Correcting for the Vertical Wave Motion Effect in S6-MF Observations of the Open Ocean

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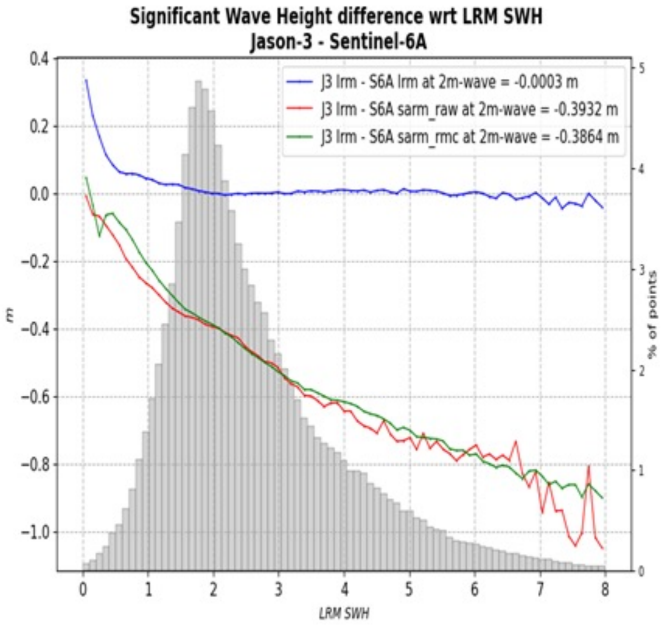
Motivation

- Since the beginning of the mission, we have been observing a strong sea state dependent bias between the S6 HR and LR SWH measurements.
- This has been attributed to the effect of vertical wave motion (VWM).



Credit: CNES

Background

- The effects of surfaces waves orbital 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, the vertical wave motion originates a degradation of the image in the azimuth dimension.
- For SAR systems with a moderate resolution, as is the case of delay/Doppler (SAR) 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].
- In SAR altimetry, the azimuth smearing leads to a broadening of the waveform, which, if not taken into account, originates a bias in the determination of SWH.

Resolution Degradation

- For our analysis, we assume that the effect of vertical wave motion is an azimuthal resolution smearing as described in [Alpers and Bruening, 1986].
- The spread of the facet velocities within a resolution cell causes a broadening of the stationary along-track point target response (AT-PTR). Assuming that the facet velocities within a resolution cell are approximately Gaussian, the broadening or azimuth smearing (AS) can be calculated by convolving the AT-PTR with a Gaussian function, whose rms width equals:

$$\sigma_{AS} = \frac{R}{V}\sigma_v$$

where:

- R: radar Range
- V : spacecraft velocity
- σ_v : standard deviation of radial facet velocity within the resolution cell.

- Assuming deep-water waves and that the dispersion relationship applies, we can compute σ_v for unidirectional waves, bypassing the use of any spectrum of any further assumptions, as:

$$T_{02} = 2\pi\sqrt{\frac{M_0}{M_2}} = \frac{\pi}{2}\frac{H_s}{\sigma_v}$$

where T_{02} is the spectral mean wave period and H_s is the significant wave height.

Resolution Degradation

- Through empirical observations we determined that the azimuth smearing predicted in [Alpers and Bruening, 1986] is overestimated. This is in agreement with previous studies of spectral analysis of SAR images over the ocean; Vachon et al. 1994, Kerbaol et al. 1998, Stopa et al. 2015.

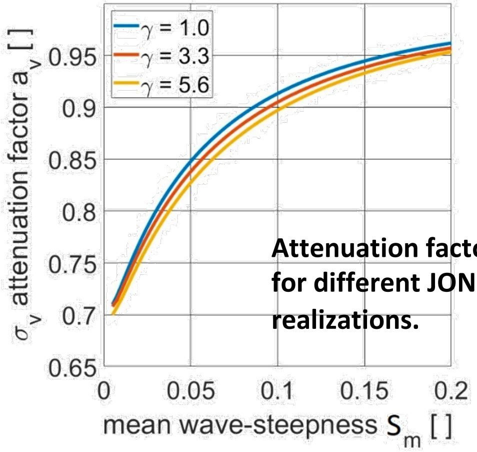
- We therefore developed our own derivation of the azimuth smearing based on Second-Order Stokes waves theory, and determined that Alpers and Bruening's resolution degradation had to be corrected by an attenuation factor, linked to the correlation of surface slopes and vertical velocities, which can be expressed as a function of mean wave-steepness, Sm.

  [*On the Effect of Weakly Nonlinear Deep-Water Waves on SAR Altimetry Signals*, Buchhaupt, et al., accepted, ASR, in press].

- The mean wave steepness can be computed as:

$$S_m = \frac{1}{\sqrt{2\pi(1+\upsilon^2)g}}\frac{\sigma_v^2}{H_s/4}$$

  where n is the spectral frequency width, and g is the gravitational acceleration.
  - ν = 0.39 for a JONSWAP spectra.
  - ν = 0.425 for Pierson-Moskowitz spectra.



Attenuation factor, *av*, computed for different JONSWAP spectra realizations.

Numerical Simulations

delay/Doppler map computation and retracking

- Through numerical simulations we aimed at reproducing the effect of the VWM in the retrieval of geophysical parameters.
- We computed delay/Doppler maps are computed for a Sentinel-6/MF standard configuration, based on the surface integral of the radar equation:

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

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

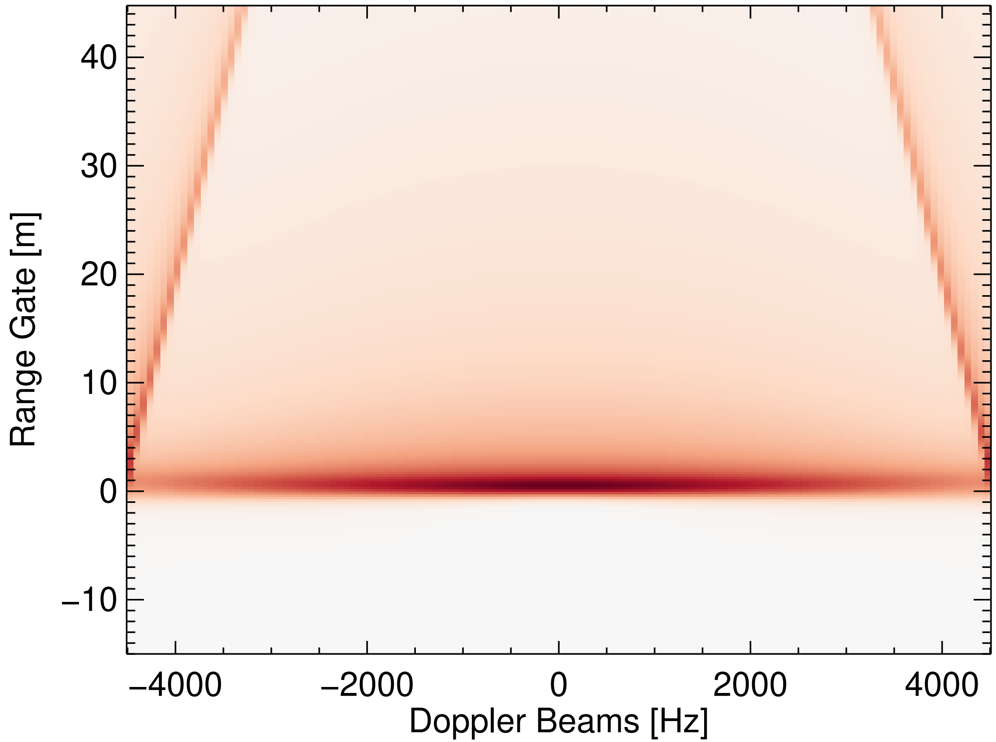
$$\chi(\delta\tau, \delta f) \approx \mathrm{sinc}\left[B\,\delta\tau\right] \mathrm{sinc}\left[T_i\,\delta f\right]$$

  - B: Chirp signal bandwidth, T_i: Coherent integration time (burst duration for delay/Doppler)
- …where the effect of wave height and wave vertical motion is considered as:

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

  - σ_z: standard deviation of PDF of heights (assumed Gaussian)
  - $<(\delta x)^2>$: Azimuth smearing [Alpers, 1986], with attenuation factor [Buchhaupt, et al.]

Numerical Simulations
delay/Doppler map computation and retracking

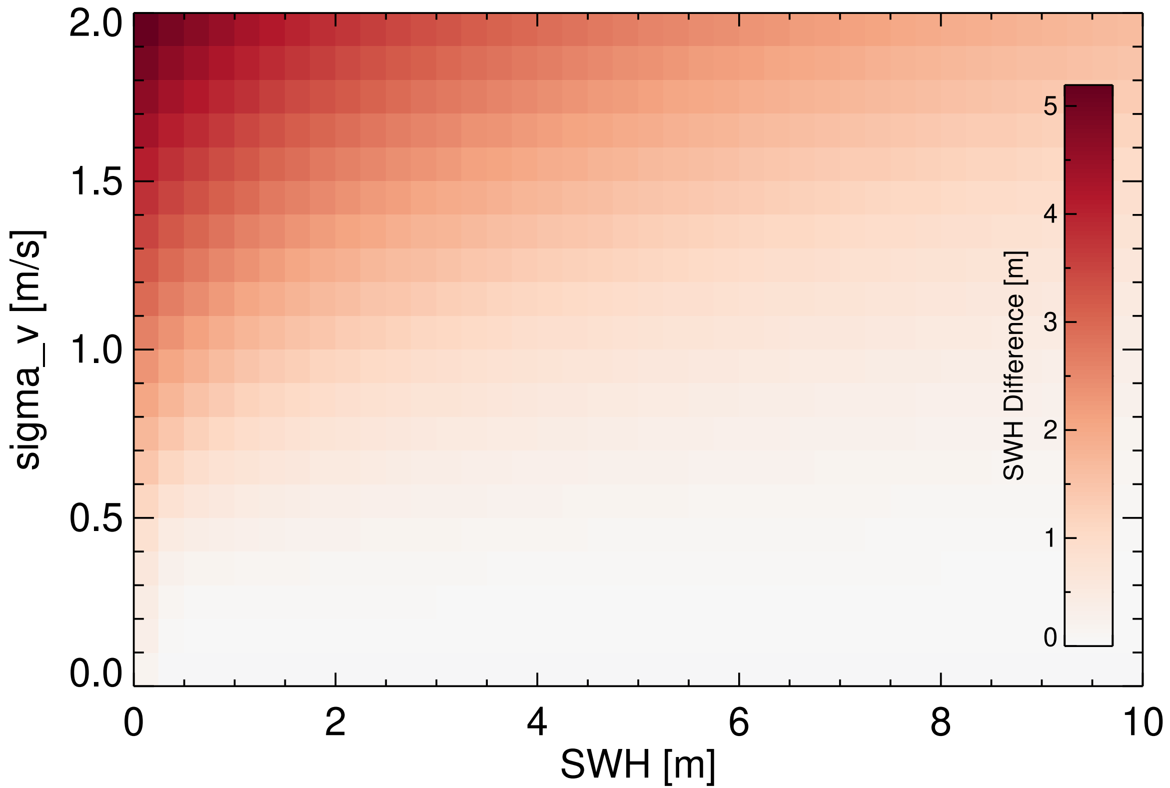


S6/MF simulated DDM example, for SWH = 2 m and σ_v = 0.5 m/s

- The effect of the azimuth smearing is then determined by retracking the VWM affected DDM with a model that does not include such effect.

SWH LUT Correction

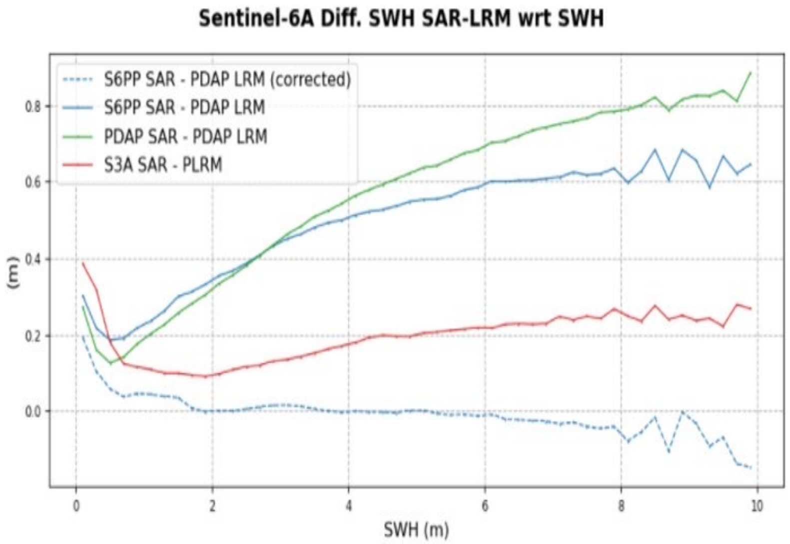
- Based on these simulations, we can now compute a correction for the SWH bias as a function of SWH and σ_v:



SWH LUT Correction

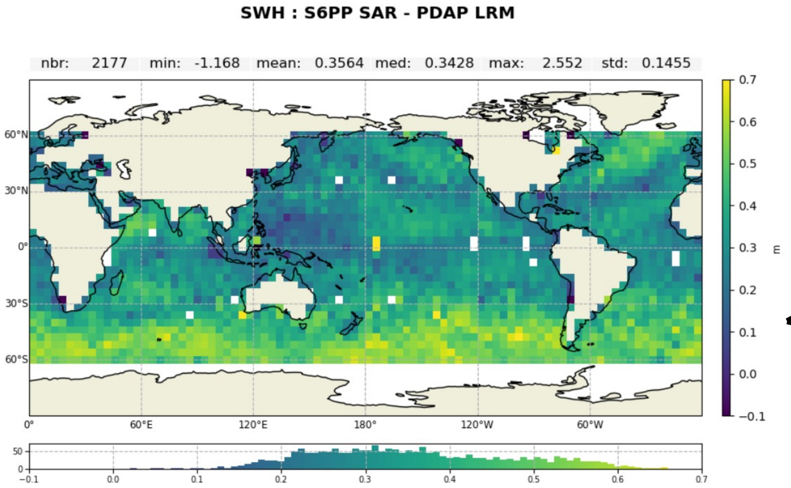
Assessment (CNES/CLS)

- The SWH LUT Correction Drastically reduces HR SWH bias with respect to the low resolution mode data over the open ocean.
  - The results were obtained with CNES's S6PP, using a frequency domain fast convolution numerical retracking approach [Buchhaupt, 2018].
  - σ_v is computed based on the Meteo France WAve Model (MFWAM) mean wave period.
  - PDAP presents an additional bias, which is still under investigation.

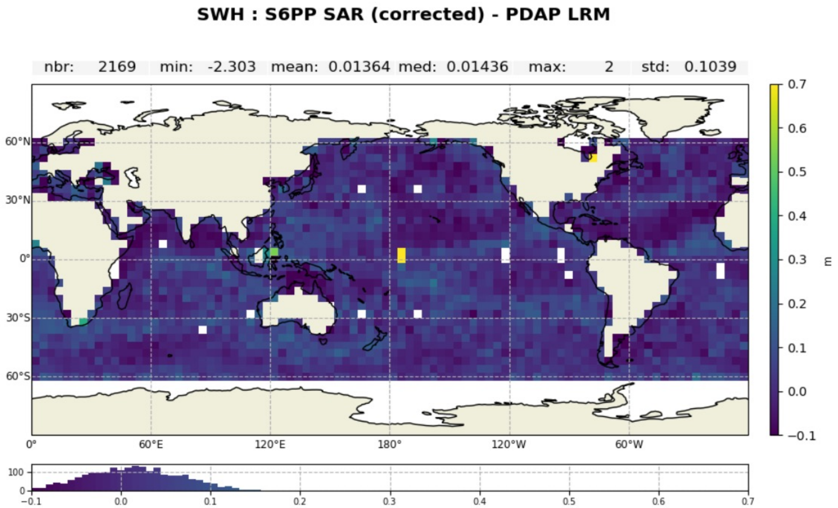


SWH LUT Correction Assessment (CNES/CLS)

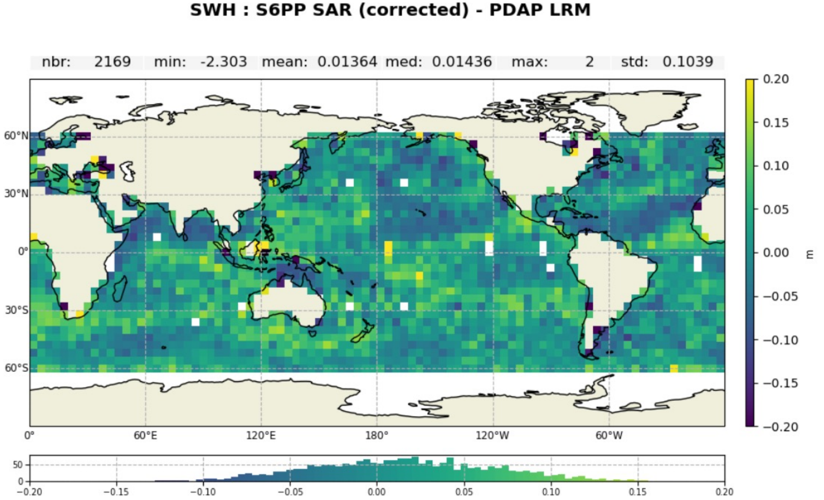
PDAP



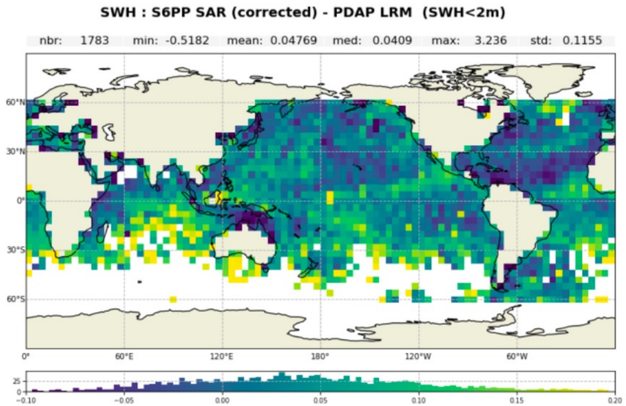
With NOAA's Correction (same scale)

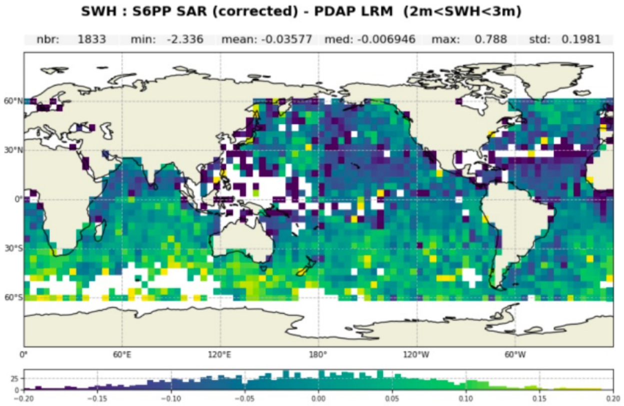


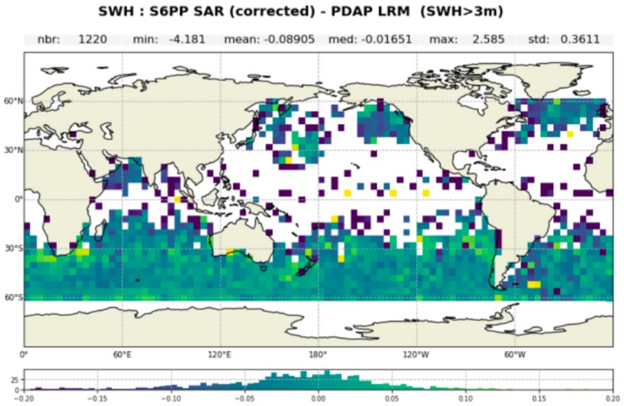
With NOAA's Correction (zoom)



SWH LUT Correction Assessment (CNES/CLS)







With LUT correction, the average SWH SAR bias wrt LRM is minimum for waves between 2 and 3 m :

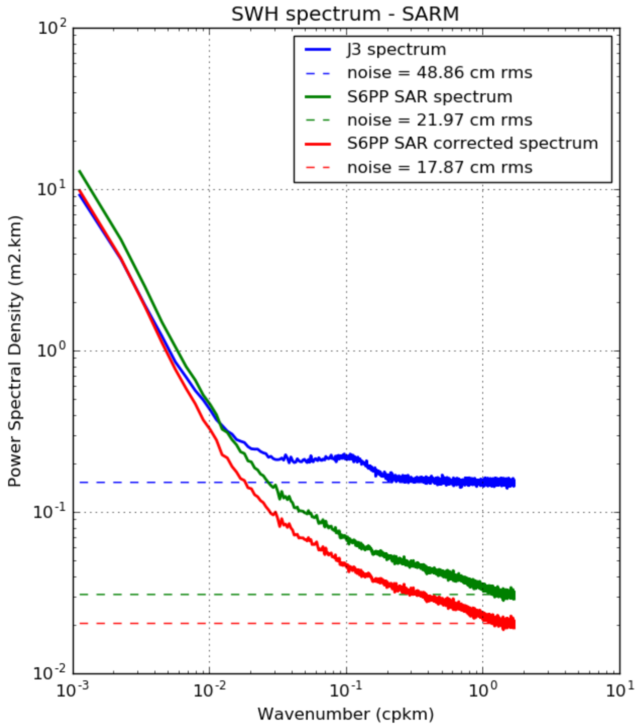
- 4.1 cm bias for SWH < 2 m
- -0.7 cm bias for 2 < SWH < 3 m
- -1.6 cm bias for SWH > 3 m.

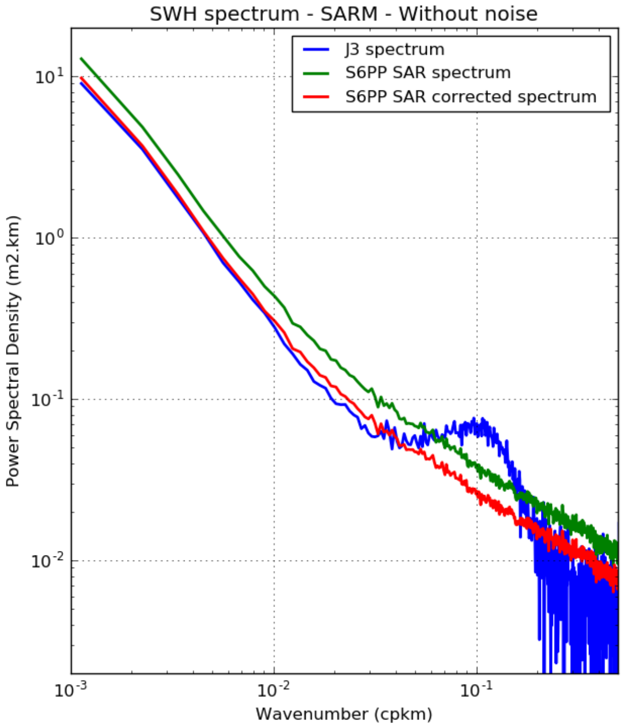
The geographical patterns are stronger for waves below 2m, while the map is cleaner/smoother for SWH>3

SWH LUT Correction

Assessment (CNES/CLS)

- The analysis of the SWH spectrum shows that the application of the SWH LUT Correction reduces the noise level and makes the longer wavelengths to be in agreement with J3.



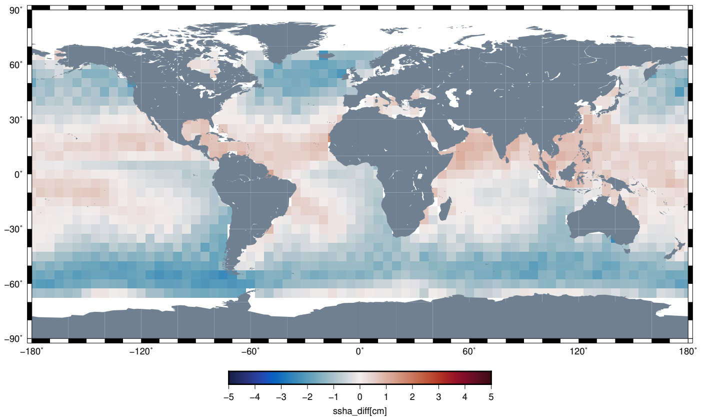


Conclusions

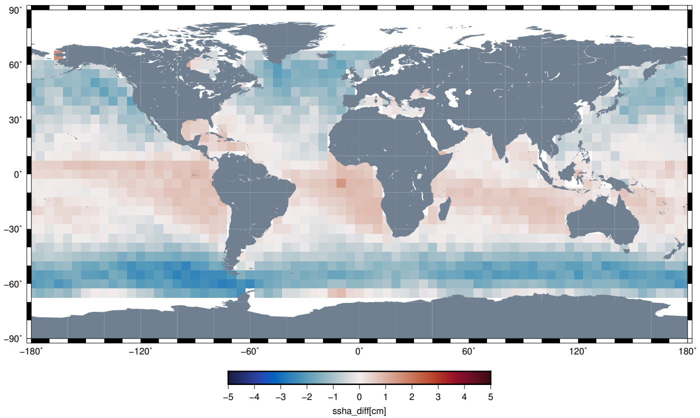
- The SWH sea state dependent biases between the Sentinel-6/MF HR and LR data are now understood at agency level. Its origin has been attributed to the ocean waves' vertical motion.
- We have generated a look up table correction for the HR SWH measurements, that depends on the LR SWH and mean wave period (from wave model).
- The application of this correction highly reduces the biases between the HR and LR SWH measurements and cleans up the SWH spectrum.

SSHA HR – LR, Asc – Des

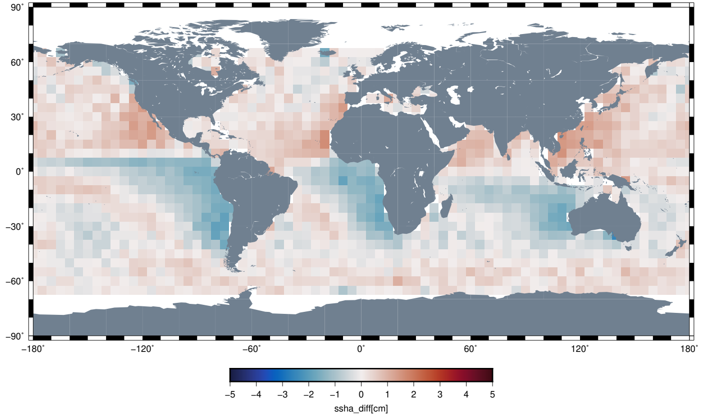
HR - LR SSHA difference - Ascending



HR - LR SSHA difference - Descending



HR - LR SSHA difference – Ascending - Descending



Geographical distribution of SSHA biases between asc. and des. orbits for HR data are correlated with meridional winds patterns.

SSHA HR – LR Difference

The **bias between HR & LR in SSHA** is linked to the **relative wind direction** with respect to the satellite heading…**the bias is in the HR data!**

The **source of this SSHA** bias is attributed to a **Doppler shift** associated to the **cross-correlation between waves orbital velocity and waves slopes**, showing up as an **apparent horizontal wave motion**.

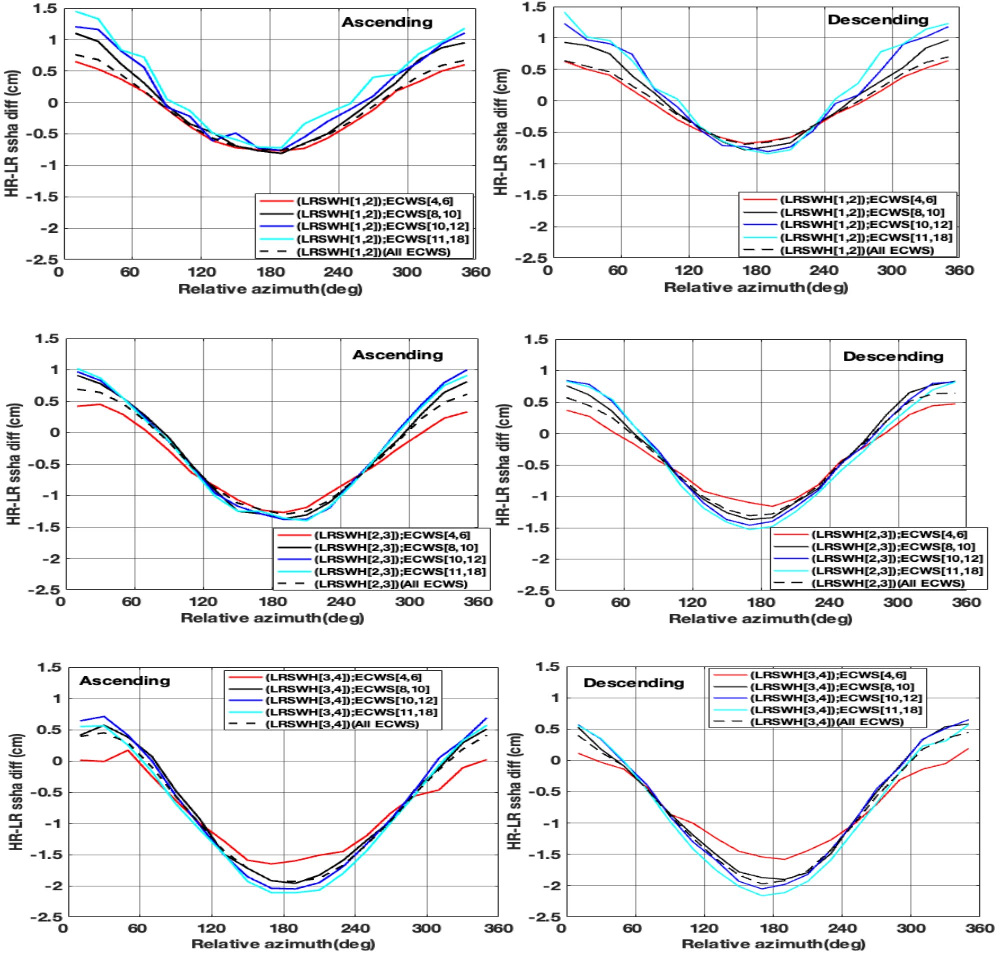
The bias is stronger and with **opposite sign for up-wind and down-wind, zero for cross-wind,** and **SWH dependent.**

This explains the bias between asc. and des. passes for persistent meridional wind regions...

However, **local wind a waves conditions drive the biases between the HR and LR SSH measurements.**

This issue is now "fairly" well understood…

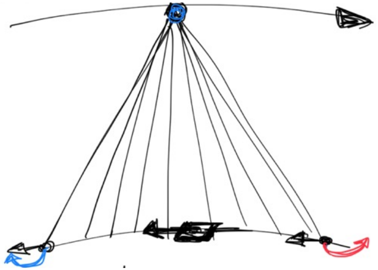
See 2D-numerical Retracking presentation by
C. Buchhaupt, A. Egido, L. Fenoglio, W. Smith presentation.



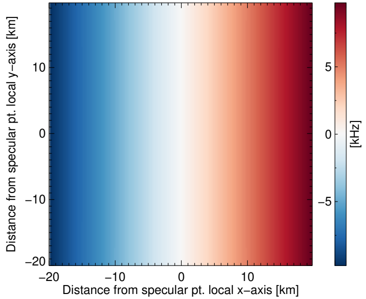
Data and Images courtesy of:
Hui Feng, Doug Vandemark, University New Hampshire.

Wind/Waves induced Doppler

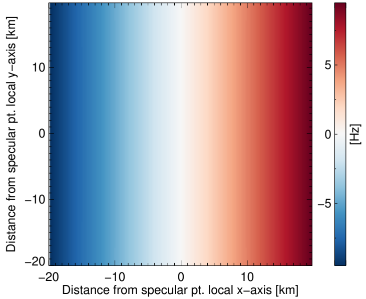
Numerical Simulations – Up-Wind



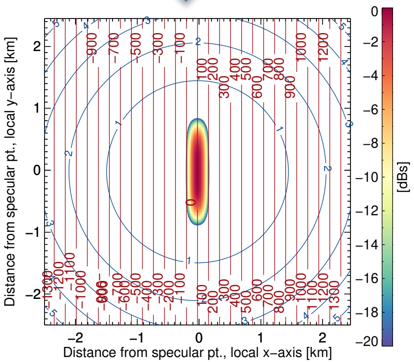
Platform motion Doppler



Surface motion Doppler (7 m/s)



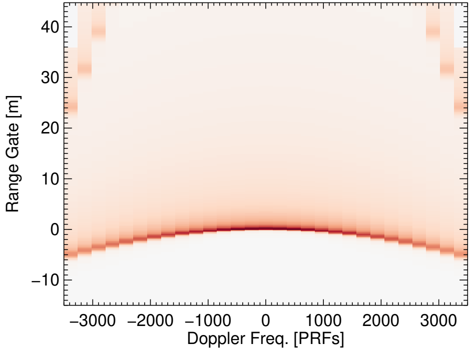
Effect amplification x100



Flat sea surface impulse response

IsoDoppler curves (red); IsoDelay curves (blue)

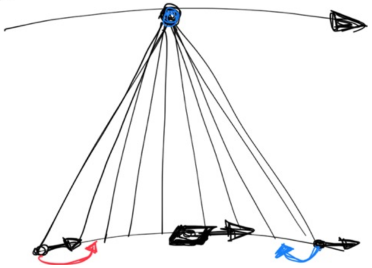
- Points on-ground "expand":
  - Aft. Beam points move away from nadir. (negative Doppler, blue arrow)
  - Fore beam points move closer to nadir. (positive Doppler, red arrow)
- Iso-Doppler curves compress; for the same Doppler bandwidth, less points on the surface are observed; stack span shrinks.
- RCMC is overestimated.



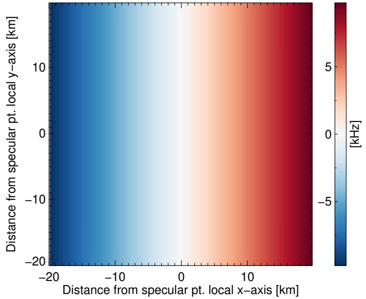
Delay/Doppler Stack

Wind/Waves induced Doppler

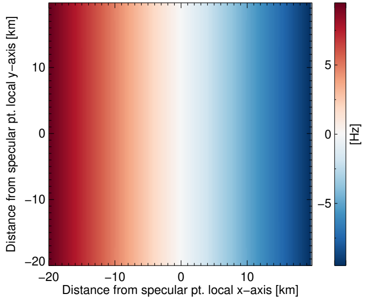
Numerical Simulations – Down-Wind



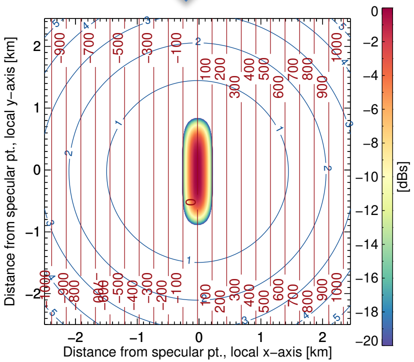
Platform motion Doppler



Surface motion Doppler (7 m/s)



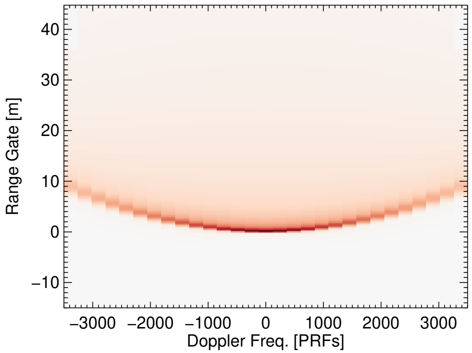
Effect amplification x100



Flat sea surface impulse response

IsoDoppler curves (red); IsoDelay curves (blue)

- Points on-ground "compress":
  - Aft. Beam points move closer to nadir. (positive Doppler, red arrow)
  - Fore beam points move away from nadir. (negative Doppler, blue arrow)
- Iso-Doppler curves separate; for the same Doppler bandwidth, more points on the surface are observed; stack span expands.
- RCMC is underestimated.



Delay/Doppler Stack

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.

[Alpers and Bruening, 1986] W. R. Alpers and C. Bruening, "On the Relative Importance of Motion-Related Contributions to the SAR Imaging Mechanism of Ocean Surface Waves," in IEEE Transactions on Geoscience and Remote Sensing, vol. GE-24, no. 6, pp. 873-885, Nov. 1986.

[Buchhaupt, et al, 2018] Buchhaupt, C., Fenoglio-Marc, L., Dinardo, S., Scharroo, R., Becker, M., (2018), A fast convolution based waveform model for conventional and unfocused SAR altimetry, Advances in Space Research, Volume 62, Issue 6, Pages 1445-1463, ISSN 0273-1177, https://doi.org/10.1016/j.asr.2017.11.039.