On the Effect of Surface Motion in SAR Altimeter Observations of the Open Ocean

Alejandro Egido (1,2), Chris Ray (1,3)

(1) NOAA-LSA, United States

(2) GST Inc., United States

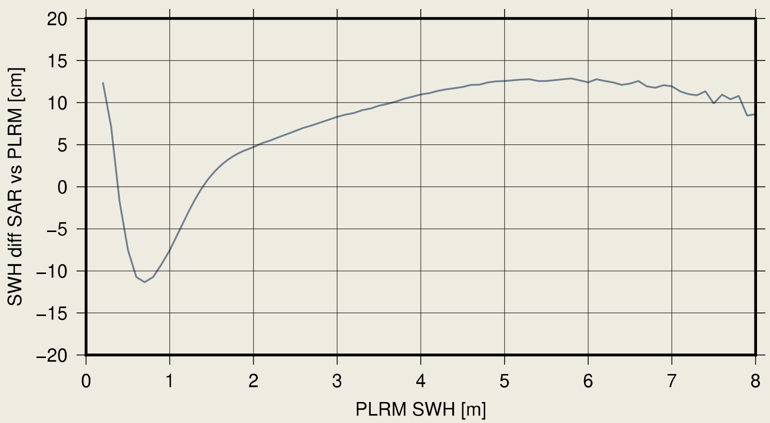
(3) UMD, United States

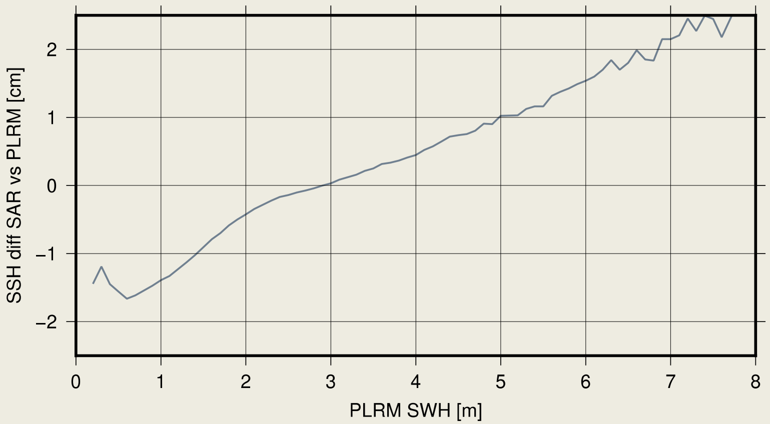
Laboratory for Satellite Altimetry
NOAA·NESDIS·STAR

Motivation for this work

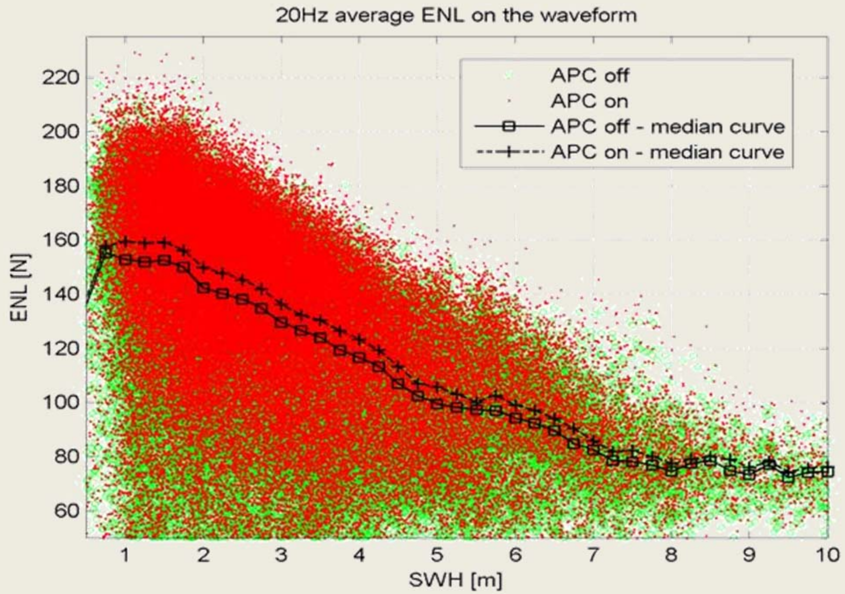
Could all this be related to vertical wave motion?

Existing sea-state dependent trends when comparing SAR vs PLRM for SSH and SWH, already previously observed by [Raynal, et al, OSTST 2018]
Data Source: Sentinel-3A, RADS





Decreasing Effective Number of Looks for a delay/Doppler altimeter as a function of SWH



[Scagliola, Dinardo, Fornari, "An extended Analysis of Along-Track Antenna Pattern Compensation for SAR Altimetry", In proceedings, IGARSS 2015]

Introduction & Background

- The effects of surfaces waves motion on synthetic aperture radar (SAR) images of the ocean surface has been an intense topic of study for a number of decades, [Hasselmann, et al., 1985], [Alpers and Bruening, 1986].
- As the SAR locates targets on the azimuth dimension based on their Doppler history, the main effect of the surface motion is a misplacement of targets within the image.
- In the case of a distributed target as the ocean surface, this displacement originates a degradation of the image in the azimuth dimension.
- The final SAR along-track resolution over the ocean surface can then be written as:

$$\rho'_{aN}(x) = \left[\rho_{aN}^2 + \left(\frac{\pi}{2}(R/V)\,\hat{a}_r(x_0)T\right)^2 + \left(\rho_a \frac{T}{\tau_s}\right)^2\right]^{1/2}$$

  - First term: the system native along track resolution;
  - Second term: induced by the vertical acceleration of surface scatterers (*velocity bunching*);
  - Third term: linked to the loss of coherence due to the dispersion of the vertical motion of the scatterers within the instrument resolution cell (*azimuth smearing*).
- For SAR systems with a moderate resolution, as is the case of delay/Doppler altimetry, waves of intermediate wavelengths are the ones that play a more significant role, and in this case, it is the finite surface coherence that induces the degradation of azimuth resolution, [Alpers and Bruening, 1986].

Azimuth Resolution Degradation

- For our analysis, we will assume that the effect of vertical wave motion is an azimuthal resolution smearing as described in [Alpers and Bruening, 1986].

- Assuming that the ocean wave spectrum can be described by a Pierson-Moskowitz spectrum, then the azimuth smearing can be obtained as:

$$\langle(\delta x)^2\rangle^{1/2} = (R/V)\left[\frac{\alpha}{4}\left(\frac{\pi}{\beta}\right)^{1/2} U^2 \operatorname{erf}(\gamma\rho/U^2)\right]^{1/2}$$

  - R: radar Range
  - V: spacecraft velocity
  - α, β, γ: constants
  - ρ: radar resolution
  - U: wind speed at 19.5 m; assuming a fully developed sea, can be related to wave height as:

$$U^2 = 47.4\ H_s$$

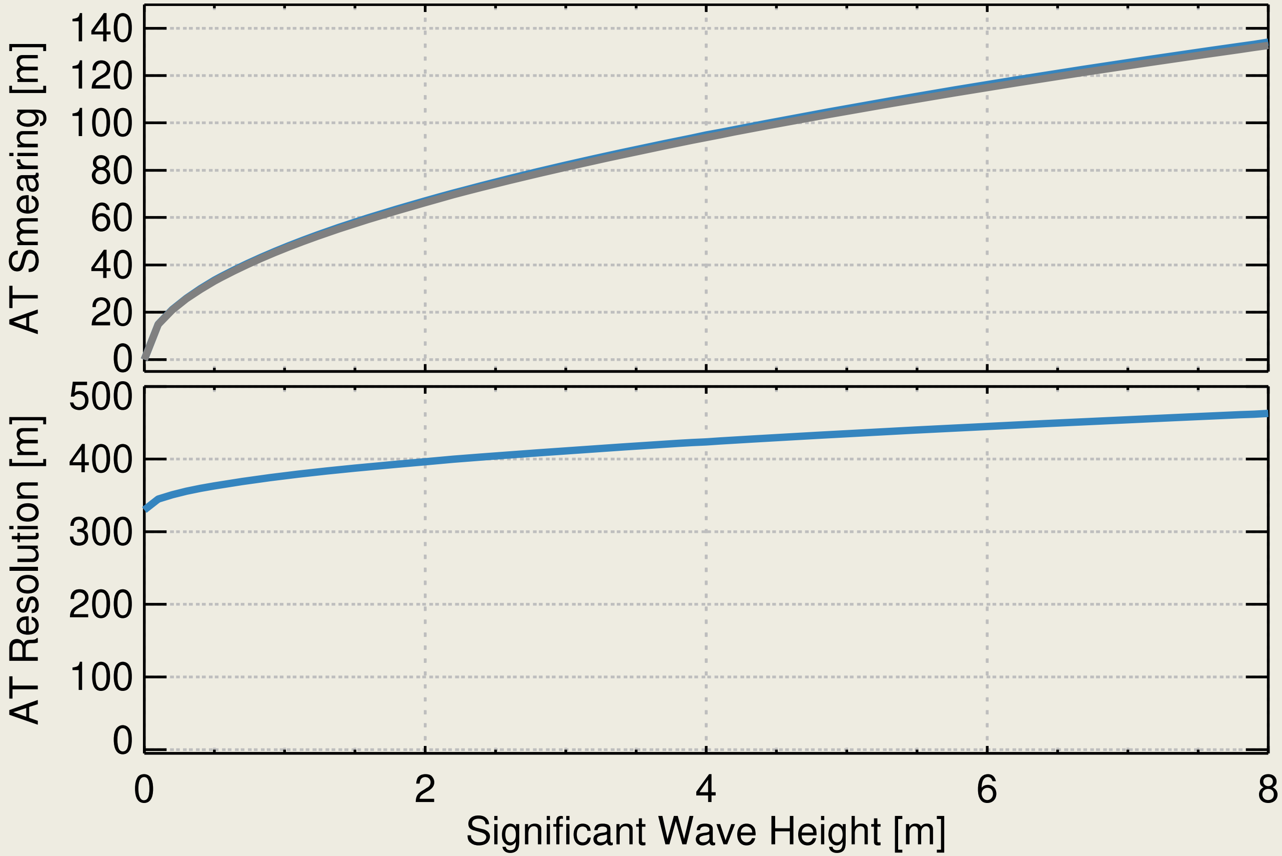
- For typical altimeter configuration, the azimuth smearing equation can be approximated as:

$$\langle(\delta x)^2\rangle^{1/2} = 0.44\ (R/V)H_s^{1/2}.$$

- At all effects, this can be interpreted as a widening of the azimuth point target response (PTR).

Azimuth Resolution Degradation

Azimuth Smearing (due to vertical wave motion) and total Along-track resolution for a delay/Doppler altimeter as a function of SWH.
Top panel, exact (blue) and approximate (grey) AT smearing, both overlapped.



Validating the Resolution Degradation Hypothesis

- Measuring the final resolution, including the vertical motion effect, is not an easy task…
- An option to measure resolution over the ocean is to measure the auto-correlation function (ACF) width of speckle noise.

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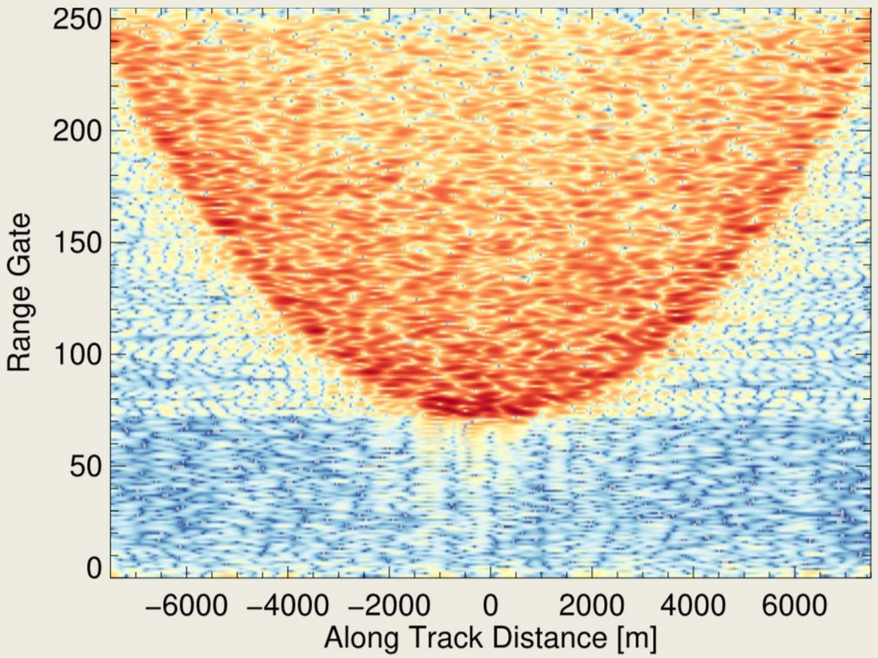
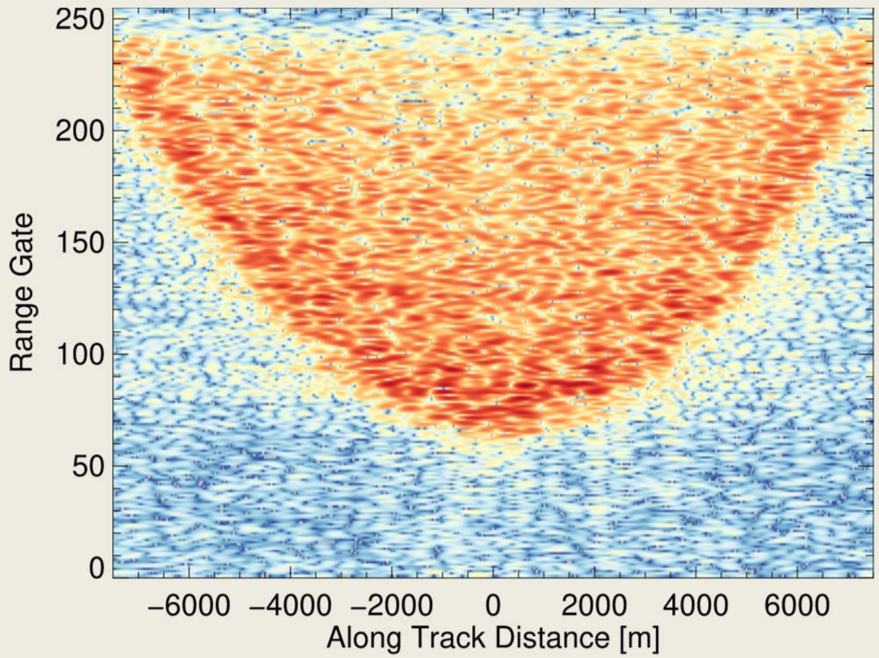
- An option to measure resolution over the ocean is to measure the width of the speckle noise auto-correlation function (ACF).
- To analyze that, we compute a delay/Doppler observation every 5 meters along the track, to have a good sampling of the ACF.

SWH ~1.5 meters



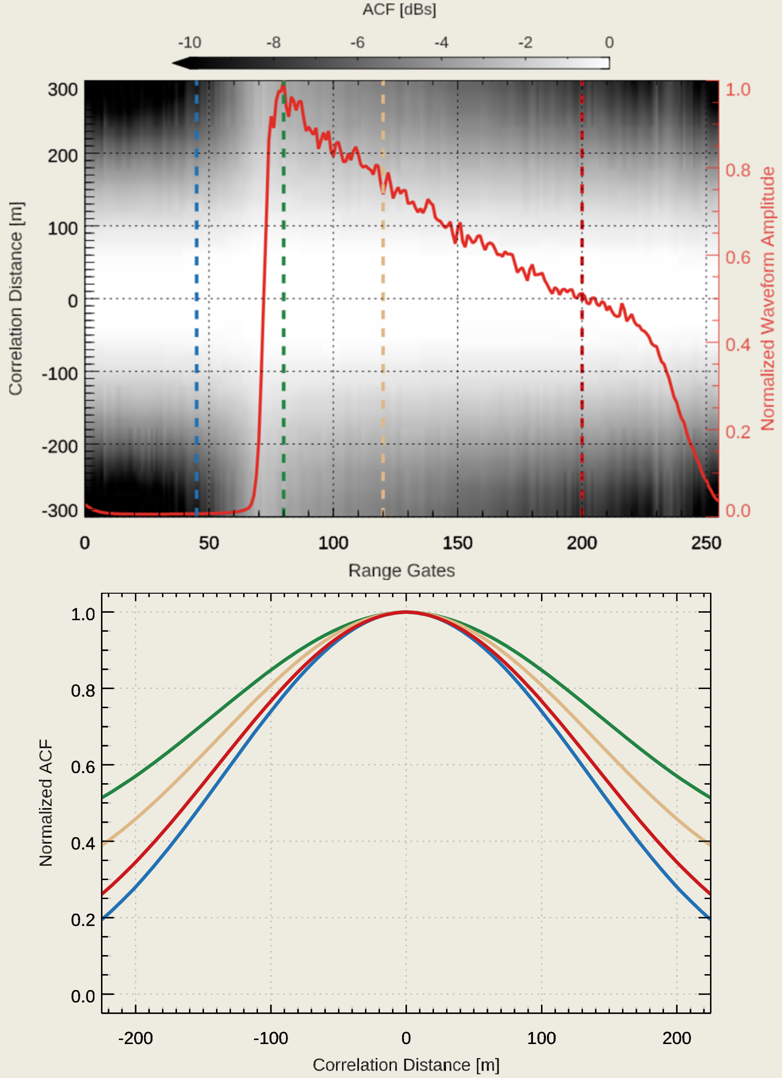
SWH ~5.5 meters



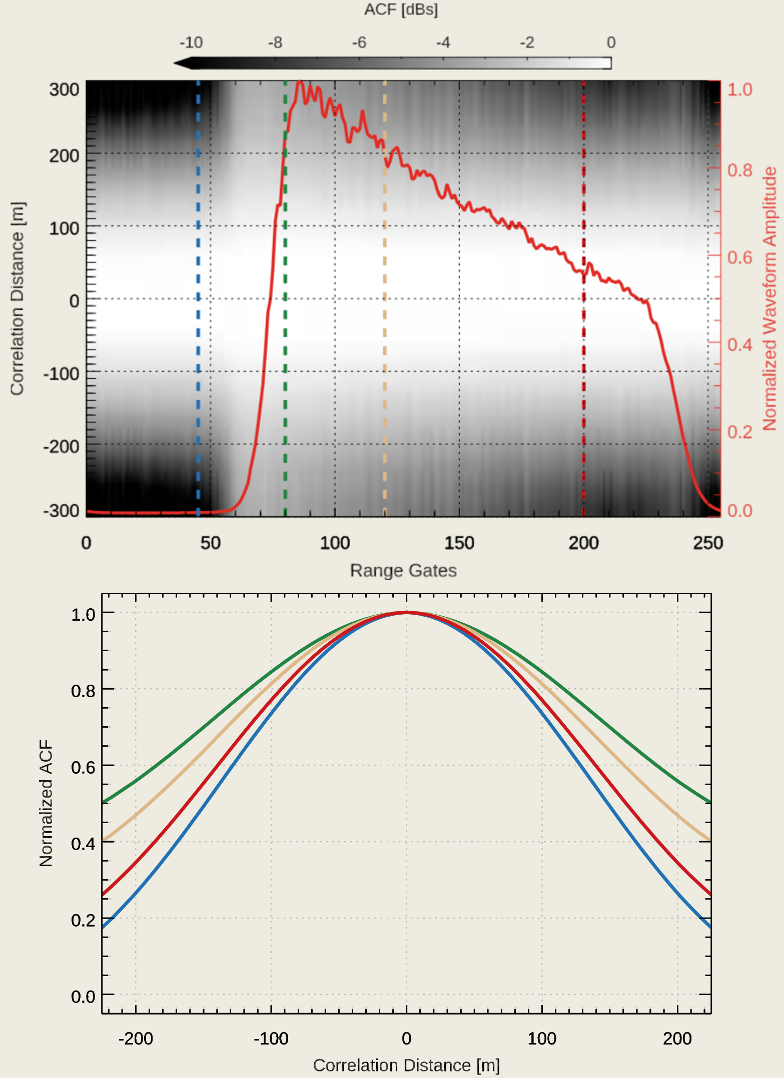
Validating the Resolution Degradation Hypothesis

Along-Track autocorrelation function

SWH ~1.5 meters

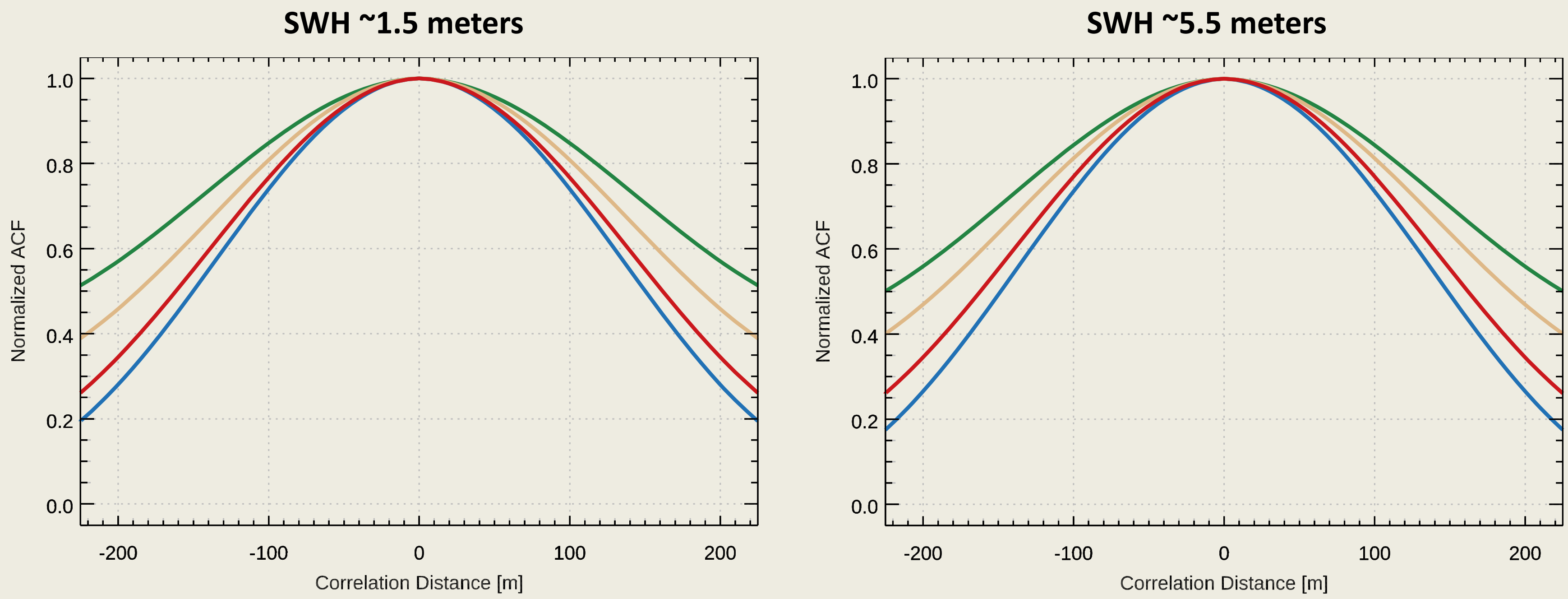


SWH ~5.5 meters



Validating the Resolution Degradation Hypothesis

Along-Track autocorrelation function



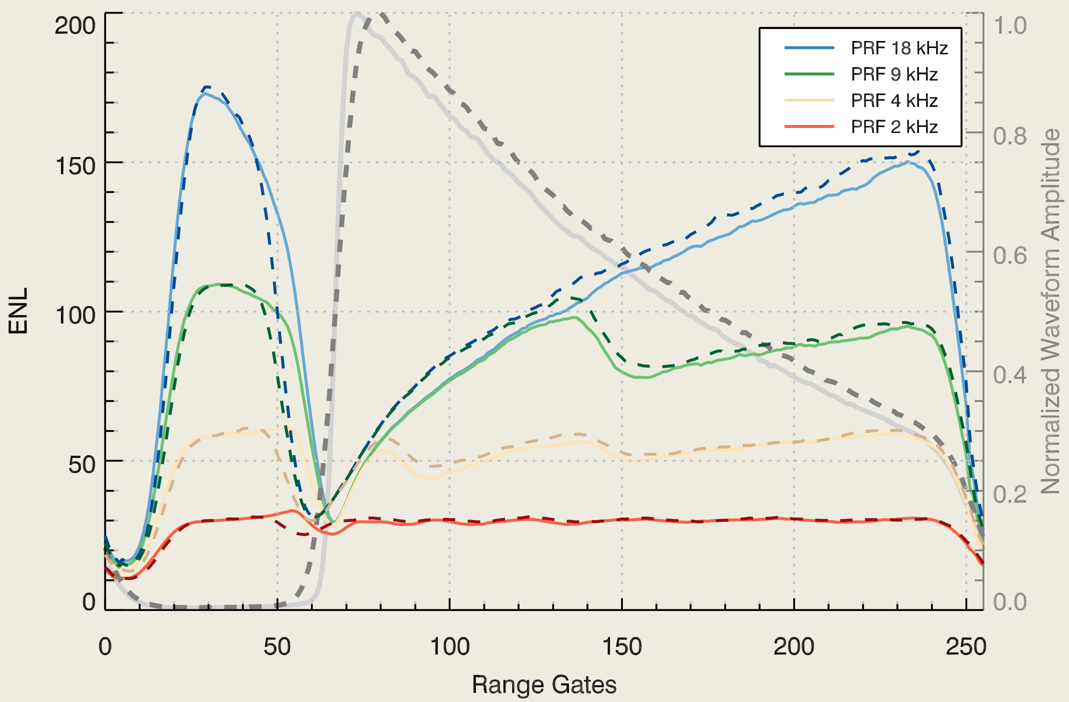
- No significant variation of ACF width…this suggests that single scatterers are essentially “frozen” during focusing, and therefore, not affected by vertical wave motion.
- The vertical motion only displaces the apparent location of targets, but does not change the instrument PTR width; recall that the smearing is due to the vertical velocity spreading within the instrument footprint.
- So how to validate the resolution degradation hypothesis…

Look at the Effective number of looks!

Validating the Resolution Degradation Hypothesis

Effective Number of Looks

- Effective number of looks for pseudo-Low Resolution Mode data



- 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

- However, the situation is reversed for delay/Doppler…

Validating the Resolution Degradation Hypothesis
Effective Number of Looks

SWH ~1.5 meters

From the (*forever*) in-review paper on ASR 25 years of altimetry Special Issue:

The Case for Increasing the Posting Rate in Delay/Doppler Altimeters

Alejandro Egido[a,b,*], Salvatore Dinardo[c], Christopher Ray[a,d]

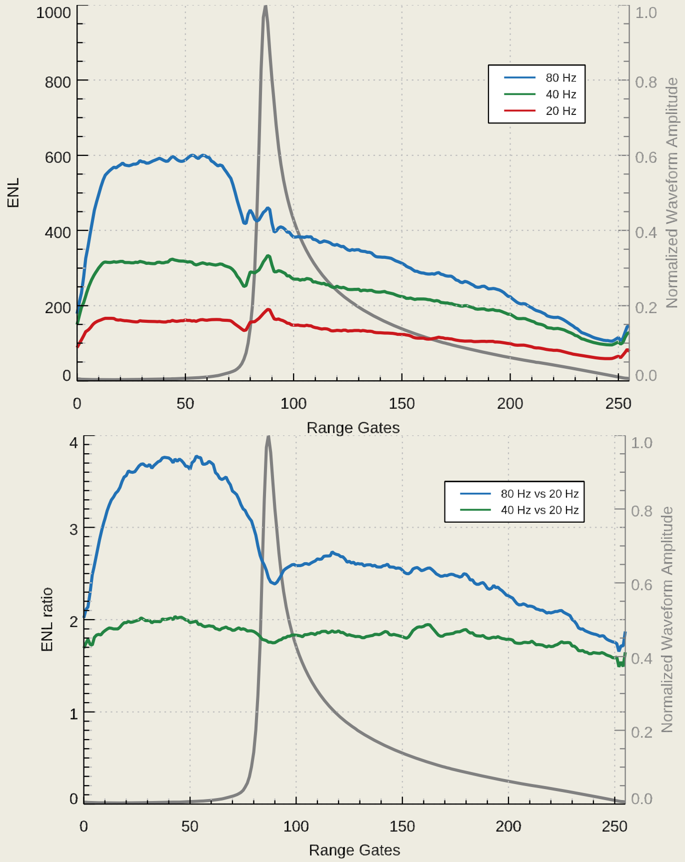
[a] *NOAA Laboratory for Satellite Altimetry, College Park, MD, USA*
[b] *Global Science & Technology, Inc., Greenbelt, MD, USA*
[c] *HeSpace/EUMETSAT, Darmstadt, Germany*
[d] *Saint Mary's College of California, Moraga, CA, USA*

Analysis of the Effective number of looks to justify an increase in the posting rate of delay/Doppler altimetry data.

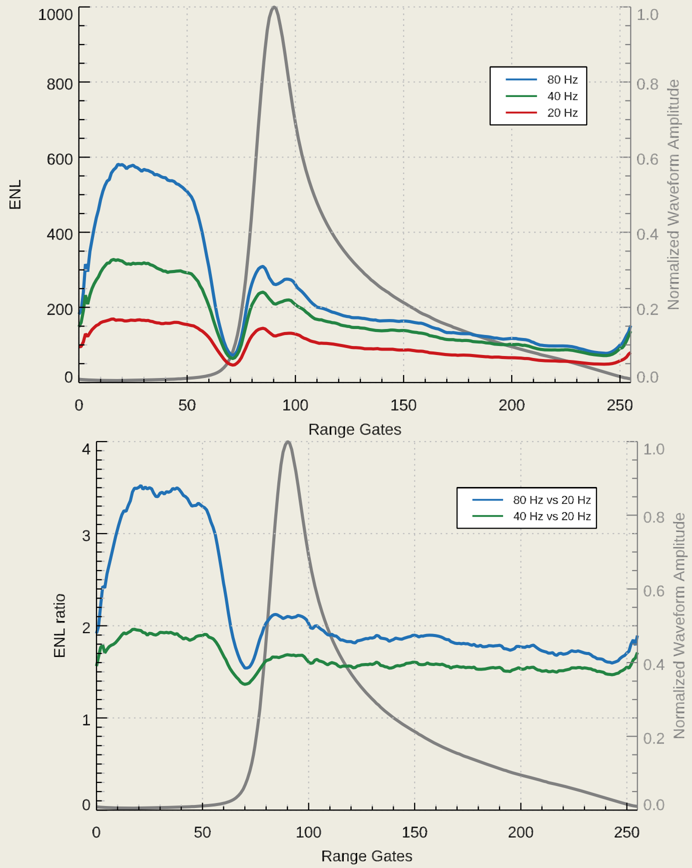
Validating the Resolution Degradation Hypothesis

Effective Number of Looks

SWH ~1.5 meters



SWH ~5.5 meters



- Reduction of ENL at higher SWHs could be attributed to faster changes of ocean parameters.
- However the reduction in ENL ratio (80 vs 20 Hz and 40 vs 20 Hz) is a clearer indication that there "*ought to be*" a degradation in the multilooking, related to the lower along-track resolution.
- A 30-40 % decrease on ENL ratio is consistent with the along-track resolution degradation.

Numerical Simulations

delay/Doppler map computation

$$\text{DDM}(\tau, f) = \frac{\lambda^2}{(4\pi)^3} \int_A \frac{G^2(\vec{\rho})\sigma^0(\vec{\rho})\chi^2(\delta\tau, \delta f)}{R^4(\vec{\rho})} d\vec{\rho}$$

- G: Antenna Gain
- σ^0: Radar Backscattering
- χ: Woodward-Ambiguity Function (WAF)
- R: Distance to point on surface

$$\chi(\delta\tau, \delta f) \approx \text{sinc}\,[B\,\delta\tau]\,\text{sinc}\,[T_i\,\delta f]$$

- B: Chirp signal bandwidth
- T_i: Coherent integration time (burst duration for delay/Doppler)

For altimeter geometry σ^0 and R can be considered to be mostly constant over the antenna footprint, and therefore:

$$\text{DDM}(\tau, f) \approx K \int_A G^2(\vec{\rho})\chi^2(\delta\tau, \delta f) d\vec{\rho}$$

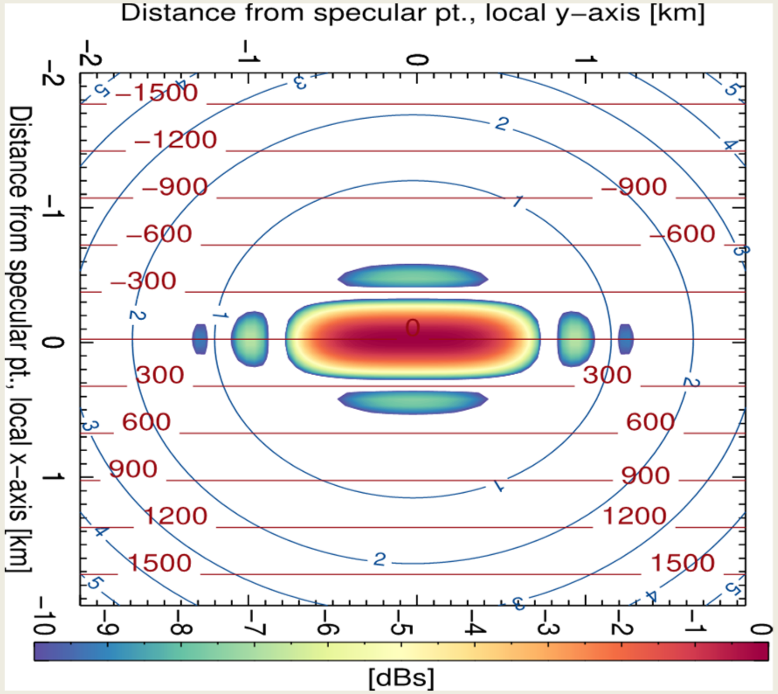
Numerical Simulations

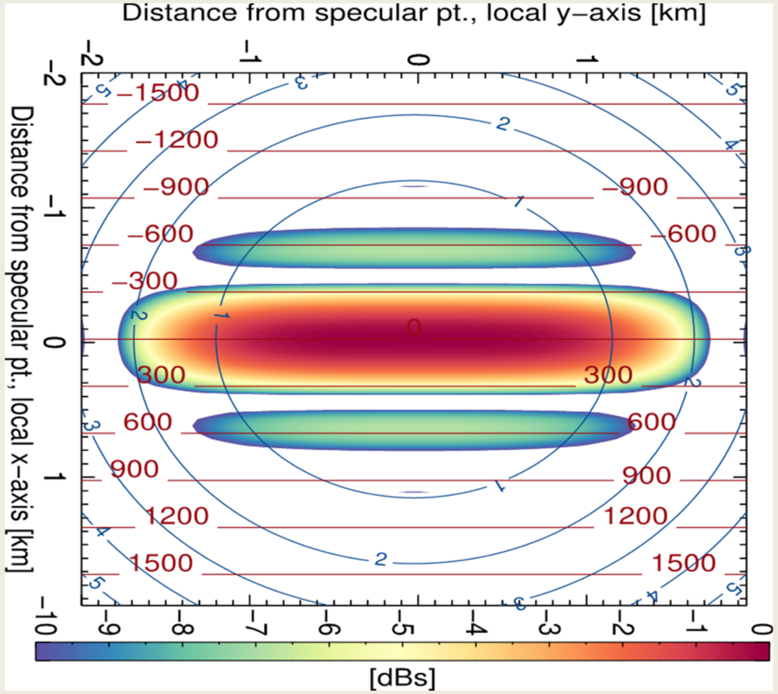
Effect of Vertical Wave Motion: AT Resolution Degradation

- The effect of wave height and wave vertical motion is considered as an

$$\chi(\delta\tau, \delta f; \sigma_z) \approx \text{sinc}\,[B\,\delta\tau] * g(\tau;\sigma_z) \cdot \text{sinc}\,[T_i\,\delta f] * g(\delta f; \langle(\delta x)^2\rangle)$$

  - σ_z: standard deviation of PDF of heights (assumed Gaussian)
  - $<(\delta x)^2>$: Azimuth smearing [Alpers, 1986]

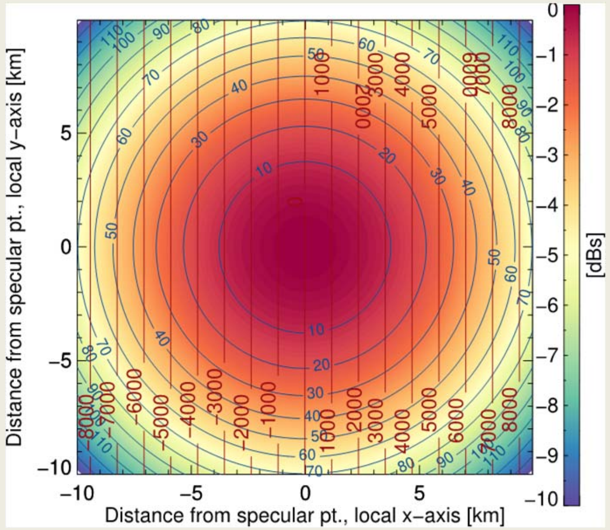




Numerical Simulations

Simulator Configuration

- For the simulations we chose a typical Sentinel-3 configuration:
  - Height over ellipsoid = 800 km
  - Spacecraft velocity = 7500 m/s
  - Chirp bandwidth = 320 MHz
  - Pulse Repetition Frequency = 18.181 kHz
  - 64-pulse bursts
  - No along-track or across-track windowing
  - Antenna Beam width = 1.1 deg
  - SWH range = [0, 8] meters

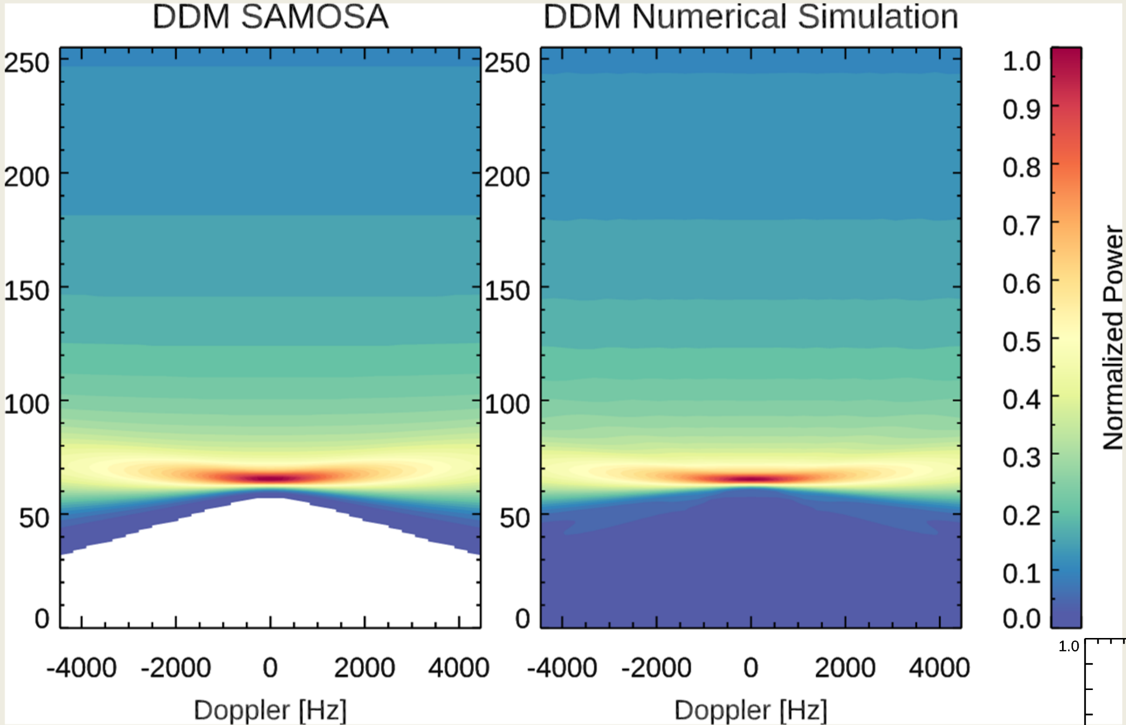


Antenna Pattern projected on the surface

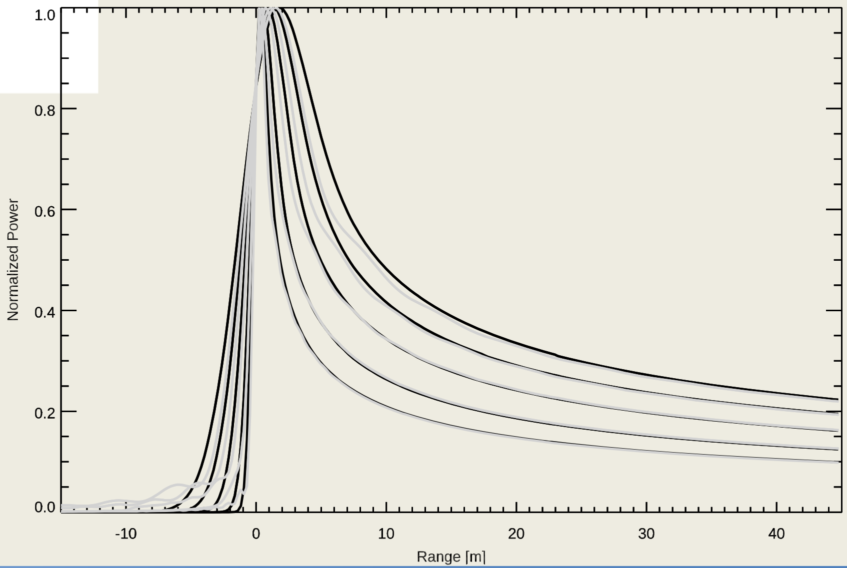
- In order to concentrate on the effect of vertical wave motion (along-track resolution degradation) in the retrieval of geophysical parameters, the simulations were performed *without* speckle or thermal noise.
- Likewise, a flat surface was utilized and the effect of waves was considered just by convolving the response with the wave heights pdf (in fast time) and the resolution smearing along-track.

Numerical Simulations Results

Qualitative comparison numerical DDM vs SAMOSA model



DDM Comparison, SAMOSA vs Numerical



Waveform Comparison for different beams, SAMOSA vs Numerical

Numerical Simulations Results

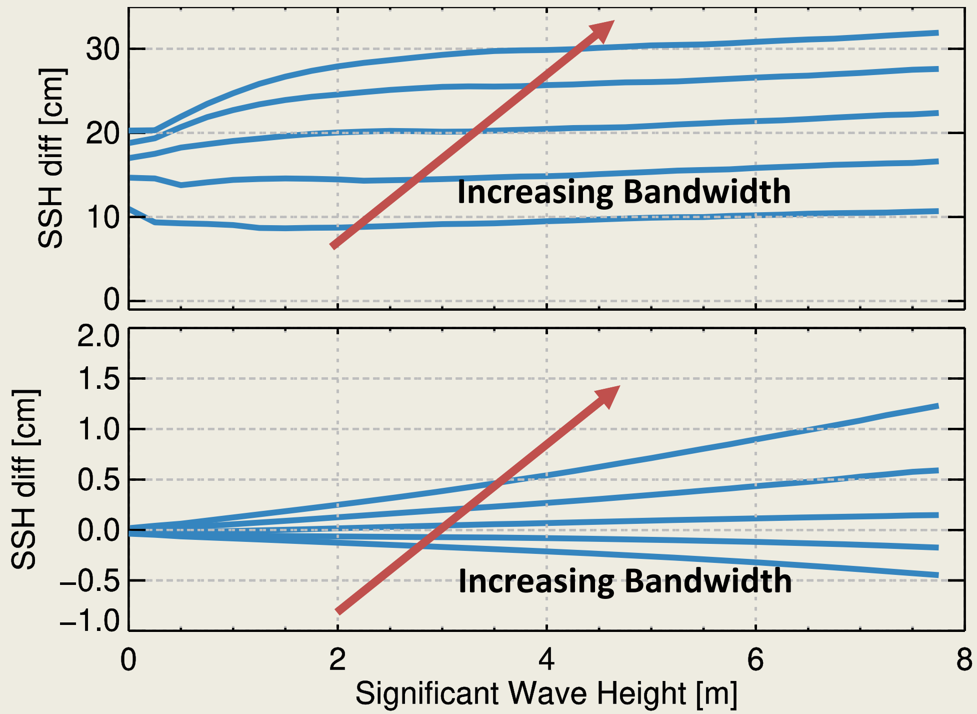
Geophysical Parameter Estimation

- The geophysical parameters retrieval was performed by retracking the numerically computed DDMs.
- For retracking, the same numerical model was used without including the azimuthal resolution degradation due to vertical wave motion.
  - We considered using the SAMOSA model for retracking, however that could introduce biases in the estimation of parameters due to possible discrepancies between the numerical computation and the analytical model, so we ruled out that option.
- The retracking is performed by a Least-Mean Square Error minimization.
- For an efficient computation we implemented a fast convolution method based on Fast Fourier Transforms (FFT).
- The *"null-hypothesis",* i.e. numerical computation performed *without* vertical motion, show virtually no errors in the estimation of significant wave height and sea surface height.

Numerical Simulations Results

Geophysical Parameter Estimation

- Simulations were performed for several Doppler bandwidths:
  - [4000, 6000, 8000, 10000, 12000] Hz
- The vertical motion effect appears to be more significant for outer beams of the DDM given the more noticeable biases with higher bandwidth
- For 12000 Hz (closer configuration to S3 delay/Doppler processing) there is a good qualitative agreement in the trend of the biases with respect to the SAR vs PLRM error analysis, for both SWH and SSH!!



Conclusions and future work

- Vertical wave motion has a significant impact on delay/Doppler altimeter waveforms.
  That could lead to systematic errors in the estimation of geophysical parameters.
- To analyze these effects, we have developed a SAR altimetry numerical simulator.
- We assume an along-track resolution degradation due to vertical wave motion based on a classical SAR paper [Alpers and Bruening, 1986].
  - We have observed that the ENL ratio between 80 Hz and 20 Hz delay/Doppler waveforms presents a similar degradation with wave height as the along-track resolution variation.
- The simulations do not include thermal or speckle noise, just to concentrate on the effect of along-track resolution degradation on the retrieval of geophysical parameters.
- Retracking results with a model that doesn't include vertical wave motion present significant sea state dependent errors, whose trends are comparable to the SAR vs PLRM trends observed in Sentinel-3A data.
- Those trends are highly dependent on the DDM processing options → cooperation with Sentinel-3A ground processor teams necessary!
- The vertical wave motion effect will soon be implemented in the NOAA/LSA SAR Altimetry Processor.
  - We will use that to retrack S3A data to verify if sea-state dependent biases can be mitigated.

References

[Hasselmann, et al., 1985], Hasselmann, K., Raney, R. K., Plant, W. J., Alpers, W., Shuchman, R. A., Lyzenga, D. R., Rufenach, C. L., and Tucker, M. J. (1985), Theory of synthetic aperture radar ocean imaging: A MARSEN view, J. Geophys. Res., 90(C3), 4659– 4686, doi:10.1029/JC090iC03p04659.

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