Making It COOL:
Enhancing ESA's COmbination at the Observation Level

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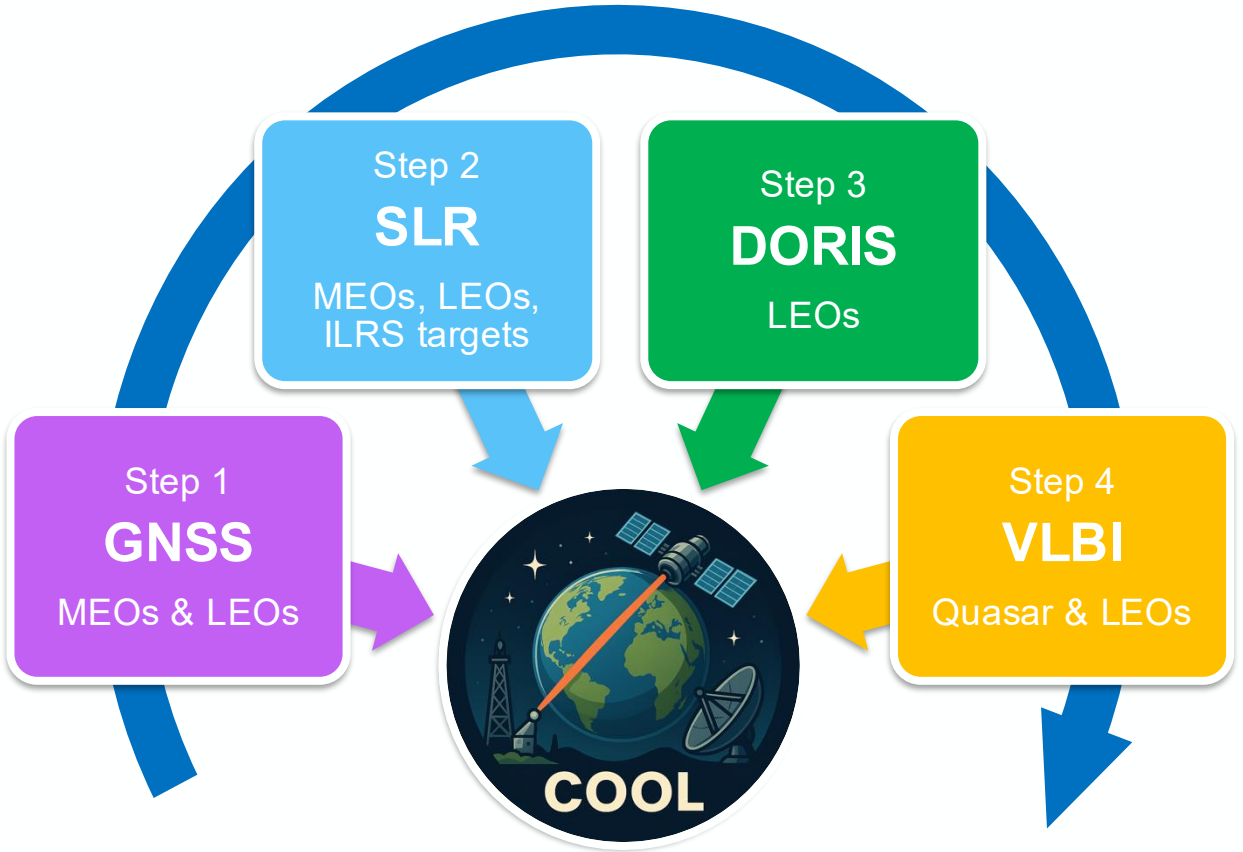
Outline

- COmbination at the Observation Level (COOL)
  - Concept, current status and objectives
- Orbit comparison of the different COOL solutions
- COOL and NEQ stacking
  - Combination of methodologies
  - MGNSS, ILRS and IDS solutions
- Effects on the Earth Orientation Parameters
- Obtention of a Geocentre approximation
- Effects on the Terrestrial Scale
- Summary and conclusions

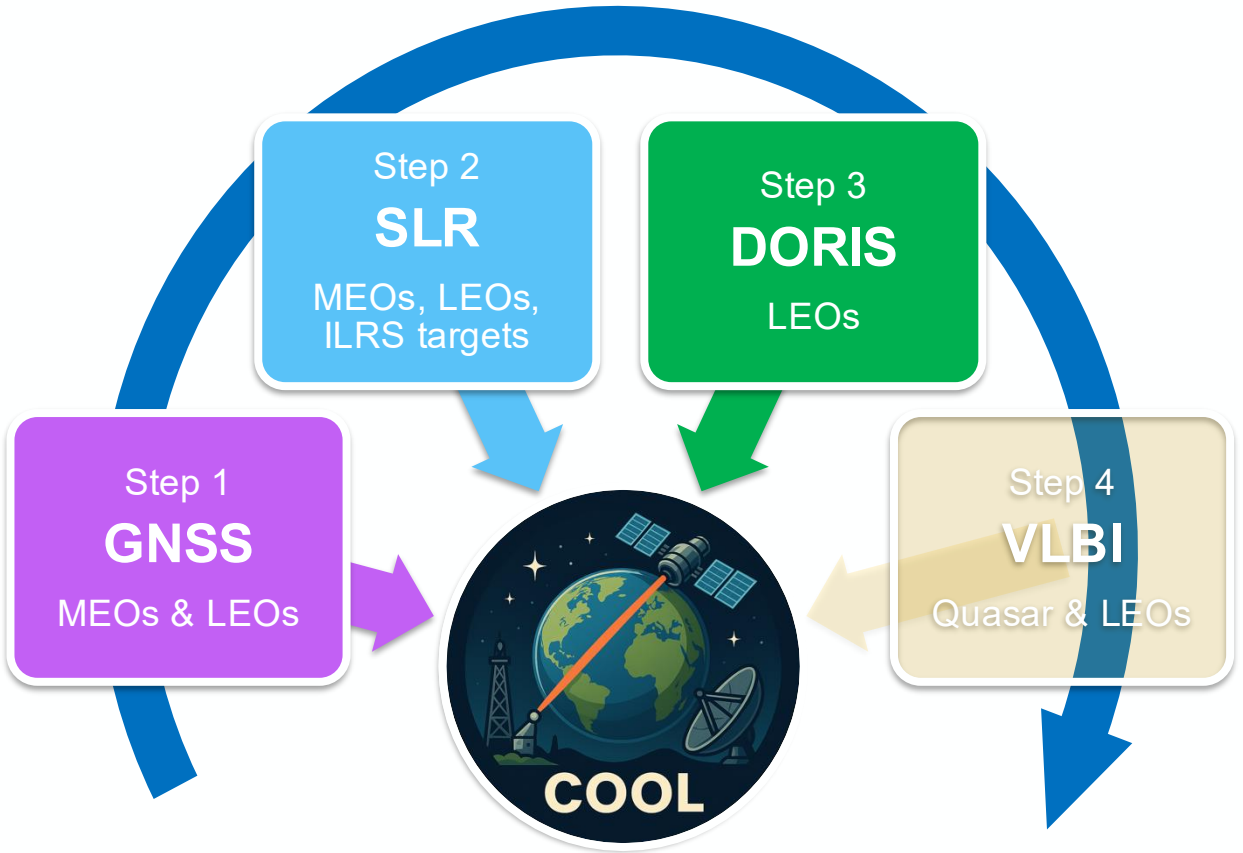
COmbination at the Observation Level - COOL



Main objectives:

- Combine **all 4 geodetic techniques** together in one single processing run
- Benefit from the **strengths of each technique**
- Detect and **reduce technique-specific systematics**
- Exploit additional **Normal Equation Stacking**
- Get the **ESA Precise Navigation System (EPNS)** software and knowledge ready for routine **Genesis** processing, contributing to the achievement of the mission objectives

COOL – Current Status



Step 1

GNSS and Sentinel satellites

- **Sentinel satellites** added to **Galileo** and **GPS** processing
- **Sentinel satellites** added to the **Multi-GNSS** processing

Step 2

SLR to Galileo, Sentinel and ILRS targets

- **SLR observations to Galileo and Sentinel** added to the GNSS processing at the observation level
- **SLR observations to ILRS** targets added to the GNSS processing at the normal equation level

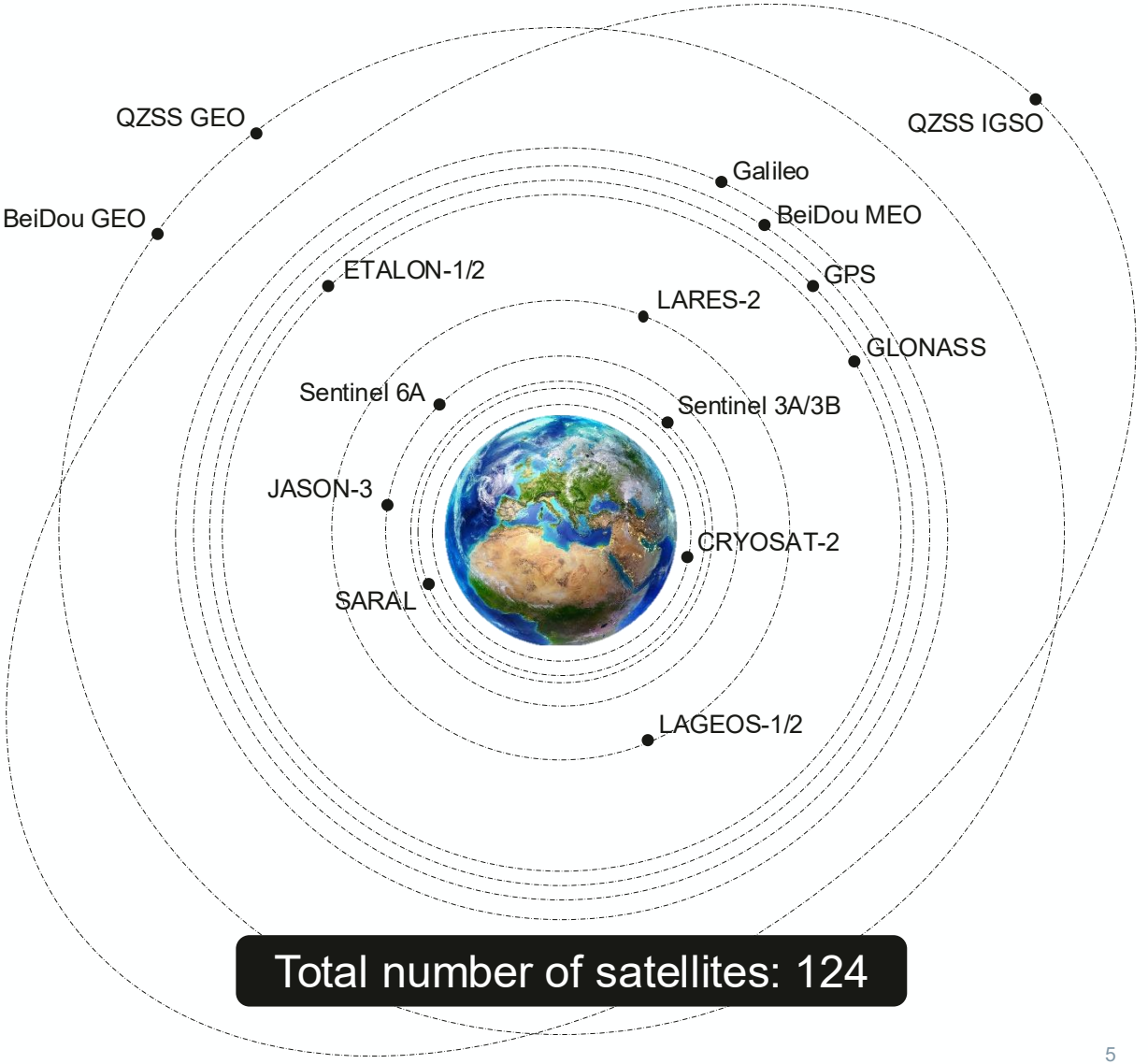
Step 3

DORIS from Sentinel and IDS satellites

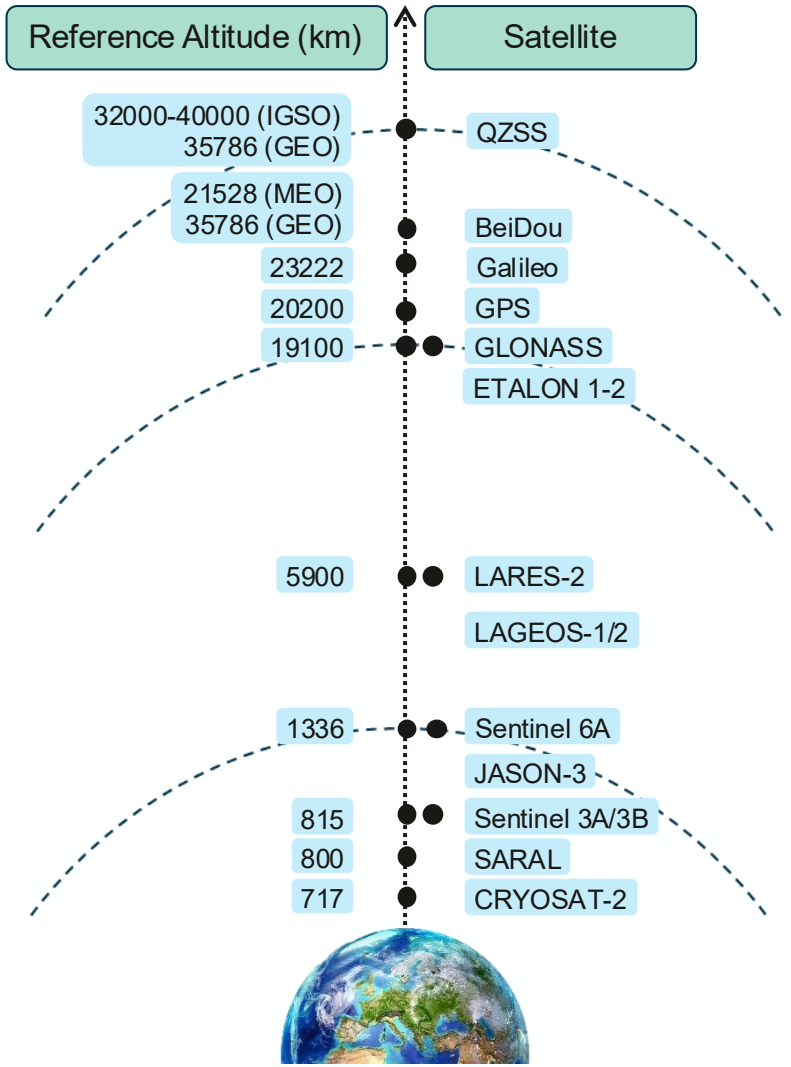
- **DORIS observation to Sentinel** added to the GNSS+SLR processing at the observation level
- **DORIS observations to IDS targets** added to the COOL processing at the normal equation level

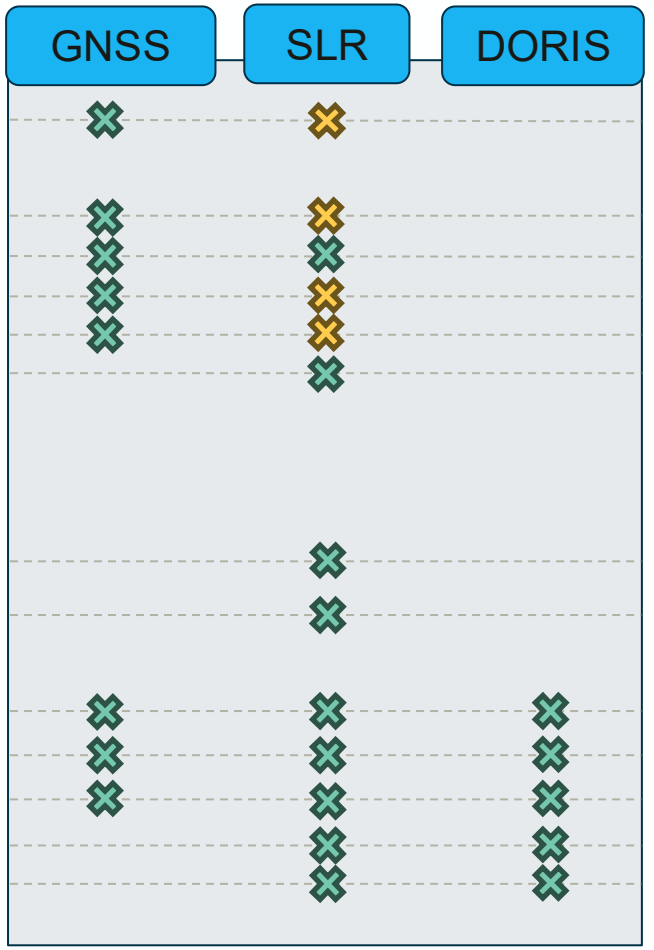
List of Satellites in the Combined Processing

Galileo	25	Sentinel-6A	1
GPS	32	SARAL	1
GLONASS	23	JASON-3	1
BeiDou	29	CRYOSAT 2	1
QZSS	4	ETALON-1/2	2
Sentinel-3A	1	LAGEOS-1/2	2
Sentinel-3B	1	LARES-2	1



Combining Measurement Types





Processing

- Software: EPNS 1.3.1 (dev version)

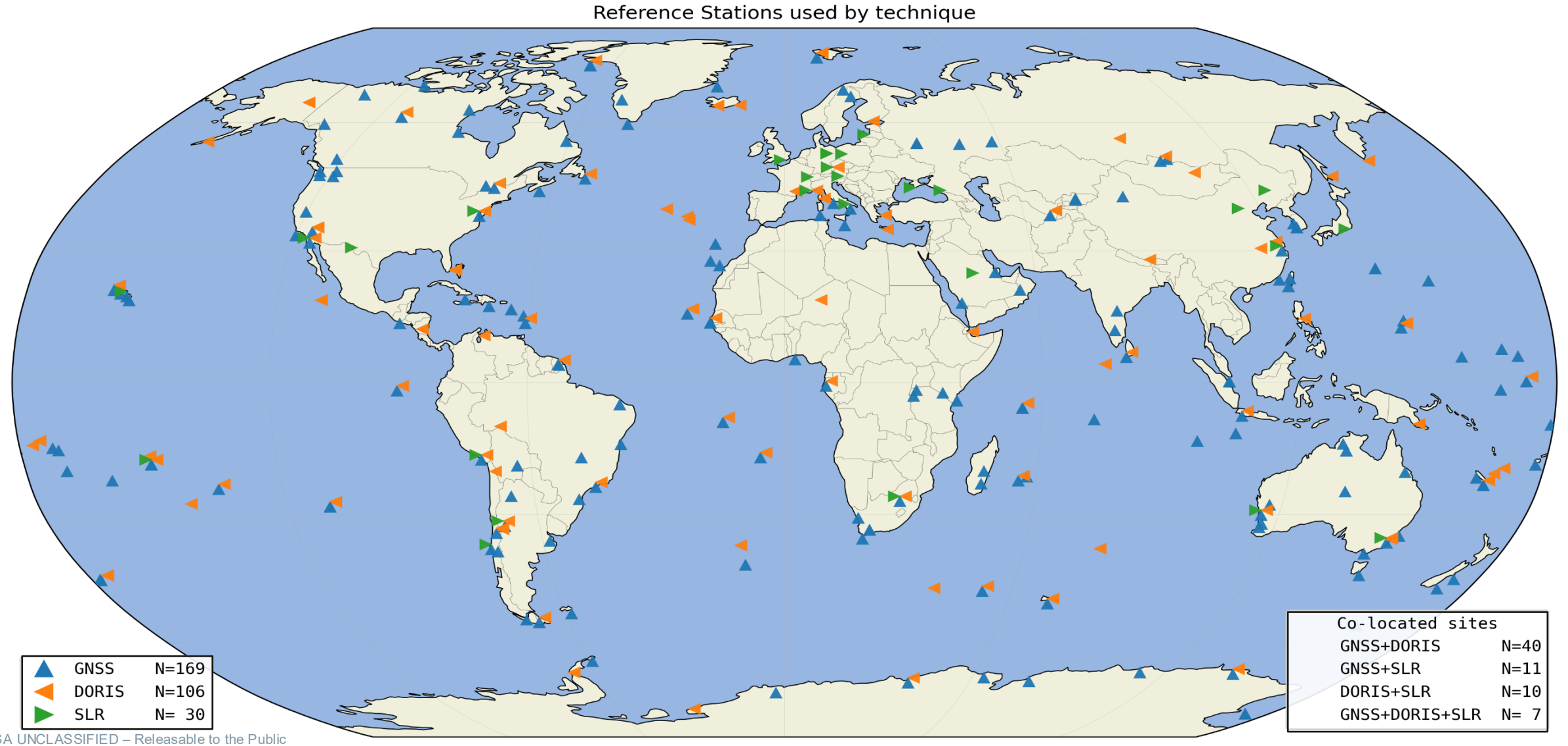
Models and Reference Frame

- ITRF2020-u2023 reference frame
- IERS2010 standards
- GNSS corrections from esa23 ANTEX
- Sentinel corrections from sen20 ANTEX

Observations

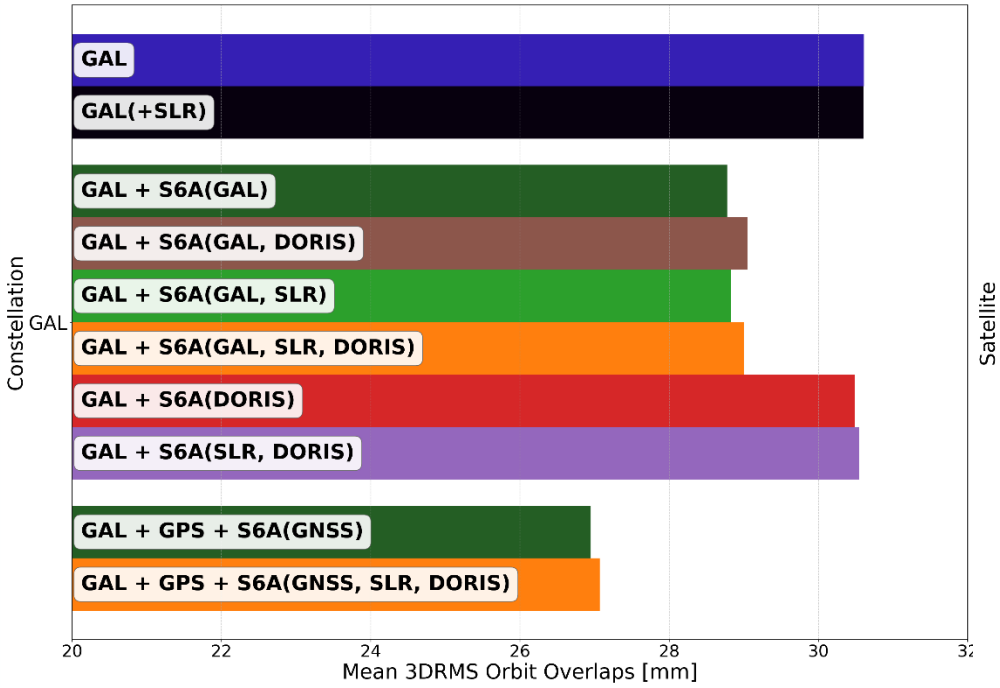
- Time span: 01/01/2024 – 29/02/2024
- Arc length: 24 h
- # stations GNSS: Up to 200 per constellation
- # stations SLR: Up to 30 stations
- # stations DORIS: Up to 60 stations
- 300/30s sampling rate of GNSS observations

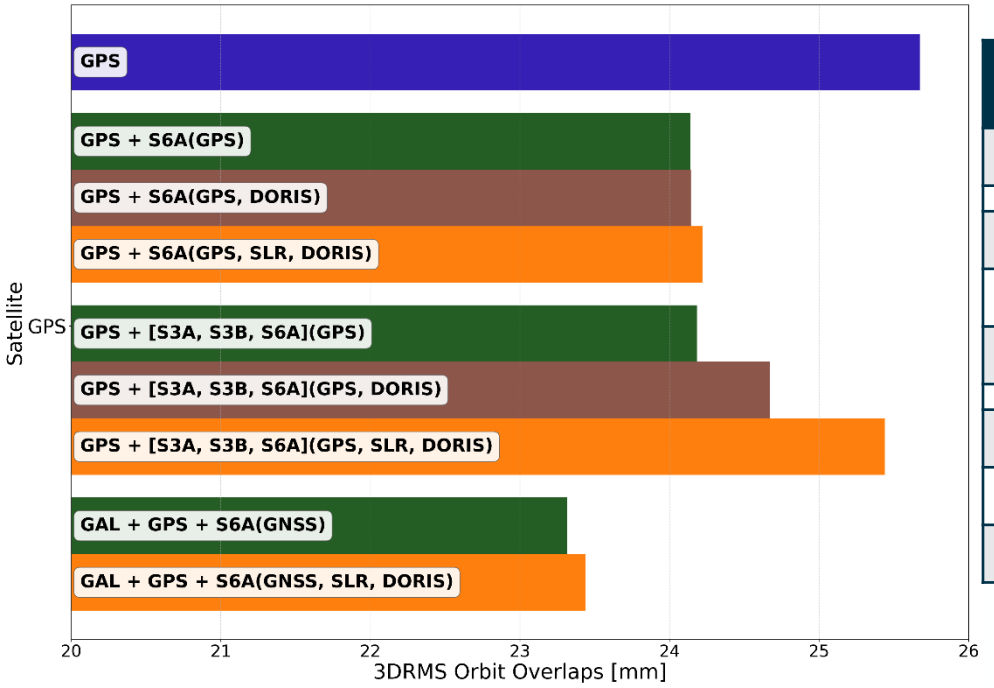
Distribution of Reference Stations



Satellite Orbit Overlaps (Galileo and GPS Combinations)

The **orbit overlaps at the midnight epoch** between 24h-arc solutions are computed to **analyse internal consistency**





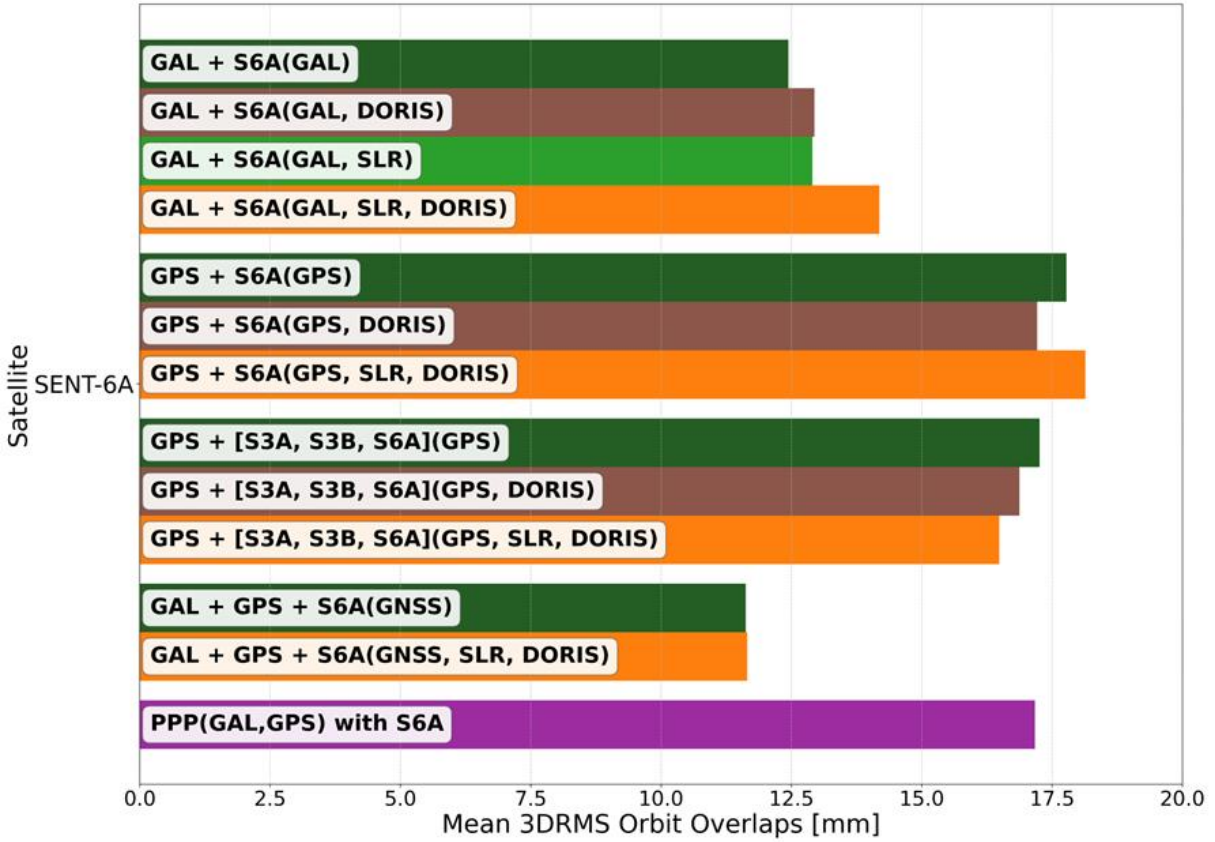
Label	Description
GAL	Galileo
S3A	Sentinel-3A
S3B	Sentinel-3B
S6A	Sentinel-6A
S6A(GPS)	GPS-only obs.
S6A(GAL)	GAL-only obs.
S6A(GNSS)	GAL&GPS obs.

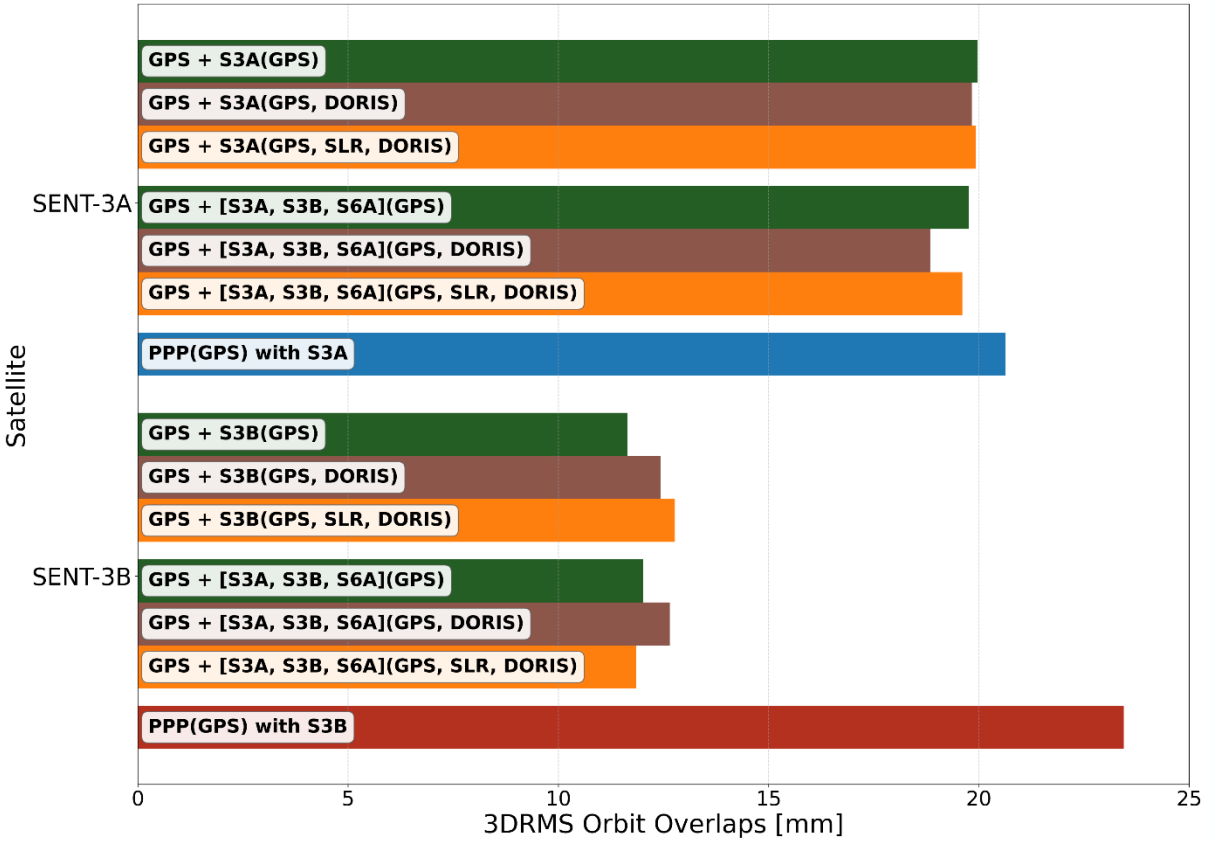
*S3A & S3B GPS-only obs.

- **All combinations either improve or maintain the 3D RMS values** over the 60 days compared to the standalone Galileo/GPS solutions
- Sentinel-6A (S6A) solutions based only on GNSS observations result into the best overlapping agreement
- **Sentinel DORIS observations slightly degrade this metric** when added along GNSS and SLR, and are not good enough for standalone solutions
- The addition of more Low Earth Orbiting satellites does not further improve the solution, and can even degrade it
- The **COOL processing of Galileo (GAL) and GPS together results in the best agreement**

Satellite Orbit Overlaps (Sentinel Satellites)

The **orbit overlaps at the midnight epoch** between 24h-arc solutions are computed to **analyse internal consistency**

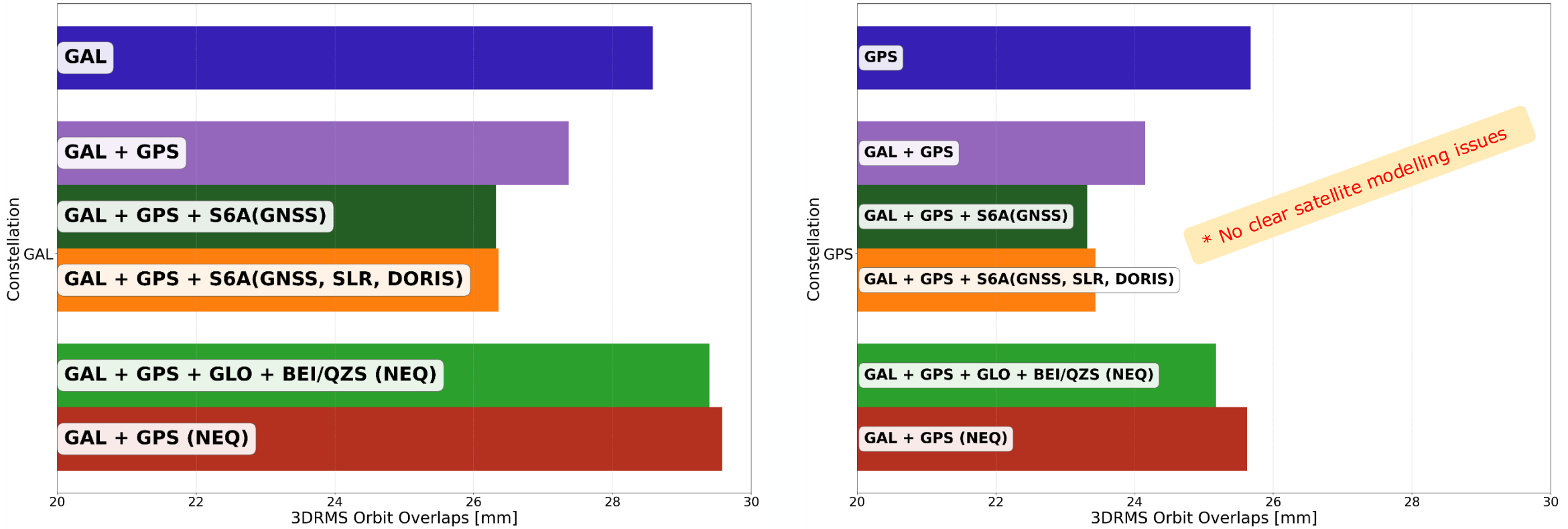




- **All combinations either improve or maintain the 3D RMS values** over the 60 days compared to the PPP solutions
- Sentinel-6A shows clear differences depending on the processed GNSS observables, with the usage of both Galileo and GPS being the best

COOL vs. NEQ stacking internal consistency check

The **internal consistency** of the COOL and NEQ methodologies is analysed to spot inconsistencies of the processing

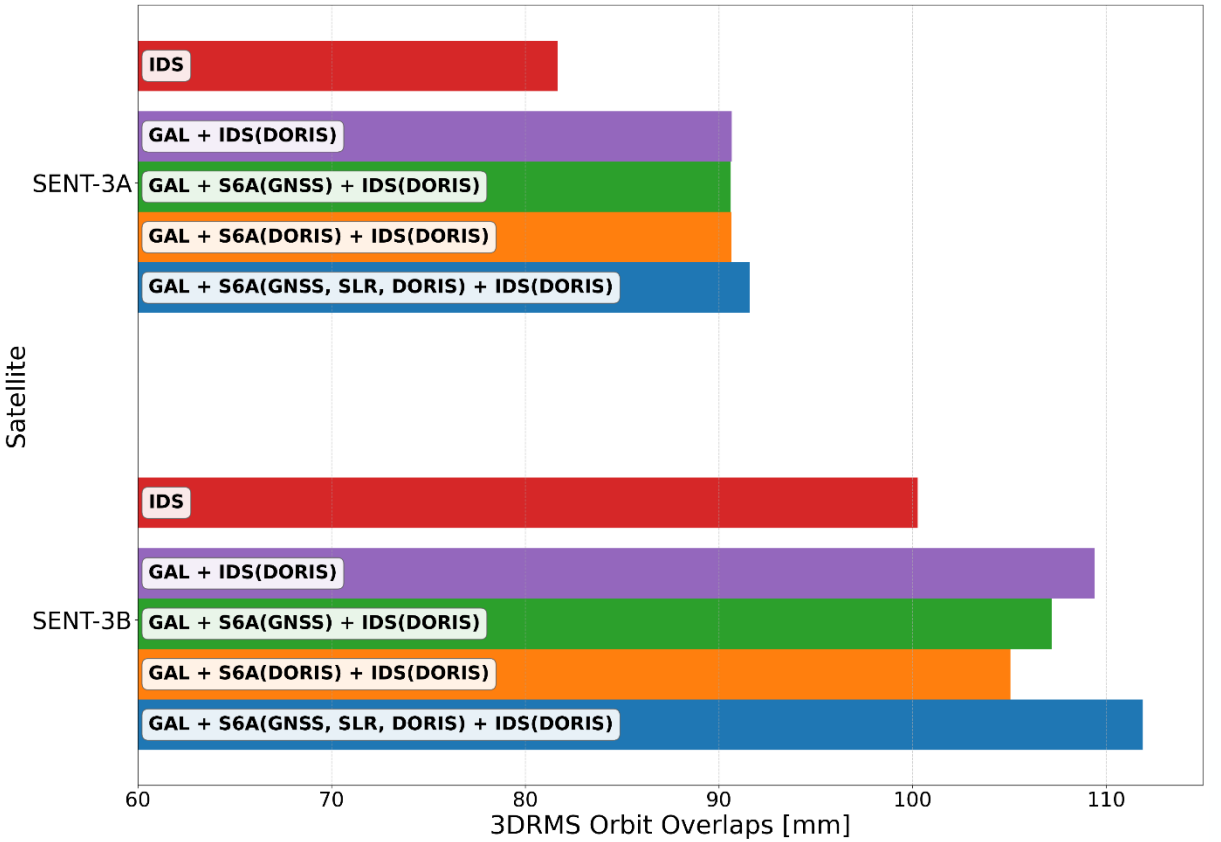


- **All COOL combinations either improve the 3D RMS values** over the 60 days compared to the standalone Galileo/GPS solutions
- However, the equal weighting of the **NEQ stacked solution degrades the performance of Galileo, while slightly improving that of GPS**
- The Galileo solution seems to be more susceptible to degradation when combining independent station clocks

Internal Consistency of the IDS solution

The **internal consistency** of the IDS solutions is analysed to spot inconsistencies of the processing

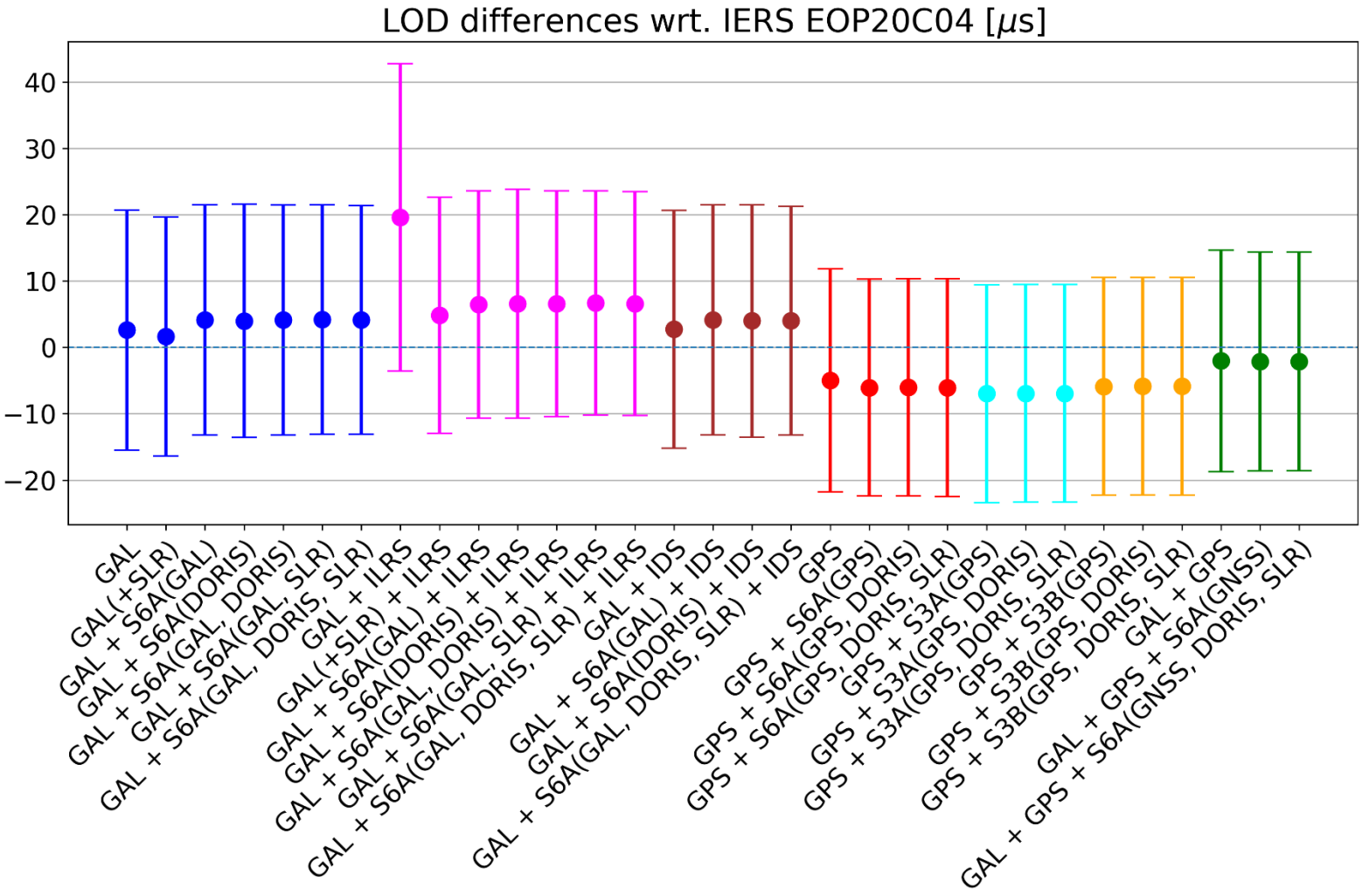
This IDS solutions is comprised of:



- The IDS-only solution shows a much larger orbital inconsistency than when using GNSS observations alone as DORIS is usually much more vulnerable than GNSS to arc-to-arc dynamic inconsistencies
- All COOL combinations are degraded compared to the IDS solution

Earth Orientation Parameters wrt. IERS EOP20C04

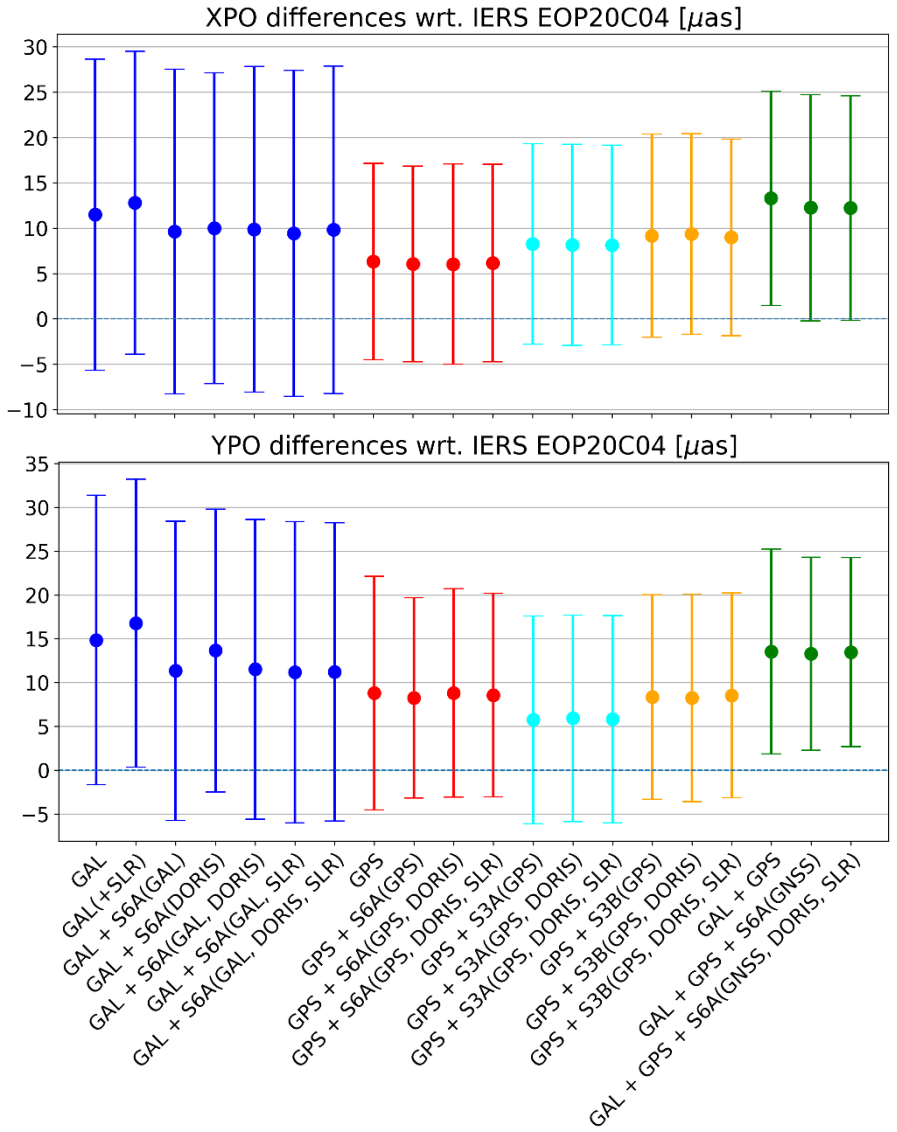
The ERP differences against IERS EOP20C04 are computed to **analyse external consistency**

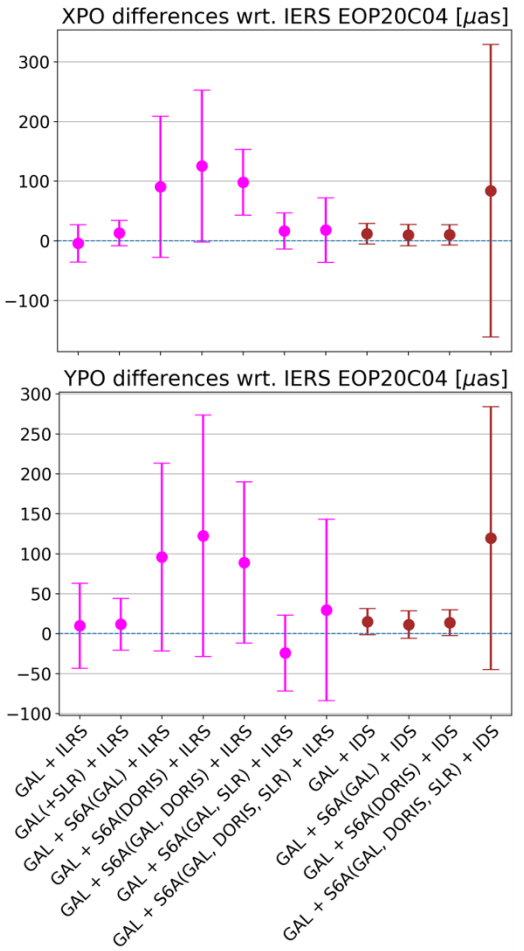


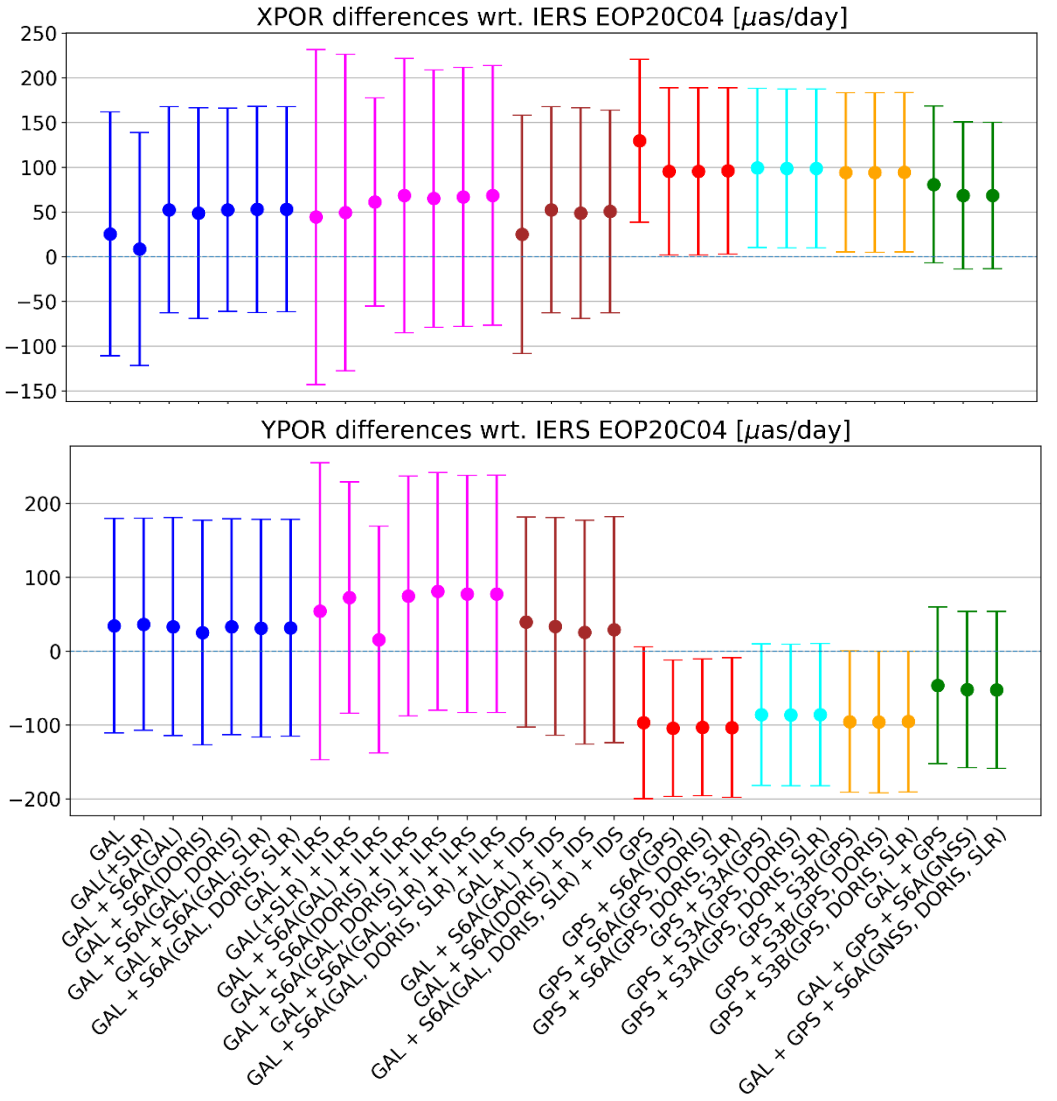
Main findings

- The addition of Sentinel satellites maintains or slightly enlarges the differences wrt. the reference
- **The COOL processing of Galileo (GAL) and GPS together results in the best agreement**
- The ILRS standalone combination poorly influences the solution
- The IDS standalone combination does not influence the LOD estimates

Earth Orientation Parameters wrt. IERS EOP20C04



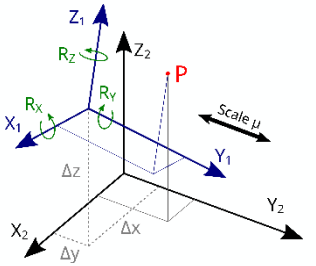


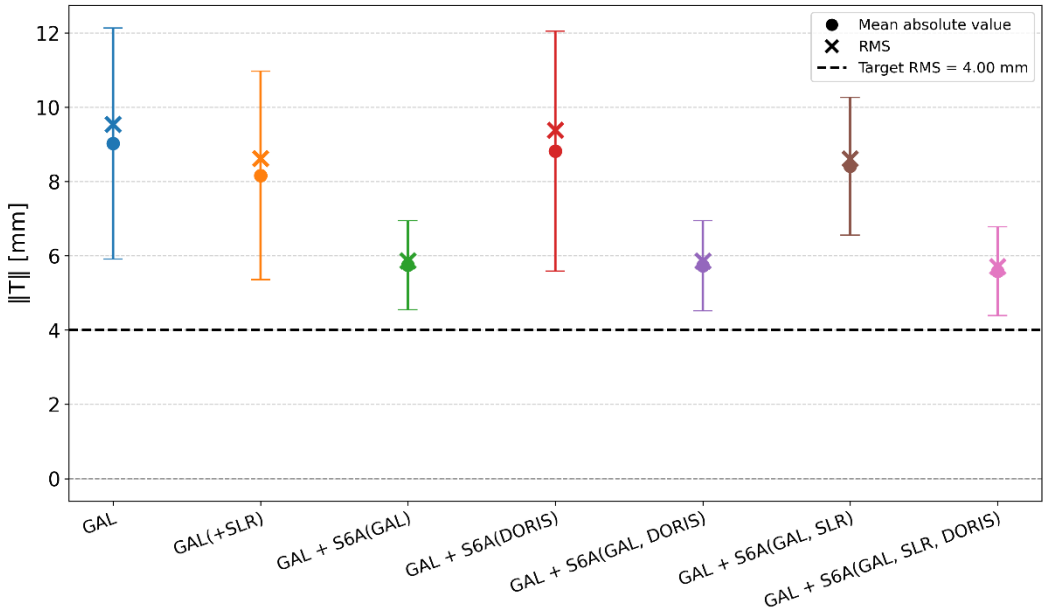


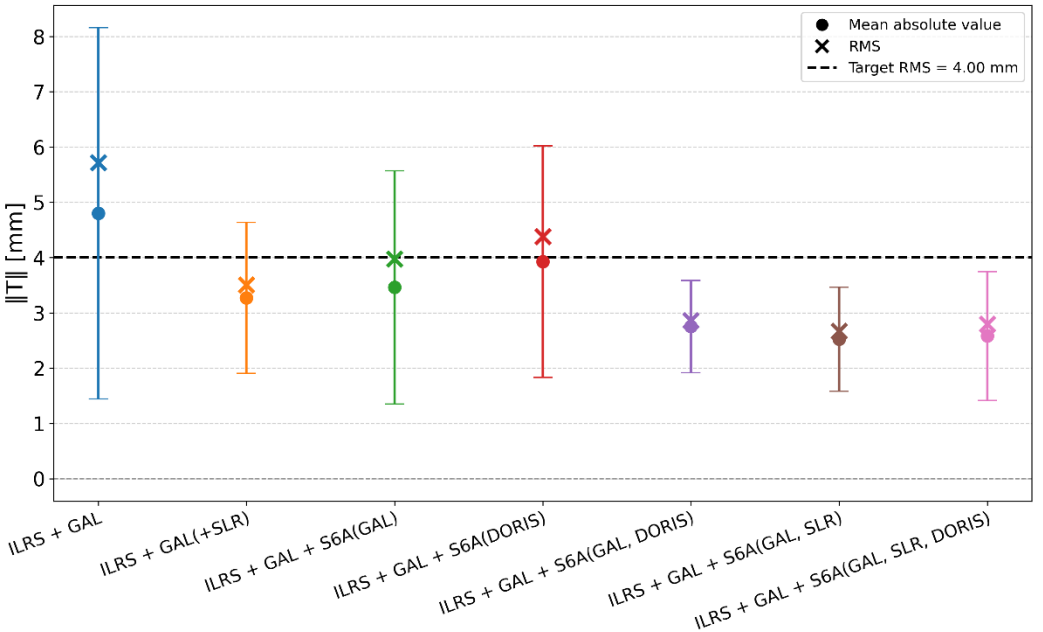
Geocentre Approximation

- Considering the origin of the ITRF2020-u2023 as a reference Geocentre, two sets of solutions are created to analyse the stability of the origin.
- The ITRF alignment is based on the IGS20 core stations and the extended ILRS station list
- Applied minimum constraint condition : No-Net-Translation (NNT), No-Net-Rotation (NNR)

Helmert Transformation Cases	
Reference	**Free Translation**
NNT	Free Translation
NNR	NNR
Free Scaling	Free Scaling





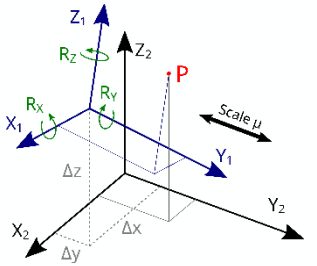


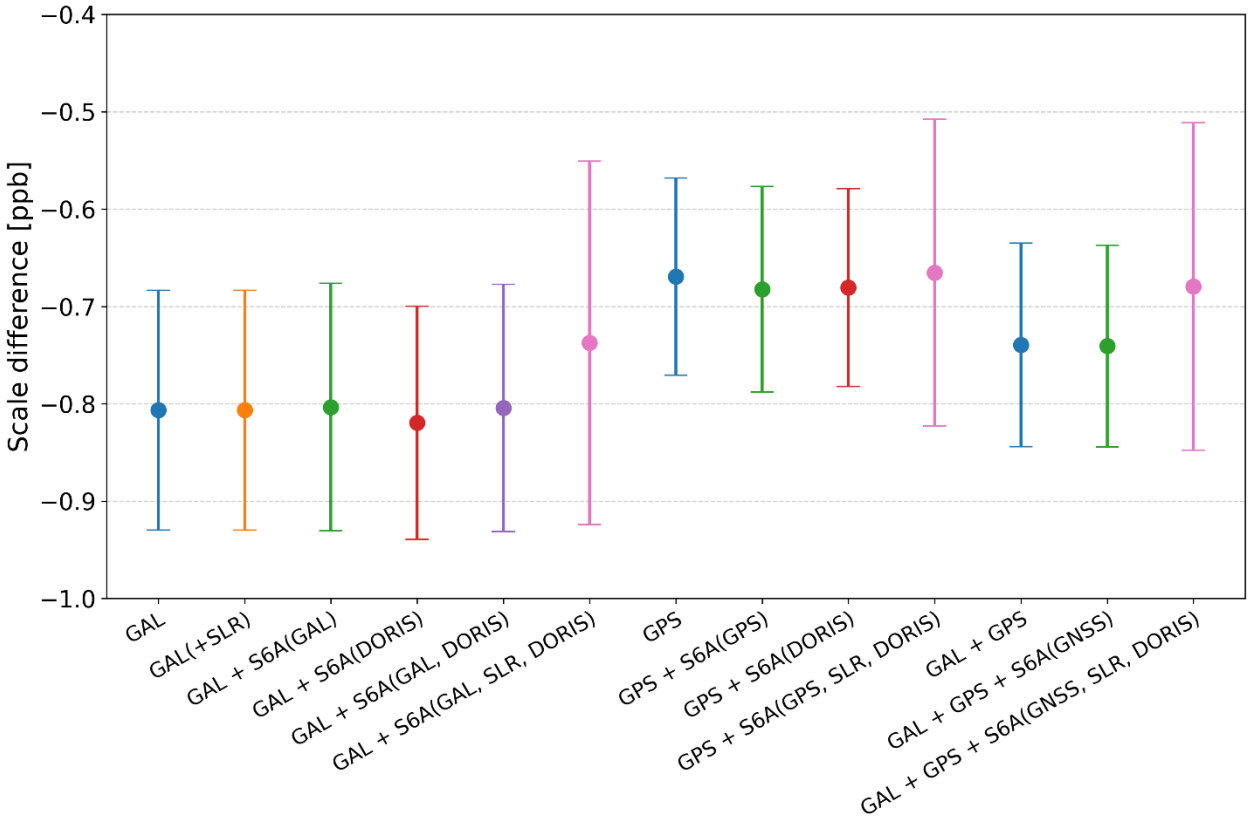
- As a target RMS, the annual expected geocentre motion is considered from a 26-year weekly LAGEOS-1/2 SLR series [Yu et al. (2021)]
- The addition of Galileo SLR observations or Sentinel-6A GNSS, SLR and DORIS observations bring the solutions closer to the ITRF origin
- The addition of the ILRS targets further reduces the geocentric offset. However, several cases reduce the RMS below the target

Scale comparison wrt. ITRF coordinates

- Comparison of the nominal COOL solution against the same COOL solution with station coordinates constrained to the ITRF a priori values.
- Results based on equal weighting of all stations (GNSS, SLR and DORIS, as applicable) with removal of outliers

Helmert Transformation Cases	
Reference	**Fixed Stations**
NNT	NNT
NNR	NNR
Free Scaling	Free Scaling





Main findings

- Galileo scale offset is consistent with the use of esa23.atx and the different Galileo z-PCOs
- As expected, Sentinel-6A alone does not contribute further independent scale information
- The effect of SLR seems to be minimised due to the low number of observations

Conclusions and Next Steps

- Our software can properly combine GNSS, SLR and DORIS observations both at the observation and at the normal equation level, allowing a modular design to get the best of both methodologies
- The COOL methodology allows to …
  - improve the internal consistency of the Galileo and GPS orbits
  - maintain or improve the Earth Orientation Parameter agreement with respect to the IERS EOP20C04
  - improve the Geocentre consistency with the ITRF while exhibiting reduced uncertainty
  - maintain the terrestrial scale difference stable with respect to the ITRF coordinates across solutions
- Inconsistencies between COOL and NEQ stacking results have been spotted at the multi-GNSS level
- DORIS observations seem to be only a good addition on top of other solutions, mostly GNSS-based
- The ILRS and IDS external inputs give us an insight into the benefits and drawbacks of independent NEQs

Next steps:

- Understand, and possibly solve, the aforementioned inconsistencies between the different observables
- VLBI integration along with the active development of VLBI-to-satellite functionality in our software (EPNS)