Geodesy & Earth Observation

F.G. Lemoine

NASA GSFC, Greenbelt, Maryland, USA

Outline

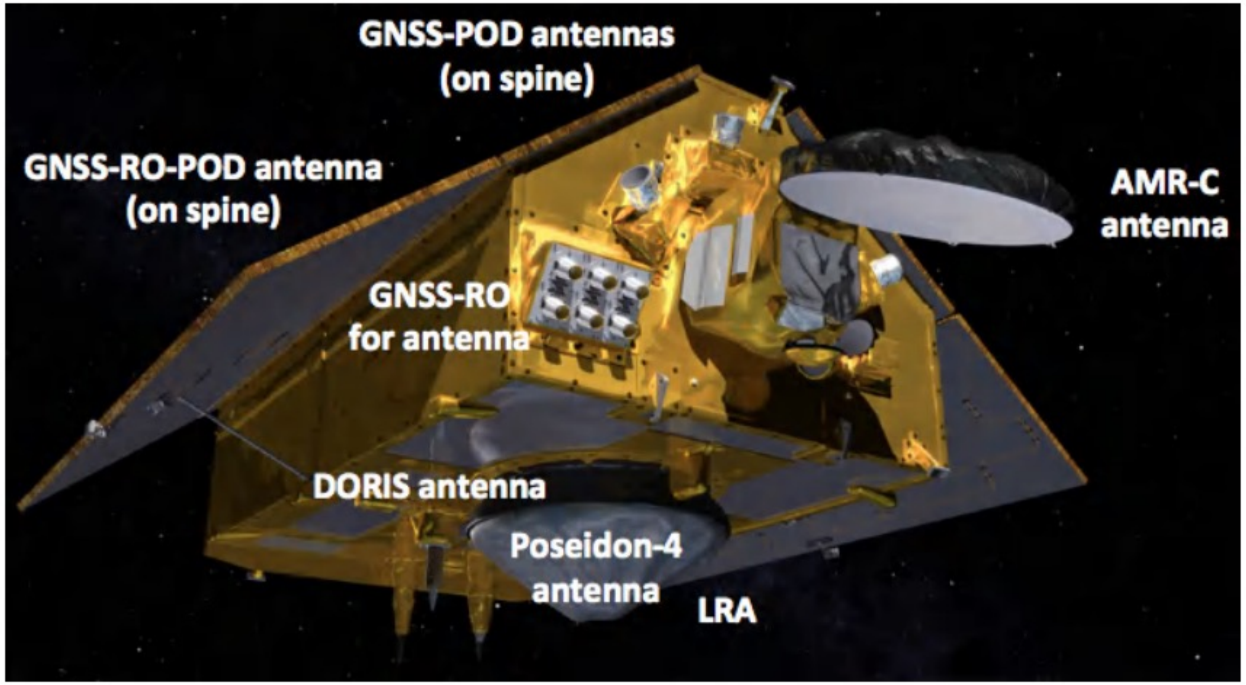
(1) Quality of Current GNSS POD.

(2) Future evolution of the Altimeter Satellite Constellation.

(3) Determination of the Earth Energy Imbalance and Implications for Geodesy

Some highlights from the 2022 OSTST meeting

Sentinel-6 MF:
A new laboratory for metrology in orbit



- The satellite co-locates 3 types of POD instruments, GNSS (GPS+Galileo), DORIS and SLR.
- It also includes two GNSS antennas and three GNSS receivers.
- The colocation of these instruments on a stable, rigorously engineered platform, allows POD with unprecedented accuracy, and precise determination of measurement and timing offsets.
- Over time we will gain a better handle on remaining systematic sources of error in altimeter measurement system.

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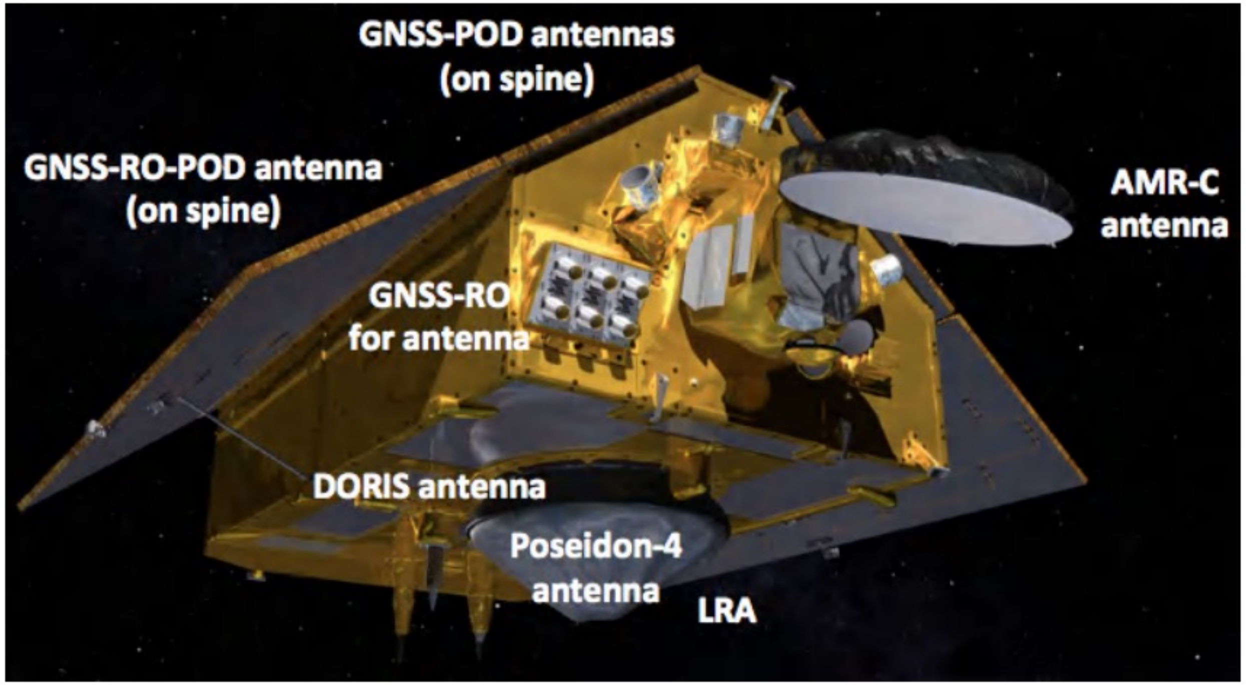
A new laboratory for metrology in orbit



S/C shape means there is significant self-shadowing, for Solar radiation pressure, earth-radiation pressure. Presently, these forces are modelled using a box-wing (macromodel), which has proven to be inadequate. Efforts to improve force modelling are underway & SLR will be important to validate these model improvements.

We will use SLR data to verify improvements to SRP modelling for Sentinel-6A.

Candidate models to be tested:

- Ray-tracing-derived accelerations (from ESA).
- Macromodel tuned with GNSS data (Univ. Colorado).
- Improved micromodel (provided by S6A project ESA POD Document)
- New tuned model (provided by CNES).

Sentinel-6 MF:
GNSS Performance (1)

Jason-3 vs. Sentinel-6 MF Radiometric Performance

- Focus on validating S6-MF Trig GNSS-POD Receiver against J3 IGOR+.
  - Both have BlackJack heritage.
- S6-MF receiver performs slightly better than J3.
  - Except: Higher pseudorange residuals.
  - S6-MF provides 1-sec tracking data vs. 10-second on J3.

2020-12-18 to 2022-02-26

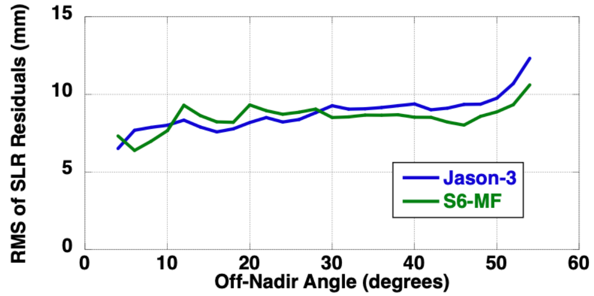
	J3	S6
Median Satellites Tracked	9.5	10.3
Median Track Length (min)	38.6	40.8
Median RMS Phase Residual (mm)	4.39	4.35
Median RMS Range Residual (mm)	375	568
Median Radial Orbit Overlap (mm)	0.96	0.89

March 8, 2022 OSTST Mini-POD SDD-1

(Desai et al., March 2022)

Independent SLR Residuals

- SLR residuals computed for same best 8 SLR stations and data period:
  - 2020-12-18 to 2022-02-26
- J3 and S6 GPS-only POD solutions have < 1 cm radial orbit accuracy.



March 8, 2022 OSTST Mini-POD SDD-2

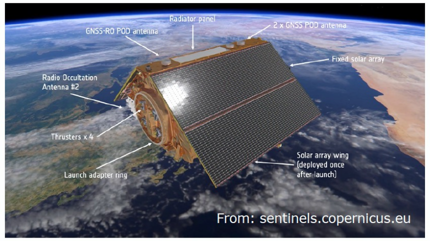
(Desai et al., March 2022)

Sentinel-6 MF permits Multi-GNSS POD

Sentinel 6 POD - Number of GNSS observations

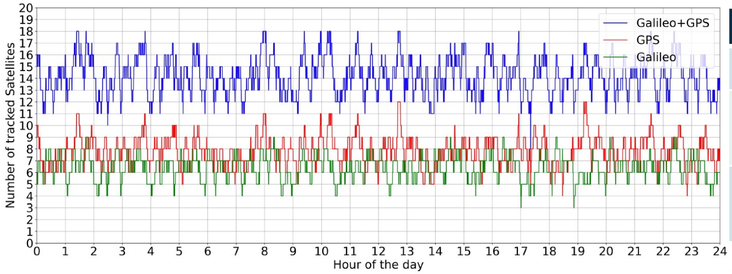
Two redundant GNSS receivers (RUAG PODRIX) on-board Sentinel-6, which provide:

- Galileo signals: E1-C, E5a-Q
- GPS signals:
  - L1 P(Y), L2 P(Y) – Block IIR
  - L1 C/A, L2C-L – Blocks IIR-M, IIF, III
  - L5 signals could be tracked



From: sentinels.copernicus.eu

RUAG PODRIX receiver, from: ruag.com



Observations	Galileo	GPS		Galileo + GPS
Frequency & Signal	E1-C E5a-Q	L1 C/A L2C-L	L1 P(Y) L2 P(Y)	all
Total 24h #obs.	55k	53k	14k	122k
		67k		
Average #obs. per epoch	6.4	6.1	1.7	14.2
		7.8		

1 obs. = dual-freq code+phase obs.

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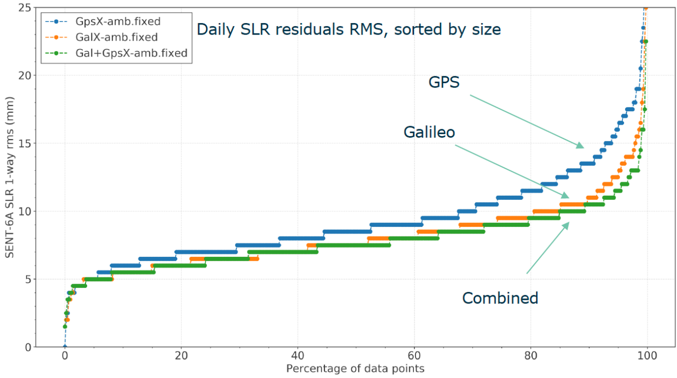
→ THE EUROPEAN SPACE AGENCY

(Gini et al., OSTST 2022)

Sentinel 6 POD - External validation – Laser Ranging residuals

- High performance of all 3 solutions with the SLR independent validation
- In terms of residuals mean all solutions show a bias of ~1.4mm
- In terms of residuals RMS, the combined solution performes the best, followed by Galileo (within a sub-millimeter difference)
- The combined solution shows ~99% of the data points with RMS < 1.5cm
- The GPS-only solution shows again higher residuals than the other two solutions

	Galileo	GPS	Galileo + GPS
SLR res. Mean (mm)	1.4	1.4	1.5
SLR res. RMS (mm)	8.1	9.3	7.8



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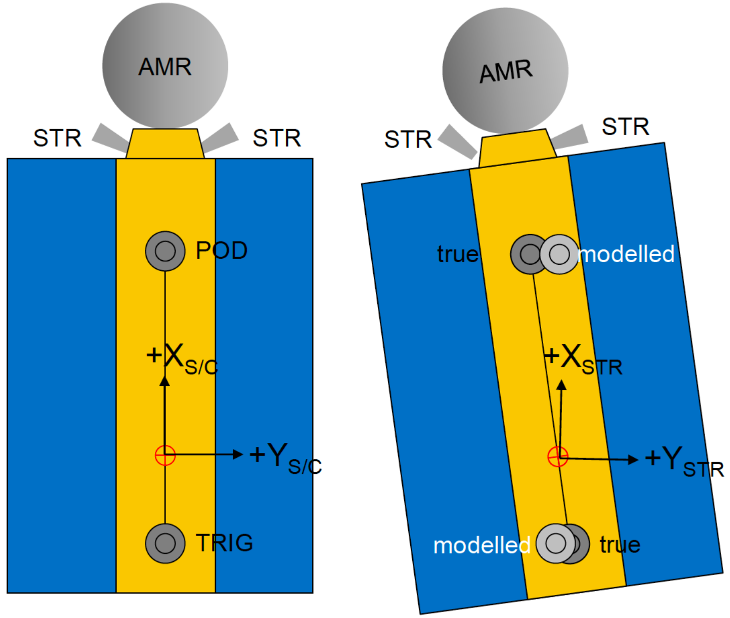
→ THE EUROPEAN SPACE AGENCY

(Gini et al., OSTST 2022)

Sentinel-6 MF allows s/c baseline measurements

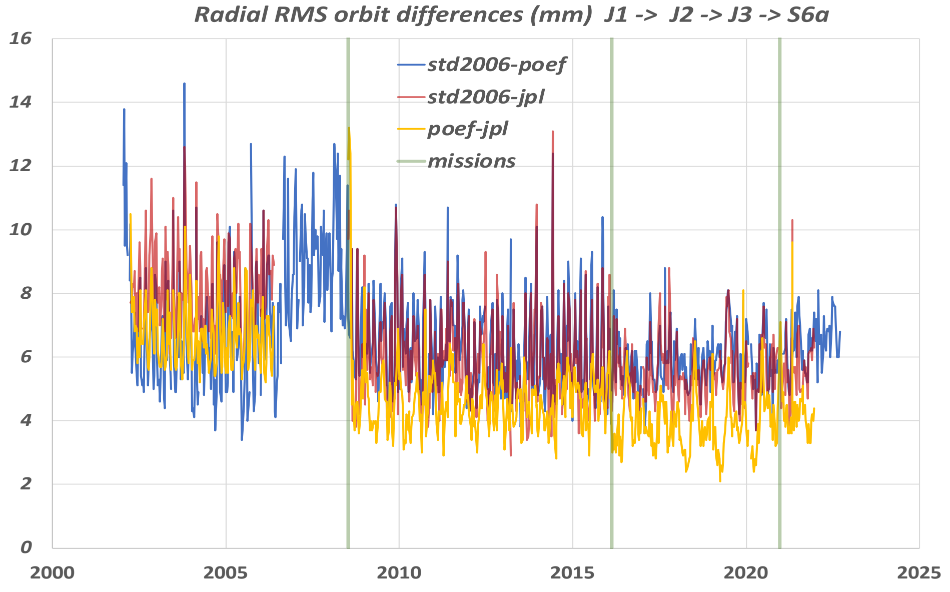
Impact of Attitude Bias (Star Camera Misalignment?)

- 14 mm offset @ 1875 mm distance (and 3 mm offset @ 400 mm distance) correspond to 0.43° yaw angle offset
- Could be caused by STR misalignment or erroneous STR-to-S/C alignment matrix in ADCS
- ADCS assumes and reports nominal attitude, but true s/c body axis shows 0.43° yaw bias w.r.t. ground track and orbit
- GNSS antennas show non-nominal CoM offset that needs to be compensated by empirical forces
  - ~ –9 mm for POD(nom)
  - ~ +5 mm for TRIG
- Consistent with observed accelerations
  - ~+ 8 nm/s^2 for POD(nom)
  - ~ –4 nm/s^2 for TRIG



(Montenbruck et al., OSTST, 2022). & (Desai et al., OSTST, 2022)

Jason & S6A altimeter missions have < 10 mm radial orbit accuracy



(Lemoine et al., OSTST 2022)

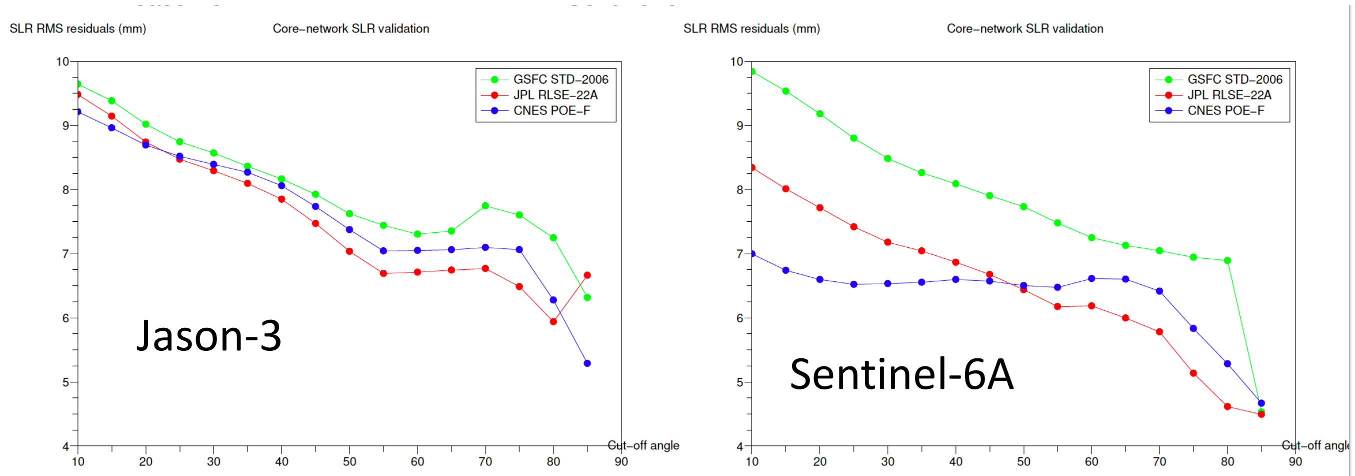


FIGURE : RMS of SLR CN residuals (mm) for Jason-3 (left) and Sentinel-6 MF (right) vs. elevation angle for the GSFC STD-2006, JPL RLSE-22A, and CNES POE-F orbit solutions.

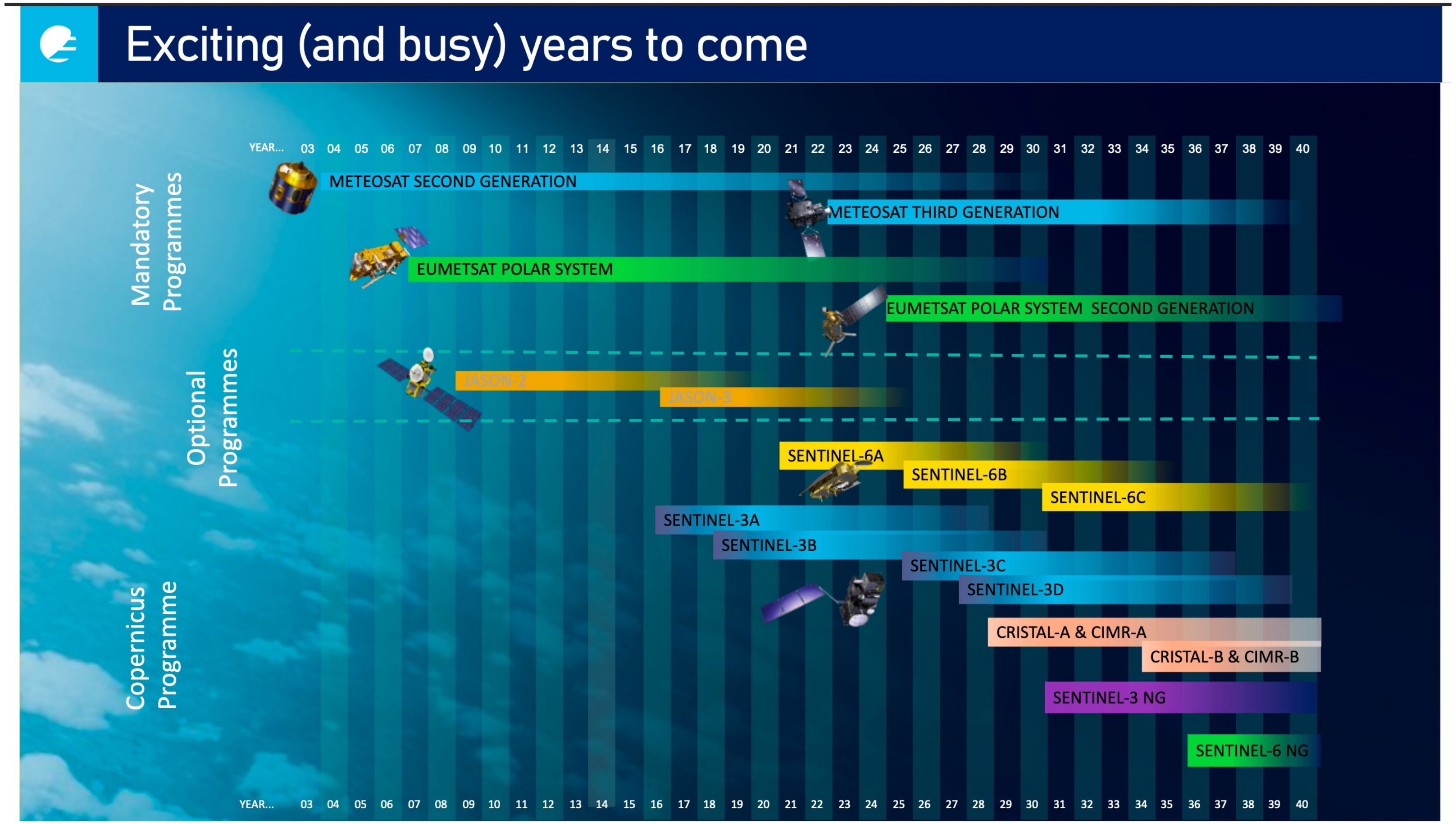
(Couhert et al., OSTST 2022)

Differences between CNES (GPS+DORIS), JPL (GPS-only) & GSFC (SLR+DORIS-dynamic) orbits provide information on relative radial orbit quality: Jason-1: 8-10 mm RMS; Jason-2, 6-8 mm; Jason-3 & S6A: 5-7 mm.

With this test, GNSS-orbits agree at 4-5 mm but we need external information to provide a relative assessment.

Future evolution of the Altimeter Satellite Constellation.

Future evolution of the operational ocean radar altimeter satellite constellation (1)



(Eumetsat Program Overview, 2022 OSTST Meeting)

Polar orbit ocean radar altimeters:

Sentinel-3A/3B: Currently on-orbit.

Sentinel-3C/3D: Successor missions, 2025 & 2027.

Reference Mission (Mean Sea Level) Inclination=66 degrees.

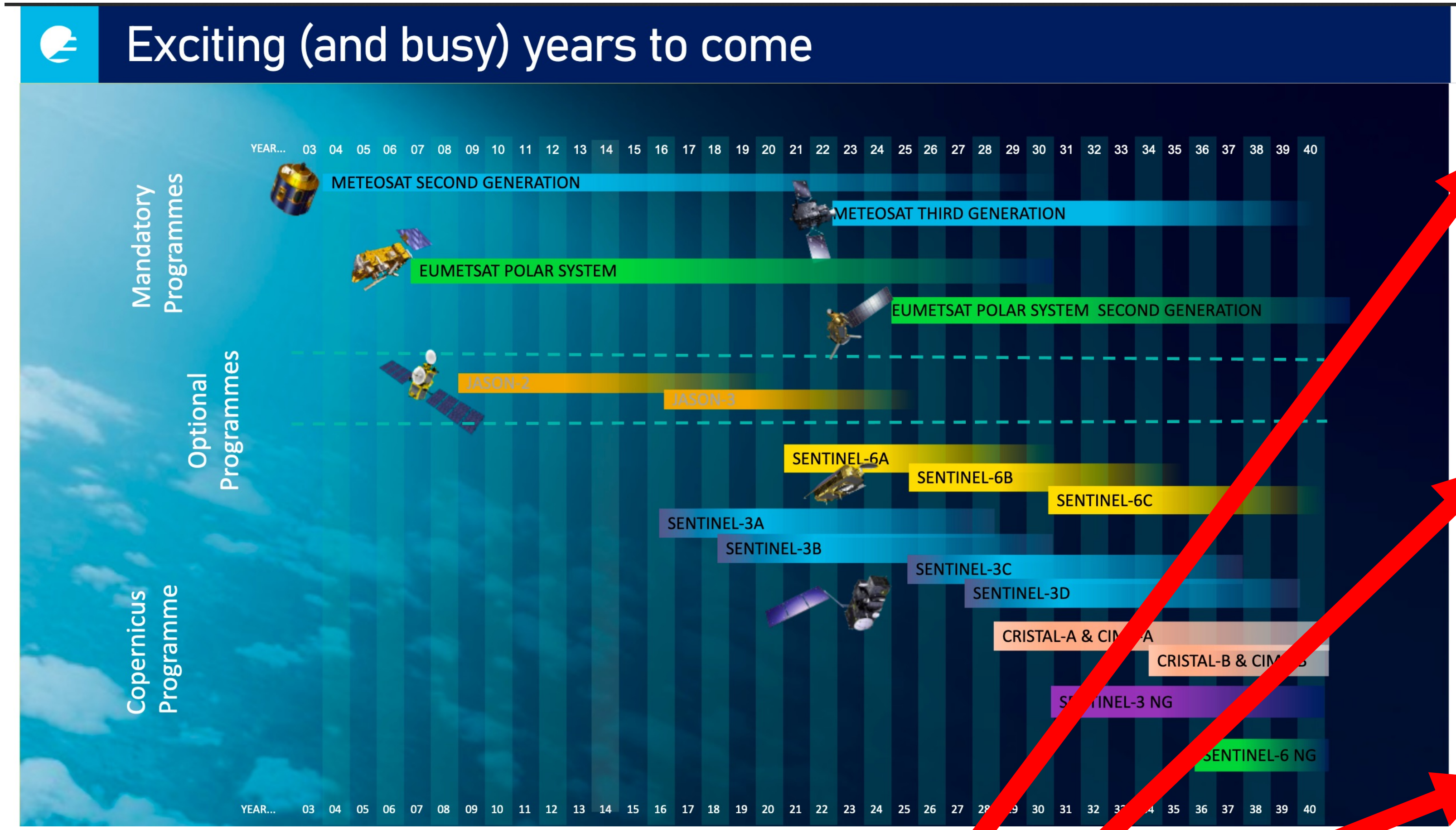
Sentinel-6A: on-orbit.

Sentinel-6B & 6C. Successor missions, 2025 & ~2030.

Polar orbit cryosphere mission (CryoSat-2 successor mission)

CRISTAL-A, CRISTAL-B: TBC.
2028 & 2034.

Future evolution of the operational ocean radar altimeter satellite constellation (2)



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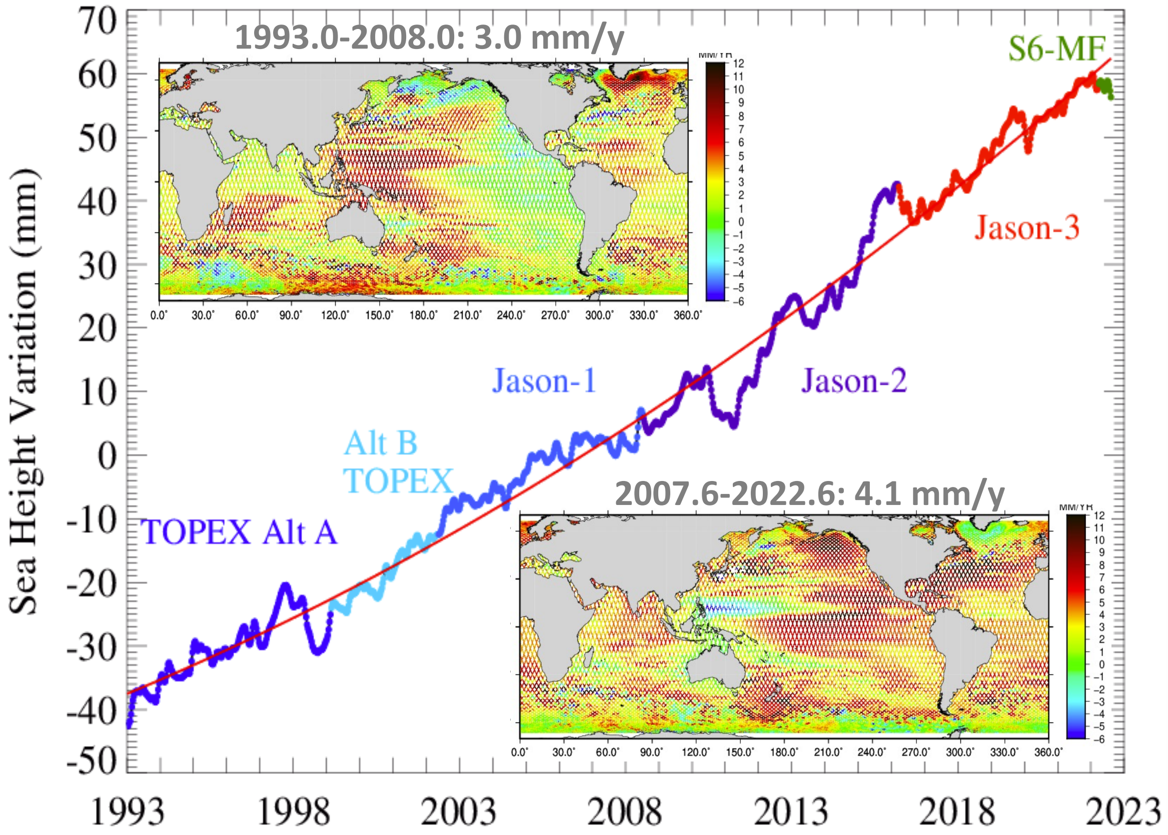
Polar orbit cryosphere mission (CryoSat-2 successor mission)

CRISTAL-A, CRISTAL-B: TBC. 2028 & 2034.

All future missions will include tandem flight modes for intermission instrument calibration.

GMSL Determination



The measurement of Global Mean Sea Level (GMSL) is a key indicator of climate change. With the determination of an acceleration, we can make a data-driven estimate of the near-term impact on coastal communities, as well as assess what climate trajectory we are actually following.

SLR is a key component of this sea level observing system, through POD, and verification of orbit stability and accuracy, and its ability to help discriminate and validate improvements to satellite or geophysical models.

The linear sea level rate is estimated at 3.4 mm/y ± 0.4 mm/y with an acceleration of 0.080 mm/y^2 ± 0.025 mm/y^2 . (Beckley et al., OSTST2022).

Improvements in the Scientific Requirements for Altimeter Measurements

New stability requirements for altimetry (1)

- New **stability uncertainty requirements** have been established for **altimetry** to address scientific questions (Meyssignac et al., OSTST 2019, in prep.) such as:
  - closing the sea level budget and identifying the missing contributions;
  - constraining projections of future sea level rise and its contributions;
  - estimating the Earth's energy imbalance and constraining the Earth energy budget.

	Current uncertainty over 20 years (Ablain et al., 2019; Guérou et al., submitted)	**Requirements at decadal time scales (endorsed by C3S)**
GMSL trend	0.3-0.5 mm/yr	< 0.1 mm/yr
GMSL acceleration	0.07-0.12 mm/yr²	< 0.05 mm/yr²

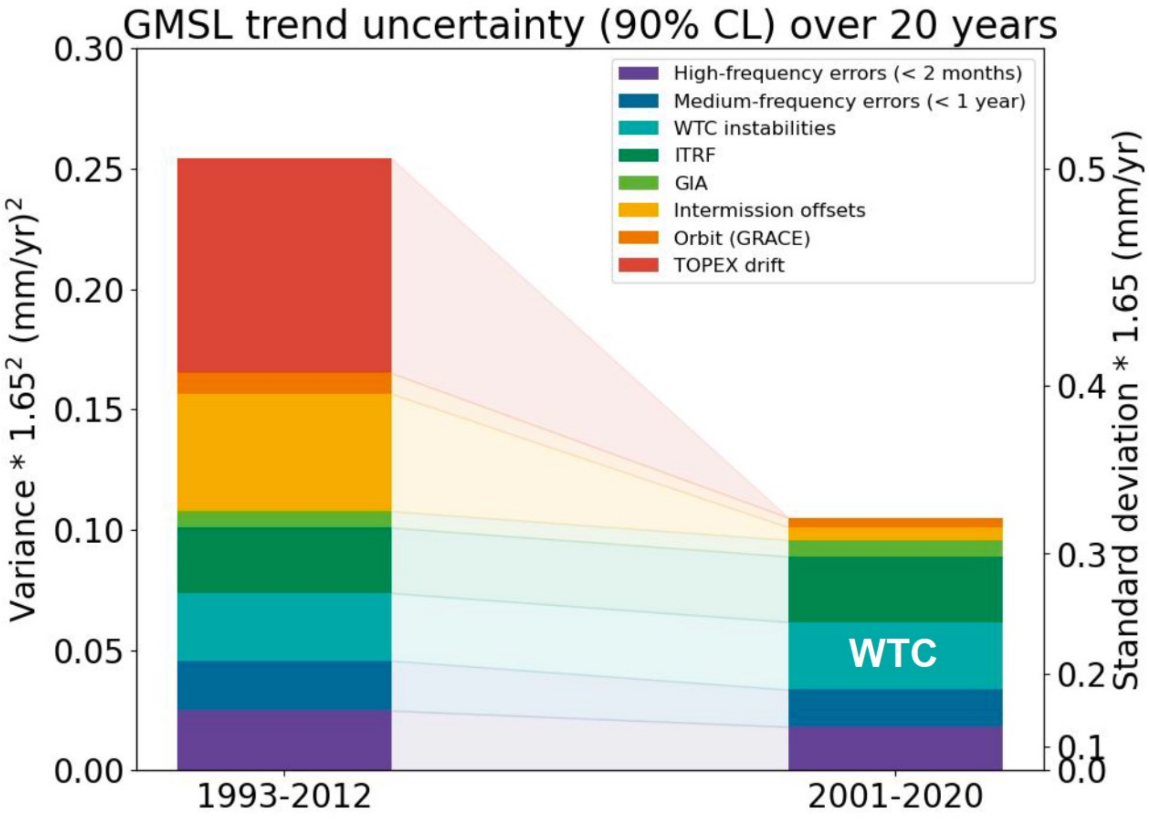
} 5-95 % confidence level

(Barnoud et al., OSTST 2022)

The new requirements have been accepted by the Copernicus Climate Change Service, but the impact on future missions (beyond Sentinel-6B) or on other systems (like POD requirements or the ITRF) have not been worked out.

New stability requirements for altimetry (2)

(Barnoud et al., OSTST



The challenge will be to reduce the different sources of error in the altimeter system to meet the new requirement. In the current estimates, the ITRF error is is of the same order as the Wet troposphere correction error. Whether the future error budget is compatible with GGOS requirements of the IAG remains to be determined.

- Don't expect any relaxation in the GGOS requirements for the reference frame (0.1 mm/yr over 10 yrs), or 1 mm in position for the ITRF.

Caveats

This presentation has not discussed:

- **Contribution of SLR to mass change estimation from GRACE FO**:

  → through determination of C_{20} & C_{30} & tracking of geodetic SLR satellite constellation.

- **Determination of geocenter and relationship to mass change**:

  → The degree one component of mass change is not observable from GRACE & GRACE FO, and so must be provided by a model or through an external geophysical solution.

- **Improved determination of the GM of the Earth**. Error in GM (scale of the reference frame) is of order 1 ppb (larger than the GGOS requirements).

Summary

• GNSS POD continues to improve. We need the ability to properly evaluate and verify the performance of GNSS-determined orbits, and isolate measurement-model and geophysical-model-related errors.

• SLR is a key component of an altimeter satellite observing system for direct POD (in component with DORIS) and POD verification (with GNSS).

• We need SLR systems that are stable in the long-term, have highly accurate (mm-level) normal points, with minimal (mm-level) long-term biases.

Unmodelled biases are deleterious to providing an absolute error calibration of orbit accuracy for altimeters that measure GMSL.