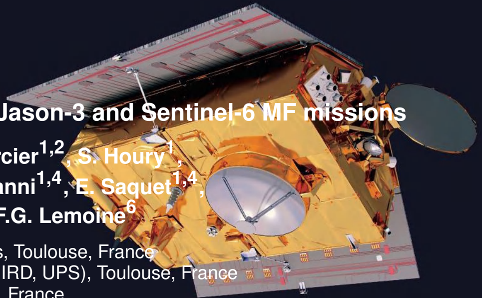
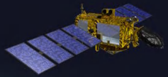
CNES POE-F precise orbit performances for the Jason-3 and Sentinel-6 MF missions



A. Couhert[1,2,*] J. Moyard[1], F. Mercier[1,2], S. Houry[1],
T. Braz[1,3], V. Debout[1,3], G. Katsigianni[1,4], E. Saquet[1,4],
with inputs from S. Desai[5], F.G. Lemoine[6]

[1] Centre National d'Etudes Spatiales, Toulouse, France
[2] GET–Université de Toulouse (CNES, CNRS, IRD, UPS), Toulouse, France
[3] Space CS-SI, Toulouse, France
[4] Collecte Localisation Satellites, Toulouse, France
[5] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[6] NASA Goddard Space Flight Center, Greenbelt, MD, USA

[*] Mail : alexandre.couhert@cnes.fr



Source : Adapted from EUMETSAT & NASA/JPL

2022 OSTST Meeting
Venice, Italy
November 1, 2022

INTRODUCTION

1. THE COPERNICUS SENTINEL-6 MF MISSION

❖ A successful cooperation between NASA, ESA, EUMETSAT, NOAA, CNES, and the European Commission

- The new reference mission :
  - Designed to ensure the long-term continuation from the Jason satellite series of decades-long climate records as the most accurate source of observations of mean sea-level rise at global, regional, and coastal scales.
  - For more than 15 months (December 18, 2020 – April 7, 2022) Sentinel-6 MF flew 30 seconds behind Jason-3 on the same ground track.
- Time periods for POD validations :
  - Limited to the *tandem mission formation* : Jason-3 (cycles 180–226) & Sentinel-6 MF (cycles 5–51).

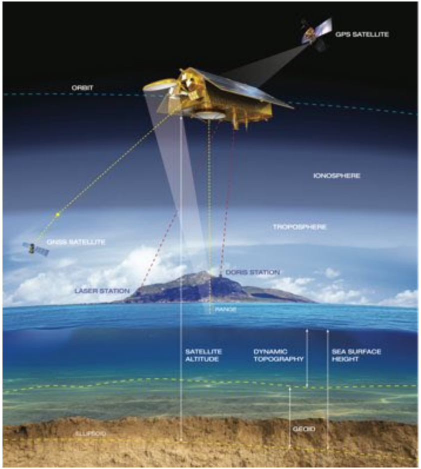


FIGURE : Tracking sea level [EUMETSAT].

Satellite main features

- Sentinel-6 MF is equipped with the following scientific instruments :
  - Poseidon-4 dual frequency (C-band and Ku-band) radar altimeter,
  - Advanced Microwave Radiometer - Climate (AMR-C),
  - GNSS-POD (Precise Orbit Determination) based on a PODRIX *GPS+Galileo receiver*,
  - DORIS receiver (DGXX-SEV) & Ultra Stable Oscillator (USO) linked with GNSS-POD clock,
  - Laser Retroreflector Array (LRA),
  - GNSS-RO (Radio Occultation) based on a TriG GPS receiver (forward, backward, upward antennas).

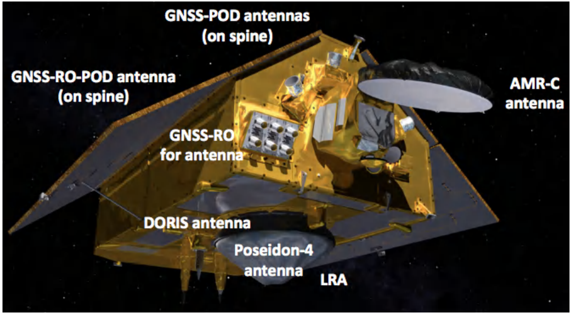


FIGURE : Spacecraft & instruments [adapted from NASA].

- **Evolutions of Sentinel-6 CNES POE-F orbits with respect to the associated reference solutions of Jason-3**
  - Making use of both GPS and Galileo constellations :
    - DORIS+GPS+Galileo orbit solutions,
    - Introduction of two independent Phase Center Variation (PCV) maps for GPS and Galileo,
    - Estimation of two independent clocks for GPS and Galileo per epoch.
  - Parameterization to better account for residual measurement/dynamic modeling errors :
    - Estimation of two daily independent Z Phase Center Offsets (PCO) for GPS and Galileo,
    - Solve for daily cross-track accelerations to mitigate mismodeled Solar Radiation Pressure (SRP).
- **Comparisons with the latest GSFC & JPL POD standards for orbit modeling**
  - NASA/GSFC STD-2006 :
    - SLR+DORIS solution over Jason-3 and Sentinel-6 MF.
  - JPL RLSE-22A :
    - GPS-based (*TriG POD*) solution over Jason-3 and Sentinel-6 MF.

2.1 Performance of the Tracking Instruments

- **DORIS receivers behave similarly for Jason-3 and Sentinel-6 MF**

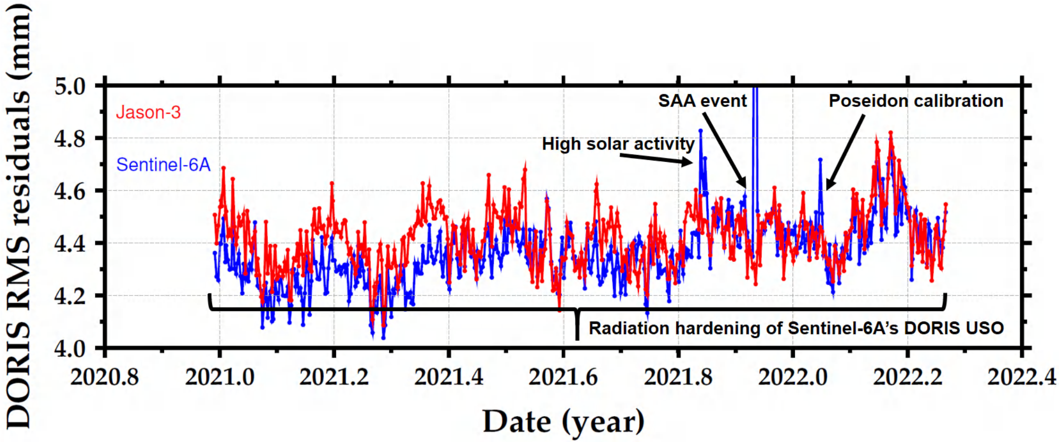


FIGURE : RMS of DORIS post-fit residuals for Sentinel-6A and Jason-3.

❖ Sentinel-6 MF USO shared by the DORIS and PODRIX GNSS receivers

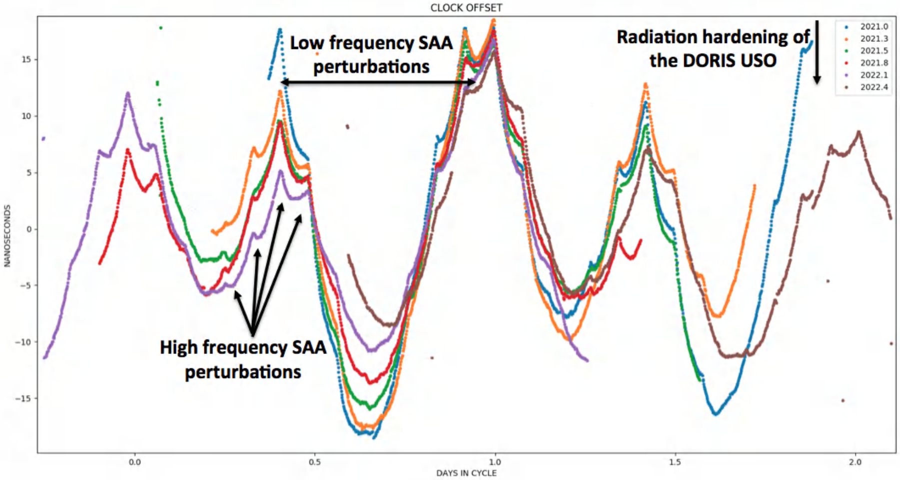


FIGURE : GPS clock estimates (s), w/o 2^{nd} order polynomial, with relativistic correction.

GPS and Galileo phase center signatures in the radial direction

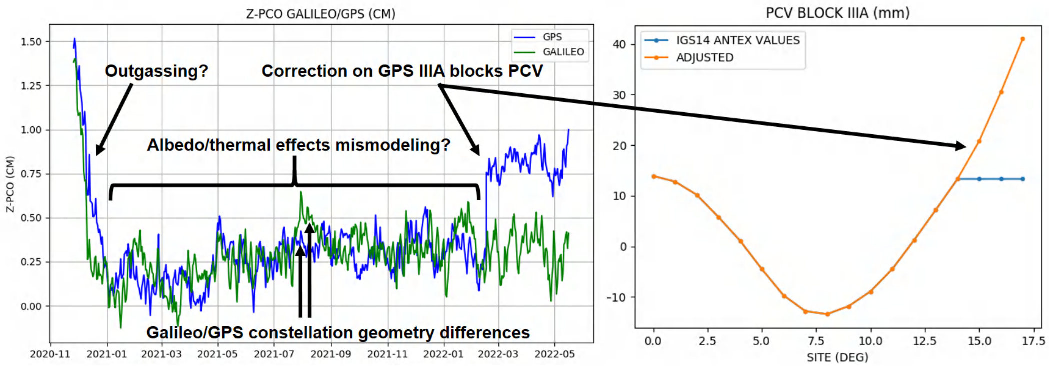


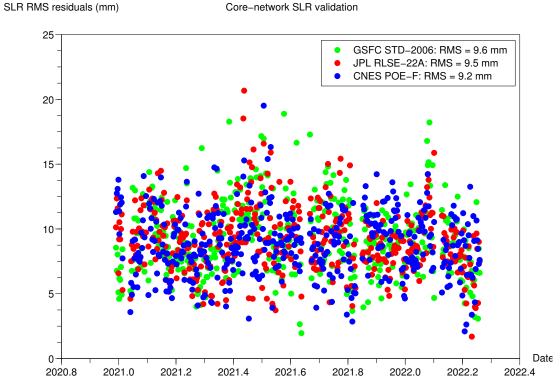
FIGURE : Daily Z-PCO adjusted for GPS & Galileo (left) and GPS Block IIIA PCV extension (right).

2.2 Precision Orbit Ephemeris (POE) metrics

❖ **External orbit comparisons : *3-D* orbit accuracy validation with SLR**

➢ $9.2 - 9.6$ mm for Jason-3 and $7.0 - 9.8$ mm for Sentinel-6 MF at all elevations.

- Jason-3 :
- Sentinel-6 MF :



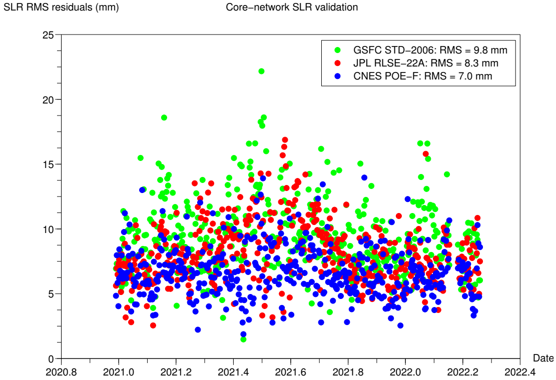


Figure : RMS of SLR CN residuals (mm) for Jason-3 (left) and Sentinel-6 MF (right) vs. time for the GSFC STD-2006, JPL RLSE-22A, and CNES POE-F orbit solutions.

External orbit comparisons : *Radial* orbit accuracy validation with SLR

- $5.3 - 6.7$ mm for Jason-3 and $4.5 - 4.7$ mm for Sentinel-6 MF at high elevations.
  - Jason-3 :   Sentinel-6 MF :

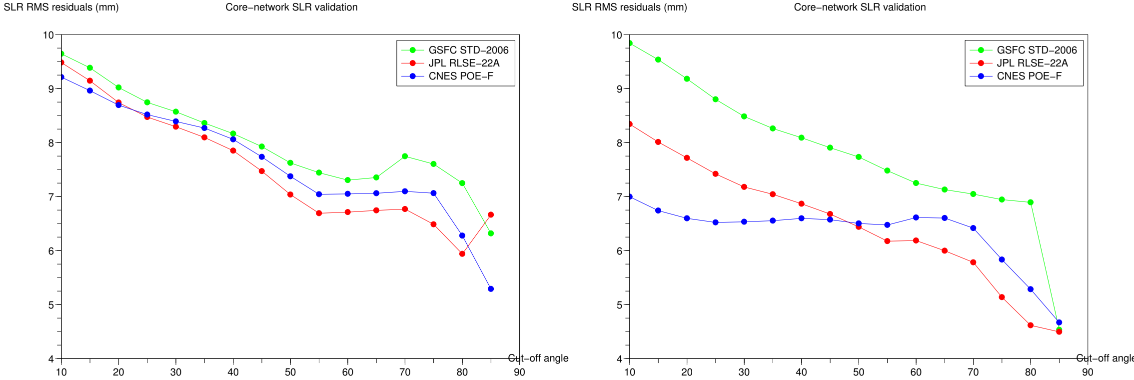


FIGURE : RMS of SLR CN residuals (mm) for Jason-3 (left) and Sentinel-6 MF (right) vs. elevation angle for the GSFC STD-2006, JPL RLSE-22A, and CNES POE-F orbit solutions.

2.2 Precision Orbit Ephemeris (POE) Metrics

- **External orbit comparisons : *Annual* radial orbit errors at regional scales**
  - Geographically correlated radial difference (mm) 365-day signals with CNES POE-F orbits :
    - Jason-3 : Sentinel-6 MF :

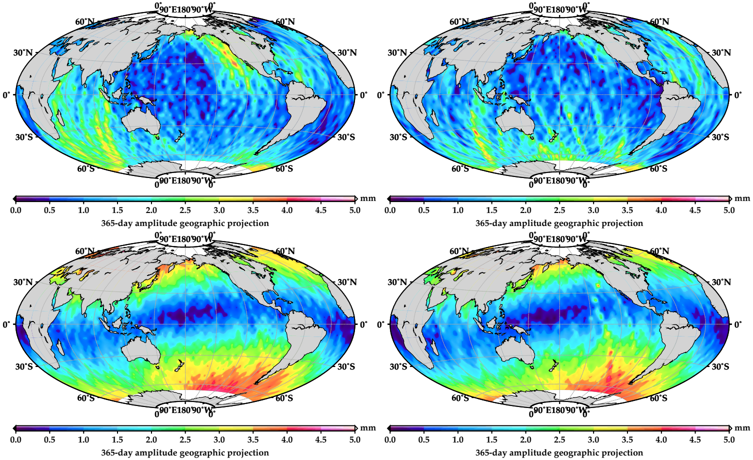


Figure : GSFC STD-2006 (top) & JPL RLSE-22A (bottom) for Jason-3 (left) & Sentinel-6 MF (right).

2.2 PRECISION ORBIT EPHEMERIS (POE) METRICS

- **External orbit comparisons : *Secular* radial orbit errors at regional scales**
  - Geographically correlated radial difference (mm/y) drifts with CNES POE-F orbits :
    - Jason-3 : Sentinel-6 MF :

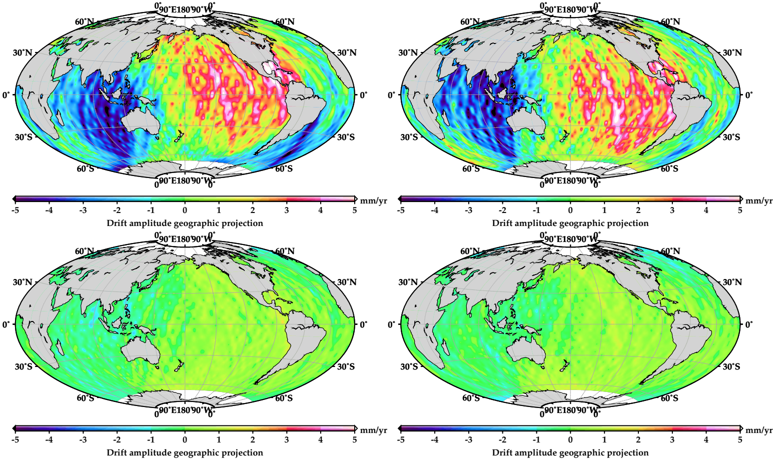


FIGURE : GSFC STD-2006 (top) & JPL RLSE-22A (bottom) for Jason-3 (left) & Sentinel-6 MF (right).

❖ Recommendation for the attitude regime of S6 MF from the OSTST POD group

➢ *Apply yaw flip to fly backward for a duration of 4 days, at each occurrence of near-zero values of solar beta angle (i.e., every 60 days), to calibrate in-flight the POD instruments :*

- First identification of a $-7\ \mathrm{mm}$ Y (cross-track) error in the GPS/Galileo phase center location, owing to the decoupling from miscentering of the orbit around the Earth's CM and miscalibrated SRP model.

Date		01/07/21	→	05/07/21	
S6 attitude:		flip	backward	flip	
Beta angle:	-10°	-5°	0°	5°	10°

- Additional yaw flipping and SLR measurements were required in the along-track direction to decouple time-tagging errors from errors in the center of phase offset of the POD instruments.

Date			05/09/21	←	01/09/21
S6 attitude:			flip	backward	flip
Beta angle:	-10°	-5°	0°	5°	10°
Date			05/11/21	→	09/11/21
S6 attitude:			flip	backward	flip
Beta angle:	-10°	-5°	0°	5°	10°
Date			27/02/22	→	03/03/22
S6 attitude:			flip	backward	flip
Beta angle:	-10°	-5°	0°	5°	10°
Date			29/04/22	←	25/04/22
S6 attitude:			flip	backward	flip
Beta angle:	-10°	-5°	0°	5°	10°

Nominal attitude: AMR in front following the velocity vector

Along-track inconsistencies as seen by SLR

- SLR identification of a $5\ \mathrm{mm}$ X (along-track) error in Sentinel-6A LRA optical center location (*offset on each side of the flip* where the beta angle is close to zero) & a $4\ \mathrm{mm}$ DORIS time-tagging offset (*common bias* before and after the flips) :

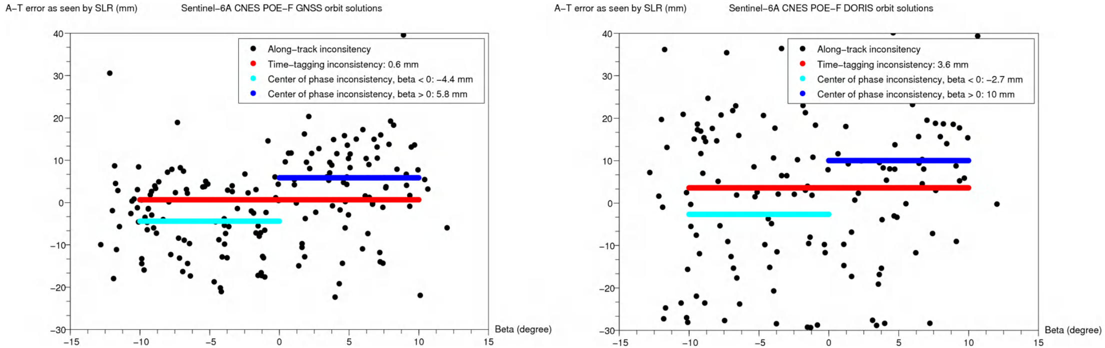


FIGURE : SLR-derived along-track Sentinel-6A CNES POE-F GNSS (left : $5\ \mathrm{mm}$ X-PCO & $1\ \mathrm{mm}$ time-tagging) and DORIS (right : $6\ \mathrm{mm}$ X-PCO & $4\ \mathrm{mm}$ time-tagging) obit error v.s. beta angles.

2.3 LESSONS LEARNED FROM THE YAW FLIP EXPERIMENT

❖ Along-track inconsistencies as seen by SLR

➢ $5\ \mathrm{mm}$ X (along-track) error in Sentinel-6A LRA optical center location confirmed with independent JPL GPS-based (*TriG POD*) solution & a $7\ \mathrm{mm}$ GPS TriG time-tagging offset :

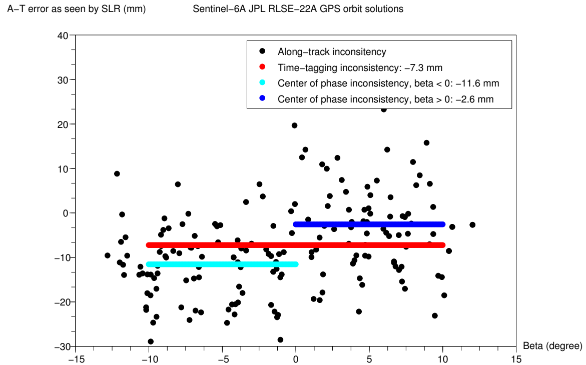


FIGURE : SLR-derived along-track Sentinel-6A JPL RLSE-22A GPS ($5\ \mathrm{mm}$ X-PCO & $7\ \mathrm{mm}$ time-tagging) obit error v.s. beta angles.

BACKUP TRANSITION TO THE NEW POE-G STANDARDS

Measurement models

- Earth Orientation Parameters :
  - Diurnal and semidiurnal tidal variations in polar motion from Desai and Sibois (2018).
- Displacement of reference points :
  - ITRF/DPOD/SLRF2020,
  - FES2022 ocean tide loading,
  - Non-tidal annual and semi-annual loading deformations from ITRF2020.
- Geocenter variations :
  - Non-tidal *annual and semi-annual* geocenter motion model from ITRF2020.
- Propagation delays :
  - POD instrument phase center location improvements.
- DORIS :
  - Relativistic corrections for the on-board frequency,
  - Improved phase data-screening.
- GNSS :
  - Improved ambiguity-fixing strategy,
  - Use of IGS satellite attitude quaternions in the ORBEX (ORBit EXchange) format.
- Improved empirical accelerations definition.

Dynamic models

- Geopotential :
  - Updated time-variable gravity field model,
  - FES2022 ocean tides.
- Surface force :
  - *Earth radiation pressure* model based on CERES data (Clouds and Earth's Radiant Energy, NASA),
  - New DTM-2020/NRLMSIS 2.0 thermosphere models,
  - SRP model tuning.

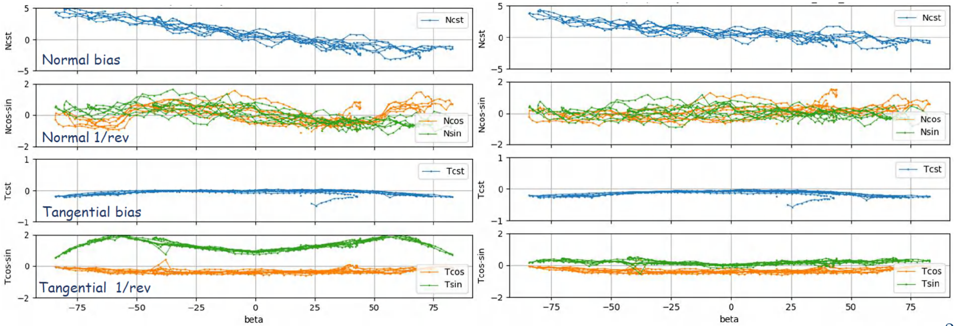


FIGURE : Sentinel-6 MF pre-launch (left) & final (right) SRP model empirical corrections (m^2).

SLR availability

- Tracking network :
  - 16 stations routinely track Sentinel-6A (22 for Jason-3).
  - The top three stations with most tracking of Sentinel-6A are Yarragadee (Australia), Herstmonceux (England), Mt. Stromlo (Australia).
- Normal points :
  - 230 daily SLR *normal points* for Sentinel-6A (280 for Jason-3).

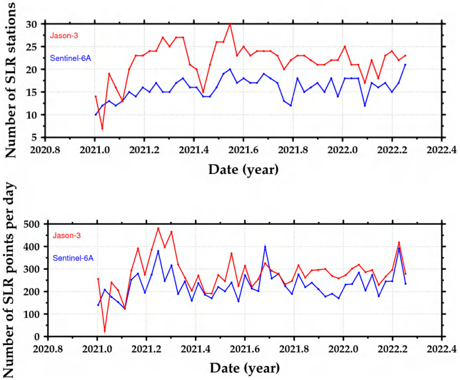
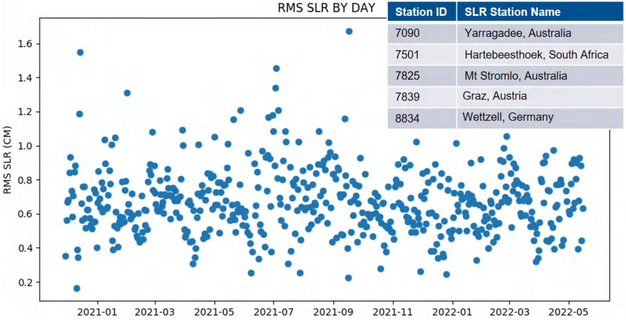


FIGURE : Number of SLR stations (top) / points (bottom) for Sentinel-6A & Jason-3.

BACKUP PRECISION ORBIT EPHEMERIS (POE) METRICS

Independent orbit validation with SLR Core Network (CN) stations

- RMS of SLR residuals from current 5 *best performing SLR stations* $\sim 7\ \mathrm{mm}$ at all elevations (3-D) and $\sim 5\ \mathrm{mm}$ at high elevations (radial).



Station ID	SLR Station Name
7090	Yarragadee, Australia
7501	Hartebeesthoek, South Africa
7825	Mt Stromlo, Australia
7839	Graz, Austria
8834	Wettzell, Germany

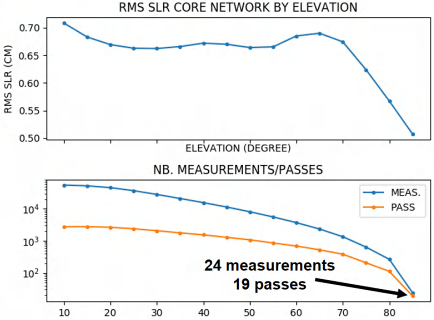


FIGURE : RMS of SLR CN residuals (mm) for the Sentinel-6 MF CNES POE-F orbit solution vs. time (left) & elevation angle (right).

External orbit comparisons : Radial orbit errors at global scales

- The nadir surface of Sentinel-6 MF (up to 5 times bigger than Jason-3) exposes the orbit to solar/Earth/thermal radiation pressure perturbations exhibiting in the radial direction.
  - Jason-3 : Sentinel-6 MF :

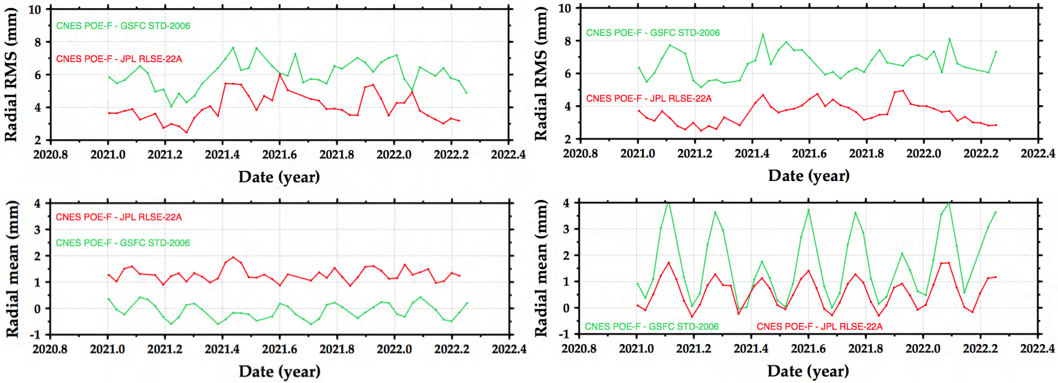


FIGURE : Radial RMS (top) and mean (bottom) orbit differences (mm) between CNES POE-F – GSFC STD-2006 and CNES POE-F – JPL RLSE-22A for Jason-3 (left) and Sentinel-6 MF (right).

- **External orbit comparisons : Static radial orbit errors at regional scales**
  - Geographically correlated radial difference (mm) bias signals with CNES POE-F orbits :
    - Jason-3 : Sentinel-6 MF :

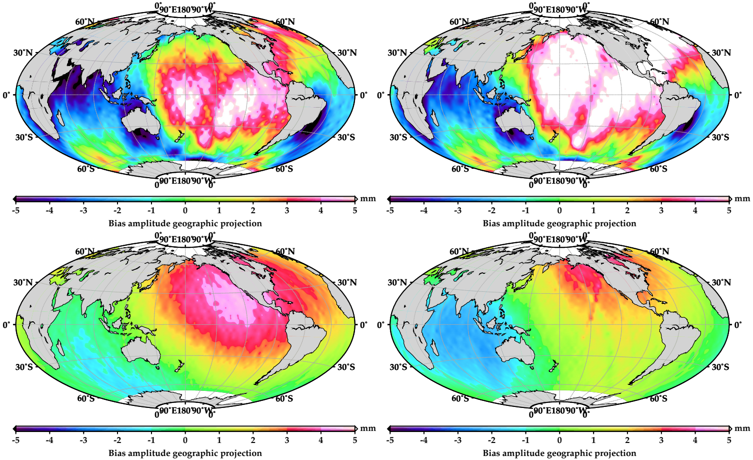


FIGURE : GSFC STD-2006 (top) & JPL RLSE-22A (bottom) for Jason-3 (left) & Sentinel-6 MF (right).

Backup Precision Orbit Ephemeris (POE) metrics

- **External orbit comparisons : Draconitic radial orbit errors at regional scales**
  - Geographically correlated radial difference (mm) 59-day signals with CNES POE-F orbits :
    - Jason-3 : Sentinel-6 MF :

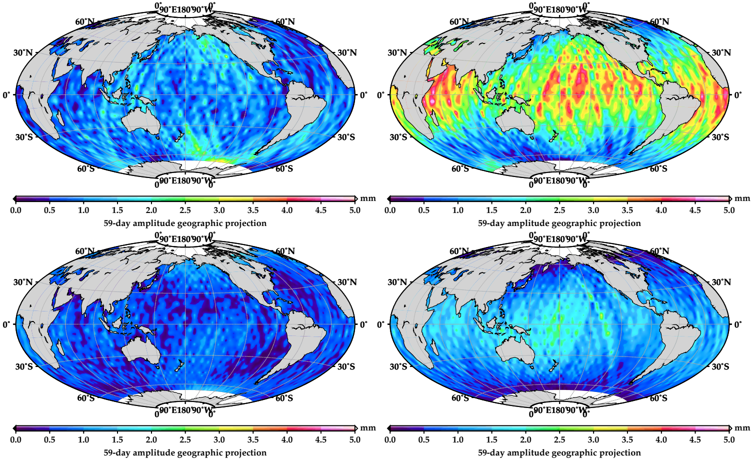
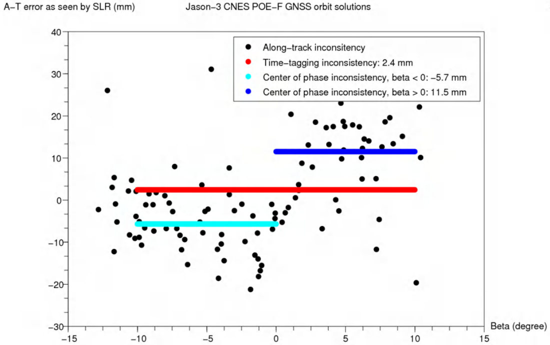


Figure : GSFC STD-2006 (top) & JPL RLSE-22A (bottom) for Jason-3 (left) & Sentinel-6 MF (right).

BACKUP LESSONS LEARNED FROM THE YAW FLIP EXPERIMENT

- **Along-track inconsistencies as seen by SLR**
  - SLR identification of a $8\ \mathrm{mm}$ X (along-track) error in Jason-3 GPS phase center location (*offset on each side of the flip* where the beta angle is close to zero) :



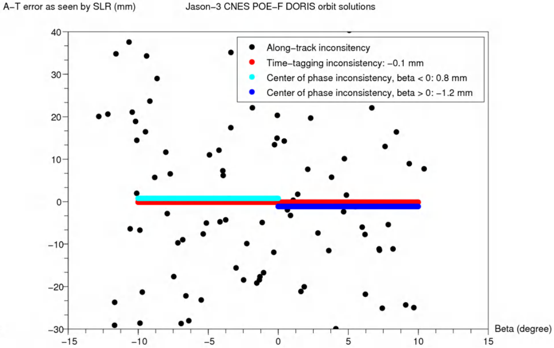


FIGURE : SLR-derived along-track Jason-3 CNES POE-F GPS (left : $8\ \mathrm{mm}$ X-PCO & $2\ \mathrm{mm}$ time-tagging) and DORIS (right : $1\ \mathrm{mm}$ X-PCO & no time-tagging) obit error vs. beta angles.

Along-track inconsistencies as seen by SLR

- SLR identification of a $4\ \mathrm{mm}$ X (along-track) error in Jason-3 GPS phase center location & $9\ \mathrm{mm}$ GPS time-tagging offset (*common bias* before and after the flips) with JPL orbits :

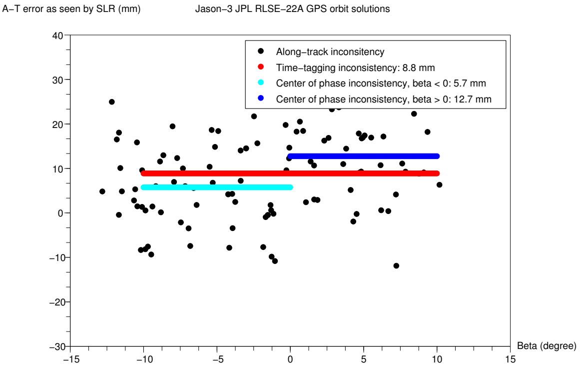


FIGURE : SLR-derived along-track Jason-3 JPL RLSE-22A GPS ($4\ \mathrm{mm}$ X-PCO & $9\ \mathrm{mm}$ time-tagging) obit error v.s. beta angles.