S6-JTEX Final Review

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Exploiting the S6-MF ENL for sea state applications

This case study is aimed at verifying the existence of a discrepancy in S6-MF geophysical parameters obtained starting from low-resolution mode waveforms because of the higher pulse repetition frequency.

Copernicus Sentinel-6 Michael Freilich is the first altimeter operating in a continuous high-rate pulse mode, i.e. interleaved mode.

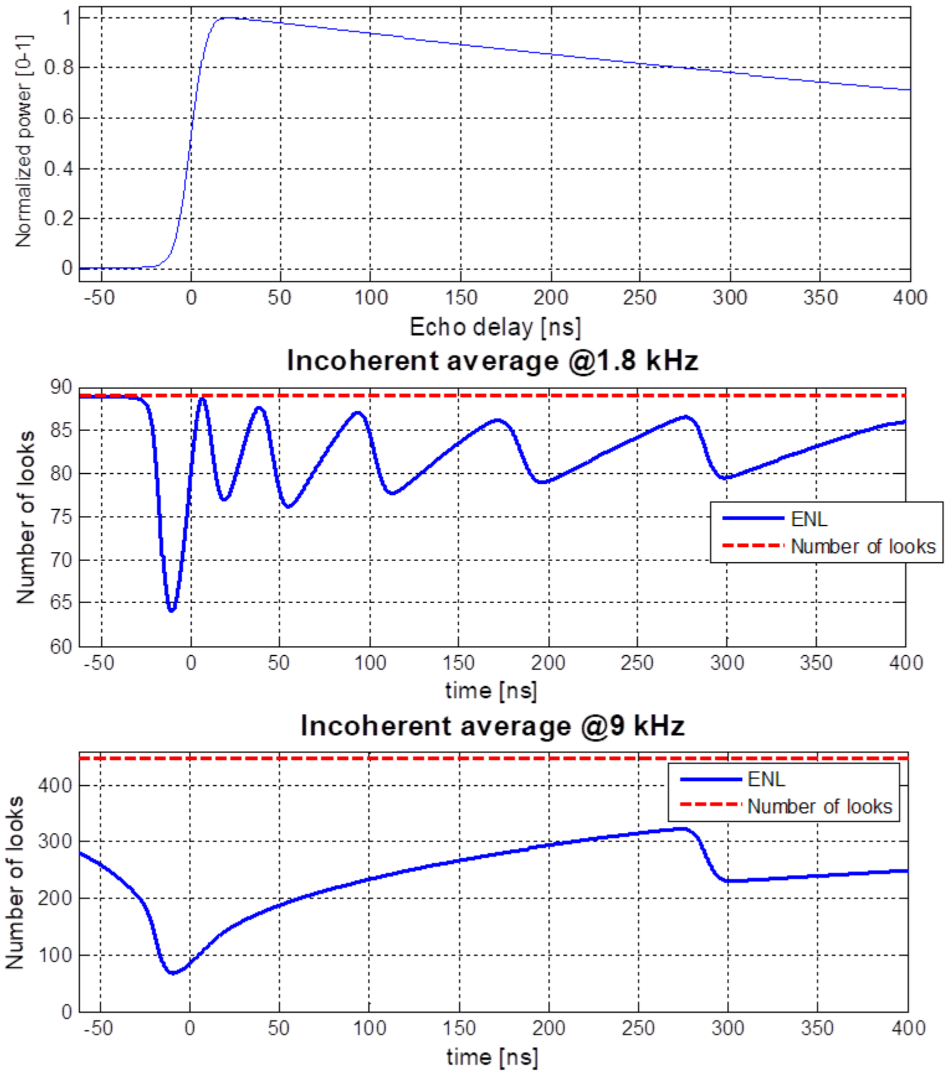
- Production of low-resolution mode measurements with a pulse repetition frequency of ~9KHz for Ku-band as well as the processing of high-resolution echoes on ground.
- Obtaining an elevated number of highly correlated single looks with respect to the fewer number of Jason-3 slightly correlated altimeter

Previous studies

- Exploiting a theoretical model, it has been shown in previous work (Scagliola, 2016) that for LRM waveforms the averaging of an higher number of correlated single looks (~9KHz) allows to obtain an higher ENL with respect to the averaging of fewer almost uncorrelated single looks (~1.8KHz *).

- In (Egido and Smith, 2019) it was verified that despite the fact the at higher PRFs the noise in the estimation of geophysical parameters is reduced, the significant dependence of the statistical properties on the range gate also introduces significant biases in the retracked parameters

*the maximum PRF at which statistical independence could be achieved is of ~2 kHz for Ku-band nadir-looking pulse-limited radar altimeters (Walsh, 1982)

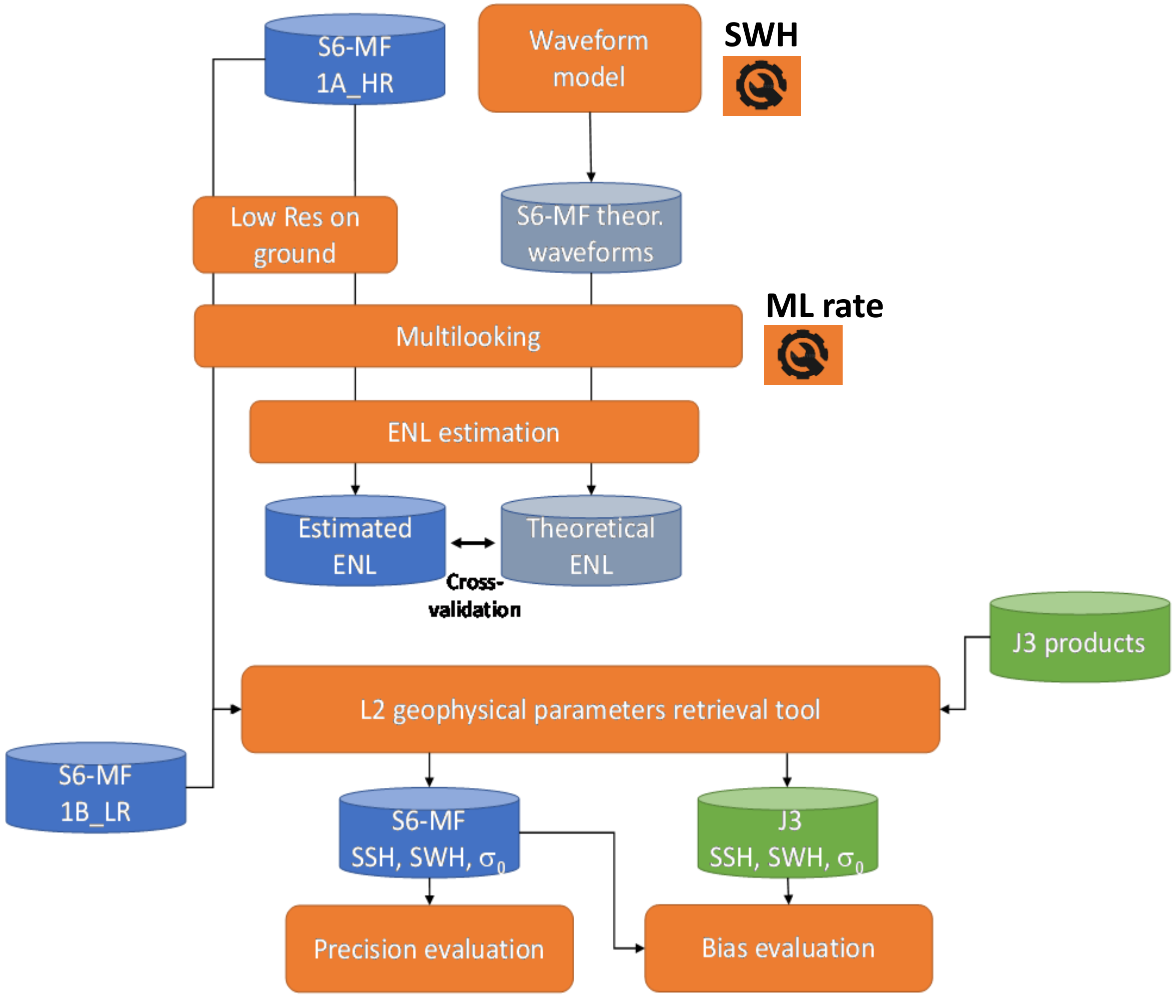


Exploiting the S6-MF ENL for sea state applications

- ✓ Evaluation of the autocorrelation properties by making use of a theoretical waveform model

- ✓ Theoretical results compared with the ENL estimated from real S6-MF data

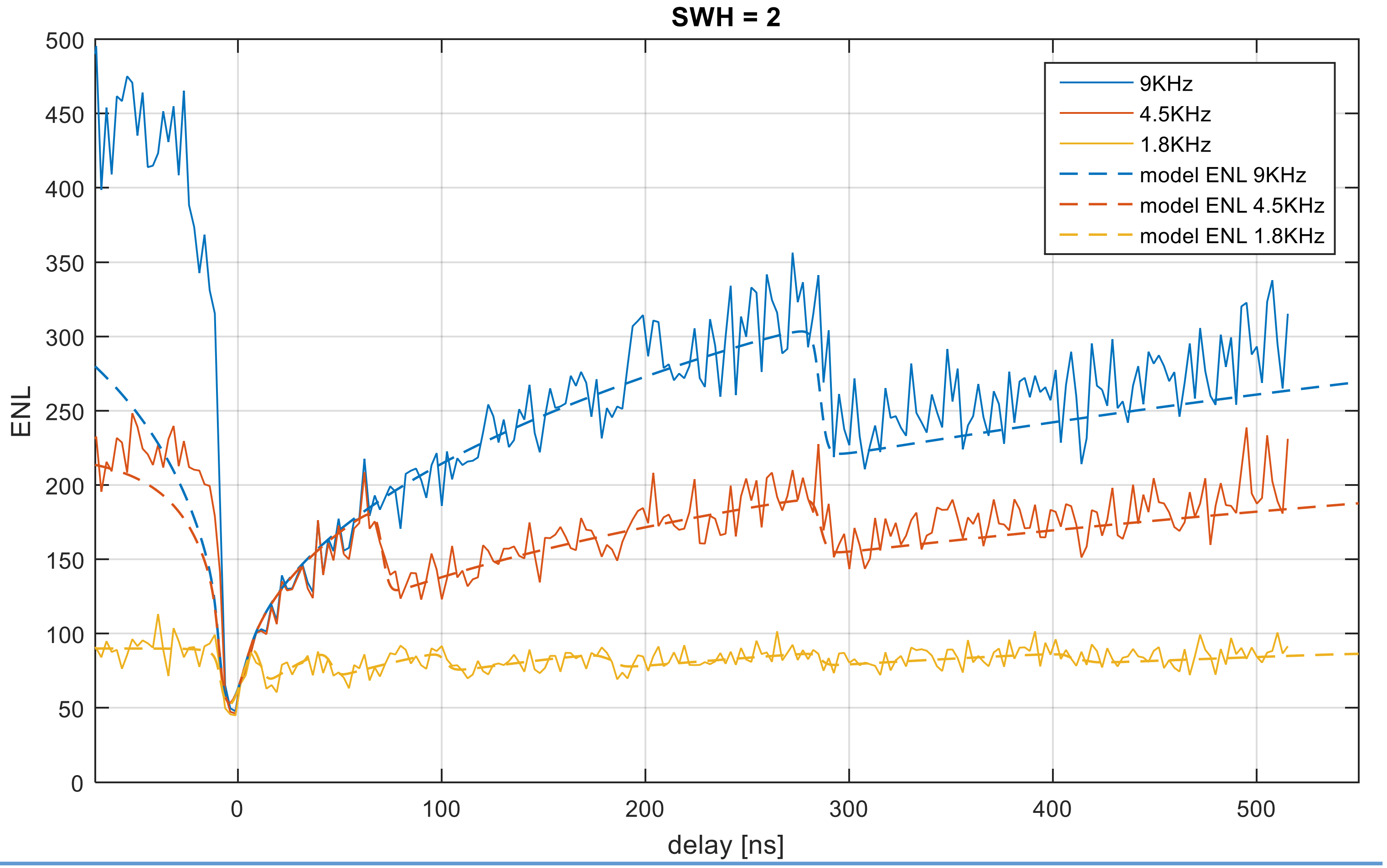
- ✓ Aresys L2 geophysical parameters retrieval tool exploited to verify the effect of the varying ENL on the precision of the retrieval of the geophysical parameters as a function of the multilooking posting rate



Evaluation of ENL from S6-MF real data – SWH = 2

Empirical ENL evaluated over 400 multilooked waveforms:

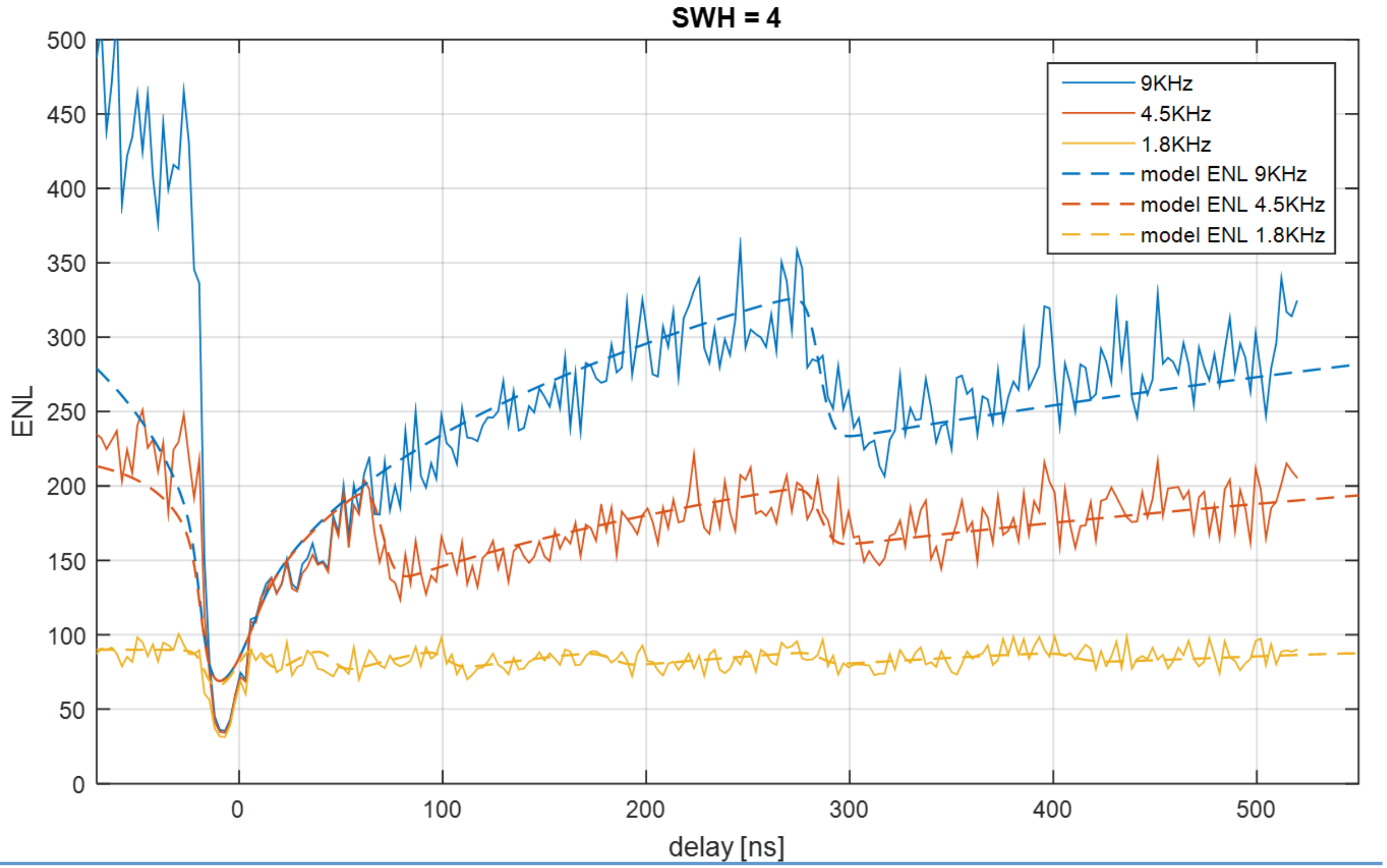
- Good agreement between the empirical ENL and the theoretical curve
- Model fails to predict correct ENL in the thermal noise area
- On leading edge area empirical ENL slightly differ from theoretical one



Evaluation of ENL from S6-MF real data – SWH = 4

Empirical ENL evaluated over 360 multilooked waveforms:

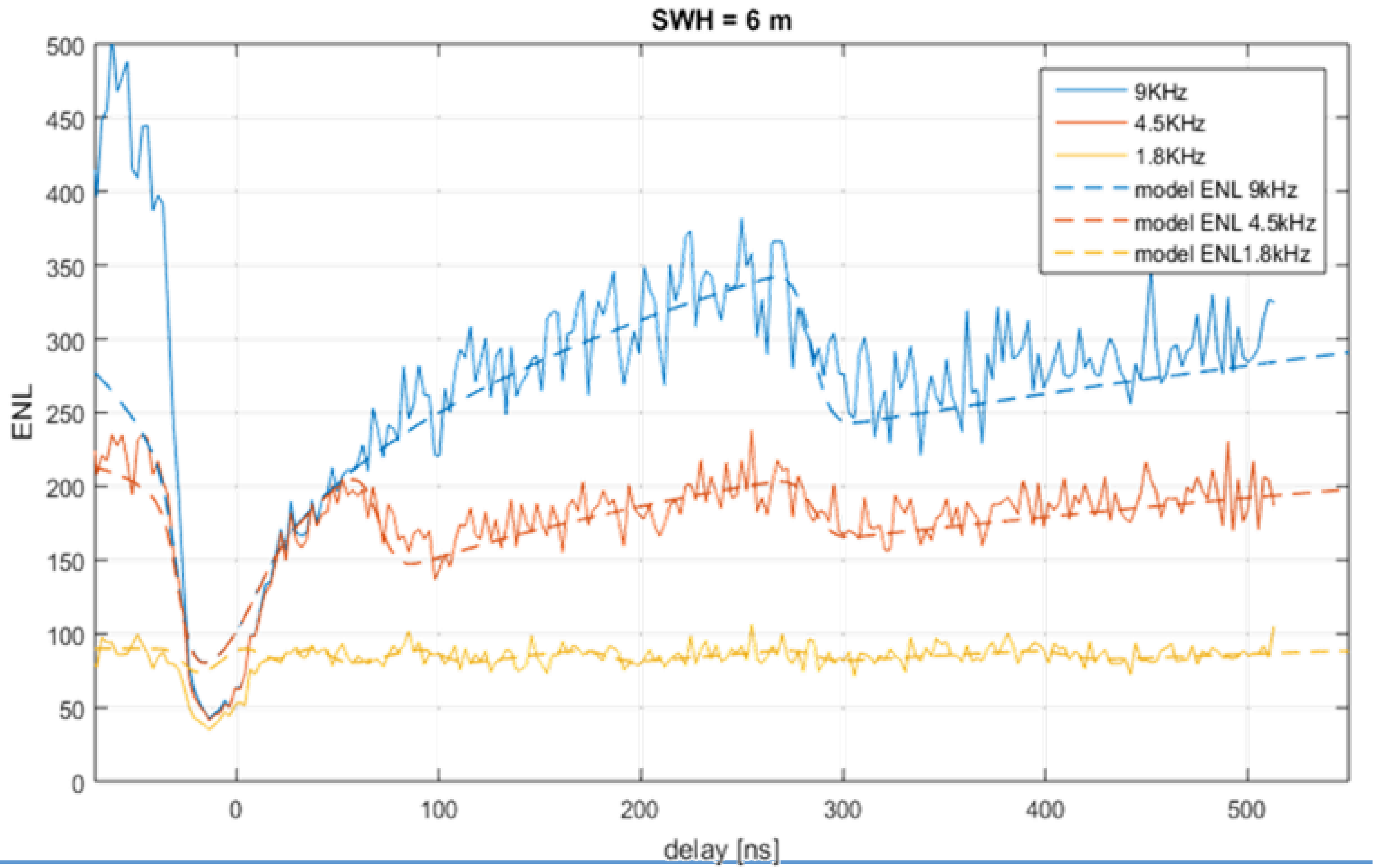
- Good agreement between the empirical ENL and the theoretical curve
- Model fails to predict correct ENL in the thermal noise area
- On leading edge area empirical ENL slightly differ from theoretical one



Evaluation of ENL from S6-MF real data – SWH = 6

Empirical ENL evaluated over 400 multilooked waveforms:

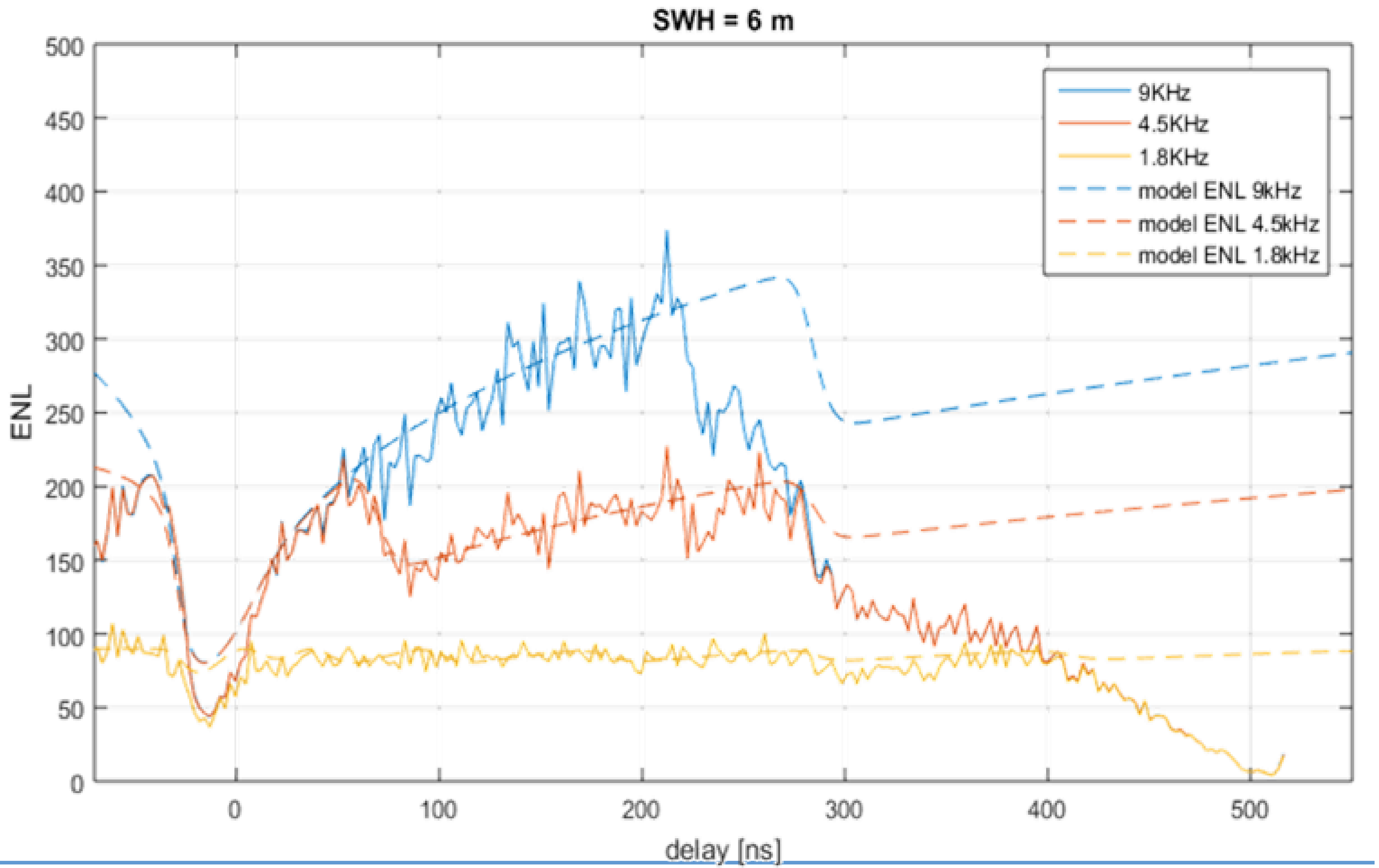
- Good agreement between the empirical ENL and the theoretical curve
- Model fails to predict correct ENL in the thermal noise area
- On leading edge area empirical ENL consistently differ from theoretical one, differences increasing with SWH



Evaluation of ENL from S6-MF real data – SWH = 6

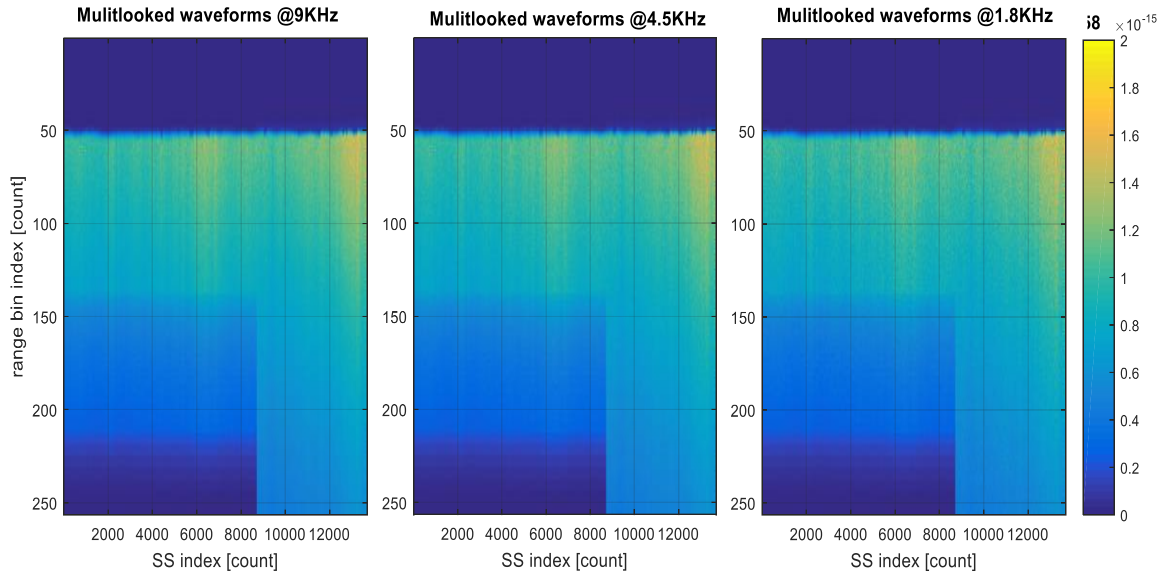
Empirical ENL evaluated over 400 multilooked waveforms **for RMC case**:

- Good agreement between the empirical ENL and the theoretical curve
- Model fails to predict correct ENL in the thermal noise area
- On leading edge area empirical ENL consistently differ from theoretical one, differences increasing with SWH



Data processing steps

- Processing of Cycle 9 pole-to-pole L1A HR data:
  → All 240 data L1A-HR data processed up to “L1B LR” (720 files)



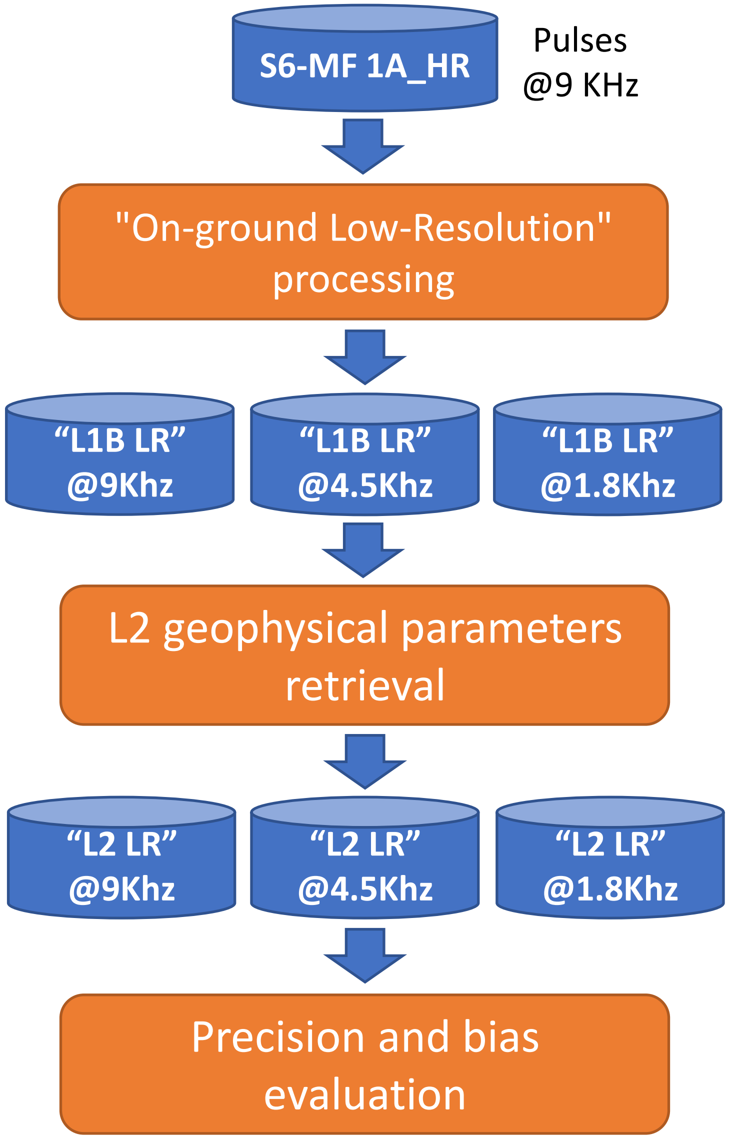
9KHz → 1.8KHz

Increasing speckle

Decreasing pulse to pulse correlation

Decreasing ENL

“constant” ENL over range

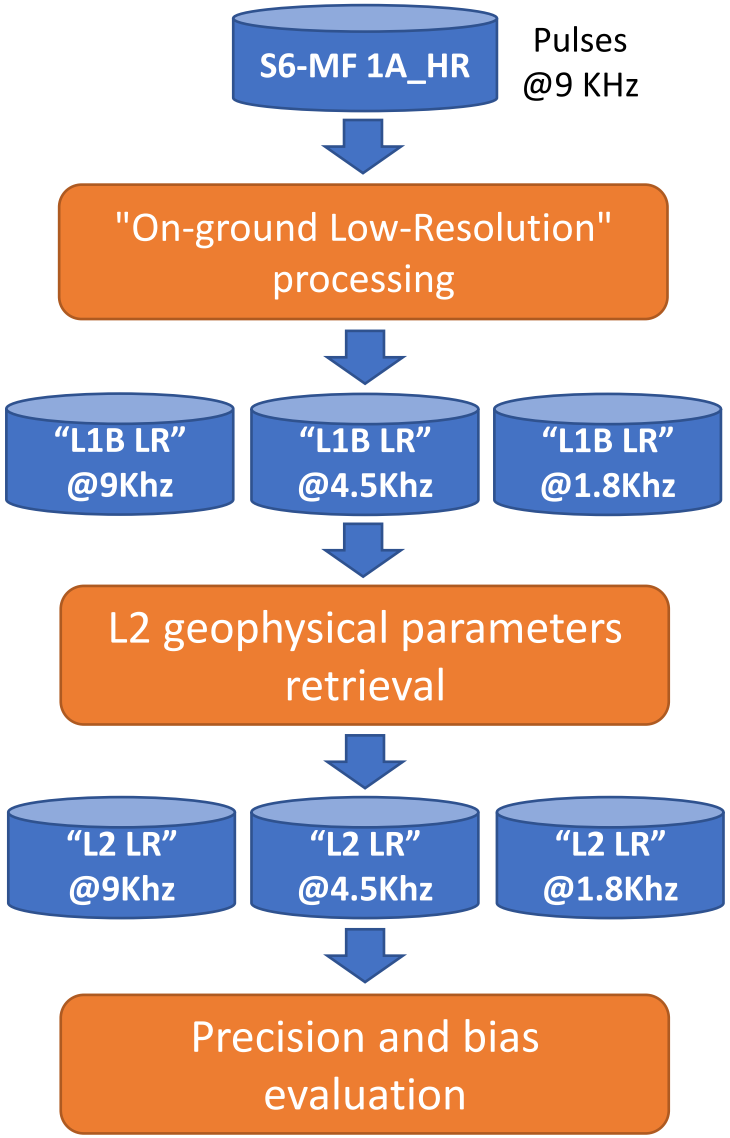


Data processing steps

- Processing of Cycle 9 pole-to-pole L1A HR data:
  → All 240 data L1A-HR data processed up to “L1B LR” (720 files)

  → All “L1B LR” products processed up to L2

  → Precision and bias evaluation concluded



Aresys L2 geophysical parameters retrieval tool

- Based on waveform model from [1] for LR waveforms
- Retrieval of SWH, SSH and Sigma0 estimates from L1B products through iterative fitting routine based on Levenberg-Marquardt optimization algorithm
- Multi-mission tool: Sentinel-6, Cryosat-2, Sentinel-3. <u>Validated for Jason3 data</u>

- Altitude
- Velocity
- PRI
- Pitch
- Roll
- Antenna parameters
- Wavelength

Get waveform impulse response from model $X^{IR}(\tau)$

$$X^{IR}(\tau) = X(\tau) * p_t(\tau) * p_z(\tau)$$

Surface impulse response

$$X(\tau) = 2A\exp\left[-\left(\delta - \frac{\beta^2}{8}\right)\tau\right]U(\tau) - A\exp[-\delta\tau]U(\tau)$$

Where:

- U(t) is the unit step function
- A is the amplitude term
- δ and β depend on the off-nadir angle and the antenna beamwidth
- Valid for mispointing angle up to 0.8 deg

System PTR

$$p_t(\tau) = \left|\frac{\sin(\pi B\tau)}{\pi B\tau}\right|^2$$

Sea Surface height PDF

(Gaussian)

$$p_z(\tau) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(\tau/\sqrt{2}\sigma)^2}$$

[1] Amarouche, L., P. Thibaut, O. Z. Zanife, J.P. Dumont, N. Steunou, & P. Vincent, 2003: Improving the Jason1 ground retracking to cope with attitude effects. Marine Geodesy, Special Issue on Jason1 Calibration/Validation, Part 2. DOI:10.1080/01490410490465210

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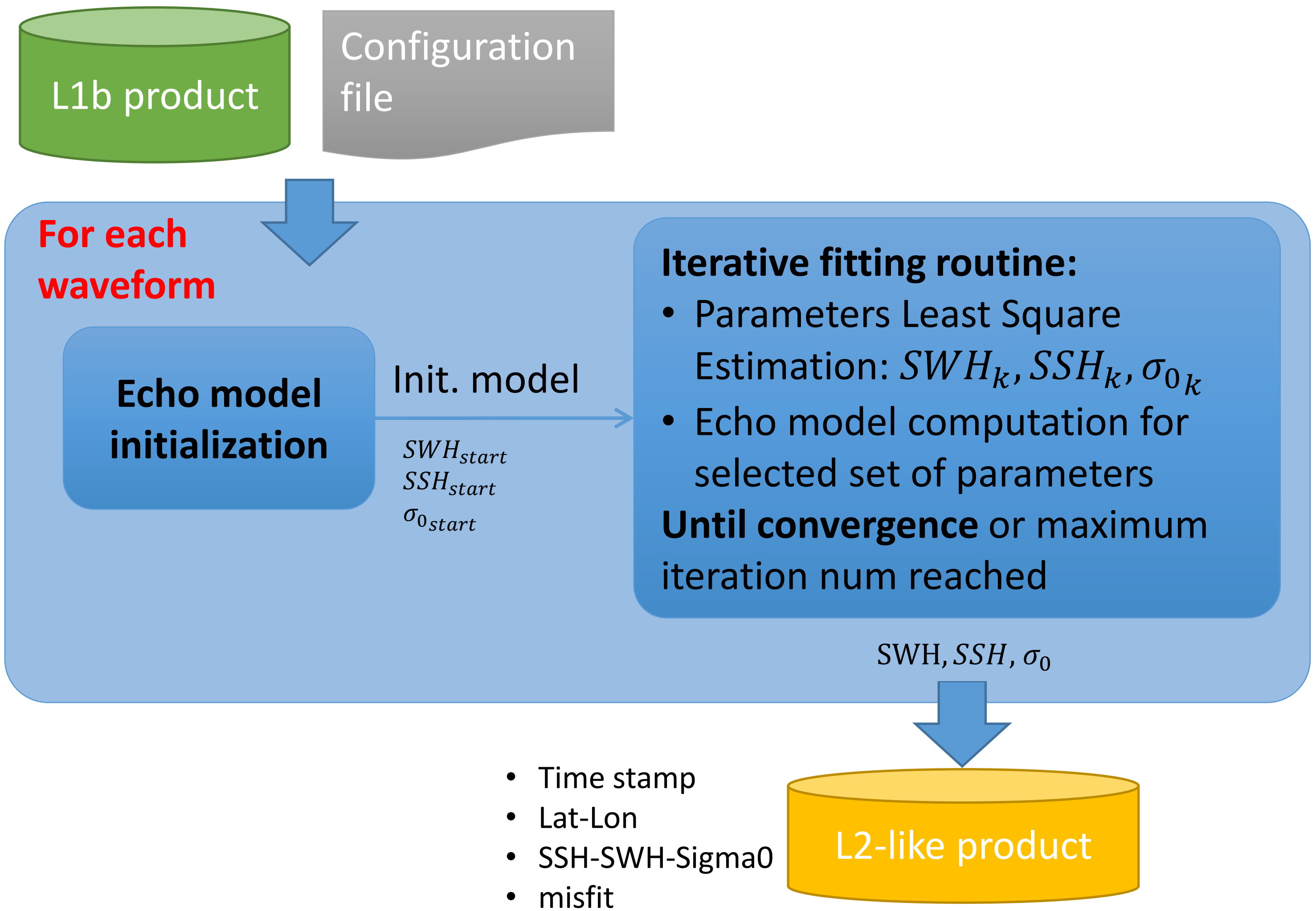

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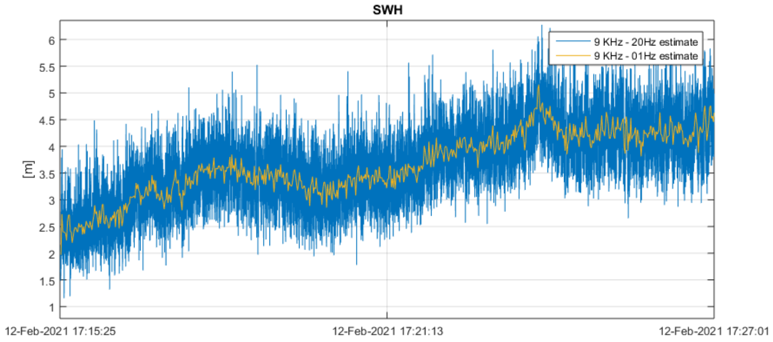
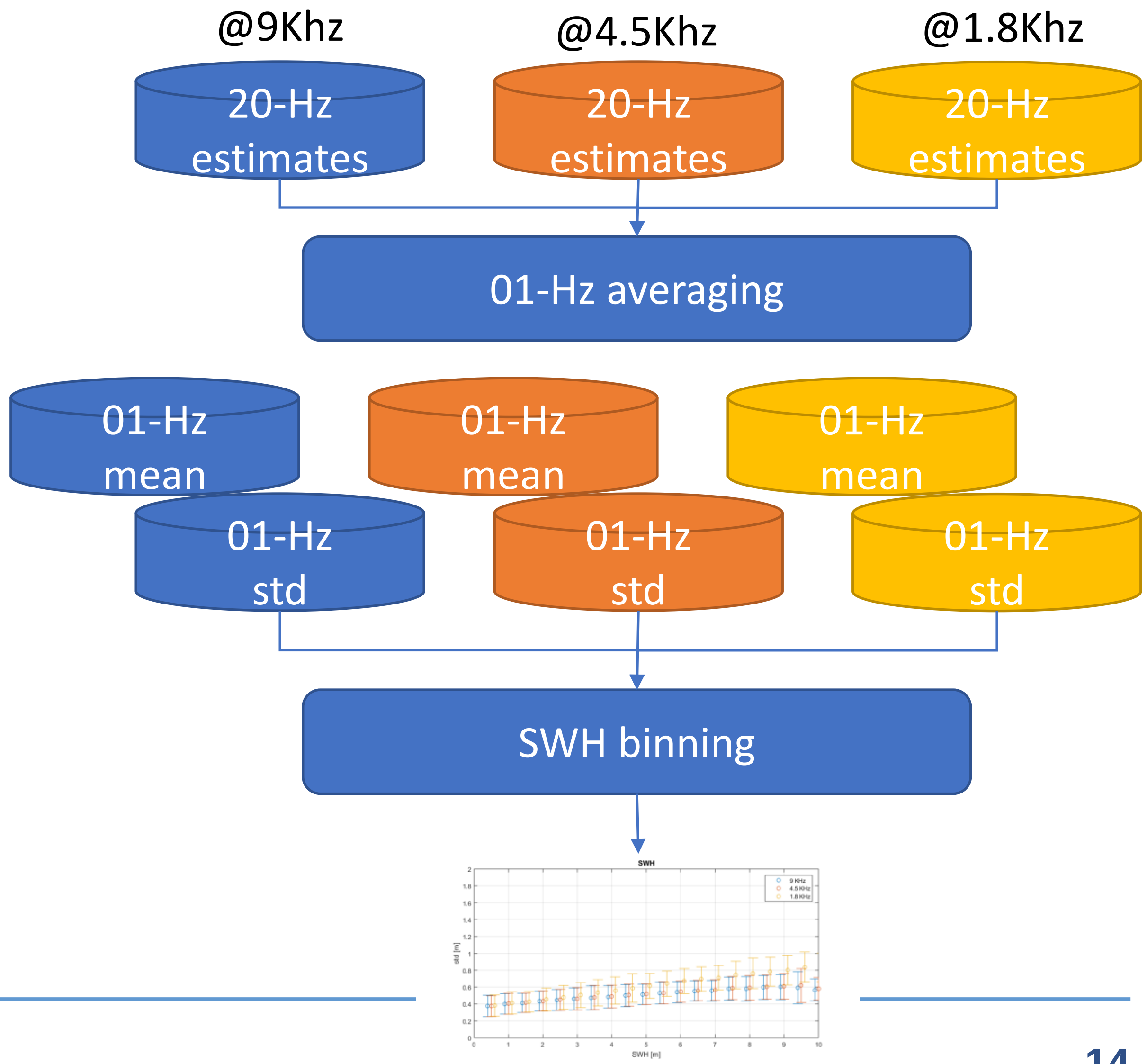
L2 geophysical parameters retrieval analysis

- 01-Hz estimates computed from retracked 20-Hz measurements



- Precision analysis:
  - → 01-Hz std (i.e. standard deviation of 20Hz averaged values around the 01-Hz average) binning w.r.t. SWH value
  - → Binning is performed w.r.t. 01-Hz SWH value for the @9KHz case



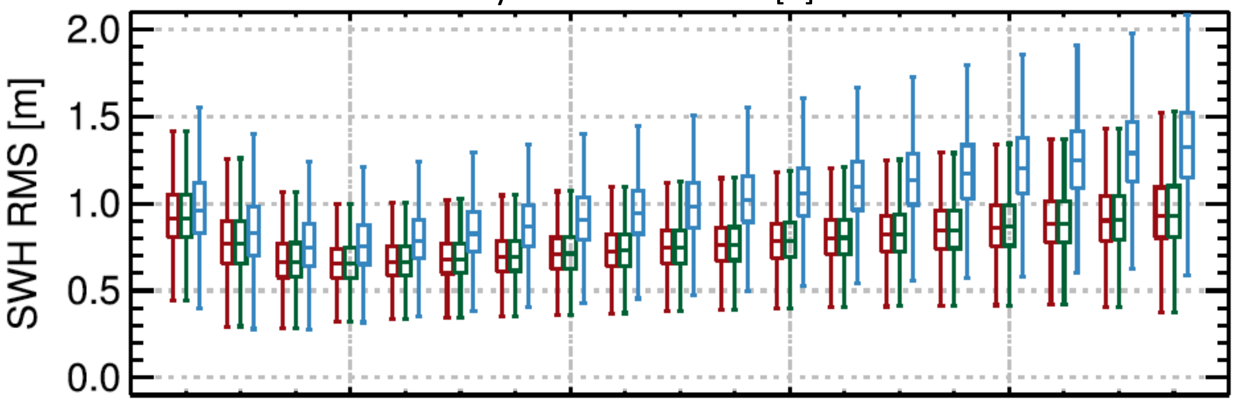
Precision analysis - SWH

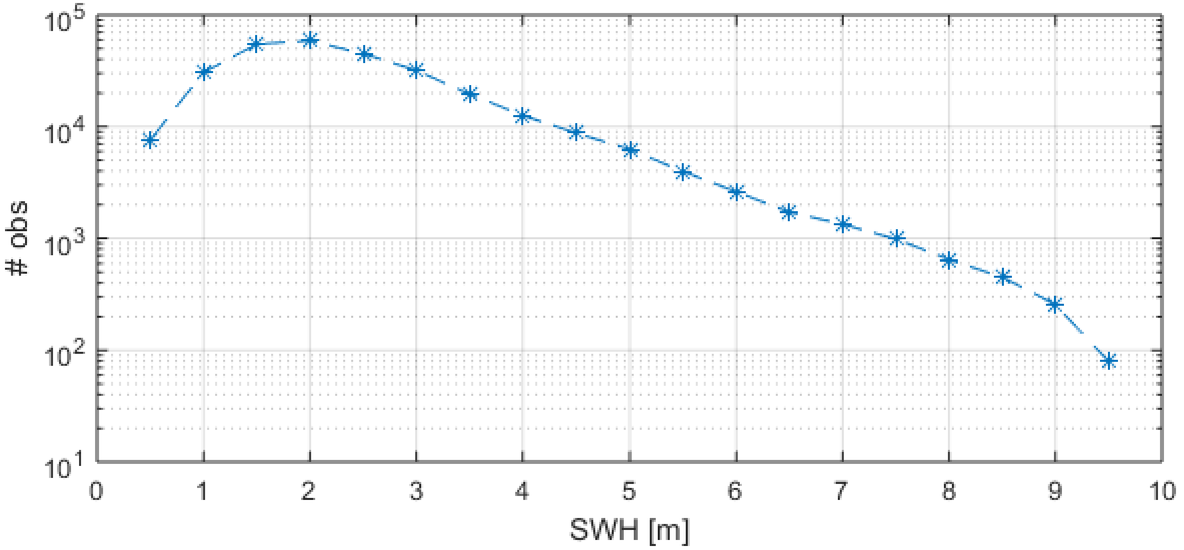
- As expected, a decrease in std is obtained when considering 9-KHz measurements w.r.t 2-KHz ones

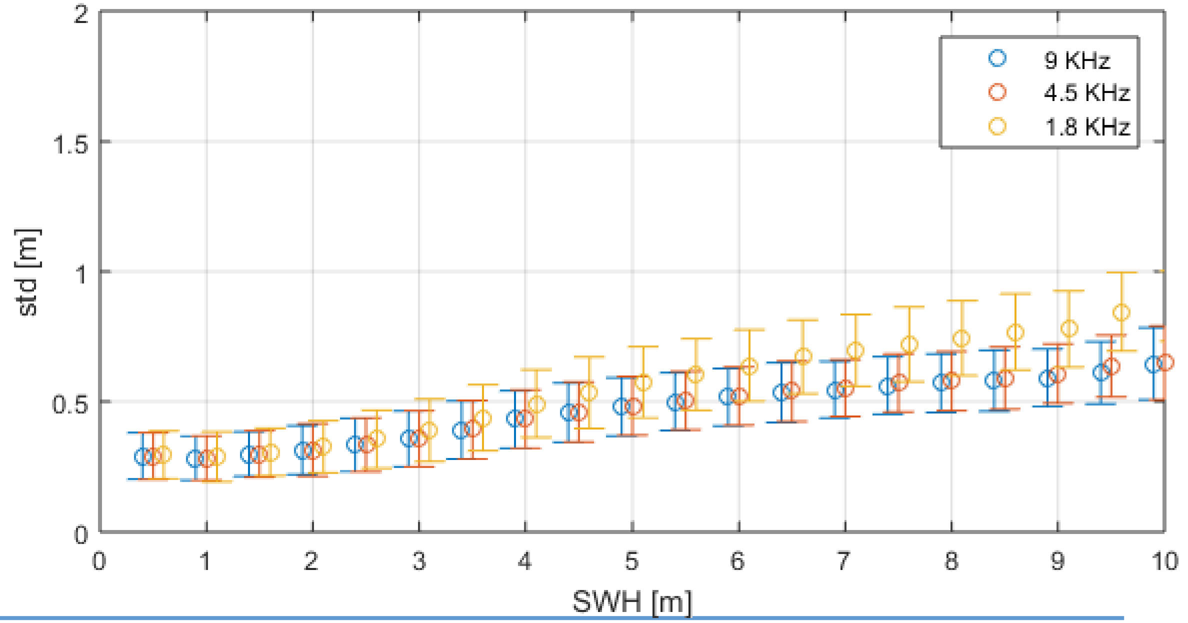
- Larger effect on higher SWH due to faster decorrelation of consecutive pulses

- Similar results from [2]:

Cryosat results from [2]



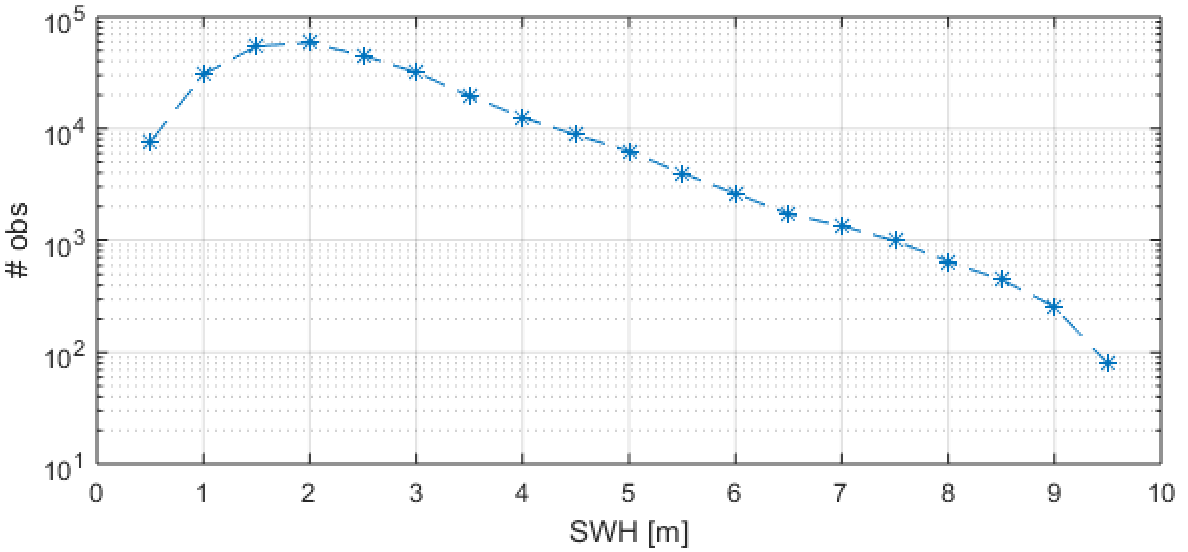


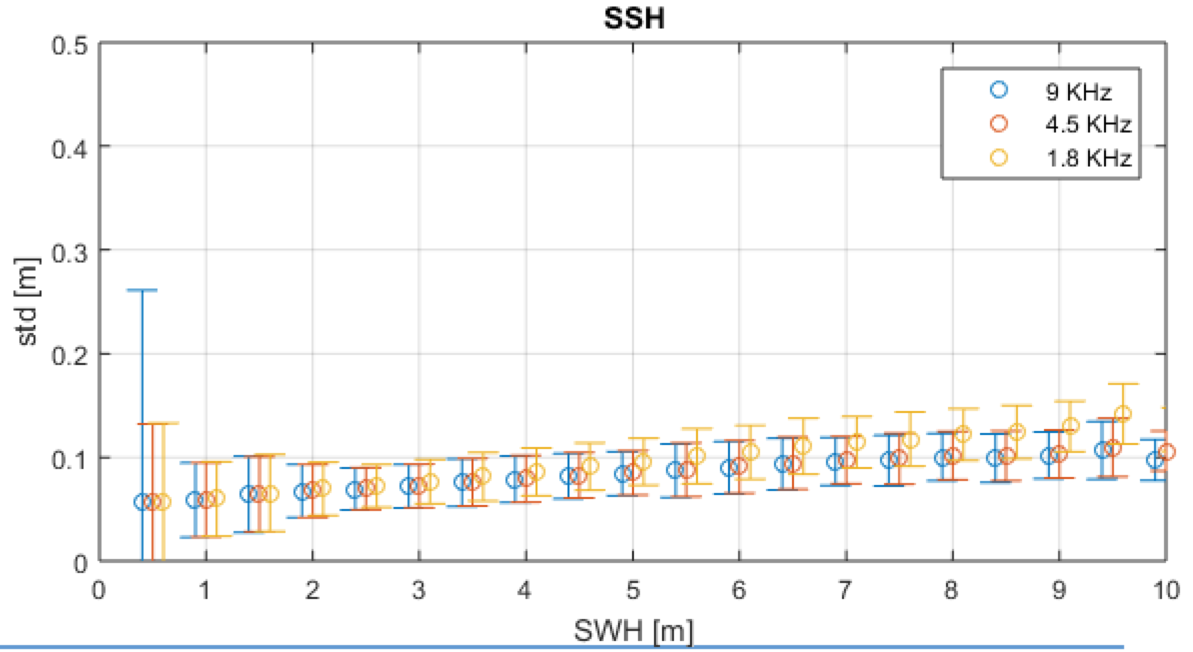


[2] Egido, A., Smith, W.H.F., 2019. Pulse-to-pulse correlation effects in high prf low-resolution mode altimeters. IEEE Trans. Geosci. Remote Sens. 57, 2610–2617.

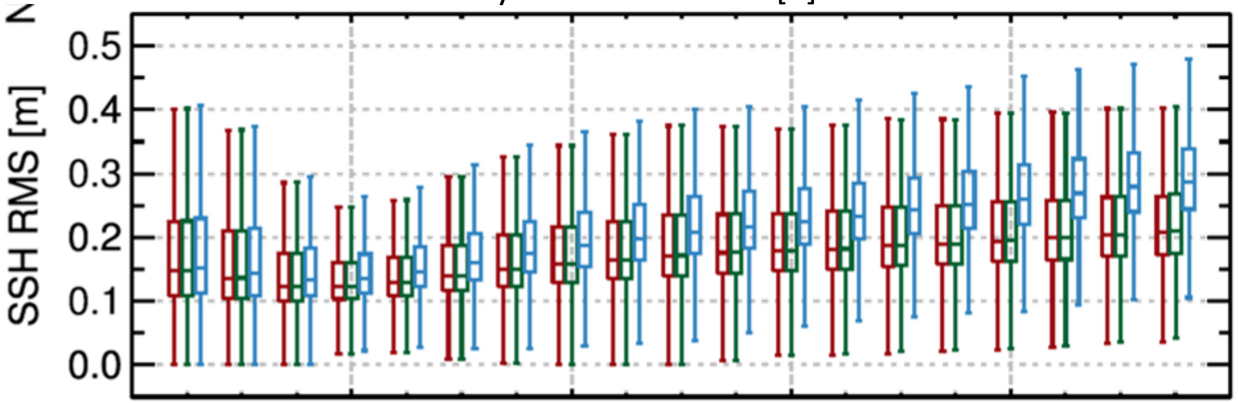
Precision analysis - SSH

- As expected, a decrease in std is obtained when considering 9-KHz measurements w.r.t 2-KHz ones
- Larger effect on higher SWH due to faster decorrelation of consecutive pulses
- Similar results from [2]:





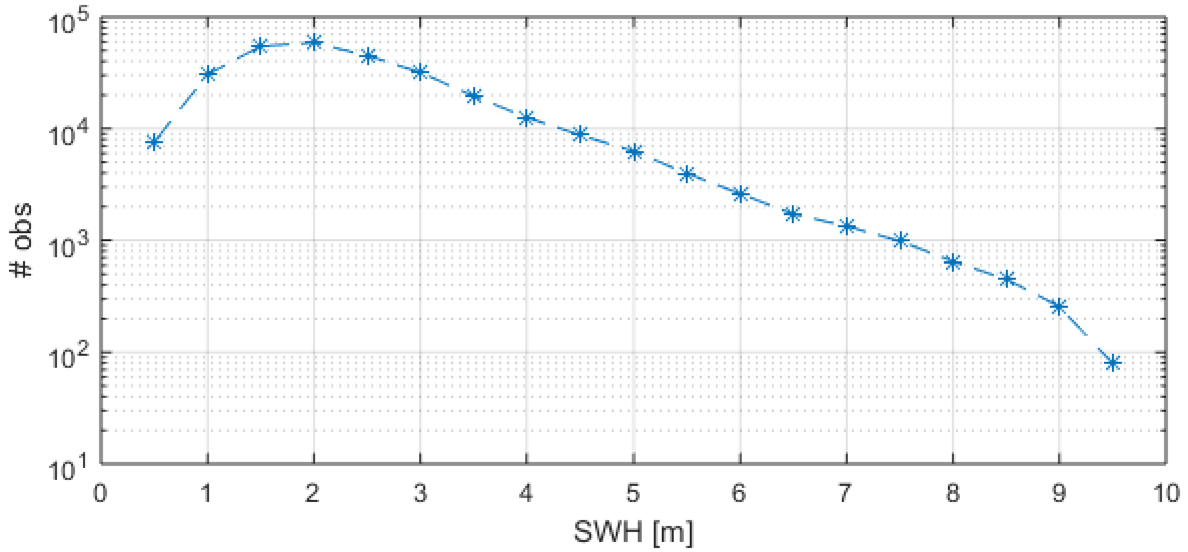
Cryosat results from [2]

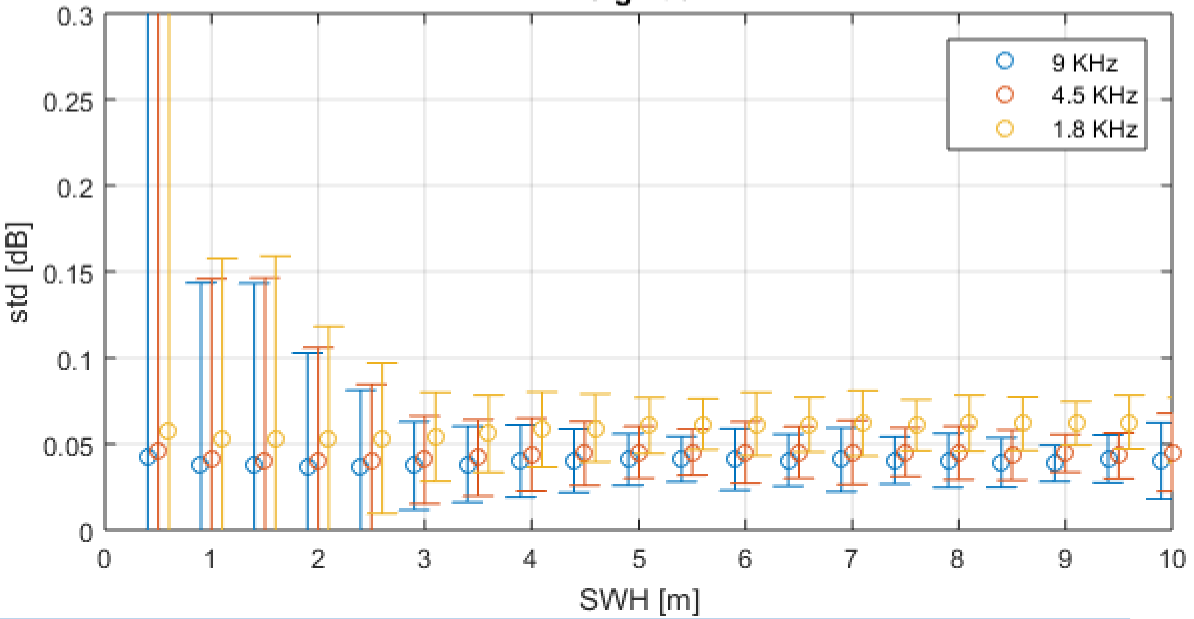


[2] Egido, A., Smith, W.H.F., 2019. Pulse-to-pulse correlation effects in high prf low-resolution mode altimeters. IEEE Trans. Geosci. Remote Sens. 57, 2610–2617.

Precision analysis – σ_0

- As expected, a decrease in std is obtained when considering 9-KHz measurements w.r.t 2-KHz ones
- No visible dependence on SWH
- Similar results from [2]:





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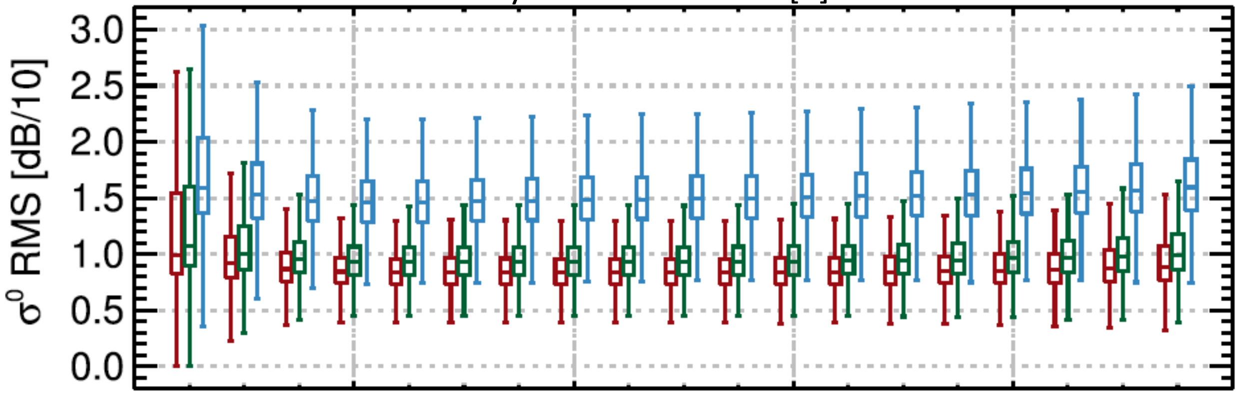
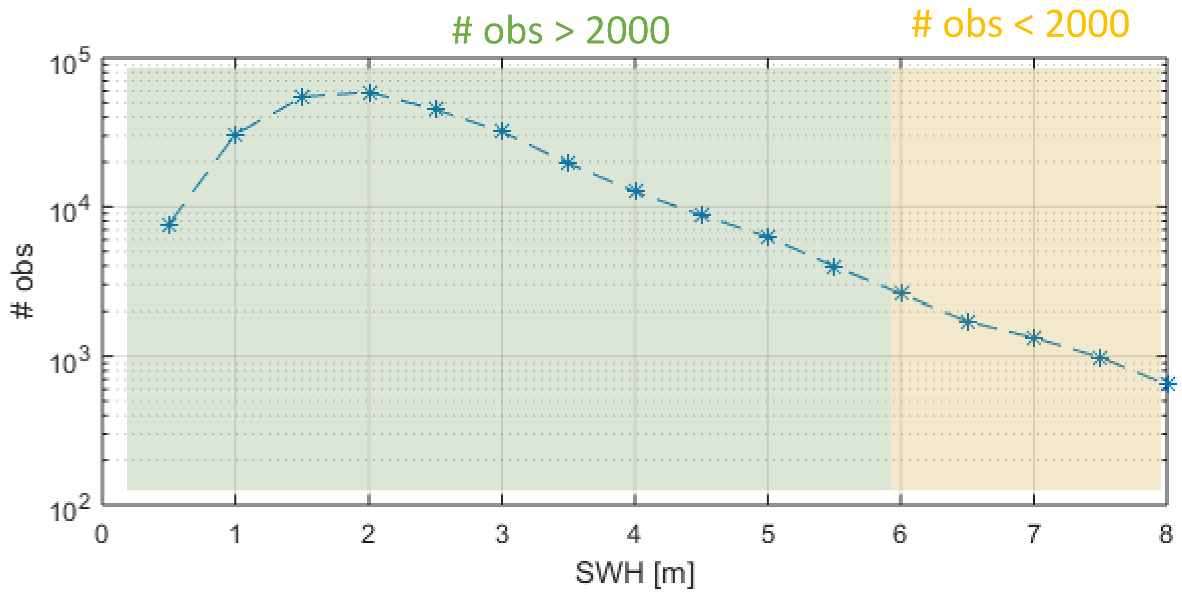
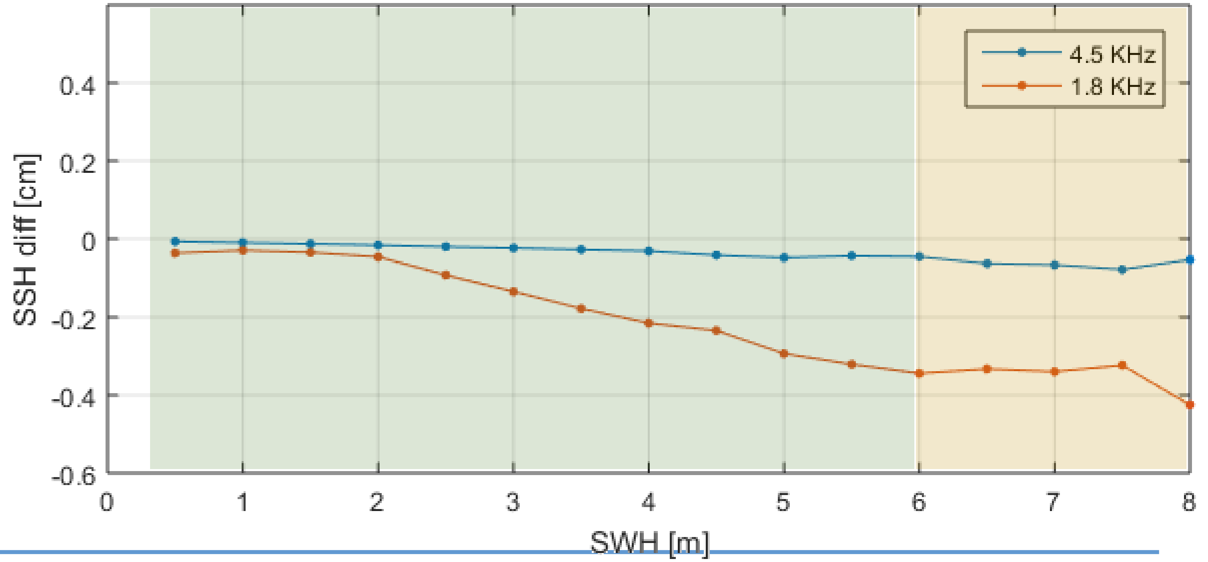


[2] Egido, A., Smith, W.H.F., 2019. Pulse-to-pulse correlation effects in high prf low-resolution mode altimeters. IEEE Trans. Geosci. Remote Sens. 57, 2610–2617.

Bias evaluation – SSH

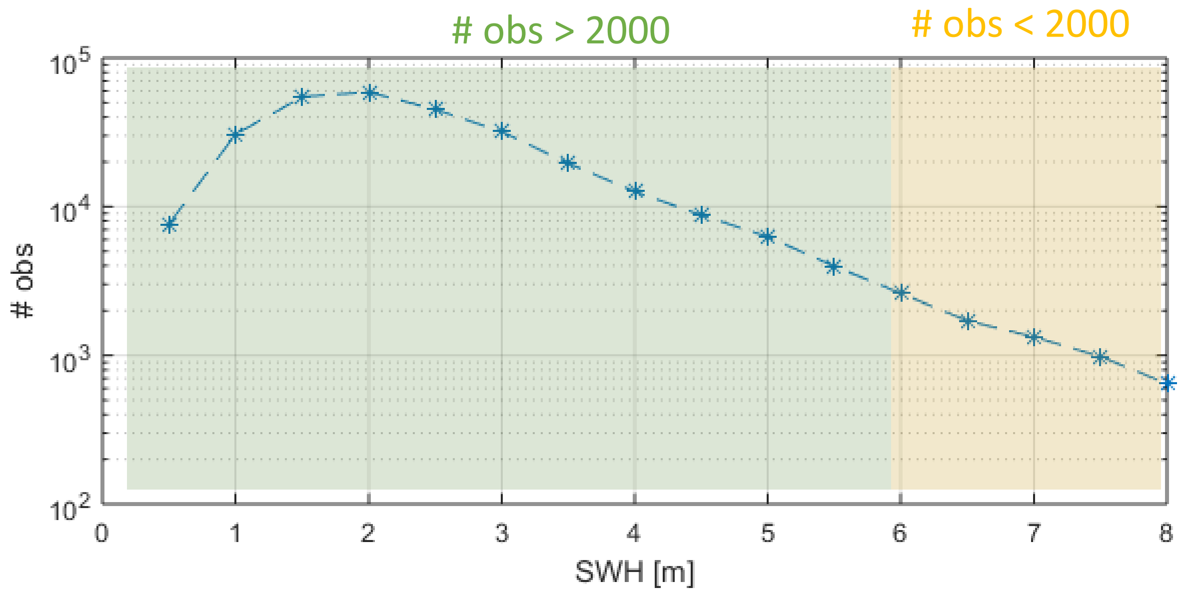
- The bias of the 4.5/1.8 KHz SSH values has been evaluated w.r.t. the 9KHz value
  - → 01Hz averaged values
  - → the difference between the 9KHz and the 4.5 / 1.8KHz retrieved parameters is computed
  - → binning is applied with respect to the 9KHz SWH values
- SSH bias increasing with SWH. Up to -0.45 cm for higher SWH values (less reliable results due to lower sample size)
- These results confirm the need to apply a correction in the processing chain for high PRF LRM altimeter as in S6-MF, for improving the quality of these products.

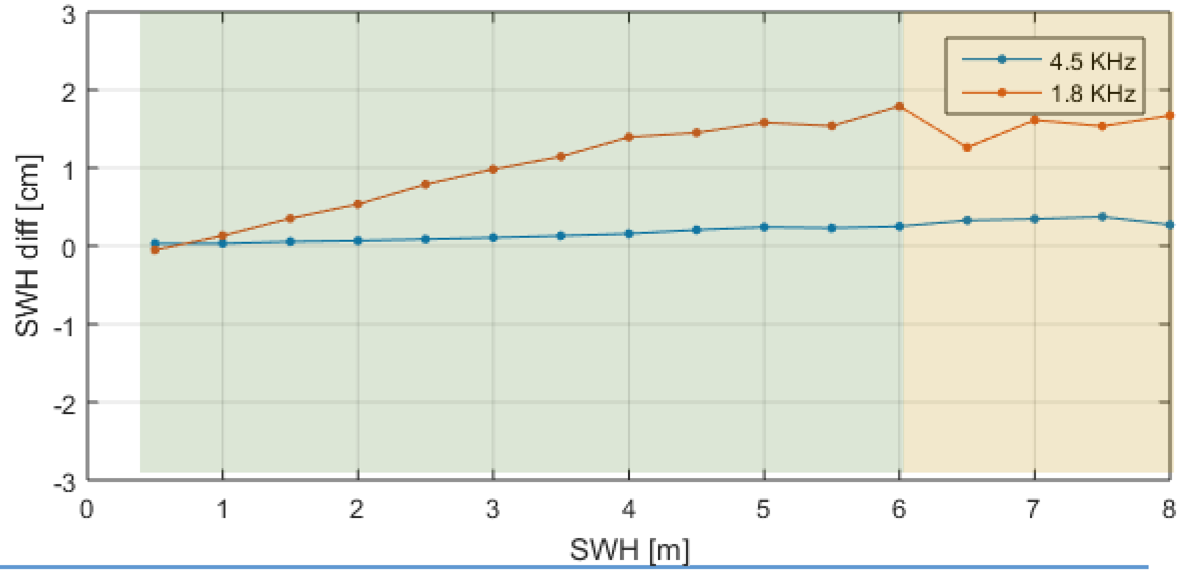




Bias evaluation – SWH

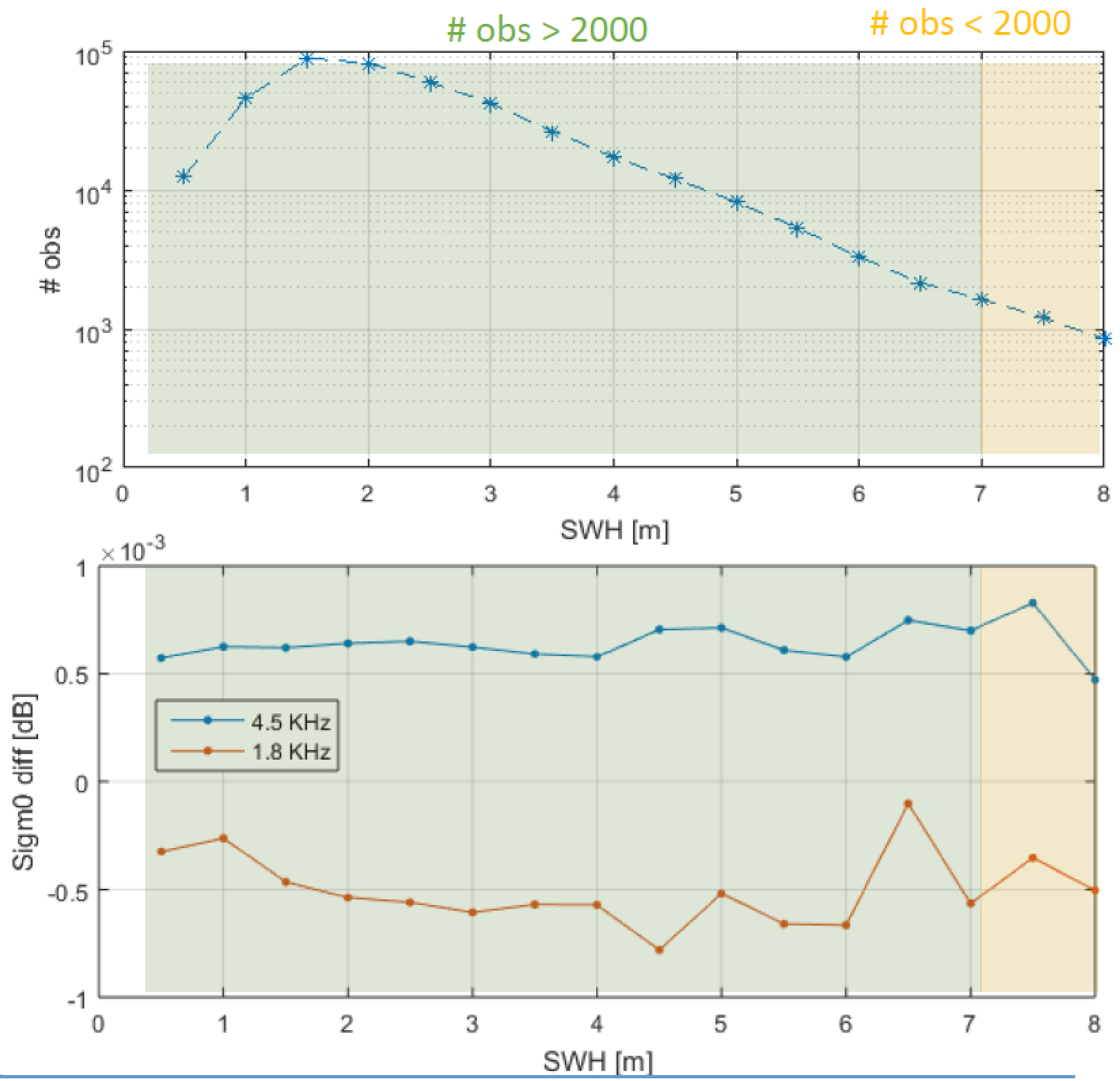
- The bias of the 4.5/1.8 KHz SWH values has been evaluated w.r.t. the 9KHz value
  - → 01Hz averaged values
  - → the difference between the 9KHz and the 4.5 / 1.8KHz retrieved parameters is computed
  - → binning is applied with respect to the 9KHz SWH values
- SWH bias increasing with SWH. Up to 2 cm for SWH values greater than 6m (less reliable results due to lower sample size)
- These results confirm the need to apply a correction in the processing chain for high PRF LRM altimeter as in S6-MF, for improving the quality of these products.





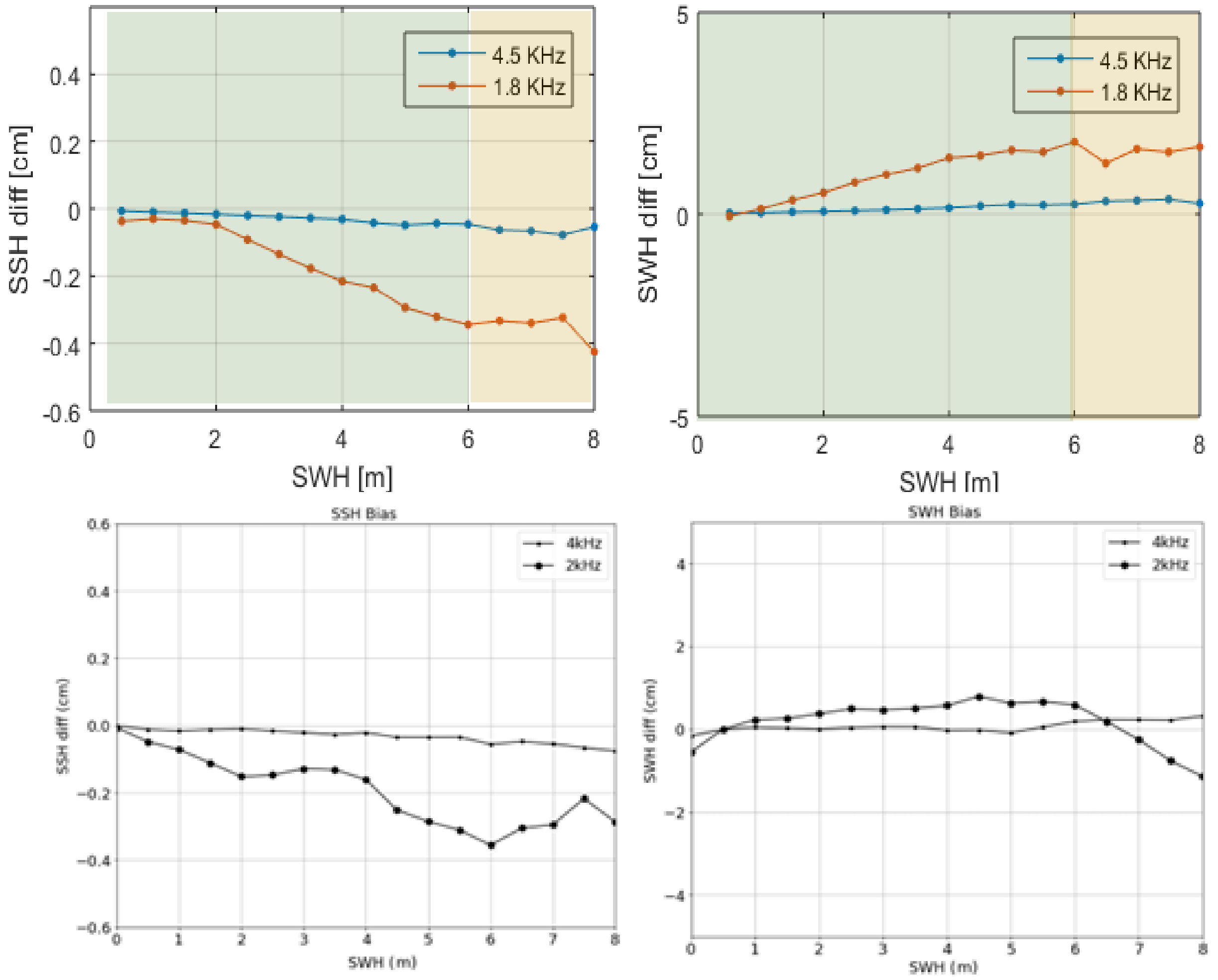
Bias evaluation – Sigma0

- The bias of the 4.5/1.8 KHz Sigma0 values has been evaluated w.r.t. the 9KHz value
  - → 01Hz averaged values
  - → the difference between the 9KHz and the 4.5 / 1.8KHz retrieved parameters is computed
  - → binning is applied with respect to the 9KHz SWH values
- Sigma0 bias show little/no dependence on SWH. Very small (ad opposite) values (+0.0007 dB and -0.0005 dB) found for the different processing configurations



Bias evaluation – SWH and SSH

- The bias of the 4.5/1.8 KHz SSH and SWH has been evaluated w.r.t. the 9KHz value
  - → 01Hz averaged values
  - → the difference between the 9KHz and the 4.5 / 1.8KHz retrieved parameters is computed
  - → binning is applied with respect to the 9KHz SWH values
- SSH bias increasing with SWH. Up to -0.45 cm SWH values < 6 m
- SWH increasing with SWH. Up to 2 cm for SWH values greater than 6m
- These results confirm the need to apply a correction in the processing chain for high PRF LRM altimeter as in S6-MF, for improving the quality of these products.



Preliminary confirmation obtained from CNES analysis (by Claire Maraldi) during commissioning phase using MLE4 retracker (Dinardo et al., 2022)

Conclusions

- As for Cryosat-2 and Sentinel-3 missions (Egido and Smith, 2019; Clerc et al., 2020), **pulse-to-pulse correlation effects were analyzed** theoretically for the S6-MF mission (using ENL methodologies), then characterized with real LR data **for different pulse-decimation configurations (PRF) and sea-state conditions**

- ENL analysis confirms the higher number of looks gained with a 9kHz PRF, even when partially correlated waveforms are taken

- **Increasing the PRF** improves the precision of the measurements but **introduces estimations biases due to the use of a non-optimal estimation method** (least-squares estimator that does not account for the varying noise statistics across the waveform). Biases could be corrected **empirically using LR LUTs** (or Maximum Likelihood Estimators) to ensure data continuity of this mode with previous Jason time series

Paper submitted

"Exploiting the Sentinel-6 Michael Freilich Equivalent Number of Looks for Sea State Applications"

Table of contents:

- Introduction
- Pulse-to-pulse correlation model and ENL
- Power correlation analysis
- ENL analysis
- Discussion
- Conclusions


MDPI

Article

Exploiting the Sentinel-6 Michael Freilich Equivalent Number of Looks for Sea State Applications

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Abstract: Sentinel-6 Michael Freilich (S6-MF) is the first altimeter operating in a continuous high-rate pulse mode, i.e. interleaved mode. This ensures the generation of Low-Resolution (LR) mode measurements with a Pulse Repetition Frequency (PRF) of ∼ 9 kHz (variable along the orbit) for Ku-band as well as the processing of High Resolution (HR) echoes on ground. This operating mode provides an elevated number of highly correlated single looks with respect to the fewer number, weakly correlated echoes of Jason-3 altimeter. A theoretical model has been exploited to envisage the correlation properties of S6-MF pulse limited waveform echoes for different sea-state conditions; after that, the model has been validated by comparison with the Equivalent Number of Looks (ENL) empirically estimated from real data. The existence of a significant dependence of the statistical properties in range has been verified, and its impact on the precision and on the accuracy in the estimation of the geophysical parameters has been assessed in case of the 9 kHz PRF of S6-MF. Finally, by applying pulse decimation before the multilook processing, an investigation on new processing techniques has been performed, aimed at exploiting the higher ENL in S6-MF low-resolution mode waveforms.

Keywords: Sentinel-6; Jason-3; Delay-Doppler altimeter; Sea-state; geophysical parameters.

1. Introduction

The radar altimetry measures the two-way travel time of a radar pulse between the satellite antenna and the Earth's surface at the nadir of the spacecraft. This measurement is performed through the collection of the waveforms bounced back by the reflecting facets within the altimeter footprint. While the traditional pulse-limited radar altimeters were used to collect information on the sea level and slope [1], the delay-Doppler concept [2], thanks to the higher along-track resolution, has been used to get information of the shape, balance velocities and contribution to sea level of the Earth's large ice sheets [3,4] as well as marine ice thickness [5].

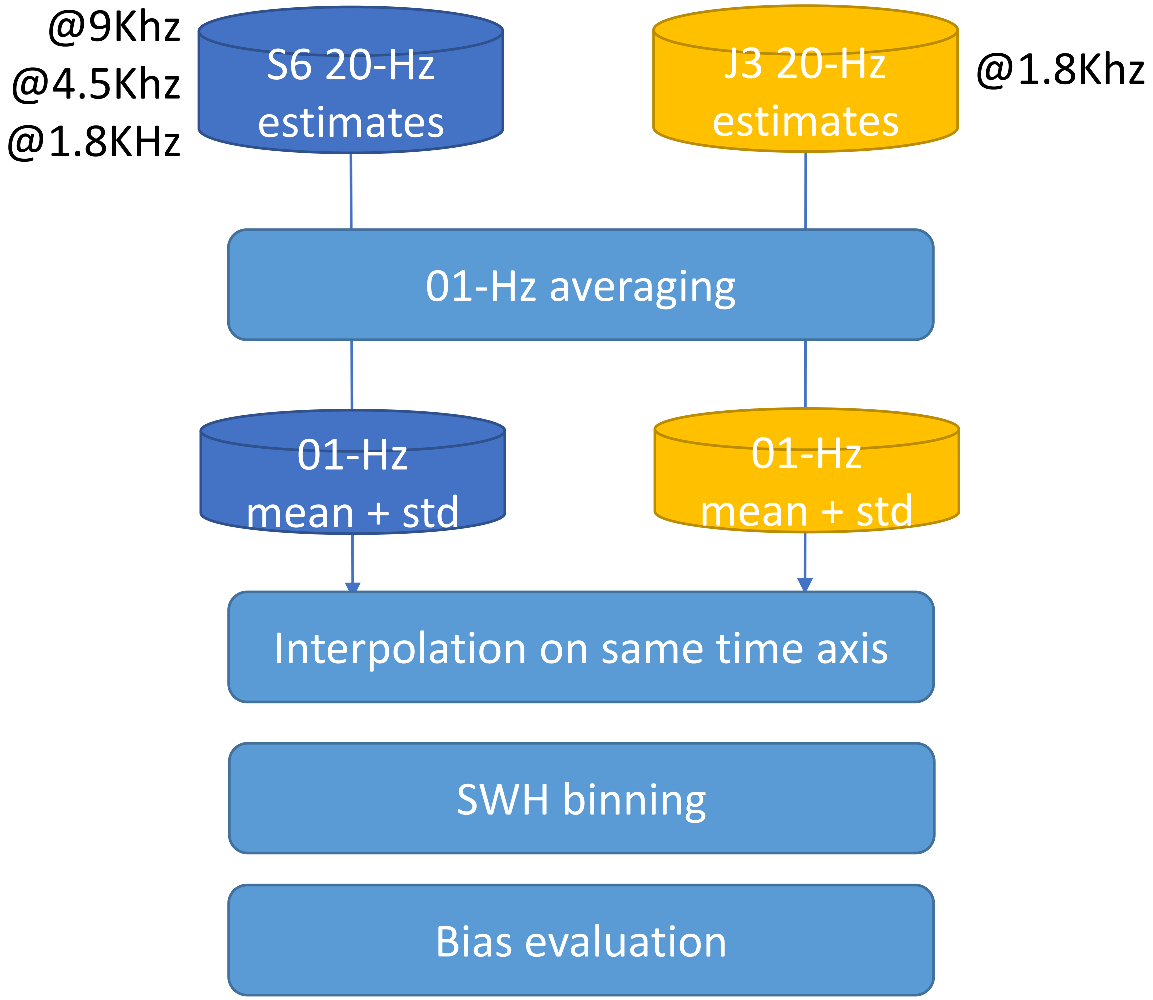
Radar echoes are intrinsically affected by noise speckle, due to incoherent summation of many randomly phased scatterers from the surface. Multilooking, i.e. incoherent averaging of single look echoes, is performed in order to achieve a speckle reduction. Delay/Doppler (DD) altimetry has shown to be more effective in reducing the speckle since a higher number of looks than in the conventional radar altimeter is gained. This is due also to the increasing Doppler bins, as explained by Raney in [6].

However, according to the correlation among the averaged single looks, the Effective Number of Looks (ENL) is reduced. By definition, the ENL is the number of independent observations that are obtained by the radar from a distributed target per unit of time. The ENL can be achieved

Thank you

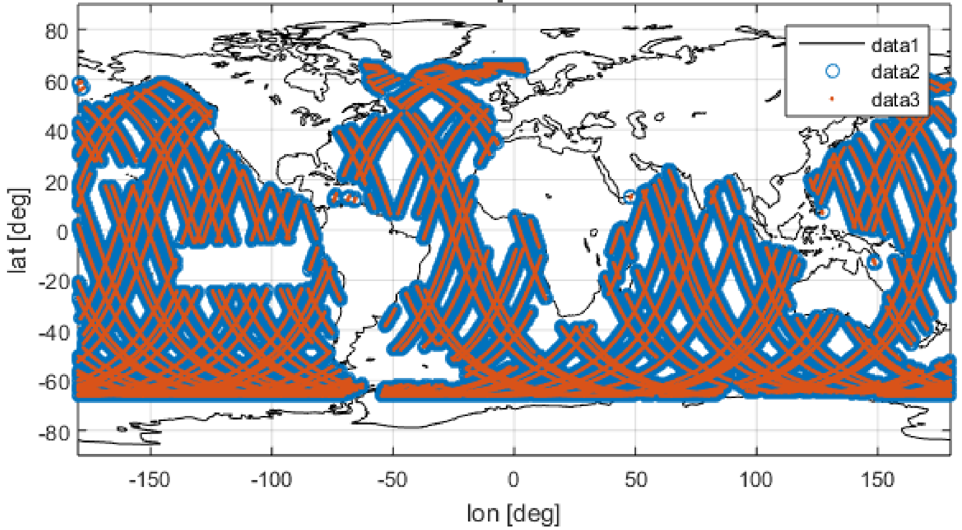
Bias evaluation – SWH and SSH

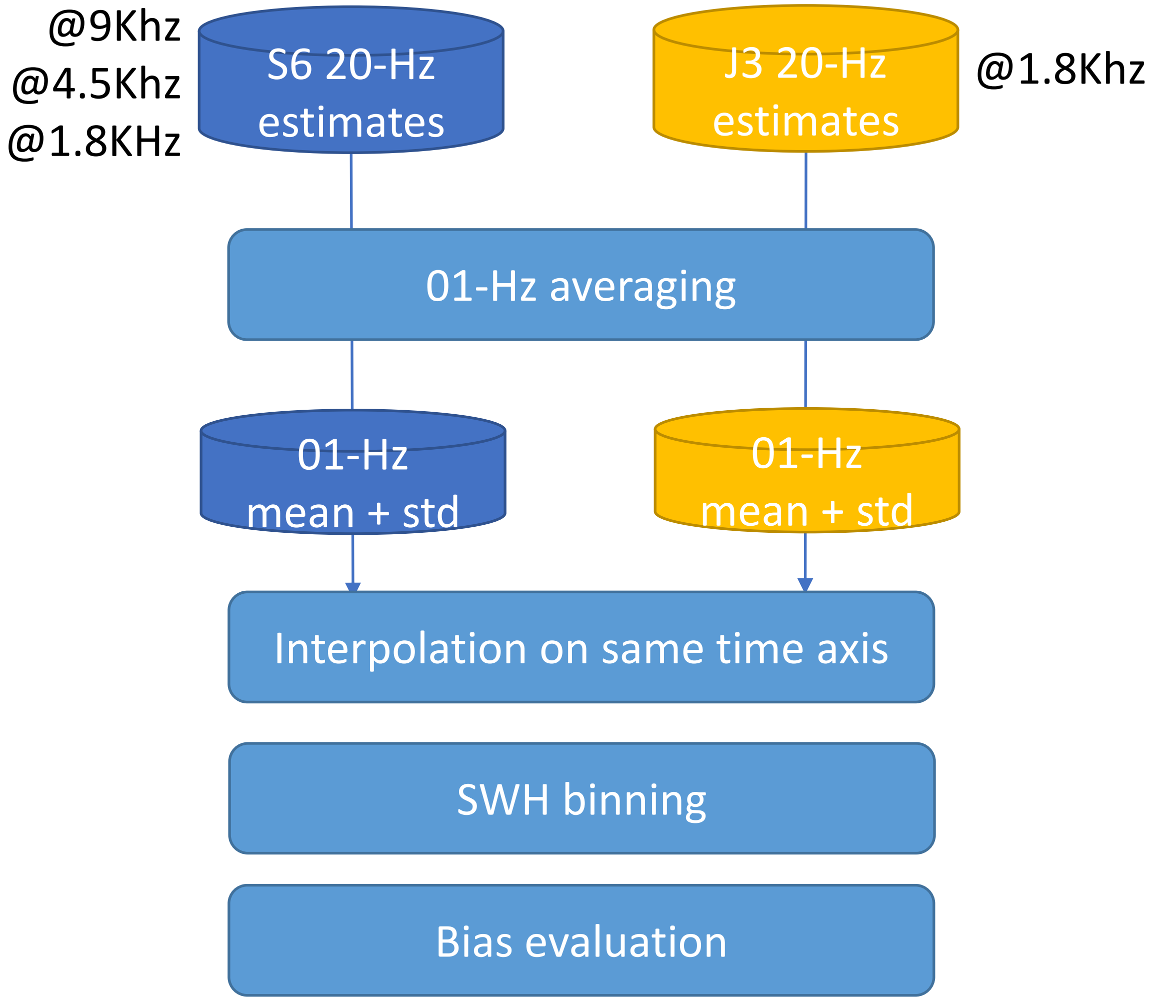
- Comparison between:
  - → Sentinel-6 L2 data (at different multilooking rates) from Aresys retracker
  - → Jason-3 L2 data from Aresys retracker



Bias evaluation – SWH and SSH

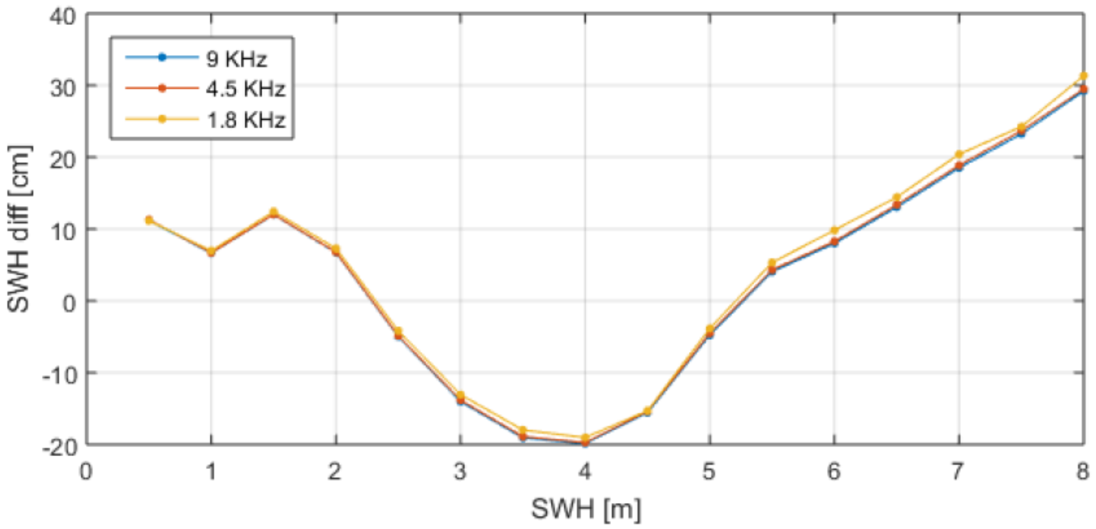
- Comparison between:
  - → Sentinel-6 L2 data (at different multilooking rates) from Aresys retracker
  - → Jason-3 L2 data from Aresys retracker
- Interpolation on same geographical location axis (accounting for time f observation) to obtain 1-to-1 correspondence of 01Hz values:





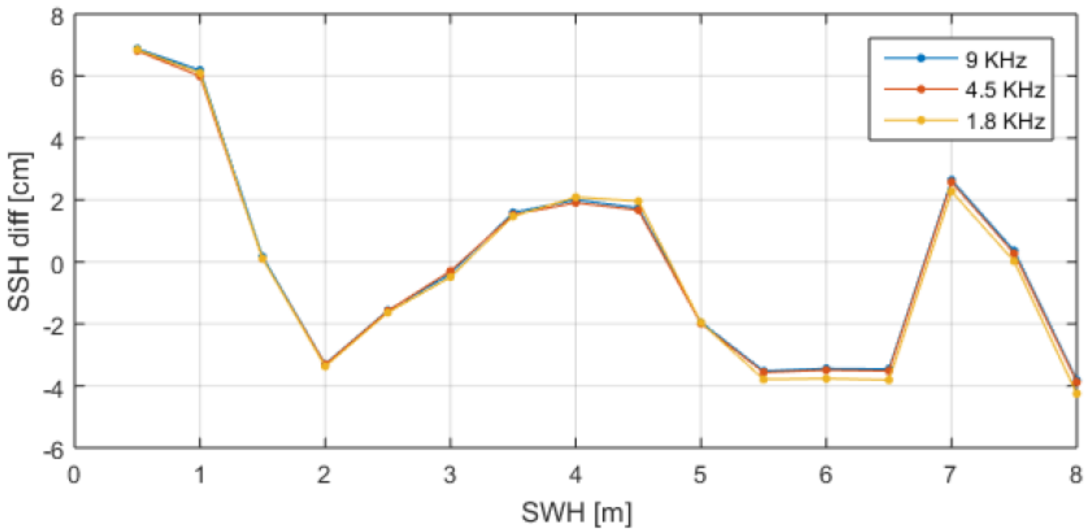
Bias evaluation – SWH

- Comparison between:
  - → Sentinel-6 L2 data (at different multilooking rates) from Aresys retracker
  - → Jason-3 L2 data from Aresys retracker
- A mean bias of 36cm has been removed from data before comparison
- Differences ranging from -20cm to +30 cm measured for SWH, with a strong, non monotonic dependence on SWH



Bias evaluation – SSH

- Comparison between:
  - → Sentinel-6 L2 data (at different multilooking rates) from Aresys retracker
  - → Jason-3 L2 data from Aresys retracker
- A mean bias of 1.07m has been removed from data before comparison
- Differences ranging from -4cm to +6 cm measured for SSH, with a non monotonic dependence on SWH



Bias evaluation – Sigma0

- Comparison between:
  - → Sentinel-6 L2 data (at different multilooking rates) from Aresys retracker
  - → Jason-3 L2 data from Aresys retracker
- A mean bias of 0.85dB has been removed from data before comparison
- Very small bias, ranging from 0.04 dB to +0.06 dB cm, measured for Sigma0, with a monotonic dependence on SWH