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SSB modeling from CFOSAT data

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Context

- CFOSAT is a science mission designed to study ocean surface wind and wave conditions and no topographic data are delivered by the SWIM nadir Ku-band instrument because of the poor orbit accuracy.

- Although at the last OSTST meeting, it was shown that CFOSAT can provide an interesting set of Sea Level Anomaly (SLA) data relevant to enrich the DUACS products for the benefit of the Copernicus Marine Service users [Faugère et al , 2022]. This required the use of a multi-mission approach to obtain good quality SLA data at mesoscale range.

- CFOSAT mission offers an unprecedented opportunity to get collocated SLA and wave spectra data. This should give direct assess to sea state parameters more relevant to explain how sea state impacts conventional altimetric measurements in order to ultimately come up with a correction strategy which is both as precise and as physically motivated as possible.

Faugère et al [2022]: "CFOSAT Sea level and current demonstration products", OSTST'2022 presentation available @ https://ostst.aviso.altimetry.fr/fileadmin/user_upload/OSTST2022/Presentations/CFO2022-CFOSAT_Sea_level_and_current_demonstration_products.pdf

Outline

➢ **The question to answer: "Are the collocated SWIM off-nadir wave spectra valuable for improving the description of the Sea State Bias (SSB) behavior and thus the nadir altimetric SLA precision ?"**

- Build a collocated CFOSAT SLA/wave spectra dataset
- Select the empirical SSB model to use for correcting CFOSAT SLA
- Identify the most representative theoretical SSB model of how the sea state affects the measurement and for which the relevant sea state parameters can be computed from CFOSAT spectra
- Compare the performances of the selected theoretical SSB model fed with CFOSAT data with those obtained with standard empirical models
- Assess the quality of the CFOSAT SLA within the conventional altimetry constellation when using its best SSB solution

Building the combined nadir/off-nadir dataset

- Nadir SLA data @5-Hz as used in Faugère et al [2022] → consistent with Jason-3 data @ large and meso-scales
    - As much as possible aligned with 2021 standards used for Copernicus Marine Environment Monitoring System (CMEMS) products
    - ADAPTIVE retracking as provided by the CFOSAT processing chain
    - No precise positioning system (no Doris/GPS) → use the large scale of the constellation (DUACS maps) for wavelength > 800km
    - No radiometer → use of ECMWF Model
    - SSB = -3.5% SWH (reference model)
    - 2021 year-period (no more gaps due to micro-cut episodes)
- Parameters derived from off-nadir wave spectra from 10° beam @ 0.1 Hz
    - Use of L2P off-nadir products (L2PBOX) provided by CMEMS → homogeneously reprocessed Level 2+
- Combination of nadir @ 5-Hz with off-nadir data @ 0.1 Hz → dataset @ 5-Hz
    - Step 1: linear interpolation in time of wave parameters computed from consecutive off nadir boxes on each side of the satellite track → from 0.1 Hz to 5 Hz
    - Step 2: across-track interpolation between wave parameters @ 5-Hz on each side of the satellite track to get values @ nadir position @ 5 Hz

Jason-3 SSB model (GDR-F version) as the empirical bias reference

- Presence of surface waves is a source of bias in the measured SLA which is well-known in the context of conventional altimetry, and referred to as the Sea State Bias (SSB):

SSB = Electromagnetic (EM) Bias + Skewness Bias + Processing Bias

Electromagnetic (EM) Bias: associated to different reflectivity linked to:
Hydrodynamic modulation : Correlation of short waves slopes with long waves heights
Tilt modulation : Correlation of long waves slopes with long waves heights

Skewness Bias: connected with the inherently nonlinear dynamics of water waves and involved long waves height third order moment

Processing Bias: not related directly to the surface but depending on the sea state

- Correcting it requires
  - a representative model of how the sea state affects the measurement → very complex and not all aspects well understood
  - a knowledge of the sea state at the time of the observation → only few parameters are observed

- Use of empirical corrections in conventional altimetry to operationally correct for these 3 contributions → Jason-3 models (GDR-F versions, both 2D and 3D) used in this study as empirical reference
  - developed for ADAPTIVE data as provided by nadir CFOSAT processing chain
  - currently used for different missions: Jason-3 and Jason-2 (GDR-F reprocessing) with ADAPTIVE data

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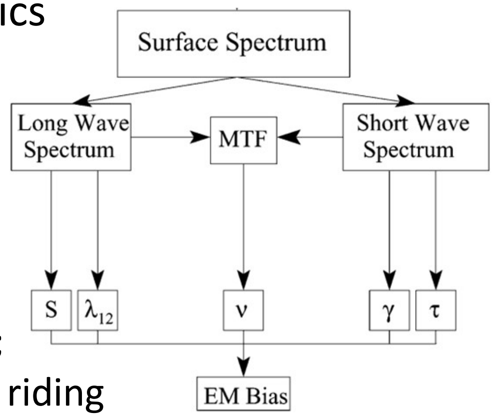
Millet et al [2006]'s model as the theoretical EM bias reference

- EM bias model by Millet et al [2006]:
  - represents 1 contribution amongst 3 in SSB modelling
  - uses the physical optics scattering approximation with a sea surface model that includes the effects of hydrodynamic modulation and tilt long-wave statistics

$$\text{EM bias} = -\,Hs\,(\gamma\,\upsilon\,S_l + \tau\,\lambda_{12})$$



Hs : wave height → either from wave spectra or nadir estimation;
S_l and λ_{12} : long-wave statistics (RMS long-wave slope and height-slope cross-correlation) → newly computed from CFOSAT spectra;
γ, υ and τ : factors which incorporate the effect of short-wave roughness riding on the long waves → use values provided in this paper for C-band

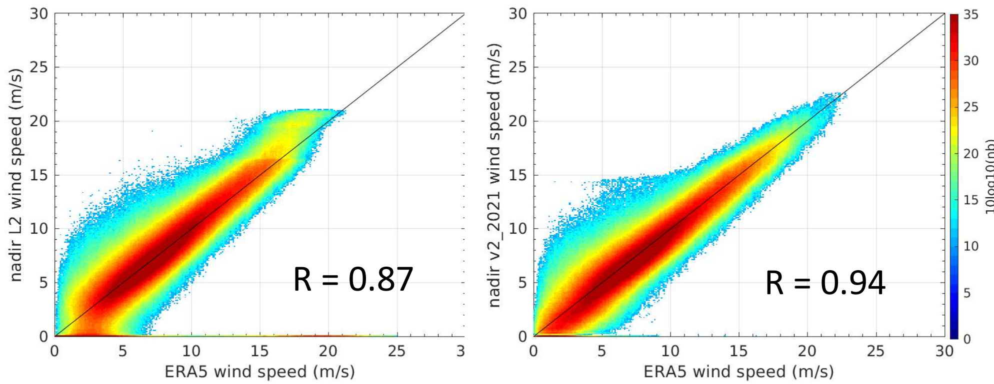
  - validated with measured data from two tower radar experiments

Millet F.W., K. F. Warnick, J. R. Nagel, and D. V. Arnold (2006): "Physical optics-based electromagnetic bias theory with surface height-slope cross-correlation and hydrodynamic modulation," IEEE Transactions on Geoscience and Remote Sensing, Vol. 44, No. 6, pp. 1470- 1483.

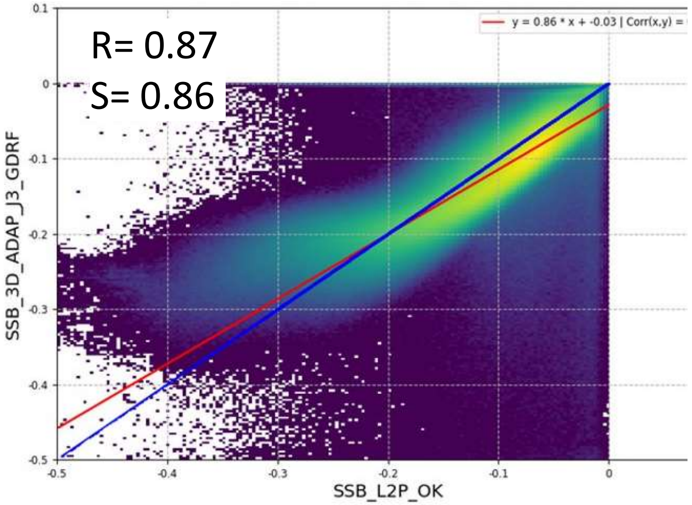
SSB models summary and Wind Speed information

- CFOSAT SSB models:
  - Reference model used in Faugère et al
    - SSB_L2P_OK = -3.5% SWH_nadir
  - Jason-3 SSB models (both 2D and 3D) rely on wind speed :
    - 2D_SSB (SWH_nadir, Wind Speed_nadir)
    - 3D_SSB (SWH_nadir, Wind Speed_nadir, MFWAM T02) with MFWAM (Météo-France WAve Model) being a third-generation numerical wave model operated by Météo-France
  - Millet et al [2006]' SSB model
    - Only containing EM bias term
    - SSB_Millet_bis uses SWH from nadir data (N.B. SSB_Millet computed with the SWH coming from wave spectrum has also been analyzed but its values are less accurate because of the impact on SWH of the presence of parasitic peaks in the low-frequency part of the spectrum)

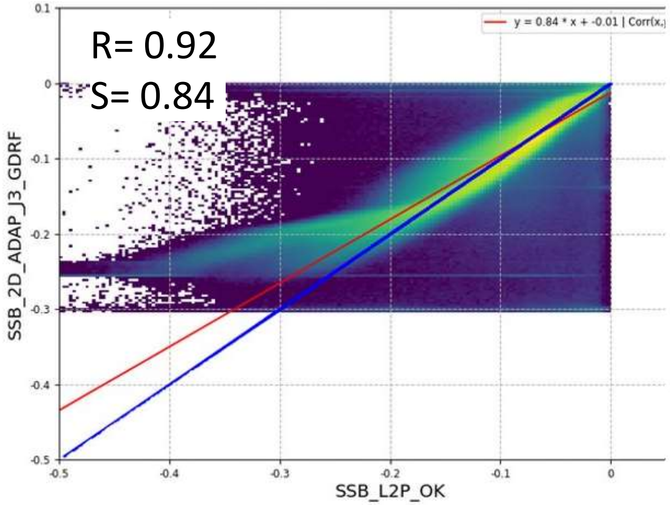
- Wind speed information used for empirical SSB models:
  - Not from the L2 nadir products or the SCAT sensor
  - Recomputed values with a wind speed model developed by CLS in 2021 from nadir sigma0 and SWH



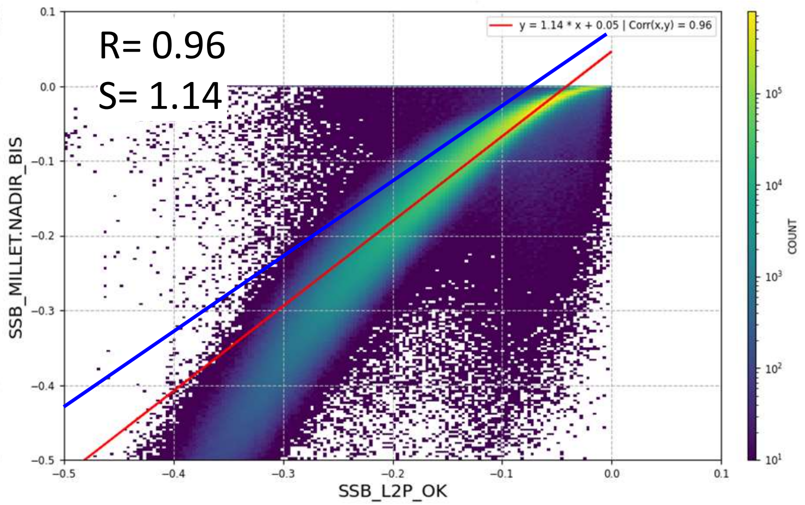
SSB comparison



SSB_3D_J3 vs SSB_L2P_OK



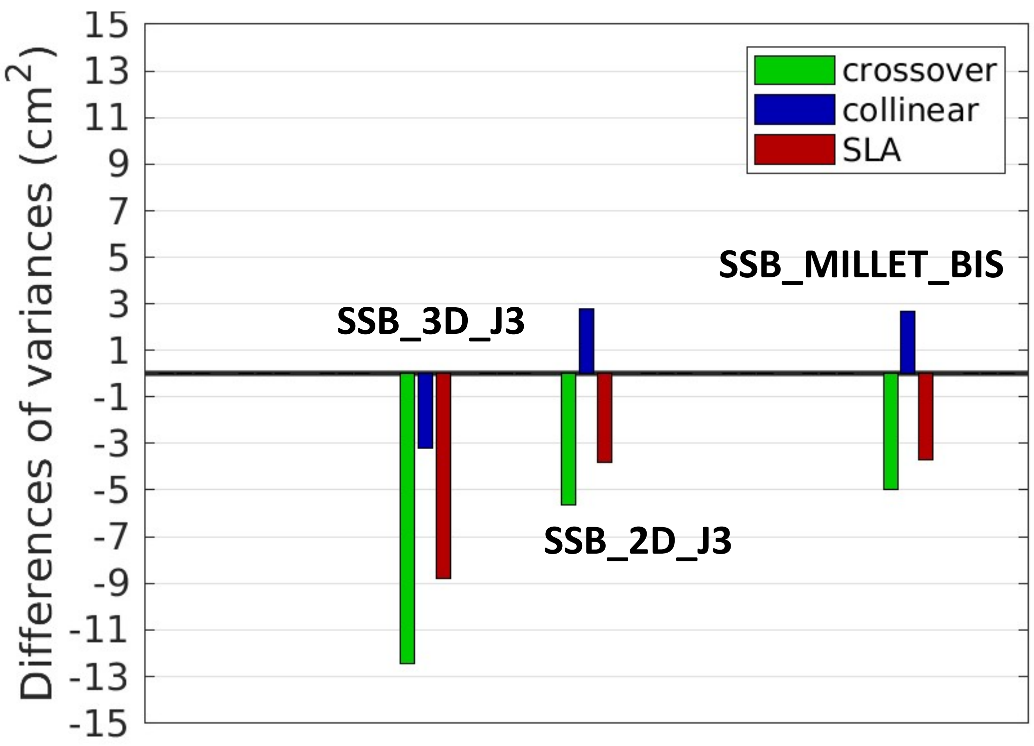
SSB_2D_J3 vs SSB_L2P_OK



SSB_Millet_bis vs SSB_L2P_OK

- The different SSB estimations are rather similar for small SSB corrections and differ more significantly in the cases of large corrections

Performance evaluation based on variance of SLA



- Evaluation performed on 3 datasets
  - COL_ΔSLA: collinear SLA differences (Δt @13 days)
  - CRO_ΔSLA: crossover SLA differences (Δt <10 days)
  - SLA, seasonal and interannual variations around MSS
- SSB_L2P_OK used as reference model
- Negative values of differences of SLA variances indicate that tested SSB model reduces more the SLA variance than when one compute SLA with the reference SSB model, i.e. more accurate SLA are obtained when applying the tested model
- SSB_Millet_bis and SSB_2D_J3 give comparable performances
- SSB_3D_J3 model outperforms all the others

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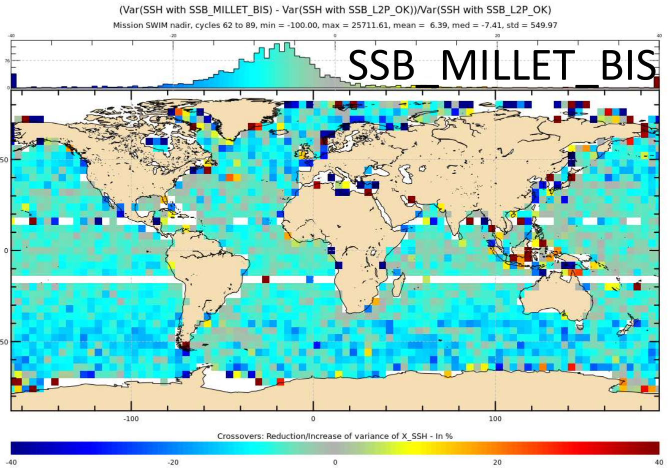
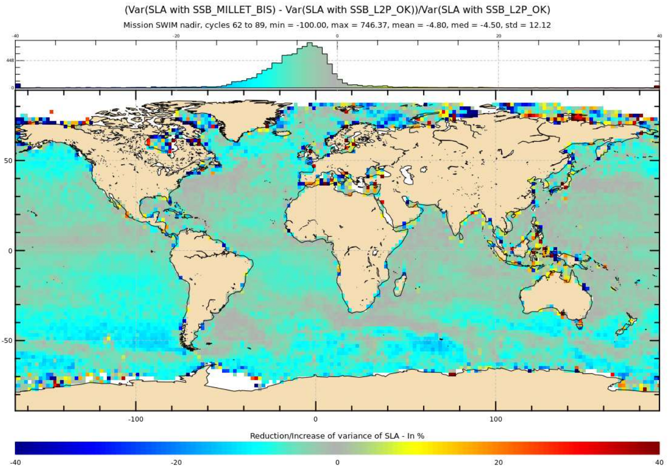
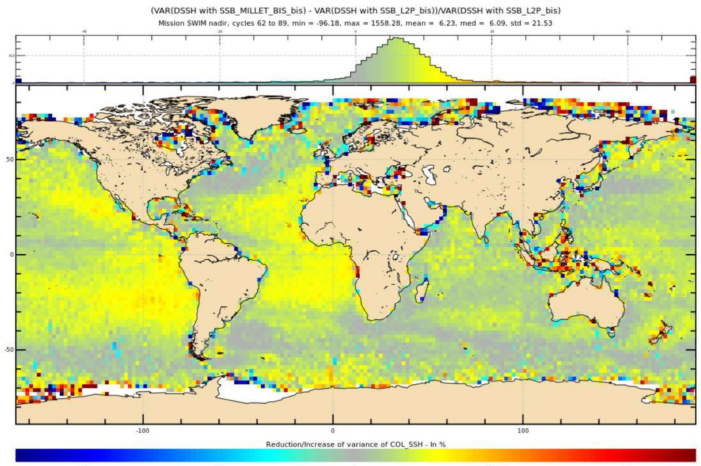
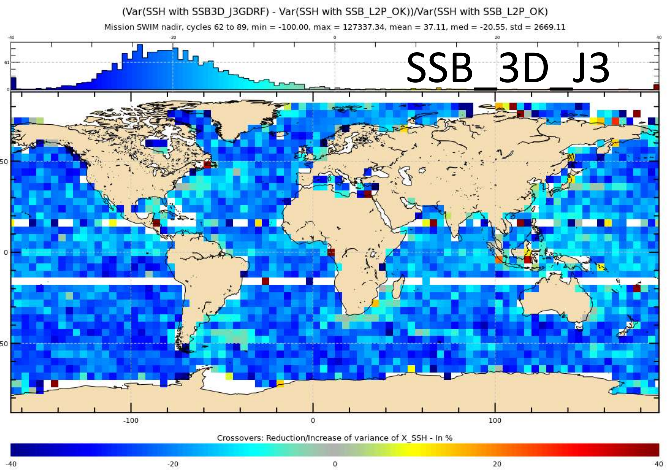
Maps of variance comparison (%), SSB_L2P used as reference

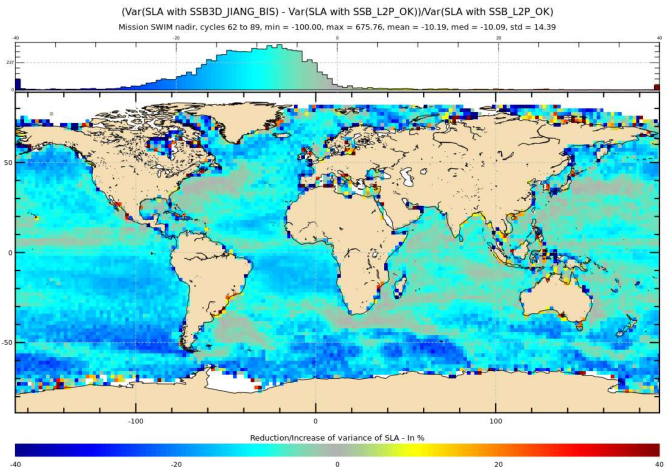


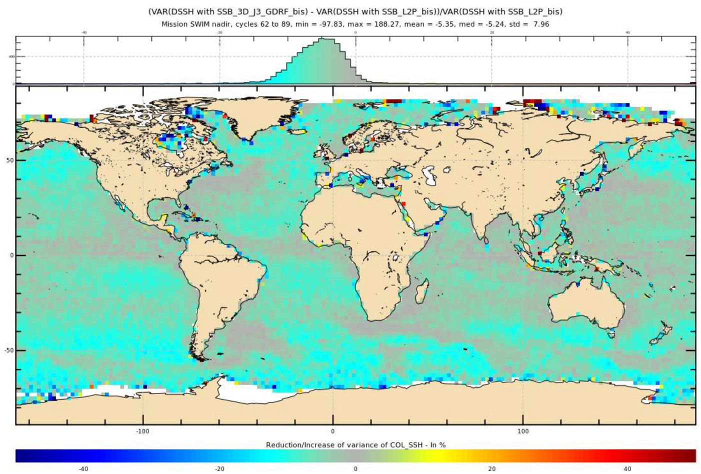




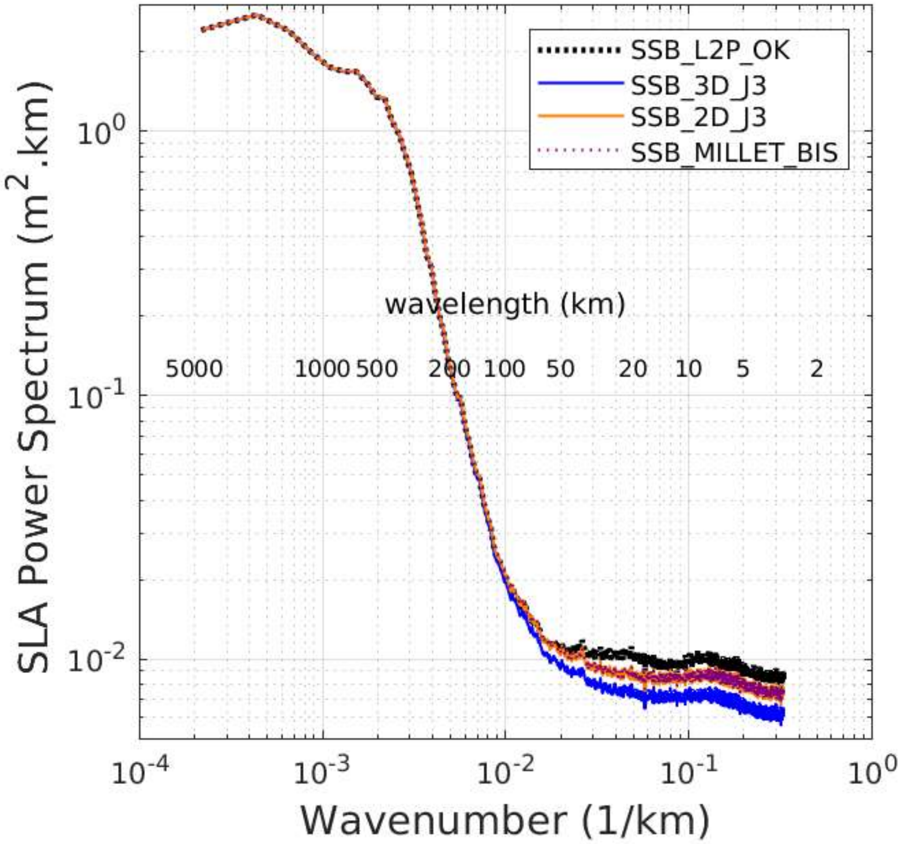
CRO_ΔSLA | SLA | COL_ΔSLA

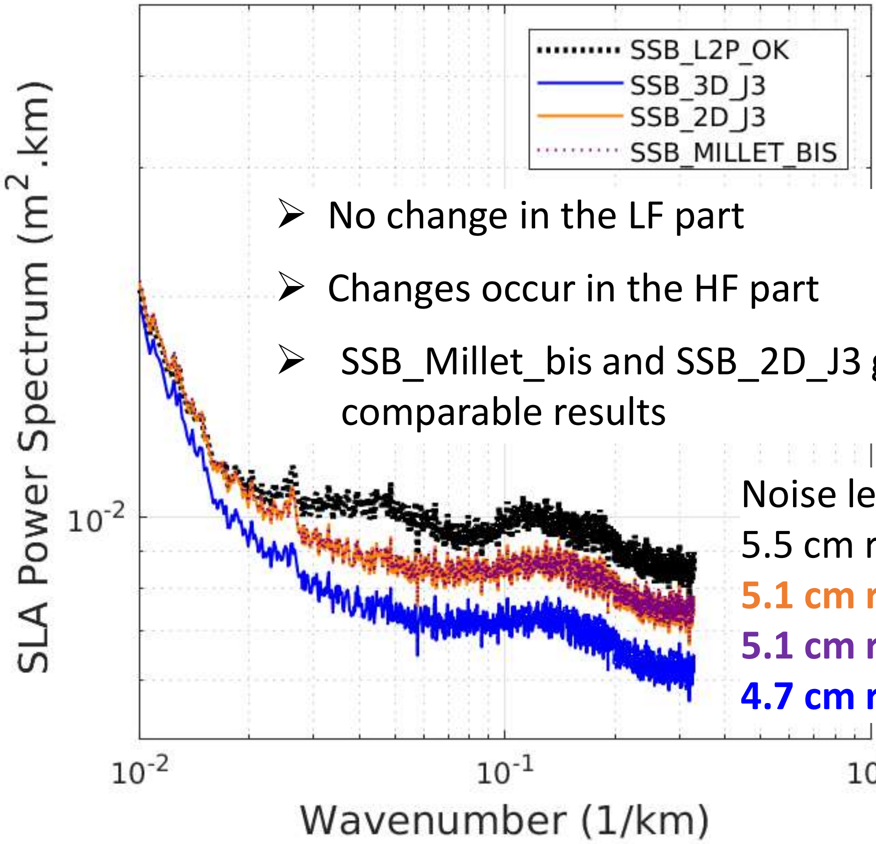






CFOSAT SLA spectra comparison

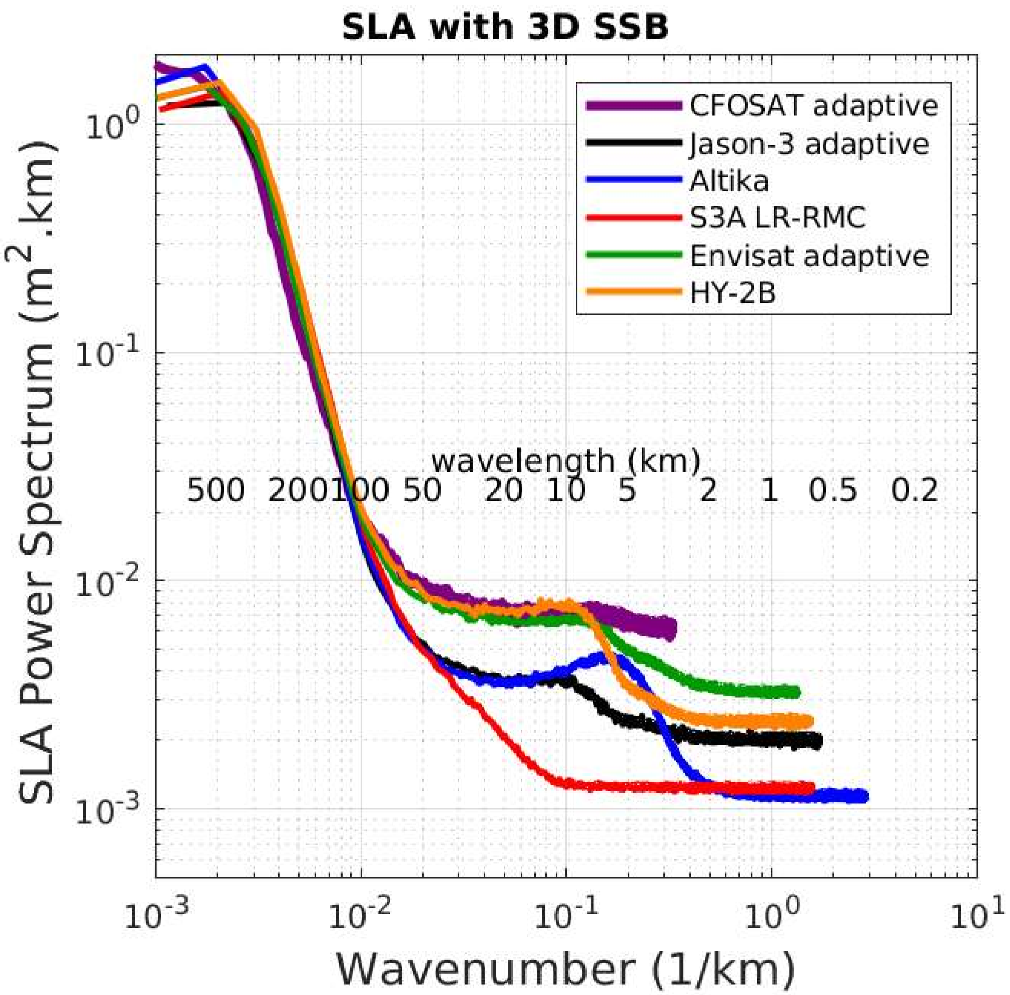




- No change in the LF part
- Changes occur in the HF part
- SSB_Millet_bis and SSB_2D_J3 give comparable results

Noise level:
5.5 cm rms
5.1 cm rms
5.1 cm rms
4.7 cm rms

CFOSAT SLA quality in the conventional altimetry constellation



- ➢ The different results presented before allow us to provide a more general feedback on the CFOSAT SLA quality as used in Faugère et al [2022]:
  - the accuracy of the SLA can be improved by using a better SSB model
  - when applying for example the SSB_3D_J3 model, very good consistency of CFOSAT SLA with both Envisat and HY-2B data are observed

Conclusions

- **"Are the collocated SWIM off-nadir wave spectra valuable for improving the description of the Sea State Bias (SSB) behavior and thus the nadir altimetric SLA precision ?"** → Answer is YES
- The performances obtained with SSB_Millet_bis are comparable to results observed with SSB_2D_J3. Even if this latter model is not the nominal one used for Jason-3 SLA (based on MLE4 data), all official and operational versions of empirical SSB model consist today in 2D versions.
- The good performance obtained with SSB_Millet_bis indicates promising perspectives to reconcile empirical and theoretical approaches by having good observables parameters of sea-state conditions at the time of the satellite observation.
- Future work in empirical SSB modelling should consider the use of the 2 newly derived parameters: height/slope cross skewness and the RMS of the long-wave slopes from CFOSAT spectra.
- This theoretical model from Millet et al. [2006] performed very well, although we used simplified small-scale modelling. Further analysis is required to refine the representation of small scales, which should improve the performance of the correction.
- More generally, there is also real need for better knowledge of the complexity of the phenomena at stake (physics of the sea surface at short scales, including wave-current interactions and interaction between the surface and the radar signal, along with nonlinear properties of ocean waves and connection between long-wave height–slope cross-correlation and short-wave hydrodynamic modulation effects).

Thank you

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