Analysis of waves dynamics impact on Sentinel-6MF delay/Doppler measurements

L. Amarouche, N. Tran, T. Pirotte, M. Mrad, H. Etienne, T. Moreau (CLS)

F. Boy, C. Maraldi (CNES)

C. Donlon (ESA)

OSTST meeting, Puerto Rico, United States: November 7 – November 11 2023

FORUM Presentation

Context

- The S6-MF mission continues the innovative record of altimetric delay/Doppler technique [Raney, 1998] started with the Cryosat-2 mission and continued with S3-A/B worldwide.
- This technique has demonstrated interesting capabilities over the oceans and has opened up a vast field of investigations such as the observability of ocean phenomena on a small scale. However, various studies have highlighted certain limitations due to the sensitivity of delay/Doppler measurements to ocean waves, leading to errors in the estimates.
- It is therefore important to fully understand the content of the delay/Doppler altimeter signal:
  - To mitigate waves impact on geophysical estimates and ultimately
  - Improve our understanding of any small-scale observations,
- Among the phenomena likely to impact the delay/Doppler signals, we can mention:
  - The surface motion
  - Swell long wavelengths
- S6-MF mission brings new technological advances compared to previous delay/Doppler altimeters enabling us to go one step further by offering new capabilities such as:
  - provision of surface geophysical estimates at smaller scales and with even lower measurements noise than what has already been achieved by S3-A/B from the interleaved operating mode;
  - simultaneous generation of both conventional low-resolution mode (LRM) and SAR mode or High Resolution (HR) data.

In this presentation, we will use Sentinel-6MF data to characterize the impact of waves dynamics on the delay/Doppler measurements and propose perspectives studies to mitigate these effects.

Quick overview of the research studies on the sea state impact on delay Doppler measurements

Various studies pointed out significant benefits of Delay/Doppler technique over LRM in terms of improved measurement errors and finer along-track spatial resolution [Boy et al., 2017]. However, some downsides have also been highlighted due to sensitivity of the Delay/Doppler processing to the ocean waves:

- The impact depends strongly on the waves period and energy, but also on their propagation direction with respect to the satellite track [Aouf et Phalippou, 2015; Abdalla and Dinardo, 2016; Moreau et al., 2018; Reale et al., 2018; Rieu et al., 2020].
- Swell induces an increase of the high-frequency noise on the estimated parameters, but also of the SSH variance at longer wavelengths because of the spectrum aliasing [Reale et al., 2020; Rieu et al., 2020].
- Orbital velocities [Boisot et al., 2016; Buschaupt, 2019 and 2020; Egido et al., 2020, Amarouche et al., 2019; Tran et al., 2020] induced by all the sea states (wind waves and swell), whatever their direction, can also alter the SAR mode signal leading to biases on SWH estimates which can in turn induce a bias in SSH through the SSB correction.
- Other phenomena can furthermore affect the delay/Doppler measurement leading possibly to additional biases in SSH estimates. They may be related to nonlinear effects of waves leading to upwave/downwaves SSH and SWH biases and variability [Amarouche et al. 2019, Tran et al. 2020].
- Wind direction with respect to satellite direction has been recently observed on Sentinel-3 and Sentinel-6 data [E. Cadier]. Different authors analysed this phenomena [E. Egido, D. Vandemark, H. Feng, N. Tran].
- Different authors proposed new algorithms or empirical correction for these phenomena [A. Egido et al. 2022, C. Buchhaupt et al. 2023].

Study Objectives

- To caracterise the different ocean waves dynamics affecting the delay/Doppler altimeter signal and the corresponding estimates (mainly the range and SWH)
- To propose perspective studies to develop reliable solutions to mitigate waves impact on SSH (and SWH)

To this end:

- We used Sentinel6-MF data and external parameters from wave and currents models (ERA5 and MERCATOR) to caracterise the range and SWH estimates behavior.
- Focusing on the upwave/downwave and wind direction dependency by analysing the impact of Vertical Velocity assymetry due to currents and, difference of roughness between upwave and downwave due to wind speed.
- The analysis is based on altimeter SWH and range HR (High Resolution) and LR (Low Resolution) differences with respect to different geophysical parameters derived from model data. These parameters are: model SWH, Wind Speed, Vertical Velocity, Stokes Drifts and other surface currents.
- Our study was also based on theoretical analysis and simulation.

In this presentation, only the results on the real data analysis are shown.

Data Used (1/2)

- Sentinel-6 MF L2 LR and HR data over ocean:
  - Data from the 2022 reprocessing. We used cycles from 42 to 78.

- ERA5 wave model parameters
  - Significant height of combined wind waves and swell (SWH)
  - Mean_zero_crossing_wave_period (T02)
  - 10-m u-component of wind (U_Wind_Speed)
  - 10-m v-component of wind (V_Wind_Speed)
  - u-component stokes drift (U_Stokes_Drift)
  - v-component stokes drift (V_Stokes_Drift)
  - Mean_wave_direction (Mean_Wave_Direction)
  - Significant height of total swell (shts)
  - Mean direction of total swell (mdts)
  - Significant height of wind waves (shww)
  - Mean direction of wind waves (mdww)
  - …

Computation of new parameters from ERA5 parameters:

- Vertical Velocity Standard Deviation (from SWH and T02)
- Wind direction wrt satellite direction (from U_Wind and V_wind)
- Wind Speed Proj. on Satellite Direction
- Stokes drift direction wrt satellite direction
- Stokes drifts Velocity Proj. on Satellite Direction
- Waves propagation direction (total, swell, wind waves) wrt satellite direction

Data Used (2/2)

➢ MERCATOR model parameters

Global Ocean Physics Analysis and Forecast

Spatial extent Global

Spatial resolution 0.083° × 0.083°

Temporal resolution Hourly

Variables

- Eastward sea water velocity (Total Surface Current U)
- Northward sea water velocity (Total Surface Current V)
- Sea surface wave stokes drift x velocity
- Sea surface wave stokes drift y velocity

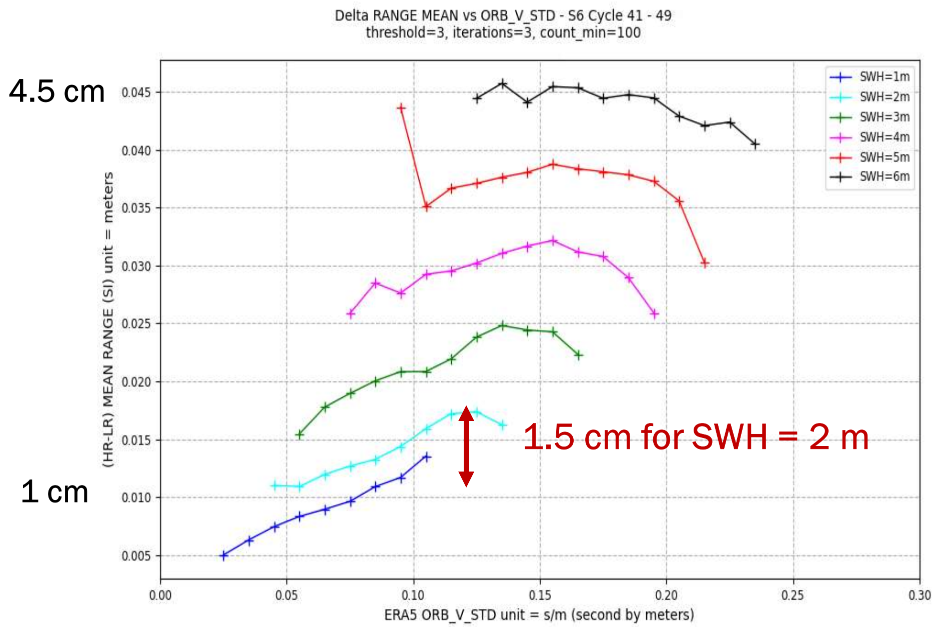
Computation of new parameters from MERCATOR parameters:

- Total Surface Currents No Stokes (Total surface currents minus Stokes)
- Total Surface Currents No Stokes direction wrt satellite direction
- Total Surface Currents No Stokes Proj. on Satellite direction
- Stokes Drift MER direction wrt satellite direction
- Stokes Drift MER Velocity Proj. on Satellite direction

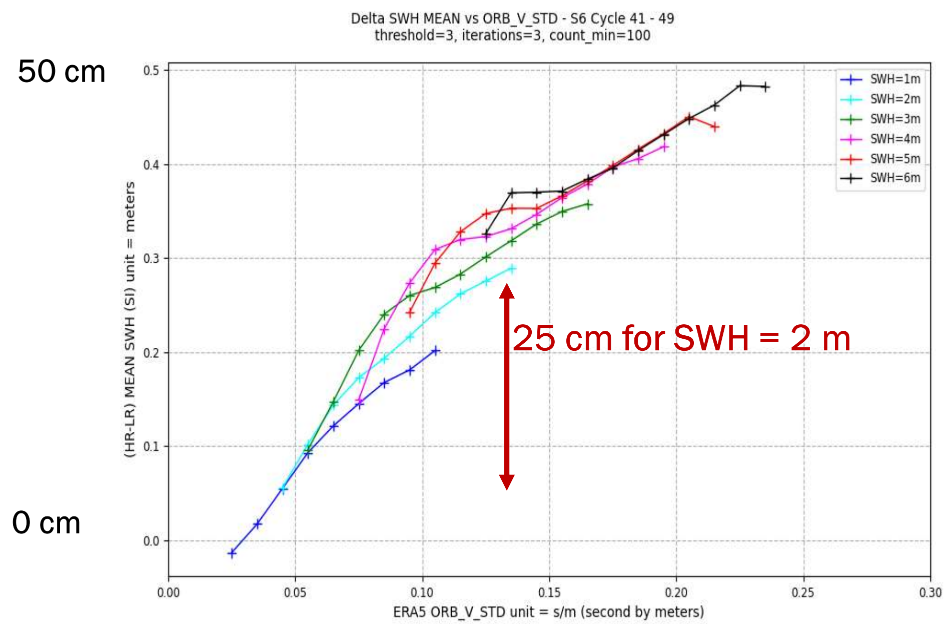
CLS

Vertical Velocity impact on the range and SWH

Range Difference HR−LR wrt ERA5 Vertical Velocity



SWH Difference HR−LR wrt ERA5 Vertical Velocity



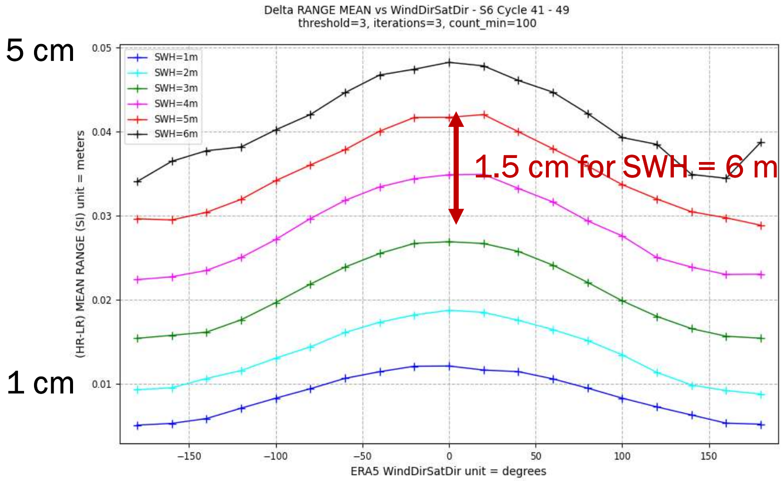
Increase of SWH HR-LR diffrences with increasing Vertical Velocity.

Range HR-LR differences depend on Vertical Velocity and SWH,

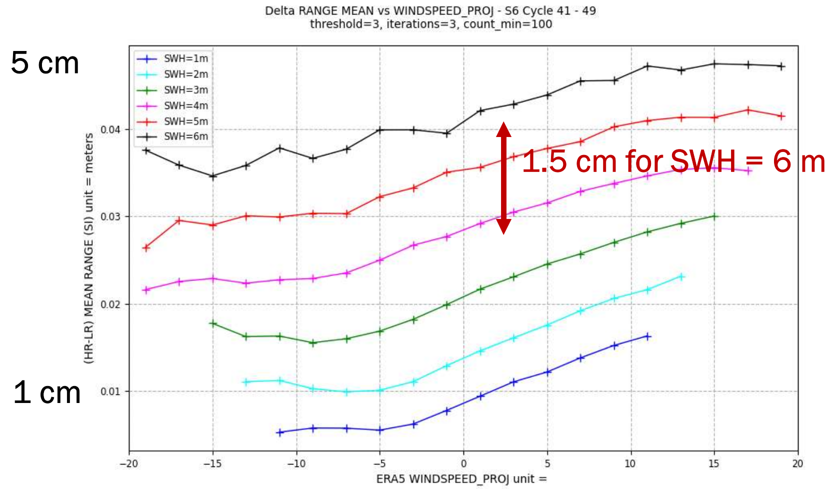
This effect comes in addition to the classical Sea State Bias.

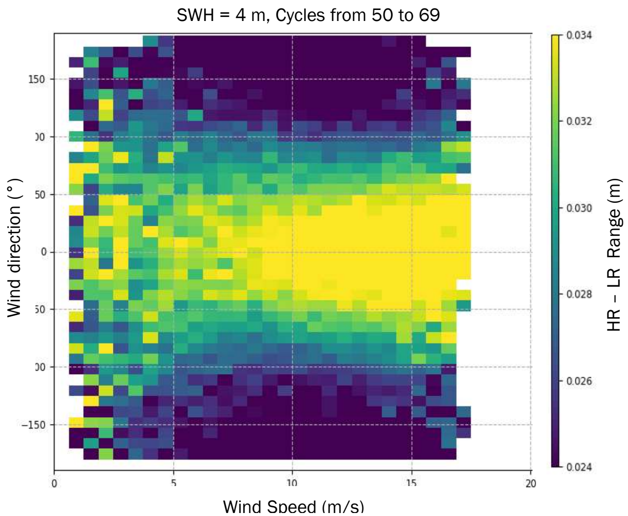
Wind Speed impact on the range

Range Difference HR−LR wrt ERA5 **Wind Speed Direction**



Range Difference HR−LR wrt ERA5 **Wind Speed Along-track Component**



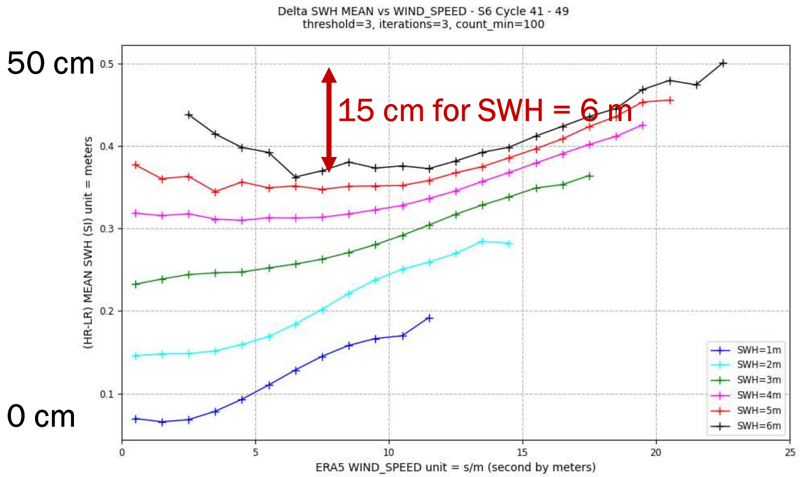


HR-LR **range differences** depend on **Wind Speed** and **Wind Direction wrt. Satellite direction.**

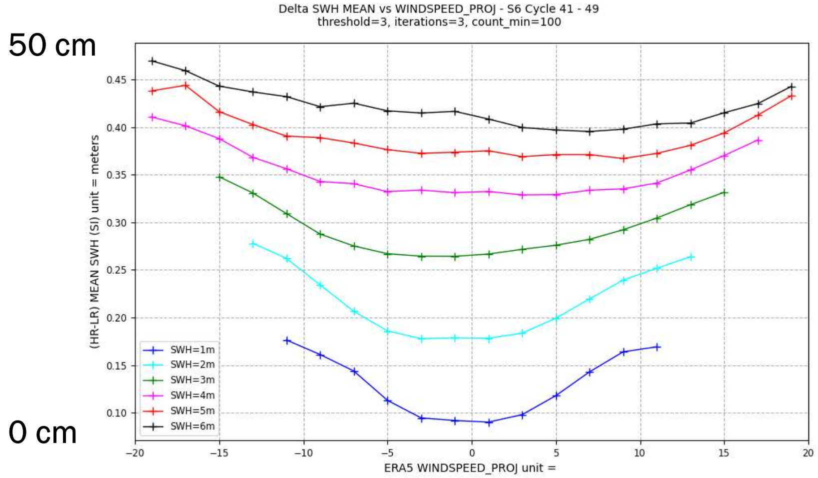
The dependency on wind direction wrt satellite direction can’t be explained only by the wind
=> Need to consider the currents component in the along-track satellite direction

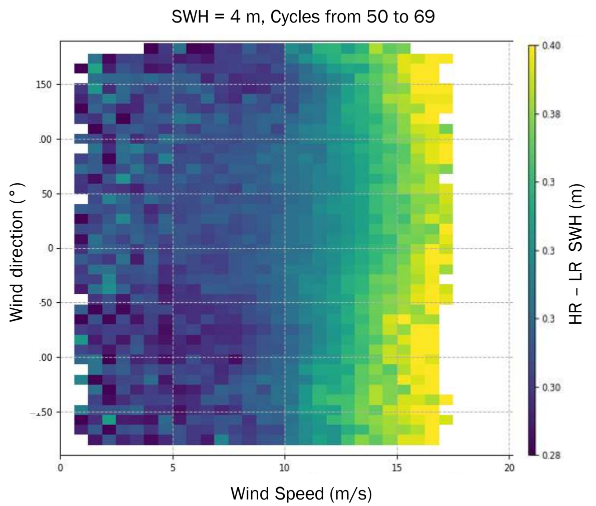
Wind Speed impact on SWH

SWH Difference HR–LR wrt ERA5 **Wind Speed**



SWH Difference HR–LR wrt ERA5 **Wind Speed Along-track Component**





Clear dependency of **SWH** on **wind speed**
Small dependency on **wind speed direction** for **high SWH**

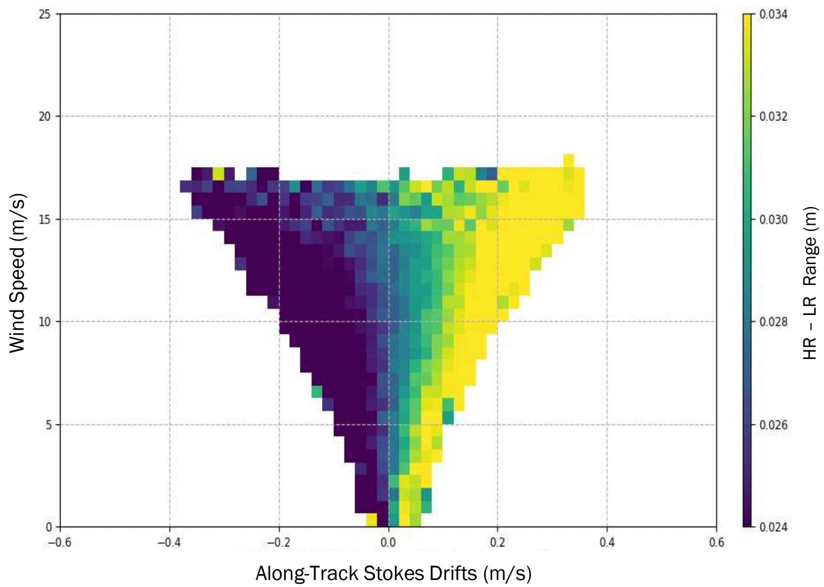
The last correction that is being introduced on Sentinel-6 operational processing is based on LUT with SWH and T02 from wave model as inputs [Egido et al. 2022].

New correction using SWH, Vertical Velocity **and Wind Speed** should be developed in the future

Wind Speed and Stokes drifts impact on the range

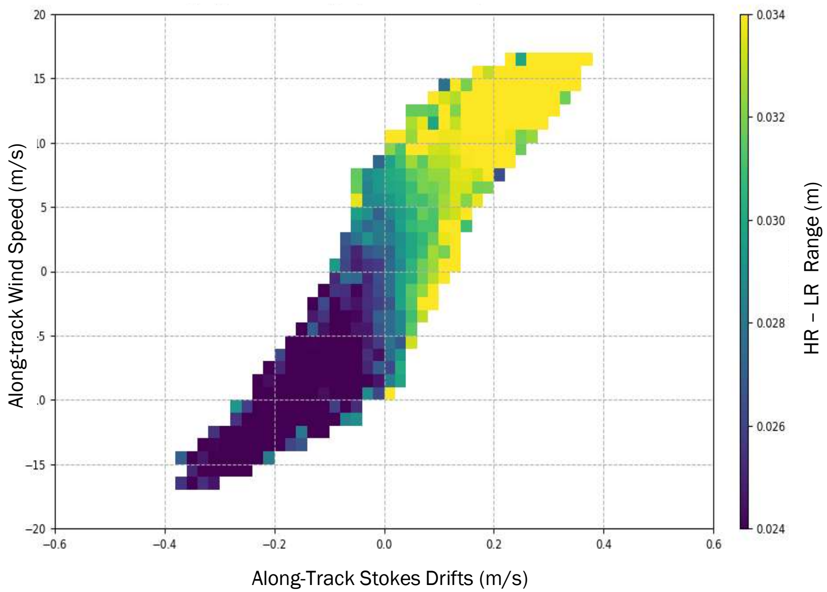
Range Difference HR–LR wrt ERA5 Wind Speed and along-track Stokes Drifts

SWH = 4 m, Cycles from 50 to 69



Range Difference HR–LR wrt ERA5 Along-track Wind Speed and Along-track Stokes Drifts

SWH = 4 m, Cycles from 50 to 69



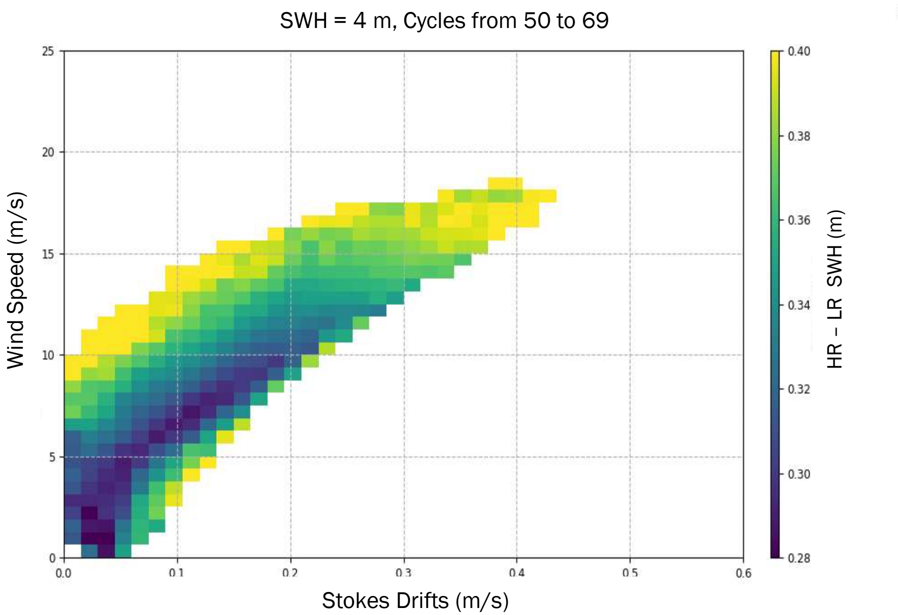
Clear dependency of HR–LR range differences on Wind Speed and along-track Stokes drifts

The observed dependency on wind direction is probably due to the high correlation between wind and stokes drifts

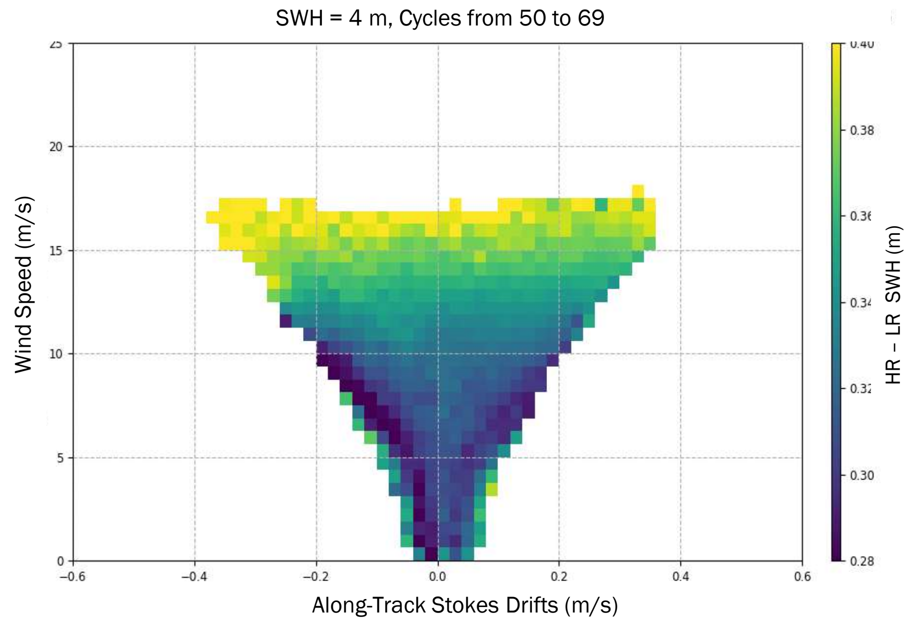
→ Stokes drifts in along track direction are the main contributor to the HR-LR range differences dependency on satellite direction

Wind Speed and Stokes drifts impact on SWH

SWH Difference HR−LR wrt ERA5 **Wind Speed** and **Stokes Drifts**



SWH Difference HR−LR wrt ERA5 **Wind Speed** and **Along-track Stokes Drifts**



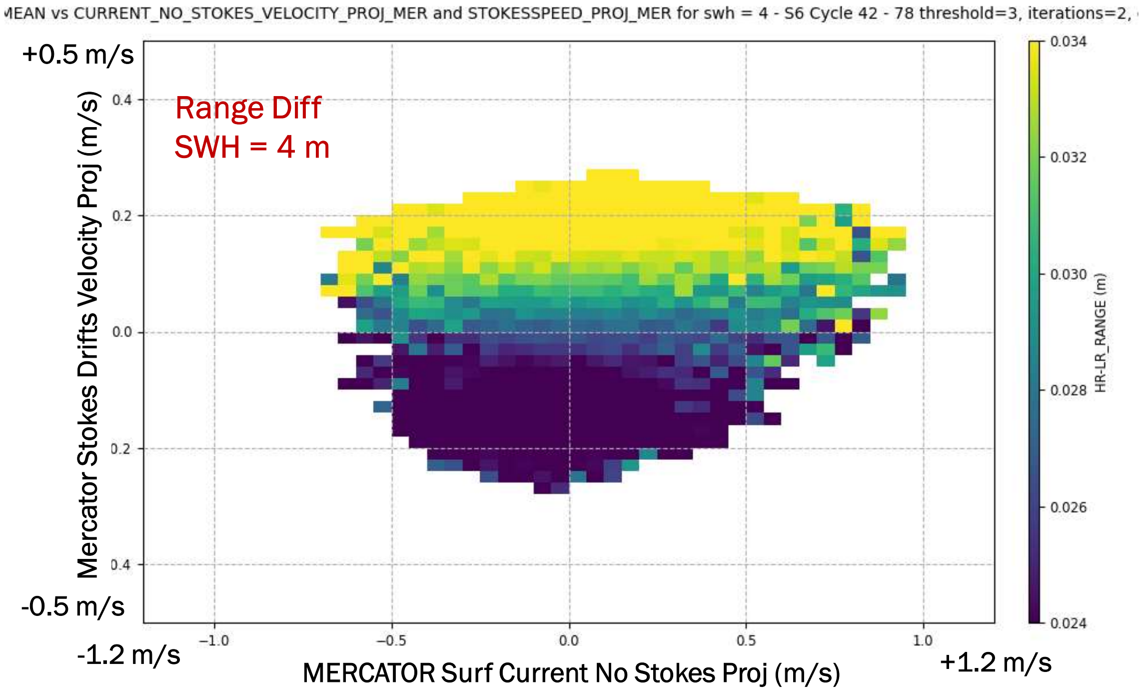
Small dependency of SWH HR−LR differences on Stokes drifts but no impact of Stokes Drift direction

➡ HR-LR **SWH** differences are **impacted** mainly by **Wind Speed**

MERCATOR Surface Currents Analysis

Are delay/Doppler estimates impacted the other surface currents than Stokes Drifts ?
=> Use of MERCATOR surface currents to compare Stokes Drifts to the other surface Currents.

Range HR−LR Differences wrt
Mercator Surf Current No Stokes Proj Sat Dir (x axis) and
Mercator Stokes Drifts Velocity Proj Sat Dir (y axis)



Even total surface currents velocity can reach much higher values than Stokes drifts velocity we observe Higher dependency of HR range on the along-track Stokes Drifts Velocity rather than on the other surface currents.

This behaviour wrt surface currents can be explained by 2 effects:

- Surface Currents other than Stokes Drifts are not correlated with Wind Speed => less occurrences of co-existence of Orbital Velocity/WindSpeed/Along-track Currents.
- The wind driven surface velocity can be locally much higher than the Stokes Drift Velocity value which is associated to the overall drift of waves crests with the waves propagation.

Summary, Conclusions

- We analysed one year (cycles from 42 to 78) of the reprocessed Sentinel-6MF LR and HR data.
- Differences of Range and SWH between HR and LR modes have been characterised wrt to surface parameters extracted from **ERA5** files and **MERCATOR** model by using 2D or 3D diagnoses.
- Surface parameters analysed are: SWH, Wind Speed, Vertical Velocity, Stokes Drifts and other surface currents.
- Below a synthesis of the findings:

Depends on →	SWH	Wind Speed	Vertical Velocity	Stokes Drifts	Other Surface Currents
Range HR-LR	X	X	x	X (along-track)	x
SWH HR-LR	X	X	X	x (total)	x

The results of the above data analysis combined with the theoretical and simulation analysis (not shown in this presentation) allow us to conclude that delay/Doppler processing measurements are impacted by the combination of three phenomena : **Vertical Velocity, Wind Speed** (inducing **roughness assymetry** between **upwaves** and **downwaves**) and **along-track Stokes Drifts.**

Recommendations for the future (1/2)

Develop a correction for HR data: **SWH** (before the range correction) and **range**

❖ Correction 1

Correct **SWH** first, using:

1. SWH (estimated from altimeter retracking)
2. Vertical velocity (using T02 and SWH from wave models)
3. Wind speed (from models)
4. Stokes Drifts Velocities (from models. Less prioritiy)

Wind speed should be added as an input parameter to SWH operational correction [Egido et al. 2022]

A look up table can be built by minimizing the SWH estimates HR-LR differences as function of SWH, Vertical Velocity, Wind Speed (+Along-track currents)

❖ Correction 2

Then develop an empirical method to correct the **range or SSH** including the classical SSB (tilt and hydronamic modulations) and the new effects (dynamics), using:

1. Corrected SWH (from Correction 1)
2. Altimeter Wind speed
3. Mean Wave period (T02)
4. Along-track Stokes Drift Velocity (from models)
5. Vertical Velocity (less priority)

Current 3D SSB model (items 1–3)

CLS

Recommendations for the future (2/2)

- As shown above, it is important for delay/Doppler altimeters to develop new SSH corrections moving from the classical SSB to Pseudo-SSB correction using more than 3 parameters.
- However, this requires extending the current SSB method (the non-parametric empirical method developed by Gaspar and Florens, 1998) to consider more than 3 parameters for the estimation.
- A work plan has been established between CLS, CNES and Mathematics Experts to develop such a method in 2024.
- As soon as the new method is available, we will work on the new Pseudo-SSB correction using the parameters identified in this study (see previous slide).
- In the meantime, we are working on an alternative correction consisting in applying the classical SSB correction first (3D model) and then applying a second correction by minimizing the HR-LR range differences as a function of Along-track Stokes Drifts, Wind Speed and Vertical Velocity.

Note that, even the conclusions and recommendations of this study have been derived from Sentinel-6MF data, they are applicable to all delay/Doppler altimeters measurements over ocean including Sentinel-3 and CRISTAL.

CLS

Thank you

lamarouche@groupcls.com