Impact of the ocean waves on the Delay/Doppler altimeters: Analysis using real Sentinel-3 data

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Context

- The Delay/Doppler measurement mode, operated globally on Sentinel-3 A and B, demonstrated his interesting capabilities over ocean and opened up a wide field of investigations;
- Indeed, the improvement of the along-track resolution and the reduction of the measurement noise raise the question of the observability of small scales ocean phenomena;
- However, to be capable of interpreting correctly any small scales observations, it is mandatory to fully understand the content of the Delay/Doppler signal;
- Among the phenomena likely to impact the Doppler signals if they are not considered in the processing, we can mention the surface movement combined with the presence of waves.
- A first theoretical analysis performed in the context of a CNES/CLS/MIO PhD (Boisot, 2015) have highlighted the possibility of encountering sea state situations where the Doppler frequency of the radar signal can be significantly affected (Boisot et al. 2016 in IEEE TGRS).
- A second theoretical analysis have shown a possible non negligible impact of waves movements on the altimeter performances (Amarouche et al., OSTST 2019). This analysis has been confirmed using real Sentinel-3 data analysis.

In this presentation, we will focus on the impact of waves motion on the Delay/Doppler processing performances using Sentinel-3 real data analysis.

Conclusions of the theoretical analysis (Amarouche et al. at OSTST 2019)

Theoretical analysis and simulations provided a first characterization of the biases and noises on the Delay/Doppler altimetry geophysical estimates, induced by the surface motion and by the presence of waves.

Very good agreement has been found between the theoretical analysis and the simulation results.

Phenomenon	For a given SWH value	SWH Bias	SWH Noise	Range Bias	Range Noise
Orbital Velocity	Decreasing λ or increasing the Significant Slope All scales, all directions	↗	→	→	→
Long waves geometry	Increasing λ Along-track direction	↘	↗	→	↗
Long waves phase velocity	Increasing λ Along-track direction	↗	↘	→	↘

At a first order and neglecting non linear effects, there is no bias on the range estimates => No direct Pseudo-SSB effect.

However, future studies will be needed to check the impact of the surface non-linearities on the range

Objectives of the present study and content of the presentation

A new analysis with real Sentinel-3 data has been performed:

- To verify the results from the theoretical and simulation-based analysis
- To characterize and assess the impact linked to time evolution of the short and long wavelengths but also to significant slope (correlated with large orbital velocity)

Content of the presentation

➢ Dataset description

➢ Results on non-directional impacts

➢ Results on directional impacts

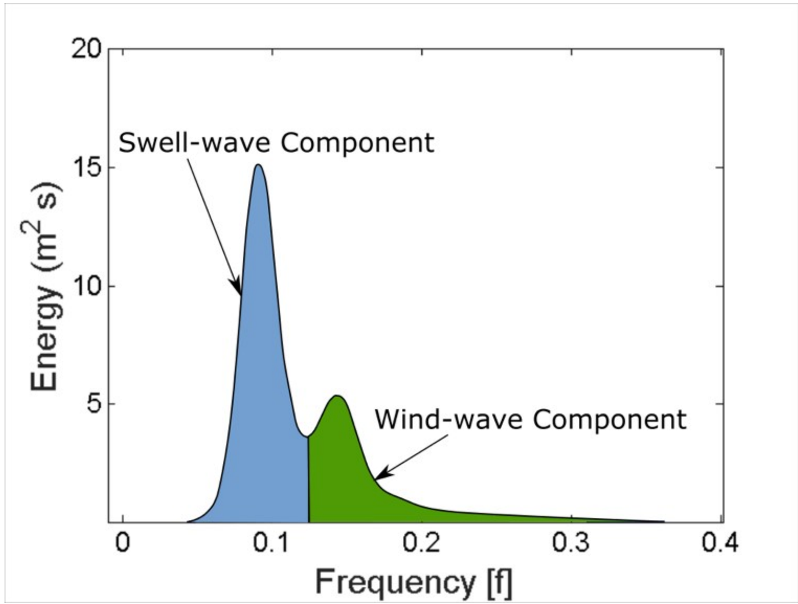
Dataset description

- S3APP v2.1 20-Hz database:
  - Use of 4 months of data to compute global statistics (oct 2016, jan / apr / jul 2017)
  - Comparison of SAR / LRRMC / PLRM behaviors:
    - ✓ LRRMC is supposed to be less affected by long-wavelengths than SAR
    - ✓ But LRRMC should have the same influence of orbital velocity as SAR
- Use of parameters from wave models (ERA-5, MFWAM and WW3)

	SWH	Tp	Tm	T01	T02	Mean Dir
ERA-5	x	x	x	x		x
MF-WAM	x				x	
WW3	x				x	

- Additional parameters computed from models:
  - wavelength (L) and significant slope (S) from period data
  - azimuth angle (az) from mean wave direction

Wave spectra parameters definition



m0 = area under spectral curve = total variance
→ SWH = 4 sqrt(m0)

Tp = peak period associated with the highest energy (swell component or wind-wave component)

T01 = m0/m1, wave period corresponding to the mean frequency of the spectrum, which is less dependent on high-frequency noise than T02

T02 = sqrt (m0/m2), average wave period theoretically equivalent with mean zero-crossing period (~Tz)

Tm = mean of all wave periods

$$m_x = \iint f^x S(f,\phi)\, df\, d\phi$$

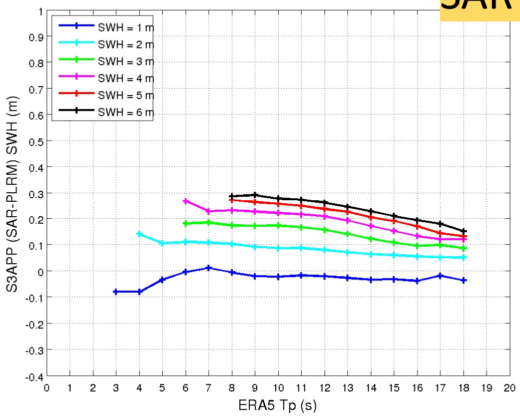
m_x : $x-$*order moment*
S : *wave height spectrum*
f : *wave frequency*
ϕ : *wave direction*

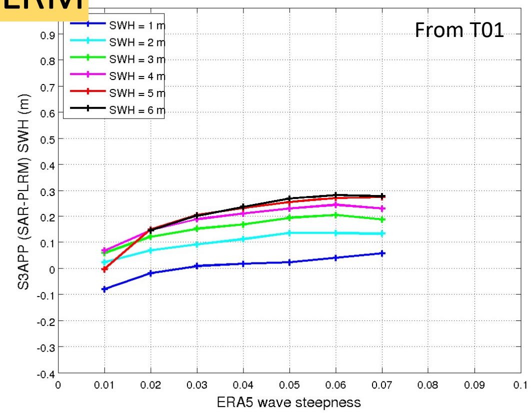
Behaviors without looking at direction

Impact on SWH biases

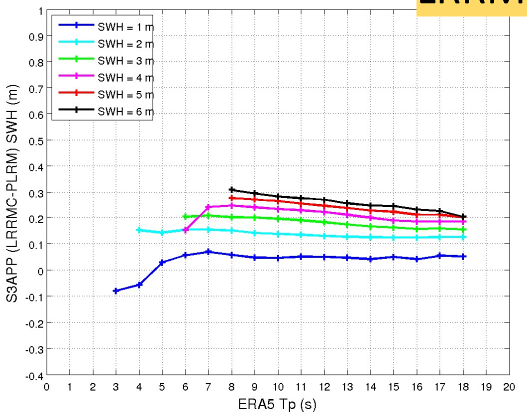
wrt T: Effects of long wavelenghts | wrt S: Effects of vertical velocity

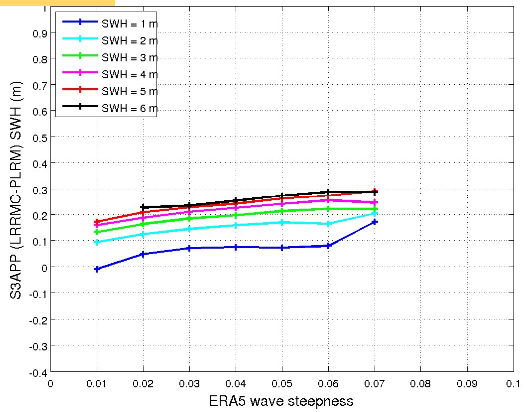
SAR - PLRM





LRRMC - PLRM





Low peak period values

- ✓ Domination of orbital velocity effects
- ✓ SAR-PLRM and LRRMC-PLRM SWH biases of the same order of magnitude

High peak peridod values

- ✓ Domination of swell effects
- ✓ Higher impact on SAR than LRRMC

Low Steepness values

- ✓ Domination of swell effects
- ✓ Higher dependency on SWH of SAR-PLRM SWH biases than LRRMC-PLRM

High Steepness values

- ✓ Domination of orbital velocity effects
- ✓ Same impact on SAR as LRRMC

✓

For a given SWH value :

Wave period ↗ => Wavelength ↗ => SWH Bias ↘ => Impact on the SAR mode

Steepness ↗ => Orbital velocity ↗ => Horizontal Doppler Shift ↗ => SWH Bias ↗ => Same impact on the SAR and LRRMC modes

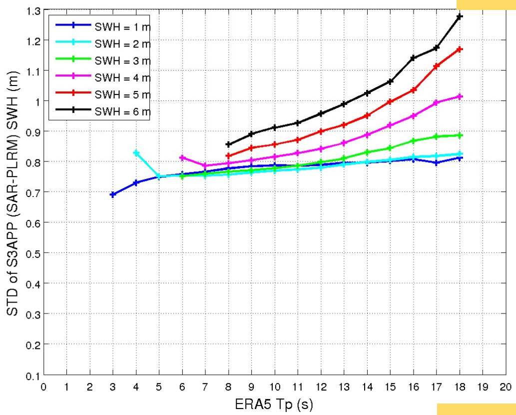
This is consistent with the previous qualitative theoretical analysis

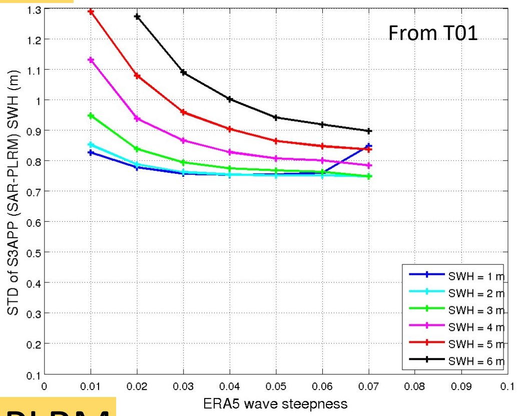
Impact on SWH variability

wrt T: Effects of long wavelenghts

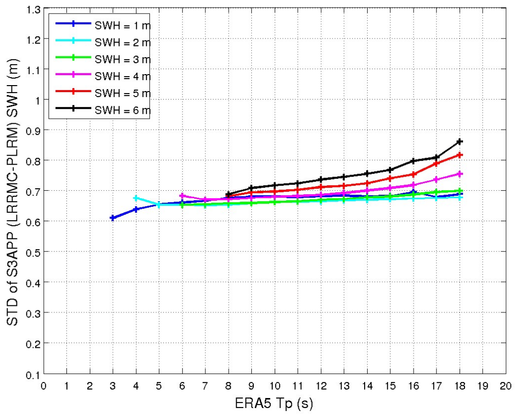
wrt S: Effects of vertical velocity

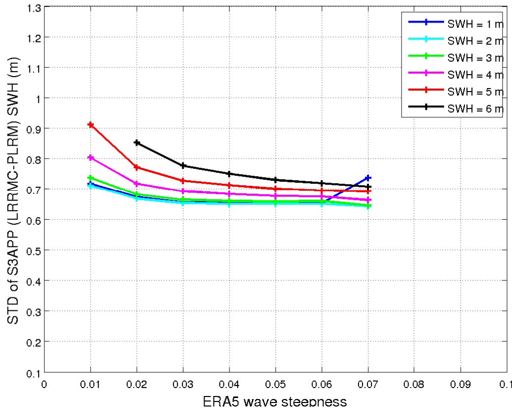
SAR - PLRM





LRRMC - PLRM





Low peak period values

- ✓ Domination of orbital velocity effects
- ✓ SWH variability of the same order of magnitude for SAR and LRRMC

High peak peridod values

- ✓ Sensitivity of the SAR mode to the high wavelengths swell effects
- ✓ SAR SWH variability higher than LRRMC

Low Steepness values

- ✓ Domination of swell effects
- ✓ SAR SWH variability incerases and is higher than LRRMC SWH variability

High Steepness values

- ✓ Domination of orbital velocity effects
- ✓ Same impact on SAR and LRRMC

✓

For a given SWH value :

Wave period ↗ => Wavelength ↗ => SWH variability ↗ => Impact on the SAR mode

Steepness ↗ => Orbital velocity ↗ => Swell effects↘ => SWH variability ↘ => Same impact on the SAR and LRRMC modes

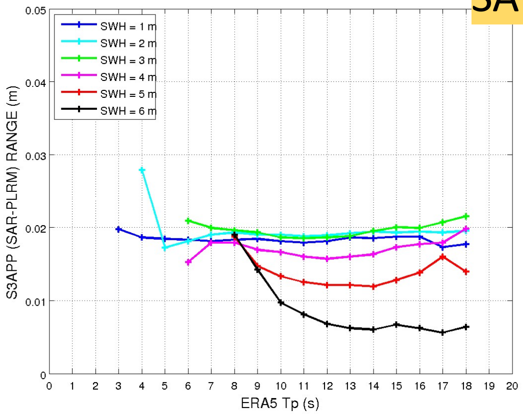
This is consistent with the previous qualitative theoretical analysis

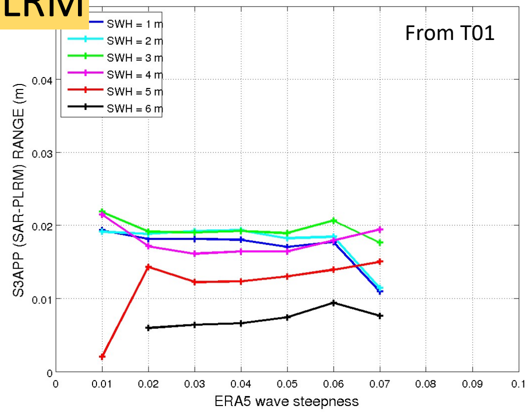
Impact on range biases

wrt T: Effects of long wavelenghts

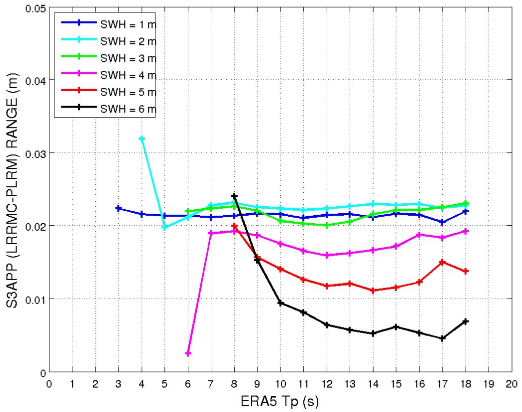
wrt S: Effects of vertical velocity

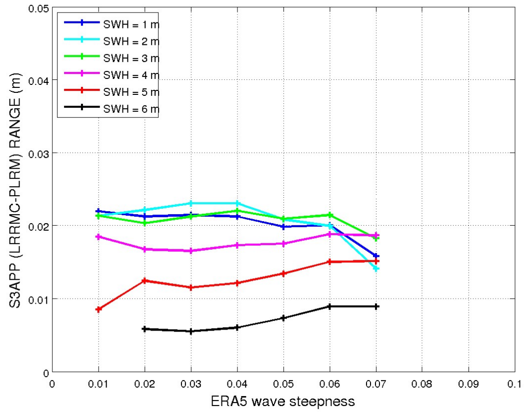
SAR - PLRM





LRRMC - PLRM





- ✓ Same range bias is observed for both SAR and LRRMC modes
- ✓ Dependency on the peak period
- ✓ However, no steepness dependency is observed
- ✓ Same behaviour for SAR and LRRMC
- ✓ To be further analysed: May be related to non linear effects

Additional SSB on the SAR/LRRMC modes ?

3D SSB because of Tp dependency ?

?

For a given SWH value :

Identification of non-linear effects that were not yet analysed theoretically (analysis expected in the work perspectives)

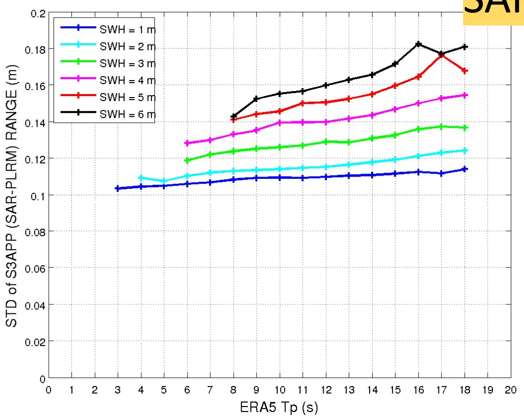
Range biases to be further analysed.

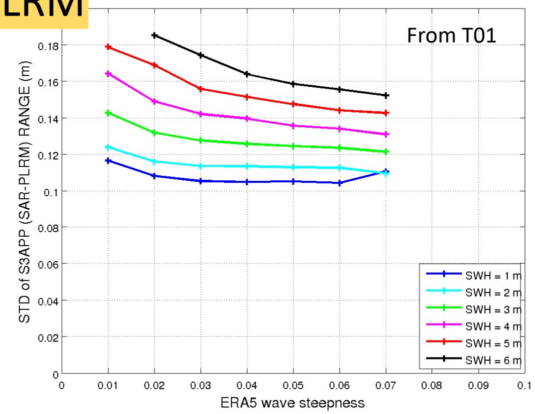
Impact on range variability

wrt T: Effects of long wavelenghts

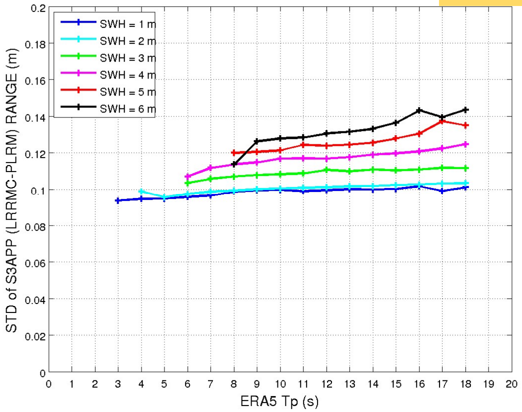
wrt S: Effects of vertical velocity

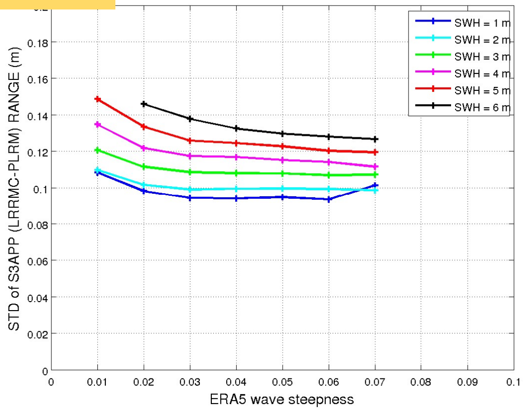
SAR - PLRM





LRRMC - PLRM





Low peak period values

- ✓ Domination of orbital velocity effects
- ✓ SAR range variability is closer to LRRMC range variability

High peak peridod values

- ✓ Domination of swell effects
- ✓ SAR range variability is significantly higher than LRRMC range variability

Low Steepness values

- ✓ Domination of swell effects
- ✓ SAR range variability is significantly higher than LRRMC range variability

High Steepness values

- ✓ Domination of orbital velocity effects
- ✓ SAR range variability is of the same order as LRRMC range variability

For a given SWH value :

Wave period ↗ => Wavelength ↗ => range noise ↗=> Impact on the SAR mode

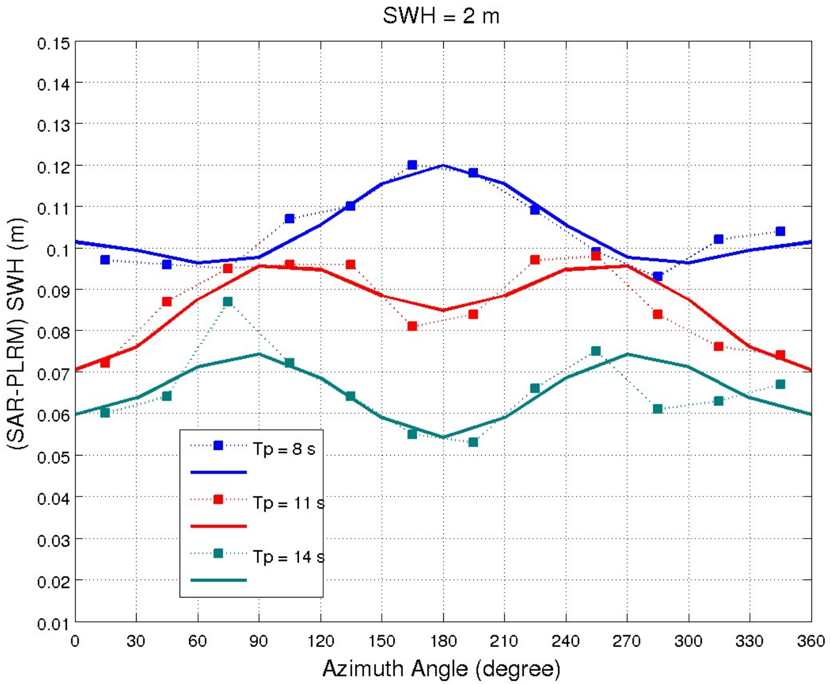
Steepness ↗ => Orbital velocity ↗ => Horizontal Doppler Shift ↗ => Same impact on the SAR and LRRMC modes

This is consistent with the previous qualitative theoretical analysis

Behaviors wrt wave direction

Examples of behaviour with wave direction

SAR-PLRM SWH Bias

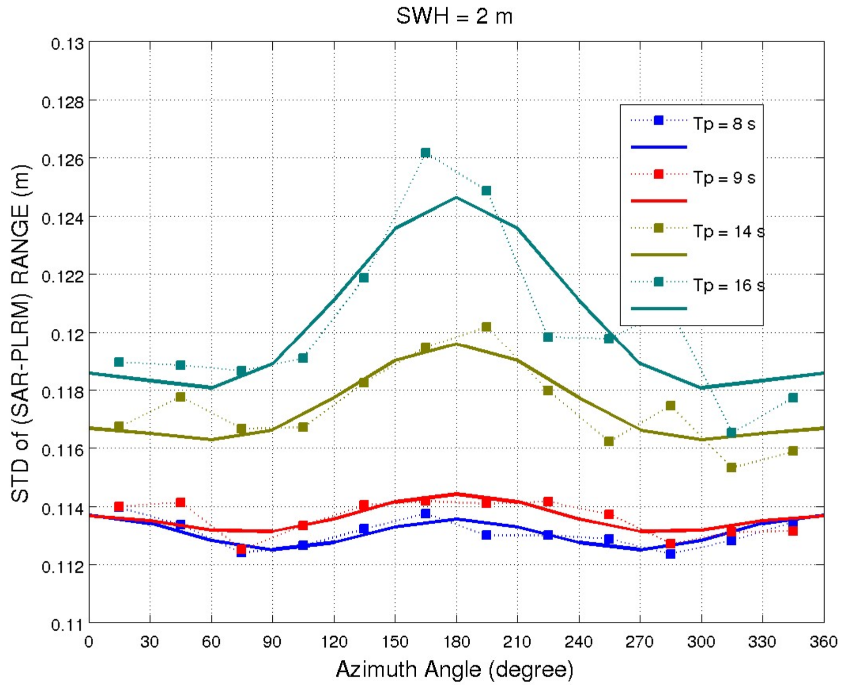


Upwave look direction(0°)
→ satellite direction
← wave direction

Downwave (180°)
→ satellite direction
→ wave direction

Crosswave (90 or 270°)
→ satellite direction
↑ or ↓ wave direction

SAR-PLRM range variability



SWH bias decreases with increasing peak period for alongwaves direction (upwave and downwave) = > Consistent with theoretical analysis
For Tp = 8 s, the behaviour is different. **Azimut dependency to be further analysed.**

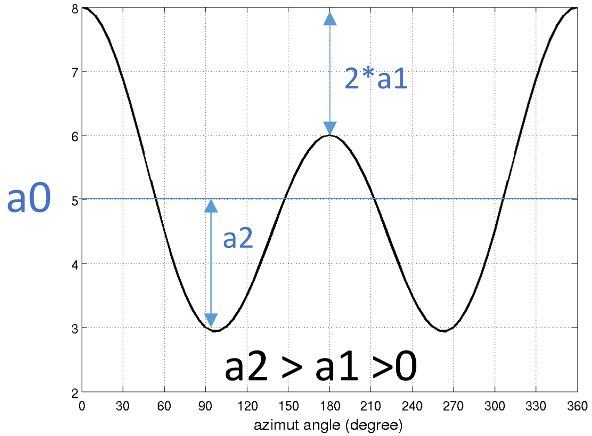
A difference in range variability is observed between upwaves and downwaves. **To be further analysed.**

Wave direction impact modeling

azimuth angle (az) = wave direction vague – satellite flying direction
(direction with respect to north in both cases)

Modeling based on the function   a0 + a1 cos(az) + a2 cos(2 az)

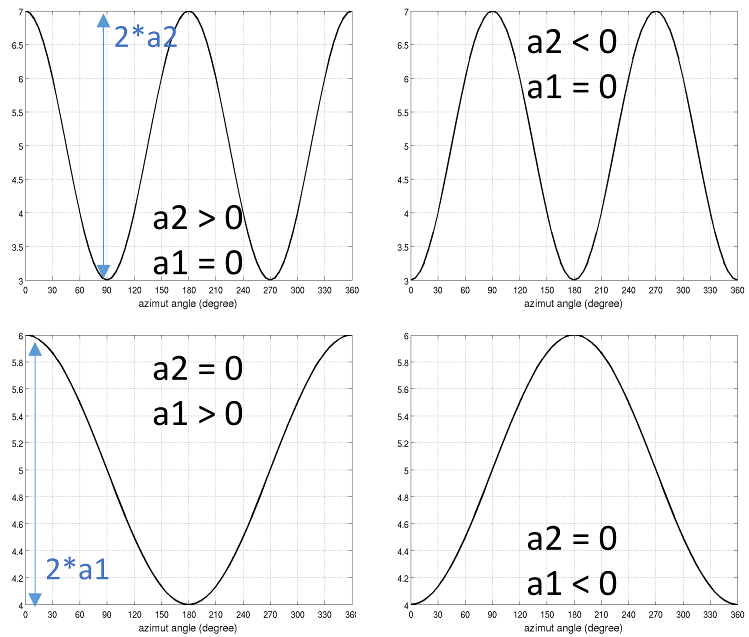
Upwave look direction(0°)
→ satellite direction
← wave direction



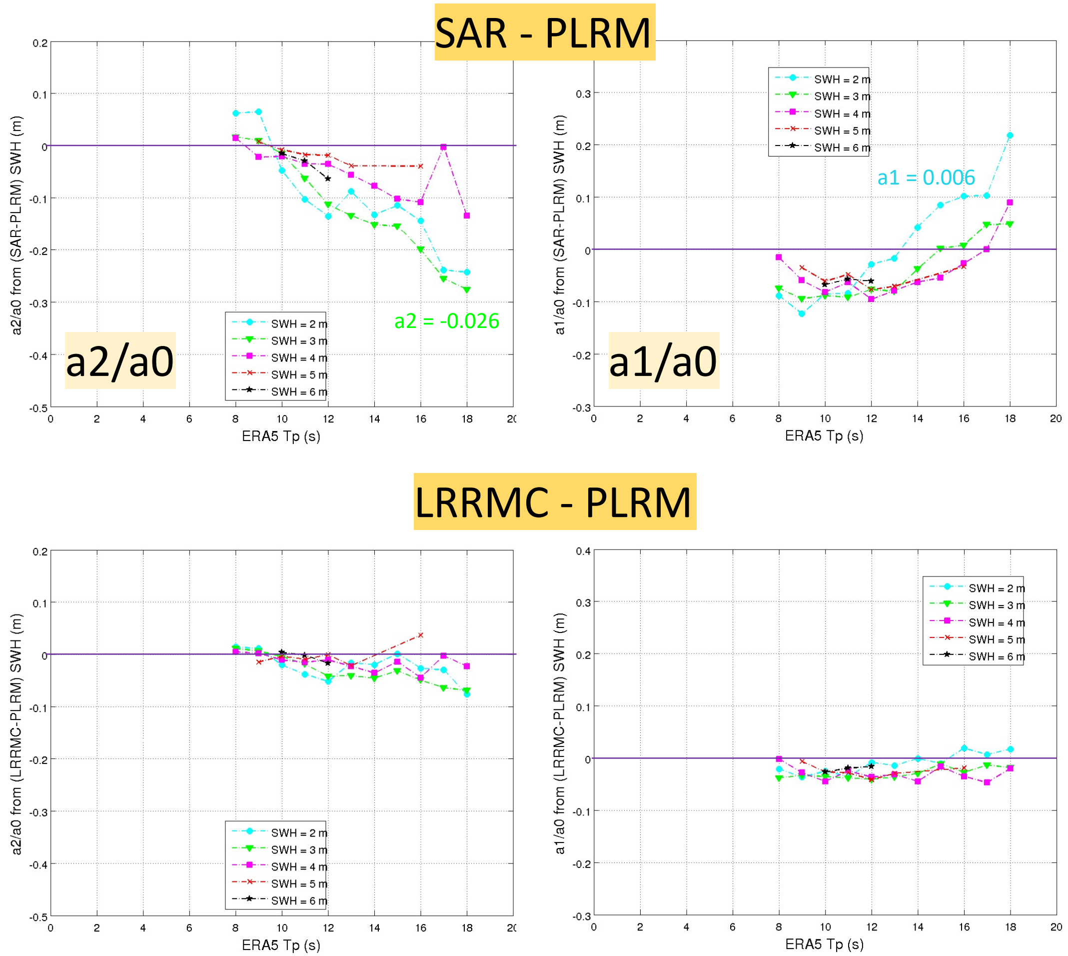
Downwave (180°)
→ satellite direction
→ wave direction

Crosswave (90 or 270°)
→ satellite direction
↑ or ↓ wave direction

a1 ≠ 0 => Upwave/Downwave
a2 ≠ 0 => Crosswave/Alongwave



Impact on SWH biases



- ✓ Crosswave/Alongwave effect on SAR SWH bias
- Bias increasing with increasing wave period
- No crosswave/Alongwave effect on LRRMC

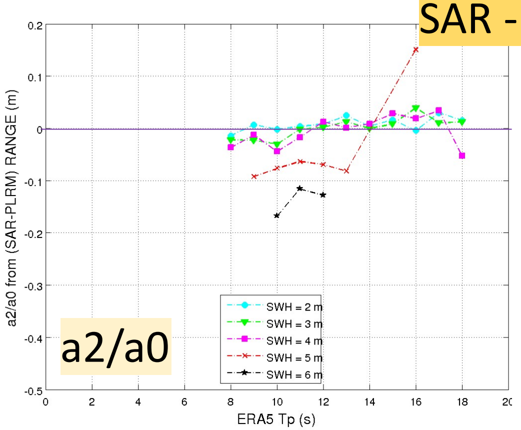
- ? Upwave/Downwave effect depending on wave period to be further investigated

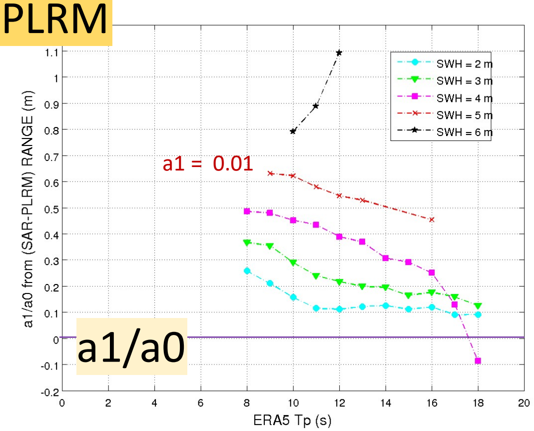
a1 ≠ 0 => Upwave/Downwave
a2 ≠ 0 => Crosswave/Alongwave

CLS

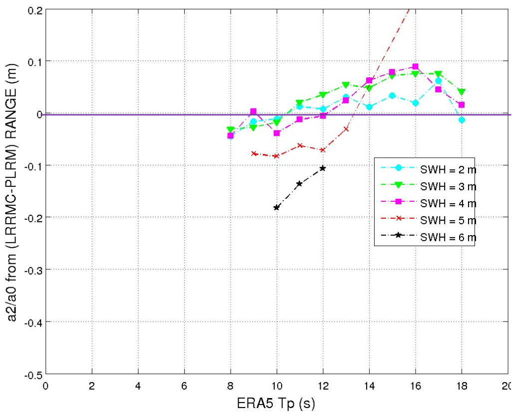
Impact on range biases

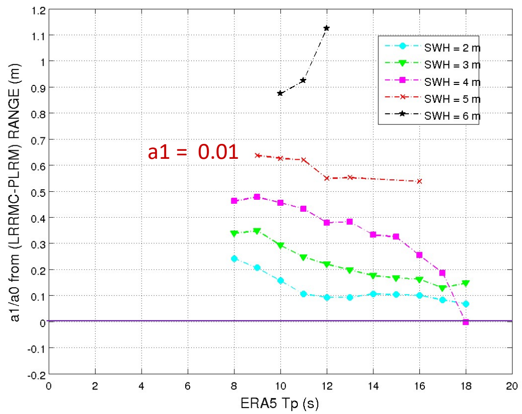
SAR - PLRM





LRRMC - PLRM





?

- A range bias wrt PLRM is observed for SAR and LRRMC => Probably linked to orbital velocity and not to high wavelengths
- Also observed a non negligible Upwave/Downwave effect on the range bias increasing with decreasing peak period
- This effect is also observed on LRRMC with the same order of magnitude

$\Rightarrow$ Probably due to non linear effects of the waves not yet considered in the theoretical analysis

$\Rightarrow$ **To be further investigated**

a1 ≠ 0 => Upwave/Downwave
a2 ≠ 0 => Crosswave/Alongwave

Summary, Conclusions & Perspectives

- Very good agreement between the results using real data analysis and those from theoretical analysis and simulations:
  - ✓ Bias on SWH due to orbital velocity
  - ✓ Noise on range and SWH due to high wavelengths swell propagating along the satellite direction
- Real data analysis allowed to identify new effects not yet analysed theoretically:
  - ✓ A range bias between SAR and PLRM dependent on SWH and peak period = > Additional SSB to be estimated using 3D model ?
  - ✓ An upwave/downwave bias between SAR and PLRM range has been identified. Same behaviour of SAR and LRRMC => Effect of waves non linearities ?
- The perspectives of this work are:
  - ✓ Consolidation of the above results using a higher amount of real data
  - ✓ Performance of a new theoretical analysis, accounting for the waves non linearities and their impact on the Delay/Doppler signal, to investigate the observed range bias and upwave/downwave effects
  - ✓ Development of a new SSB or pseudo SSB solutions accounting for the conclusions of the above investigations

Thank you !

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