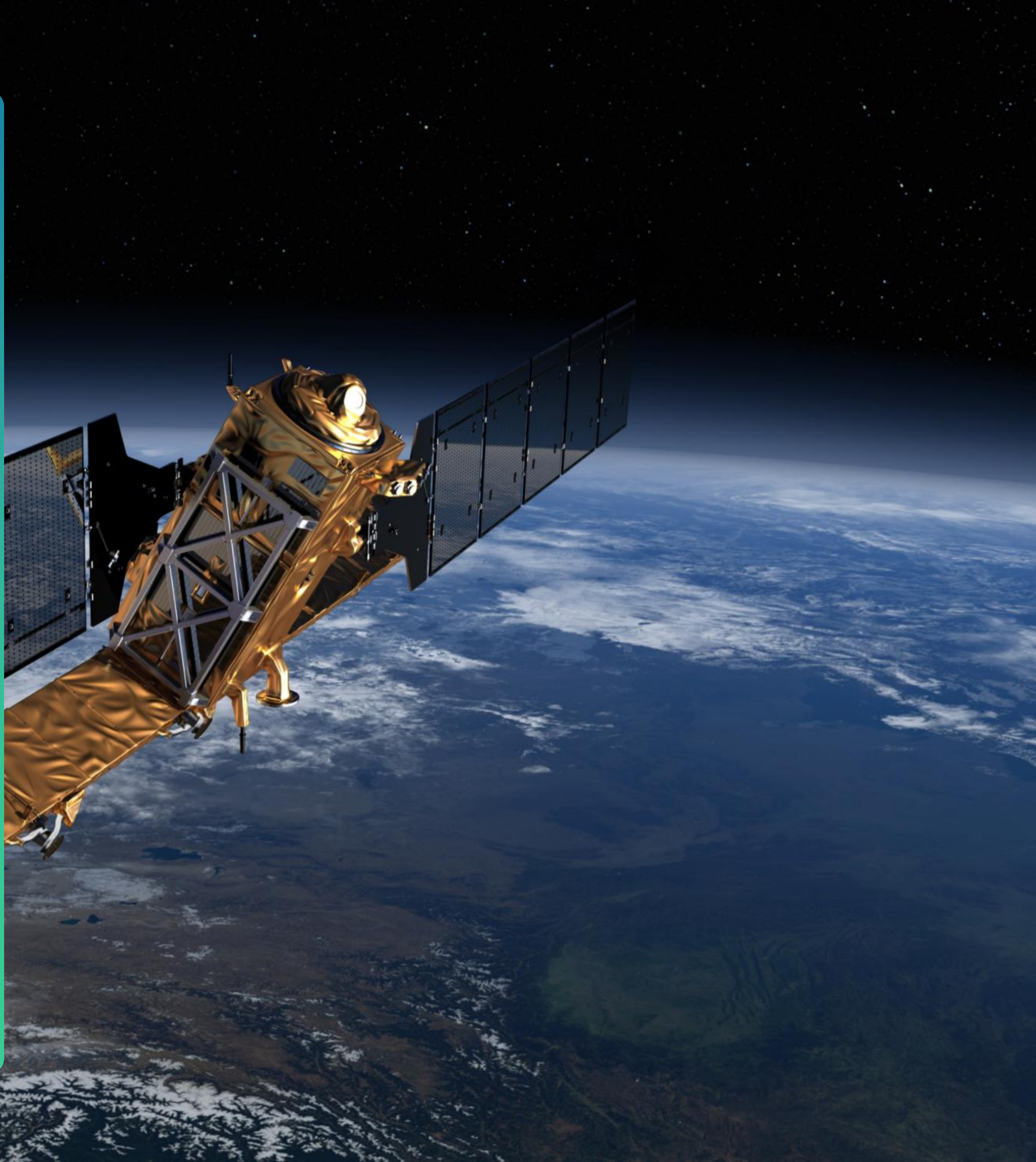
Summary of previous orbit definition studies (2009) & new challenges for the reference S6NG orbit

L. Carrere (CLS)



Outline

1. Context and objectives of the post-EPS study in 2009

2. Methodology used

3. List of orbit candidates and preliminary selection criteria

4. Summary of the results of the post-EPS study
   - Tides and HF
   - Ionospheric & tropospheric corrections
   - Ocean applications : mesoscale, climate signals, MSL, others …

5. Context and new challenges for the S6NG orbit definition

Context of the post-EPS study started in 2009

Post-EPS = post EUMETSAT Polar System for timeframe 2020 onward

Objective : address the question of a possible orbit change for the reference orbit for the time frame of 2020-onward

The continuous sampling of the ocean by altimetry measurements since 1990s has permitted the development of both operational oceanography and climate monitoring

Thanks to *accurate reference altimetry missions*, altimetry is a key component for the Mean Sea Level monitoring, a crucial contribution to climate change survey

The near real time and operational constraints are critical to address for operational oceanography

Optimizing future altimeter missions is a complex problem with many conflicting requirements, constraints and issues to be taken into account : diversity of user requirements and ocean & climate applications, optimize altimeter system error budget, minimize mission coast, consider the multi-mission, multi-agency context, continuity between successive missions for climate change estimation…

Therefore optimizing a future altimeter mission should be done within a realistic multi-mission context (at the foreseen flying date of 2020 here), and the complementarities between these missions should be taken into account.

Starting recommandations for the 2009 Post-EPS orbit study

The Venice Symposium on 15 years of Progress in Altimetry (March 2006), produced a consensus set of recommendations concerning the *transition of satellite altimetry into a sustained global system supporting operational oceanography and climate monitoring*. Then, these recommendations were detailed and an implementation plan was proposed over the next 15 years (workshop of Assmannshausen, Germany, 2008). The main recommendations were:

- **Maintain continuity of high-accuracy Jason altimetry.**
- **Maintain continuity with altimeters on at least two complementary, high-inclination satellites.**
- **Extend the capability of altimetry to denser observational coverage through swath altimetry.**

- Maintain an open data policy including near-real time data for operational purposes.
- Maintain a continuing partnership & collaboration between engineering and science, research and operations, and international partners.

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Main topics adressed

The 2009 study has addressed more specifically the following topics:

- Ensure high accuracy altimetry.
- Envision other orbits and configurations than the ones of the present Jason-1 and Jason-2 missions.
- Review all observation needs and all possible error sources in order to optimize the orbit of future altimeter reference mission
- Take into account the most probable multi-mission context for the time frame around 2020 (2-satellite constellations with Sentinel-3)

Basic requirements were :

- consider an operational reference altimetry mission, with a pulse-limited instrument, oriented towards ocean applications and climate
- consider a multi-mission context
- consider tides as a crucial issue, with some weakening of the tide aliasing constraints following experts’ recommendations.
- check the impact of orbits’ characteristics on major applications of altimetry + review of observation needs and possible error sources + check orbits’ costs

Study consortium and thematic experts

Consortium led by CLS, with Mercator-Ocean (main partner) and EADS/Astrium, and with the support of several thematic experts in the different domains of investigation :

- Tides/high frequencies experts from LEGOS (F. Lyard), CNES (A. Lombard), NASA/GSFC (R. Ray), AER inc (R. Ponte), CLS (F. Lefèvre);
- POD experts from CNES (L. Cerri, N. Picot) and CLS (P. Escudier);
- Mission costs experts from Astrium (E. Malliet, S. Boulade);
- Climate experts from NASA/JPL (C. Perigaud);
- Mean Sea Level experts from LEGOS (A. Cazenave) and CLS (M. Ablain);
- Mesoscale observation community from Mercator-Ocean (Y. Drillet, O. Legalloudec), Ifremer (P.Y. Le Traon) and CLS.

Global methodology

1. Preliminary analysis of past and planned altimeter missions to extract recommendations for the reference orbit optimization study:
   - Particularly the aliasing of tides is a crucial issue and it was one of the drivers of the choice of the TOPEX/Poseidon-Jason's orbit.
   - In 2009, tidal signals are well known in the open ocean. However issues remain in coastal areas and for internal tides.
   - => *aliasing of tides by altimeter sampling remains a challenge as it may pollute other signals of interest*
2. Generation of a wide range of orbit candidates when considering wide ranges of altitudes, inclinations and periods.
3. Selection of a few orbit candidates for a Post-EPS altimeter mission when applying or relaxing the tide aliasing criteria.
4. Each preliminary Post-EPS candidate *has been assessed in terms of sampling capability*, in order to filter out sub-optimal choices (to avoid S3-A, S3-B redundancy for example) and highlight potentially optimal choices
5. Then a more in-depth assessment helped quantifying the *differences between remaining orbit candidates depending on each application of altimetry*: mesoscale observation, climate, MSL monitoring, and other applications like SWH, geodesy, hydrology…
6. A cost analysis has been performed to quantify the interest of using a lower orbit than the Jason-'s one, in terms of launch, mission duration, etc.
7. As the orbit determination remains a major contributor to the error budget of high precision reference altimeter missions, the POD (Precise Orbit Determination) issue has been addressed specifically to determine the impact of orbits candidates on POD accuracy.
8. Finally in the eventuality of a wide-swath altimeter sensor, the compatibility of orbit candidates with such a technology has also been investigated.

A wide list of orbits can be considered

- Starting with raw recommendations for optimization of orbit geometry :

  - Altitude between 800 and 1400 km : air-drag and solar radiation exposure trade-off (Berthias 2008)

  - Repeat cycle between 10 and 35 days (mesoscale observation + long-term continuity challenge)

  - High inclination to get more polar ocean observations

  - No sun-synchronous orbits because they do not allow aliasing of daily signals

>44000 orbits candidates !

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Post-EPS orbit selection criteria

- Tidal aliasing issues
  - No sun-synchronous orbits (to allow aliasing of daily signals)
  - Consider 14 waves: main tides M2, N2, O1, Q1, S2, K2, S1, P1, K1, Mm, Mf and three NL waves (M4, MS4, M6).
  - K1 alias is important
  - No aliasing at annual or semi-annual frequencies
  - No aliasing to very long period: good aliasing frequency is over 2 cpy
  - Minimize the time needed to separate major tides constituents
- Good mesoscale observability : Scales of ~150 km, cycles <15-20 days
- HF signals observability : 3-4 days subcycles are preferred
- Climate issues
  - Need to avoid the [40 .. 70 days] aliasing band
  - No aliasing at annual or semi-annual frequencies + good separation with Sa Ssa
  - No aliasing close to 3 or 6 cpy (120-60 days climate signals)
- Low altitudes to reduce mission costs

Tidal aliasing considerations

Aliasing of tides is a challenge as it may pollute other signal estimations, particularly in the aliasing band of 40-70 days and the semi-annual/annual band.

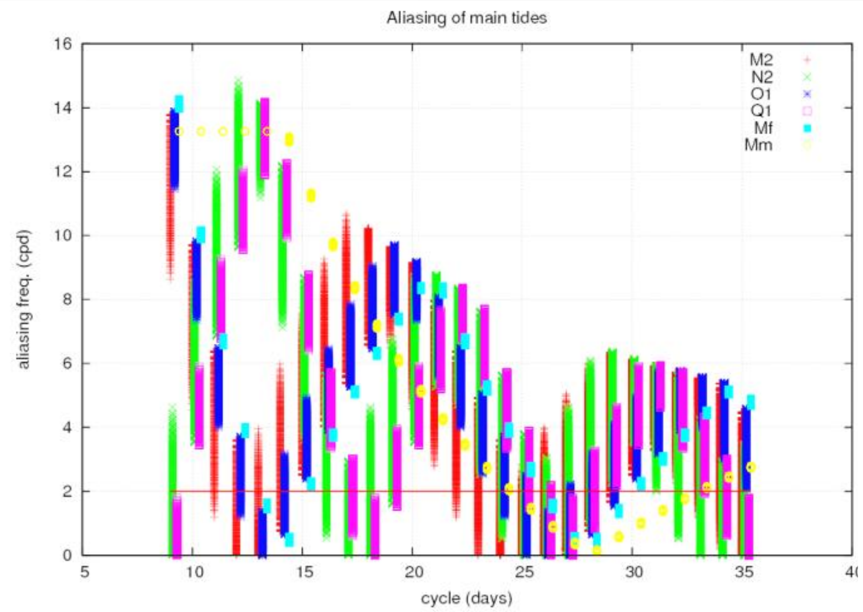
Preliminary orbit selection => M2, N2, O1, Q1, Mm, Mf, S2, K2, S1, P1, K1 + M4, MS4 and M6

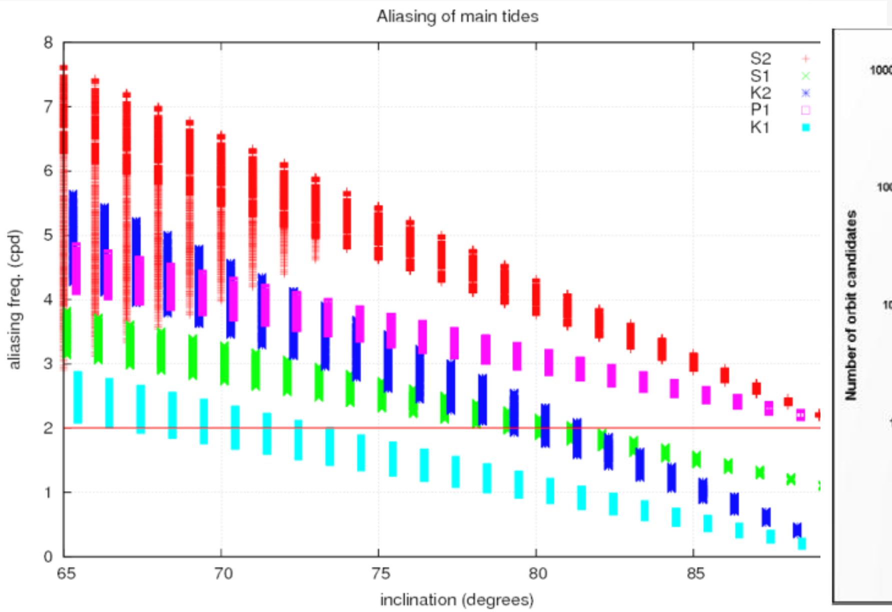
No retrograde orbit is selected according to the aliasing threshold at 2 cycles per year, the most restrictive waves being S2 and P1 => only prograde orbits have been considered

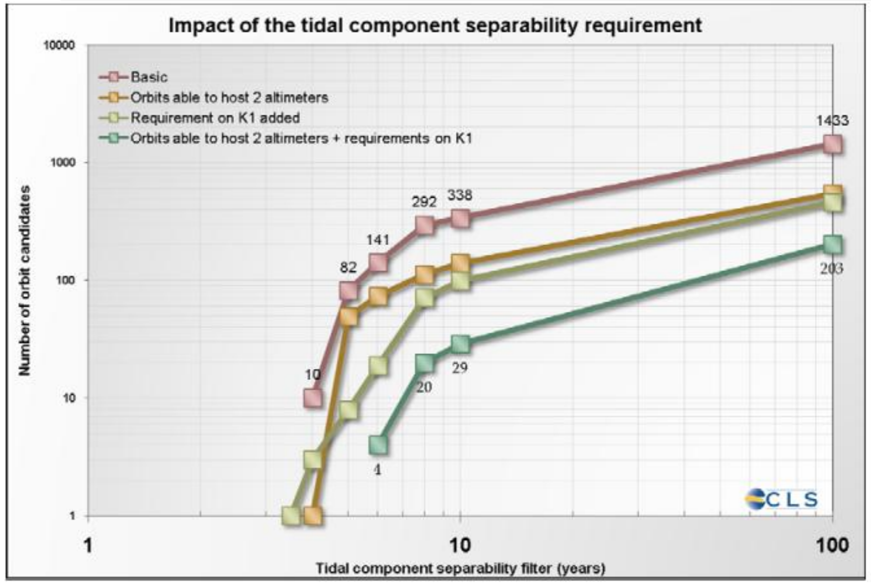
Inclination < 81° for S1 and K2

Inclination < 72° for K1

=> very constraining criteria and trade-off have been proposed to fulfill other requirements (mesoscale, climate …)







Orbit candidates selection – trade-offs

As all those criteria are very constraining, trade-off and priorities were needed => two strategies have been followed:

- The first strategy considers that **tide aliasing is a priority**, which means **that most aliasing frequencies must be over 2 cycles per year (cpy), and that there is a good separability of most waves.** This last criterion means that two tidal waves with close frequencies can be observed and separated within a reasonable time of observation.
- The second strategy considers that **tide aliasing is not a priority** as tides are already well known but **climate purposes are now a priority** (good separability criteria with Sa, Ssa and less alias in the [4-9 cpy] band as possible); the **mesoscale observation is also a priority** (3-4 days sub-cycles only).

=> **12 orbits candidates have been short listed** (9 + 3): these orbits are consistent with classical mono-mission constraints for altimetry, and with the first order applications requirements. *Notice that many other orbits could be available relaxing or changing the selection criteria.*

Short-listed orbits	
Cycles	9-22 days
Inclinations	65-76°
Altitudes	800-1300km

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The post-EPS orbit candidates short-listed

★ Orbits pre-selected for in-depth tests in 2009

Selected on tidal criteria

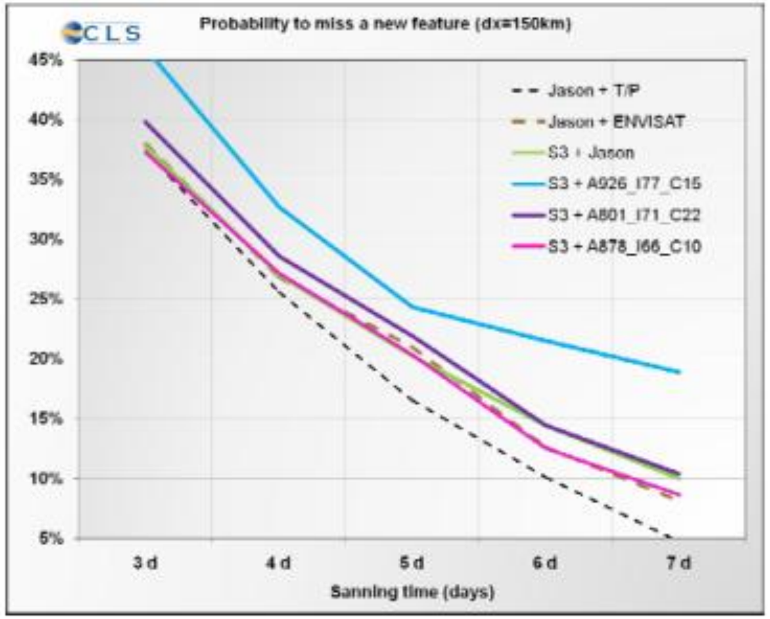
Relaxing tidal criteria

12 orbits	Altitude (km)	Inc (deg)	Cycle (days)	Exact repeat cycle (days)	Tide Aliasing	Tide separability (years)	Optimisation for 2 satellites	Sub-cycle (days)	S1 aliasing (days)	rev/day
A878_i66_c10 ★	878.731	66	10	9.901936	K1 included	3.5 y	no	1	100.97	13+9/10
A1150_i72_c11	1150.317	72	11	10.917843	No K1	4 y	yes	5	132.89	13+2/11
A964_i74_c19	964.879	74	19	18.860482	No K1	5 y	yes	3	135.18	13+13/19
A835_i75_c19	835.619	75	19	18.860551	No K1	5 y	yes	1	135.25	14+1/19
A1076_i68_c11	1076.855	68	11	10.904653	no K1, but alias K1>2cpy afterall	6y	yes	3	114.36	13+4/11
A801_i71_c22 ★	801.857	71	22	21.810438	K1 inluded	6 y	no	7	115.05	14+3/22
A1361_i65_c11	1361.612	65	11	10.905338	K1 included	6 years	yes	3	115.20	12+7/11
A912_i70_c11	912.147	70	11	10.905479	K1 included	8 years	yes	5	115.37	13+9/11
A822_i68_c15	822.474	68	15	14.858551	K1 included	8 years	yes	1	105.04	14+1/15
A1104_i76_c16	1104.802	76	16	15.895629	K1<2cpy	-	no	3	152.3	13+5/16
A923_i67_c9	923.365	67	9	8.915522	K1>2cpy	-	no	4	105.53	13+7/9
A926_i67_c13 ★	926.436	67	13	12.878103	K1>2cpy -	-	no	4	105.64	13+10/13

More analysis on the 3 pre-selected orbits

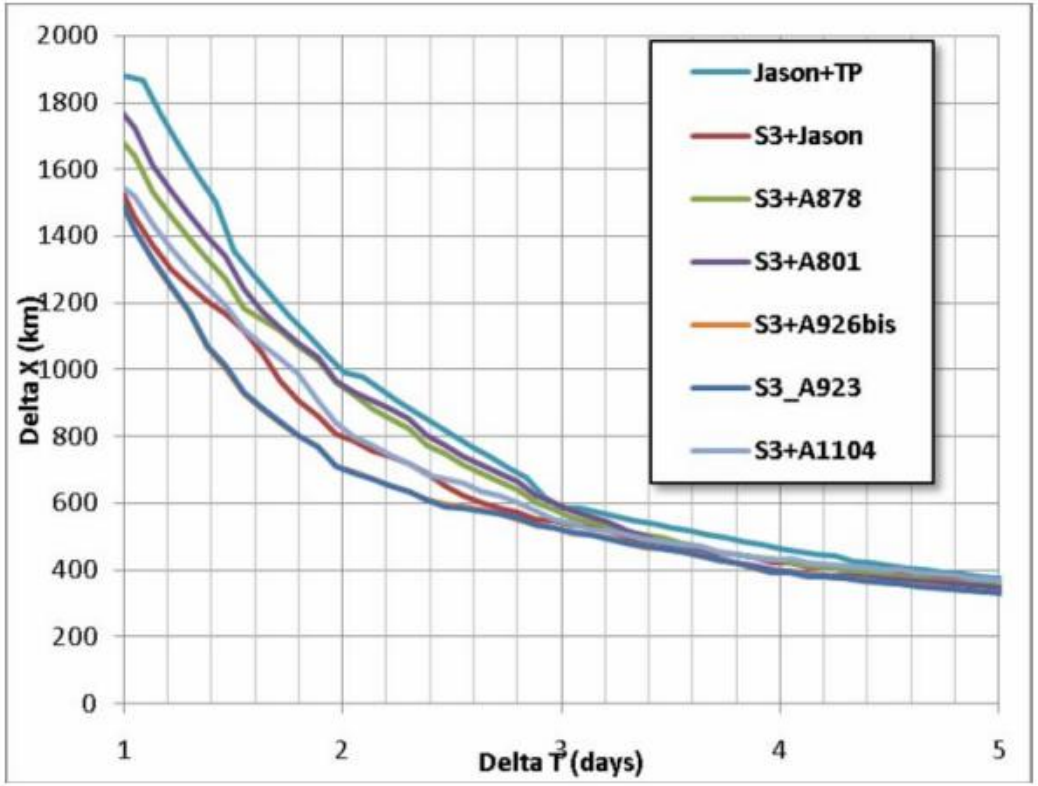
- In a theoretical and multi-mission context
- Both purely geometrical analysis and complete OSSE
- For high frequency signals aliasing
- For main applications of altimetry: mesoscale observation, climate, MSL monitoring, and other applications like SWH, geodesy, hydrology…

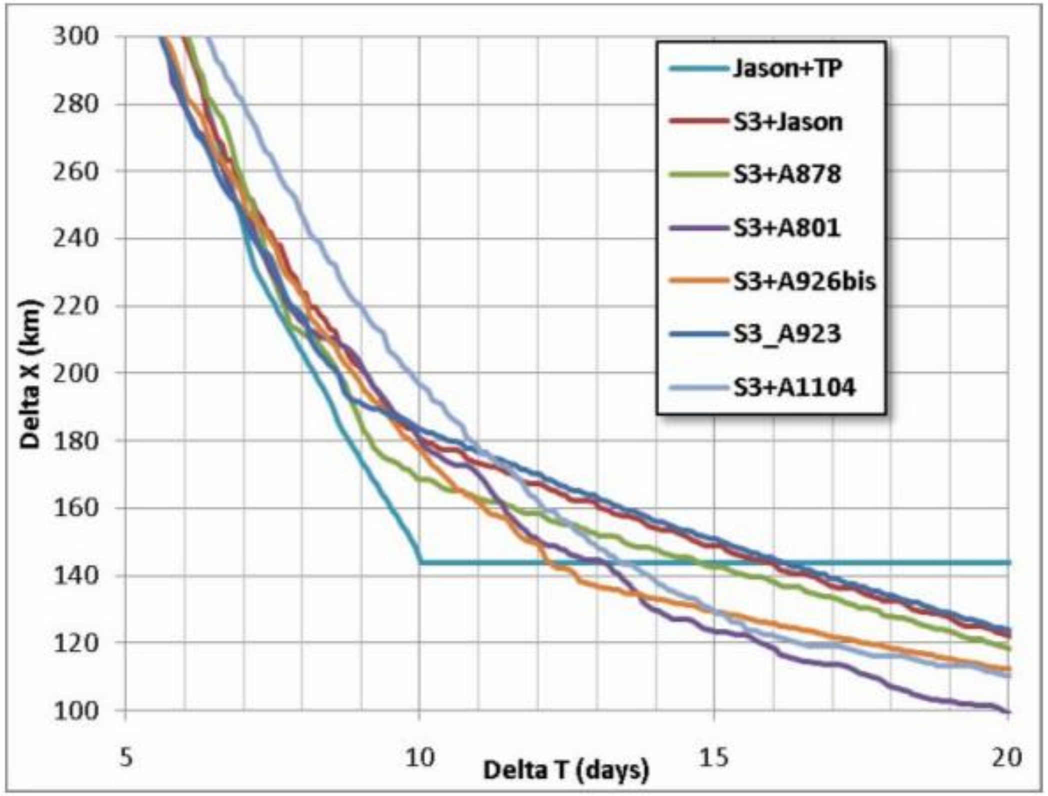
Mesoscale sampling capability analysis



The objective was to maximize the sampling density and to minimize the redundancy of the altimeter NADIR constellation (+S3)

Geometrical analysis of observable scales, coverage, sampling quality and homogeneity, structure detection and monitoring capability, crossover angle and sampling, ground track angle



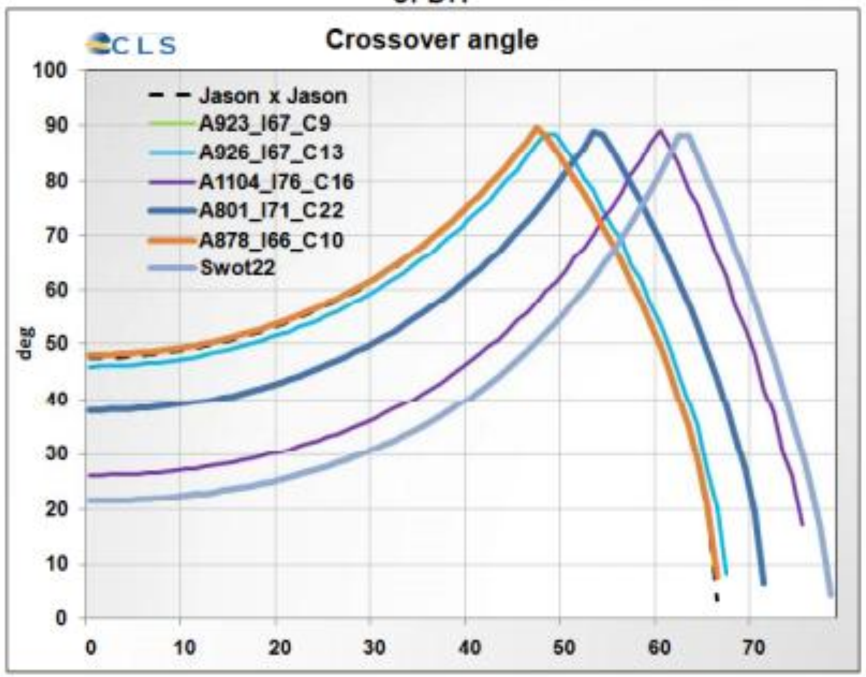


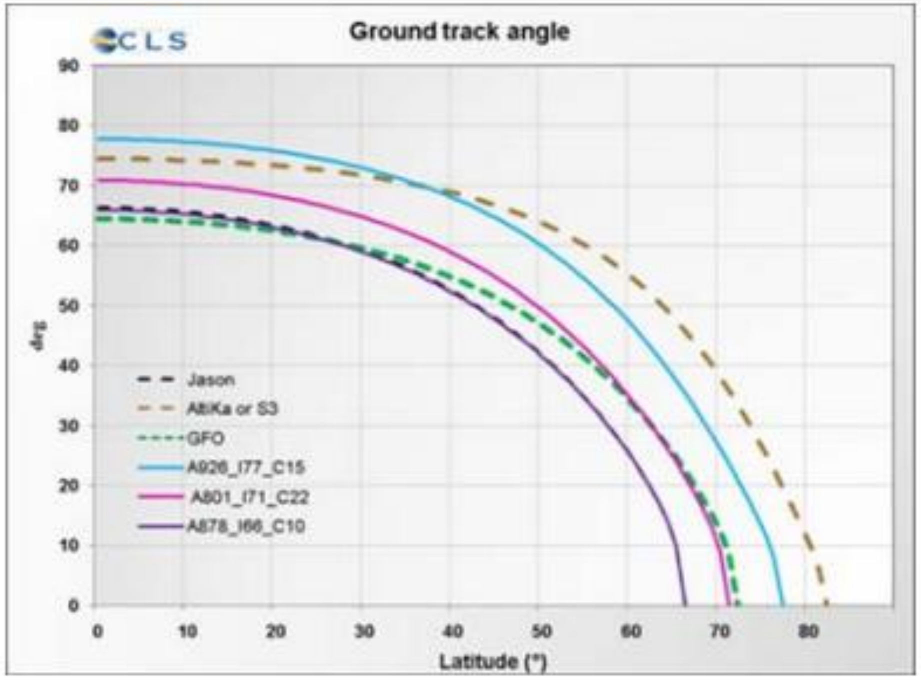
Mesoscale sampling capability analysis

The crossover angle (or track angle to equator plane) has a strong impact on geostrophic velocity observations :

45° tracks (=90° crossovers) allow an isotropic velocity observation and lower cross angles create better observations on U and worse on V (EN vs S3)

Crossovers angle as a function of latitude for each orbit

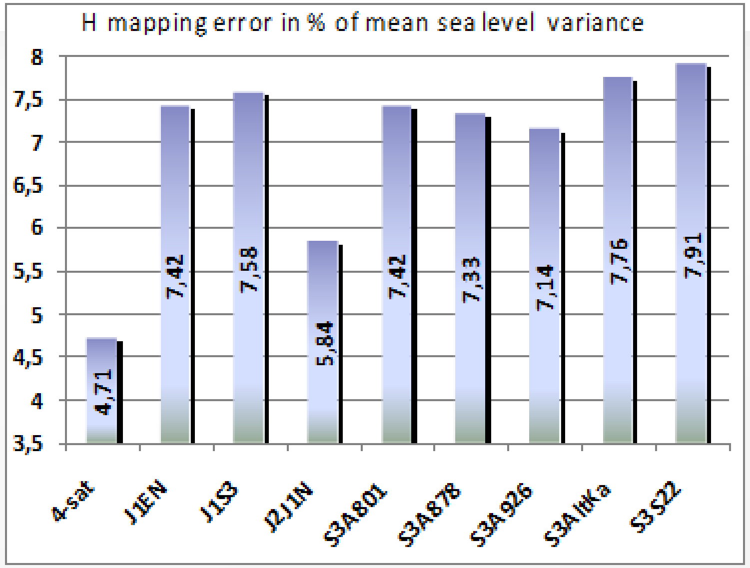




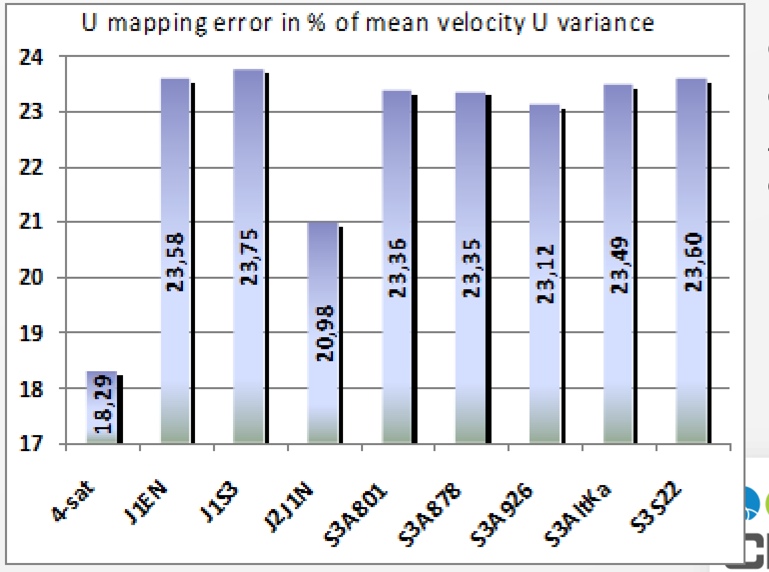
Mesoscale application performances – operational oceanography

1. OSSE in a mapping context (CLS)
   - 4-satellites constellation is better
   - J2-J1N optimized const. is better than other 2-sat const.
   - *A926 & A878 orbits slightly better in 2-sat configuration with S3*
   - Stronger differences between orbits in mono-sat. context

2. Eddies detection in altimetry maps (Mercator-Ocean)
   - Main diagnosis produced is the number of eddies detected during one year of simulation
   - The interest of the optimized 2-satellites constellation is proved with similar results as the 4-satellites constellation
   - S3A926 and S3A878 are the “best” configurations with very close results; S3A926 is slightly better in a few areas (Zapiola, Algulhas, east Austalia).



SSH



Geostrophic currents - zonal component

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Impact of new orbits on MSL estimations

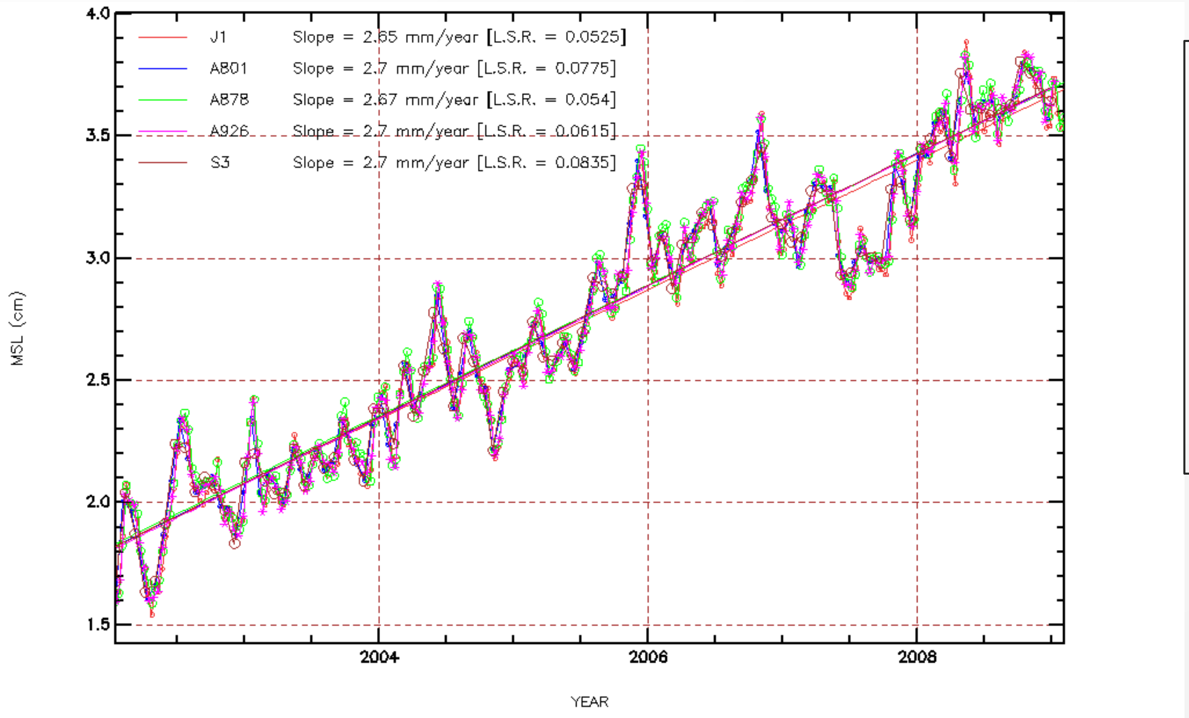
Collaboration with experts from LEGOS/CTOH

Analysis on Jason-1 period (261 cycles = 7y)

The long-term ocean state is modeled by the best observed products available at the time of the study : weekly PVA/DUACS maps available at CLS operationally (Aviso 2009)

Global and regional MSL tendencies are deduced following Ablain et al. (2009).

Global MSL trend computed for latitudes between +/- 66°



Different orbit configurations do not impact the global MSL trend on J1 period : differences < 0.05mm/y

However some more studies could be performed to check the impact of high latitudes sampling.

⚠ *estimation methods not as accurate as today + period was too short…*

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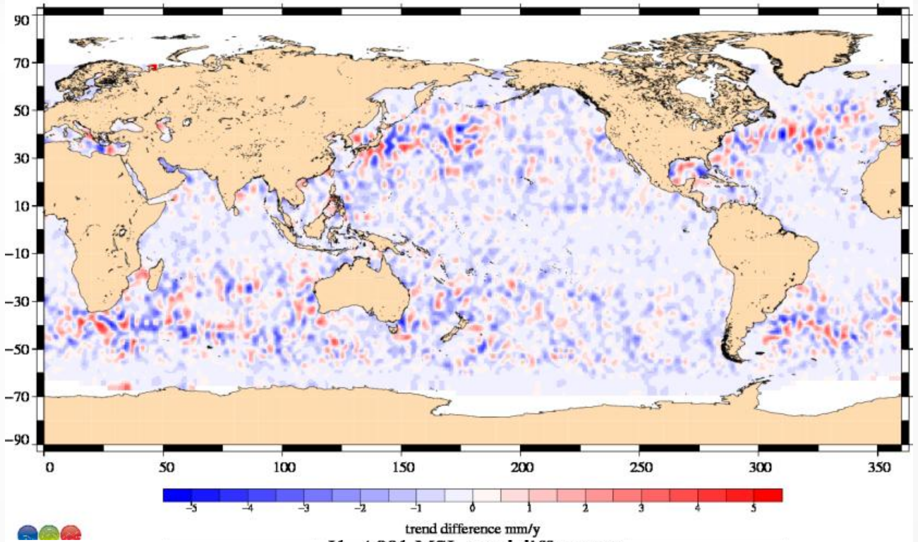
Impact of new orbits on regional MSL estimations

J1 and A878 have similar orbits (same cycle) and their regional trends are also similar except in high variability areas.

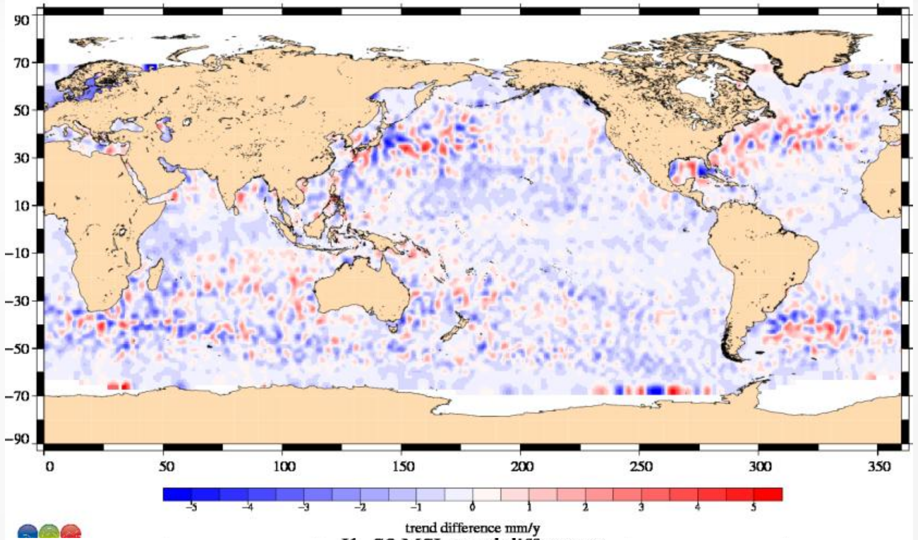
Regional trend differences between J1 and other candidates can be stronger: ~2mm/y

Need to sample the high latitudes ? => A801 better

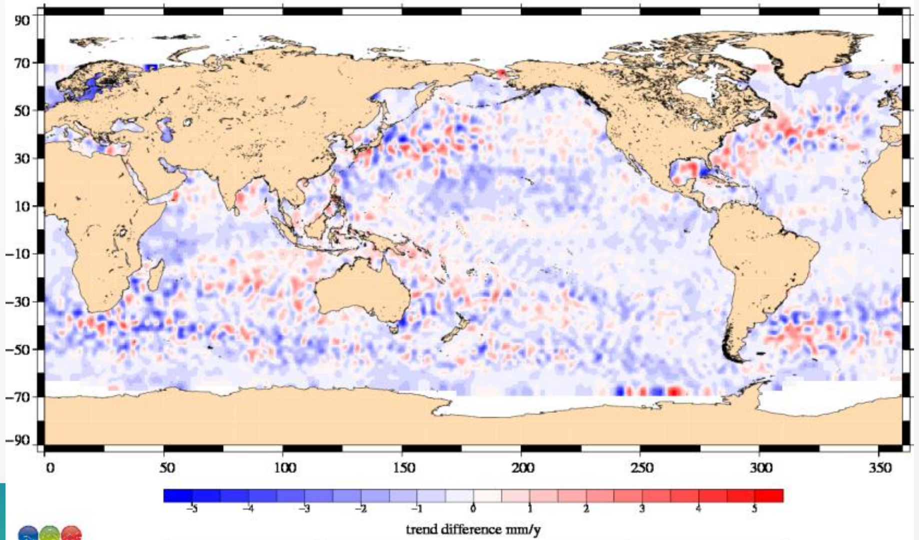
J1–A878 MSL trend differences



J1–A926 MSL trend differences

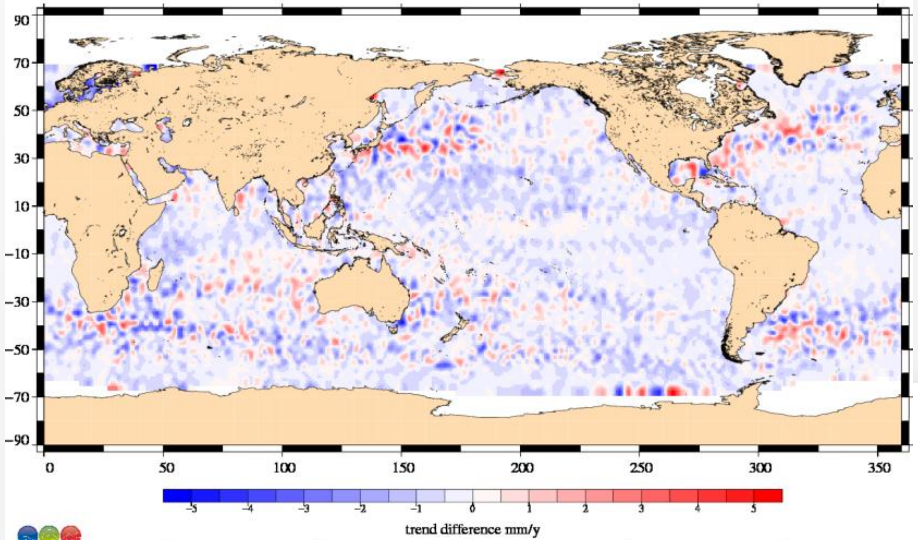


J1–A801 MSL trend differences



Nb of data	:	9257	St. Dev	:	1.8330497	Skewness	:	−0.2934593	Minimum	:	−35.0417767
Mean	:	−0.0681326	Rms	:	1.8343155	Kurtosis	:	59.5011578	Maximum	:	38.1381641

J1–S3 MSL trend differences



Nb of data	:	9262	St. Dev	:	1.83913	Skewness	:	−0.74089	Minimum	:	−35.58100
Mean	:	−0.06057	Rms	:	1.84012	Kurtosis	:	61.11571	Maximum	:	36.16012

Analysis of orbits for climate applications

Collab with C. Perigaud (JPL)

Tropical oceans play a key role in the coupling with the atmosphere from wind bursts to decadal adjustments. They interact with the tropical atmosphere at rapid scales with a wealth of intraseasonal signals, challenging the inverse barometer correction with consequences on the global scale.

The intraseasonal signals is divided into 3 bands here:

- [10-to-40 day] band = biweekly and monthly signals common to climate and tides,
- [40-to-70 day] band = the Madden Julian Oscillations (MJO) which have a maximum over the Indian and Pacific warm pools at the 60 days resonance of equatorial waves in the Indian ocean. The MJO band is also centered on the 60 days aliasing of M2/S2 by TPJ.
- [70-to-130 day] band, called LISO for Low-Frequency Intraseasonal Oscillations = covers some peaks of variability at 90 and 120 days in the Indian and Atlantic basins

Following IPCC conclusions (2007; RD43), current *progress in climate evolution crucially depends on our ability to monitor and understand the poleward transport of energy by the oceans and atmosphere*. *The ocean contribution to this transport and its coupling to the atmosphere is still unclear due to the short duration of climate data records*. Even with more than 17 years of TPJ data available, the aliasing of K1 into semi-annual, and the aliasing of M2 & S2 into ~60 days, are the biggest sources of confusion remaining today in altimetric records. **If one wants future altimetry to contribute to the monitoring of global sea level rise and water mass changes, these aliasing problems need to be solved by future orbits.**

Analysis of Post-EPS orbit candidates:

- The 3 orbits perform better than TP/Jason, EN, GFO, SWOT and Grace, in that their aliasing of the big lunisolar tide K1 will no longer be aliased into important climate signals: they will alias K1 into signals with a period shorter than semi-annual.
- A926 is the least favorable because the diurnal tide O1 and the major Lunar long period tide Mf are aliased into signals longer than semi-annual (439 and 224 days respectively).

HF signals aliasing - 1

Collab with LEGOS (F. Lyard), CNES (A. Lombard), NASA/GSFC (R. Ray), AER inc (R. Ponte)

HF barotropic signals => OSSE to evaluate the impact of observing system data in numerical analysis (ensemble twin-experiment method, Mourre et al 2004)

- using TUGO model on bay of Biscay + ARPEGE forcing
- Short simulations of 15 days

Use a “simplified” assimilation scheme(s-EnROOI), with no sequential control of the model, which allow a quick execution of the simulator

The results are very similar whatever the configuration tested and the reduction gain can have a strong variability from one time step to the other

A significant part of the *simulation score is dictated by the constellation’s ability to observe the right place at the right time on a few localized events* (to observe and to fix specific forcing/model limitations).

Ideally this natural effect would be statistically smoothed out by a long simulation over a large area.

=> the current simulation context (small area, 15 days simulation, only one winter event studied here) is too limited to get realistic statistics here

HF signals aliasing - 2

Analysis on mapped SLA products (Pujol et al. 2007) : both altimetric sampling and mapping procedures induce temporal and spatial aliasing of the HF signal

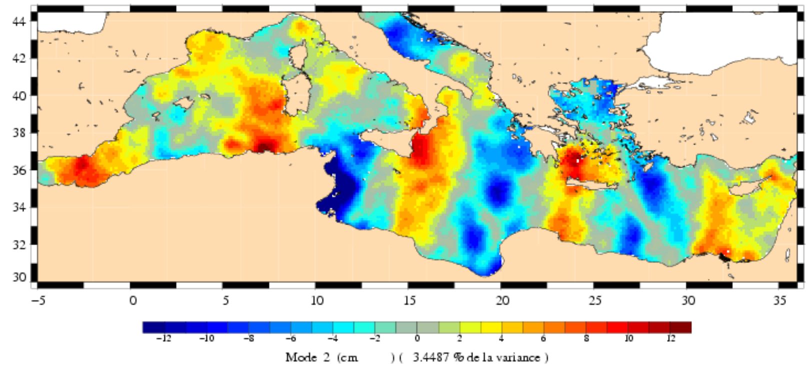
Study the aliasing effect induced by the Altimeter Observing System (AOS) using an OSSE (Observing System Simulation Experiment) with barotropic surface variability simulated with the MOG2D model. Analysis done on the Mediterranean Sea.

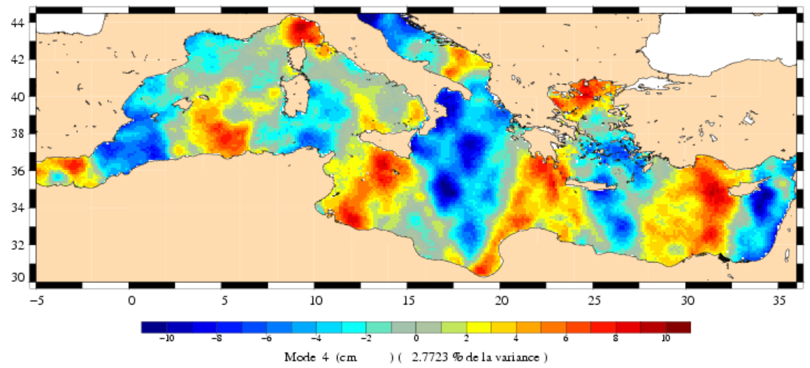
Residual HF long wavelengths signals due to residual HF errors (bad altimeter sampling of HF, spatial resolution, forcing errors, physics of he model …) *have a significant signature on the maps of SLA => 10-25% of total variability*

These errors can be corrected by more careful consideration of their characteristics in terms of spatial distribution induced by altimetric along-track sampling

=> *Errors can also be attenuated by increasing the altimetric spatial coverage* through the merging of different satellites : need to maximize sampling with S3

EOF decomposition of the HF (periods < 30 days) component of AOS signal (real altimetric mapped data). Spatial component for the second mode (left), and fourth mode (right) => modes due to a bad satellite sampling of high frequencies





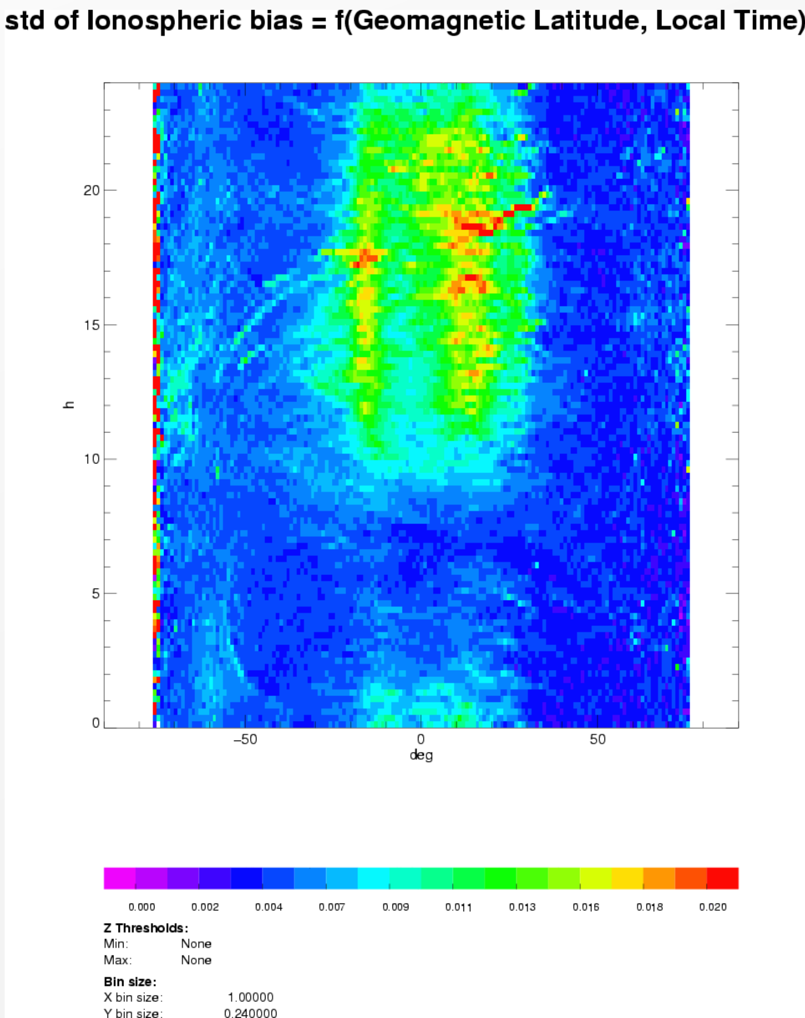
Ionospheric correction

As the electronic content highly depends on solar activity, the ionospheric correction is also strongly correlated to solar activity and the satellite local time + diurnal cycle => possible aliasing problems…

The best correction is provided by dual frequency measurements if available, else from GPS maps (GIM)

Dual-frequency iono correction depends on SSB (error on SSB differences between 2 bands)

=> Accuracy of the correction depends on payload



Structure of the GIM correction error relative to the dual frequency correction for Jason-1 (non-sun-synchronous), as a function of latitude and of local time.

Dry tropospheric correction

The same high frequency signals occur as for the inverse barometer correction

Lack of accuracy of the S1 and S2 (diurnal, semi-diurnal) atmospheric tides in the current atmospheric models.

The impact of pressure errors in the dry troposphere correction is about 4 times lower than for the inverted barometer correction

Today, trends in atmospheric models' pressure may affect this correction too : to be checked

Wet tropospheric correction

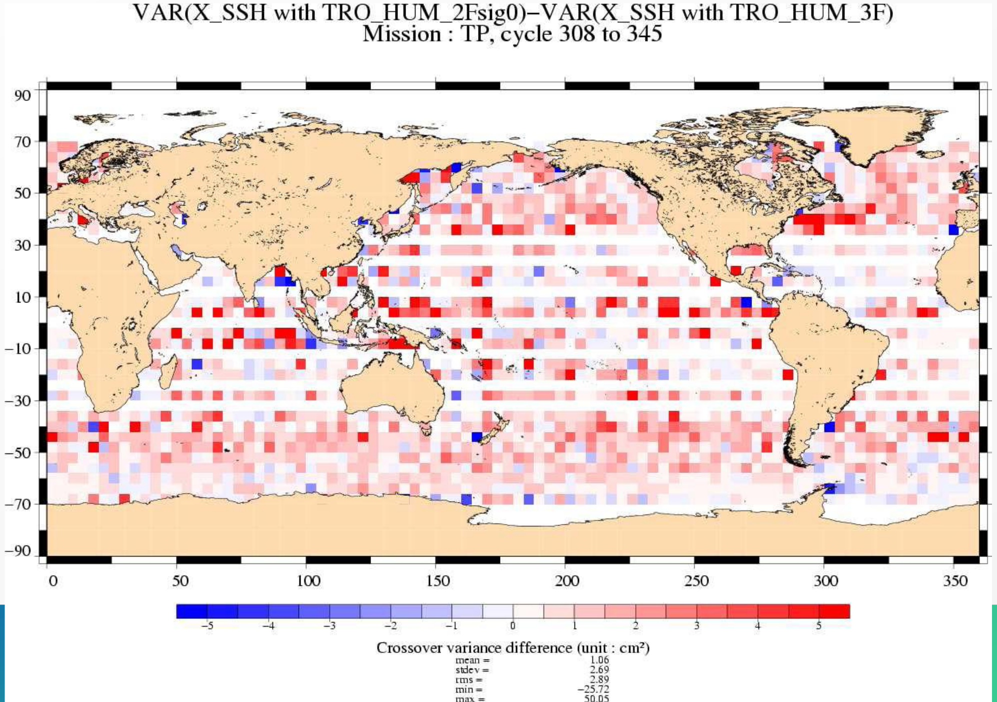
Several studies done within Sentinel-3 mission definition :

-MWR or model

-2-frequency radiometer / 3-frequency radiometer

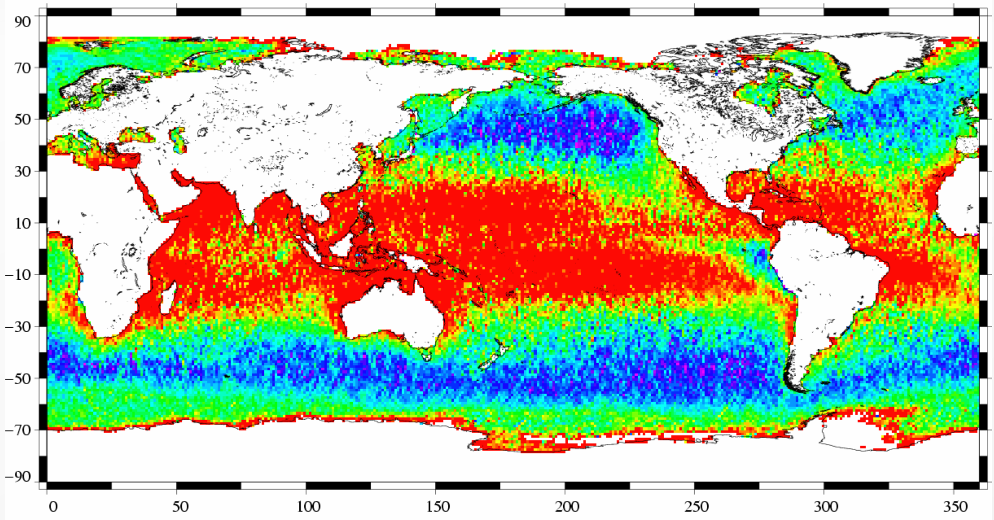
=> Accuracy of the correction depends on payload and not on orbit

Gain in crossover variance when using a 3-frequency radiometer correction instead of a 2-frequency correction

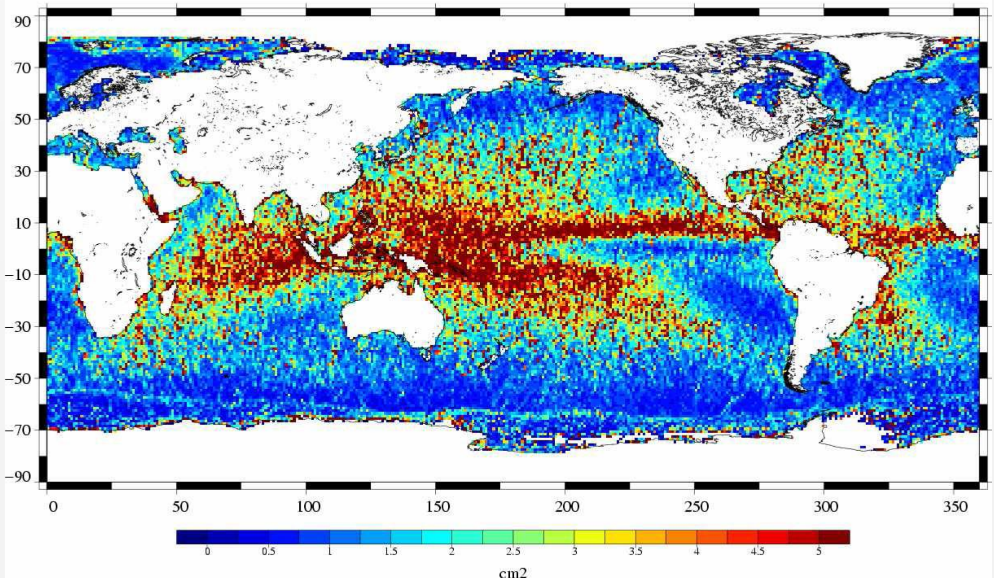


ECMWF – MWR for 2004 – ENVISAT mission

Map of the Wet Troposphere Correction difference mean



Map of the Wet Troposphere Correction difference variance



Other applications

- Sea State:
  - Decorrelation scales of 1000km & 24h are significantly different from the classical SSH user requirements
  - Traditional nadir alti and Post-EPS candidates are not optimized to monitor these signals
  - Critical needs for sea state applications are **data latency and instrument technology more than orbit**

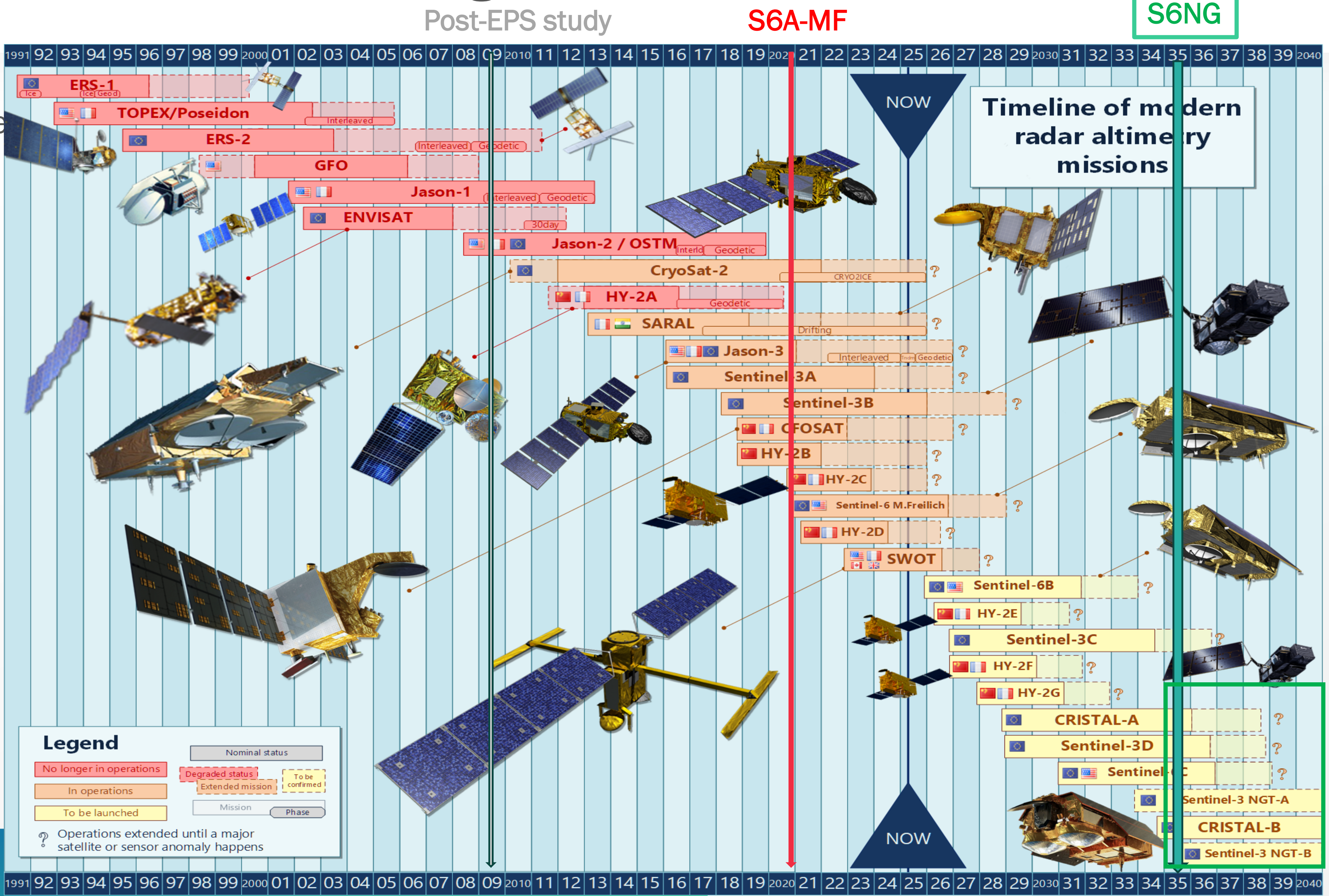
- Capability to observe the Arctic and Antarctic ice sheets:
  - The higher inclination, the better, but this in contradiction with a good observation of K1 tide (incl < 72°)
  - Experts recommend is to have the lowest orbit as possible to minimize the size of the altimeter & radiometer footprints

- Hydrology:
  - Wide-swath better suited
  - The suitability of the orbit candidates can be analyzed in terms of inland target sampling capability

Mission name	Percentage of inland water coverage (%) SWOT is taken as the reference
SWOT	100
TP-Jason	60
A878_i66_c10	59.7
A926_i67_c13	75
A801_i71_c22	125

New context and challenges for S6NG orbit definition

- Differe



New context and challenges for S6NG orbit definition

- Different satellite constellation envisionned in 2035 vs 2020
  - S3-NGtopo will have similar orbit as S3 + wide-swath
  - 2-sat & 3-sat constellations can be analyzed

- Better accuracy of models and corrections available now :
  - Even the more within 2035 thanks to SWOT …
  - But errors may remain in some regions (coastal, high-latitudes, non-stationnary internal tides …) + long-term trends…

- Main requirements for S6NG mission:
  - Reference mission
  - MSL evolution & climate signals are critical to follow in a changing climate context
  - non-sun-synchronous orbit

Tides and HF challenges

- SWOT data will help improving tide knowledge and models but with some limitations :
  - 20 y of SWOT ~10y of T/P-Jason time-series for mesoscale pollution in tidal estimations
  - SWOT orbit has a more heterogeneous sampling
  - Lack of accuracy of L3 products in coastal and polar regions + pb of the cross-calibration correction
  - => some errors may remain in theses regions
- Minor and compound tides + K1
- Non-stationary internal tides
- Solar tides still an issues: gravitational & atmospheric forcing + possible residual errors of the measurement system
  - => Changing both orbit and instruments at the same time is challenging !
  - => Need a long-enough calval phase : 1 year to sample all meteo conditions …
  - Only non-synchronous orbits are recommanded for reference
- New issues raised concerning long-term trends in tides and DAC (Ray & Schindelegger 2025) => is it observable with a continuous orbit and a changing orbit ? Can we correct that ?
- Changing orbit => residual tidal errors will pollute the MSS/MP estimation for some time (SWOT mission lifetime may be not long enough …)

Mesoscale and operational oceanography

- If the wide-swath altimetry become the norm => shall ensure a good mesoscale observation, but calibration issue may remain to solve
- Else, need to optimize the 2035 altimetry constellation for operational oceanography (mesoscale …)

- L3/L4 products :
  - A reference mission is used to calibrate all others => need to quantify the impact of a changing orbit on multi-mission calibration + all-the-more needed if changing instrument/techno also
  - Tandem phase is very important to learn about the mission error budgets : one year is ideal

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Preliminar orbit candidates for S6NG

From CLS consortium 2009 study

	Altitude (km)	Inc (deg)	Cycle (days)	Exact repeat cycle (days)	Tide Aliasing	Tide separability (years)	Optimisation for 2 satellites	Sub-cycle (days)	S1 aliasing (days)	rev/day
A878_i66_c10	878.731	66	10	9.901936	K1 included	3.5 y	no	1	100.97	13+9/10
A1150_i72_c11	1150.317	72	11	10.917843	No K1	4 y	yes	5	132.89	13+2/11
A964_i74_c19	964.879	74	19	18.860482	No K1	5 y	yes	3	135.18	13+13/19
A835_i75_c19	835.619	75	19	18.860551	No K1	5 y	yes	1	135.25	14+1/19
A1076_i68_c11	1076.855	68	11	10.904653	no K1, but alias K1>2cpy afterall	6y	yes	3	114.36	13+4/11
A801_i71_c22	801.857	71	22	21.810438	K1 inluded	6 y	no	7	115.05	14+3/22
A1361_i65_c11	1361.612	65	11	10.905338	K1 included	6 years	yes	3	115.20	12+7/11
A912_i70_c11	912.147	70	11	10.905479	K1 included	8 years	yes	5	115.37	13+9/11
A822_i68_c15	822.474	68	15	14.858551	K1 included	8 years	yes	1	105.04	14+1/15
A1104_i76_c16	1104.802	76	16	15.895629	K1<2cpy	-	no	3	152.3	13+5/16
A923_i67_c9	923.365	67	9	8.915522	K1>2cpy	-	no	4	105.53	13+7/9
A926_i67_c13	926.436	67	13	12.878103	K1>2cpy -	-	no	4	105.64	13+10/13

selected on tidal criteria (rows A878_i66_c10 to A822_i68_c15)

relaxing tidal criteria (rows A1104_i76_c16 to A926_i67_c13)

From Univ. Hambourg 2009 study

Orbit Reference	Number of orbits per cycle	Inclination [deg]	Repeat cycle [days]	Ground track separation at equator [km]	Semi-major axis [km]	Eccentricity	Altitude at equator [km]
T/P	127	66	9.91590	315.55	7727.46	0.000067	1349.3
2	296	78	20.86464	135.39	7202.94	0.001049	824.8
3	289	78	20.86890	138.67	7319.94	0.001033	941.8

climate + sampling HLat (rows 2 and 3)

Next steps

- Check complementary recommandations to take into account for the orbit selection criteria
- Select a small pool of these orbits to start analyses : 3-5
- Perform several analyses to investigate the impact of an orbit change on different parameters with a focus on MSL accuracy => ORBITAS project (cf M. Ablain presentation)

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Thanks for your attention