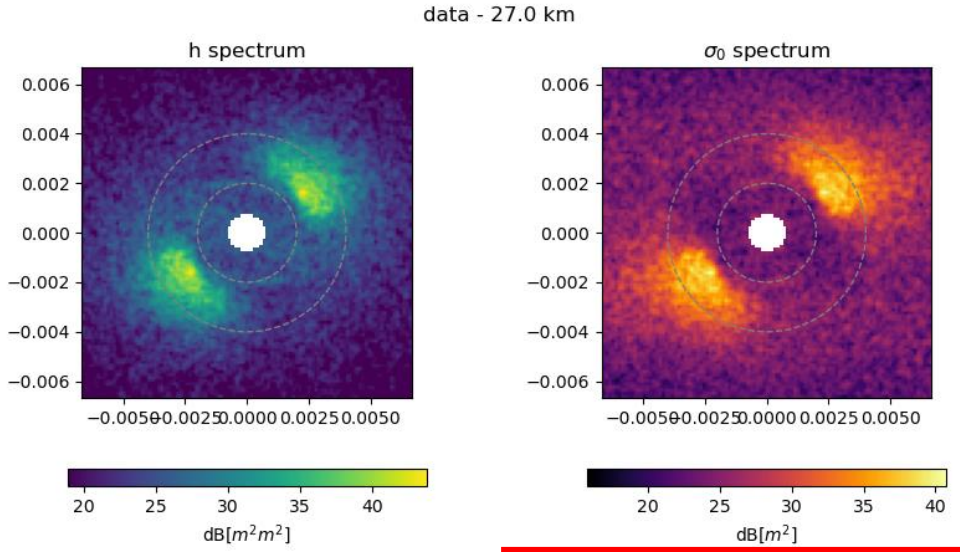
$\hat{\sigma}_0$

$Re\left(\widehat{H}\hat{\sigma}_0^*\right)$

$Im\left(\widehat{H}\hat{\sigma}_0^*\right)$

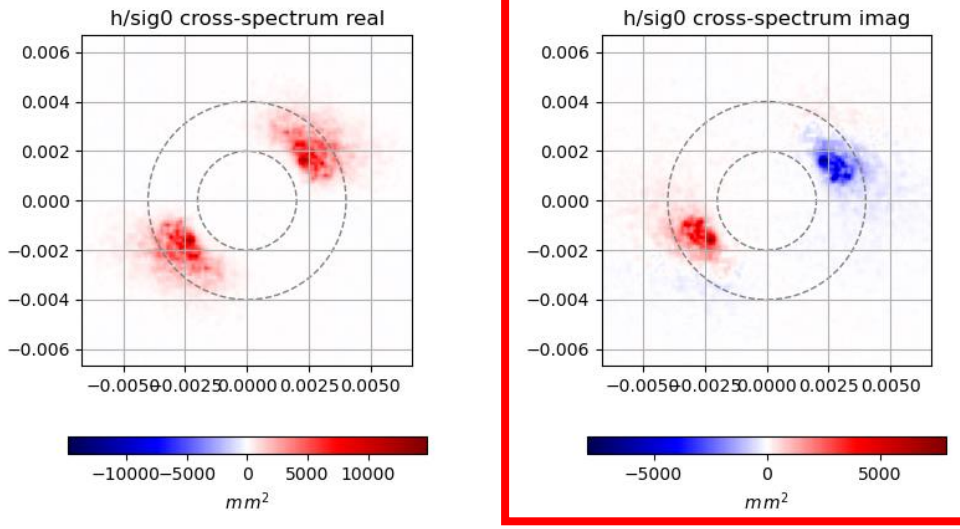
Probing properties of wave scattering in Ka-band using HR data

$\widehat{H}$



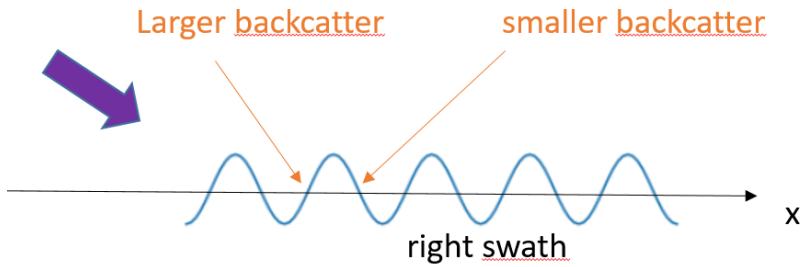
$\hat{\sigma}_0$

$Re\left(\widehat{H}\hat{\sigma}_0^*\right)$

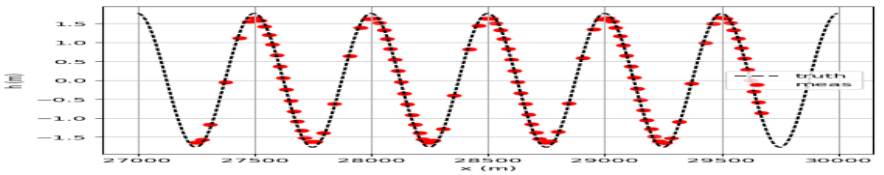


$Im\left(\widehat{H}\hat{\sigma}_0^*\right)$

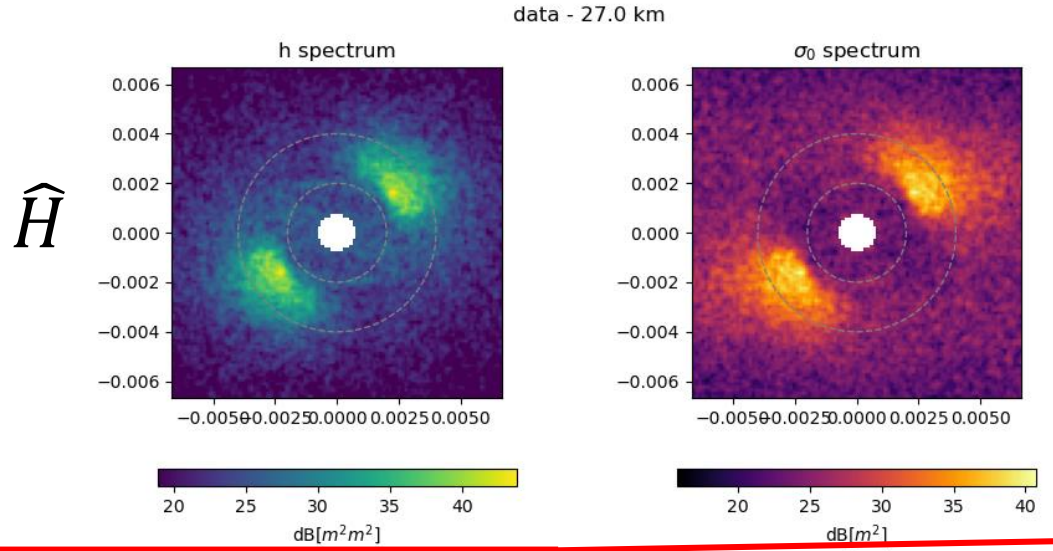
Tilt modulation



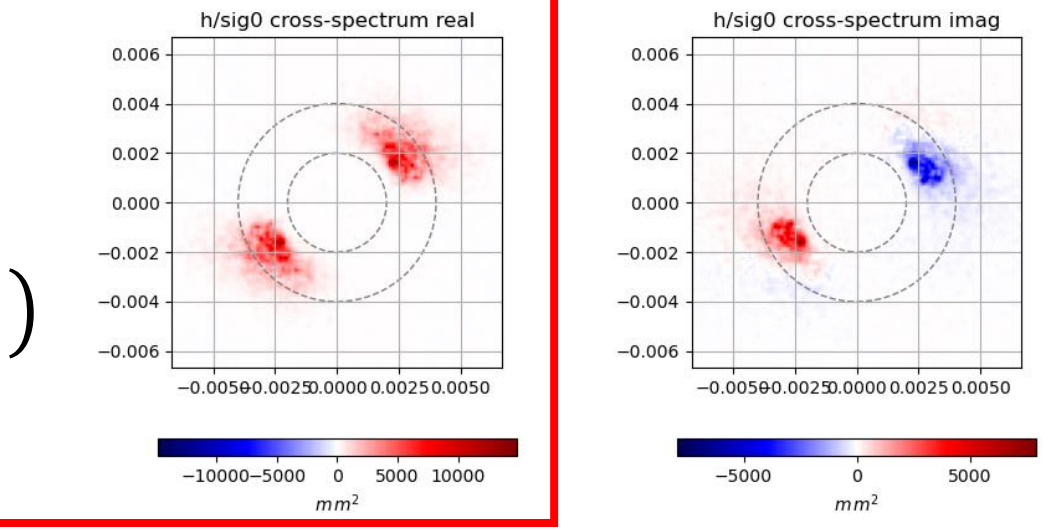
Range bunching



Probing properties of wave scattering in Ka-band using HR data



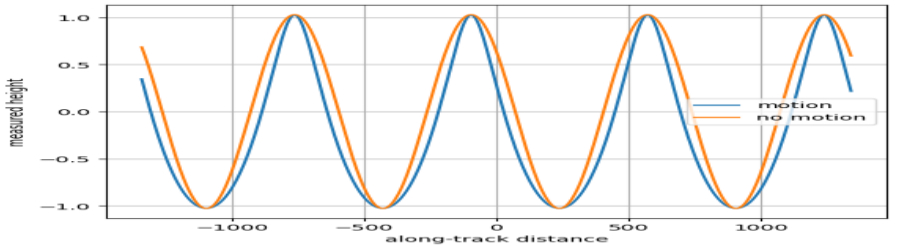
$\hat{H}$ $\hat{\sigma}_0$



$Re\left(\hat{H}\hat{\sigma}_0^*\right)$ $Im\left(\hat{H}\hat{\sigma}_0^*\right)$

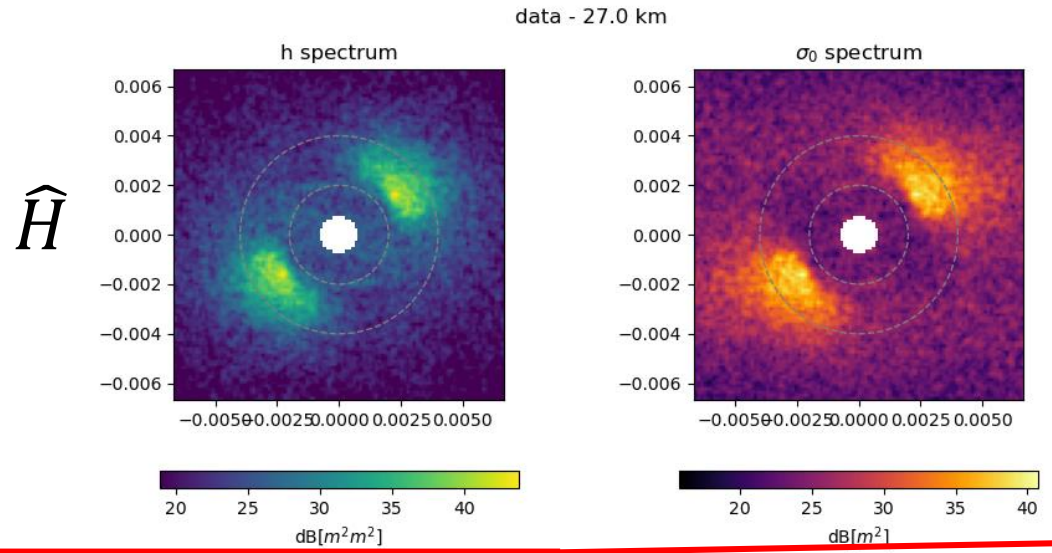
- Velocity bunching

(sign depends on propagation direction)

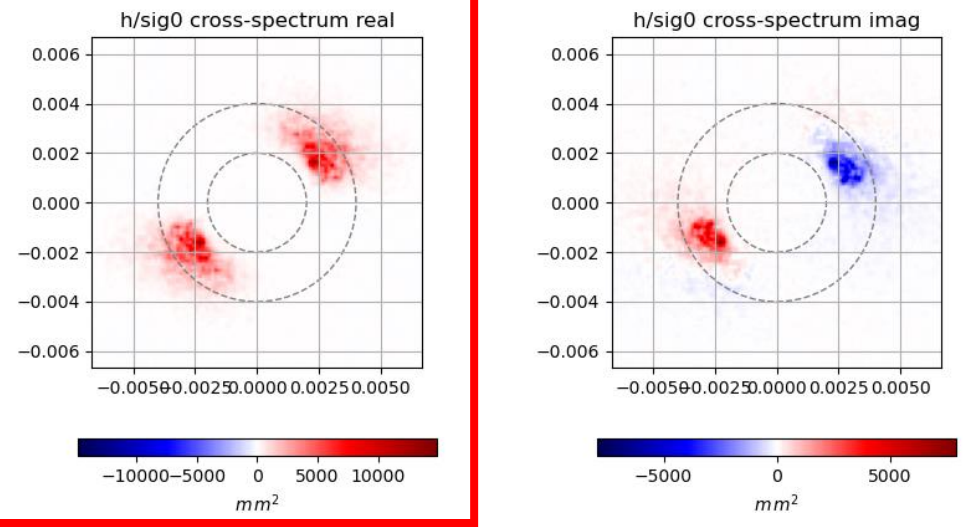


Dominant contribution to the correlation between measured height and measured backscatter

Probing properties of wave scattering in Ka-band using HR data



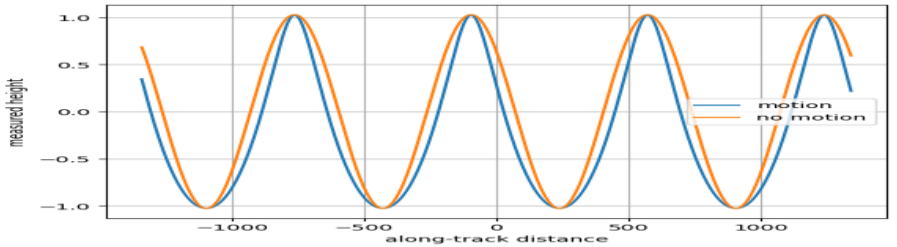
$\hat{H}$ $\hat{\sigma}_0$



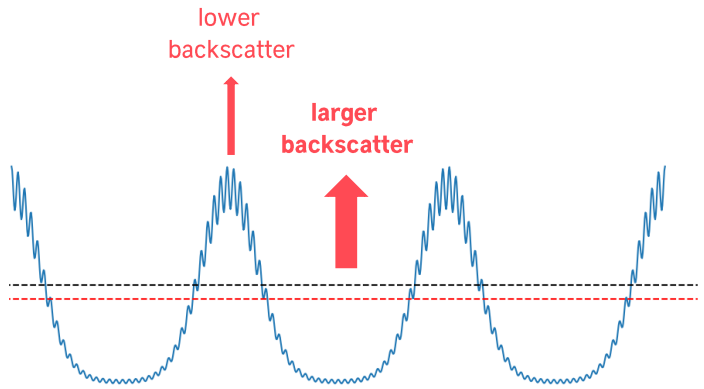
$Re\left(\hat{H}\hat{\sigma}_0^*\right)$ $Im\left(\hat{H}\hat{\sigma}_0^*\right)$

- Velocity bunching

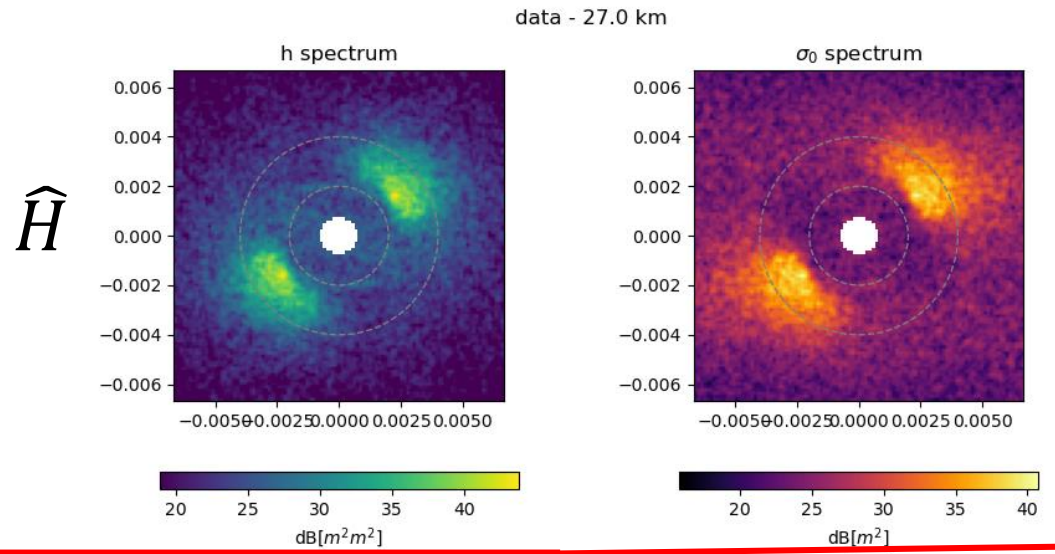
(sign depends on propagation direction)



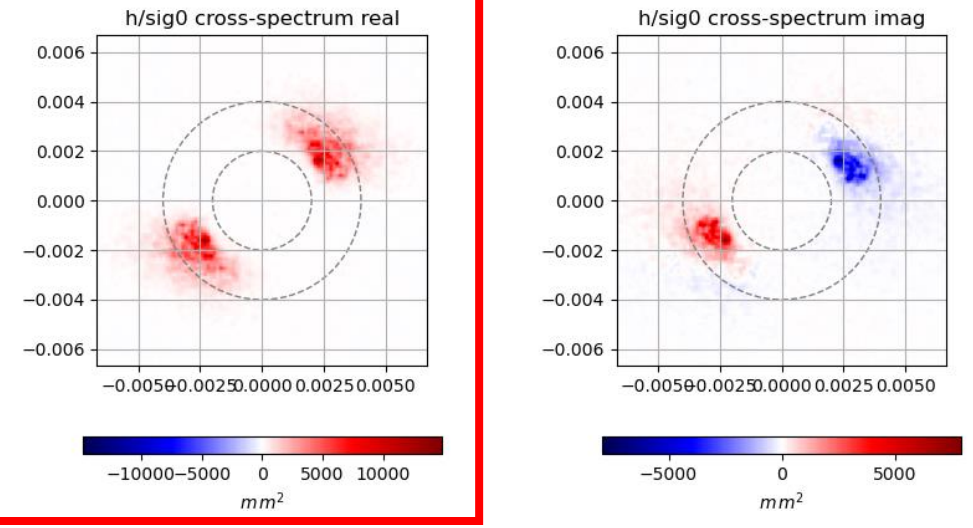
- Hydrodynamic modulation



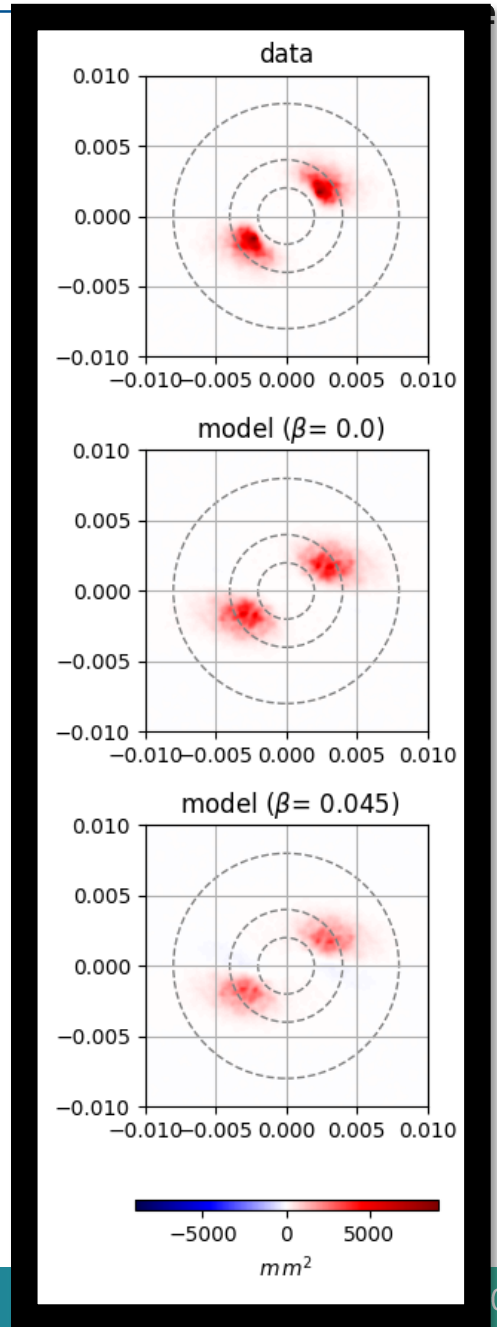
Probing properties of wave scattering in Ka-band using HR data



$\hat{H}$ $\hat{\sigma}_0$



$Re\left(\hat{H}\hat{\sigma}_0^*\right)$ $Im\left(\hat{H}\hat{\sigma}_0^*\right)$



Conclusions

- **Since launch, the model used for SSB correction** of KaRIn's height mesurement is an **empirical table built from AltiKa data** (Ka band nadir altimeter).

- **Preliminary results show that this model (AltiKa table) overcorrects the SSB.**

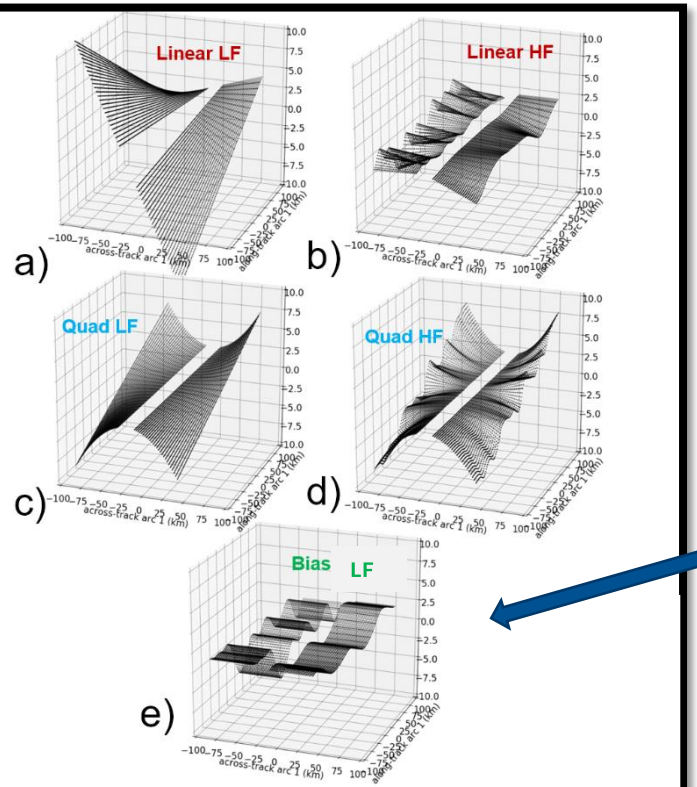
- **We are working towards an improved SSB model for KaRIn**, through a combination of
  - **empirical approaches** (requires separating SSB from KaRIn's systematic errors)
    - « direct method » : ssha averaging given sea state bins
    - « Xover method » : constraints from ssha differences at Xovers as a function of sea state
  - **theoretical modelling**
    - short term goals
      - understand contributions specific to KaRIn
      - identify relevant sea state and instrumental parameters to guide empirical approach
    - long term goal : provide a model usable for correction
  - **exploitation of HR data** to better constrain wave backscatter

BACKUP

XCAL correction : minimal refresher

3 components of KaRIN's systematic errors

- Antenna roll angle is not perfect? Phase error in processing?
  - ➡ Linear cross-track topography
- Baseline length is not perfect?
  - ➡ Quadratic cross-track topography
- Range timing bias in KaRIN?
  - ➡ Time-varying offset topography



slide borrowed from Dibarboure et al, ST 2023

- The cross-over calibration (XCAL) aims at correcting for « systematic » errors affecting KaRIn's measurement which have nothing to do with SSB.
- It is a low frequency correction (error themselves are dominated by large scales)
- Timing part of the XCAL correction is designed to match the large scales of KaRIn onto a reference surface (e.g. SWOT nadir, DUACS)

$$XCAL_{corr} = (ssha_{KaRIn}^{uncorr} - ssha_{ref})_{LF}$$

SSB, systematic errors and XCAL correction

Idealized model :

- KaRIn only affected by SSB and systematic low frequency timing error (no noise, no other sources of error e.g. tropo…)
- We have perfect knowledge of SWH_{true} (we can use it for SSB correction)
- Simplistic SSB model $SSB_{true} = -\beta_{true}\, SWH_{true}$ with constant but unknown β_{true}. Correction performed with β_{corr}.

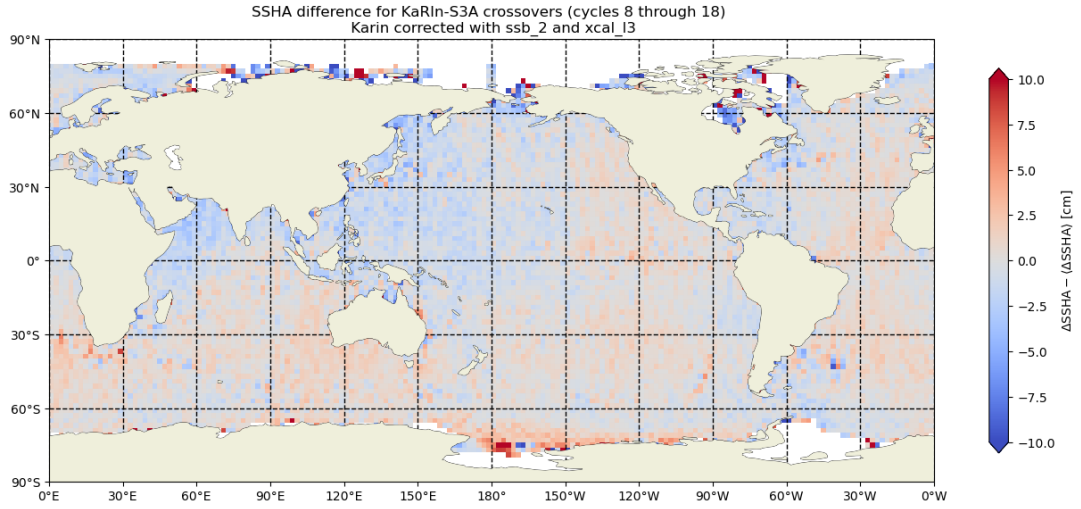
$$ssha_{KaRIn} = ssha_{true} - (\beta_{true} - \beta_{corr})SWH_{true} + \epsilon_{syst} - XCAL_{corr}$$

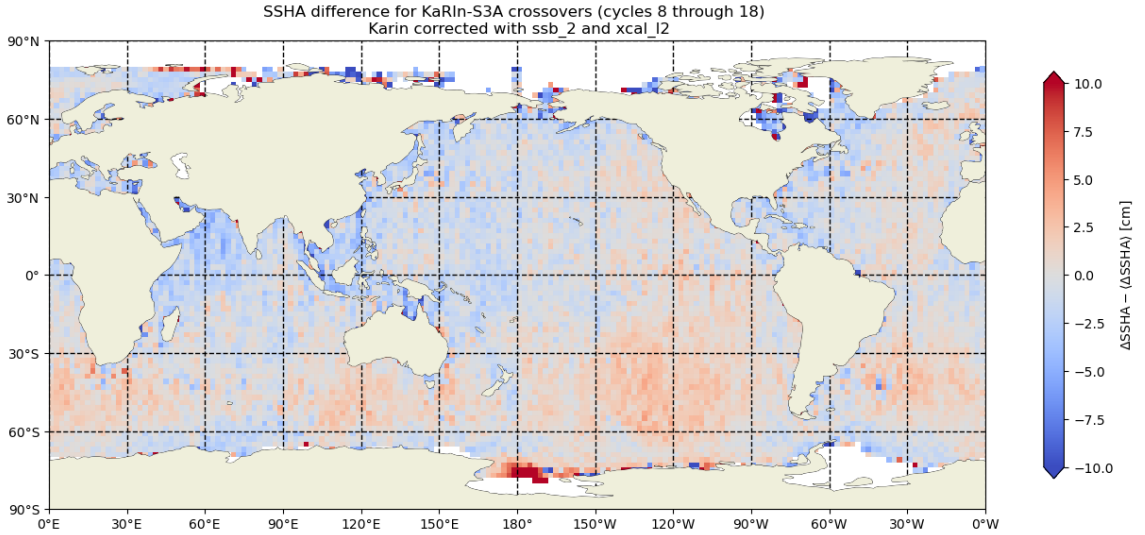
XCAL matches LF to ref : $$XCAL_{corr} = \epsilon_{syst} - (\beta_{true} - \beta_{corr})SWH_{true}^{LF} - (ssha_{true}\text{-}ssha_{ref})^{LF}$$

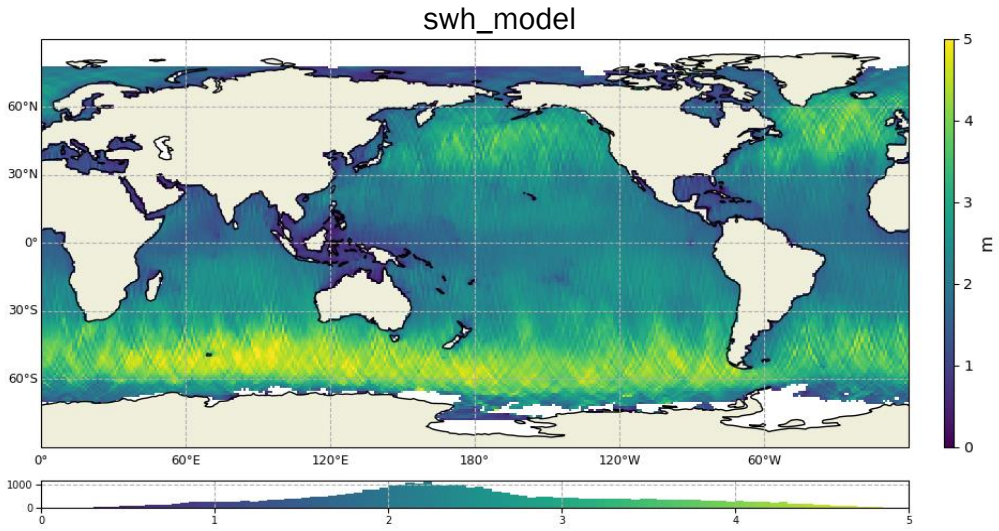
$$\boxed{ssha_{KaRIn} = ssha_{ref}^{LF} + ssha_{true}^{HF} - (\beta_{true} - \beta_{corr})SWH_{true}^{HF}}$$

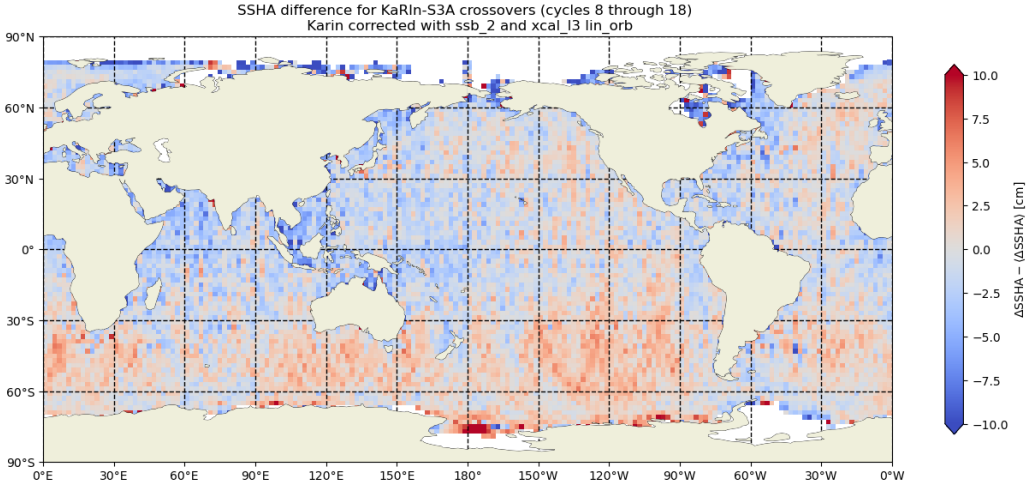
- After XCAL correction, only the residual « HF » SSB remains. But HF is everything < 1000km or 10000 km depending on the XCAL version. **The XCAL does not correct for SSB dynamically.**

- The HF variations of SWH for any given SWH bin are increasingly centered as the XCAL cutoff decreases, which explains why the curves in the previous slides flatten. **The XCAL absorbs the ssha vs SWH dependence, but not the actual SSB error.**

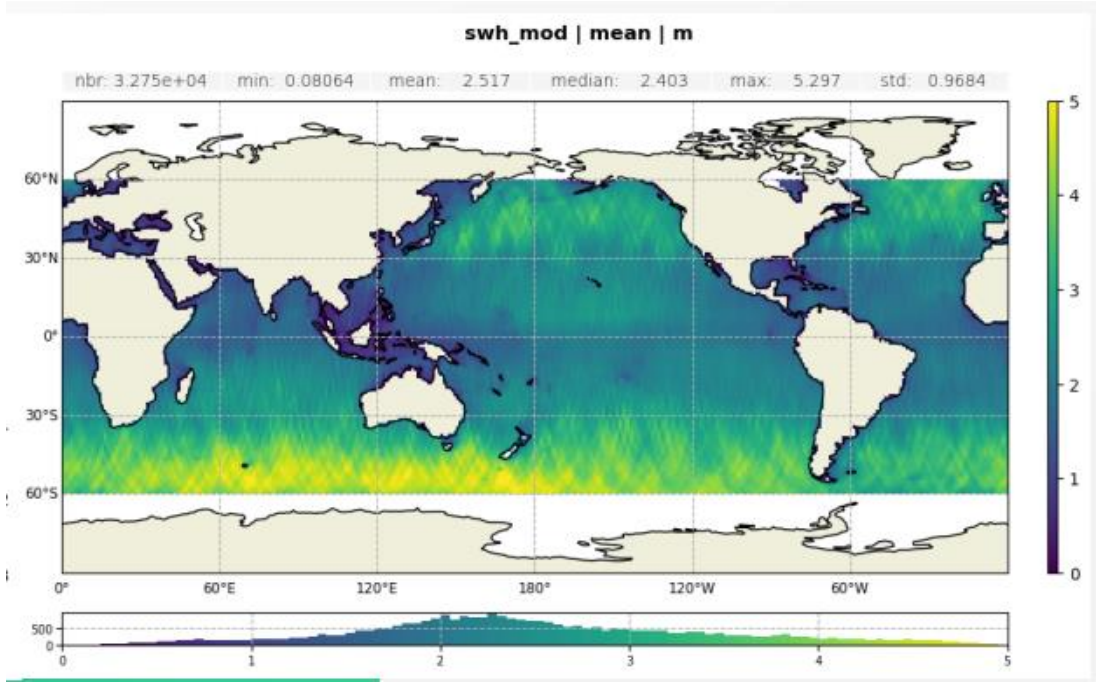

SSHA difference for KaRIn-S3A crossovers (cycles 8 through 18)
Karin corrected with ssb_2 and xcal_l3
ΔSSHA − (ΔSSHA) [cm]

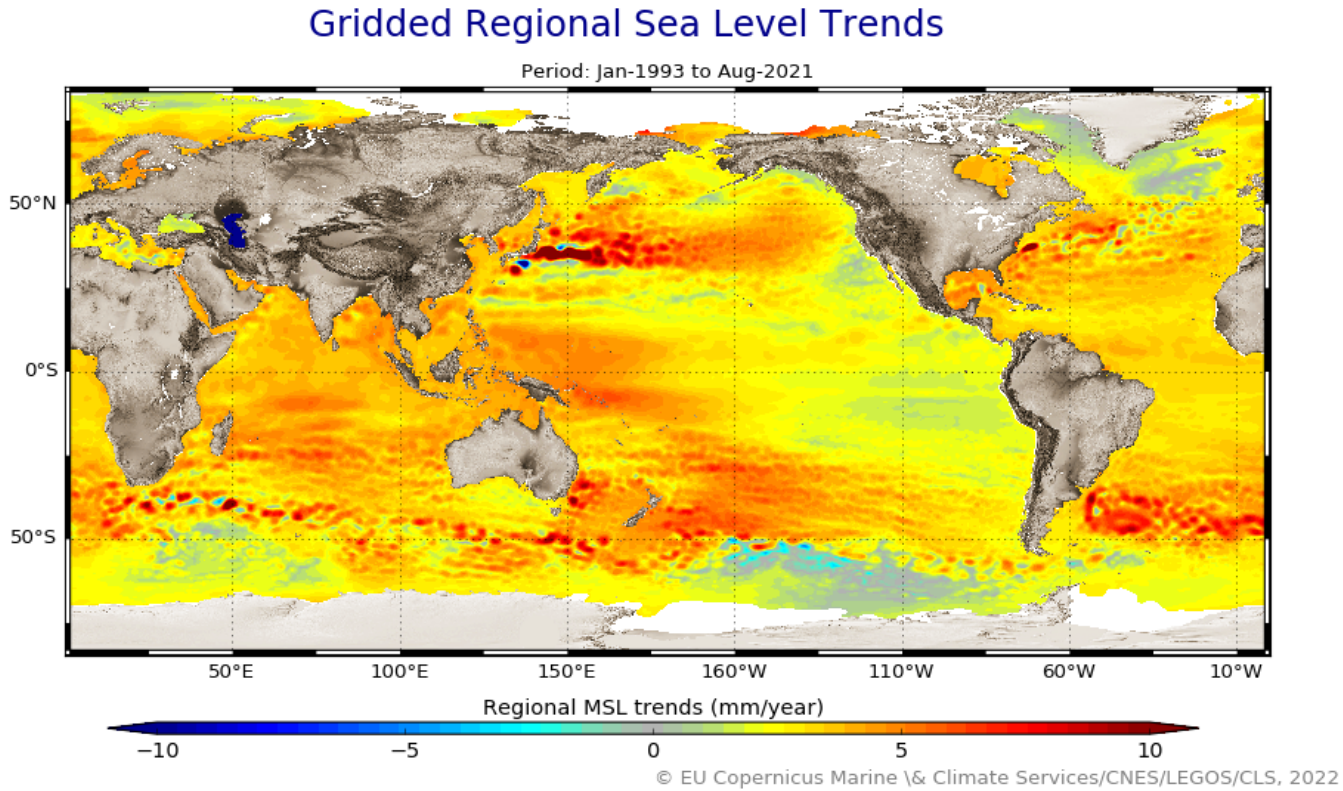

SSHA difference for KaRIn-S3A crossovers (cycles 8 through 18)
Karin corrected with ssb_2 and xcal_l2
ΔSSHA − (ΔSSHA) [cm]


swh_model
m

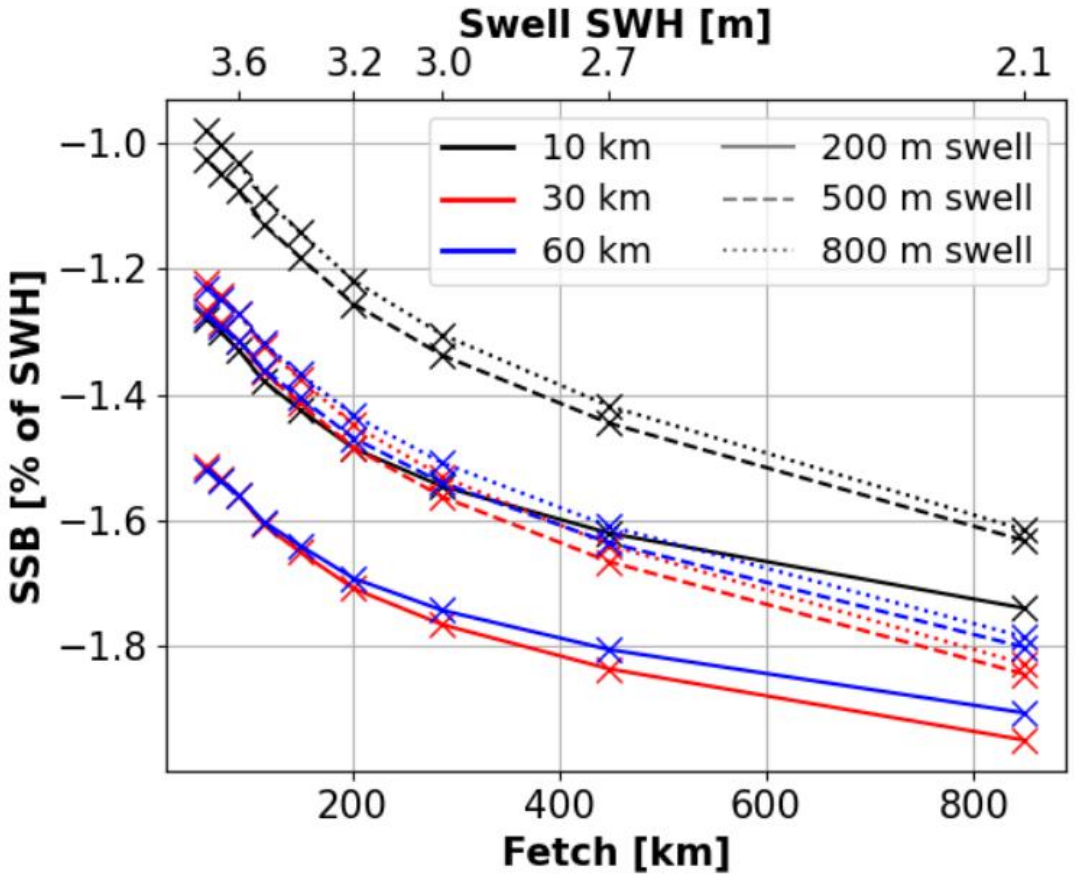

SSHA difference for KaRIn-S3A crossovers (cycles 8 through 18)
Karin corrected with ssb_2 and xcal_l3 lin_orb
ΔSSHA − (ΔSSHA) [cm]

SWH vs Regional MSL trend correlations





Theoretical SSB : quicklook at some results



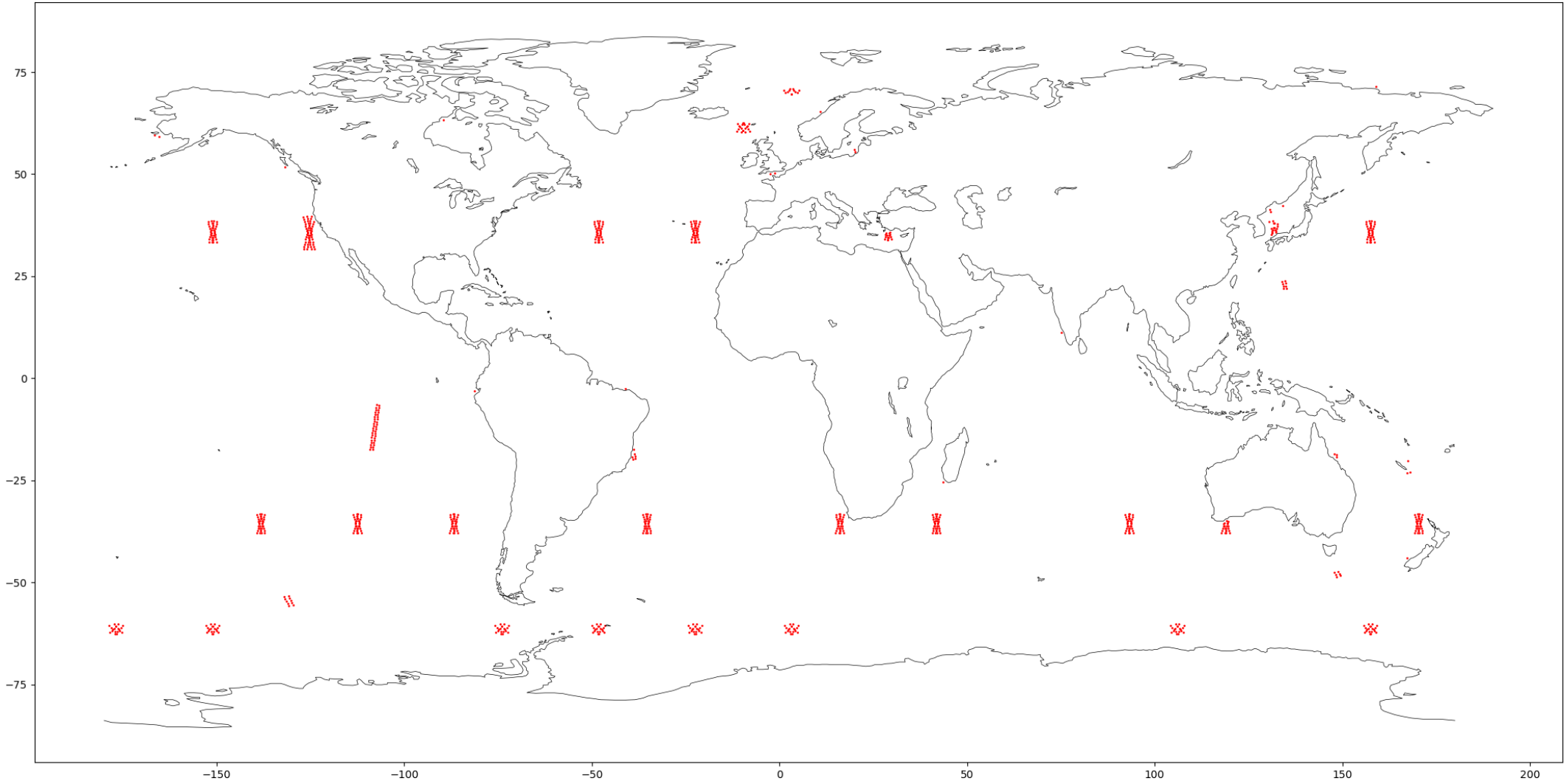
All the sea states considered here have the same SWH and wind-speed (single point in AltiKa's 2D table)

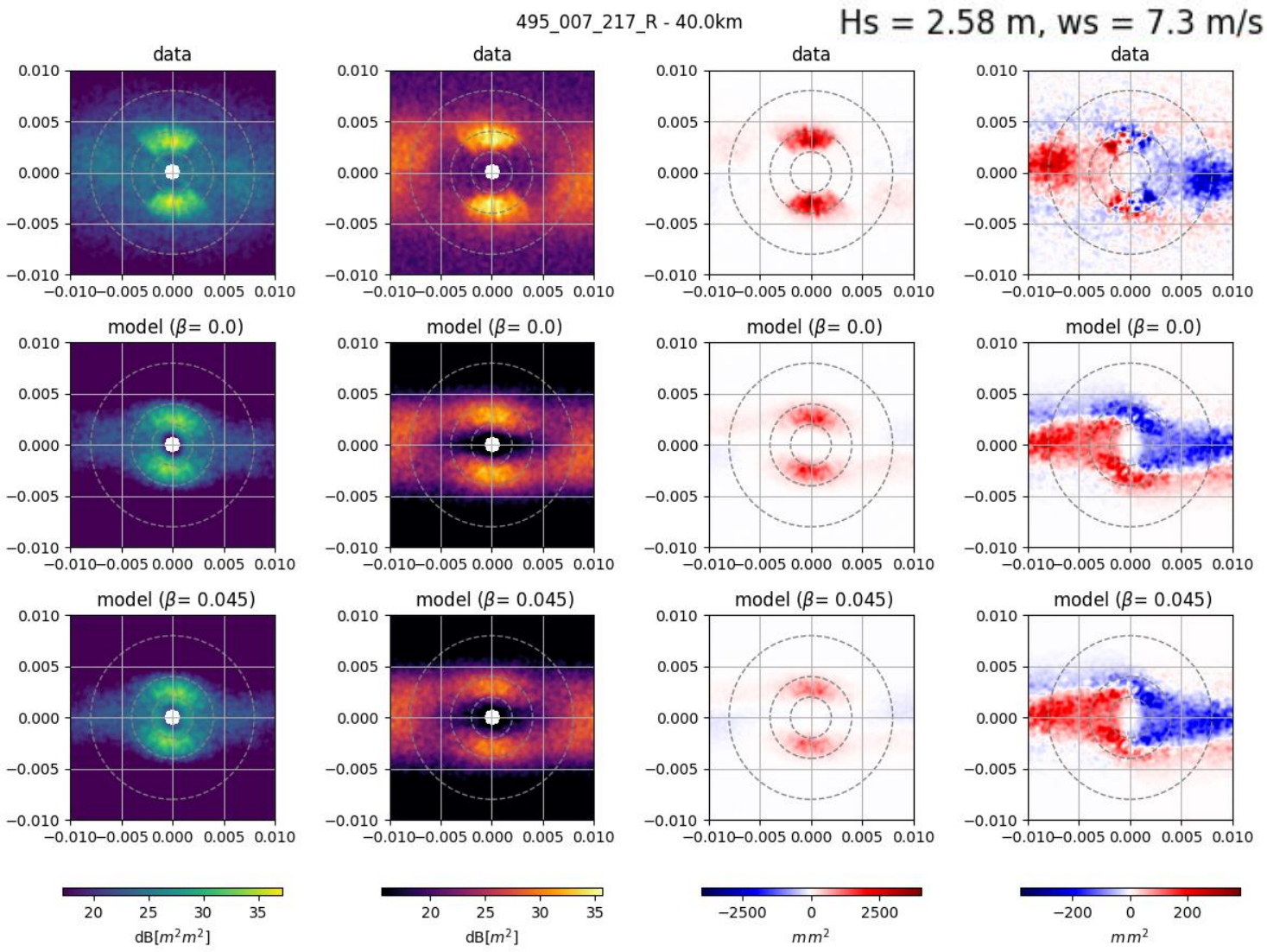
Strong depdence on wave spectrum (swell/wind-sea fraction; long waves are less non-linear)

Cal/val phase

- April to June 2023
- ~800 HR tiles
- Daily obs

➢ ~60000 obs




495_007_217_R - 40.0km
Hs = 2.58 m, ws = 7.3 m/s
data
data
data
data
model (β= 0.0)
model (β= 0.0)
model (β= 0.0)
model (β= 0.0)
model (β= 0.045)
model (β= 0.045)
model (β= 0.045)
model (β= 0.045)
0.010
0.005
0.000
−0.005
−0.010
−0.010 −0.005 0.000 0.005 0.010
20 25 30 35
dB[m^2m^2]
20 25 30 35
dB[m^2]
−2500 0 2500
mm^2
−200 0 200
mm^2