Impact of the ocean waves motion on the Delay/Doppler altimeters measurements

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Context

- The Delay/Doppler mode, initially designed on CryoSat-2 for polar ice observations and then 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 important to fully understand the content of the Delay/Doppler signal;

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- However, to be capable of interpreting correctly any small scales observations, it is important to fully understand the content of the Delay/Doppler signal;
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  - The surface motion
  - Swell long wavelengths

CLS

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    - Swell long wavelengths

Previous studies have been performed in CLS showing the impact of swell long wavelengths on the estimation noise (Moreau et al. 2018 and Raynal et al. 2018).

In the present study, we will focus on the impact of time evolution of the short and long wavelengths on the Delay/Doppler processing performances.

Background analysis

- The question of the impact of the waves motion on Doppler signals has been raised for serveral years.
- A first analysis performed in the context of a CNES/CLS/MIO PhD (Boisot, 2015) that resulted in a scientific publication (Boisot et al. 2016 in IEEE TGRS).

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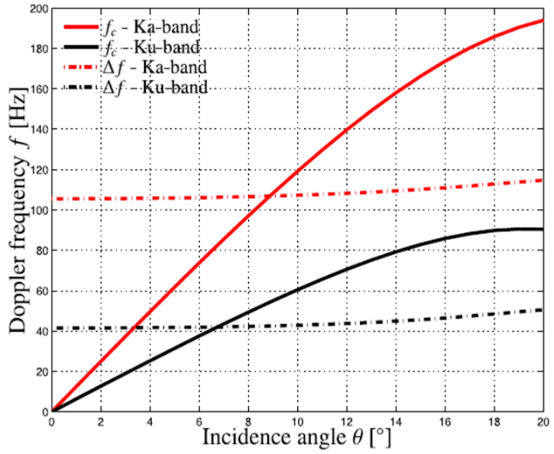

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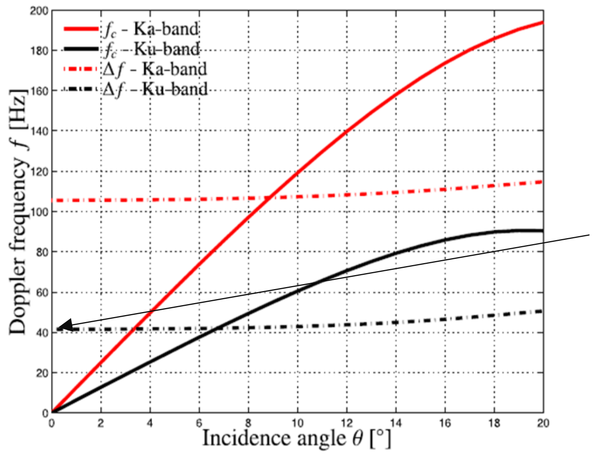

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A shift of 40 Hz induces a horizontal shift of 50 m in Ku band.

The value is to be compared to azimuth PTR width which is of the order of 300 m for S3.

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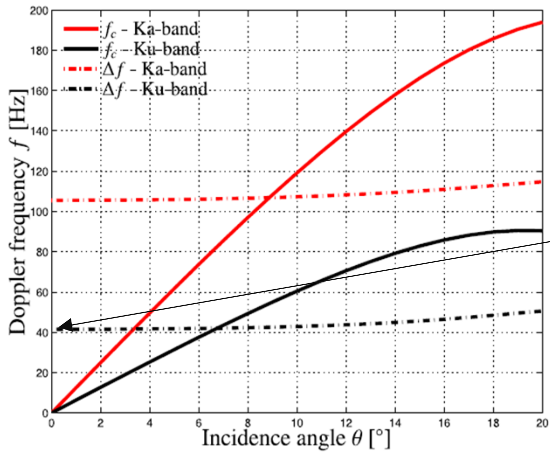

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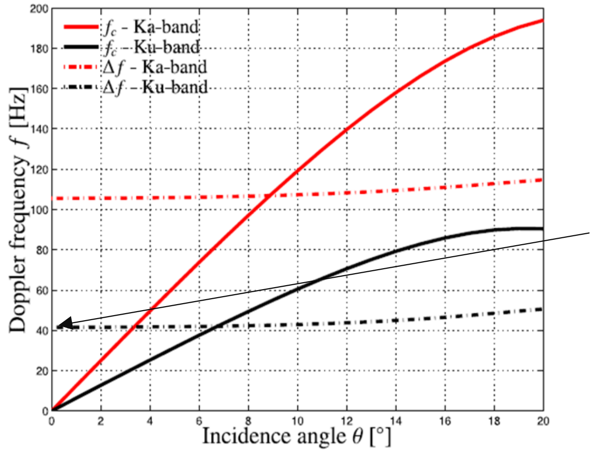

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⇒ It has been decided to perform a new study to assess the impact of these surface motions on the nadir Delay/Doppler altimeters performances.

=> This is the scope of a new R&D study, started in 2018 and performed by CLS for CNES with the support of MIO

Proposed methodology

❖ The study adressed all wave scales and is based on three types of investigations:

- A **theoretical analysis** developed the physical equations describing the evolution of the surface over time to make a first quantitative evaluation of its impact on the estimates;
- A **simulation-based analysis** allowing to verify the theoretical results;
- Finally, a more accurate validation will be done using **real SAR mode data of Sentinel-3**.

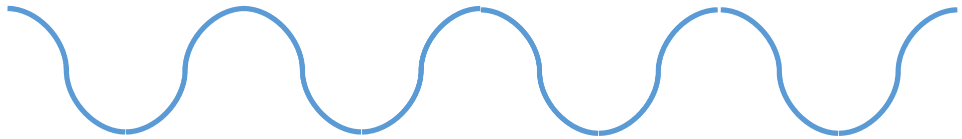
❖ It is the combination of theoretical analysis, simulation and analysis of real data that makes it possible to definitively understand and conclude on the impact of waves motion on the performance of Doppler altimetry.

This presentation gives an overview of the theoretical and simulation-based studies and first comparisons with real data.

Orbital velocity related Doppler

Considering a simple cosine wave with amplitude a, the height h at a certain surface location (r) varies with time t following:

$$h(r,t) = a \cos(kr-\omega t)$$



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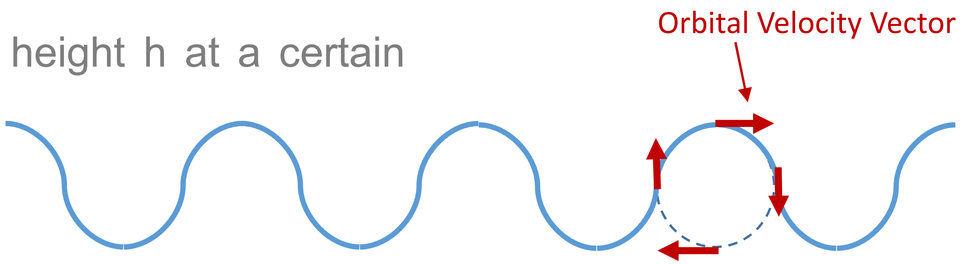

The impact on the Doppler of the signal is maximum when the surface vertical motion is maximum (orbital velocity vector vertical).

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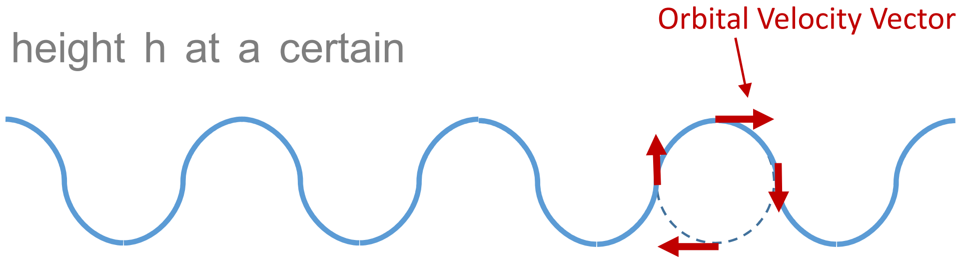


The impact on the Doppler of the signal is maximum when the surface vertical motion is maximum (orbital velocity vector vertical).

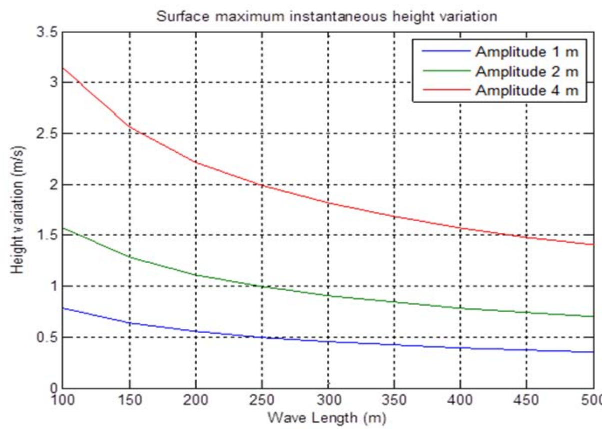
The maximum vertical velocity (or orbital velocity vector module) can write:

$$\frac{\partial h}{\partial t} = a\,\omega = a * \sqrt{g * \frac{2\pi}{\lambda}}$$

The vertical velocity can reach values of few m/s.

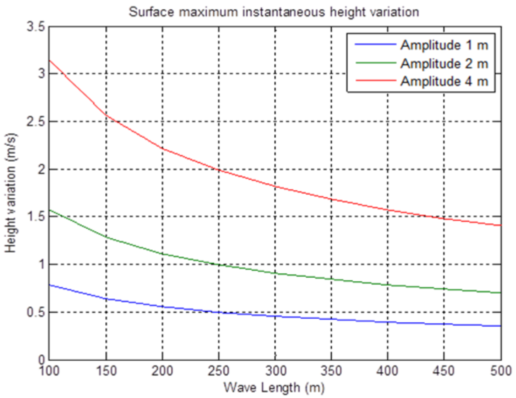
$\Rightarrow$ Vertical velocity is the higher for **High Significant Slopes**

(for short wavelengths and high amplitudes)



Maximum instantaneous surface height velocity as a function of the wave length for waves amplitudes of 1, 2 and 4 m.

Orbital velocity related Doppler



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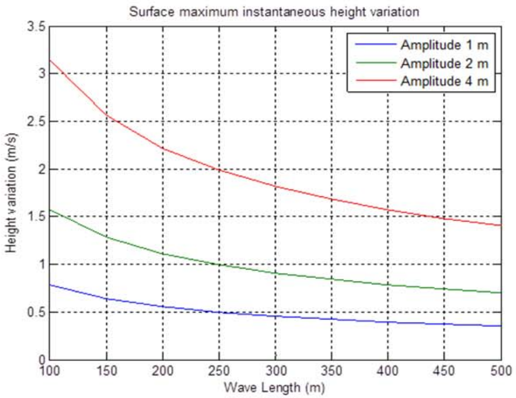

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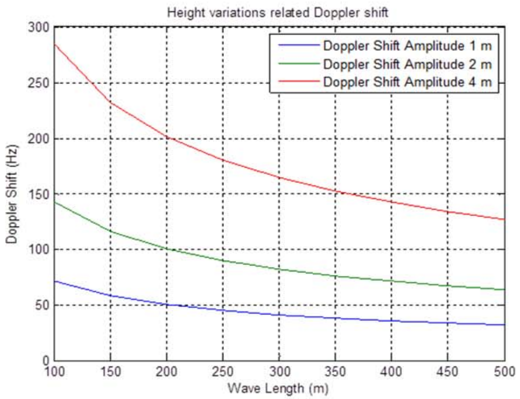
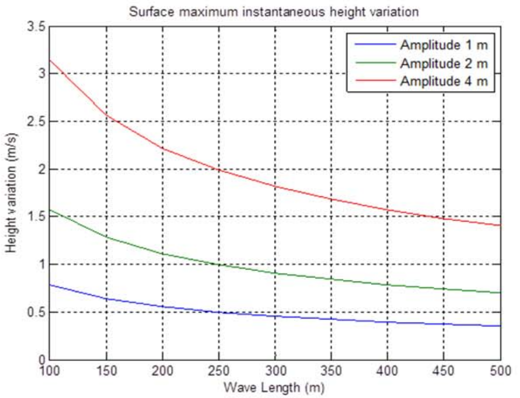


Doppler shift related to a vertical orbital as a function of the wave lengh and amplitude (Ku band)

Orbital velocity related Doppler



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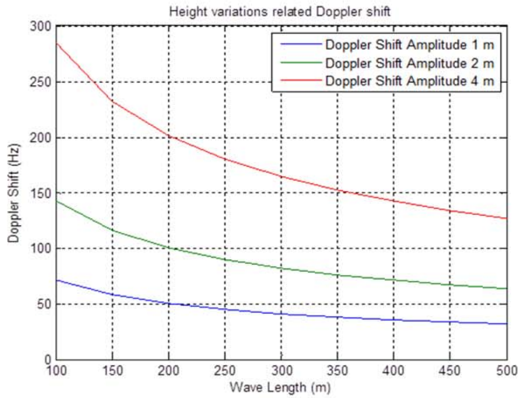

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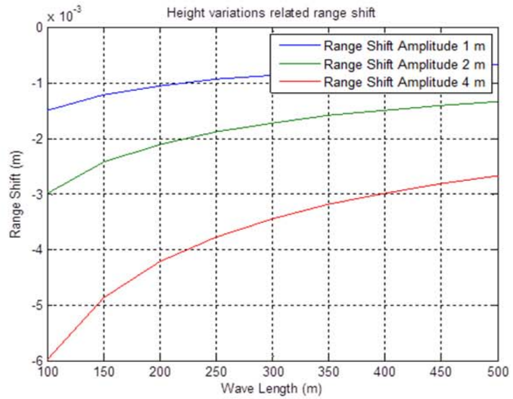
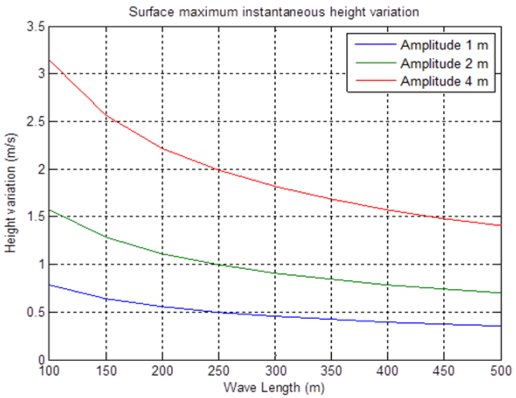


Slant range shift related to a vertical orbital as a function of the wave lengh and amplitude (Ku band).

Orbital velocity related Doppler



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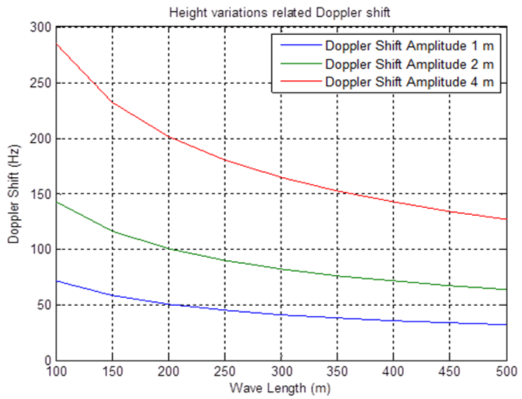

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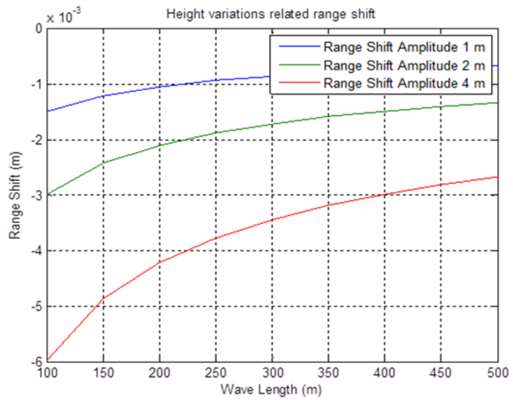

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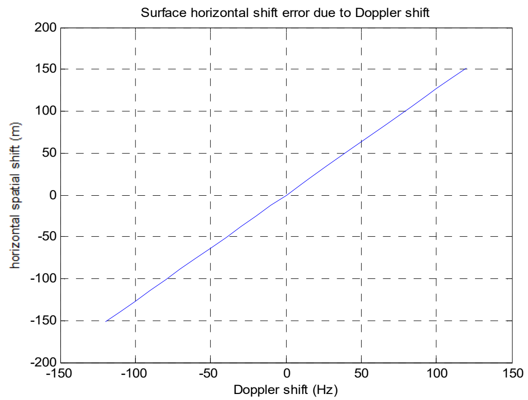

Virtual Horizontal shift in the azimut direction corresponding to the Doppler shifts (Ku band).

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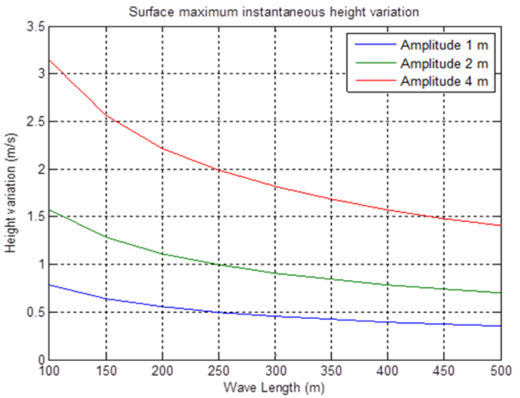

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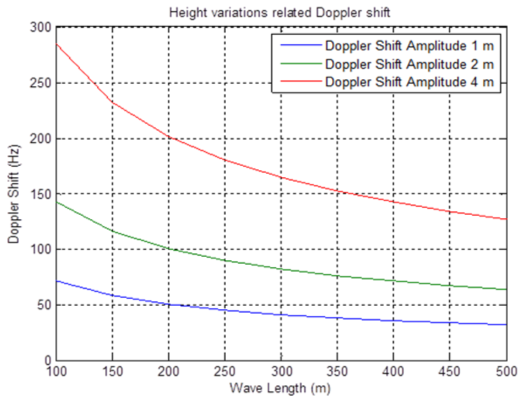

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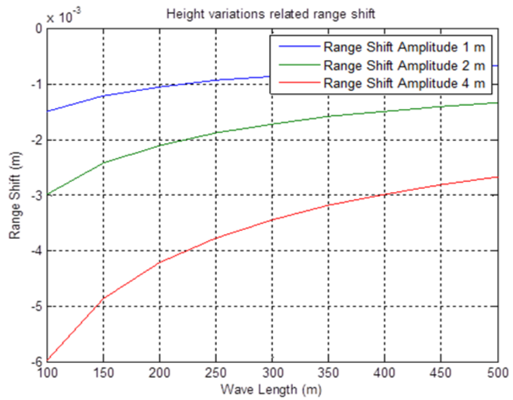

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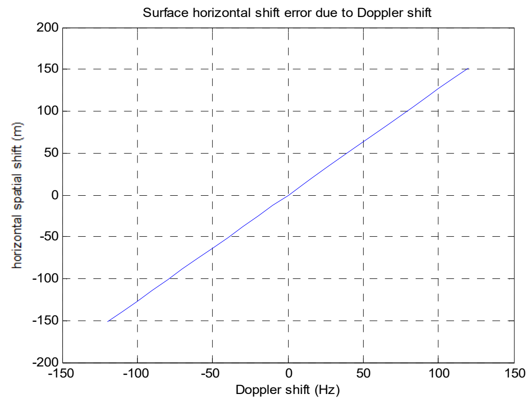


Virtual Horizontal shift in the azimut direction corresponding to the Doppler shifts (Ku band).

The impact of orbital velocity is neglible in the range direction but relatively important in the azimuth direction

⇒ Horizontal shifts affect the azimut PTR width: **Expected positive bias on SWH estimates**

⇒ Unexpected impact on the estimation noise nor on the range

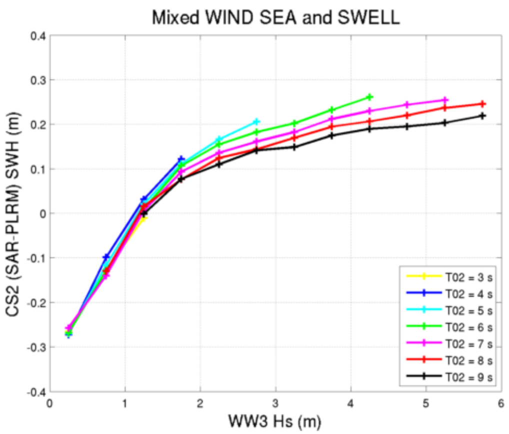
⇒ The **impact of Orbital Velocity** is **not dependent on the wave propagation direction**

⇒ The **Orbital Velocity** impact is not related to long wavelengths but to **high waves slopes**

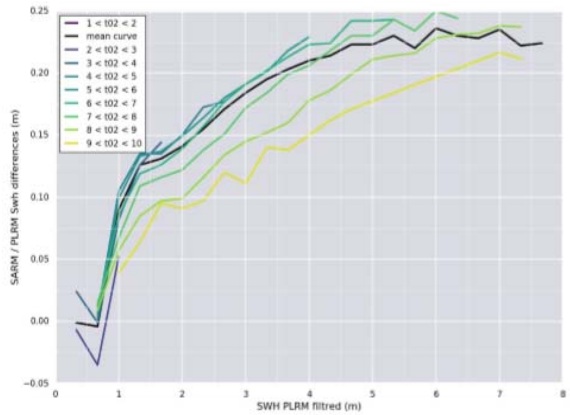
Orbital velocity related Doppler

Using the previous studies on real data of CryoSat-2 and Sentinel-3 (N. Tran and M. Raynal) we can highlight the impact of the significant slope on the SAR mode SWH estimation bias => It is illustrated by comparing SAR and PLRM.

CryoSat-2 SWH



Sentinel-3 SWH



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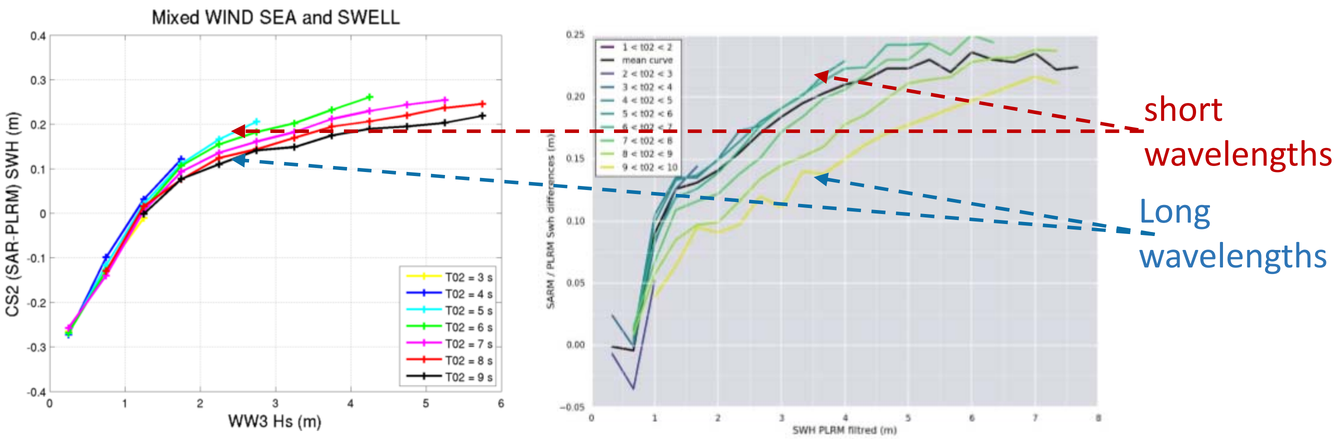
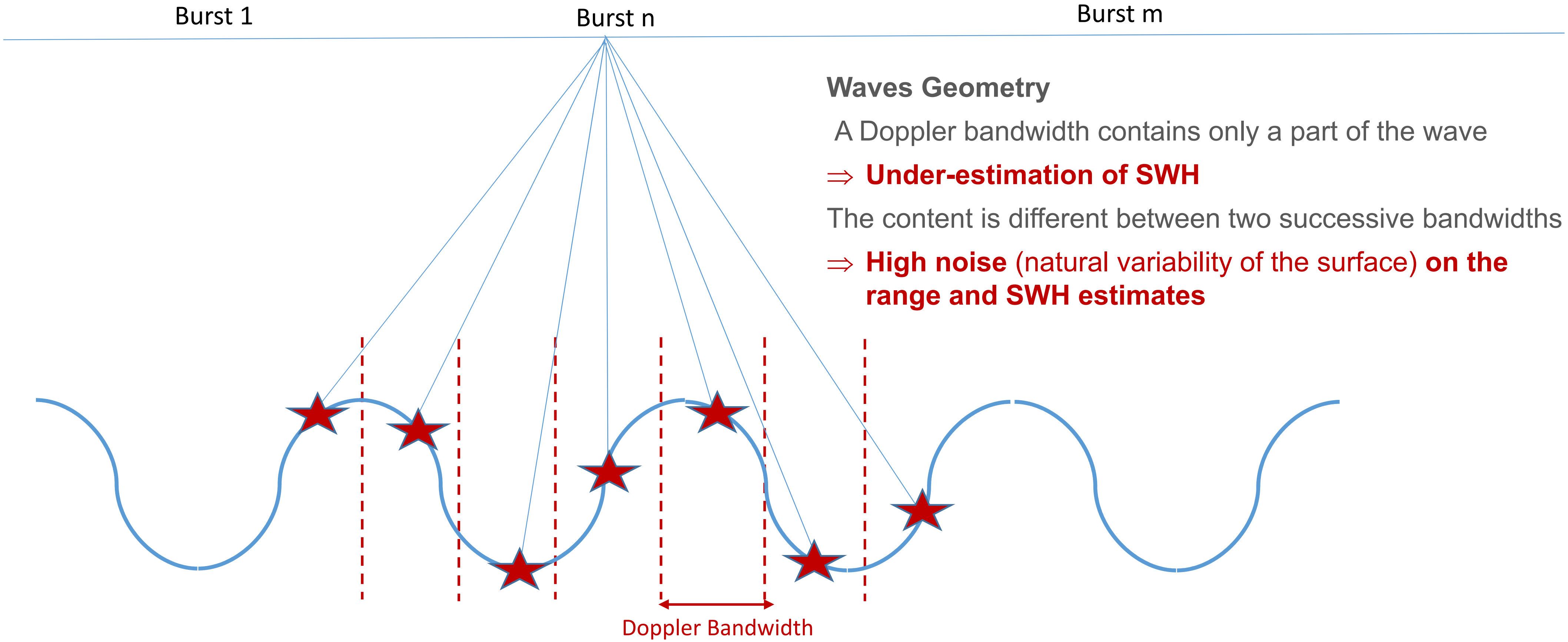


For a given SWH value :

Mean wave period T02 ↘ => Wavelength λ↘ => Orbital velocity ↗ => Horizontal Doppler Shift ↗ => SWH Bias ↗

This is consistent with the previous qualitative theoretical analysis.

Waves geometry and Phase velocity



Waves Geometry

A Doppler bandwidth contains only a part of the wave

⇒ **Under-estimation of SWH**

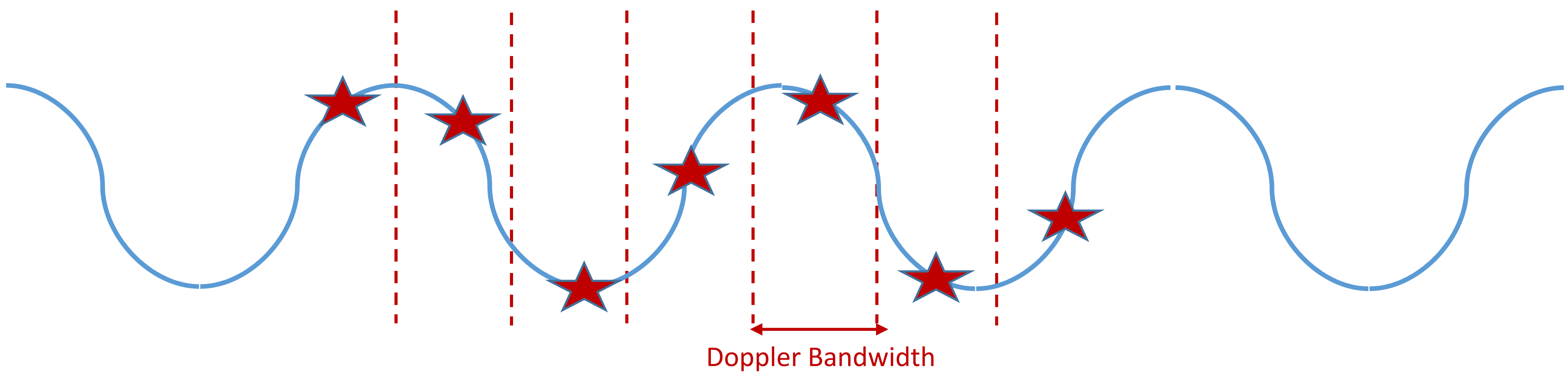
The content is different between two successive bandwidths

⇒ **High noise** (natural variability of the surface) **on the range and SWH estimates**

Waves geometry and Phase velocity

Burst 1 Burst n Burst m

A stacking is applied to Doppler beams coming from different bursts and hence that have been acquired over a relatively long period of time (~2.5 s)



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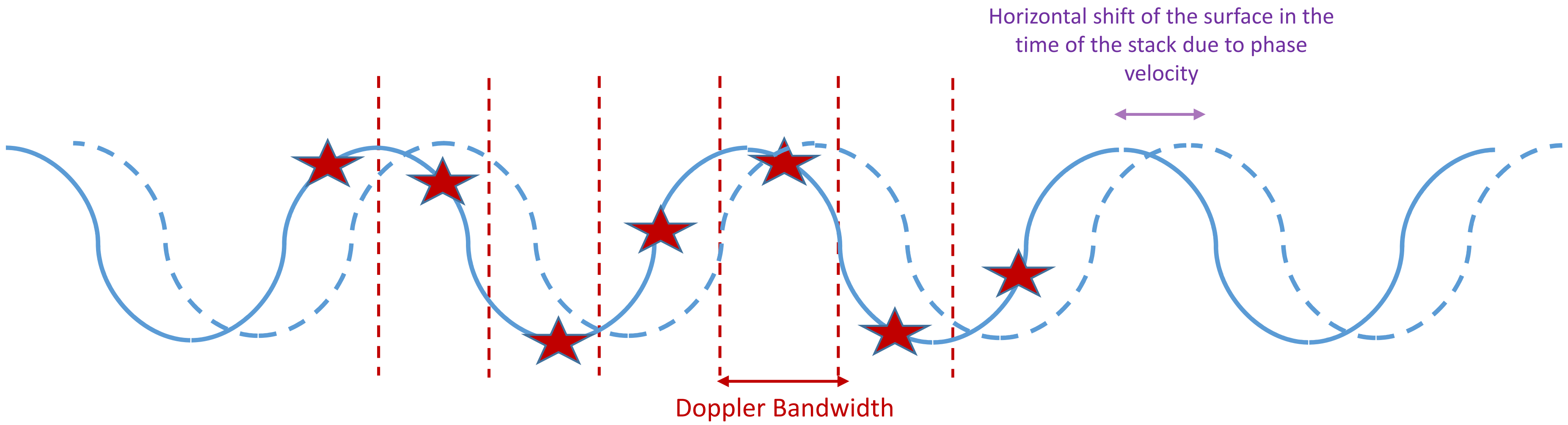

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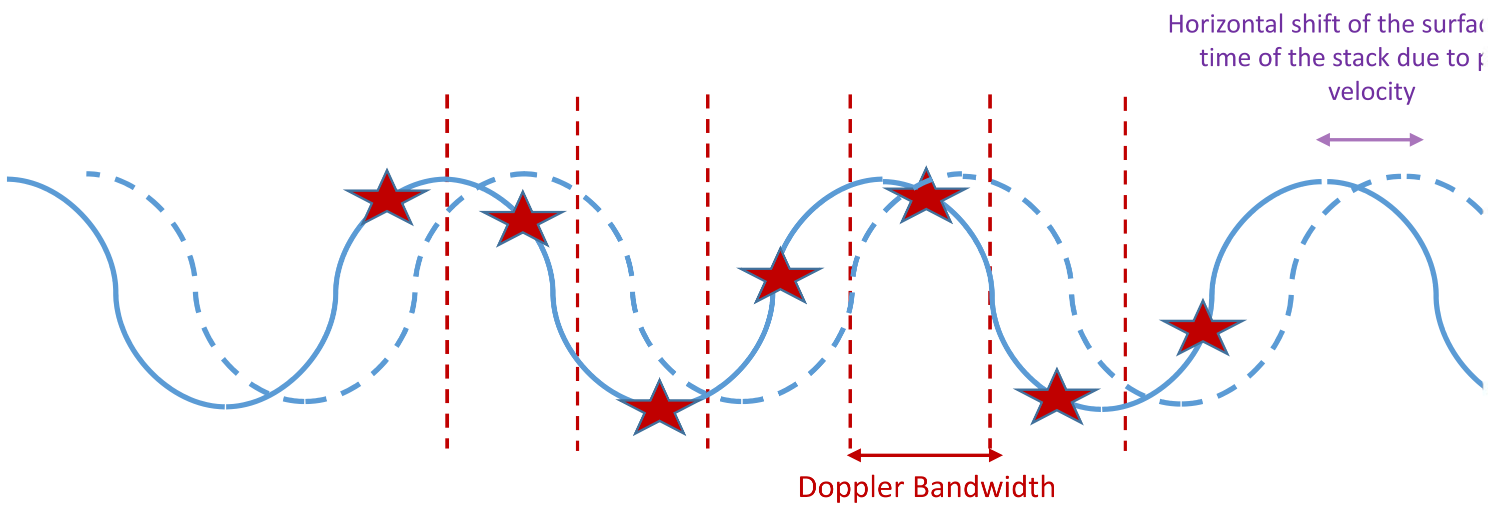
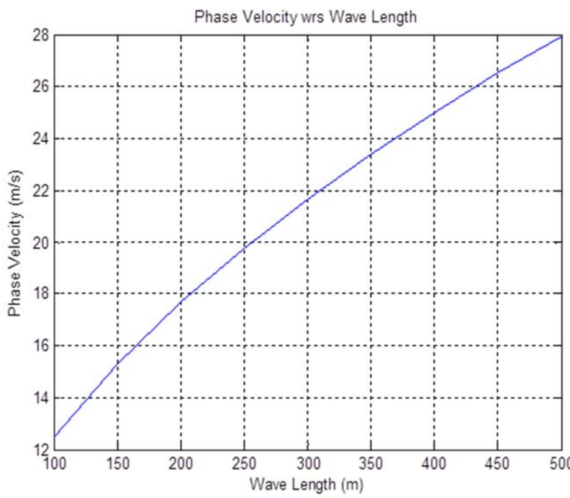
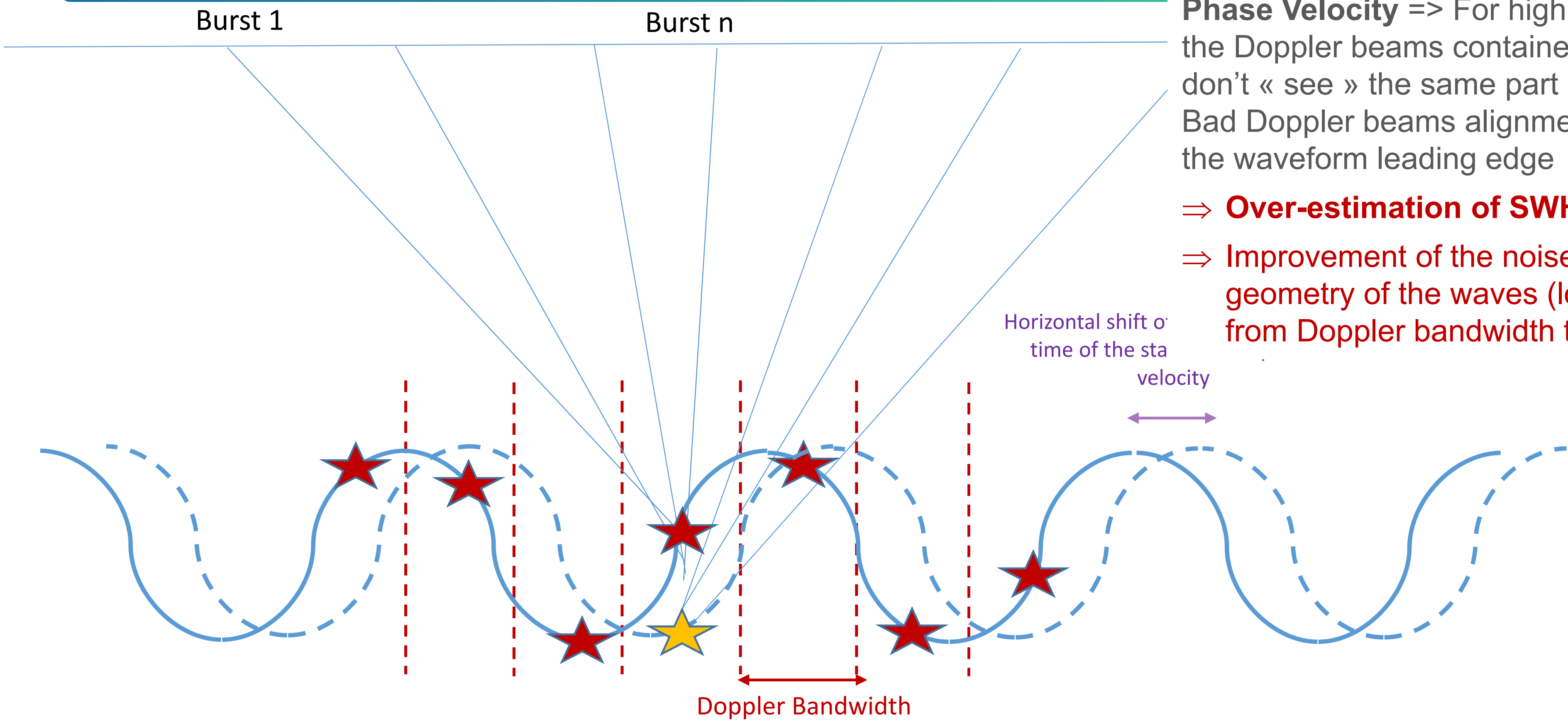




Phase velocity values relatively important in comparison to the stack duration

Phase velocity of ocean waves as a function of wave length

Waves geometry and Phase velocity

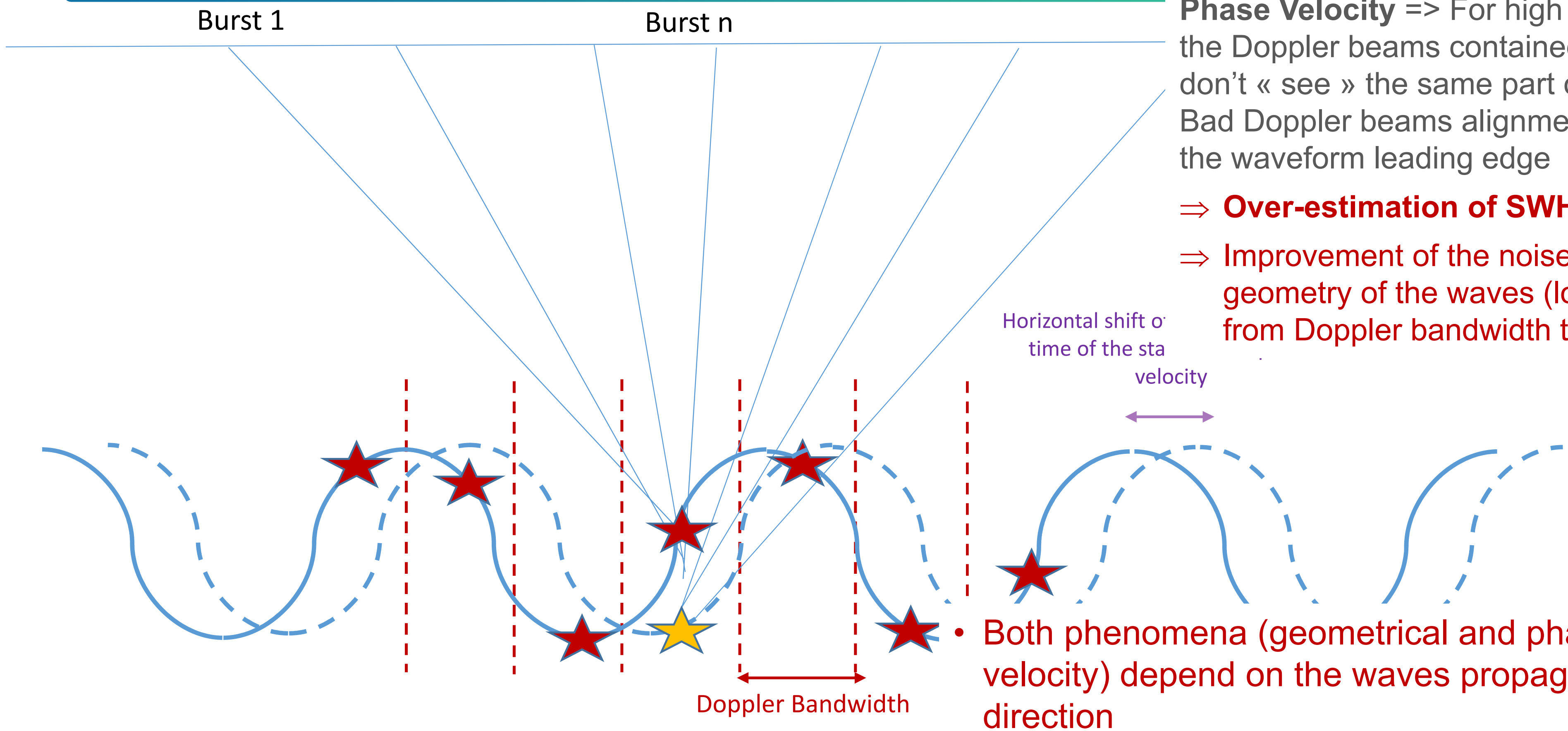


Phase Velocity => For high phase velocities the Doppler beams contained in one stack don't « see » the same part of the wave => Bad Doppler beams alignment => Widening of the waveform leading edge

⇒ **Over-estimation of SWH**

⇒ Improvement of the noise related to the geometry of the waves (lower variability from Doppler bandwidth to another)

Waves geometry and Phase velocity



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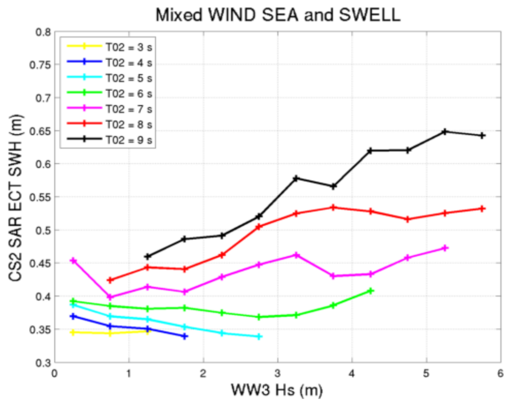
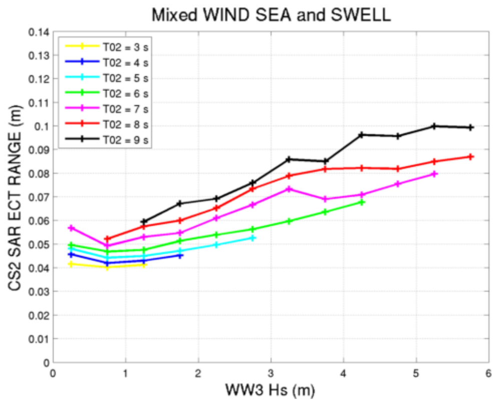
- Both phenomena (geometrical and phase velocity) depend on the waves propagation direction
- Note that the orbital velocity is also present

Waves geometry and Phase velocity

Based on previous studies on real data of CryoSat-2 and Sentinel-3, we can highlight the noise on the SAR mode SWH and range estimates induced by the waves geometry

CryoSat-2 SWH and range noise





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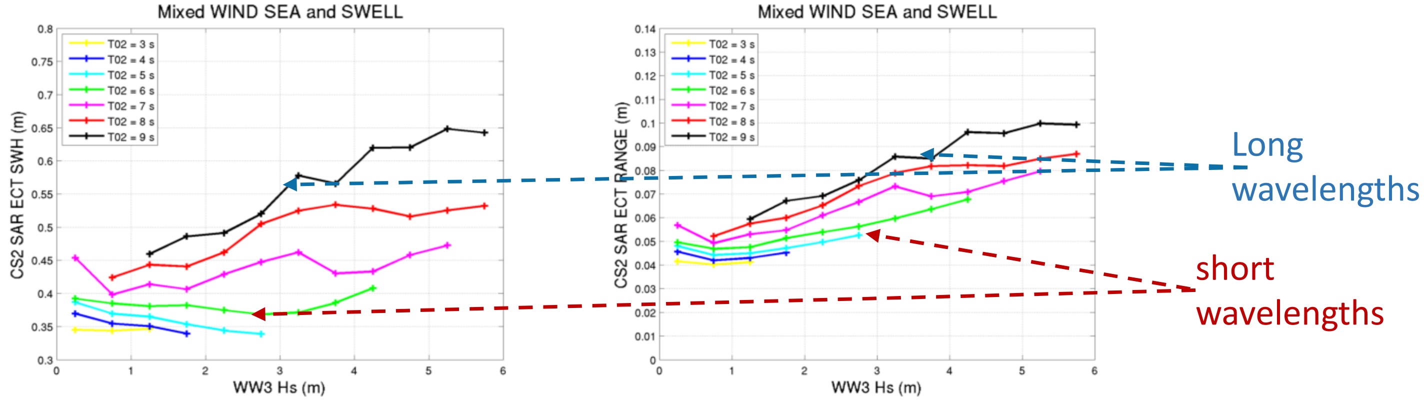

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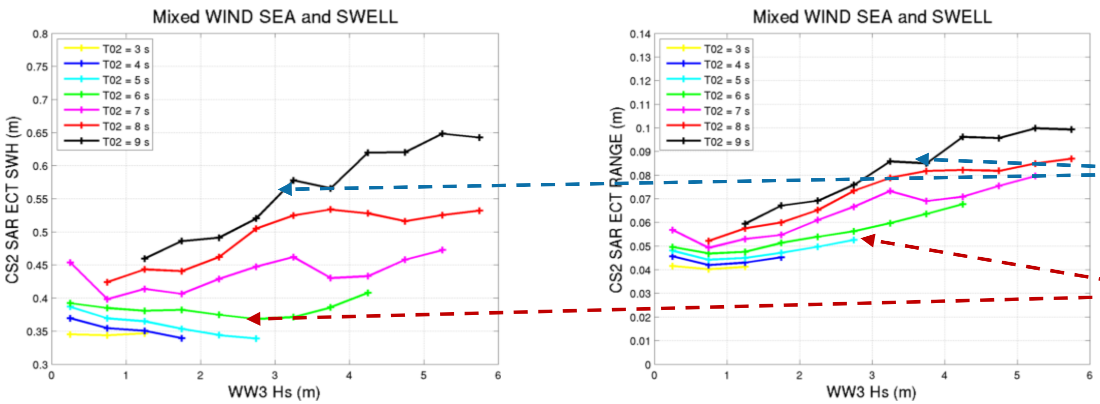

The same is observed on Sentinel-3 data

Long wavelengths

short wavelengths

For a given SWH value :

Mean wave period T02 ↗ => Wavelength λ ↗ => Estimation noise ↗

This is consistent with the previous qualitative theoretical analysis.

Simulation analysis

Simulation tools and analysis methodology

- Use of an end-to-end simulation tool representing the different stages of the measurement and the processing
- Simulated realistic ocean surface waves from ocean power spectra. They can be either **swell** or **wind waves** with possible **evolution with time** of **short** and **long scales**.
- These simulation tools have been already successfully used in CLS for all the altimetry missions.

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- These simulation tools have been already successfully used in CLS for all the altimetry missions.
- For performance evaluation assessing the impact of Doppler effect, different comparisons are possible:
  - Comparison of the estimates with real input parameters from the input scene
  - Comparison between SAR and PLRM modes estimates related to the same input scene
  - Comparison between the estimates related to static and dynamic surfaces

Simulation analysis

Simulation of Wind Waves

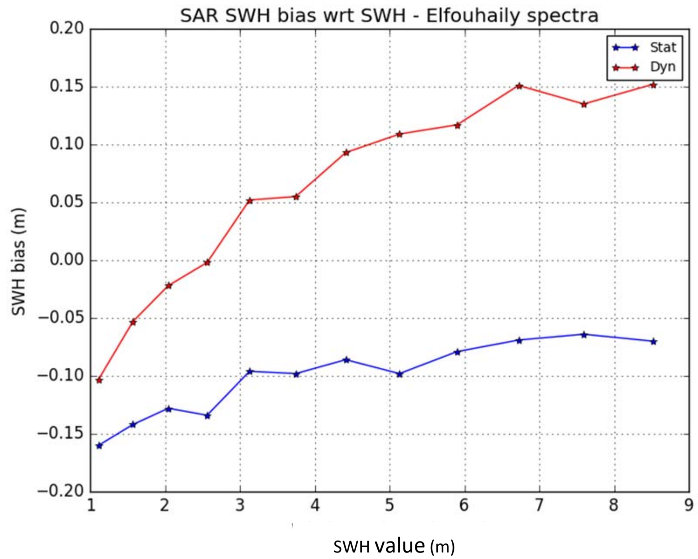
Simulation results using El-Fouhaily spectrum for different sea state conditions

Simulation of SAR and PLRM modes for static and dynamic ocean surface

The results showed a very good agreement with the theoretical analysis:

- A significant **bias** on SAR mode **SWH** is observed when the **surface is varying**.

SWH bias

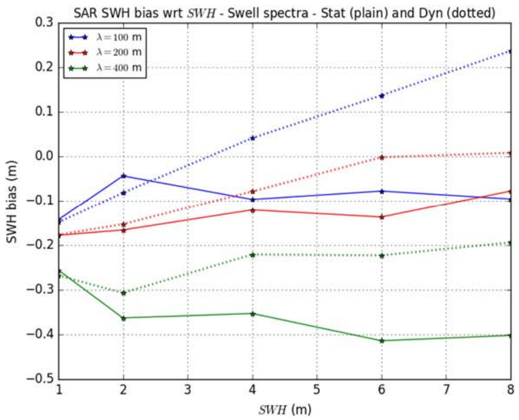


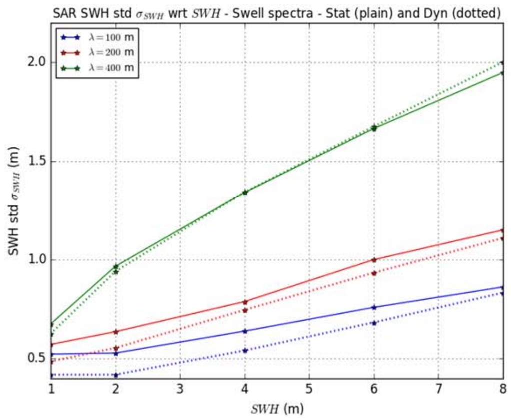
=> The high biases observed on real SAR mode SWH are not related to high wavelengths swell events but to high significant slopes

Simulation analysis

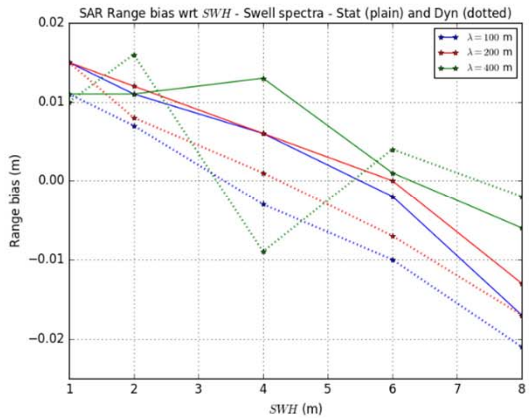
Simulation of Swell different configurations: amplitudes, directions and wavelengths

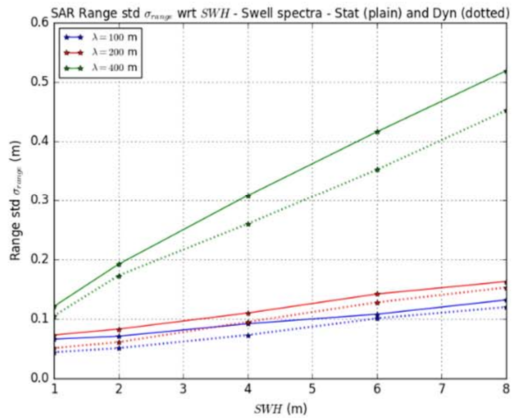
SWH bias and noise





Range bias and noise





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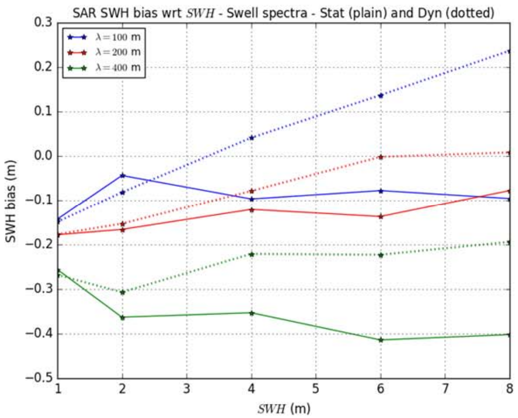
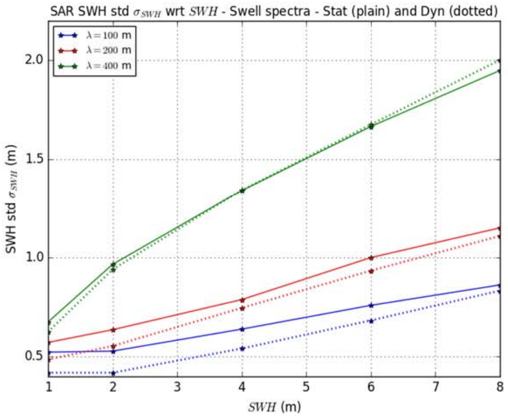
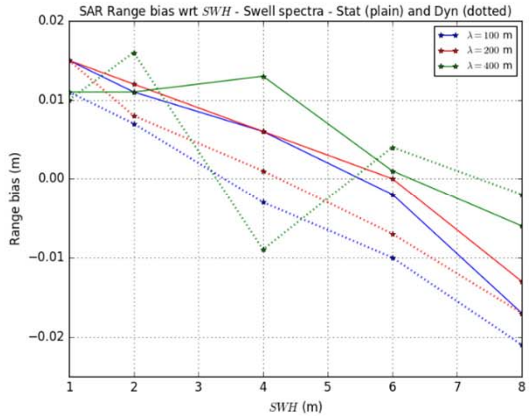
Simulation of Swell different configurations: amplitudes, directions and wavelengths

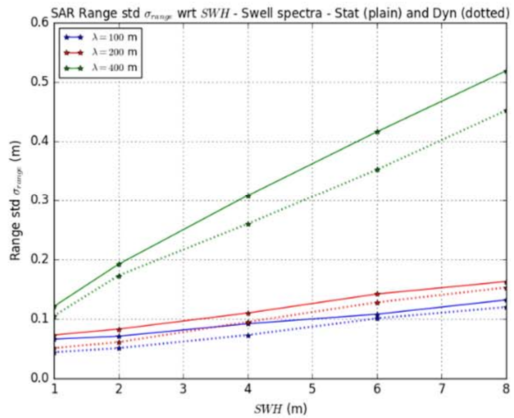
SWH bias and noise





Range bias and noise





Good agreement with the theoretical analysis.

- **SWH estimation bias** is negative for static surfaces and it is the **higher** (in absolute value) for **high wavelengths**.
- **Surface motion increases the SWH bias**: Impact of the phase and orbital velocity.
- The **noise** on the **range and SWH** increases with the **Wavelength** even if the surface is static: **Geometric effect**
- No significant effect on the range bias

Summary and conclusions

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.

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

Also a good agreement has been found with previous analysis on CS2 and S3.

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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	↗	↘	→	↘

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At a first order, 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

Next Step and perspectives

In the present study, we compared our results to previous observations on real data and we showed good agreement between them.

However, a new analysis with real data is on-going (by N. Tran) to complete the previous one by the new findings of the present study

- Focusing on areas either with high significant slopes or with high wavelengths.
- Comparing SAR and PLRM modes estimates and characterizing their behaviour with respect to the presence of high significant slopes or high wavelenths in the along track direction.

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Afterwards:

➢ Solutions to cope with the observed effects will be investigated in the future: Empirical corrections and/or improved retracking models.

➢ In our study, the ocean surface has been considered Gaussian => Other theoretical investigations are necessary to analyse the impact of non-linear surface interactions on the SAR mode estimates (in addition to the EMB).

Thank you !

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