Pulse-to-Pulse Correlation Effects on High PRF Low Resolution Mode Altimeters

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Why is the pulse-to-pulse correlation important?

- In radar altimetry, one of the most the limiting factors for the measurement precision is speckle noise.
- In fact, *speckle is actually the signal* that arises from the random combination of the radar returns from the scatterers on the surface contributing to the final echo.
- As the altimeter flies over, the variation of the path length variation between the altimeter and the scatterers on the surface creates a new set of phases that produce a new realization of the speckle noise random process.
- In speckle-noise-like signals, the power distribution is a decaying exponential function, where the mean of the signal power is equal to its variance.
- The only way to reduce speckle noise is by "*multilooking*", i.e. the incoherent averaging (in power) of multiple measurements of the surface under observation.
- The power distribution, then, tends to a Gaussian around the mean, with the variance reducing by a factor of N, where N is the number of independent observations.
- In low-resolution mode ("*conventional*") altimetry the radar returns are power detected and averaged together to beat down speckle noise…but for this process to be effective, *adjacent pulses need to be decorrelated* between each other.

Pulse-to-Pulse Correlation

Background & Motivation

- The pulse-to-pulse decorrelation was a significant topic of study during the onset of radar altimetry, with seminal works such as [Berger, 1972], [Walsch, 1974, 1982], and, [Rodriguez & Martin, 1994].

- These studies were fundamentally based on the Van Zittert-Cernicke theorem (VCT), that allows to determine the decorrelation distance, d, between two adjacent pulses coming from an uniformly illuminated circular area:

$$d = 0.305 h\lambda / r$$

h = satellite height
λ = radar wavelength
r = area radius

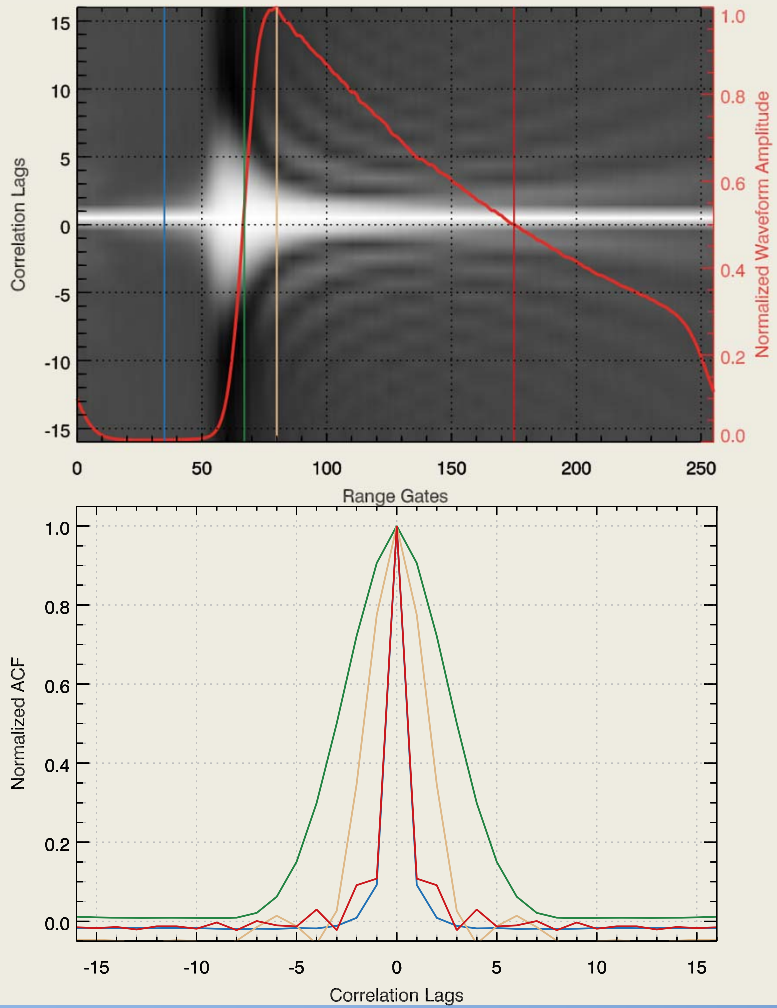
- Based on those studies, the optimal PRF for the altimeter reference missions (TOPEX, Jason 1-2-3) was determined to be between 2-4 kHz…

- So what is the effect of the partial correlation of pulses in high PRF low-resolution mode altimeters, such as Jason-CS, with a PRF of 9 kHz? Is there any more information available after a PRF of 4 kHz? Is that modifying the retracking results in any way?

- SAR Mode altimeter are a perfect tool to study this, given their very high PRF. For this study we make use of CryoSat-2 FBR SAR Mode data processed in PLRM.

Pulse-to-Pulse Power Auto-Correlation

CryoSat-2 FBR SAR Mode data, pulse-to-pulse power autocorrelation, for a SWH of 2 meters. Results consistent with [Smith & Scharroo, OSTST 2012].



- The pulse-to-pulse correlation is obtained as the speckle noise auto-correlation per range gate:

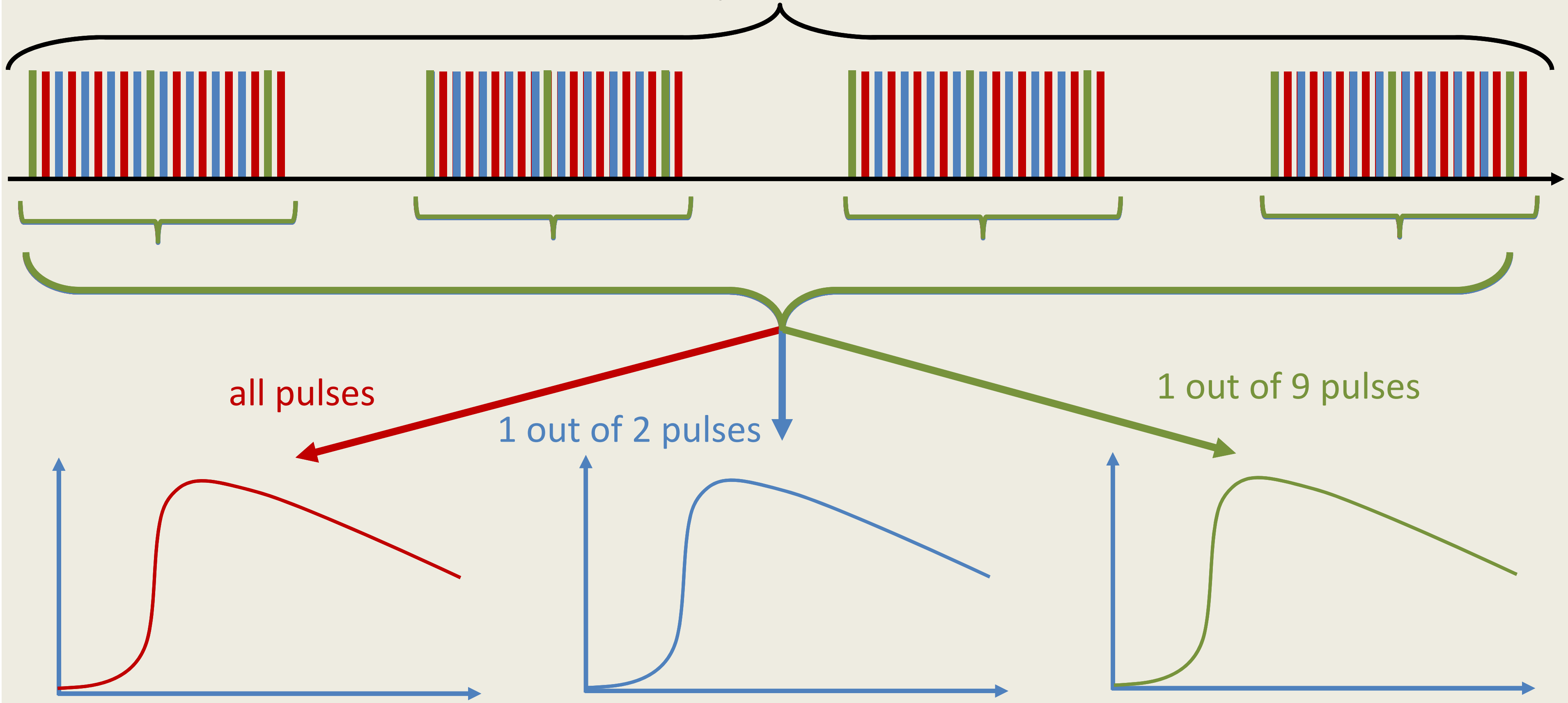
$$R(g,k) = \frac{\mathbf{E}\left[(|\psi(g,t)|^2 - \Psi(g))(|\psi(g,t+k)|^2 - \Psi(g))\right]}{\mathbf{E}\left[|\psi(g,t)|^2\right]}$$

- For the waveform leading edge the results are consistent with the VCT and Walsch.
- For the trailing edge the decorrelation is much faster than previously expected.
  - As the pulse propagates and penetrates on the surface the pulse limited footprint becomes annulus of increasing radius, but constant area.
  - These annulus cover areas on the surface of increasing Doppler shift with respect to nadir, which incurs in faster phase variations of the surface scatterers and therefore faster decorrelation of the radar returns.
- To determine the effect of this in the multilooked waveforms, we generated from SAR mode data, PLRM data at different PRFs.

Formation of Several PRFs

CryoSat-2 SAR Mode:
Burst Operation, 64 pulses per burst @ 18.181 kHz PRF

Radar Cycle → ~20 Hz



~ 18 kHz PRF
256 pulses per 20 Hz

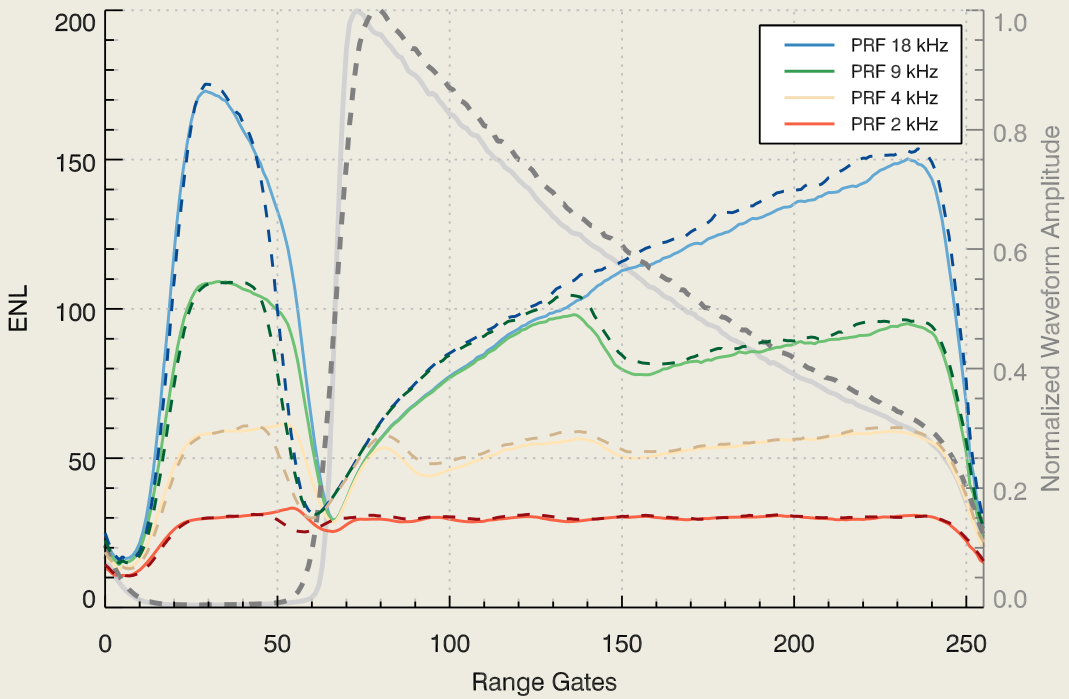
~ 9 kHz PRF
128 pulses per 20 Hz

~ 2 kHz PRF
28 pulses per 20 Hz

Effective Number of Looks (ENL)

…depending on the PRF

Effective Number of Looks (ENL) for low SWH (~2 meter) and high SWH (~5 meter), in solid and dashed lines, respectively. Incoherently averaged waveforms in gray.



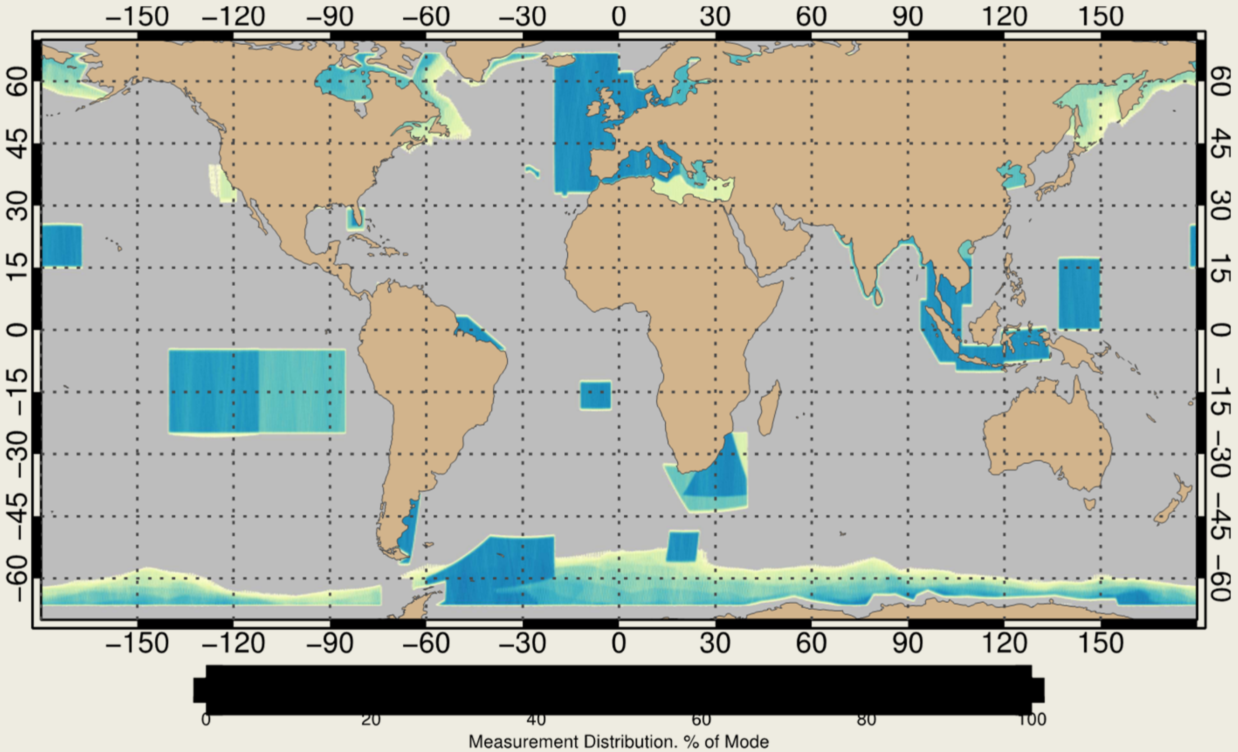
- The ENL is slightly higher for higher SWH values, indicating that pulses decorrelate faster.
- The ENL depends a great deal on the pulse-to-pulse correlation properties:
  - The ENL is lower where the ACF is wider, i.e. where pulses are more correlated with each other…
  - The ENL gain at the onset of the leading edge is small even for the 18 kHz PRF

- Towards the trailing edge, however, the ENL increases steadily for higher PRFs.
- Even the 9 and 18 kHz PRFs provide higher ENLs at the trailing edge, suggesting that there is still information available…although not equally distributed throughout the waveform.
  - [Scagliola, et al, OSTST 2016] showed similar results based on simulations for Sentinel-6

Extended Data Analysis

CryoSat-2 SAR Mode measurements distribution (2012-2016).

Total number of measurements > 12 million

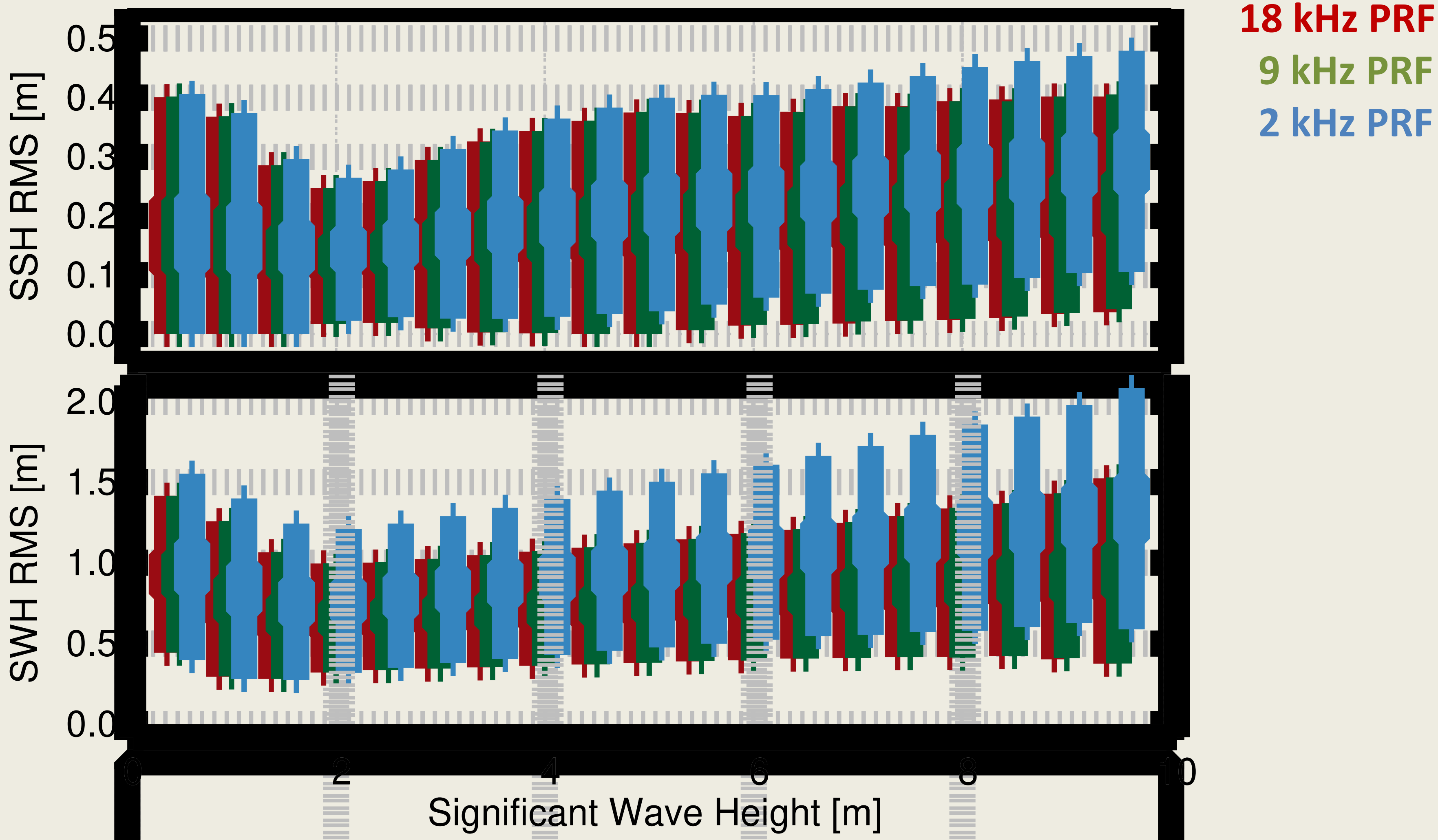


- To analyze what are the effects of the partial correlation of pulses when estimating geophysical parameters we processed 5 years (Jan 2012 – Dec 2016) of CryoSat-2 SAR Mode FBR data *a la* PLRM, with different PRFs (2, 9, and 18 kHz):
- The 20 Hz incoherently averaged waveforms are then retracked by means of an unweighted MLE4 Brown model retracker, to estimate SSH, SWH, radar cross section (σ^0), and mispointing angle (χ^2).
  - The 20 Hz retracked geophysical parameters are then reduced to 1 Hz to obtain error statistics

Performance Analysis (i)

RMS Errors

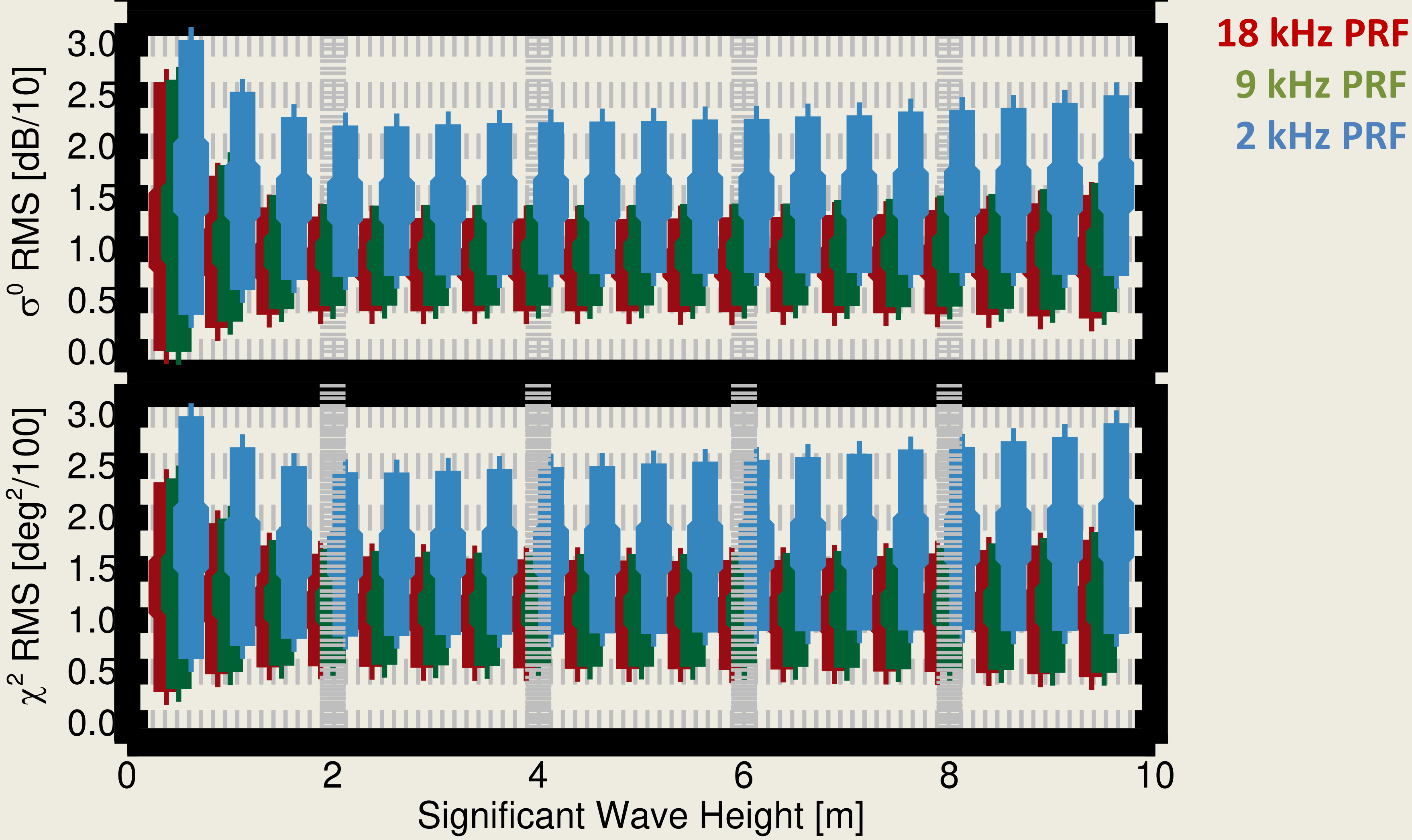
20 Hz RMS Error for MLE4 estimated parameters: SSH and SWH



Performance Analysis (i)

RMS Errors

20 Hz RMS Error for MLE4 estimated parameters: sigma0 and mis-pointing:

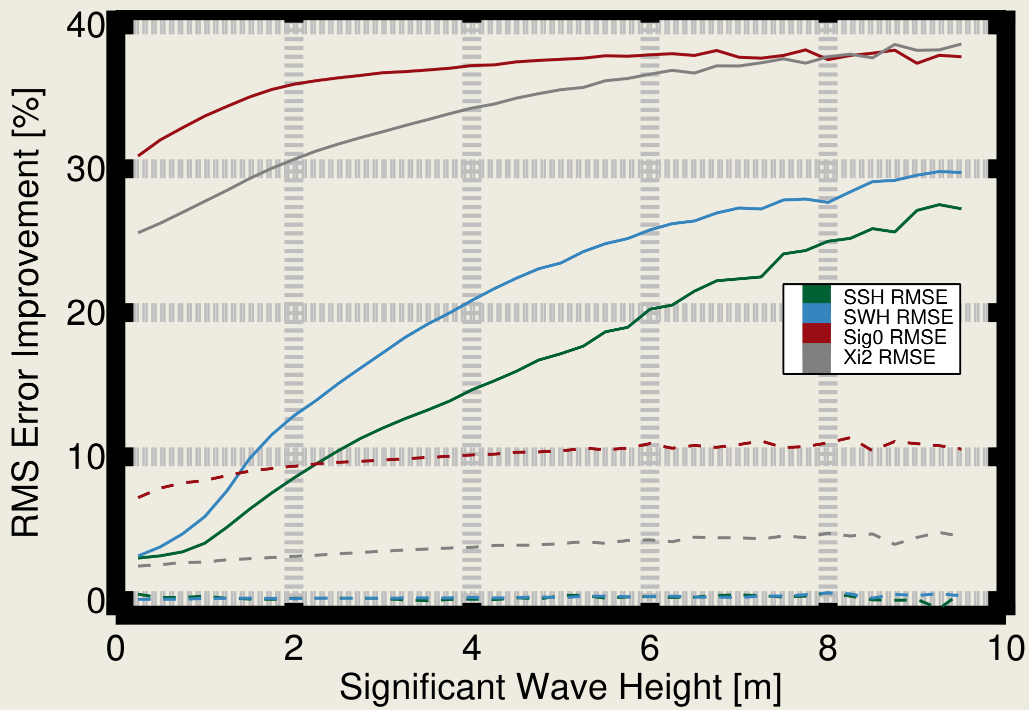


Performance Analysis (i)

RMS Errors

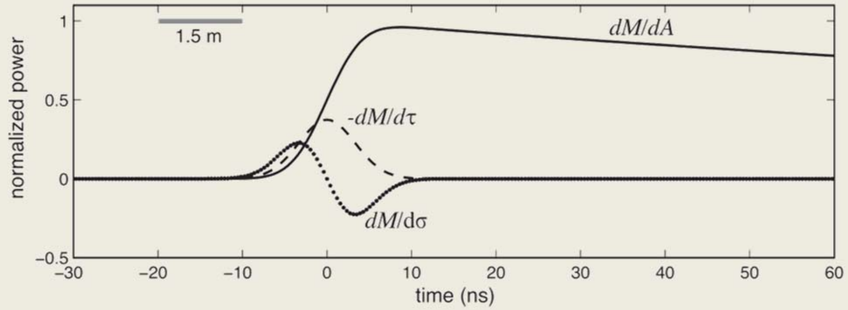
MLE4 parameters RMS Error improvement:

Dashed: 18 kHz vs 9 kHz. Solid: 9 kHz vs 2 kHz



- The 18 kHz PRF does not show any significant improvement with respect to the 9 kHz PRF for SSH and SWH. However, the improvement is noticeable for sigma-0 and mispointing angle.
- The 9 kHz PRF shows remarkable improvement with respect to the 2 kHz PRF for all parameters, especially towards high SWH.

Partial derivatives of Brown model wrt. retracking parameters [Garcia, Sandwell, Smith, 2014]

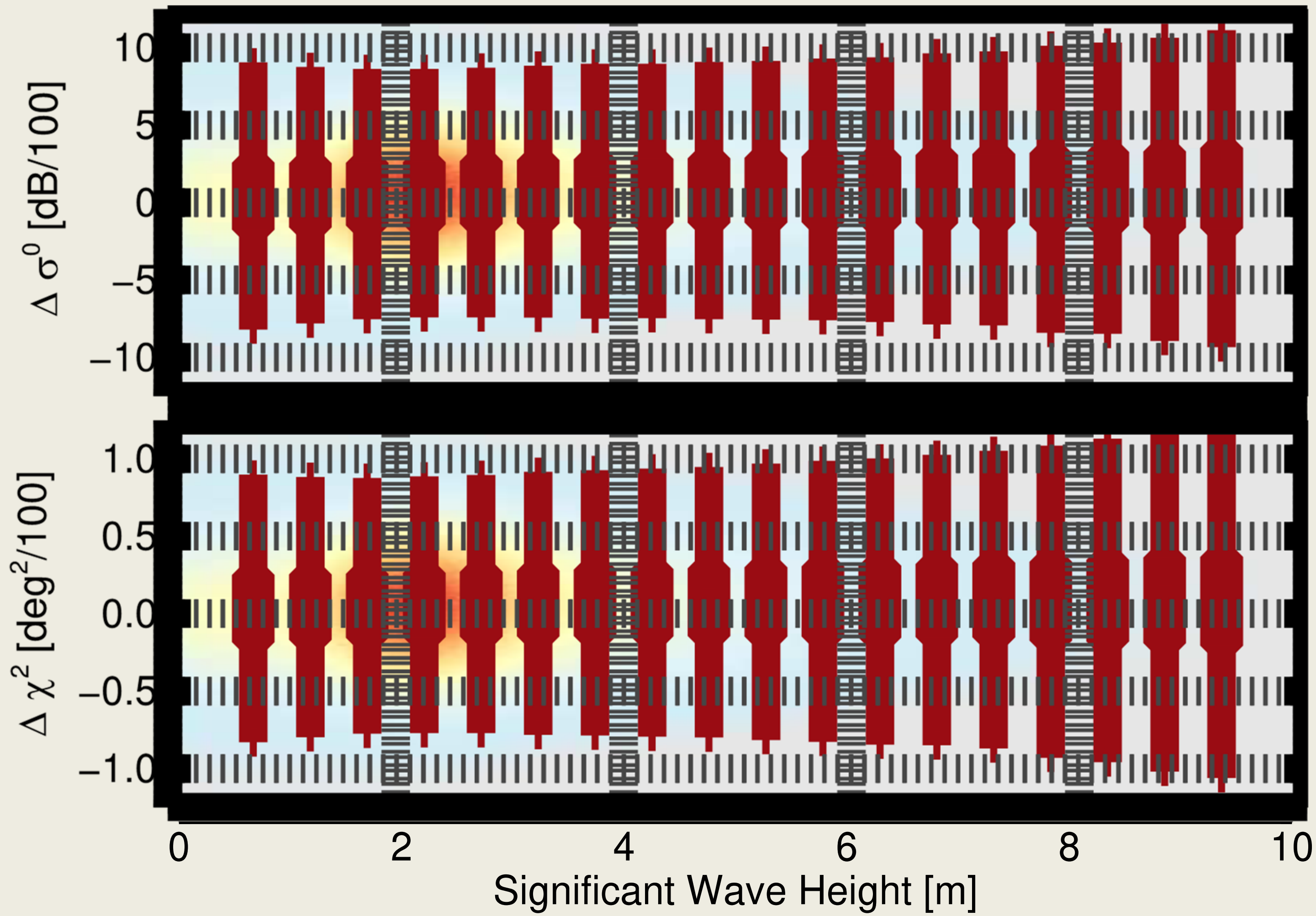


- The reason for having different improvements depending on the geophysical parameter is linked to the fact that different areas of the waveform are sensitive to different things…

Performance Analysis (ii)

Biases

2 kHz – 9 kHz mean values: sigma0 and mispointing:

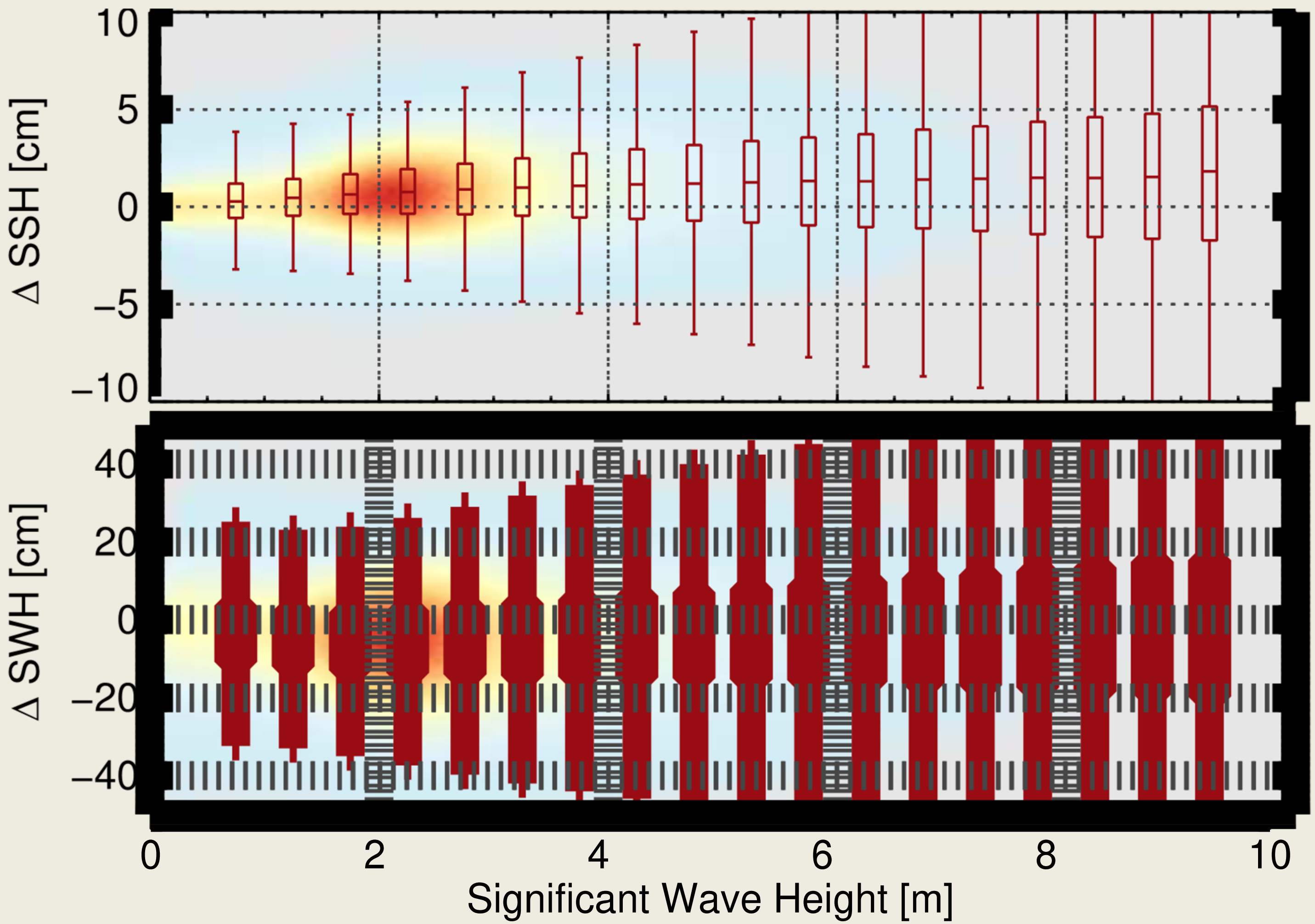


No noticeable biases in the estimation of σ^0 and χ^2.

Performance Analysis (ii)

Biases

2 kHz – 9 kHz mean values: SSH and SWH



Significant biases for SSH and SWH with a dependency on sea state!

We relate this to the different statistics along the waveform range gates and the unweighted retracking.

Conclusions

- In this study we have analyzed the pulse-to-pulse correlation of low resolution mode (LRM) pulse-limited altimeter waveforms.
- We have based our study on PLRM data obtained from CryoSat-2 SAR Mode FBR data.
- The pulse-to-pulse correlation changes depending on the waveform region:
  - For the leading edge the results are consistent with the VCT and Walsch.
  - For the trailing edge the decorrelation is much faster.
- This leads to a steadily increasing effective number of looks (ENL) in the waveform trailing edge, even for PRFs as high as 18 kHz.
- To determine the effect of the partial pulse-to-pulse correlation, we have processed and retracked 5 full years of CryoSat-2 SAR Mode data in a PLRM fashion with different PRFs.
- The results show that there are significant improvements in the estimation of geophysical parameters by increasing the PRF from 2 to 9 kHz.
  - Up to 25% for SSH and SWH, and up to 35% for sigma-0 and mispointing angle.
- The estimation of SSH and SWH at 9 kHz are biased with respect to the 2 kHz estimations. These errors would need to be accounted for and corrected.
  - This was linked to the use of an unweighted MLE4 retracker for waveforms with different statistics along the range gates. Future work implies the use of an weighted retracker.

SWH distribution