Speckle noise estimation from SWIM measurements

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Summary

- Reminder on the speckle effect perturbation
- The different speckle estimation methods studied here
- Dataset used for the current work & presentation
- Results from the different speckle elimination methods for two particular cases in the Indian Ocean
- Comparison of mean speckle spectra from the different methods
- Mean wave spectra using different speckle elimination methods
- With the cross-spectral method at high rate
    - comparison of wave spectra for the different SWIM beam (6, 8, 10°)
    - Comparison of wave parameters with the MFWAM model parameters
- Conclusions & Ongoing work

The first results of SWIM instrument data processing have demonstrated the very good capability of the instrument to provide the spectral properties of the ocean waves in the wavelength range between 70 and 500m (*Hauser et al*., 2020). The accuracy of the data strongly depends on the reliability of the speckle noise correction and the modulation transfer function. Speckle noise removal processing has been so far a major issue to deal with because all the downstream data processing as spectra partitioning or derived wave parameters is strongly dependent on the quality of its correction. In the current presentation, we use data acquired in the **speckle mode acquisition.** Speckle mode is characterized by an onboard averaging of the radar echoes in time over one third of the samples compared to the standard mode and an onboard averaging over a number of gates which is three times the ones used for standard mode (implying radial resolution loss). In the current presentation, we assess data acquired in speckle mode and apply different speckle correction methods, including specific to this acquisition mode, in the scope of retrieving relevant information which could improve the empirical correction method which is currently used.

Reminder on the speckle effect perturbation

Speckle noise affects the radar backscattered signal and hence the signal fluctuation spectrum which is inverted to estimate the wave slope spectrum from the observations.

In the spectral domain, the wave spectrum is estimated from the signal fluctuation spectrum $P_{\delta\sigma_0}$, after subtracting the density spectrum of speckle P_{sp}

$$\boldsymbol{P_{\delta\sigma 0}(k) = P_{IR}(k)P_m(k) + P_{sp}(k)}$$

where $P_{IR}(k)$ is the impulse response

The different speckle estimation methods (1)

- Ø <u>The Analytical model from theory</u> (**sp_th**) : triangle-shaped function (as for the FT of the impulse response function) whose slope depends on horizontal resolution and the level at the origin depends on both horizontal resolution and number of independent samples Nind = used at the beginning of the mission with Nind independent of viewing direction

$$P_{sp\_Nind}(k) = \frac{\delta r}{4\,\pi\, N_{ind}} \frac{1}{\sin\theta}\, tri\left(\frac{k}{2\pi}\frac{\delta r}{2\sin\theta}\right)$$

where ($\delta r/\sin\theta$) is the horizontal resolution, and N_{ind} the number of independent averaged samples

- Ø <u>The Empirical analytical model</u> (**sp_emp**) **:** derived from the CAL-VAL analysis ; Model $P_{sp}(k,\Phi)$=combination of a triangle function far from the along-track direction, with N_{ind} & dr adjusted using the empirically-estimated noise floor, and of a quadratic form close to the along-track direction. 21 parameters for 3 sea states x 7 latitude intervals. See Hauser et al, TGRS 2021 for details

- Ø <u>The mean floor noise level</u> (**sp_nfl1**) **:** mean of fluctuation spectrum at k > 0.4 rad/m (supposed not affected by waves) independent of k , variable with azimuth Φ

- Ø <u>The floor noise spectrum</u> (**sp_nfl2**) : taken as the fluctuation spectra density in the direction of minimum of fluctuation variance within each antenna half-rotation, dependent on k but independent of azimuth Φ

Several speckle correction methods have been implemented in the operational processing chain. These methods, which are adapted to the nominal acquisition mode, are shortly described in the current and the two following slides. The former theoretical model method (**sp_th**) which was applied to the data at the beginning of the mission showed weaknesses to represent the speckle around the along-track direction. To come over this problem, an empirical model (**sp_emp**) was established from the analysis of the free-wave fluctuation spectra according to azimuthal direction, latitude and sea-state (*Hauser et al,* TGRS2021). This model is the one currently used in the operational processing chain. It succeeded in providing rather accurate products. However this parametric model which depends on latitude and sea-state and which derives from a statistical study based on data acquired on a couple of days, doesn't always succeed in providing a noise model adapted to the sample (overestimation or underestimation).

The different speckle estimation methods (2)

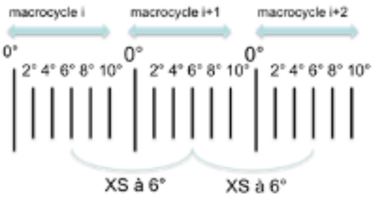
Ø The cross-spectra method (**sp_xs_low**) : First used for wave spectrum retrieval from SAR (Engen and Johnsen TGRS, 1995). P_{sp} estimated from the comparison of co-spectra and cross-spectra of signal fluctuations $\delta\sigma 0$ between two successive times t_{n-1} and t_n: $P_{sp3}(k,\Phi) = P_{\delta\sigma 0}(k,\Phi) - 2\,X_S(k,\Phi)$

where X_s is the cross-spectrum defined from the FT of the signal fluctuations $\delta\sigma 0$ within the footprint as:

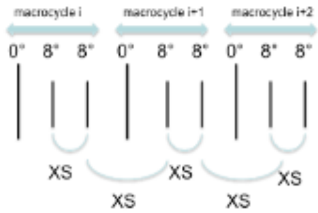
$$XS(k,\phi) = TF\left[\delta\sigma_{0\_X}(X,\phi_n,t_n)\right]TF^{*}\left[\delta\sigma_{0\_X}(X,\phi_{n-1},t_{n-1})\right]\,Migr(k,\phi)$$

Migr(k,Φ) is a migration compensating term (due to migration of the footprint over the time interval ΔT), k is the wavenumber and Φ the look direction.

In opposite to the co-spectrum of fluctuation $P_{\delta\sigma 0}(k,\Phi)$, $X_S(k,\Phi)$ is not impacted by speckle if the correlation time of speckle is less than ΔT. Typically, ΔT is equal to 220 ms in standard acquisition mode (case of cross-spectra between macrocycles in nominal/0-2-4-6-10 acquisition sequence) can be reduced in alternative macrocycle mode (ex 0-8-8) combined or not with speckle acquisition mode.



Nominal Macrocycle case
ΔT~ 220 ms



Alternative Macrocycle sequence (repeated beams)

ΔT~ 40 ms or 120 ms for mode 0-2-8-8

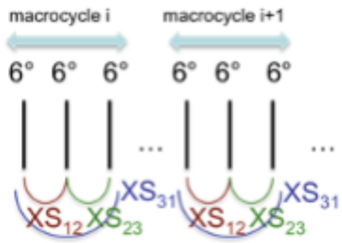
Here we describe the cross-spectra method (Hauser et l., TGRS 2017, Engen & Johnsen, IEEE_TGRS, 1995). We will name it **sp_xs_low**, "low" to distinguish it from the high cross-spectra method used in speckle acquisition mode (see next slide).

Methods of estimation specific to speckle acquisition mode (1)

- <u>The cross-spectra method in speckle mode</u> **(sp_xs_high) : same as sp_xs_low** but estimated at a higher signal sampling rate (time-integration of echoes = one third of the standard/nominal one). P_{sp3LG} estimated as a weighted average of three P_{sp} estimates:

$$P_{sp3LG}(k) = 2/5 * P_{sp12} + 2/5 * P_{sp23} + 1/5 * P_{sp31}$$

With P_{sp12} , P_{sp23} , P_{sp31} the density spectra of speckle estimated from the cross-spectrum method for 3 different combinations of echoes



ΔT~ 20-40 ms for cross-spectra estimates

In this presentation, we'll name this correction method as **sp_ws_high** for "high rate" of repetition, to distinguish it from the lower rate cross-spectra method adapted to the normal acquisition mode.

Methods of correction specific to speckle acquisition mode (2)

- The multi-integration method (**sp_multi_int**) **:** First proposed by Hauser et al, 1992 and used by Chen et al (TGRS 2020)on airborne data

estimated by comparison of fluctuation spectra estimated on different integration times

$$P_{sp} = \frac{\langle P_{\delta\_\sigma_0\_i} \rangle_i - P_{\delta\sigma_0}}{N_l - 1}$$

$\langle P_{\delta\_\sigma_0\_i} \rangle_i$ corresponds to mean fluctuation spectrum, calculated by averaging the three individual fluctuation spectra on Nimp/3 impulses (assumed independent)

$P_{\delta\sigma_0}$ the fluctuation spectrum calculated from the waveform derived from post-integration of the 3 radar waveforms, corresponding to Nimp samples. (Nl=3)

The second method specific to speckle mode acquisition is the "multi-integration" method (see Hauser et al, JGR 1992; Chen et al TGRS 2020)

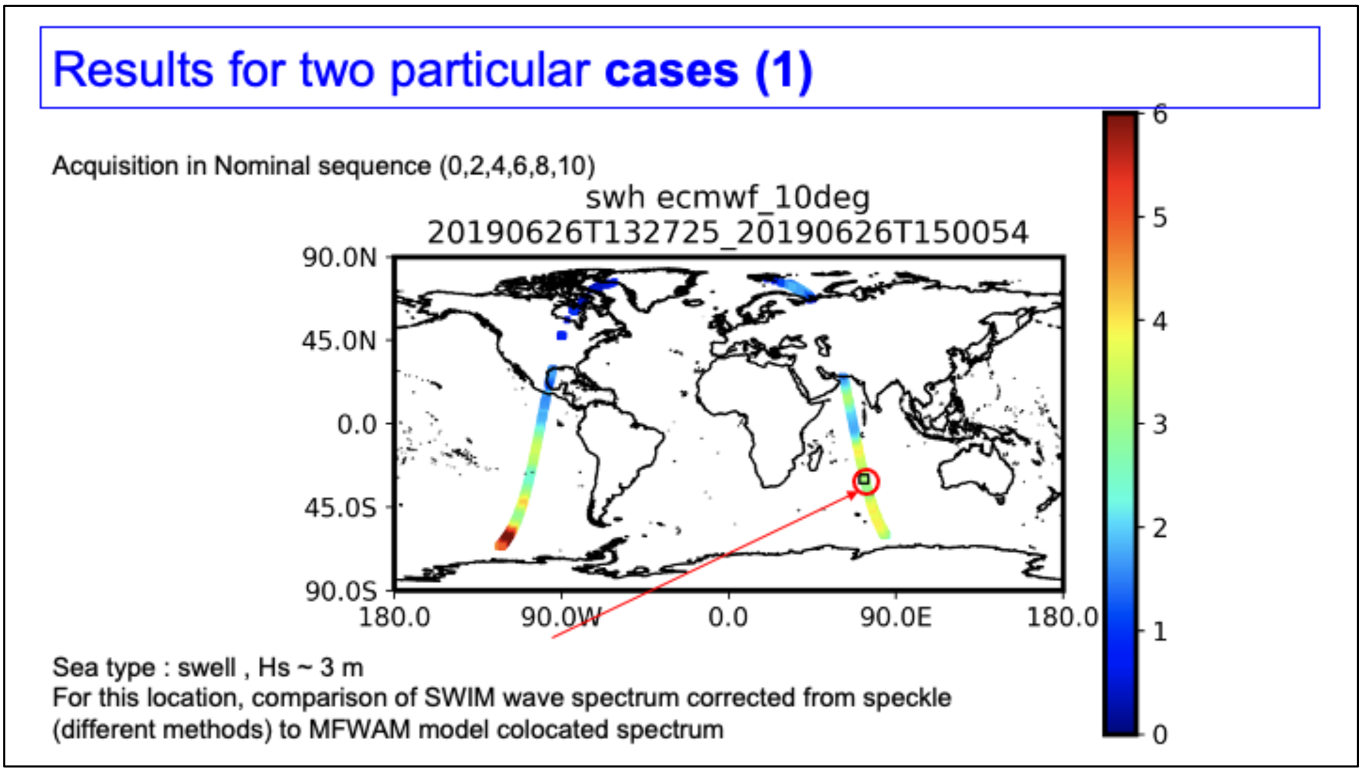
Dataset used for the present analysis

Start date	End date	Orbit cycle	Nominal (ie rotating) or Fixed	Séquence	Acquisition mode : Nominal or Speckle
26/06/2019 00:00:00	28/06/2019 00:00:00	19	N	N	S
28/06/2019 00:00:00	30/06/2019 00:00:00	19		0_2_8_8	S
30/06/2019 00:00:00	02/07/2019 00:00:00	19	N	0_2_10_10	S

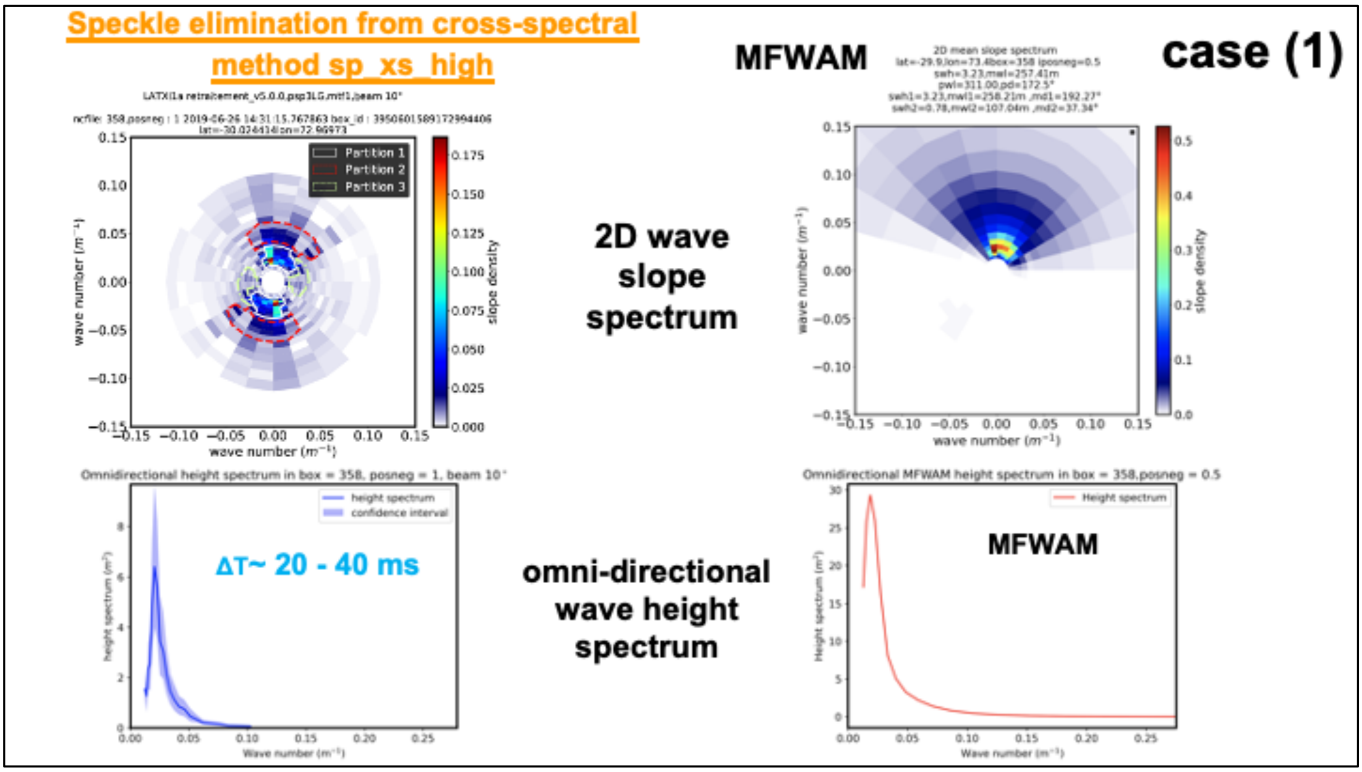
Reprocessing for tests, using :

- sp_xs_low
- sp_xs_high
- sp_multi_int
- sp_emp

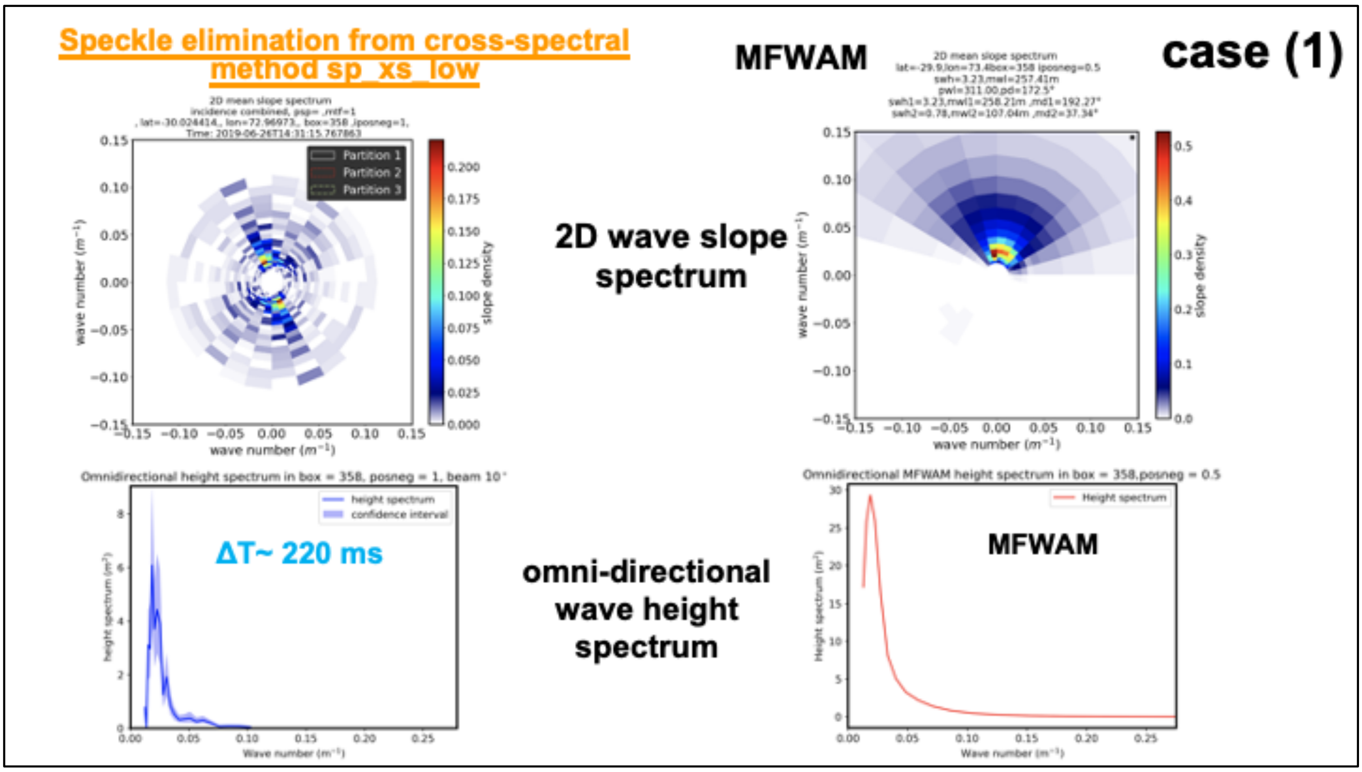
This slide presents the dates and beam sequences modes during the time interval studied, from 26/06 to 01/07/2019 included. The data were reprocessed using the different speckle methods correction.



Two particular cases are presented in the next slides. This slide shows the total significant wave height from ECMWF during a particular segment of CFOSAT, between ~13:30 and 15:00 on day 26 of June 2019. The next slides display the spectra acquired in the box (black square on the map) in the Indian Ocean.

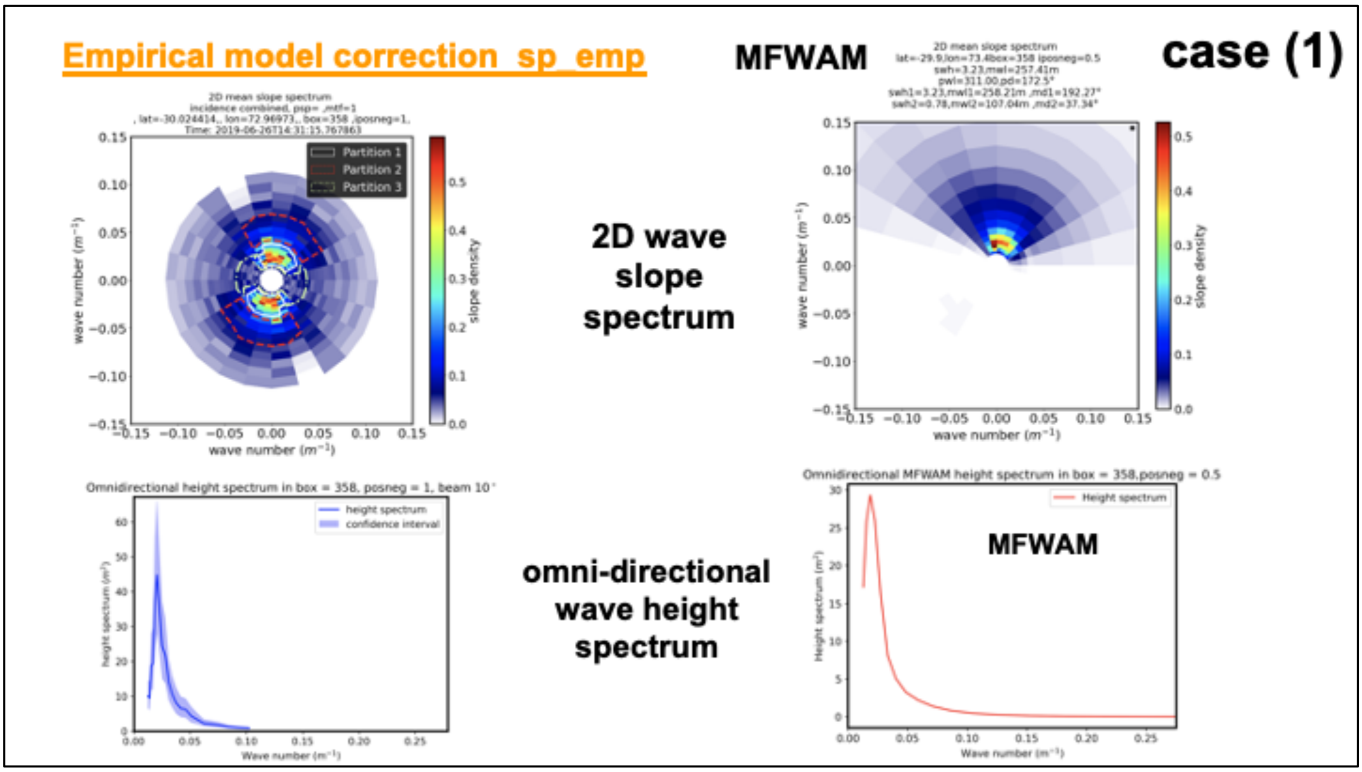


The **SWIM 2D spectrum** derived from cross-spectrum **xs_high** (Top left) displays a main wave pattern (swell) **consistent with** the colocated **MFWAM** 2D spectra (Top right). The along-track noise seems to be removed by cross-spectrum processing and is not (or hardly) visible. The average **SWIM 1D height spectrum** shape is consistent with MFWAM 1D height spectrum **but** energy is under-estimated by a factor ~5.

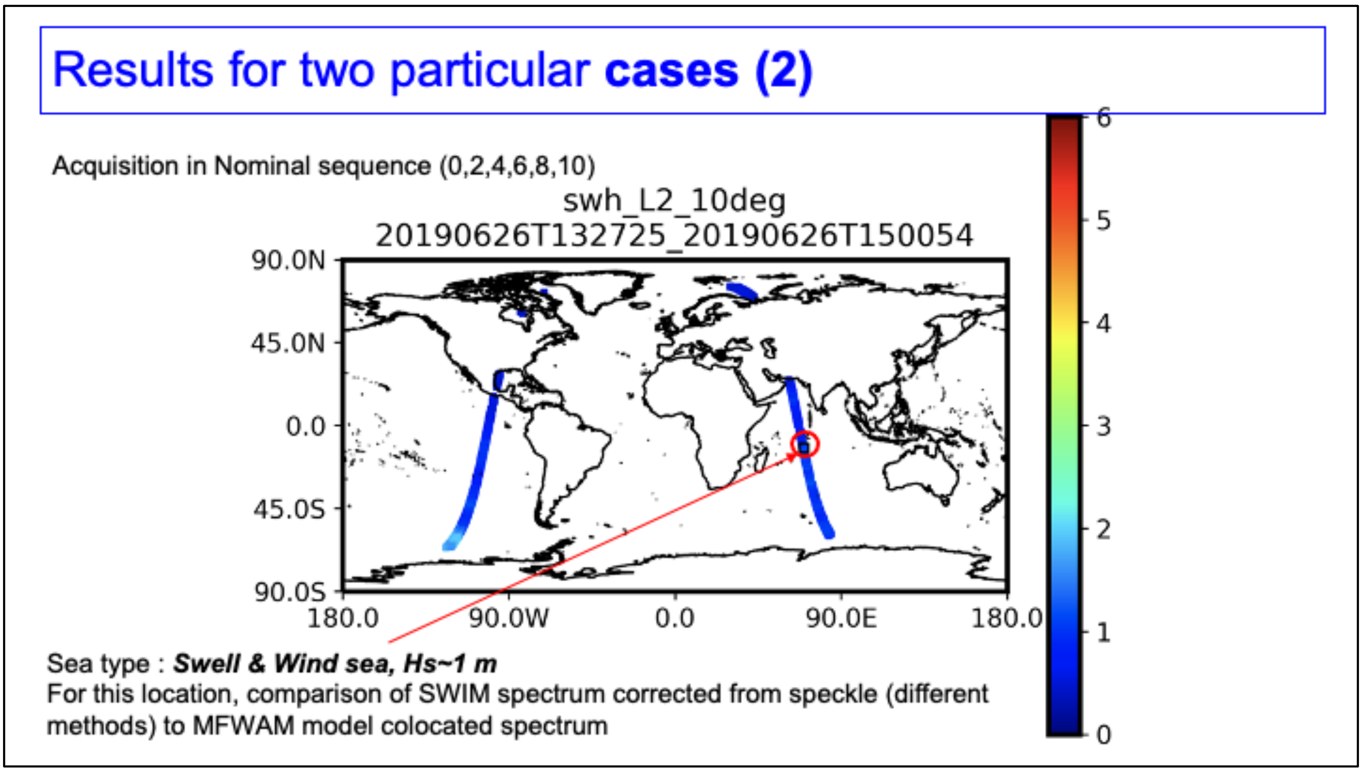


The **SWIM 2D spectrum** derived from cross-spectrum **xs_low** (Top left) is noisier and doesn't seem to match the colocated **MFWAM** 2D spectra (Top right). The peak of wave signal is not exactly colocated with MFWAM's. The average **SWIM 1D height spectrum** appears to be noisy as well and energy is low, under-estimated by a factor ~5 with respect to MFWAM.

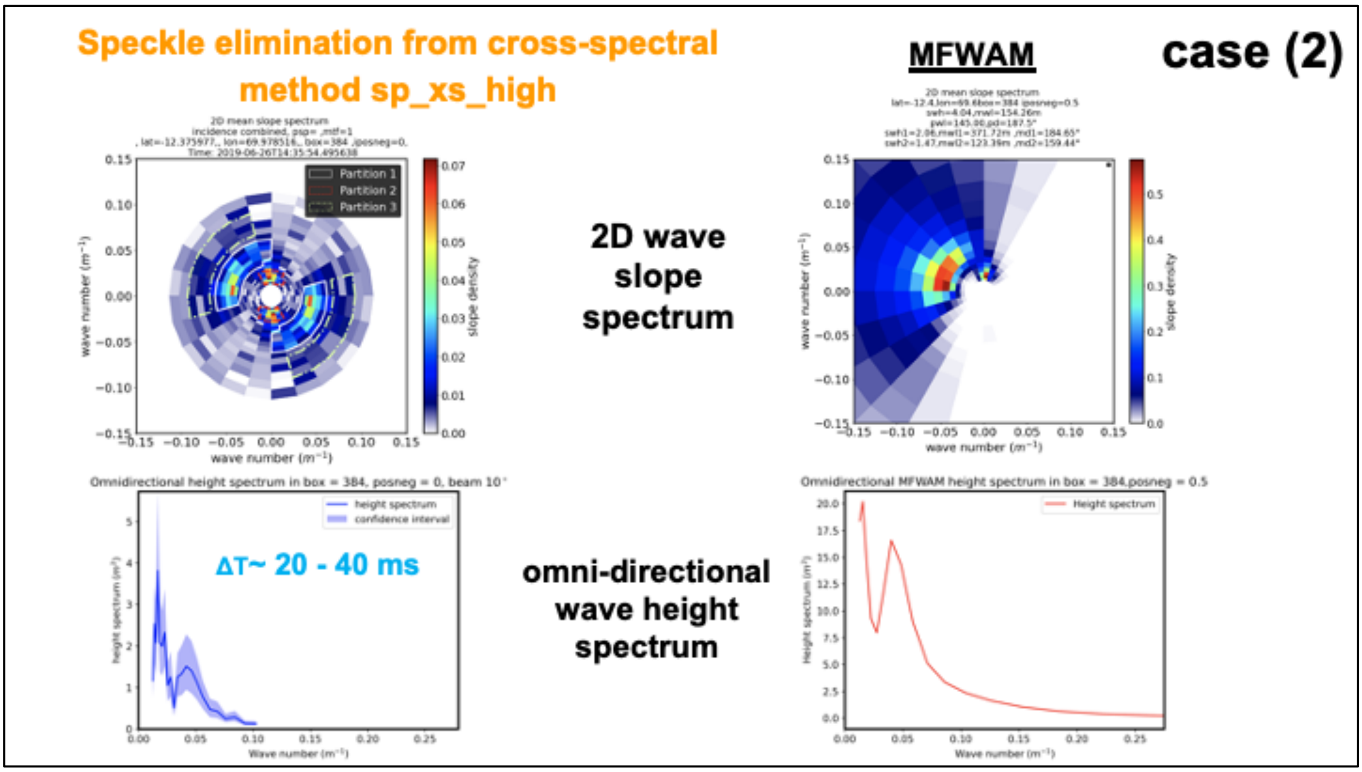
These features seem to show that time interval between two acquisitions used to compute cross-spectra is larger than the correlation time of waves.



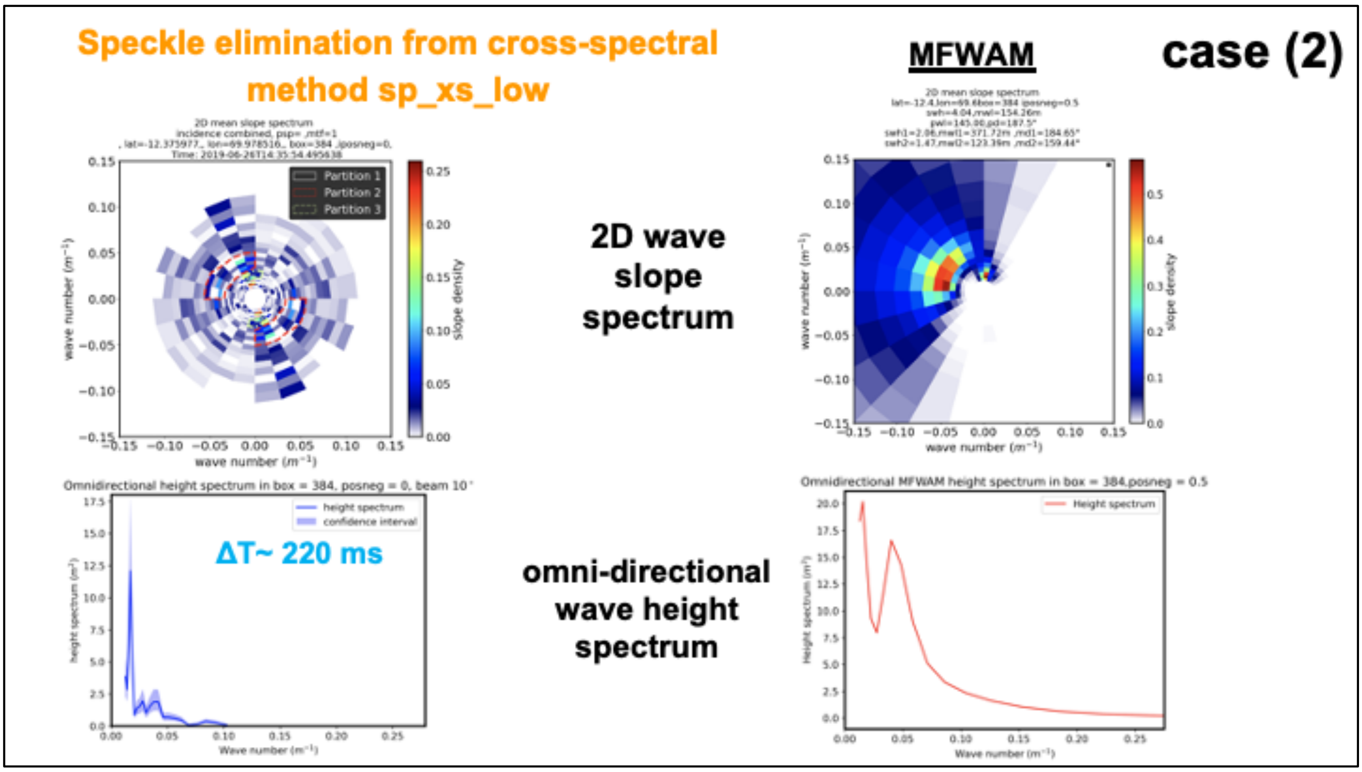
The **SWIM 2D spectrum** derived from the empirical model **sp_emp** (Top left) displays a main pattern (swell) **consistent with** the colocated **MFWAM** 2D spectra (Top right). The along-track noise seems to be overestimated at large wavenumber in the 330°-345° azimuthal direction sector. The average **SWIM 1D height spectrum** shape is consistent with MFWAM 1D height spectrum **but** energy is in this case over-estimated by a factor ~1.5.



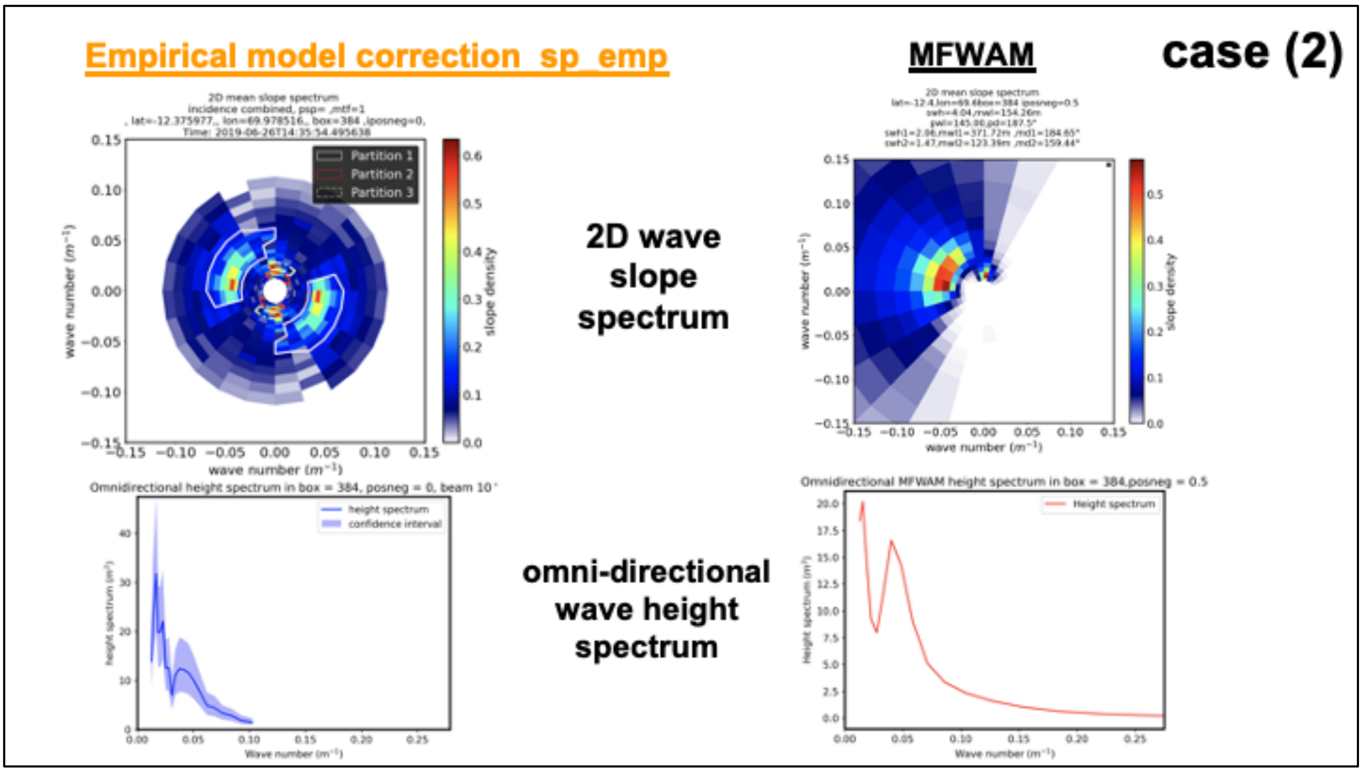
This slide shows a the total significant wave height from ECMWF during a particular segment of CFOSAT, between ~13:30 and 15:00 on 26 of June 2019. The next slides display the spectra acquired in the box (black square on the map) in the Indian Ocean.



The **SWIM 2D spectrum** derived from cross-spectrum **xs_high** (Top left) displays two nearly perpendicular wave patterns (swell and wind wave) **consistent with** the colocated **MFWAM** 2D spectra (Top right). The along-track noise seems to be removed by cross-spectrum processing and is not (or hardly) visible. The average **SWIM 1D height spectrum** shape is consistent with MFWAM 1D height spectrum **but** energy is under-estimated by a factor ~5.



Like in case (1), the **SWIM 2D spectrum** derived from cross-spectrum **xs_low** (Top left) doesn't seem to be consistent with the colocated **MFWAM** 2D spectra (Top right). The average **SWIM 1D height spectrum** appears to be noisy as well and energy is low, under-estimated.
This confirms our first conclusion that time interval between two acquisitions used to compute cross-spectra at this rate (220 ms) is too large to keep wave coherence.



The **SWIM 2D spectrum** derived from cross-spectrum **xs_emp** (Top left) displays two nearly perpendicular wave patterns (swell and wind wave) **consistent with** the colocated **MFWAM** 2D spectra (Top right). The along-track noise has been removed but correction seems a little high as we observe inside the 330°-360° azimuthal directions. The average **SWIM 1D height spectrum** shape is consistent with MFWAM 1D height spectrum **but** energy is over-estimated by a factor ~1.5.

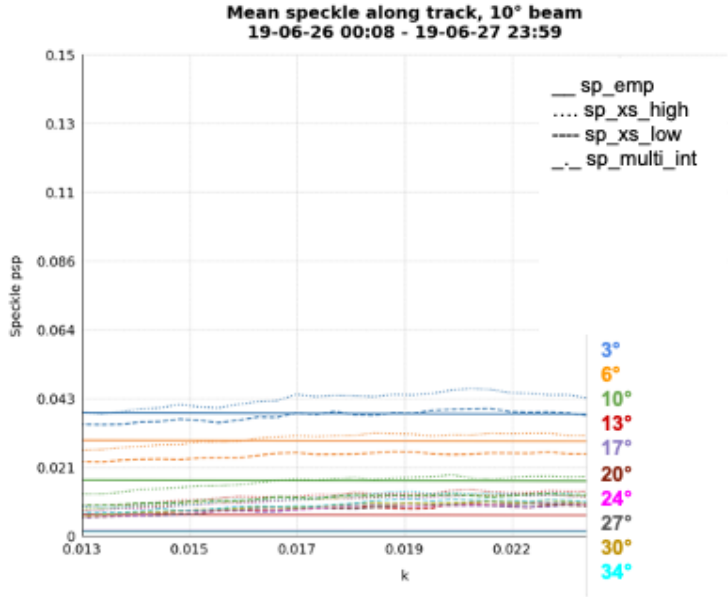
Mean speckle density spectra (function of k and azimuth)

Density spectra of speckle from the cross-spectral method sp_xs_high & sp_xs_low are **consistent with the empirical one** sp_emp in terms of

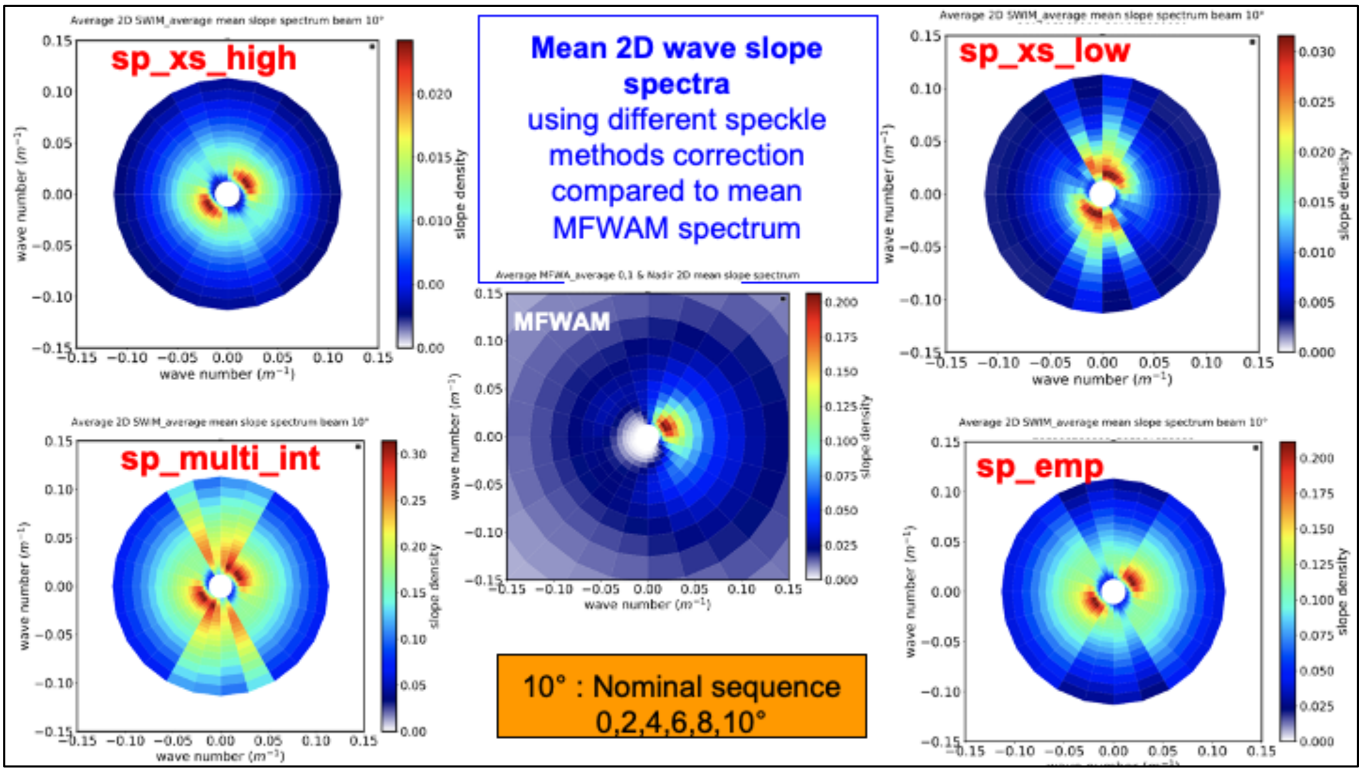
- Energy level
- Azimuthal variation
- Dependence on wavenumber k

In the along-track direction, sp_xs_high levels are higher than sp_emp

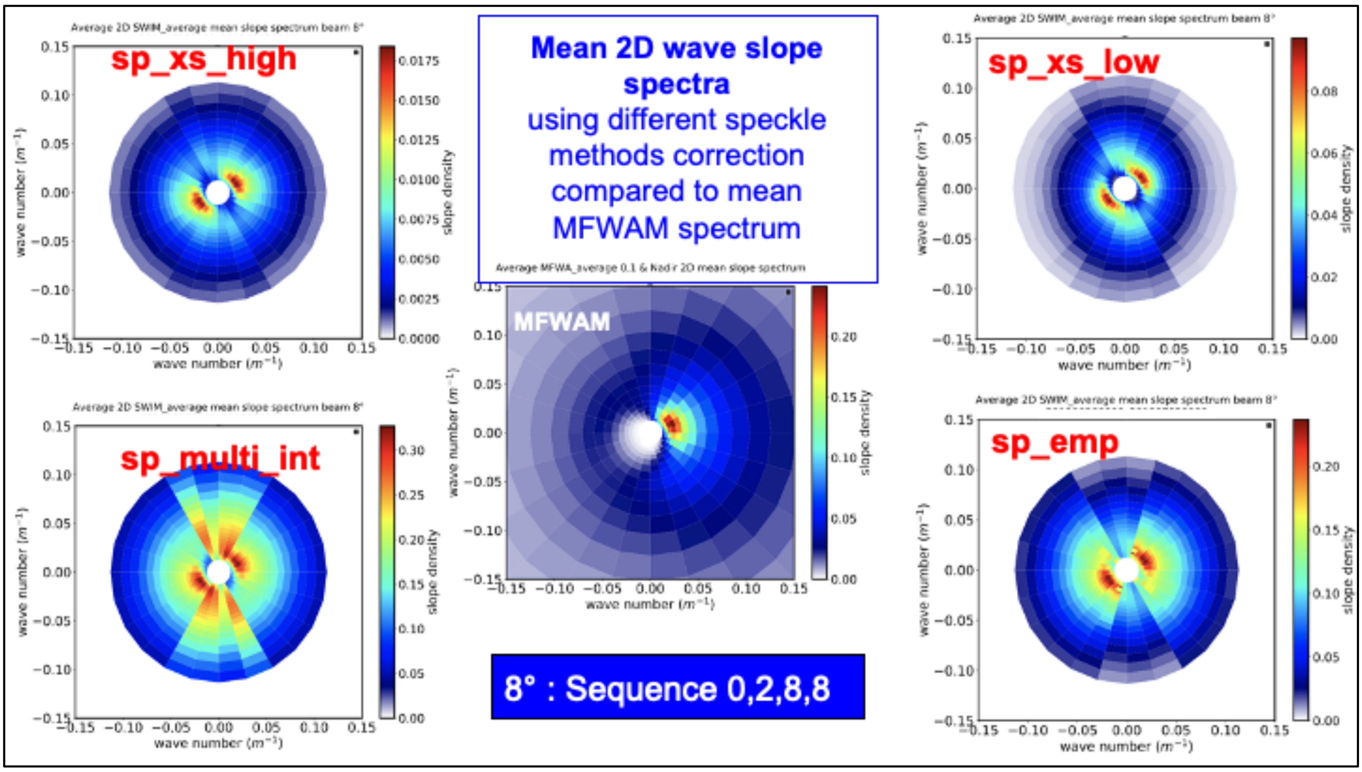
=> to be used to refine analytical model ?



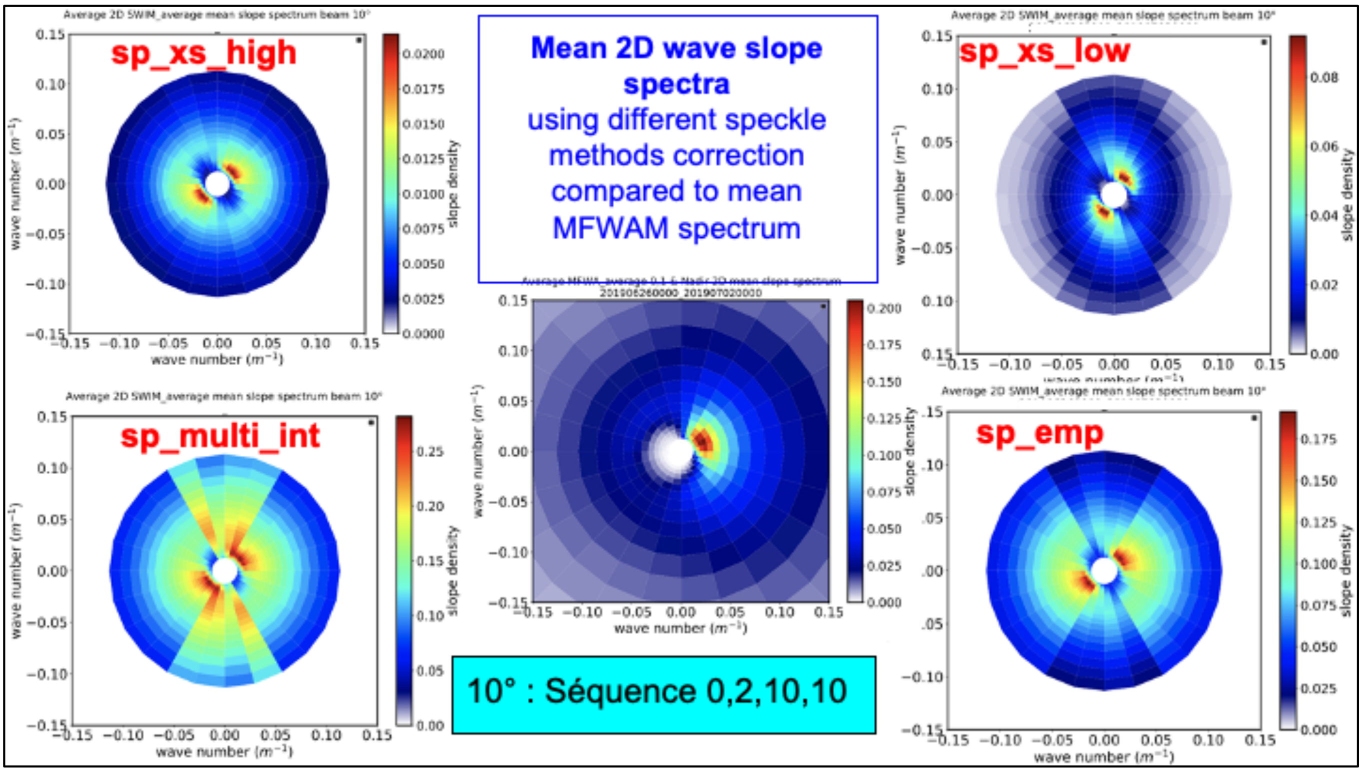
This slide presents the speckle spectra derived from 4 different speckle methods (sp_emp, sp_xs_high, sp_xs_low, sp_multi_int) in different azimuthal directions in the Local Orbital Reference (ROL) system; 0° being the direction parallel to the along-track direction (see legend of figure).



This slide displays 2D wave slope spectra averaged on a 2 day basis (26-27 june 2019) from the 4 speckle correction methods introduced earlier and the MFWAM averaged spectrum in the center. It appears here that only **sp_xs_high** and **sp_emp** are **consistent with MFWAM model**. Methods **sp_xs_low** and **sp_multi_int** displays sectors with additional/**abnormal** features in some azimuthal sectors.

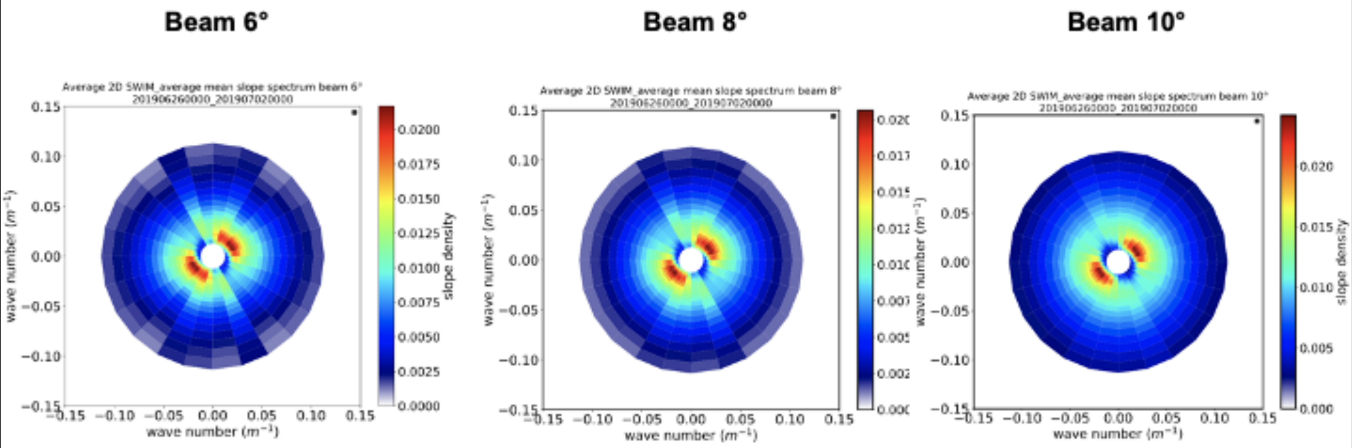


This slide displays 2D wave slope spectra averaged on a 2 day basis (28-29 june 2019) from the 4 speckle correction methods introduced earlier and the MFWAM averaged spectrum in the center, sequence with 8° beam repeated twice. It appears here that **sp_xs_high** and **sp_emp** are **consistent with MFWAM model**. Method **sp_multi_int** displays sectors with additional/**abnormal** features in some azimuthal sectors. In **sp_xs_low** average spectrum, the abnormal features are fainter than in the nominal beam sequence (previous slide), and the spectrum is closer to the model, probably because of reduced time gap between two acquisitions in cross-spectra computing (repeated beams in a sequence => ΔT < 220 ms in nominal mode) so there is a better correlation between two successive acquisitions.

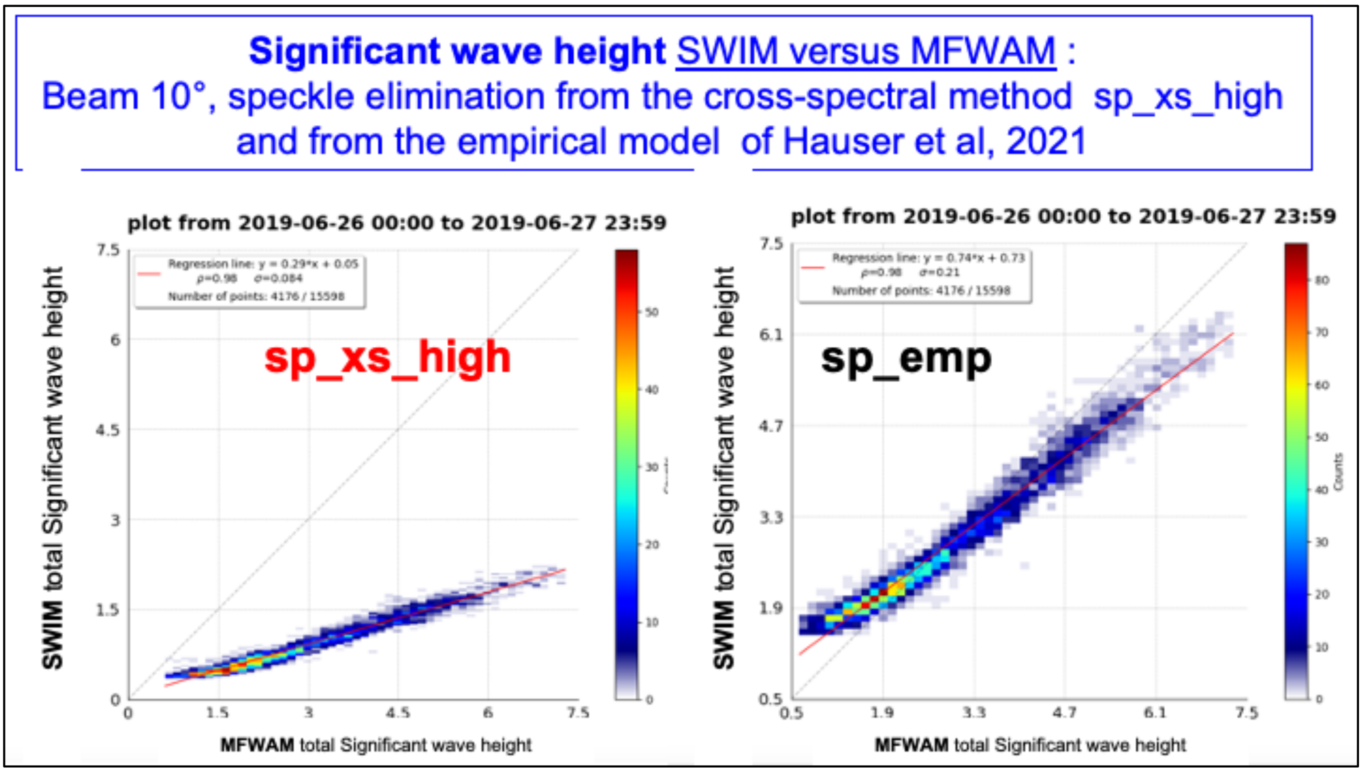


This slide displays 2D wave slope spectra averaged on a 2 day basis (30 june- 1 july 2019) from the 4 speckle correction methods introduced earlier and the MFWAM averaged spectrum in the center, sequence with 10° beam repeated twice. It appears here that only **sp_xs_high** and **sp_emp** are **consistent with MFWAM model**. Method **sp_multi_int** displays sectors with additional/**abnormal** features in some azimuthal sectors. In **sp_xs_low** average spectrum, the abnormal features are fainter than in the nominal beam sequence (previous slide), and the spectrum is closer to the model, probably because of reduced time gap between two acquisitions in cross-spectra computing (repeated beams in a sequence => $\Delta T < 220$ ms) so there is a better correlation between two successive acquisitions.

Comparison of wave spectra from the different SWIM beams - speckle estimation from the cross-spectral method sp_xs_high

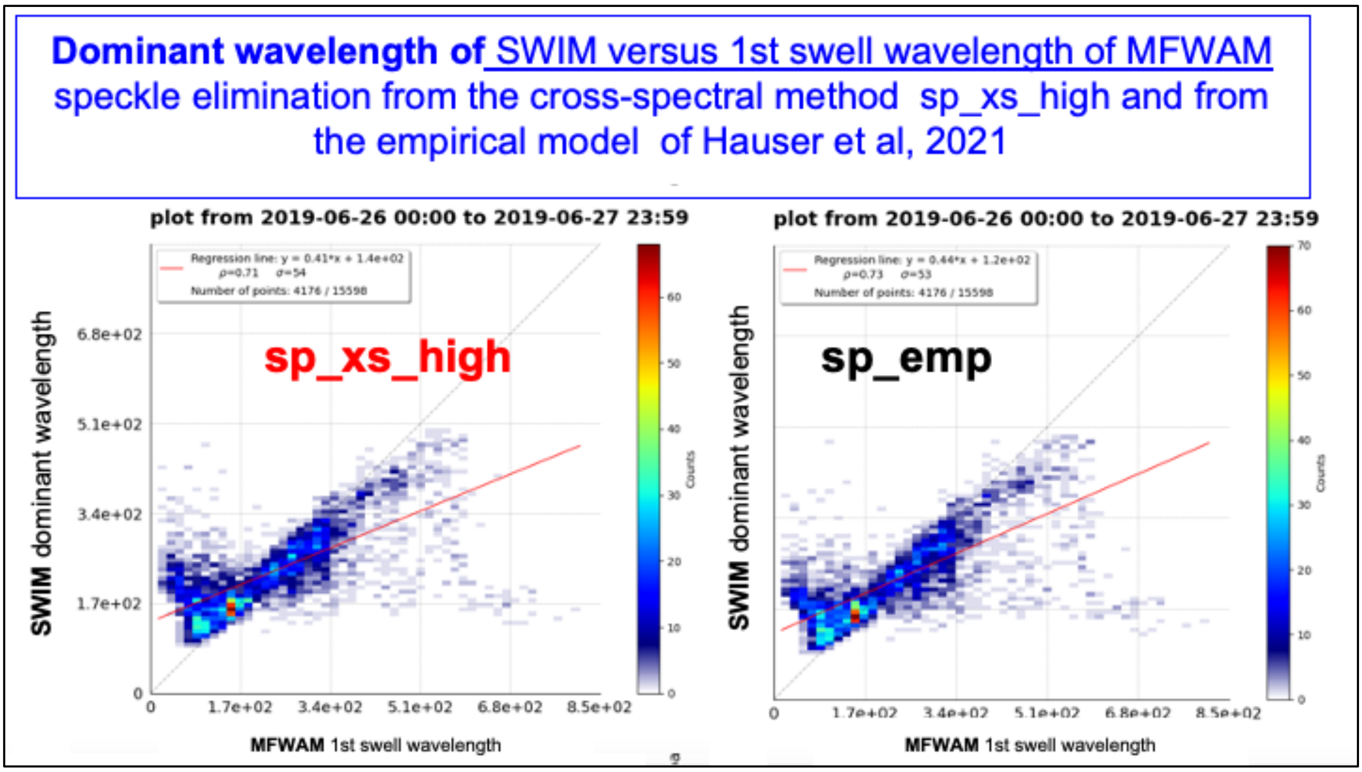


The 3 beams display similar resulting averaged spectra with **sp_xs_high** correction method. However Beam 10° gives cleaner spectrum.



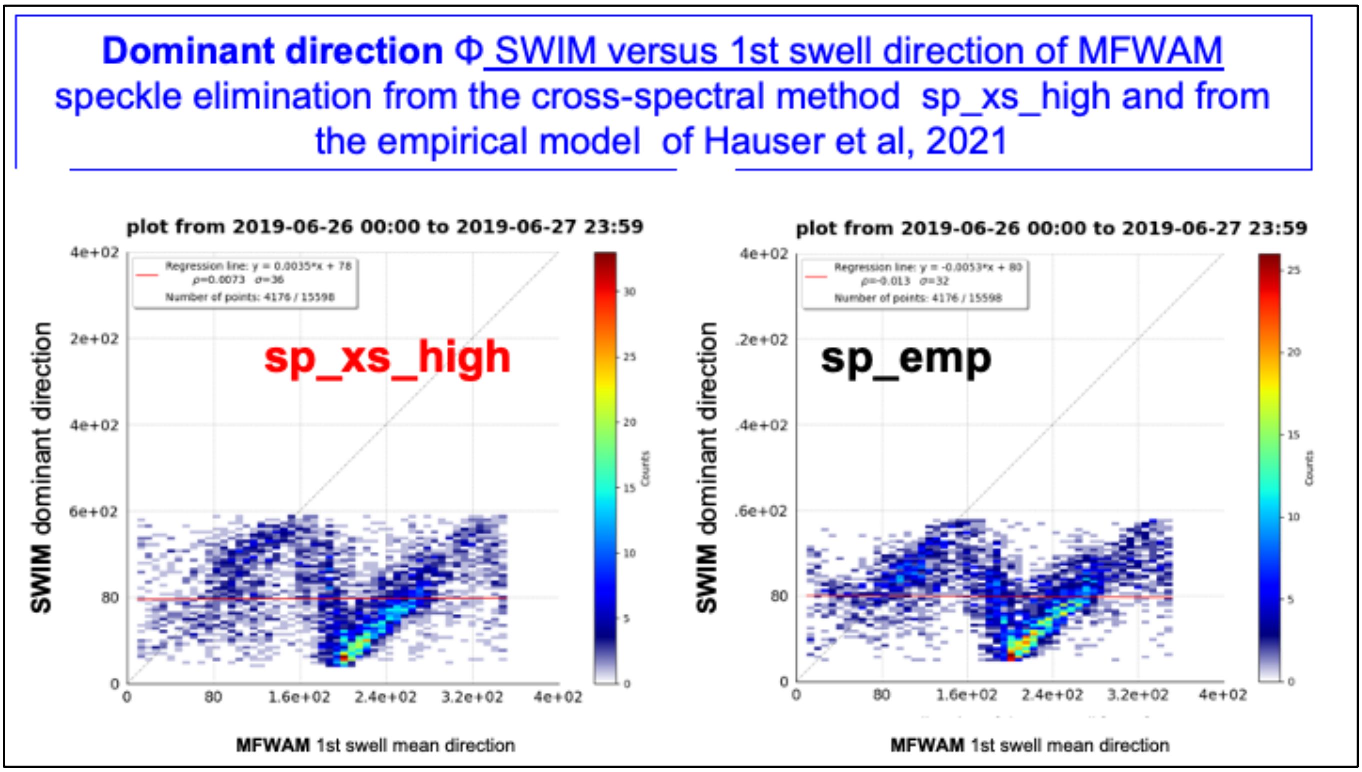
Here we present statistical 2D histogram of significant wave weight calculated from SWIM spectrum **versus MFWAM**. Left : SWIM SWH using **sp_xs_high.** Right : SWIM SWH using **sp_emp.**

It appears that in the case of **sp_xs_high, SWH** is strongly **underestimated**. A normalization issue may be the reason (under investigation). Dispersion is however weaker than in the **sp_emp** method.



Here we present statistical 2D histogram of dominant wavelength calculated from SWIM spectrum **versus first swell of MFWAM**. Left : SWIM wavelength using **sp_xs_high.** Right : SWIM wavelength derived from **sp_emp.**

It appears that both methods give similar results.



Here we present statistical 2D histogram of dominant direction calculated from SWIM spectrum **versus first swell of MFWAM**. Left : SWIM direction using **sp_xs_high.** Right : SWIM direction derived from **sp_emp.**
It appears that both methods give similar results.

Preliminary conclusions

- **sp_multi_int** (multi-temporal integration method): not relevant, for any case (configurations of sequences with either nominal or alternative macrocycles)

- sp_xs_low (cross-spectral method at low rate): not relevant for nominal macrocycle sequences (ΔT=220ms) but relevant with modified sequence like 0-2-8-8 or 0-2-10-10 thanks to the reduced time gap between two acquisitions for cross-spectra computing (ΔT~160ms).

- sp_xs_high (cross-spectral method at high rate): provides the **best results** among all the method tested to eliminate speckle noise. The wave spectra estimated with the cross-spectral method at high rate gives consistent results as shown in the comparison of the wave parameters compared to our reference (the MFWAM model), although the significant wave height Hs is significantly underestimated. The scatter on Hs is less than in the current L2 products . The results on wavelength and direction seem similar. There is no impact of macrocycle sequence like for sp_xs_low. Beam 10° seems to provide better results w.r.t 6° and 8° beams.

Ongoing work

- Analyze **sp_xs_high** in details :
  - 2D correlation between spectra (SWIM-MFWAM)
  - Presence or not of low wavenumber parasitic peaks (about this issue, see D. Alraddawi et al presentation in this meeting)
  - Understand the reason of the wave energy spectra understimation
- Analyze the L2 **parameters using sp_xs_high** :
  - bias (SWIM-MFWAM versus MFWAM) versus Hs, direction of waves, wind (hist2d)
  - Per partition :
    - Cross-assignment per wavelength
    - Cross-assignment per significant wave height
  - Signal-to-noise Ratio of **modulation** spectra
  - Complete the analysis with other data sets from another time period of SWIM acquisition in speckle mode
- **Refine the sp_emp** on the basis of **sp_xs_high** :
  - Analysis per sea states and latitudinal sectors per azimuthal sector

References

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