La précision d'orbite pour le suivi de l'élévation des océans : une mesure absolue, indépendante des mouvements de la croûte terrestre ?

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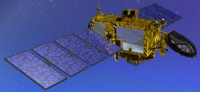


Réunion de la commission "Géopositionnement"
IGN, Paris
23 mars 2023

Source : adaptée à partir d'illustrations EUMETSAT & NASA/JPL

QU'EN PENSE CHATGPT ?

- **Pas grand chose**

  ... La mesure de l'élévation du niveau de la mer à l'aide de satellites en orbite est une mesure absolue qui n'est pas affectée par les mouvements de la croûte terrestre. Cela est dû au fait que les satellites en orbite mesurent directement l'élévation du niveau de la mer par rapport à un repère de référence défini à l'avance. Ce repère est généralement basé sur la moyenne du niveau de la mer au cours des dernières décennies...

INTRODUCTION

1.1 FLIGHT SYSTEM OVERVIEW

❖ 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 t*andem mission formation* : Jason-3 (cycles 180–226) & Sentinel-6 MF (cycles 5–51).

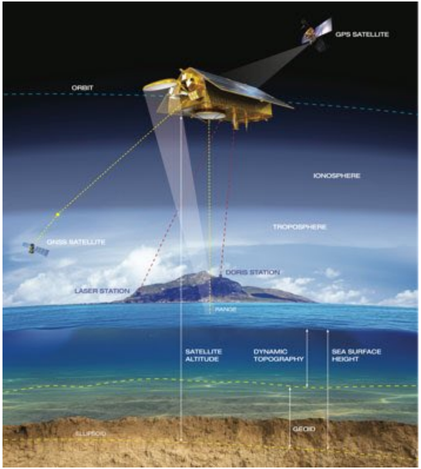


FIGURE : Tracking sea level [EUMETSAT].

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).

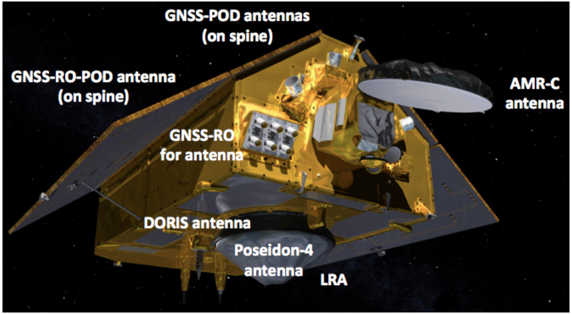


FIGURE : Spacecraft & instruments [adapted from NASA].

1.1 FLIGHT SYSTEM OVERVIEW

- **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 (SLR is saved for independent validations),
    - 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.

❖ A planet-wide mass transport within the Earth system

➢ Definitions :

- CM : Whole *Earth's center of mass* about which satellites naturally orbit.
- CE : Center of mass of the solid Earth.
- CF : Geometrical center of the Earth's surface, called *center of figure*.
- CN : *Center of network* accessible from the limited coverage of crust-fixed stations.
- Geocenter motion : temporal variations of CM (observed by satellites dynamical motion) with respect to CF (measurable from motions of stations tied to the crust).

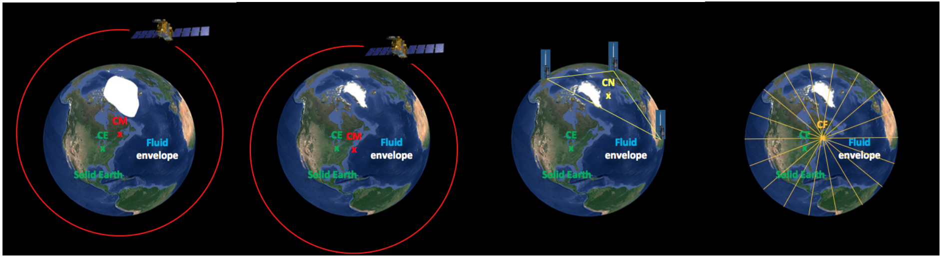


FIGURE : Differences between CM, CE, CF, and CN.

1.2 ORBIT CENTERING/STABILITY FOR SEA-LEVEL MONITORING

- **Satellite orbits connect sea level to the Earth's center of mass**
  - Orbit accuracy depends on the tracking system and Terrestrial Reference Frame (TRF) :
    - Errors in the defined **linear** origin of the TRF (Earth's CF and long-term CM) map into the orbit, and through the orbit directly to the altimeter-based sea-level measurement.
    - This will become challenging as the *Earth's shape* & *gravity field* change due to climate change.

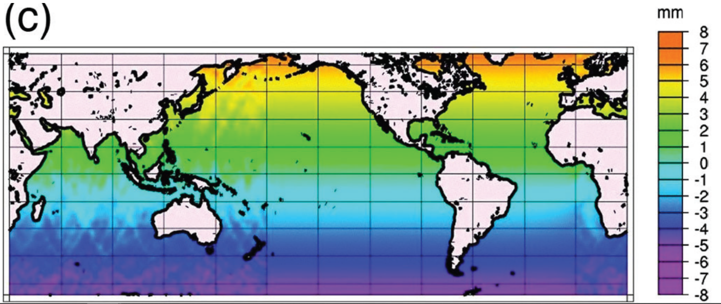
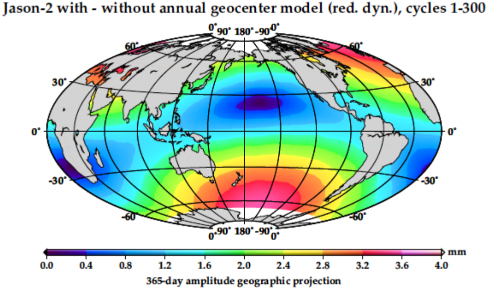


FIGURE : Global change in Sea-Surface Height (SSH) caused by a $10\ \mathrm{mm}$ poleward shift in the origin of the TRF [Morel and Willis, 2005].

1.2 ORBIT CENTERING/STABILITY FOR SEA-LEVEL MONITORING

- **New climate-driven precise monitoring of geocenter motion needs**
  - How much will sea-level rise at regional scales over the next decade and beyond ?
    - Regional sea-level patterns driven by *anthropogenic forcing* are within 0.5 mm/y (Fasullo and Nerem, 2018) ⇒ Highly stable orbits of better than 0.1 mm/y decade at regional scales are required.
    - The geocenter motion is expected to vary by as much as 50 mm over the course of the century (Adhikari et al., 2015) ⇒ Reconciling the conflict between the linear model of the ITRF origin and the non-linear nature of the geocenter motion is critical for improving the accuracy/stability of the TRF.



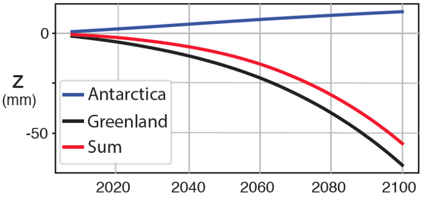


FIGURE : Annual geocenter motion effect on SSH (left) and melting of the ice sheets on century time scales causing non-linear motions in the center of mass [The US National Academies Press] (right).

ASeLSU (Assessment Sea Level rise Stability Uncertainty)

- Project team :
  - ESA : C. Donlon, R. Cullen,
  - NPL : E. Woolliams, S. Behnia, H. Cheales,
  - University of Reading : J. Mittaz,
  - CLS : S. Labroue, N. Tran, P. Thibaut, P. Prandi, S. Dinardo, A. Guérou, S. Figerou,
  - CNES/LEGOS : B. Meyssignac,
  - Magellium : A. Barnoud, M. Ablain, J. Dorandeu.
- Main question :
  - Are instrument improvements for *Sentinel-6 Next Generation* altimetry missions necessary to meet the new scientific sea level rise stability uncertainty requirements ?

		Current Sea Level uncertainty [2001-2020]	Sea Level Stability requirements over 20 years
Global scale Ablain et al., 2019	**GMSL trend**	**0.3 mm/yr**	**0.1 mm/yr**
	GMSL acceleration	**0.08 mm/yr²**	**0.05 mm/yr²**
Regional scale 1993-2019 Prandi et al., 2021	**MSL trend**	**0.8 -1.2 mm/yr**	**0.5 mm/yr**
	MSL acceleration	**0.06 - 0.12 mm/yr²**	Not defined

FIGURE : State of the art VS requirements [Meyssignac et al., 2023].

GPS and Galileo phase center signatures in the radial direction

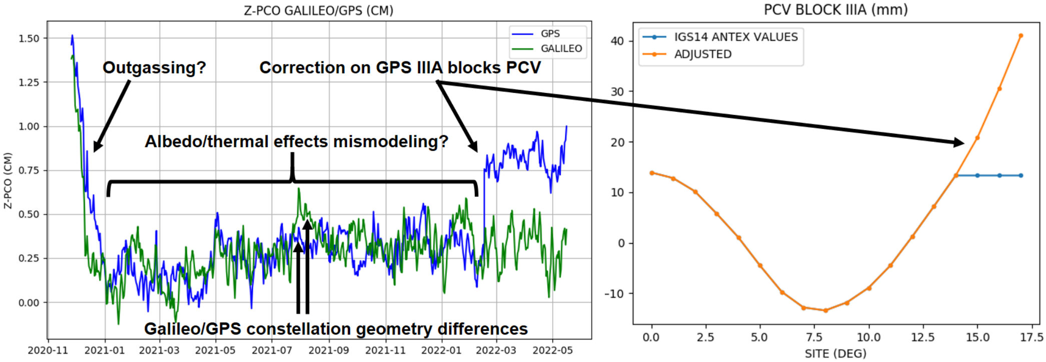


FIGURE : Daily Z-PCO adjusted for GPS & Galileo (left) and GPS Block IIIA PCV extension (right).

2.1 PERFORMANCE OF THE TRACKING INSTRUMENTS

❖ Consistent monitoring of the miscentering of the orbit around the Earth'CM

➢ Towards an indirect but finally *unambiguous* observation of the geocenter motion ?

- The equatorial (daily oscillations) and axial (bias variations) components of the CM motion exhibit independently in the satellite cross-track perturbations with an impressive temporal resolution.

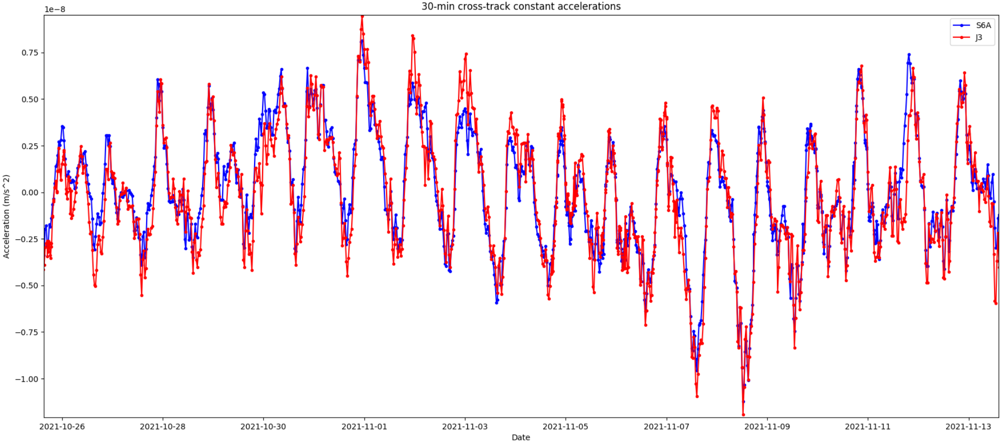
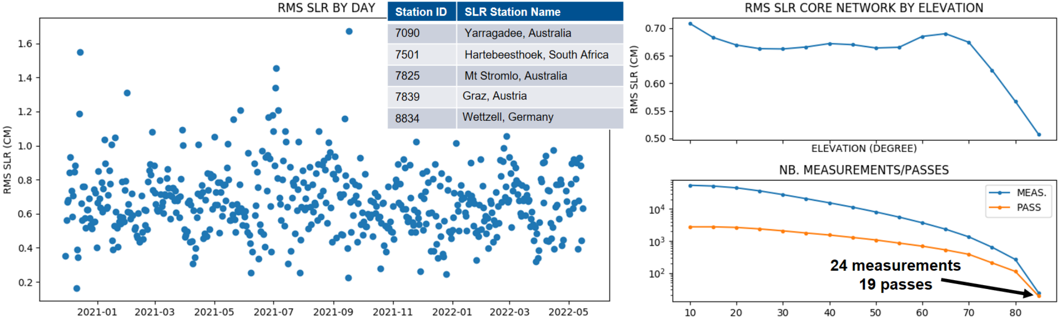


FIGURE : GNSS-based 30-min constant cross-track perturbations on Sentinel-6A & Jason-3.

Independent orbit validation with SLR Core Network (CN) stations

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

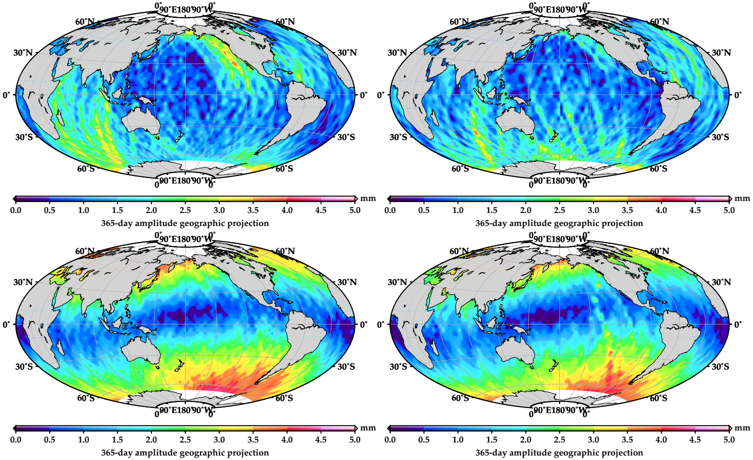


FIGURE : GSFC STD-2006 (top) & JPL RLSE-22A (bottom) for Jason-3 (left) & Sentinel-6 MF (right).

2.2 PRECISION ORBIT EPHEMERIS (POE) METRICS

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What about at higher latitudes ?

- The high-inclination polar orbits of the Sentinel-3 satellites equipped with on-board DORIS and GPS receivers enable to assess the amplitude of any miscentering effect.
  - Differences in *realization of the Earth's CM* between DORIS-only and GPS-based orbits especially reflect at high latitudes (e.g., over the Arctic ocean).
  - Preliminary analyses suggest a dominating contribution of GPS errors.

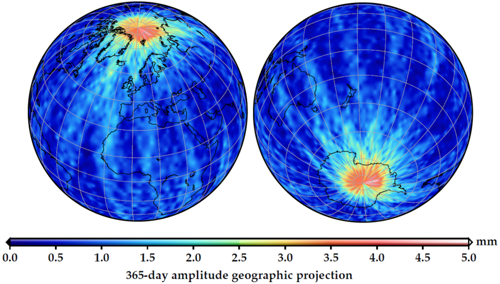

FIGURE : Sentinel-3B geographically correlated radial orbit differences at the annual period between DORIS-only and GPS-based CNES POE-F reduced-dynamic orbits.

2.2 PRECISION ORBIT EPHEMERIS (POE) METRICS

- **Impact of relying or not on DORIS ITRF2014 station heights**
  - North-South drifting effect of anchoring DORIS station heights in the *aging* ITRF2014 for Sentinel-3B (June 6, 2018 – January 28, 2023).

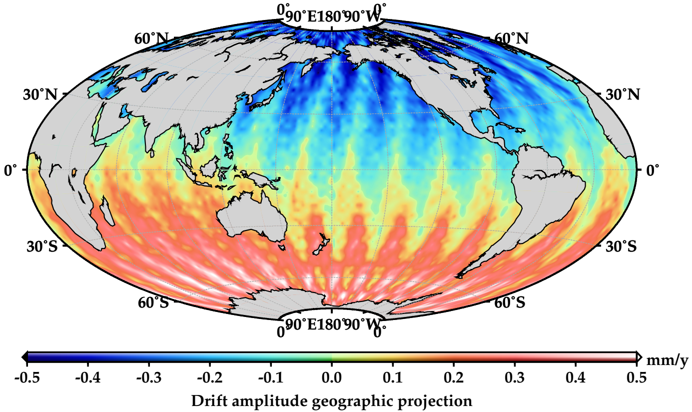

FIGURE : Sentinel-3B geographically correlated radial orbit trend differences between DORIS-only CNES POE-F reduced-dynamic orbits w/wo solving for daily station heights.

3. Focus on Satellite Laser Ranging (SLR)

- **Systematic errors/biases are a major obstacle towards fully exploiting SLR measurement accuracies for geodetic applications**
  - Biases will affect SLR validation results ⇒ reliability (e.g., for altimetry missions) ?
    - Restriction to subset of stations (8) with small biases.
    - Limited geographic distribution of SLR stations.

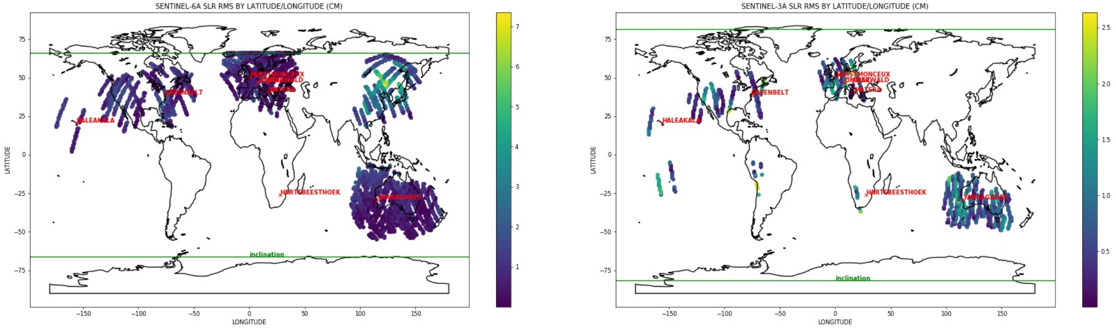

Figure : Sentinel-6 MF (left) and Sentinel-3A (right) SLR RMS (cm) residuals by latitude/longitude.

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What about in the radial direction ?

- The high-inclination polar orbits of the Sentinel-3 satellites equipped with on-board DORIS and GPS receivers enable to assess the amplitude of regional radial orbit errors :
  - SLR stations in higher latitudes are missing to have an independent evaluation over polar regions.

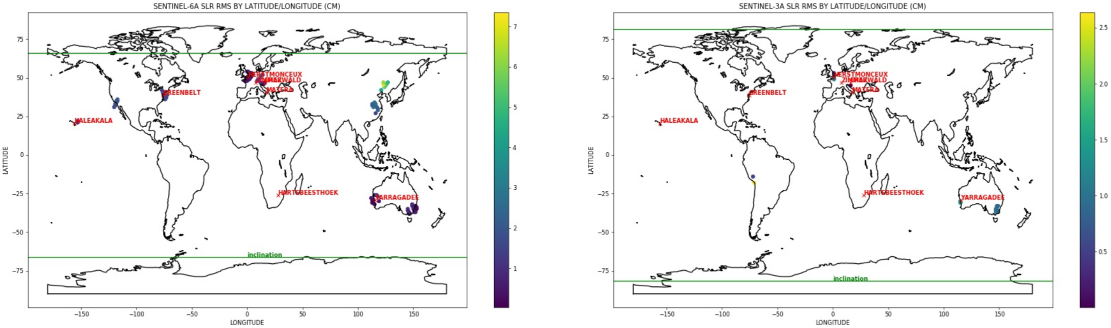

FIGURE : Sentinel-6 MF (left) and Sentinel-3A (right) high-elevation SLR RMS (cm) residuals by latitude/longitude.

3. FOCUS ON SATELLITE LASER RANGING (SLR)

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Copernicus POD Quality Working Group SLR Bias Study

- Use SLR observations to *multiple active LEOs* to address SLR station biases :
  - Article submitted to Advances in Space Research with AIUB, CLS, CNES, PosiTim.

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Millimeter accuracy SLR bias determination using independent multi-LEO DORIS and GPS-based precise orbits

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Abstract

Satellite Laser Ranging (SLR) has become an invaluable core technique in numerous geodetic applications. SLR measurements to passive spherical satellites essentially contribute to the determination of geocenter coordinates and global scale in the International Terrestrial Reference Frame (ITRF) realizations. In addition, SLR measurements to active satellites in Low Earth Orbit (LEO) are up to now mostly used for an independent validation of orbit solutions, usually derived by microwave tracking techniques based on Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) or Global Navigation Satellite Systems (GNSS). This allows for the analysis of systematic orbit errors (e.g., originating from poorly known non-gravitational perturbations or sensor offsets) not only in the radial direction (key to satellite altimetry missions), but in three dimensions.

Major obstacles to reach the millimeter accuracy and stability goals of 0.1 mm/y (at decadal time scales) of the Global Geodetic Observing System (GGOS) are unavoidable station-satellite measurement biases and on-ground/board coordinate offsets. Among the observatories of the International Laser Ranging Service (ILRS) a large diversity of measurement qualities exists, and the calibration of station-dependent errors is now necessary to further exploit SLR data for present and future climate-driven needs.

We demonstrate that the analysis of SLR data to active LEO satellites equipped with DORIS or GNSS receivers is a promising means to characterize SLR biases and their stability. Using two independent selections of Earth observation missions in LEOs (consisting of six altimetry, three magnetic field and two gravity field satellites) with three different analysis software packages (Bernese, ZOOM, Napeos), we estimate SLR range biases for all involved tracking stations on a yearly basis. We find that for many of the stations independently estimated sets of biases agree on a few-mm level and that the inclusion of satellites from multiple missions allows rendering the bias estimation more robust and in particular less prone to geographically correlated orbit errors. This shows that microwave-derived orbits of active LEO satellites, nowadays of very high quality due to numerous advances in modeling and analysis techniques, can serve as interesting sources for SLR station calibration in demanding climate applications.

FIGURE : Header of the article of Saquet et al. (2023).

3. Focus on Satellite Laser Ranging (SLR)

- **Can we use these local SLR observations to assess the stability of the orbits ?**
  - A seminar (*ITRF & POD to sea level uncertainties*) addressed this topic last week :
    - Unequal distributions of the passes, range biases and vertical ground motions mismodeling are seen.

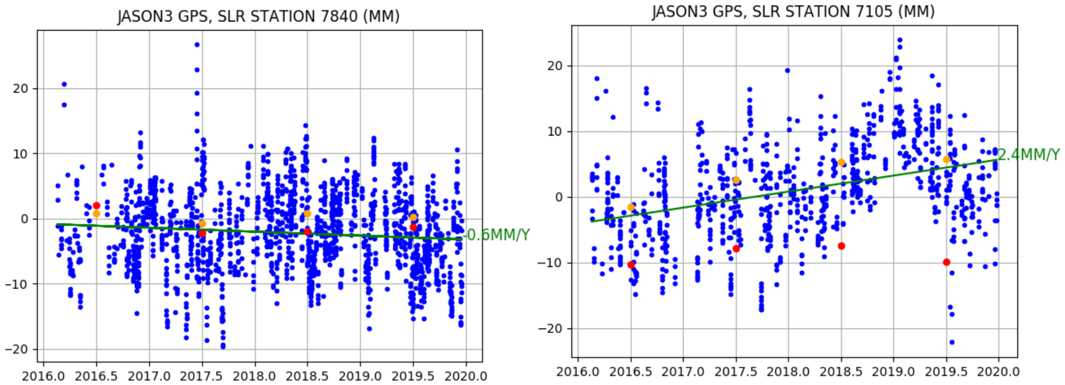

Figure : Herstmonceux (left) and Greenbelt (right) high-elevation SLR residuals over Jason-3 GPS-based CNES POE-F reduced-dynamic orbits [Moyard and Mercier, 2023].

- **Take-home messages**
  - Three independent tracking techniques is essential for the next decade challenges :
    - The *densification of the SLR network* with fully automated stations (especially at high latitudes) mapped on the DORIS network would be a strong asset.
    - The *robustness of the DORIS tracking technique* (DORIS+GNSS orbit solutions) is well appreciated since the launch of TOPEX/Poseidon for all the five past and ten currently flying altimetry missions.
  - Orbit error remains the largest source of error in the altimetry system in regional sea-level :
    - In between the sparse SLR operational stations, the DORIS and GNSS techniques are the only two sufficiently dense tracking measurements enabling to assess the *long-term regional radial orbit accuracy needed by demanding climate applications*.

Take-home messages

- The orbit accuracy depends on the accuracy of the tracking system as well as of the TRF :
  - The *win-win contribution of satellites equipped with DORIS and improvements in the ITRF* (itself necessary to POD and sea level measurements) should be considered as a whole in light of the upcoming ESA mission GENESIS and outputs of the CNES phase 0 study "DORIS on board Galileo".

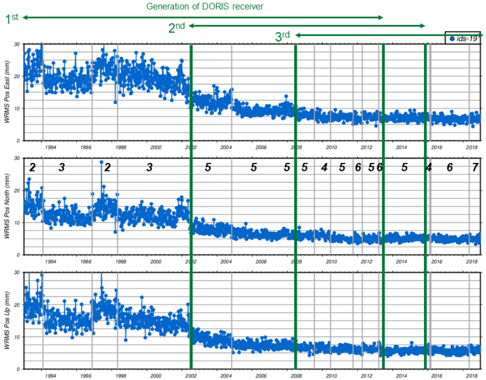

FIGURE : IDS 19 weekly solution WRMS of the station residuals w.r.t. ITRF2020 [Moreaux, 2023].