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A new way to assess and represent the error budget for any altimeter mission

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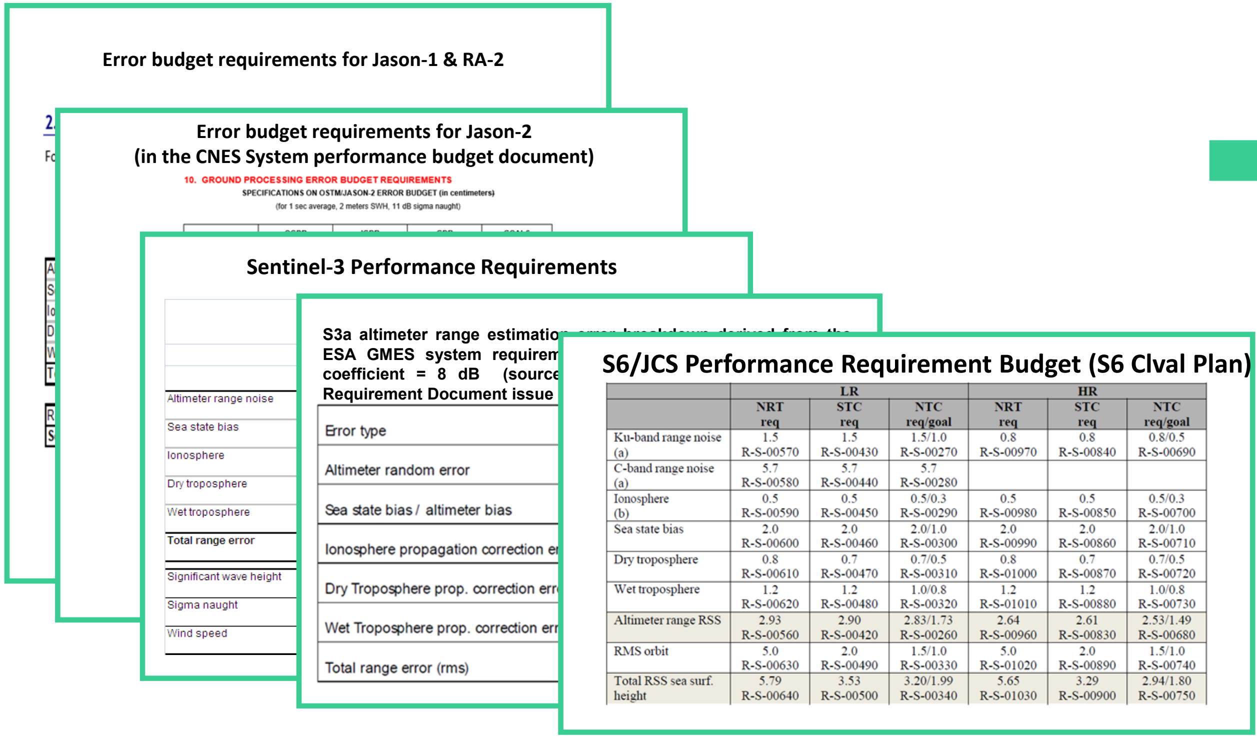
Context of the study

- ❑ A/B1 Phase of the **<u>CRISTAL mission</u>** (~POLARICE mission)   [ESA funding]
- ❑ CRISTAL is one of the 6 High Priority Candidate Missions (HPCM) now considered by ESA in phases B2/C/D/E. Altimeter mission operating in Ku/Ka band, SAR, SARin, CB/OB.
- ❑ The objective of the study was to anticipate the performances of the future CRISTAL mission (over sea ice and ocean) by developping a **<u>Mission Performance Simulator</u> (MPS)**



	LR			HR		
	NRT req	STC req	NTC req/goal	NRT req	STC req	NTC req/goal
Ku-band range noise (a)	1.5 R-S-00570	1.5 R-S-00430	1.5/1.0 R-S-00270	0.8 R-S-00970	0.8 R-S-00840	0.8/0.5 R-S-00690
C-band range noise (a)	5.7 R-S-00580	5.7 R-S-00440	5.7 R-S-00280			
Ionosphere (b)	0.5 R-S-00590	0.5 R-S-00450	0.5/0.3 R-S-00290	0.5 R-S-00980	0.5 R-S-00850	0.5/0.3 R-S-00700
Sea state bias	2.0 R-S-00600	2.0 R-S-00460	2.0/1.0 R-S-00300	2.0 R-S-00990	2.0 R-S-00860	2.0/1.0 R-S-00710
Dry troposphere	0.8 R-S-00610	0.7 R-S-00470	0.7/0.5 R-S-00310	0.8 R-S-01000	0.7 R-S-00870	0.7/0.5 R-S-00720
Wet troposphere	1.2 R-S-00620	1.2 R-S-00480	1.0/0.8 R-S-00320	1.2 R-S-01010	1.2 R-S-00880	1.0/0.8 R-S-00730
Altimeter range RSS	2.93 R-S-00560	2.90 R-S-00420	2.83/1.73 R-S-00260	2.64 R-S-00960	2.61 R-S-00830	2.53/1.49 R-S-00680
RMS orbit	5.0 R-S-00630	2.0 R-S-00490	1.5/1.0 R-S-00330	5.0 R-S-01020	2.0 R-S-00890	1.5/1.0 R-S-00740
Total RSS sea surf. height	5.79 R-S-00640	3.53 R-S-00500	3.20/1.99 R-S-00340	5.65 R-S-01030	3.29 R-S-00900	2.94/1.80 R-S-00750

- ❑ Only for ocean @Hs=2m
- ❑ Only at 1 Hz
- ❑ Simple combination (Sqrt of sum of squares) of errors whatever their space/time correlations
- ❑ Not fully correct depending on scales

Tentative to provide a more informative performance budget requirement table or in-flight performance budget

Principle of the **Mission Performance Simulator**

A **Power Spectral Density** approach has been used to derive the uncertainty estimations accounting for correlation lenghts of the different errors.
It allows describing the uncertainty variance of each source of error for all spatial and temporal frequencies.

Uncertainty modelling and PSD estimation

- Hypothesis : uncertainties are following Gaussian distributions
- Laws are described by their variance at 1 σ (*), their spatial correlation length (x) et temporal correlation length (t)
- Autocorrelation functions are modelized by exponential functions

$$\sigma^2 e^{-\frac{1}{2}\left(\frac{t}{\lambda_t}\right)^2} \; e^{-\frac{1}{2}\left(\frac{x}{\lambda_x}\right)^2}$$

- PSD is the Fourier Transform of the autocorrelation function (correlogram method)

$$\mathcal{F}(e^{-ax^2})(\xi) = \sqrt{\frac{\pi}{a}} \exp(\frac{-\xi^2}{4a})$$

The MPS :

1. Computes the individual 2D PSD of each error source
2. Combines all individual 2D PSDs to compute the total 2D PSD
3. Integrates the 2D PSD to compute 2D STD maps (space and time)

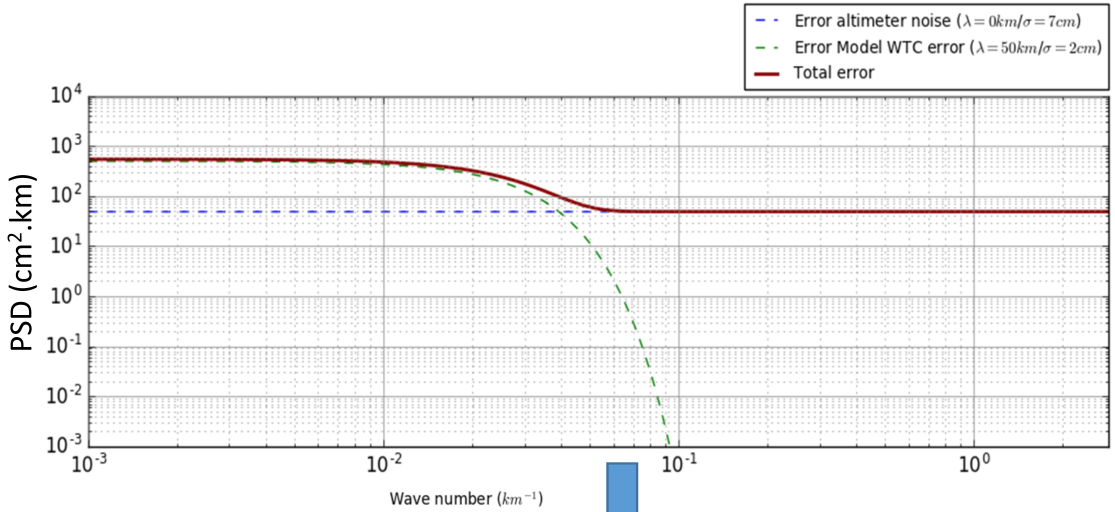
CLS

(*) 1 s means that uncertainty are estimated with a confidence level of 68%

Case 1 : 1-Dimension

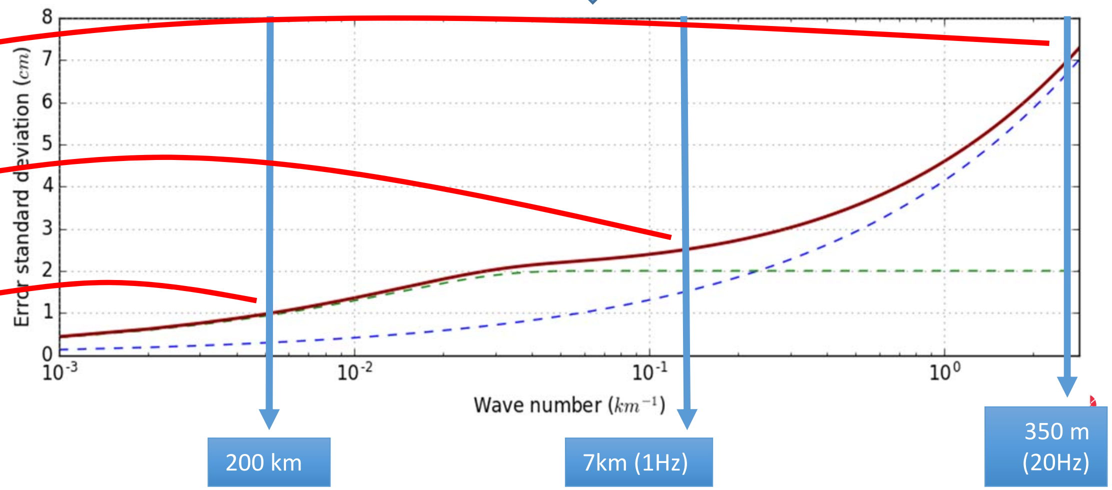
⇒ Spatial correlation only

	Error characterization	
Error source	**STD**	**Spatial correlation**
Altimeter random noise	7 cm (20 Hz)	0 km
Wet troposphere correction (model)	2 cm	50 km



⇒ Estimation of the uncertainties

Error source	350 m (20Hz)	7 km (1Hz)	200 km
Altimeter noise	7.0 cm	1.6 cm	0.3 cm
Model WTC	2.0 cm	2.0 cm	1.0 cm
Total	**7.3 cm**	**2.5 cm**	**1.04 cm**

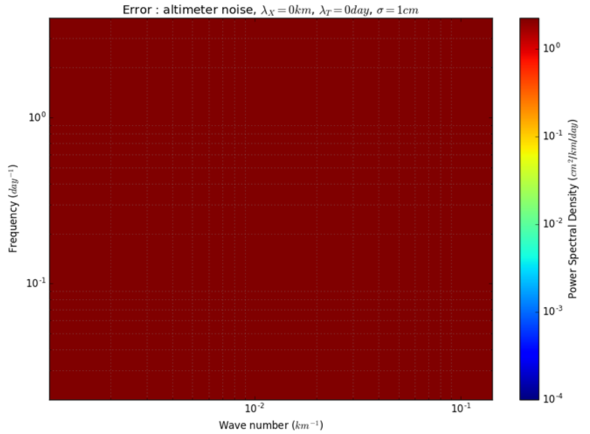


Case 2 : 2-Dimensions

⇒ Spatial & Temporal Correlations

	Error characterization		
Error source	STD	Spatial correlation	Temporal correlation
Altimeter random Noise	1.5 cm (1 Hz)	0 km	0.0 days
Wet troposphere correction	2 cm	50 km	2 days

Altimeter random noise 2D-PSD



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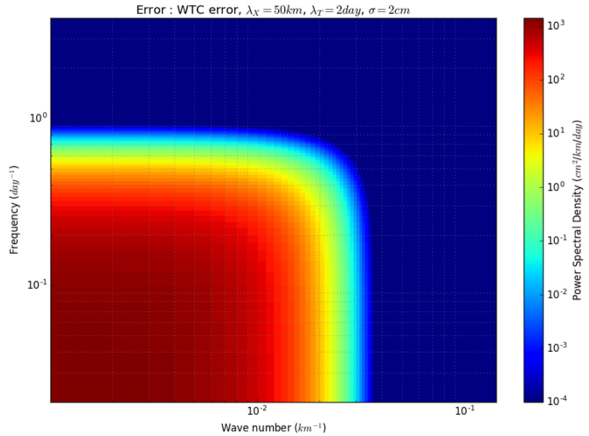
WTC error 2D-PSD



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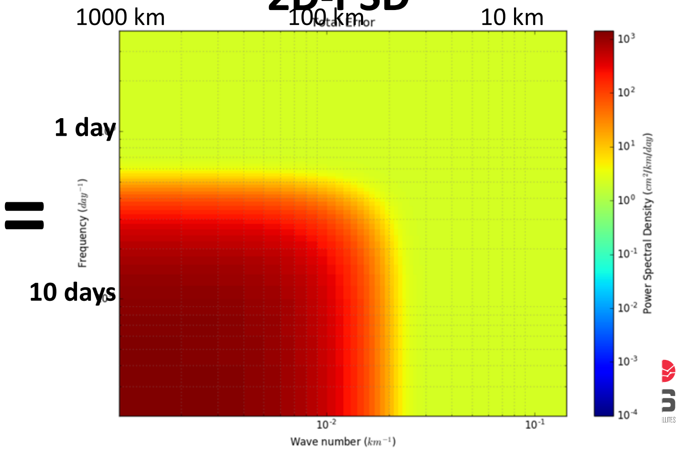
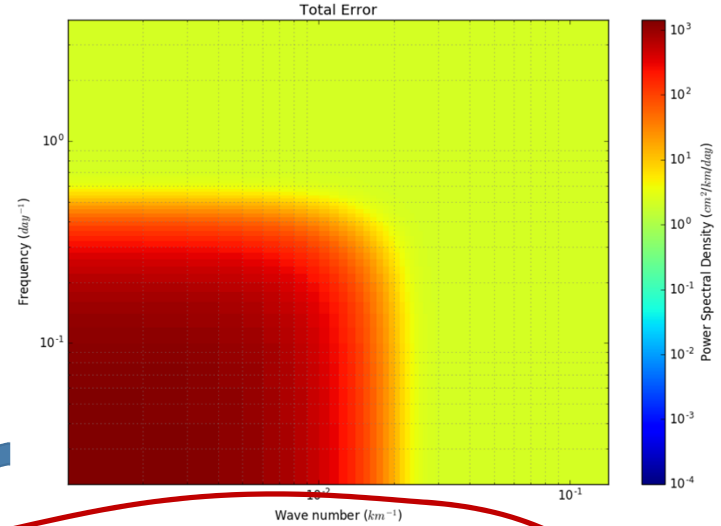
Total error 2D-PSD



Case 2 : 2-Dimensions

⇒ Spatial & Temporal Correlations

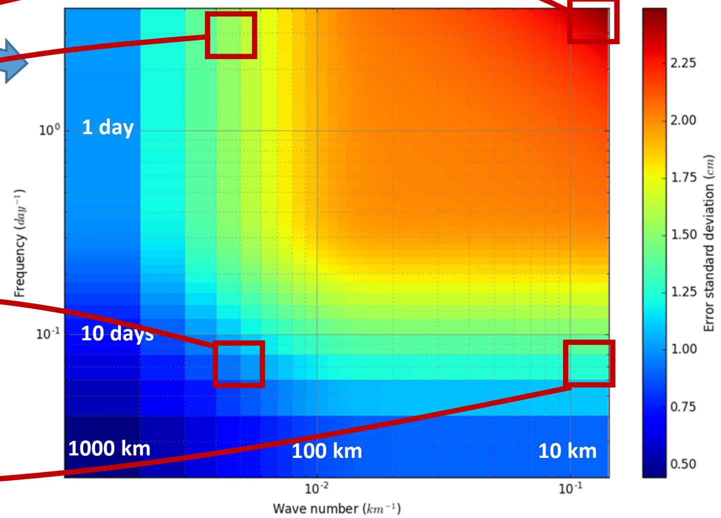
	Error characterization		
Error source	STD	Spatial correlation	Temporal correlation
Altimeter random Noise	1.5 cm (1 Hz)	0 km	0.0 days
Wet troposphere correction	2 cm	50 km	2 days



Total error 2D-PSD

⇒ Estimation of the uncertainties

	7 km (1 Hz)	150-300 km
Instantaneous	2.5 cm	1.5 cm
20--30 days	0.5 cm	0.7 cm



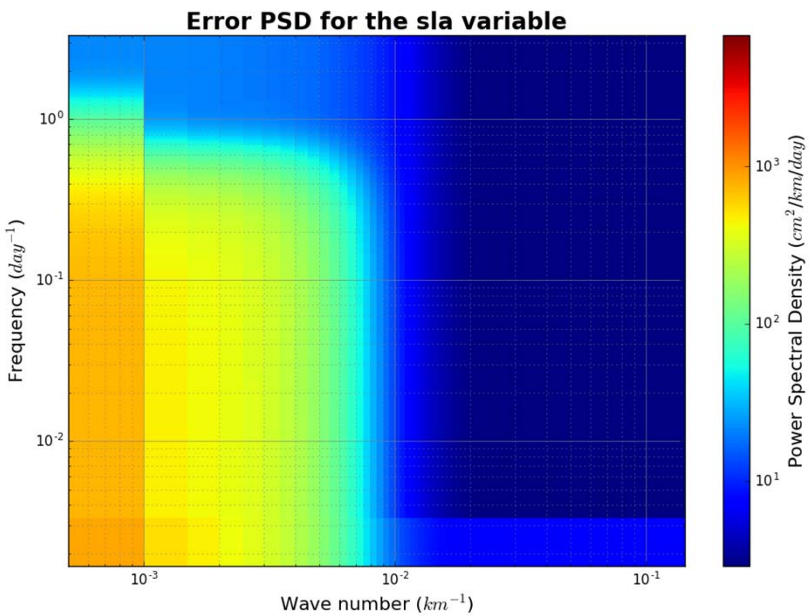
Total error 2D-STD

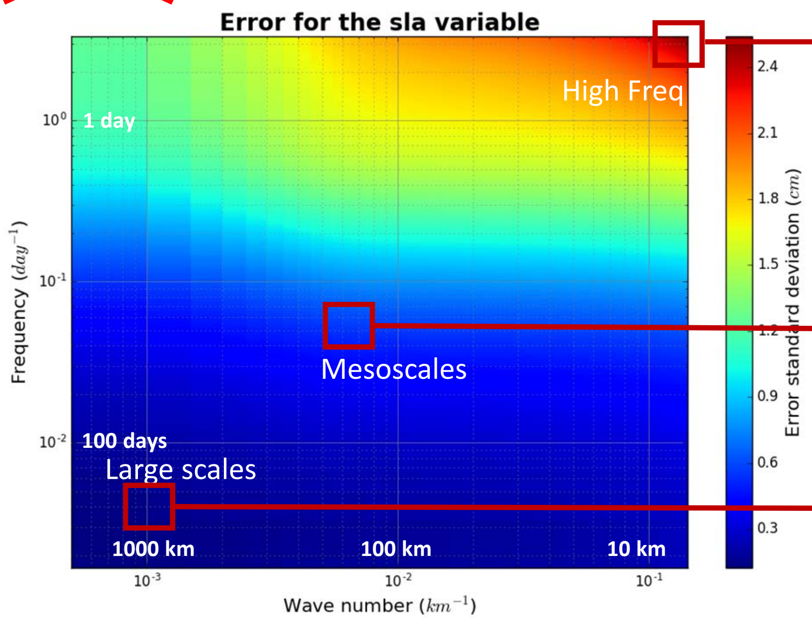
Jason-3 Performances over ocean

LRM Ku
B=320 MHz
Rad 3 channels (18/23/36)
Aux. Band = C band

Error Source	STD (cm)	Spatial correlation length	Temporal correlation length	References
Altimeter Random error	1,7	0 km	0 day	J3 performance doc (CLS)
SSB Noise	0,3	300 km	Inf.	J3 performance doc (CLS)
SSB correlated	1	100 km	1 day	Tran & al, 2019
Ionosphere	0,15	600 km	0 day	Imel & al, 1995
Wet Troposphere	1	50 km	1 hour	Brown & al, 2015; Stum & al, 2011
Dry Troposphere	0,2	600 km	2 days	J3 performance doc (CLS)
Mean Sea Surface	0,5	1 km	Inf.	Pujol & al, 2018
Ocean Tides	1	1000 km	< 1 day	Lyard & al, 2018
Orbit solution	1,5	> 10 000 km	< 1 day	Ollivier & al, 2018; Couhert & al, 2015

~~=> 2.9 cm~~





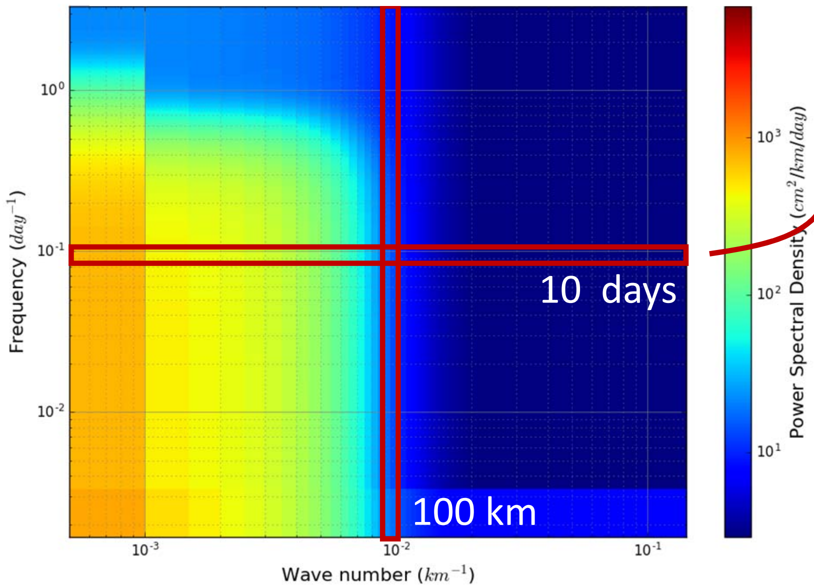
= 2,5 cm @ very short scales

= 0.54 cm @ meso scales

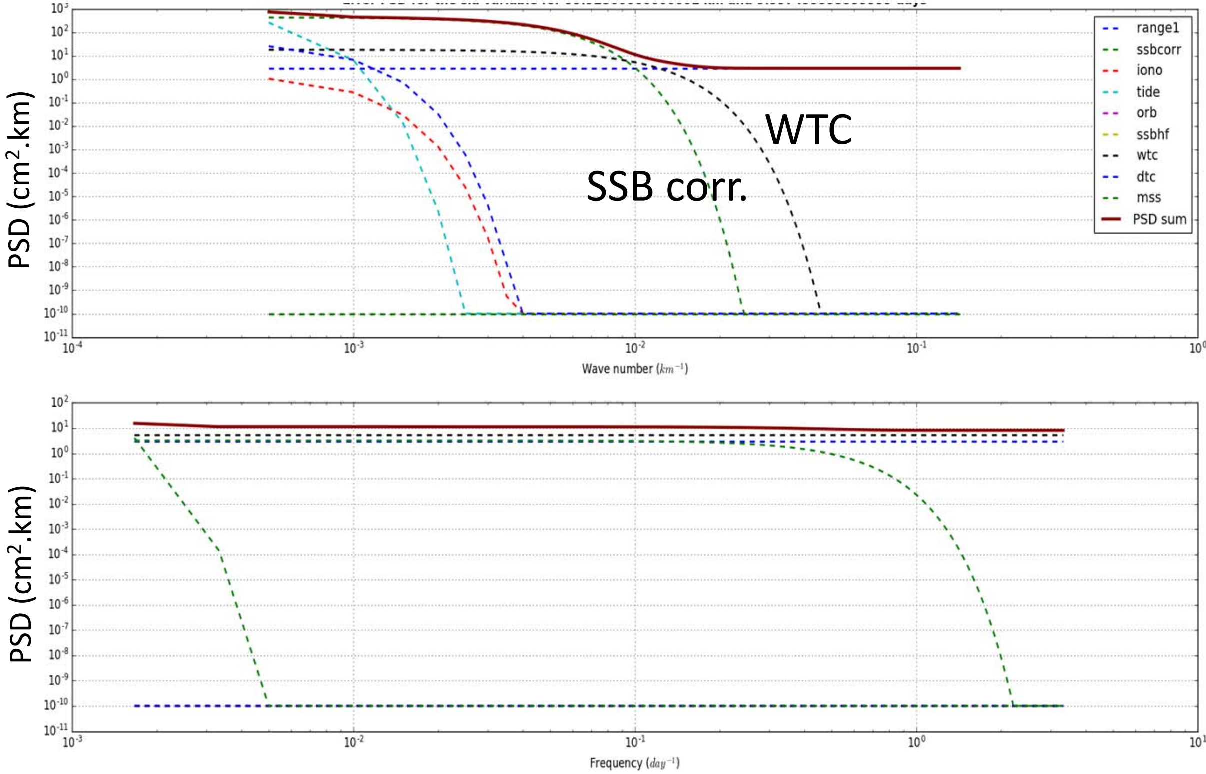
= 0.122 cm
@ large scales

Jason-3 Performances over ocean

Jason-3 PSD of the SLA Error



Jason-3 PSD of the SLA Error (10 days & 100 km)

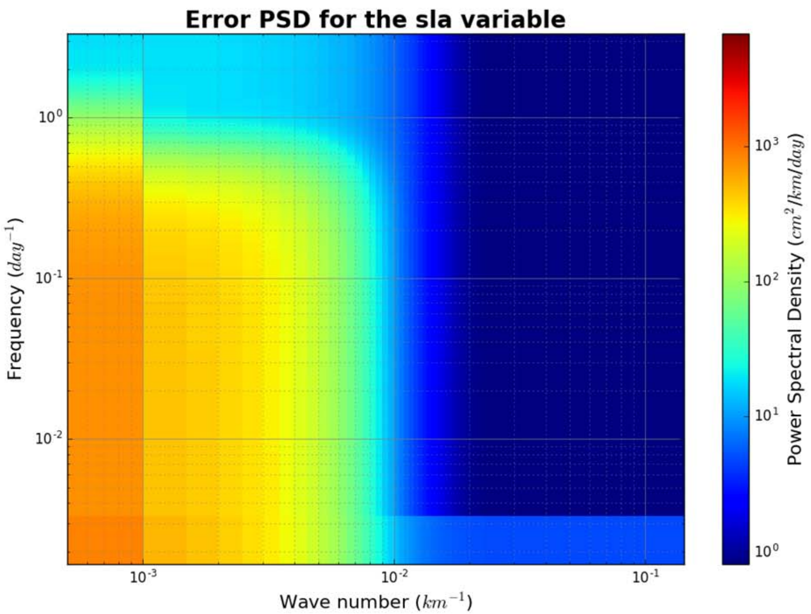


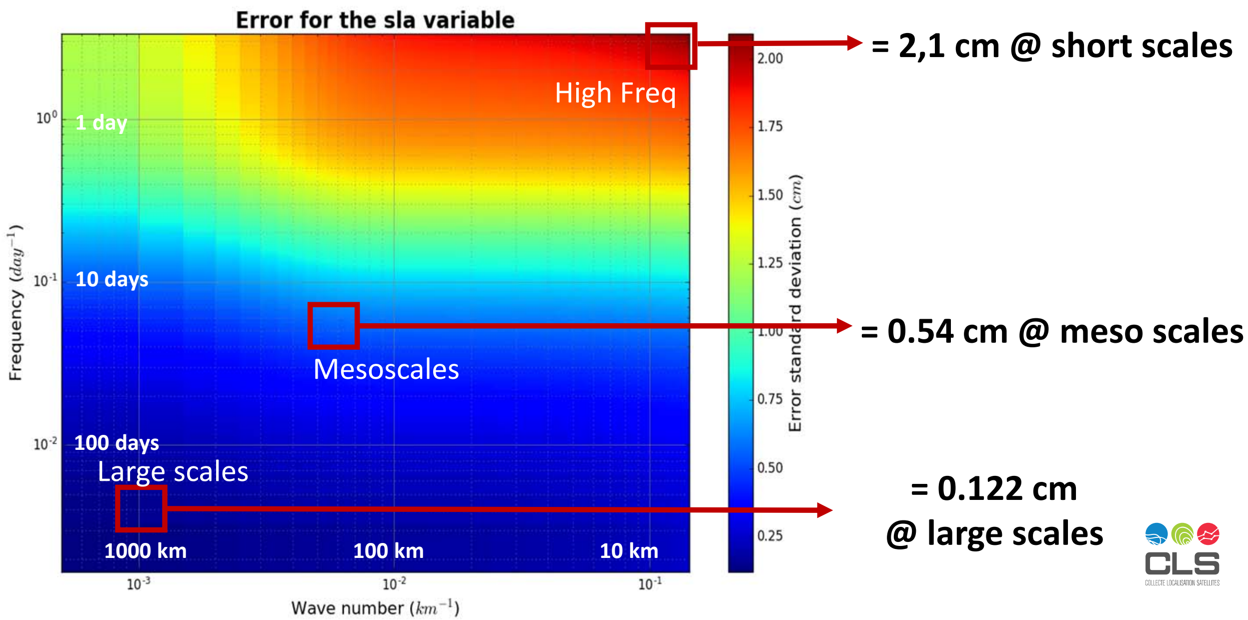
CLS

Saral/Alti-Ka Performances over ocean

LRM Ka, 40 Hz
B=480 MHz
Rad 2 channels (23/36)
Mono-Freq.

Error Source	STD (cm)	Spatial correlation length	Temporal correlation length	References
Altimeter Random error	0,9	0 km	0 day	Saral performance doc (CLS)
SSB Noise	0,3	300 km	Inf.	Saral performance doc (CLS)
SSB correlated	1	100 km	1 day	Tran & al, 2019
Ionosphere	0,03	600 km	0 day	Imel & al, 1995
Wet Troposphere	1	50 km	1 hour	Brown & al, 2015; Stum & al, 2011
Dry Troposphere	0,2	600 km	2 days	Saral performance doc (CLS)
Mean Sea Surface	0,5	1 km	Inf.	Pujol & al, 2018
Ocean Tides	1	1000 km	< 1 day	Lyard & al, 2018
Orbit solution	1,5	> 10 000 km	< 1 day	Ollivier & al, 2018; Couhert & al, 2015

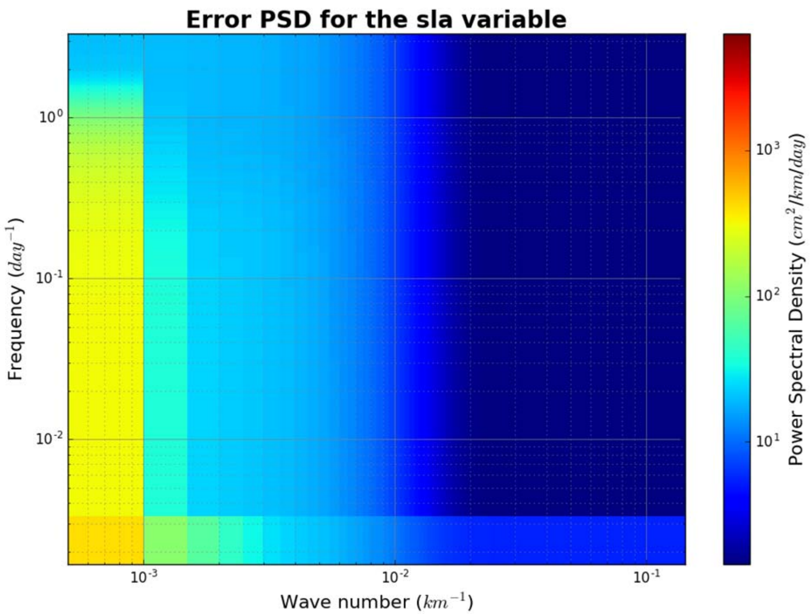


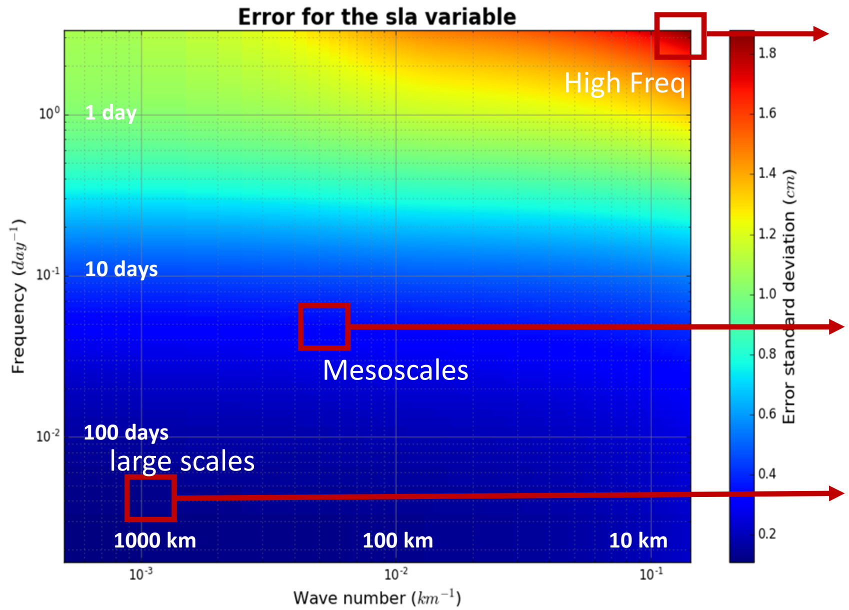


Sentinel-3 Performances over ocean

SAR Ku, Closed Burst
B=320 MHz
Rad 2 chanels (23/36)
Aux. Band = C band

Error Source	STD (cm)	Spatial correlation length	Temporal correlation length	References
Altimeter Random error	1,2	0 km	0 day	S3 performance doc (CLS)
SSB Noise	0,3	300 km	Inf.	S3 performance doc (CLS)
SSB correlated	0,1	100 km	1 day	Tran & al, 2019
Ionosphere	0,15	600 km	0 day	S3 performance doc (CLS)
Wet Troposphere	1	50 km	1 hour	Brown & al, 2015; Stum & al, 2011
Dry Troposphere	0,2	600 km	2 days	S3 performance doc (CLS)
Mean Sea Surface	0,5	1 km	Inf.	Pujol & al, 2018
Ocean Tides	1	1000 km	< 1 day	Lyard & al, 2018
Orbit solution	1,5	> 10 000 km	< 1 day	Ollivier & al, 2018; Couhert & al, 2015





= 1,86 cm @ very short scales

= 0.34 cm @ meso scales

= 0.11 cm @ large scales

CLS

Sentinel-6 Performances over ocean

SAR Ku, Open Burst
B=320 MHz
Rad 6 channels (23/36)
Aux. Band = C band

Error Source	STD (cm)	Spatial correlation length	Temporal correlation length	References
Altimeter Random error	1,2	0 km	0 day	S3 performance doc (CLS)
SSB Noise	0,3	300 km	Inf.	S3 performance doc (CLS)
SSB correlated	0,1	100 km	1 day	Tran & al, 2019
Ionosphere	0,15	600 km	0 day	S3 performance doc (CLS)
Wet Troposphere	1	50 km	1 hour	Brown & al, 2015; Stum & al, 2011
Dry Troposphere	0,2	600 km	2 days	S3 performance doc (CLS)
Mean Sea Surface	0,5	1 km	Inf.	Pujol & al, 2018
Ocean Tides	1	1000 km	< 1 day	Lyard & al, 2018
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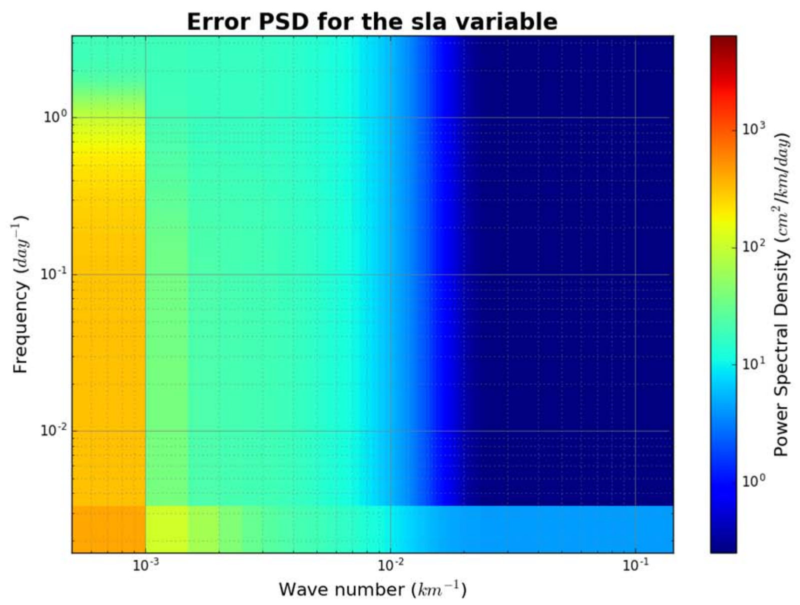
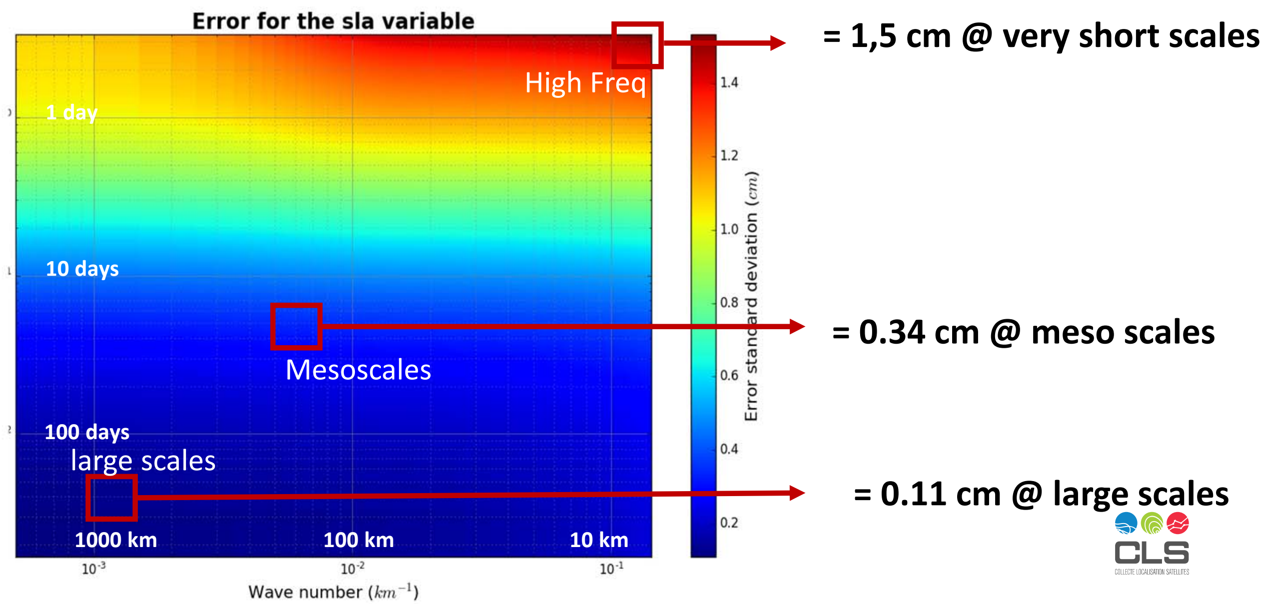
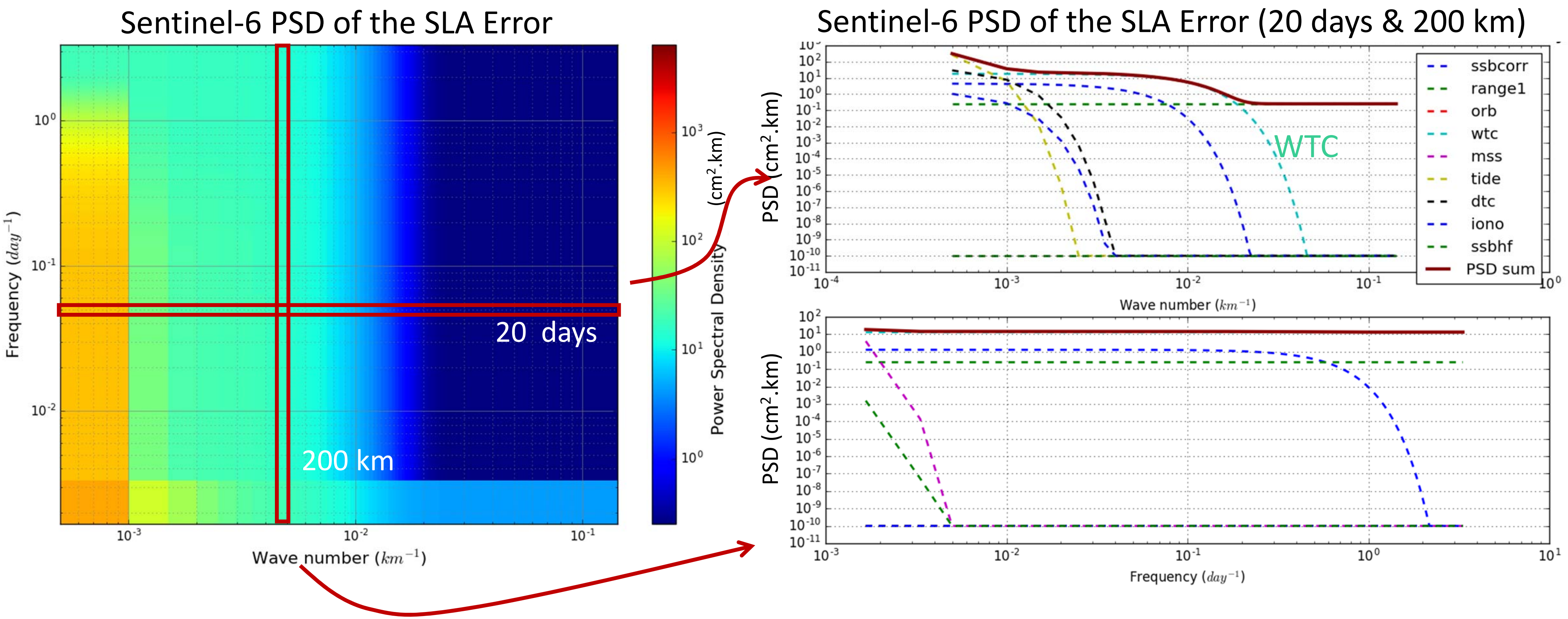


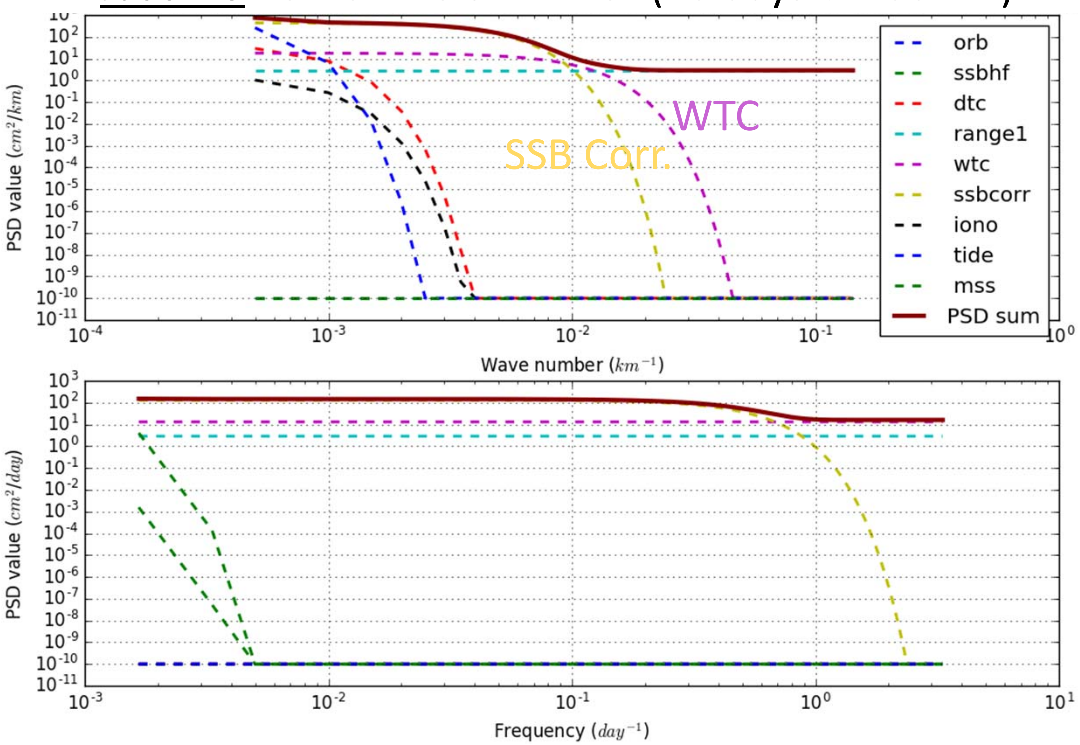


Sentinel-6 Performances over ocean

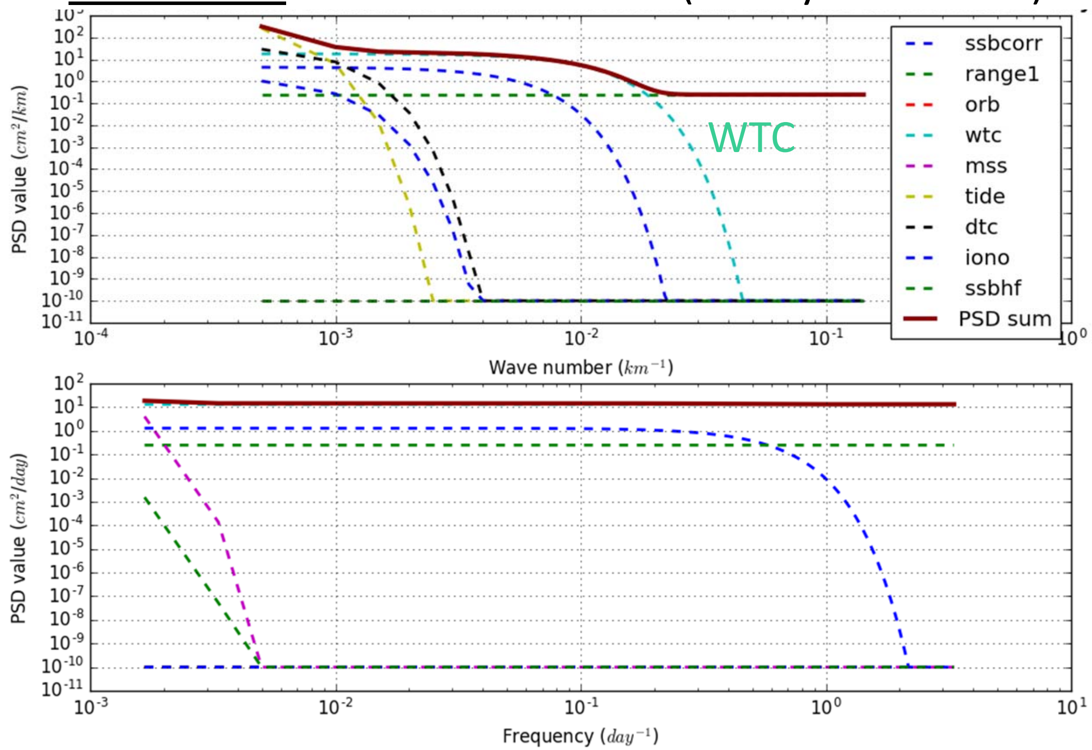


Sentinel-6 Performances over ocean

Jason-3 PSD of the SLA Error (20 days & 200 km)



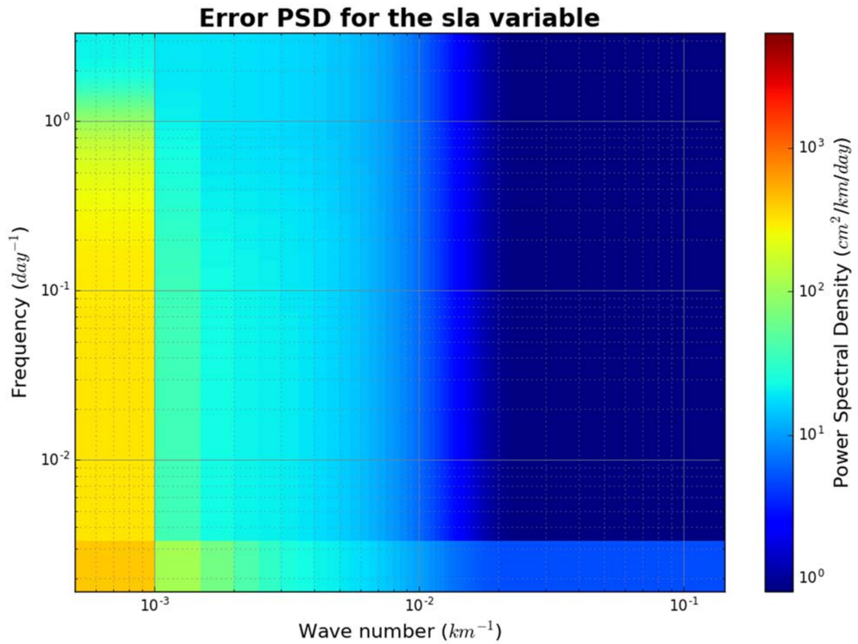
Sentinel-6 PSD of the SLA Error (20 days & 200 km)

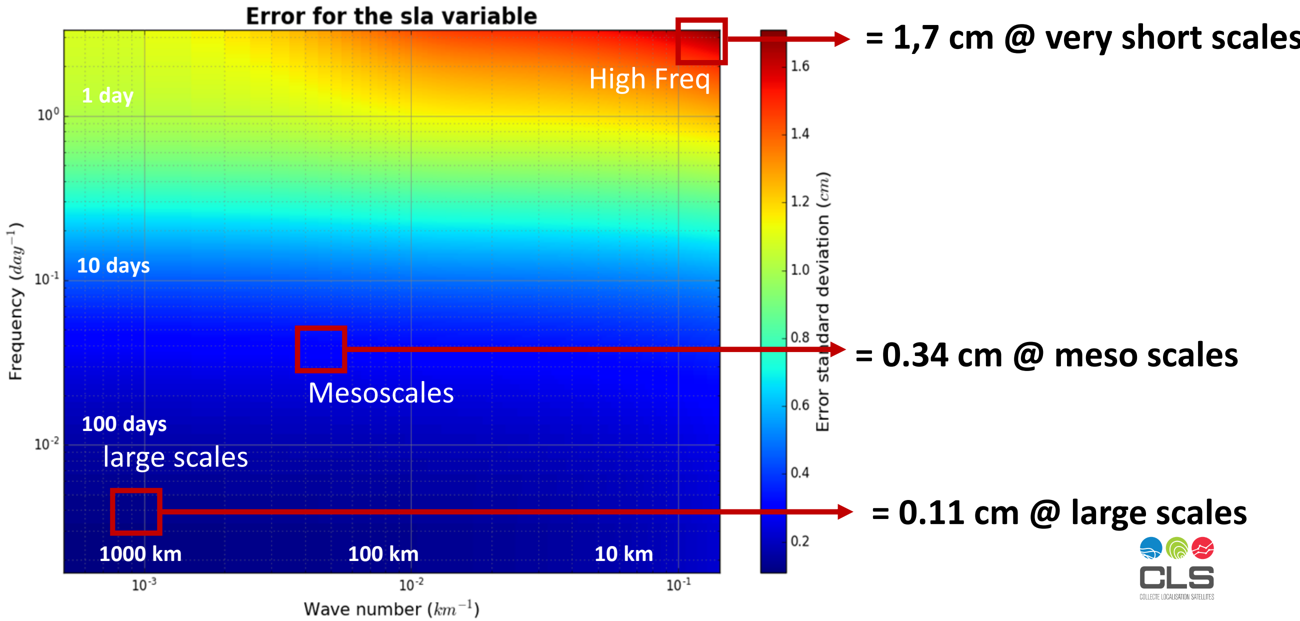


CRISTAL Performances over ocean

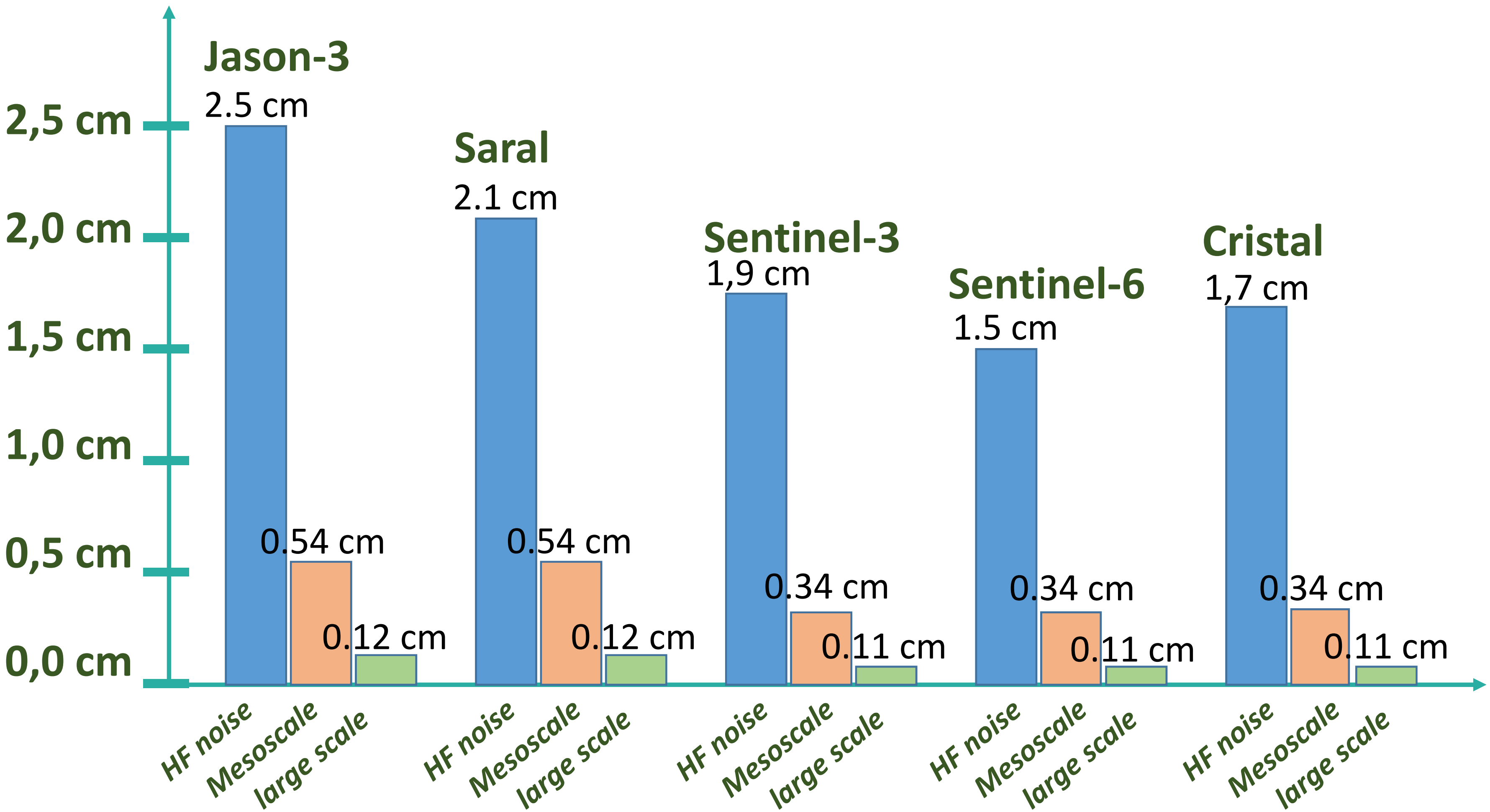
SAR Ku, Closed Burst
BW=500 MHz
Rad 3 chanels (hyp)
Aux. Band = Ka band

Error Source	STD (cm)	Spatial correlation length	Temporal correlation length	References
Altimeter Random error	0,8	0 km	0 day	S3 performance doc (CLS) + extrap. to Cristal
SSB Noise	0,3	300 km	Inf.	S3 performance doc (CLS) +extrap. To Cristal
SSB correlated	0,1	100 km	1 day	Tran & al, 2019
Ionosphere	0,3	600 km	0 day	S3 performance doc (CLS) + extrap. To Cristal
Wet Troposphere	1	50 km	1 hour	Brown & al, 2015; Stum & al, 2011
Dry Troposphere	0,2	600 km	2 days	S3 performance doc (CLS)
Mean Sea Surface	0,5	1 km	Inf.	Pujol & al, 2018
Ocean Tides	1	1000 km	< 1 day	Lyard & al, 2018
Orbit solution	1,5	> 10 000 km	< 1 day	Ollivier & al, 2018; Couhert & al, 2015





Comparison of mission performances over ocean @scales



CRISTAL Performances over sea ice (Ice Thickness)

➔ Can be derived for SLA in the leads, for Freeboard or for Ice Thickness

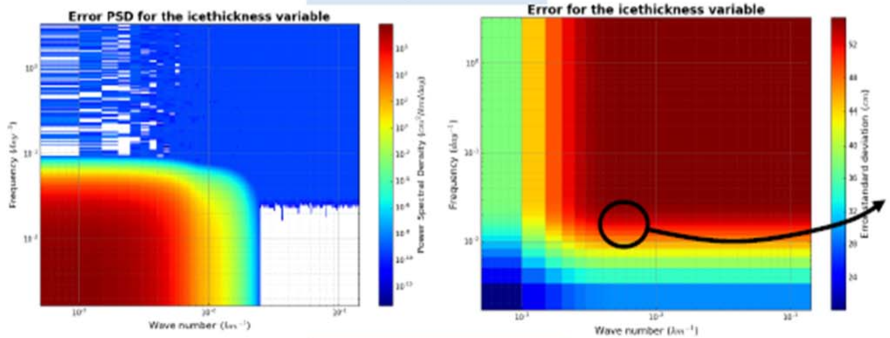
Sea Ice Thickness is derived from this equation:

- ρ_w is the water density
- ρ_{ice} is the ice density
- ρ_s is the snow density
- h_s is the snow depth
- c_s is the celerity of light in the snow
- f_{radar} is the radar freeboard

$$SIT = \frac{\rho_w}{\rho_w - \rho_{ice}} f_{radar} + \frac{\left(1 - {c_s}/{c}\right)\rho_w + \rho_s}{\rho_w - \rho_{ice}} h_s \quad \text{with} \quad \frac{c_s}{c} = (1 + 0.51\rho_s/1000)^{-1.5}$$

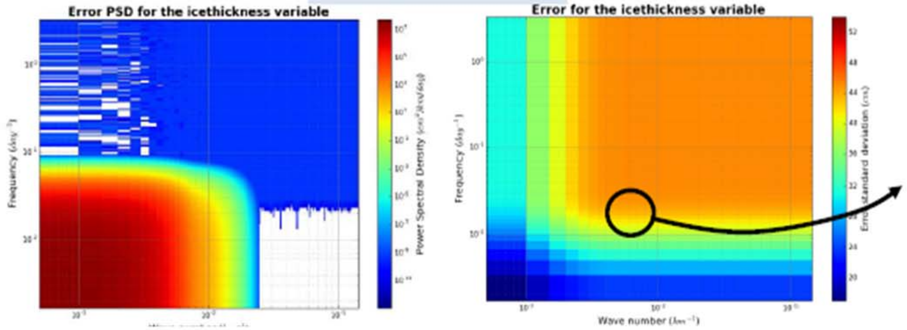
	Uncertainty	Spatial correlation length	Temporal correlation length	Références
Ice freeboard ε_{fice}	3 cm x 0.64	~200 km	~month	Ricker et al. 2014 x 0.64 (CRISTAL bandwidth)
Snow depth ε_{fhs}	6.5 cm	~200 km	synoptic	Lawrence et al. 2018
Snow density $\varepsilon_{\rho s}$	3.2 kg/m³	~100 km	~month	Warren et al. 1999
Water density $\varepsilon_{\rho w}$	0.5 kg/m³	Inf	inf	Wadhams et al. 1992
Ice density $\varepsilon_{\rho ice}$	23 kg/m³ (MYI) 35 kg/m³ (FYI)	~200 km	~month	Alexandrov et al. 2010

First year ice



53 to 56 cm
on monthly gridded
sea ice thickness
products

Multi year ice



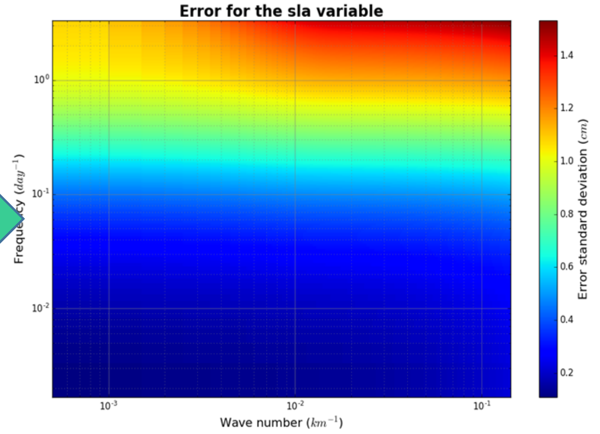
43 to 45 cm
on monthly gridded
sea ice thickness
products

Conclusions

S6/JCS Performance Requirement Budget (S6 Clval Plan)

	LR			HR		
	NRT req	STC req	NTC req/goal	NRT req	STC req	NTC req/goal
Ku-band range noise (a)	1.5 R-S-00570	1.5 R-S-00430	1.5/1.0 R-S-00270	0.8 R-S-00970	0.8 R-S-00840	0.8/0.5 R-S-00690
C-band range noise (a)	5.7 R-S-00580	5.7 R-S-00440	5.7 R-S-00280			
Ionosphere (b)	0.5 R-S-00590	0.5 R-S-00450	0.5/0.3 R-S-00290	0.5 R-S-00980	0.5 R-S-00850	0.5/0.3 R-S-00700
Sea state bias	2.0 R-S-00600	2.0 R-S-00460	2.0/1.0 R-S-00300	2.0 R-S-00990	2.0 R-S-00860	2.0/1.0 R-S-00710
Dry troposphere	0.8 R-S-00610	0.7 R-S-00470	0.7/0.5 R-S-00310	0.8 R-S-01000	0.7 R-S-00870	0.7/0.5 R-S-00720
Wet troposphere	1.2 R-S-00620	1.2 R-S-00480	1.0/0.8 R-S-00320	1.2 R-S-01010	1.2 R-S-00880	1.0/0.8 R-S-00730
Altimeter range RSS	2.93 R-S-00560	2.90 R-S-00420	2.83/1.73 R-S-00260	2.64 R-S-00960	2.61 R-S-00830	2.53/1.49 R-S-00680
RMS orbit	5.0 R-S-00630	2.0 R-S-00490	1.5/1.0 R-S-00330	5.0 R-S-01020	2.0 R-S-00890	1.5/1.0 R-S-00740
Total RSS sea surf. height	5.79 R-S-00640	3.53 R-S-00500	3.20/1.99 R-S-00340	5.65 R-S-01030	3.29 R-S-00900	2.94/1.80 R-S-00750

Error Source	STD (cm)	Spatial correlation length	Temporal correlation length	References
Altimeter Random error	1,2	0 km	0 day	S3 performance doc (CLS)
SSB Noise	0,3	300 km	Inf.	S3 performance doc (CLS)
SSB correlated	0,1	100 km	1 day	Tran & al, 2019
Ionosphere	0,15	600 km	0 day	S3 performance doc (CLS)
Wet Troposphere	1	50 km	1 hour	Brown & al, 2015; Stum & al, 2011
Dry Troposphere	0,2	600 km	2 days	S3 performance doc (CLS)
Mean Sea Surface	0,5	1 km	Inf.	Pujol & al, 2018
Ocean Tides	1	1000 km	< 1 day	Lyard & al, 2018
Orbit solution	1,5	> 10 000 km	< 1 day	Ollivier & al, 2018; Couhert & al, 2015



- New approach to synthesize & visualize the performances of the missions (past, current, future) and to assess them @ different spatial & time scales
- Correlation between time and spatial scales still to be considered
- Values & wavelengths of error can still be improved: **feel free to suggest new values and to justify them !**
- Plots for new missions (SWOT, …) or new variables can be provided (freeboard, SLA in leads, snow depth, …)

THANK YOU

CLS: for Earth, from Space

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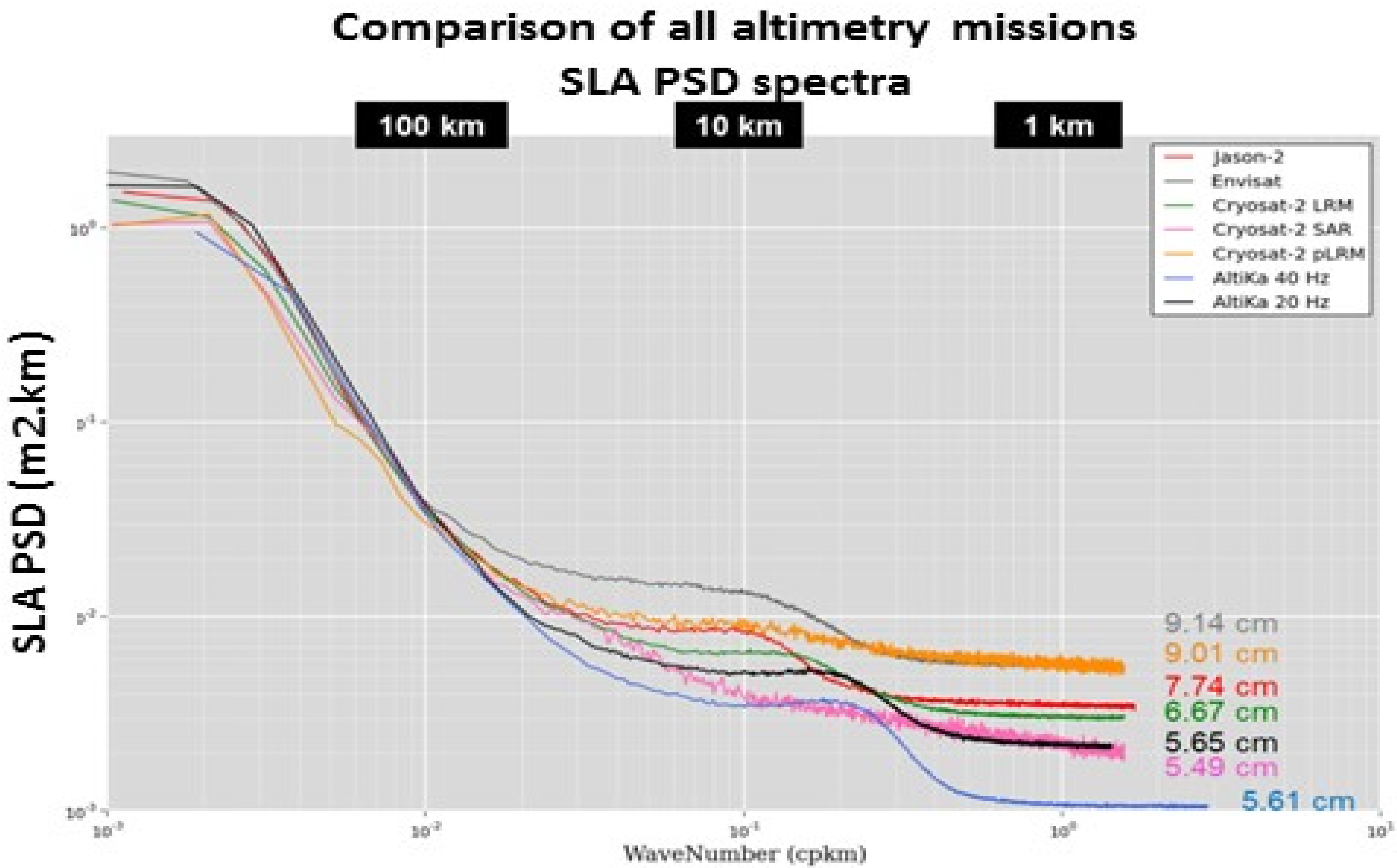
Description of the CRISTAL mission

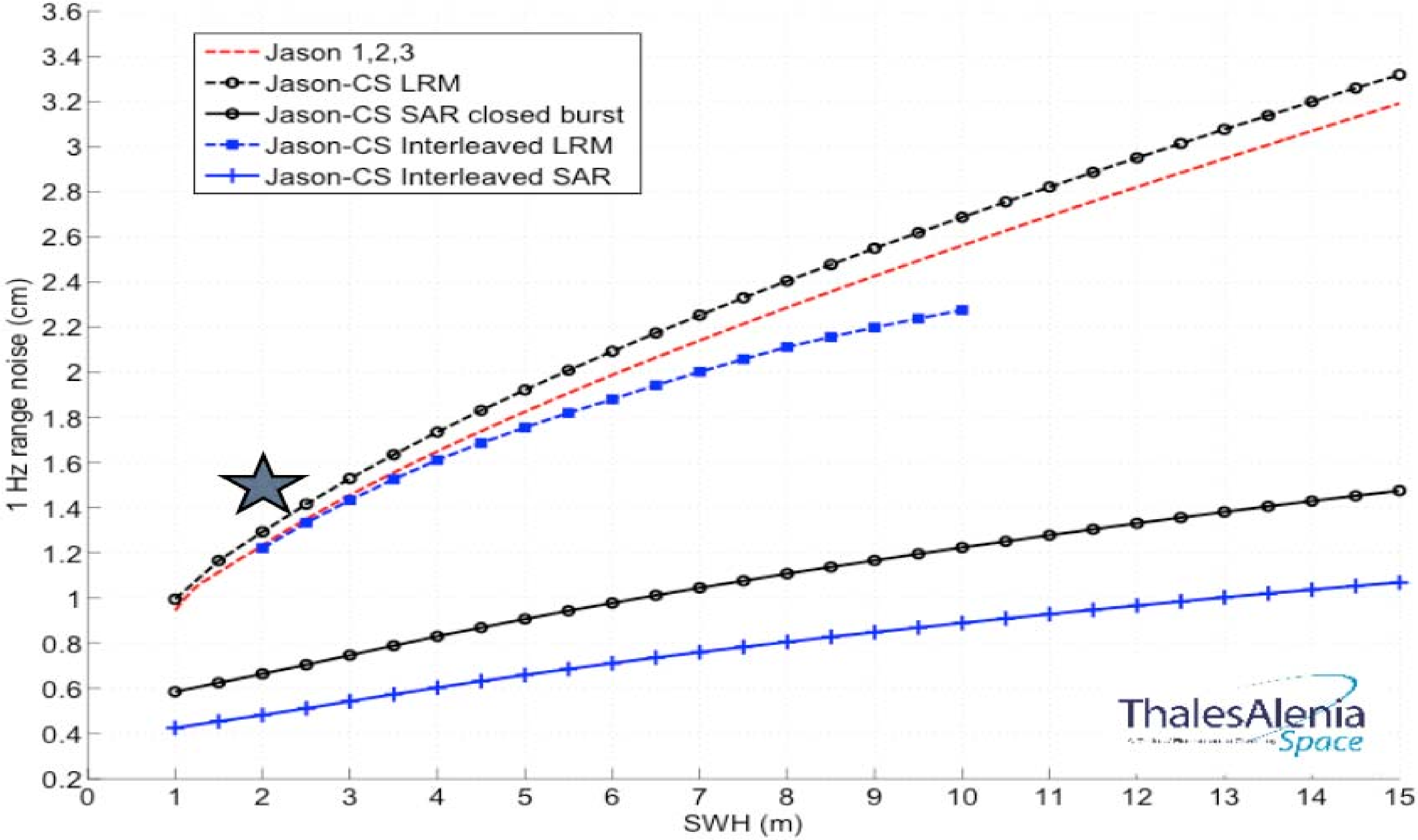
Values still to be confirmed → Phase B2/C/D studies

- Inclination ~ 92 deg;
- Sub-Cycles (TBD) ~ 5, 14, 33, 113, 392;
- Ku / Ka;
- LRM / SAR / SARin;
- Open Burst / Closed Burst;

	Open-Ocean	Sea-Ice	Ice sheets & glacier	Inland water
Operating mode in Ku band	SAR-CB	SARIn OB	SARIn-CB	?
Operating mode in Ka band	SAR-CB	SAR OB	SAR-CB	?



20-Hz altimeter range noise
(from Thibaut et al, Reston, OSTST meeting, 2015)



1-Hz altimeter range noise for closed and interleaved modes
(from Cullen et al, Southampton Jason-CS altimetry meeting, 2013)

A new way to assess and represent the error budget for any altimeter mission

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Historically, for each altimeter mission and before its launch, a performance budget is produced in order to anticipate its final potential and to compare its advantages/drawbacks with respect to other missions. It is usually presented as a simple table containing the level of error of the main contributions to the final error budget (range, orbit, Sea State Bias, Wet and Dry Tropospheric Correction, Ionospheric correction, ...).
Of course, this table is built based on the analysis of previous mission performance and taking into account the technical specificities of the new mission (instrumental characteristics such as radar frequency, radiometer (or not), or evolutions of the on-ground processing).
Once the mission is in operation, the same table is computed, based on real observations. However, this table is not satisfactory as several types of errors are given while they have different time and spatial scales of occurrence. The global value for sea level is usually considered as the quadratic sum of all sources of error (sub-mesoscales and mesoscales errors, uncorrelated errors related to the instrumental characteristics and the on-ground retracking; short time temporal errors below 10 days – SSB, Ionosphere, Troposphere, …; large scales errors from medium temporal errors (2 months – 1 year) to long-term errors (> 1 year) including inter-annual variations and drifts (important for GMSL studies for example).

A new method, based on Power Spectral Density (PSD) has been developed at CLS (in the frame of the CRISTAL Phase A/B1 study with ESTEC) accounting for spatial and temporal correlated errors, combining them and finally providing maps of errors. It gives the capability to describe the uncertainty variance of each source of error for all frequencies in the spatial and temporal dimensions. This method can either be used to describe the performances over ocean or sea ice regions. A mission performance simulation tool (MPS) has been developed in the frame of this study.

We propose in this talk to describe this method and to provide illustrations/maps of the final errors obtained for different missions over different surfaces.

Comparison between missions over ocean

Jason-3:
- short scale: 2.5 cm
- meso scale: 0.5362 cm
- climat scale: 0.122 cm

SARAL/AltiKa:
- short scale: 2.0754
- meso scale: 0.5350
- climat scale: 0.122 cm

Sentinel-3A:
- short scale: 1.8602 cm
- meso scale: 0.3428 cm
- climat scale: 0.1088 cm

CRISTAL:
- short scale: 1.6858 cm
- meso scale: 0.3426 cm
- climat scale: 0.1088 cm

Jason-CS/Sentinel-6:
- short scale: 1.5156 cm
- meso scale: 0.3419 cm
- climat scale: 0.1087 cm