Time and Frequency Domain Numerical SAR Retracking for Sentinel-6: First results prior to the S6PP Implementation

Salvatore Dinardo (CLS)
Thomas Moreau (CLS)
Claire Maraldi (CNES)
Francois Boy (CNES)
Nicolas Picot (CNES)

Context and Summary :

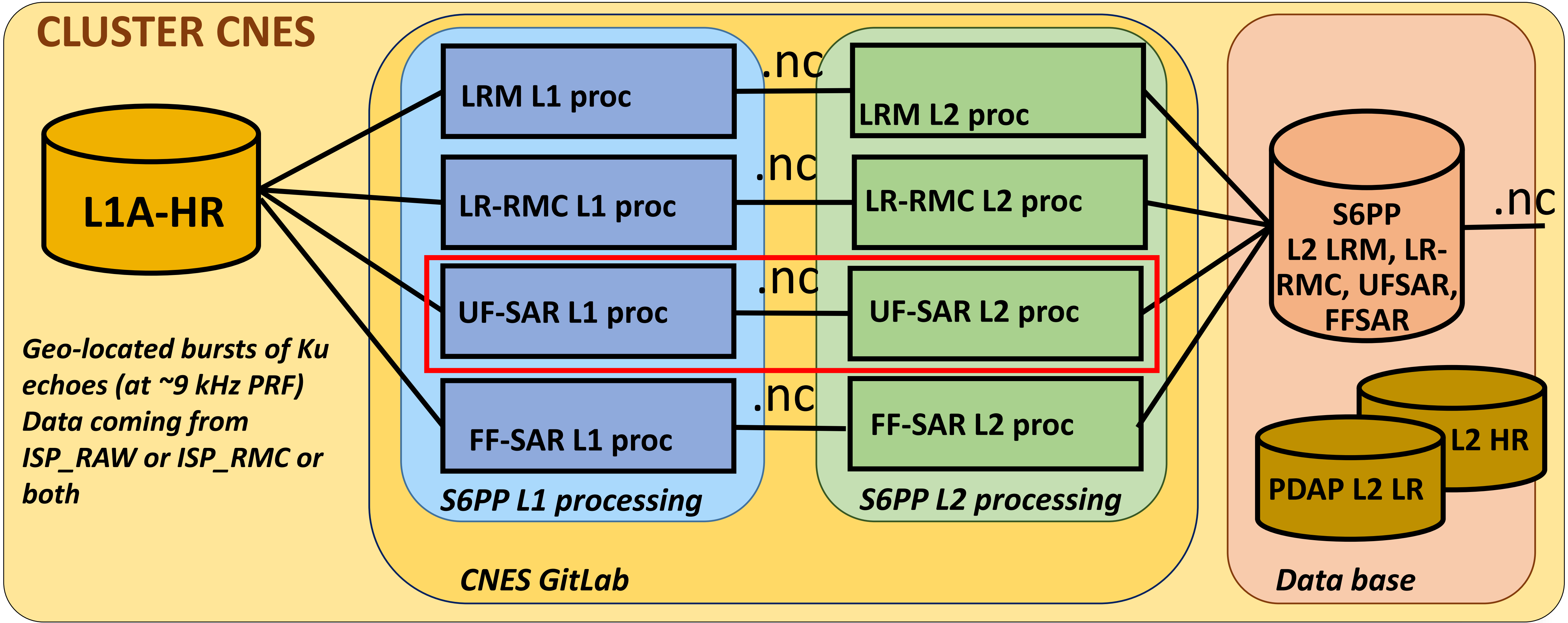
Main objective of this study is to address main concerns of the upcoming Sentinel-6 reference mission in :

- improving the quality of altimeter products
- continuing the JASON mission series in monitoring global sea levels

On that basis, the CNES initiative was to promote the development of innovative and enhanced processing algorithms that meet these requirements and which operational agencies may benefit in a second stage.
An initiative also involving a joint CNES/EUMETSAT/NOAA expert working group

S6PP Development :

CNES contracted CLS for the development of the Sentinel-6 Processing Prototype (S6PP).
S6PP will be a multi-chain (LRM,LR-RMC,FF-SAR,UF-SAR) processor. Here, we address the novelties to be implemented in the UF-SAR chain (SAR RAW and SAR RMC).



S6PP UF-SAR CHAIN:

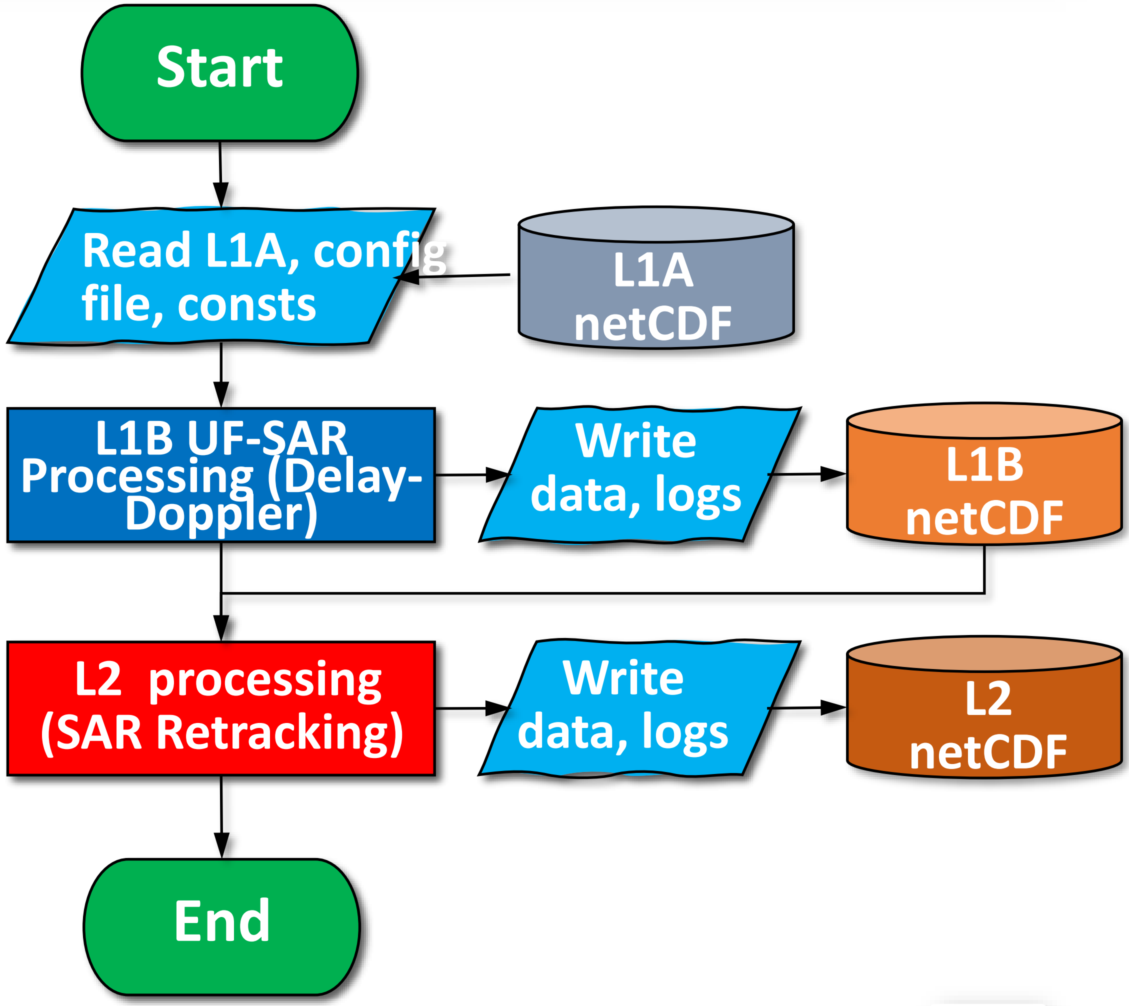
Capacity to process both SAR RAW and SAR RMC L1A data.

Strong heritage from CLS SMAP Processor (**REF1**)

At L1B, a classic Delay-Doppler is carried out with:

- Exact Beam Steeering
- Range Walk Correction
- Beam Formation by DFT or CZT algorithm (**REF2**)
- Exact Zero-Masking
- Z/P Factor of 2
- Posting rate at 20 Hz and 80 Hz

At L2, a numerical UF-SAR retracking is proposed in frequency-domain (C. Buchaupt et al., 2018) and in time-domain (S. Dinardo et al. in prep.) with Levenberg-Marquardt algorithm minimization solver



REF1: *Exploiting the Sentinel-3 tandem phase dataset and azimuth oversampling to better characterize the sensitivity of SAR altimeter sea surface height to long ocean waves (2020):* P. Rieu T. Moreau, E .Cadier, M. Raynal, S. Clerc, C. Donlon, F. Borde, F. Boy, C. Maraldi, Advances Space Research, https://doi.org/10.1016/j.asr.2020.09.037

REF2: P. Guccione, "*Beam Sharpening of Delay/Doppler Altimeter Data Through Chirp Zeta Transform*," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 46, no. 9, pp. 2517-2526, Sept. 2008, doi: 10.1109/TGRS.2008.918863

Impact of the Range Walk for S6 and implementation in the S6PP

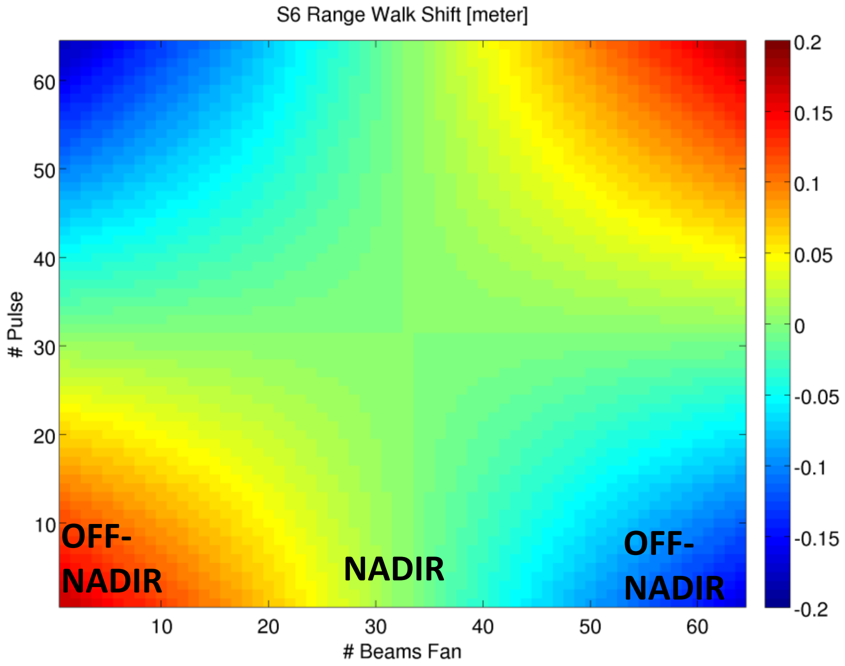
Recently Application of the Range Walk has been identified as **crucial** for the stability of the altimeter range measurements in SAR mode for S3 (J.Aublanc et al., 2020 #7 S3 ESL CM Meeting)

Moreover, Range Walk corrects for small biases in SWH (at cm level) and SSHA (at mm level or less) in SAR mode (Scagliola et al. 2019; Moreau et al, OSTST 2018)

The magnitude of the range walk correction is not the same for all the SAR missions as it depends on satellite velocity and on Pulse Repetition Interval

Hence, application of the Range Walk will improve the consistency between mono-mission SAR and PLRM and between different SAR Altimetry missions, on top of being necessary for range stability in case of strong PTR distortions

The magnitude is very small for nadiral Beams but is big (up to 20 cm) for the very off-nadir beams (below figure)



Range Walk has been implemented in processing S6 GPP data in order to assess preliminarily the impact on S6 Mission

Range Walk requires exact beam-steering in order to be applied.
For the beam-formation, alternatives to FFT (as DFT and CZT) are currently under assessment for sake of CPU time saving

General Equation of SAR Altimetry DDM Model (from Ray et. al, 2015)

The general (time-domain) DDM Model is the solution of the integral equation (Ray et al. 2015) :

$$P_{k,l} = \int_{-\infty}^{+\infty} dz \cdot PDF_z(z) \cdot \int_{-\infty}^{+\infty} dx \cdot \int_{-\infty}^{+\infty} dy \cdot \frac{\lambda_0^2 \cdot G^2(x,y) \cdot \sigma_0(x,y)}{4 \cdot \pi \cdot r^4(x,y,z)} \cdot \left|C_{k,l}(x,y,z)\right|^2$$

With $\left|C_{k,l}(x,y,z)\right|^2$ is the Instrument Impulse Power Response after Range Cell Migration Correction (RCMC) and Doppler Centroid Correction (DCC) which can be expressed as:

$$\left|C_{k,l}(x,y,z)\right|^2 = N_p \cdot N_b \cdot PTR_{range} \cdot PTR_{azimuth} \approx \left[\sqrt{N_p} \cdot \sqrt{N_b} \cdot sinc(u) \cdot sinc(k - k_l)\right]^2$$

Usually, in the SAR numerical retracker, the Azimuth (along-track) PTR is approximated by sinc^2 (as above), approximation being valid in case of S3 and CS-2.

In case of Sentinel-6, instead, we are proposing to compute the along-track PTR numerically by FFT.

This can be done either in time-domain (S. Dinardo 2021, in preparation) or in the frequency-domain (as in C. Buchaupt et al., 2018)

The range PTR will be assumed to be sinc^2 in the early stage of the mission while the Real range-PTR (from CAL1 SAR RAW or from CAL-ECHO) will be used in a second moment

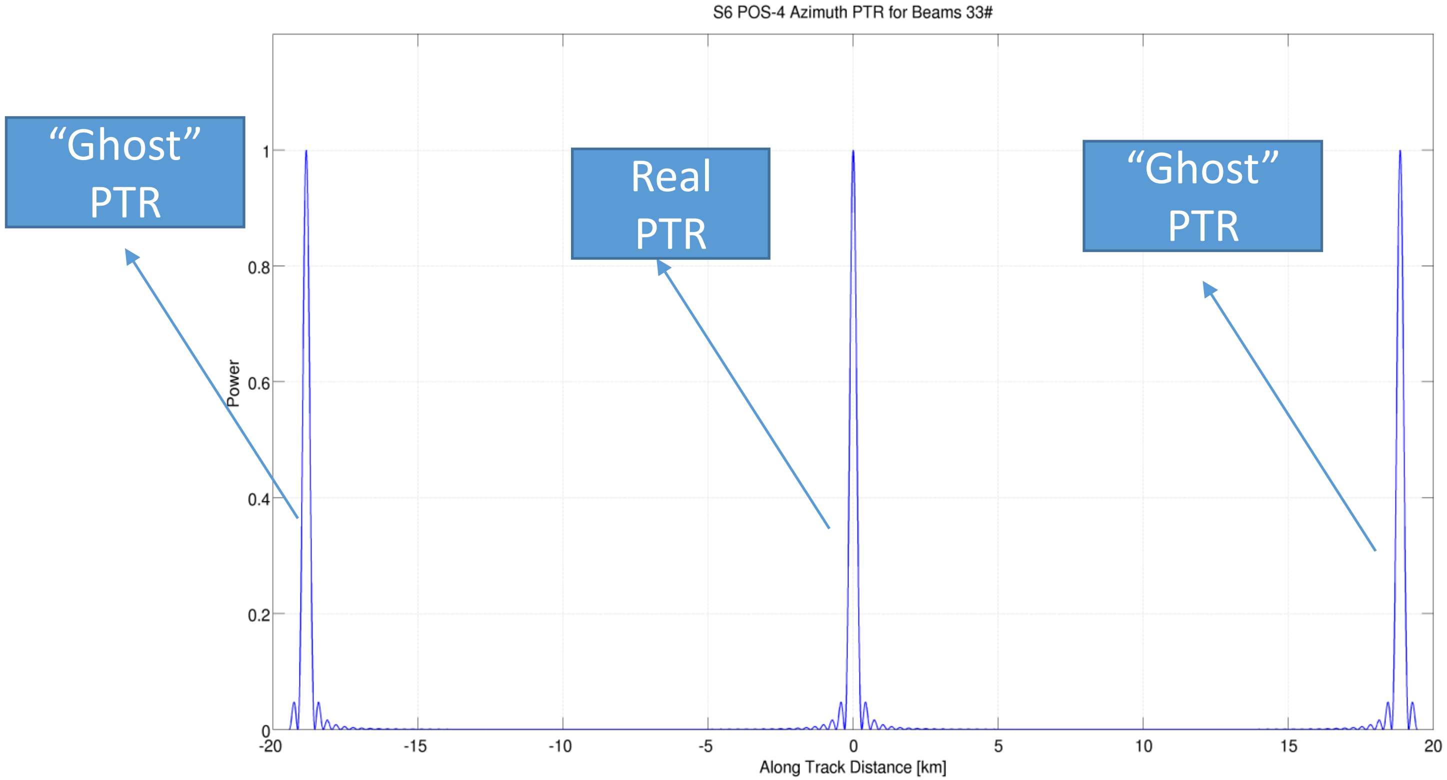
The usage of real range-PTR in convolutional model will “safeguard” from any range PTR shape distortion along the mission which might compromize the range stability of the measurements (J.C. Poisson/S.Dinardo/M.Scagliola OSTST 2020) and will avoid the computation of LUT

Numerical (Time-Domain) Retracking: Application to Sentinel-6 GPP Data

A numerical retracking (time-domain) was used to retrack the waveforms (with and without range walk) from GPP L1A data

In this numerical retracking for S6, ambiguities are natively modelized in the Delay-Doppler Map (DDM) since an “ambiguous” azimuth PTR (built by FFT) has been used in the SAR convolutional integral

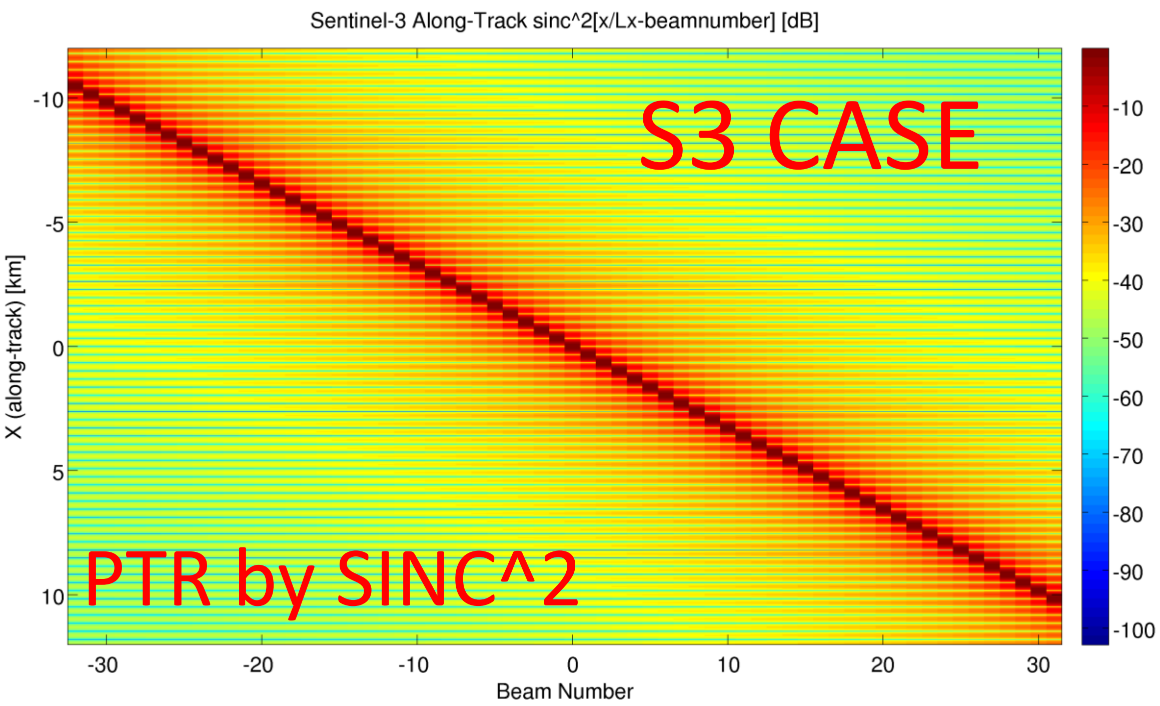
Using this approach, it is not necessary anymore to mask ambiguities out in the data using a pre-computed mask (as done in S6 GPP/PDAP side)

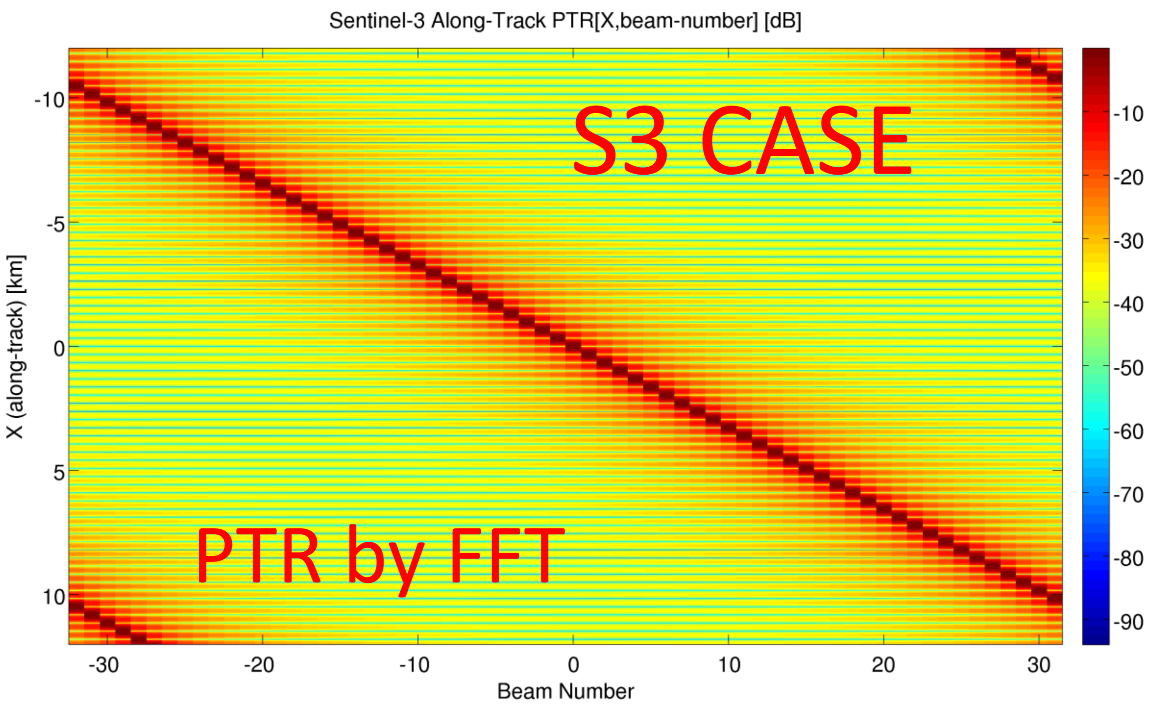


Ambiguities in case of Sentinel-3

Once Azimuth PTR is expressed as function of along-track position and beam-number, **in case of Sentinel-3**, ambiguities are confined just in the very far-nadir beams (28 to 32 and -28 to -32), as expected.

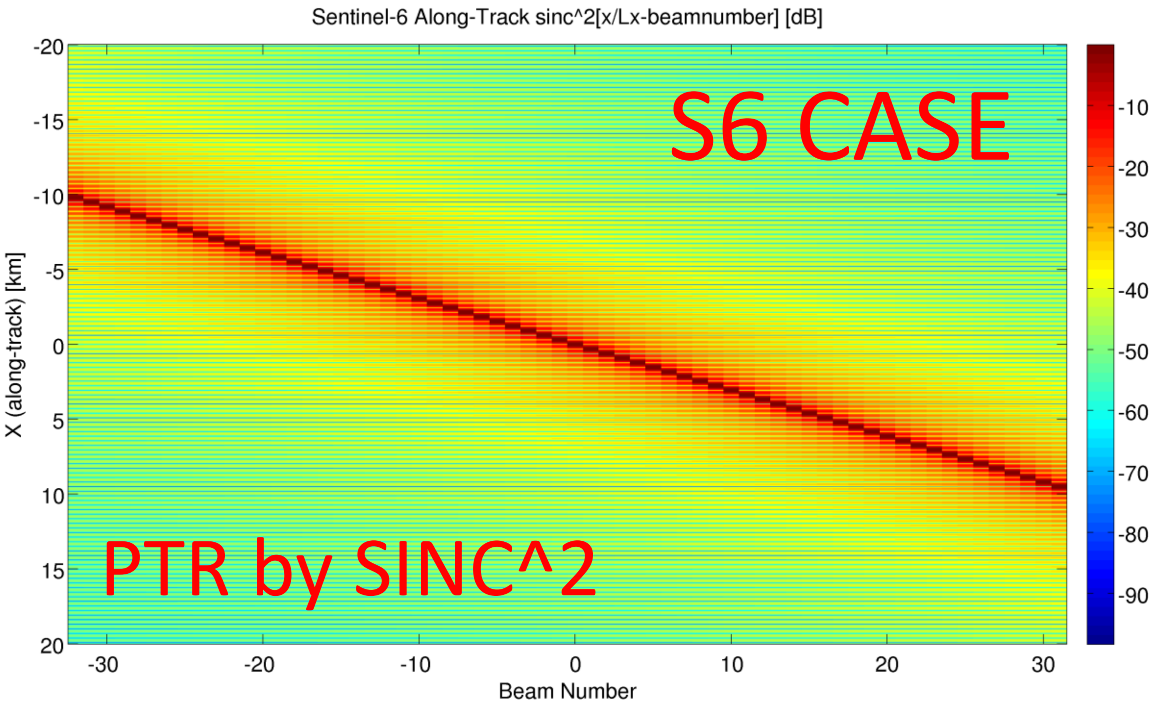
These beams are already suppressed by the zero-masking and hence no impact for S3 from azimuth ambiguities is expected.

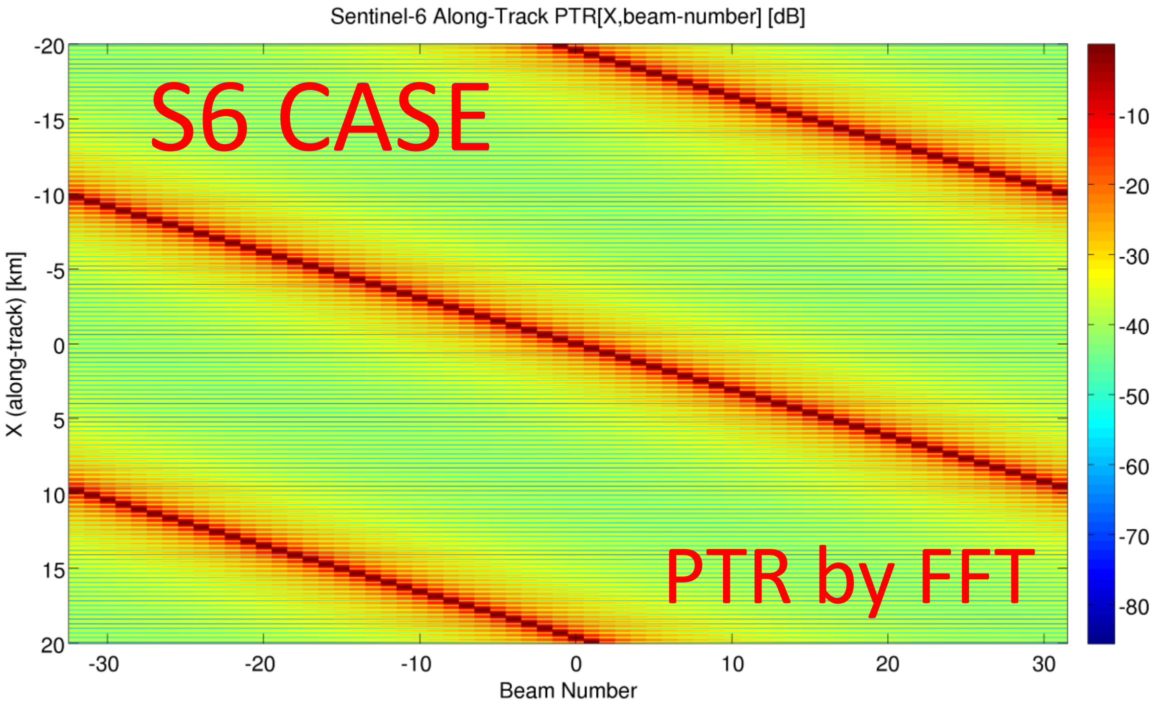




Ambiguities in case of Sentinel-6

Once Azimuth PTR is expressed as function of along-track position and beam-number, **in case of Sentinel-6**, ambiguities are present for all the beam numbers (-32 to 32), as expected.
In S6 case, these spurious signal from abiguities will then “plague” the S6 stack data (next slide)



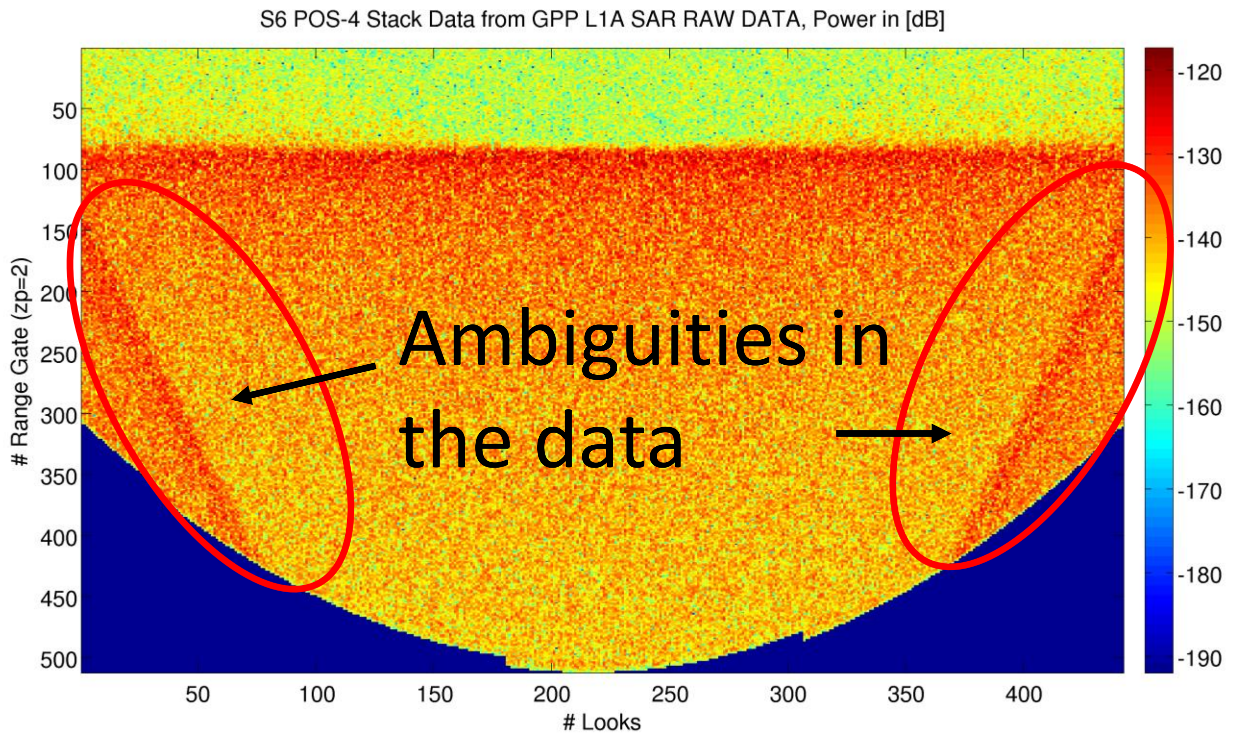


Numerical (Time-Domain) Retracking: Application to Sentinel-6 GPP Data

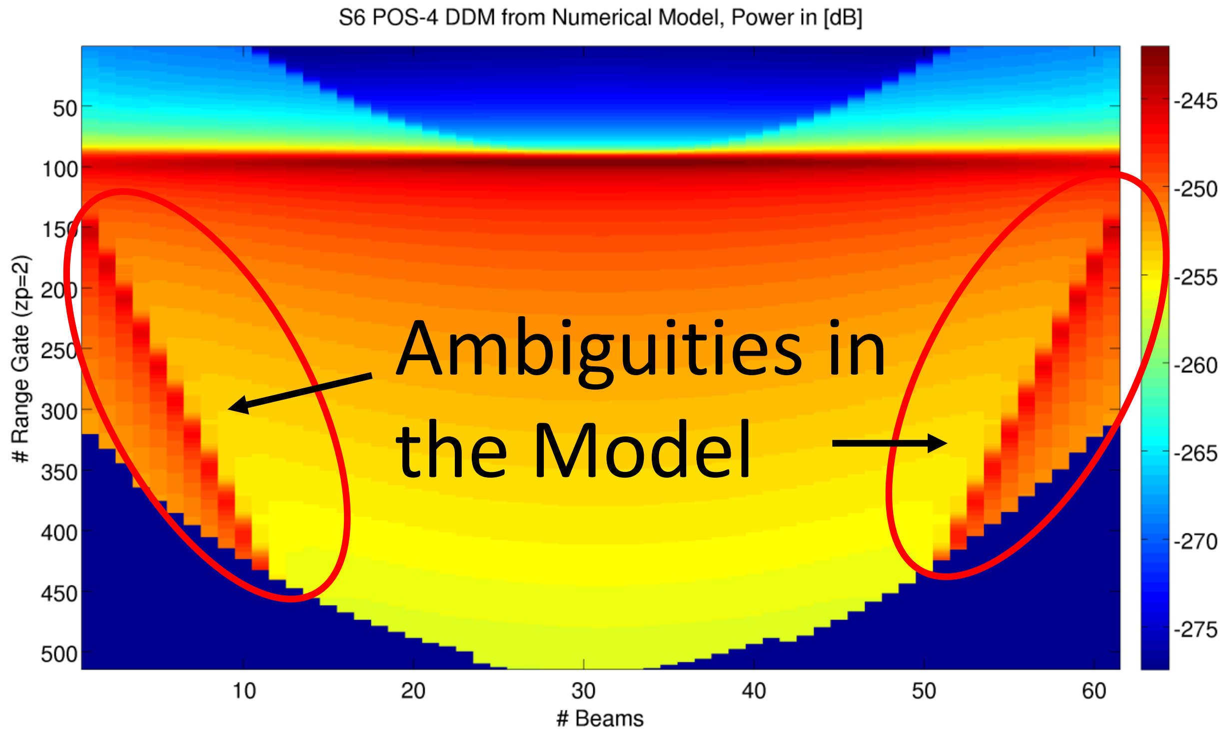
AZIMUTH PTR with ambiguities:

Convolving the azimuth "Ambiguous" PTR, DDM Model will show the aliased "wings" (ambiguities) in the same positions as in the Stack data:

STACK Data with ambiguities (SAR RAW)

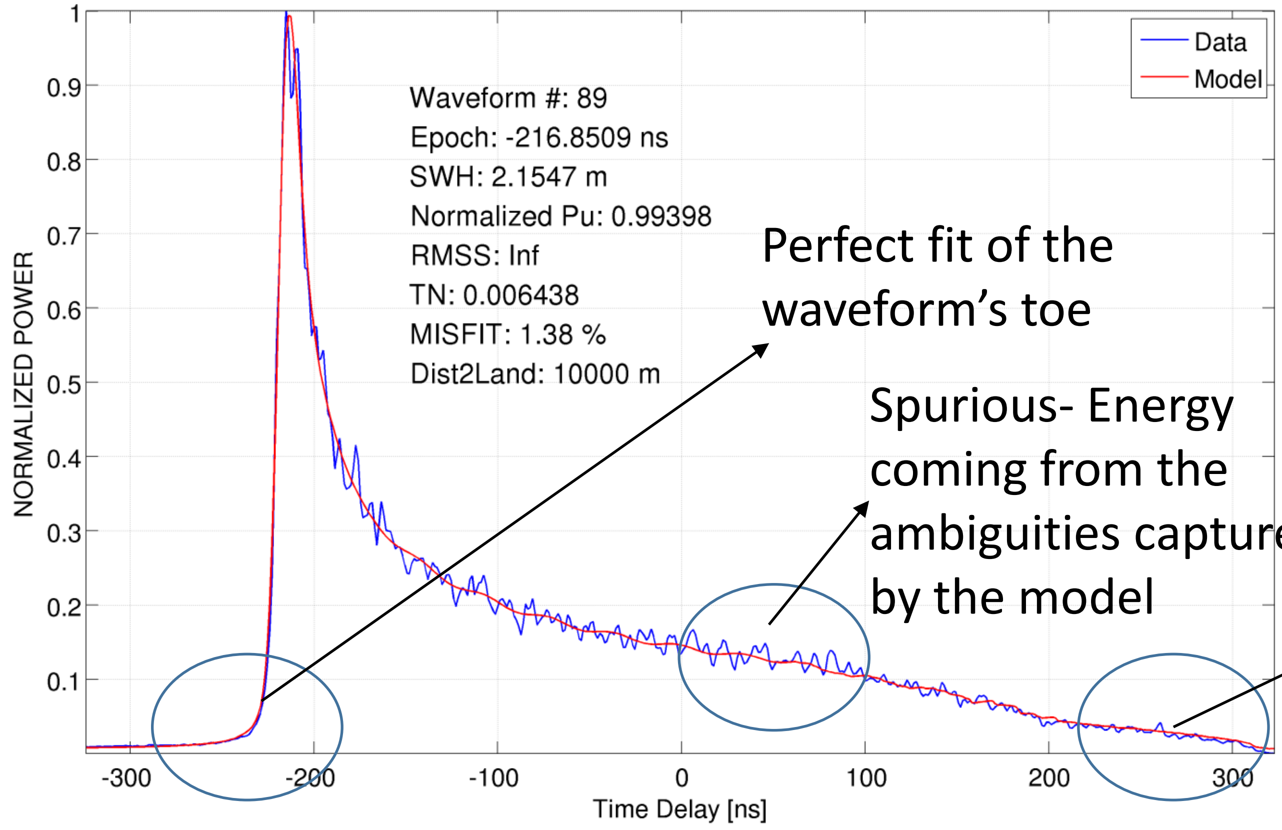


DDM Model with ambiguities (Time-Domain)



Numerical (Time-Domain) Retracking: Application to Sentinel-6 GPP Data

⇨ No need anymore to truncate the waveform appling a dedicated mask for ambiguities.
Whole Waveform can be retracked (256 gates in case of SAR RAW) and hence we can have slightly more looks/power to average in the multilooking stage



Perfect fit of the waveform's toe

Spurious- Energy coming from the ambiguities captured by the model

CASE SAR RAW

Blue waveform data

Red waveform model

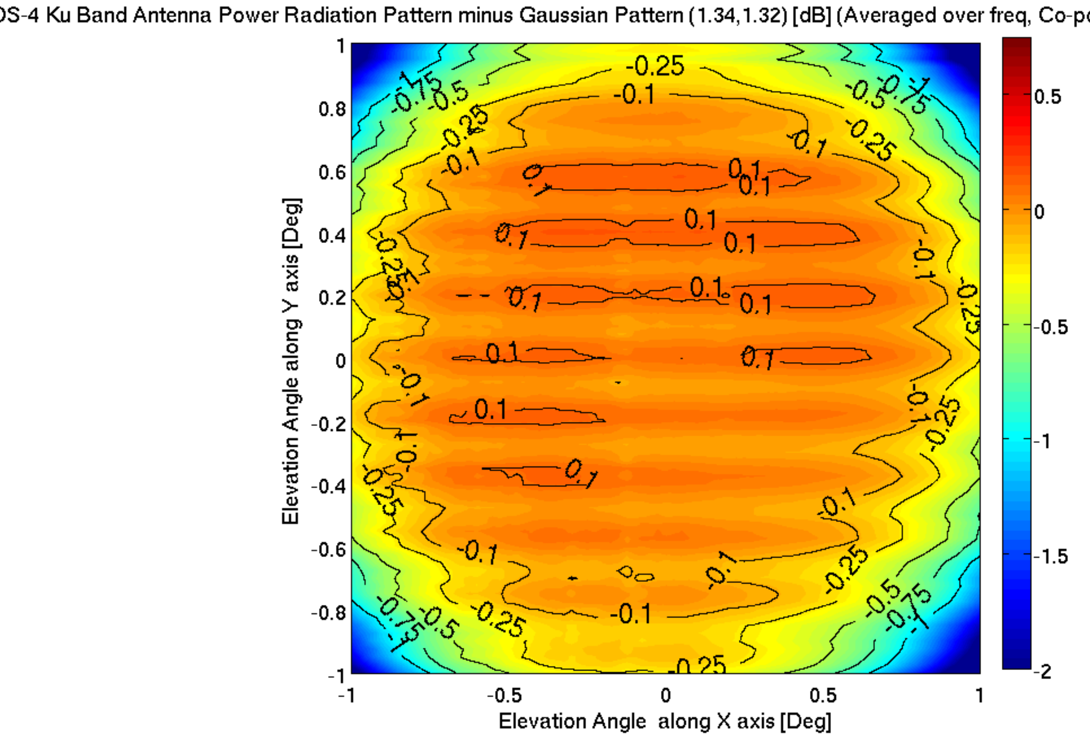
Toward trail, no more ambiguities => drop of the waveform power level again captured by the model

Impact of the Real Antenna Pattern for S6 and implementation in the S6PP

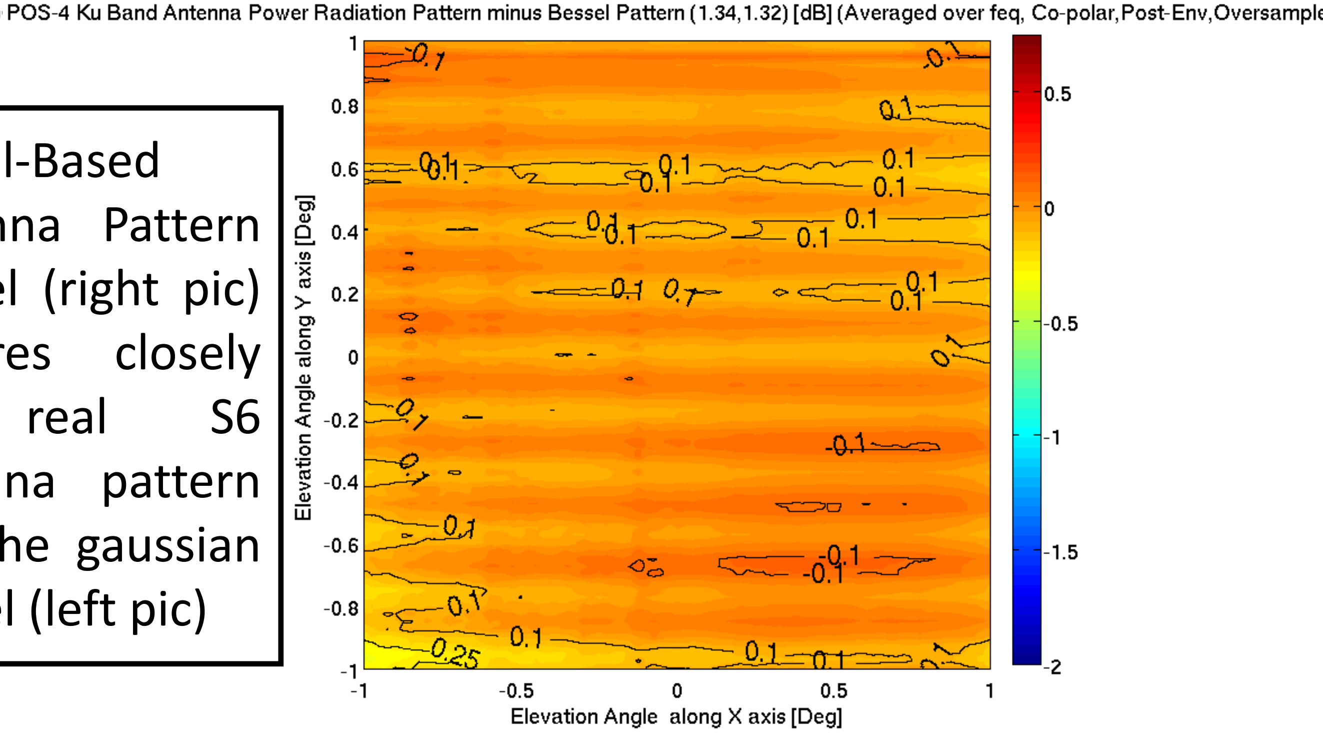
Recently, S.Dinardo has proposed a Bessel–based antenna pattern model for Poseidon Altimeter Antenna Class. The antenna model more closely will reproduce the S6 real antenna pattern than the classical gaussian pattern model. The new pattern will be used in the time-domain SAR retracker in order to validate the gaussian pattern approximation to be used in the frequency domain approach

S6 Real Pattern minus Gaussian Pattern (Oversampled)

S6 Real Pattern minus Bessel-Based Pattern (Oversampled)



Bessel-Based Antenna Pattern Model (right pic) adheres closely to real S6 antenna pattern wrt the gaussian model (left pic)



Impact of the Doppler Beam Sampling for S6 and implementation in the S6PP

In **S3**, in the PDGS SAMOSA-based retracker and S3PP numerical retracker, a beam sub-sampling is applied in generating the beam models of the SAMOSA DDM: instead to modelize all 180 beams, only 45 beams are modelized (i.e. one out of 4), making the approximation (i.e. integer truncation):

Beam_index = **int**(fd/ δfd) with δfd = PRF / Nb with Nb is PulsePerBurst and fd is the Doppler Frequency

Recently, this sub-sampling/truncation has been identified to lead to significant errors in case of **S6** by S. Figerou/ S.Dinardo (OSTST 2020) and an evolution (i.e. generalization) of the formula above has been proposed as:

Beam_index = int(fd*factor/ δfd)/factor with δfd = PRF / Nb

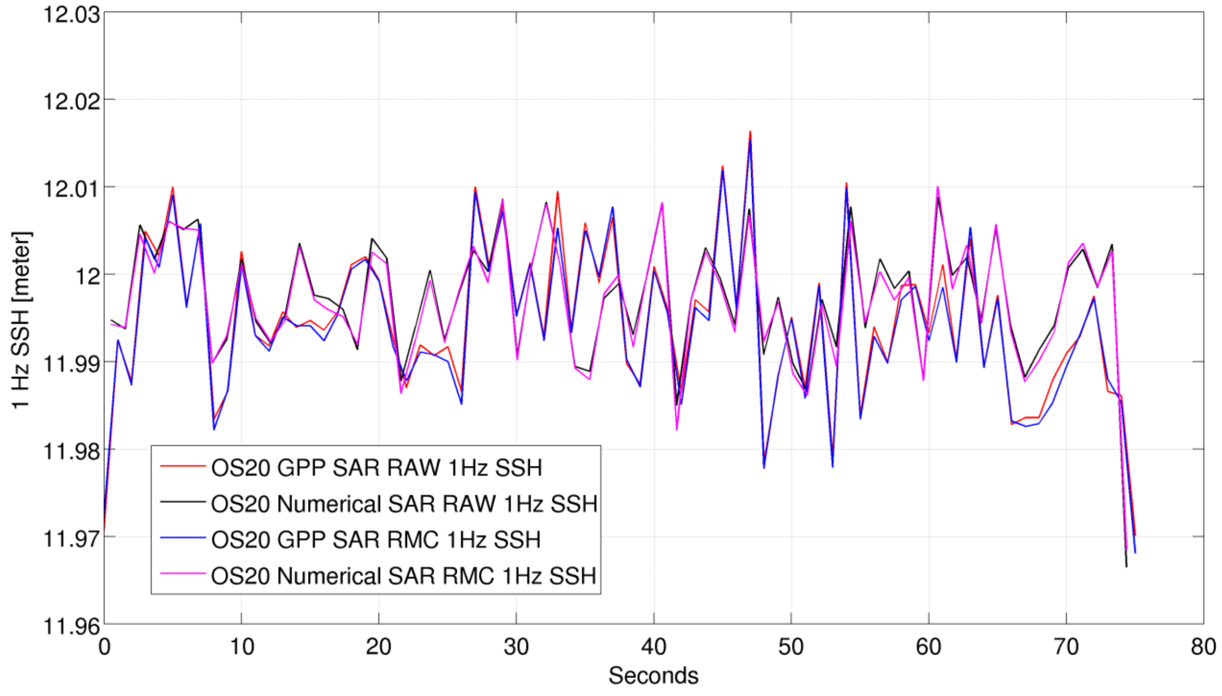
With **factor** ranging from 1 (case: one beam out of 7 considered, i.e. 64) to 7 (case: all beams considered, i.e. 448) in case of S6 Mission.

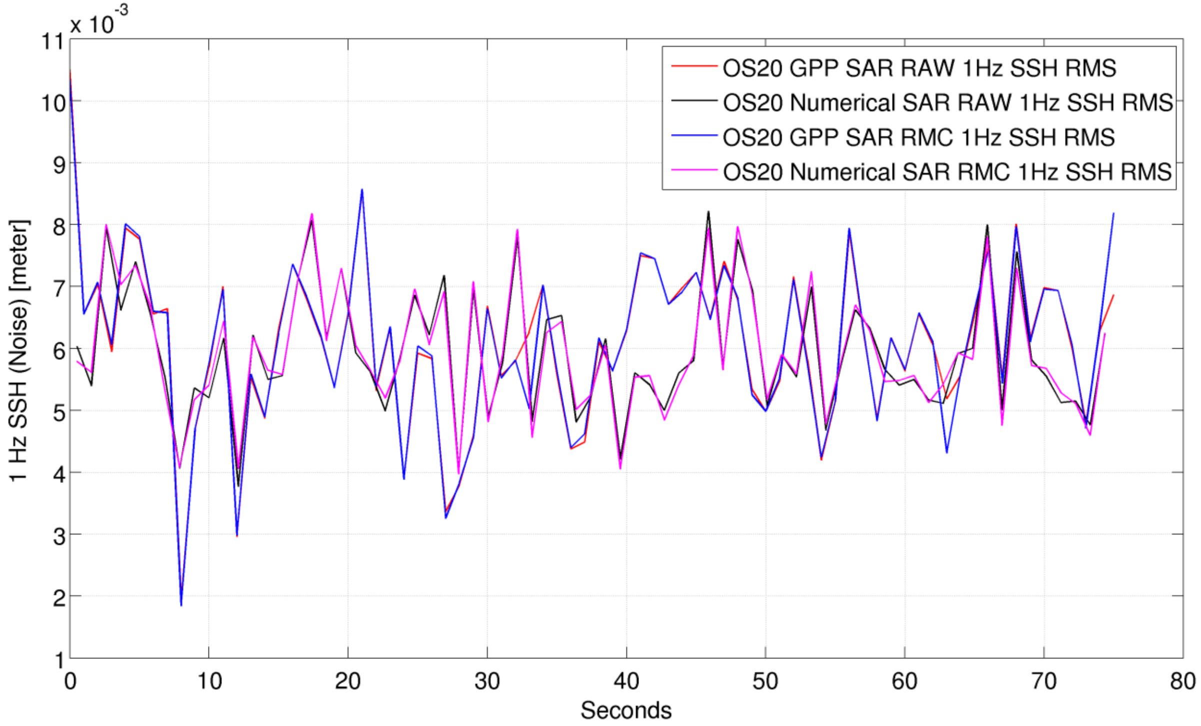
In case of **S6PP**, all the beams (448) will be generated by the numerical model in order to not be impacted by this approximation in any way.

Numerical (Time-Domain) Retracking:
Results relative to SSH along the pass (scenario OS20)

First results from the numerical retracker (time domain) show that the new ambiguity treatment approach returns results in line with GPP ones (in SAR RAW and SAR RMC).

Scenario OS20

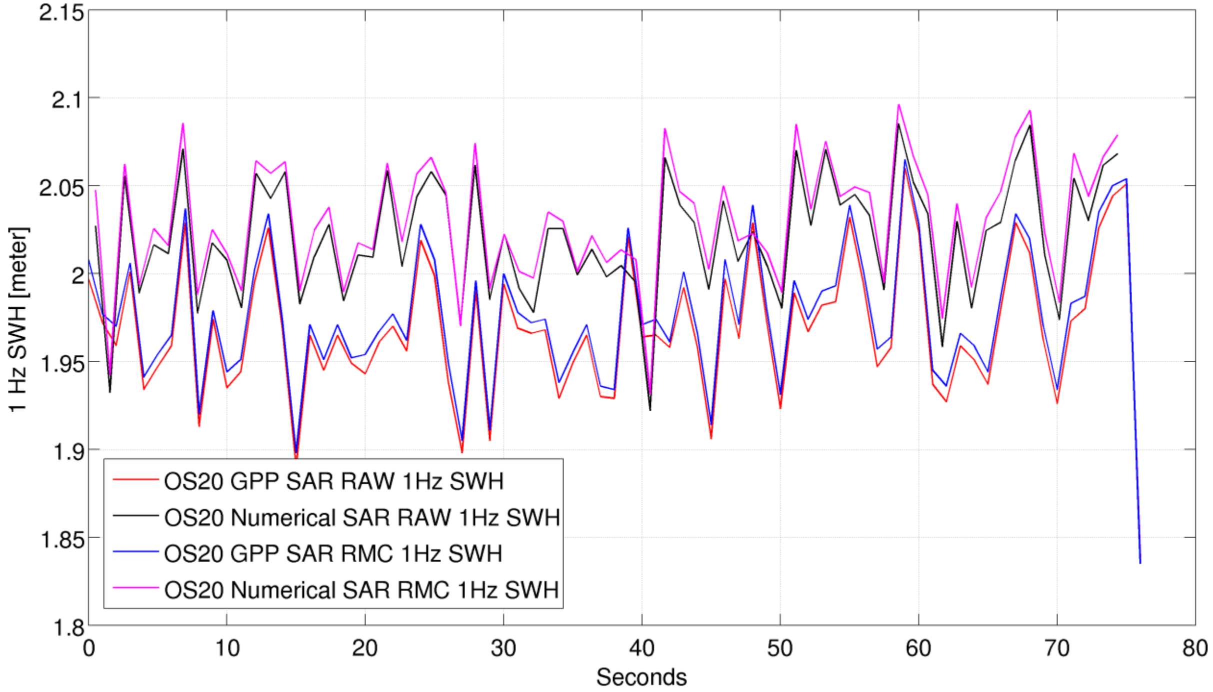


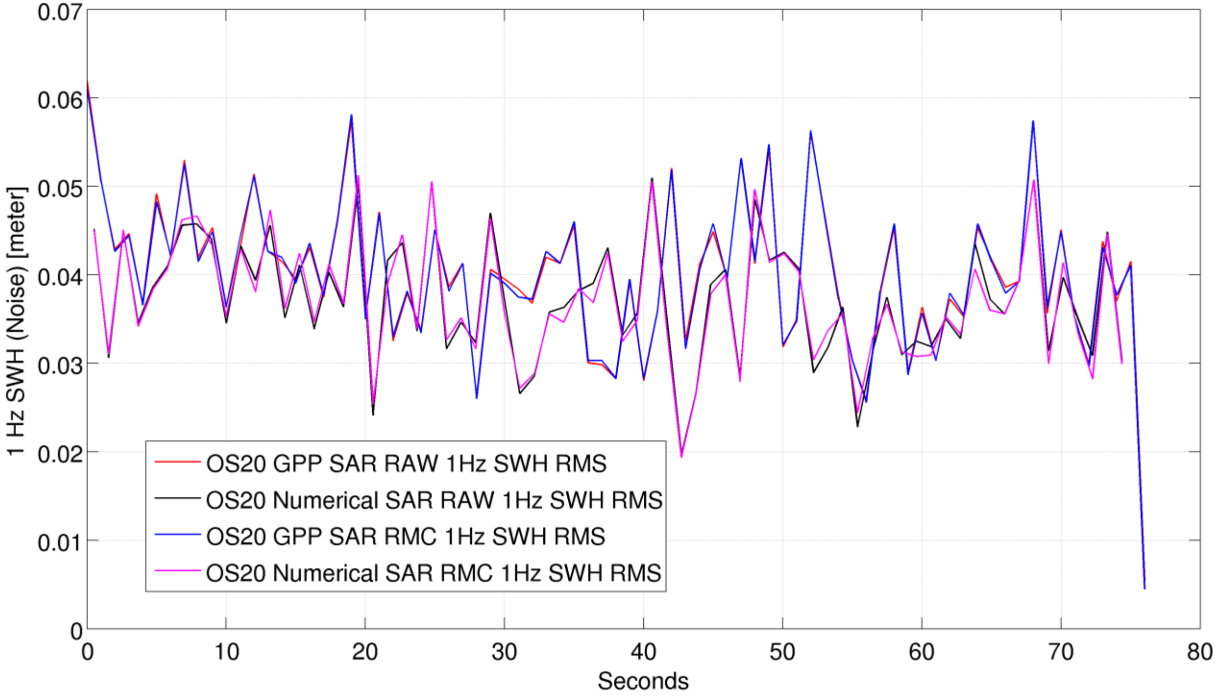


- As to SSH, first results (both in SAR SAR and SAR RMC) from the numerical retracker are very consistent with GPP results in term of bias/std (left) and noise (right).
- SAR RAW and SAR RMC are basically equivalent.

Numerical (Time-Domain) Retracking:
Results relative to SWH along the pass (scenario OS20)

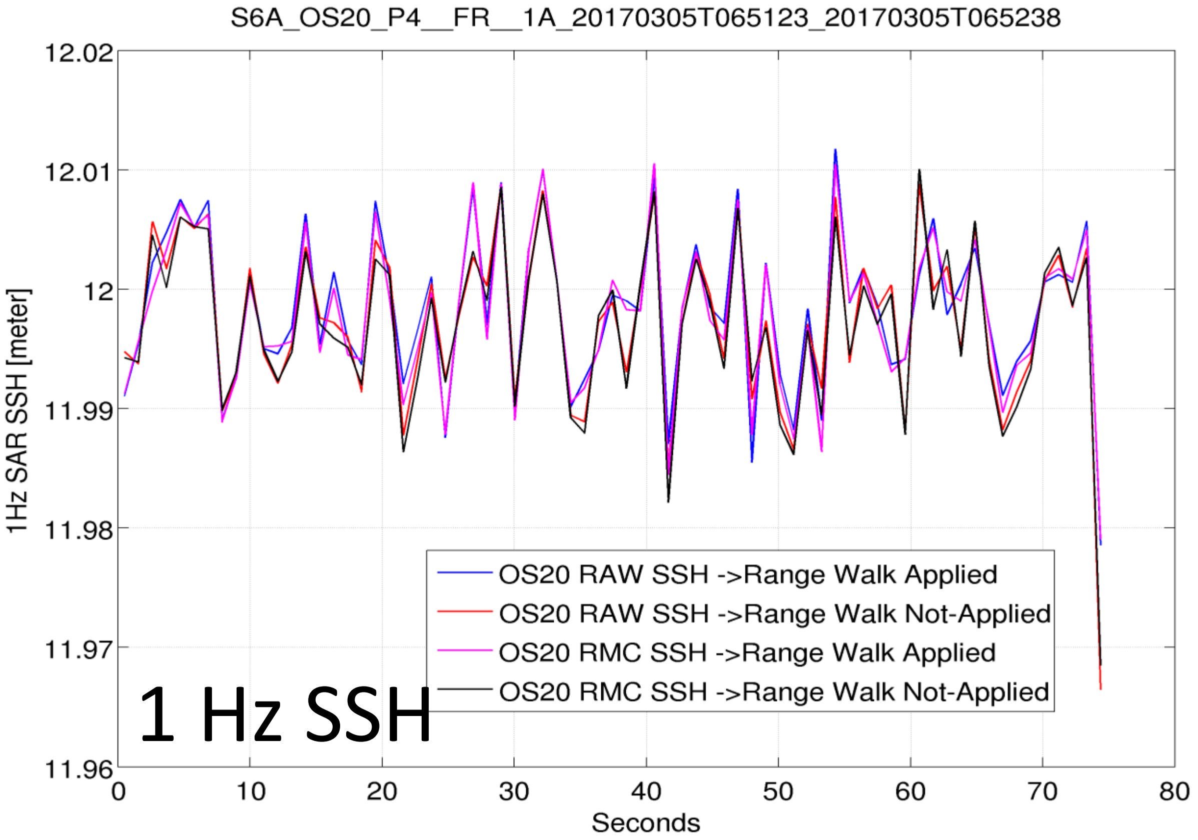
First results from the numerical retracker (time domain) show that the new ambiguity treatment approach returns results in line with GPP ones (in SAR RAW and SAR RMC). Scenario OS20

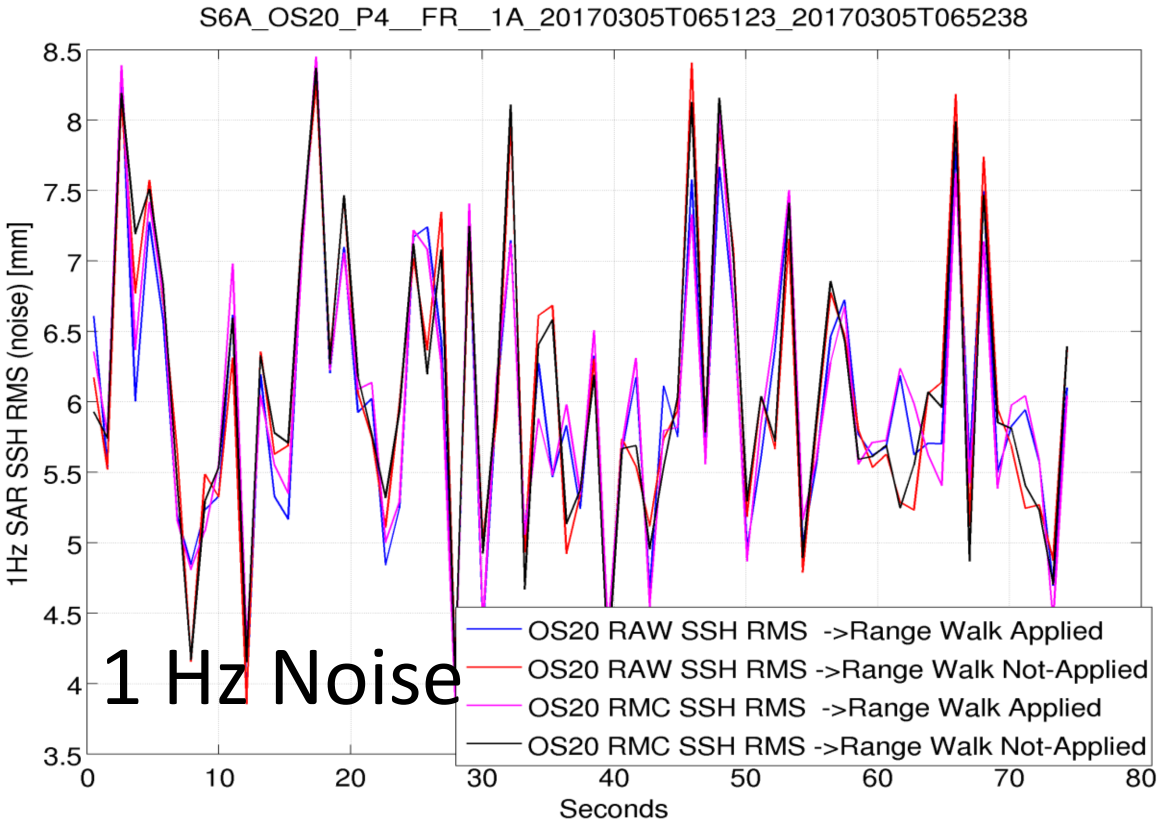




- As to SWH, first results (both in SAR SAR and SAR RMC) from numerial retracker are very consistent with GPP results in term of noise (right) and std with just a bias of 5 cm (left). SAR RAW and SAR RMC are again basically equivalent.

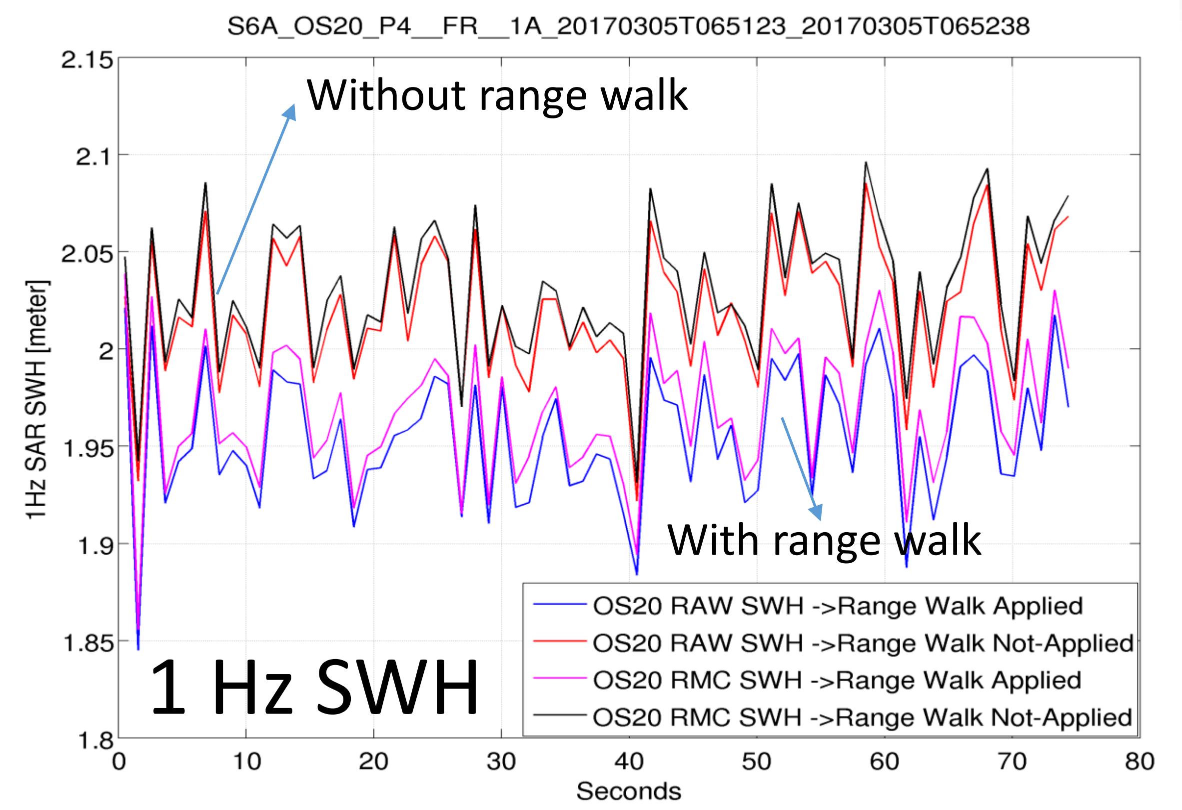
Impact of range walk using numerical SAR retracker: Results relative to SSH along the pass (scenario OS20)

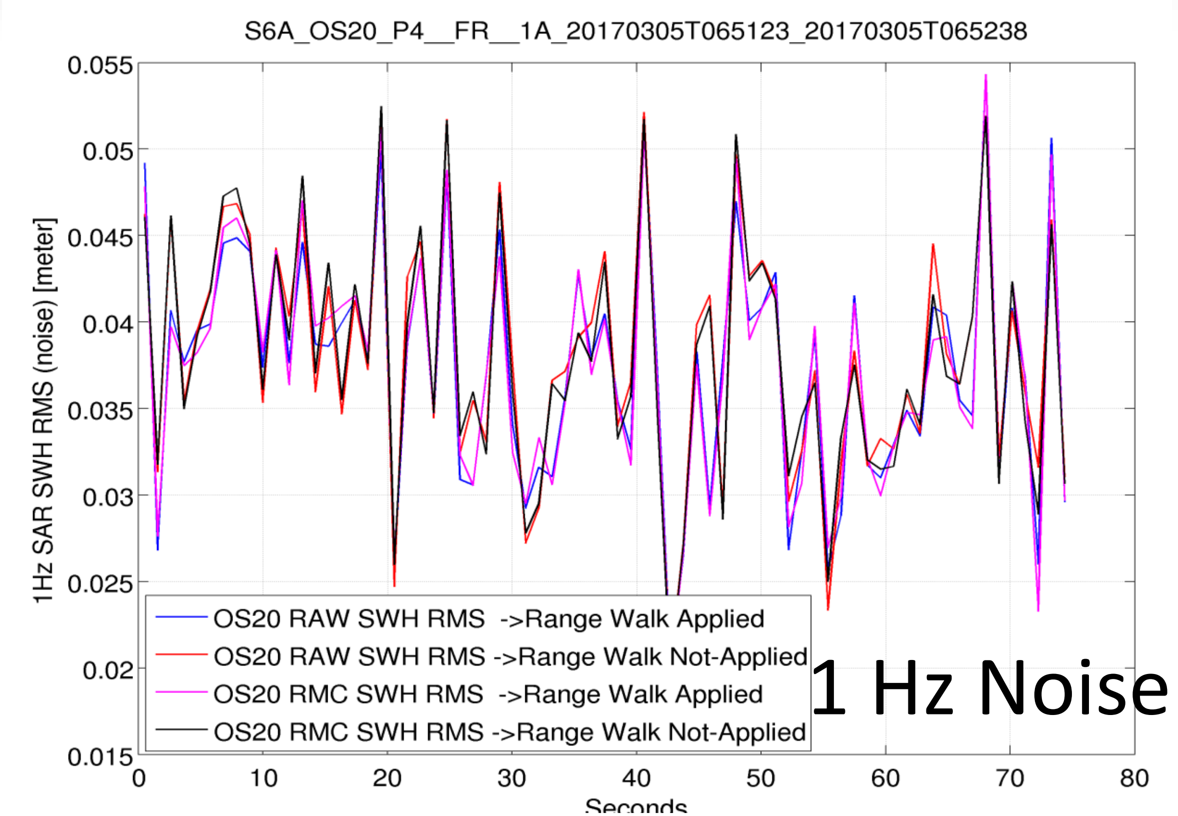




- Range Walk does not introduce a bias in range (from these simulations)
- SAR RAW and SAR RMC basically equivalent
- 1 Hz “noise” around **6 mm** for all the cases
- No significant impact from range walk on SSH noise

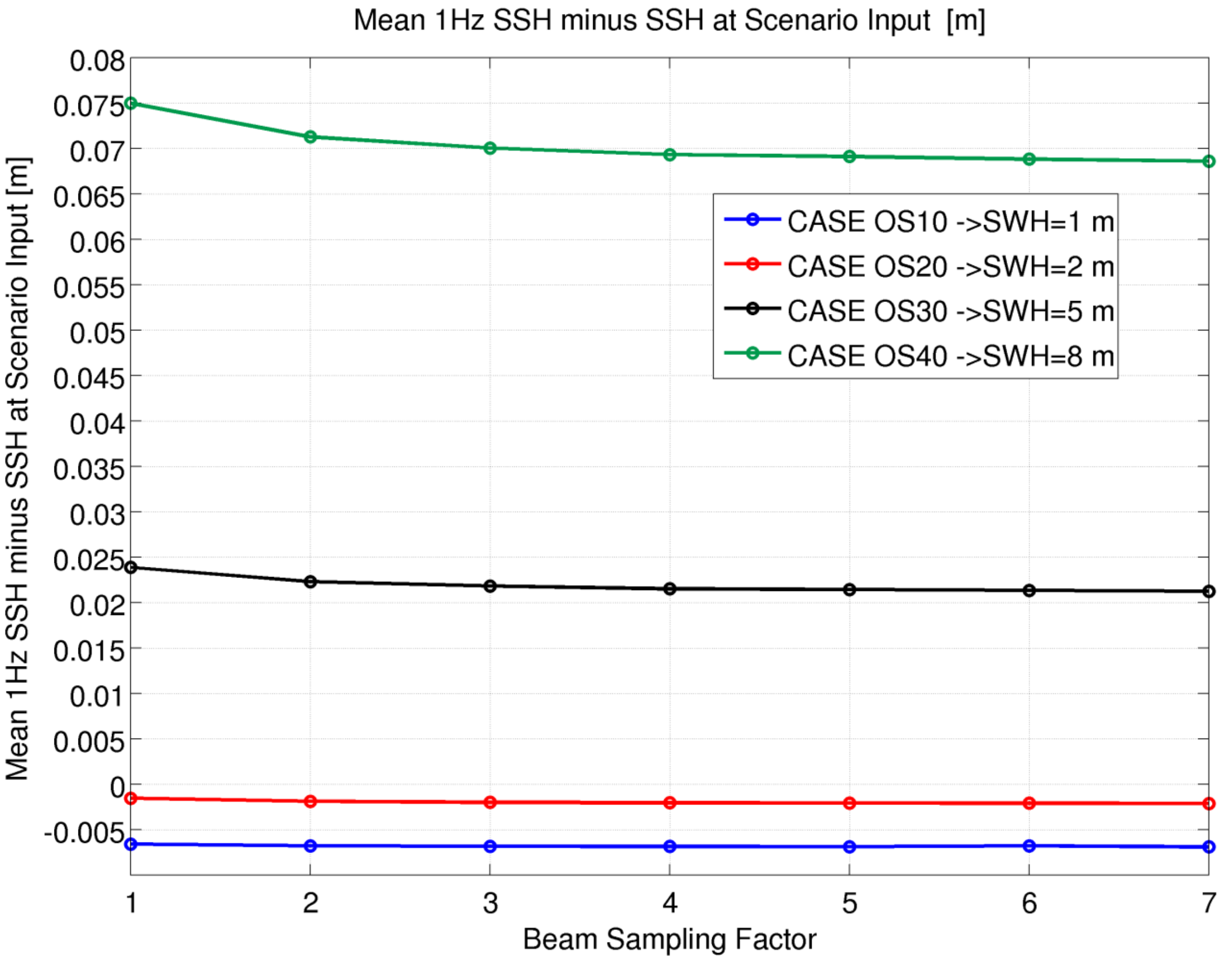
Impact of range walk using numerical SAR retracker: Results relative to SWH along the pass (scenario OS20)





- Range Walk introduces a decrease in SWH of 7 cm (average value from 2.03 m to 1.96 m)
- SAR RAW and SAR RMC basically equivalent
- 1 Hz “noise” around **3.5 cm**, only very slightly better in case of range walk application

Impact of Doppler Beam Sub-Sampling using numerical SAR retracker. Results relative to SSH ->BIAS along the pass (OS*0 Scenario)



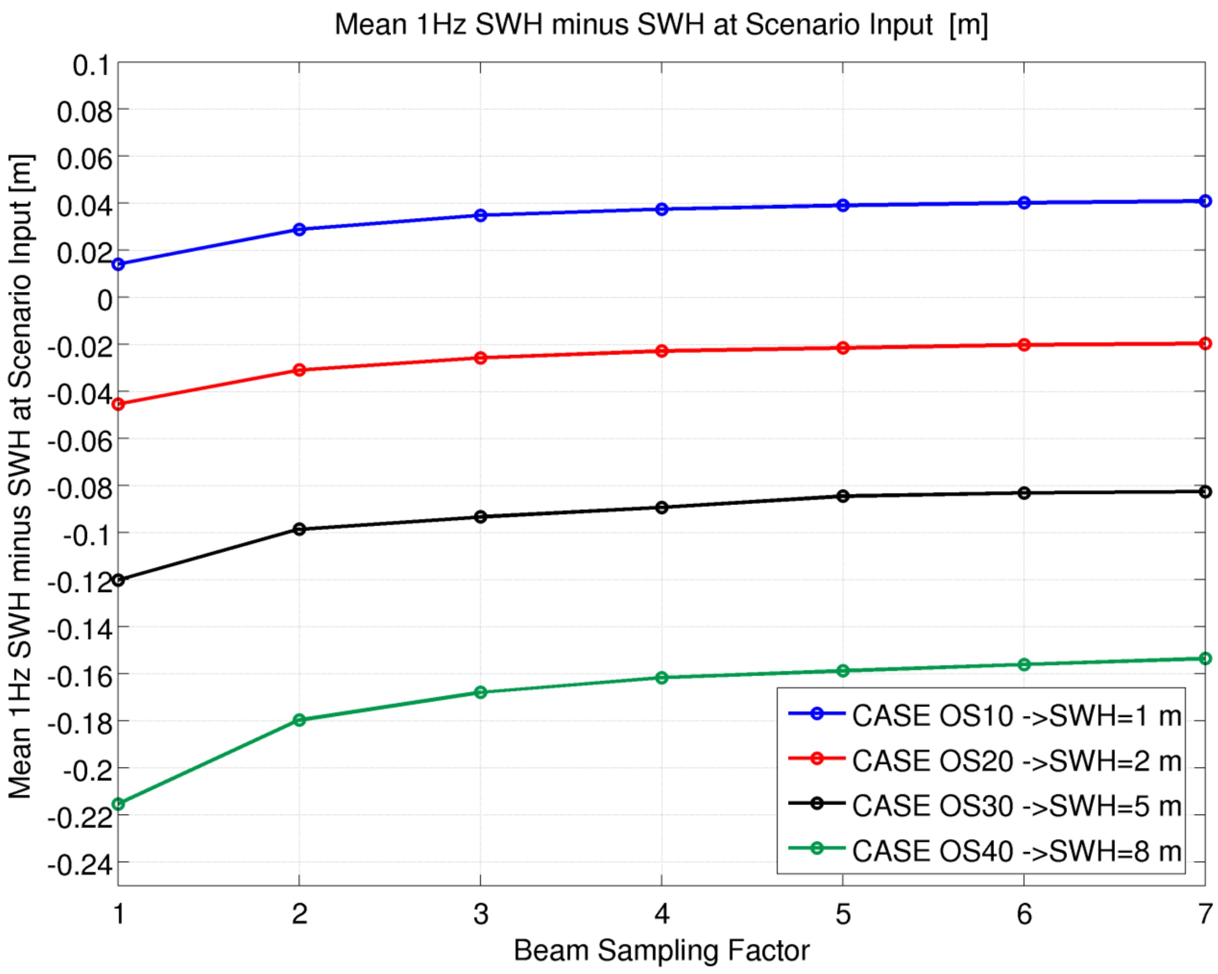
SSH Bias in meter wrt the input scenario SSH value.

Different Scenarios in the plots (OS10,OS20,OS30,OS40)

Impact at mm level only for big waves (case OS40)

No impact after a beam Sampling factor of 2

Impact of Doppler Beam Sub-Sampling using numerical SAR retracker. Results relative to SWH ->BIAS along the pass (OS*0 Scenario)



SWH Bias in meter wrt the input scenario SWH value.
Different Scenarios in the plots (OS10,OS20,OS30,OS40)
Clear Pattern is visible.
No significant change after beam Sampling factor of 3
Impact between 2 cm (small waves, case OS10) **to 6 cm** (big waves, case OS40)

Conclusions:

- Sentinel-6 mission exhibits many specificities to be accounted for in the processing phase (on board RMC compression, open-burst operation mode, Doppler ambiguities, pulse-to-pulse correlation, digital architecture, etc.)

- Current processing may be improved in that regard, but also to better address some other problematics (range walk, Doppler beam sampling, possible PTR distorsions)

- The main objective of this CNES initiative is to demonstrate the effectiveness of the new enhanced UF-SAR processing chain in order to meet both the mission requirements and operational processing constraints

- This initiative paves the way towards enhancing quality products of the upcoming reference mission, in a working strategy involving the different Agencies.