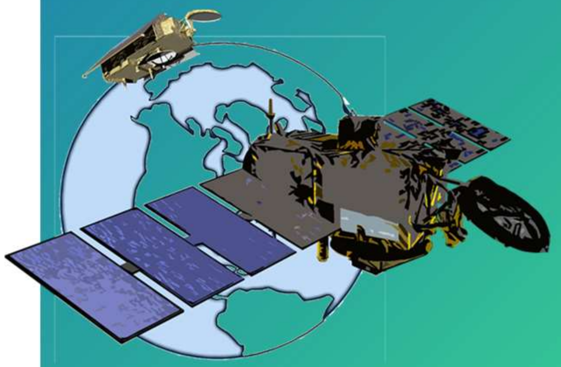


Scientific Activities: Sea State S6-JTEX-CS-05 (Study 1)

Final Review 24/04/24

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

Context and Study Objectives

- Various studies pointed out significant benefits of Delay/Doppler technique over conventional altimetry in terms of improved measurement errors and finer along-track spatial resolution.
- However, some of them have also highlighted certain limitations due to the sensitivity of delay/Doppler measurements to ocean waves and their dynamics.
- As the operational retracking methods don't account for these effects in their waveform models, these effects can lead to errors in the estimates.
- Characterized and correctly understanding these effects could improve delay/Doppler estimates and help to better exploiting the higher spatial resolution brought by this technique.
- Understanding the impact of these effects could also help estimating new surface parameters.

The objectives of this study are:

- 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)

Study Objectives

- We used Sentinel6-MF data and external parameters from wave and currents models (ERA5 and MERCATOR) to caracterize 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:
  - Vertical Velocity
  - Wind Speed and direction
  - Stokes Drifts and other surface currents.
- Our study was also based on qualitative theoretical analysis.

This presentation will focus on the main results and conclusions

Data Used (1/3)

Sentinel-6 MF Level 2 :

- LR and HR data over ocean
- Data from the 2022 reprocessing.
- We used a full year of data (cycles from 42 to 78).
- Range and SWH from MLE4 for LR and SAMOSA for HR
- No SSB correction applied to the range

Data Used (2/3)

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

Interpolation in space and time at the altimeter measurement

Data Used (3/3)

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

→

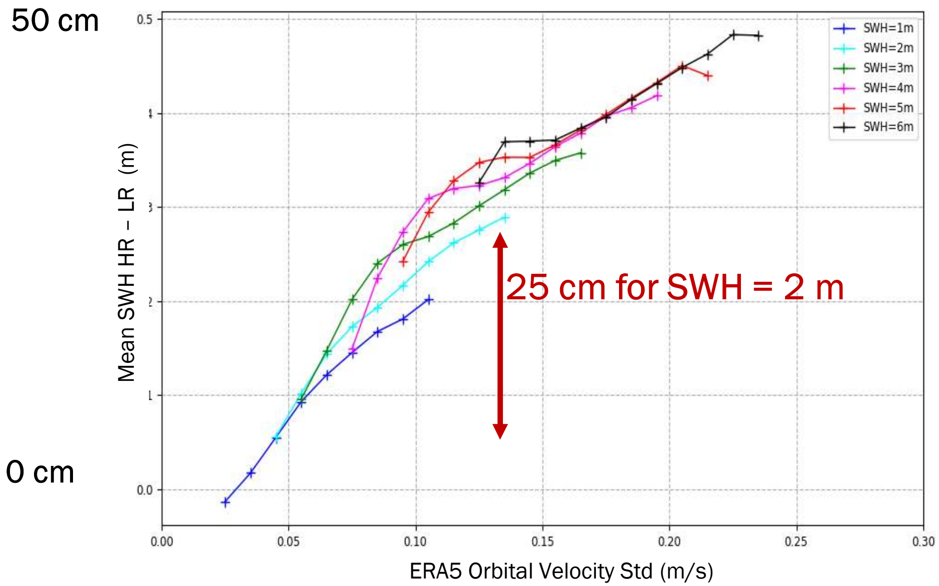
Computation of new parameters from MERCATOR parameters:

- 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

Interpolation in space and time at the altimeter measurement

Significant Wave Height and Orbital Velocity

SWH Difference HR–LR wrt ERA5 Vertical Velocity

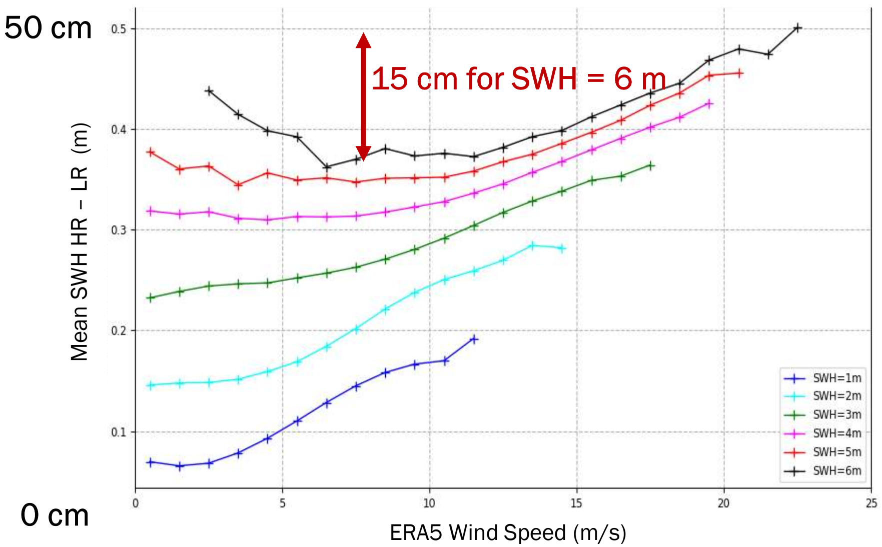


Confirmation of the **Increase of SWH** HR-LR diffrences with **increasing Vertical Velocity.**

This effect was identified some years ago on CryoSat-2 and Sentinel-3.
It has been accounted for recently on Sentinel-6 operational processing based on LUT with SWH and T02 from wave model as inputs [Egido et al. 2022].

Significant Wave Height and Wind Speed

SWH Difference HR–LR wrt ERA5 Wind Speed

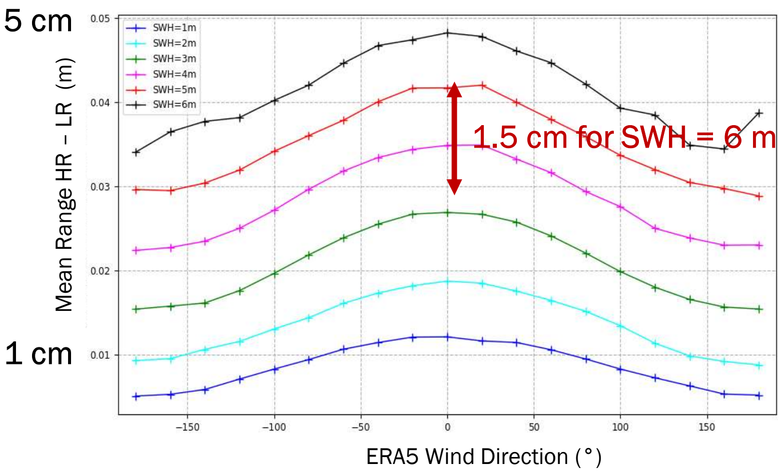


Clear dependency of SWH on wind speed and SWH

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

Range and Wind Speed

Range Difference HR–LR wrt ERA5 Wind Speed Direction

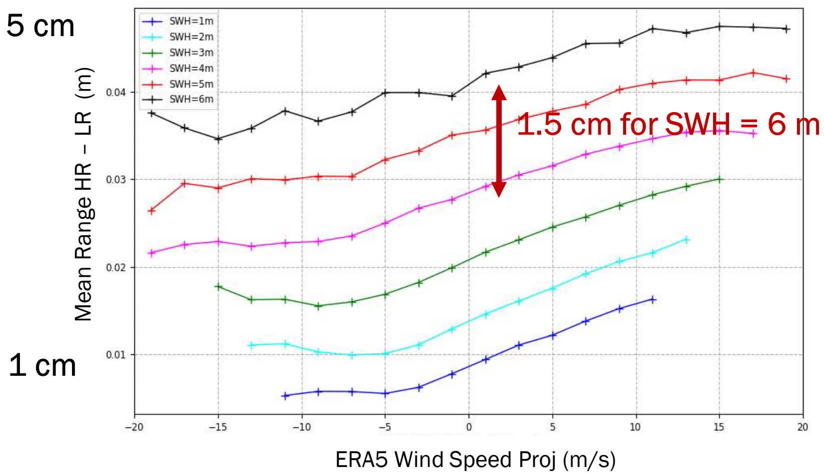


- Note that the LR data used MLE4 retracking with a skewness coefficient of -0.1.
- As no skewness in HR data => linear dependence in SWH of the differences between the HR and LR estimates.
- Not blocking for our study but welcome as helps to separate the wave dependent curves
- Our interest is the dependency on the parameter in the x axis (here wind direction).

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

Range and Wind Speed

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

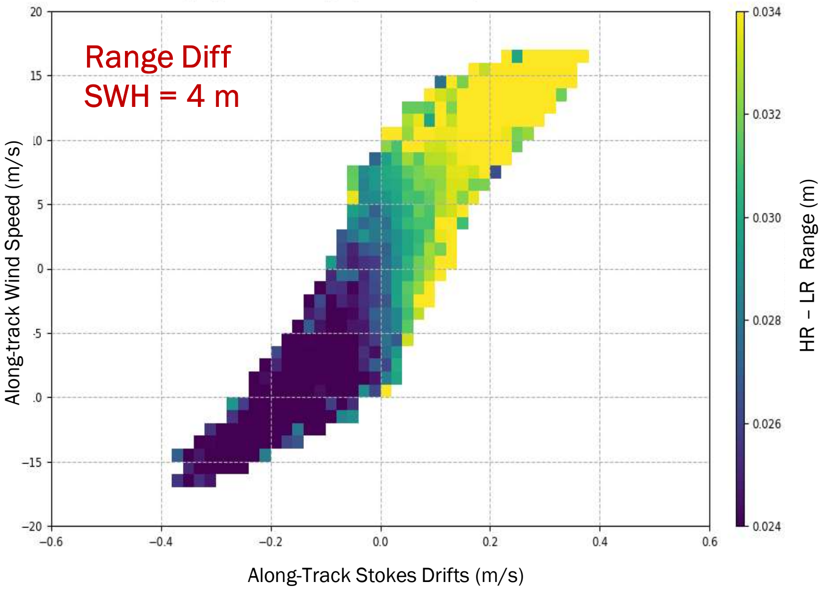


HR-LR **range** differences depend also on the **along-track wind speed** value.

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

Range and Stokes drifts

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



Clear dependence of HR–LR range differences on along-track Stokes drifts velocity rather than on wind speed.

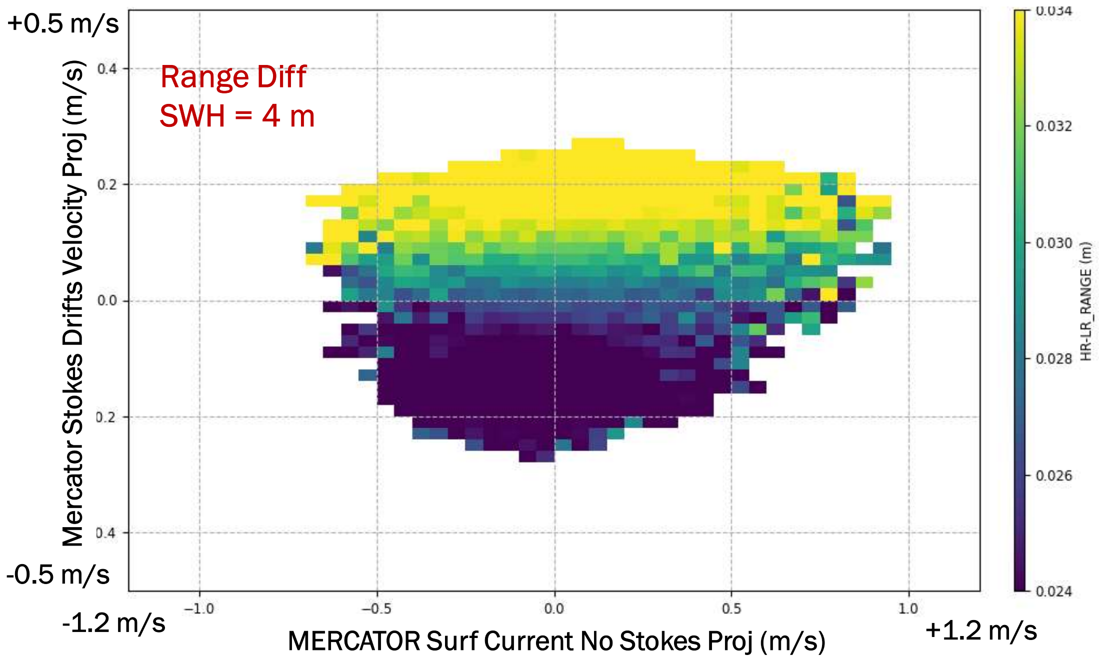
The observed dependency on wind direction is probably due to the high correlation between wind and stokes drifts

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

Range and Total Surface Currents

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 behavior 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.
- Stokes Drift Velocity value which is associated to the overall drift of waves crests with the waves propagation => The wind driven surface velocity is locally much higher than the Stokes drift velocity values

Summary, Conclusions

- We analysed one year (cycles from 42 to 78) of Sentinel-6MF LR and HR data.
- Differences of Range and SWH between HR and LR modes have been characterized wrt to different surface parameters extracted from ERA5 and MERCATOR models.
- Surface parameters analysed are: Wind Speed, Vertical Velocity, Stokes Drifts Velocity 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 allow to conclude that delay/Doppler processing measurements are impacted by the <u>combination</u> of three phenomena : **Vertical Velocity, Wind Speed** (inducing **roughness assymetry** between **upwaves** and **downwaves**) and **along-track Stokes Drifts.**

Recommendations for the future (1)

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)

(Items 1–3: Current 3D SSB model)

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Recommendations for the future (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).

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.

Status of the publication

OSTST 2023 forum presentation (instrument processing – corrections)

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

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F. Boy, C. Maraldi (CNES)
C. Donlon (ESA)

Analysis of the sea state impact on Sentinel-6MF Delay/Doppler measurements

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F. Boy[2], C. Maraldi[2],
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Abstract

We evaluated the impact of ocean wave dynamics on the estimates of significant wave height and sea surface height from Sentinel-6MF delay/Doppler measurements. To this end, we used one year of real Sentinel-6MF data and information on waves and currents from the ERA5 and MERCATOR models. A theoretical analysis was also carried out to explain qualitatively how surface dynamics impact delay/Doppler signals and hence the corresponding estimates. We concluded that delay/Doppler measurements are influenced by the combination of three phenomena: waves orbital velocity, wind speed (inducing roughness asymmetry between upwaves and downwaves) and along-track Stokes drifts. We also found that, except for Stokes drifts, the other surface currents have no impact on delay/Doppler estimates. We finally recommended to develop two new corrections, one for SWH and the second one for the range or SSH. The SWH correction should use SWH, orbital velocity and wind speed as input variables. This correction should provide improved results over the Egido et al. (2022) correction thanks to the addition of wind speed. The correction of the range could be considered as a generalized sea-state bias or pseudo sea-state bias correction, as it includes the classic SSB correction and additional surface characteristics that affect the delay/Doppler signal. This latter requires the development of a new SSB correction mathematical method.

Keywords: Satellite altimetry; Sentinel-6MF, Sea State, Ocean Waves, Sea State Bias, Delay/Doppler, Orbital Velocity, Stokes Drifts, Currents

New version of the Draft paper is available. To be completed and submitted in May

Analysis of the sea state impact on Sentinel-6MF Delay/Doppler measurements

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Other recommendations

- Exploit the sensitivity of the delay/Doppler measurements to orbital velocity and Stokes drifts to estimate these parameters, at least for some ocean sea states conditions.
- This information may be of interest if combined to the ocean wave spectra estimation methods developed recently for nadir delay/Doppler altimetry: for e.g. to improve the Modulation Transfer Function (MTF).

And beyond sea state, other investigations using Sentinel-6 MF are also interesting:

- Sentinel-6MF and in particular the 90 GHz channel to Sea Ice Concentration and Snow Depth estimation
- Sentinel-6MF analysis of the contribution of the HF channels to WTC retrieval and uncertainty

CLS

Thank you

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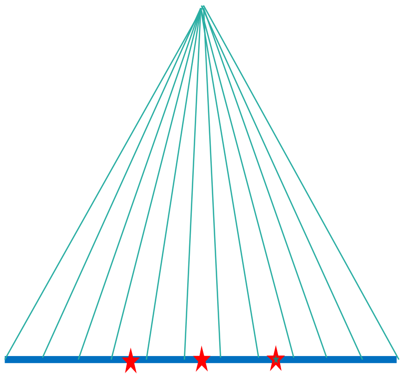
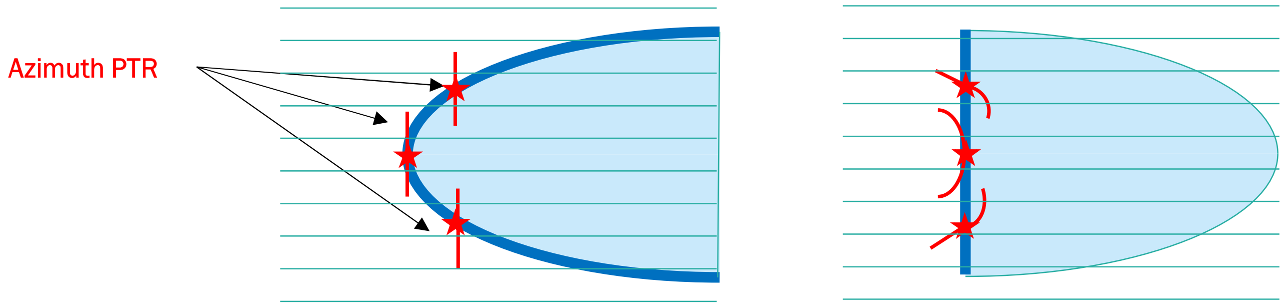
Vertical Velocity impact



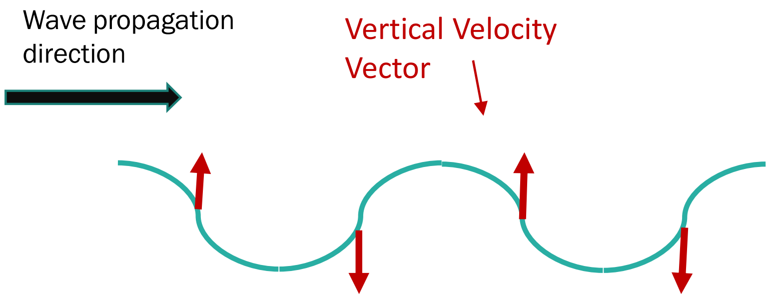
Doppler Processed Burst **before** Range Migration Correction

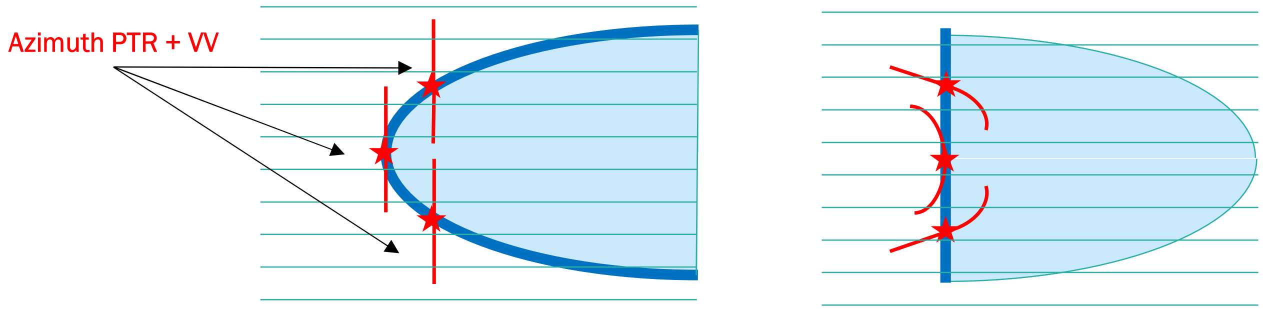
Doppler Processed Burst **After** Range Migration Correction



Vertical Velocity => Impact (larger) on the « observed » azimuth PTR

Whatever wave direction wrt satellite direction



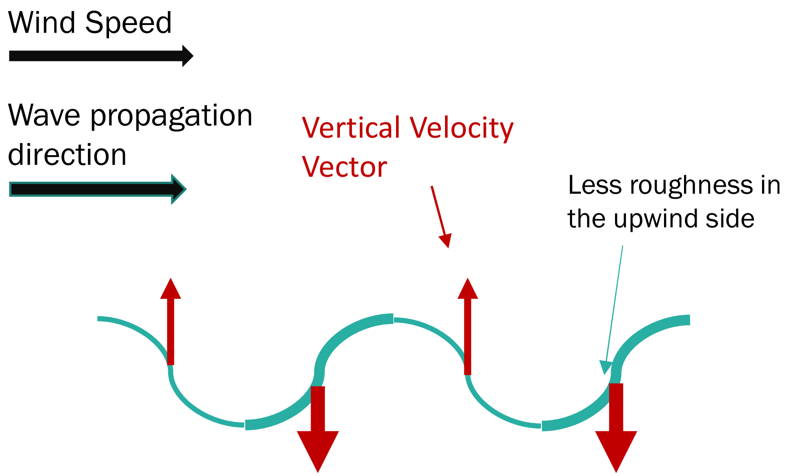


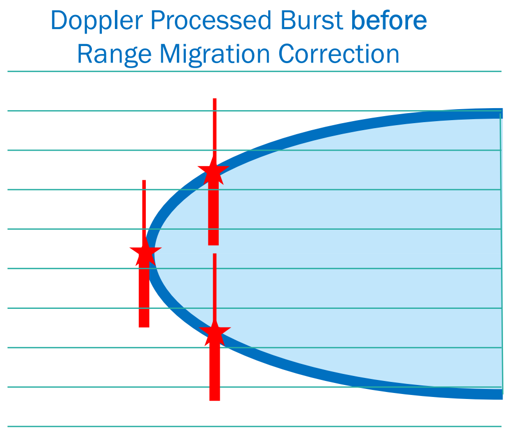
Range VV <? Range (more impact on early gates?)
SWH VV > SWH

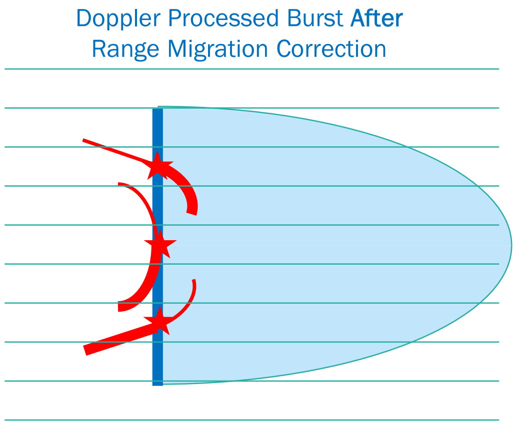
Note that the deductions on the burst basis are also applicable to the stack

Wind Speed Impact

Vertical Velocity + Wind speed // Waves







Range VV+WS < Range VV?
SWH ?

Wind Speed and Waves propagating in the same direction

⇒ More surface scatterers moving away from the satellite than those moving towards the satellite

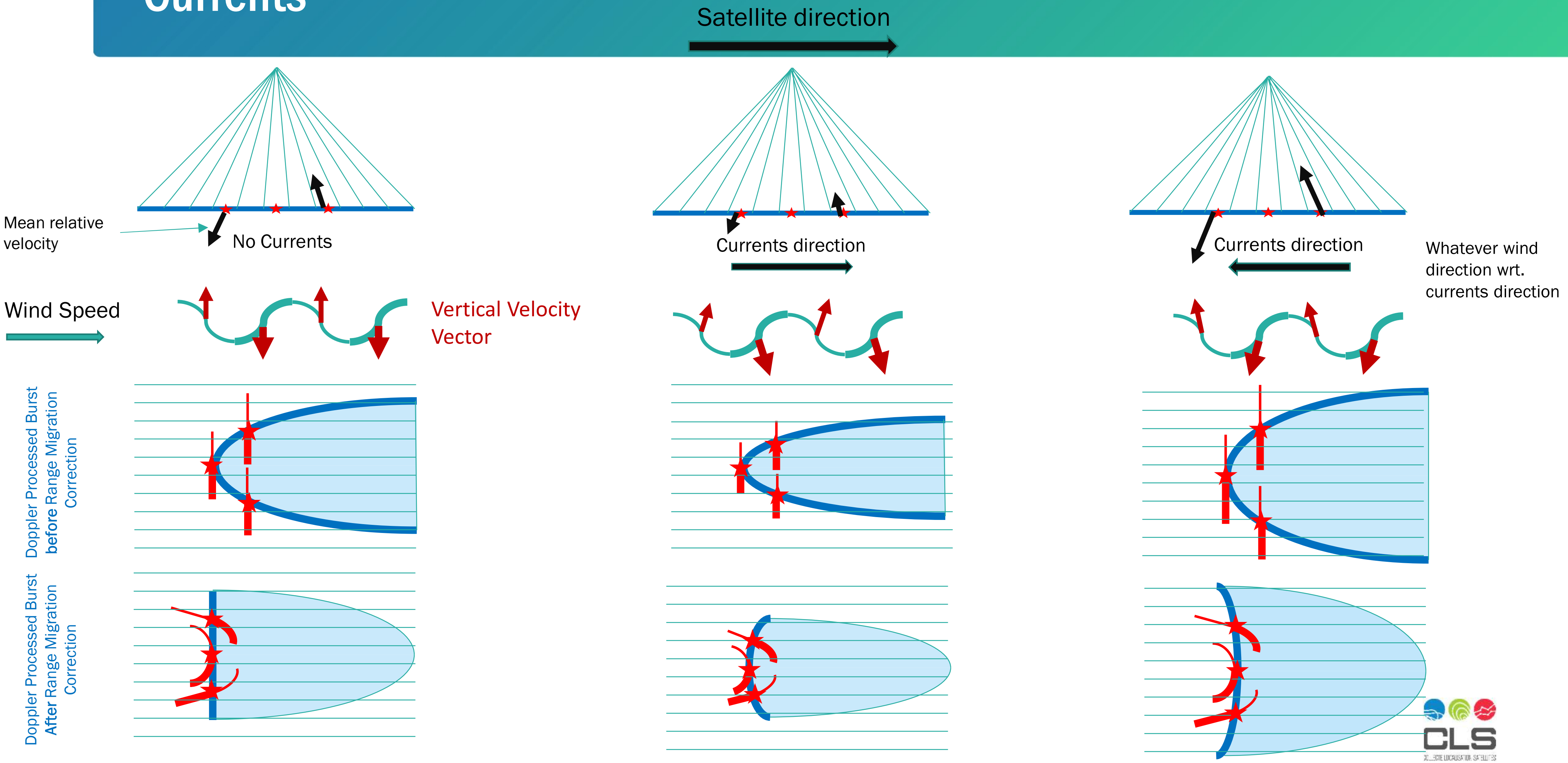
⇒ More energy is Doppler shifted towards negative Doppler frequencies

⇒ Range migration correction will shift more energy to the early range gates of the waveforms

⇒ Difficult to conclude if the impact is positive or negative bias on the Range and SWH estimates

BUT, in this configuration (no currents), any impact on the range or SWH should not be dependent on the wind direction wrt. the satellite direction

Currents



Range VV_WS =/ Range VV

Range VV_WS_C+ > Range VV_WS

Range VV_WS_C- < Range VV_WS