Integrating Four Space Geodetic Techniques for Terrestrial Reference Frame Recovery

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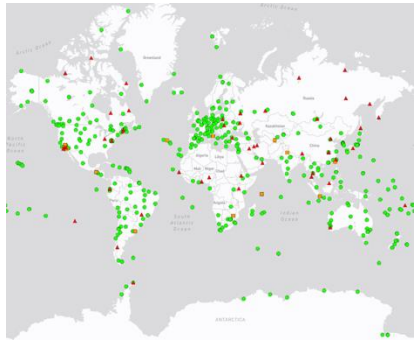
Session: From Orbits to Reference Frames: Advances in GNSS Processing

Jet Propulsion Laboratory
California Institute of Technology

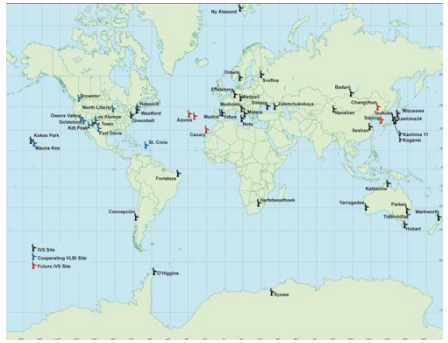
Terrestrial Reference Frame (TRF) Realizations

TRF provides a stable coordinatee system for positions and velocities on the Earth's surface

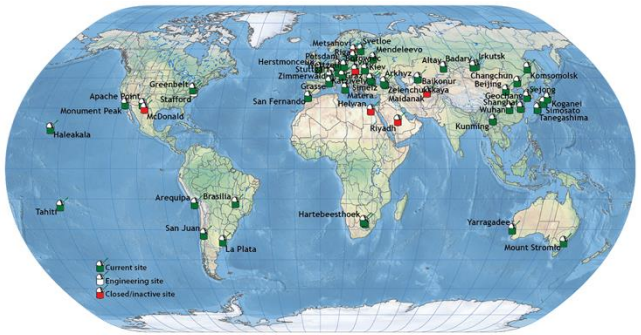
GNSS



VLBI



SLR



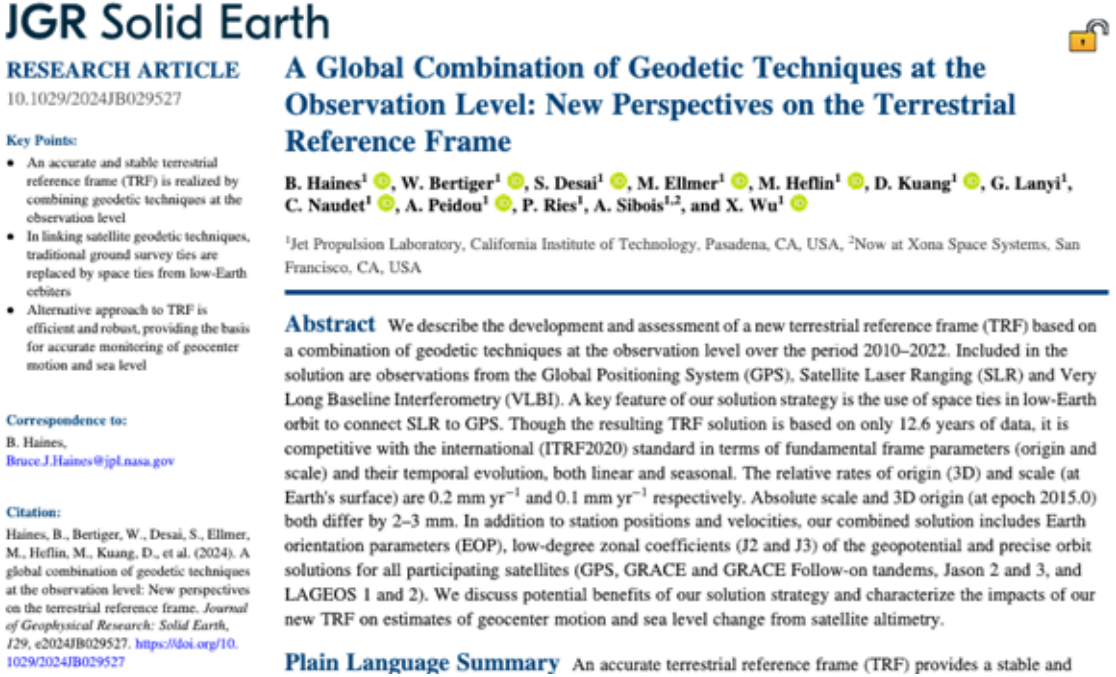
DORIS

Traditional **TRF** combines **products**

(involvement from ~30 analysis centers)

Current Standard: ITRF2020

New! **TRF** combines geodetic techniques at the **observation** level



JGR Solid Earth

RESEARCH ARTICLE

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A Global Combination of Geodetic Techniques at the Observation Level: New Perspectives on the Terrestrial Reference Frame

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Key Points:

- An accurate and stable terrestrial reference frame (TRF) is realized by combining geodetic techniques at the observation level
- In linking satellite geodetic techniques, traditional ground survey ties are replaced by space ties from low-Earth orbiters
- Alternative approach to TRF is efficient and robust, providing the basis for accurate monitoring of geocenter motion and sea level

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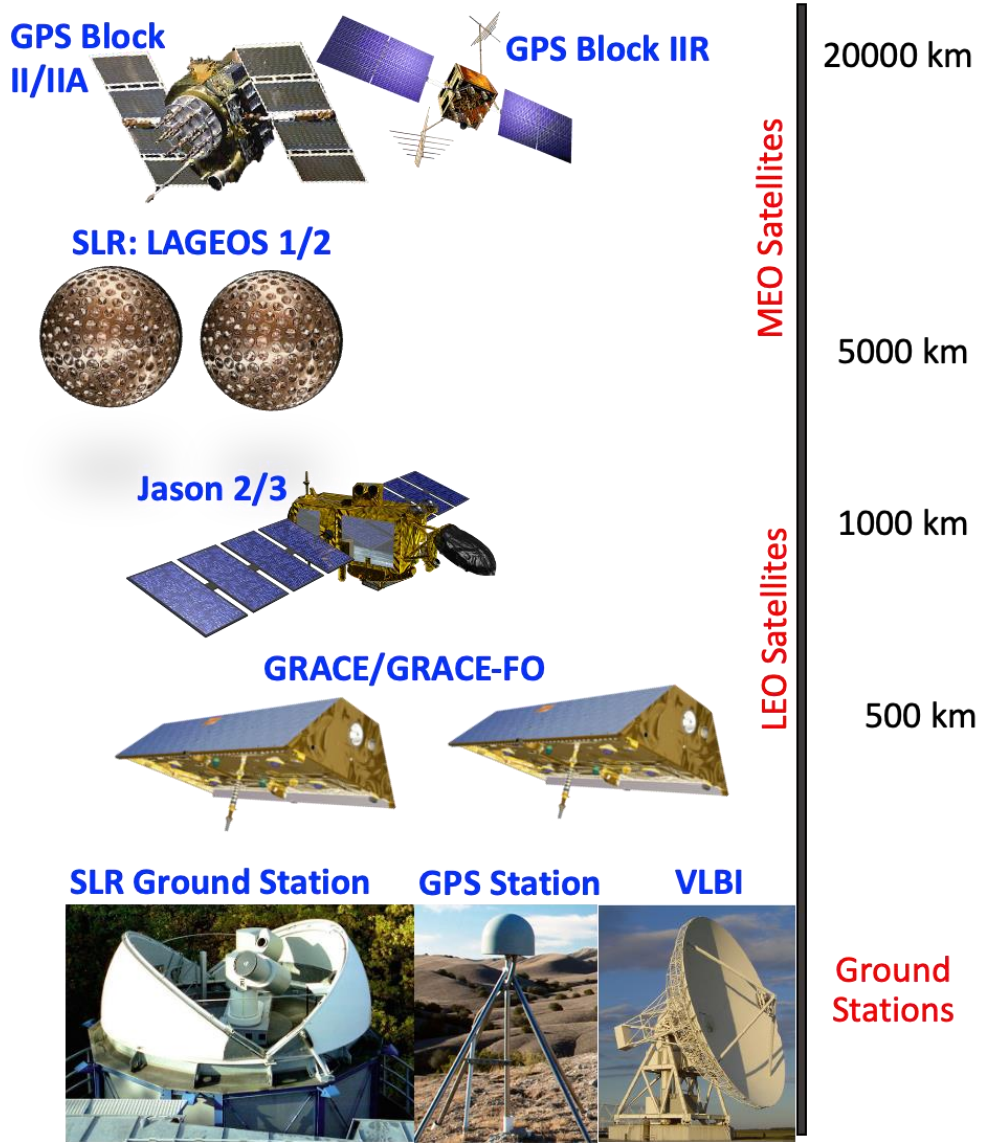
Abstract We describe the development and assessment of a new terrestrial reference frame (TRF) based on a combination of geodetic techniques at the observation level over the period 2010–2022. Included in the solution are observations from the Global Positioning System (GPS), Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI). A key feature of our solution strategy is the use of space ties in low-Earth orbit to connect SLR to GPS. Though the resulting TRF solution is based on only 12.6 years of data, it is competitive with the international (ITRF2020) standard in terms of fundamental frame parameters (origin and scale) and their temporal evolution, both linear and seasonal. The relative rates of origin (3D) and scale (at Earth's surface) are 0.2 mm yr^{-1} and 0.1 mm yr^{-1} respectively. Absolute scale and 3D origin (at epoch 2015.0) both differ by 2–3 mm. In addition to station positions and velocities, our combined solution includes Earth orientation parameters (EOP), low-degree zonal coefficients (J2 and J3) of the geopotential and precise orbit solutions for all participating satellites (GPS, GRACE and GRACE Follow-on tandems, Jason 2 and 3, and LAGEOS 1 and 2). We discuss potential benefits of our solution strategy and characterize the impacts of our new TRF on estimates of geocenter motion and sea level change from satellite altimetry.

Plain Language Summary An accurate terrestrial reference frame (TRF) provides a stable and

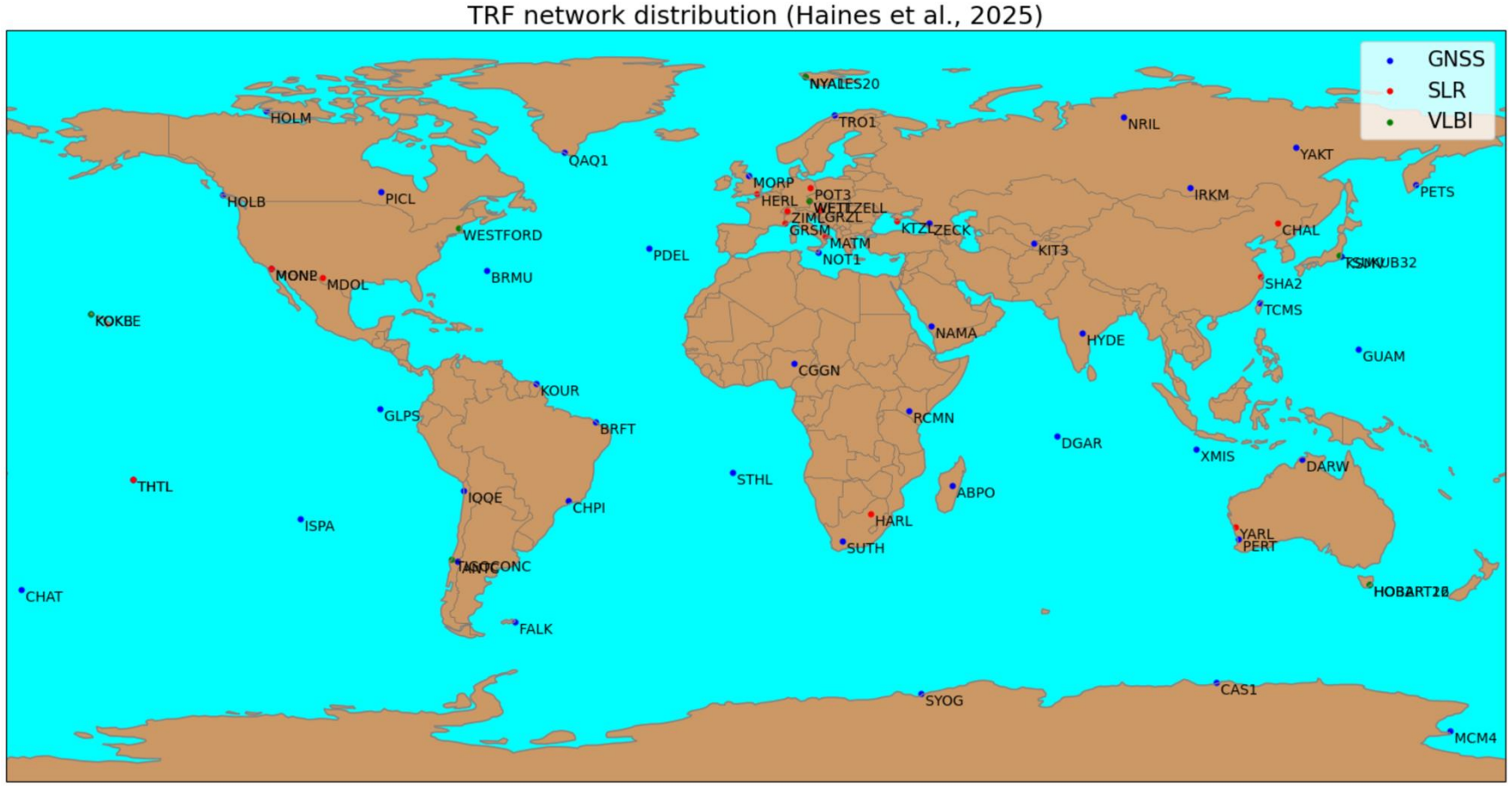
Observation-Level Terrestrial Reference Frame

Haines et al., 2024

- Combines 3 techniques (**GPS + SLR + VLBI**) at the observation level
- Dispenses with traditional ground ties for SLR/GPS
  - Connection between SLR and GPS is exclusively through space ties
  - Connection between VLBI and GPS uses traditional ground ties
- Capitalizes on strength of GPS low-Earth orbiters (LEO) observations
- Uses single software system (GipsyX) for all techniques
- Products unified with the frame
  - Precise orbits for strategic LEOs, time variable gravity & EOP
  - Independent of ITRF releases and associated cadence (few years)
- Reflects key aspects of GRASP mission concept, proposed to NASA (2011 & 2015), **and the recent announced GENESIS ESA mission.**



Three-technique Observation-Level Terrestrial Reference Frame



- From 12+ years of tracking data.
  - 2010.0 – 2022.6
- Arc length: 3.25 d
- Number of GPS stations per solution: 45
- Superset of nearly 550 stations.
  - GNSS (388)
  - SLR (47)
  - VLBI

In the plot (left)

Linear and annual motions for:

- 210 GNSS sites
- 27 SLR observatories
- 17 VLBI stations

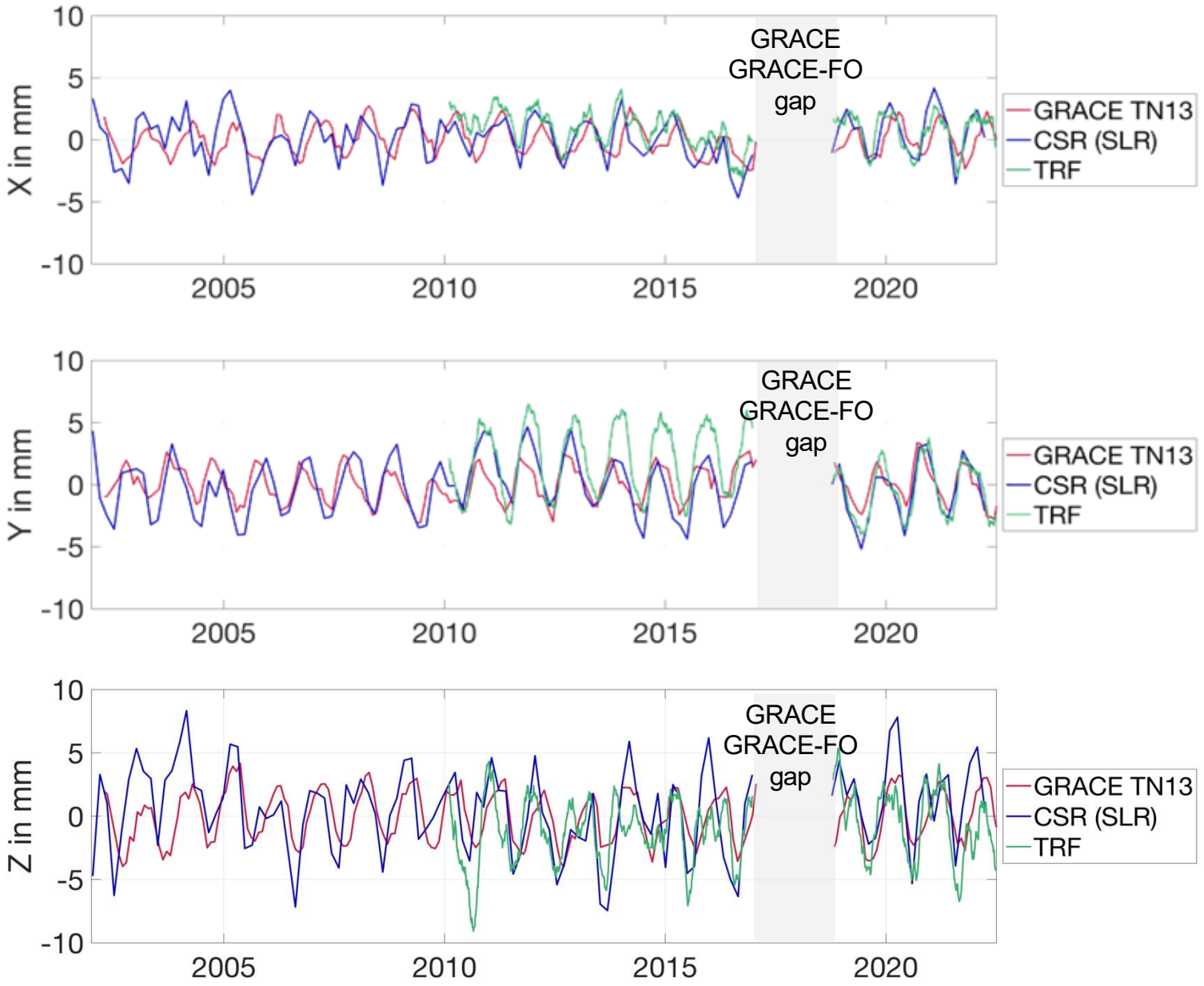
Annual Geocenter Motion

- Observation-level frame (TRF). 3-technique vs:
  - GRACE TN13 (*Sun et al. 2016*)
  - CSR SLR (*Ries, 2016*)

- Equatorial **X** component
  - Good agreement in amplitude (1–2 mm) and phase (late February).

- Equatorial **Y** component
  - Excellent agreement in amplitude (3 mm) and phase (end of November).
  - Small, but systematic departure from 2013-2016.

- **Z** (spin axis) component
  - Most difficult to determine.
  - Noisier overall.
  - Satisfactory agreement in amplitude (3 mm) and phase (February).
  - Inclusion of SLR slightly reduces amplitude (by 1 mm) vs. GPS alone.



First Four Technique Solution

Advancement: DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite

GipsyX development

One space tie: Jason 2

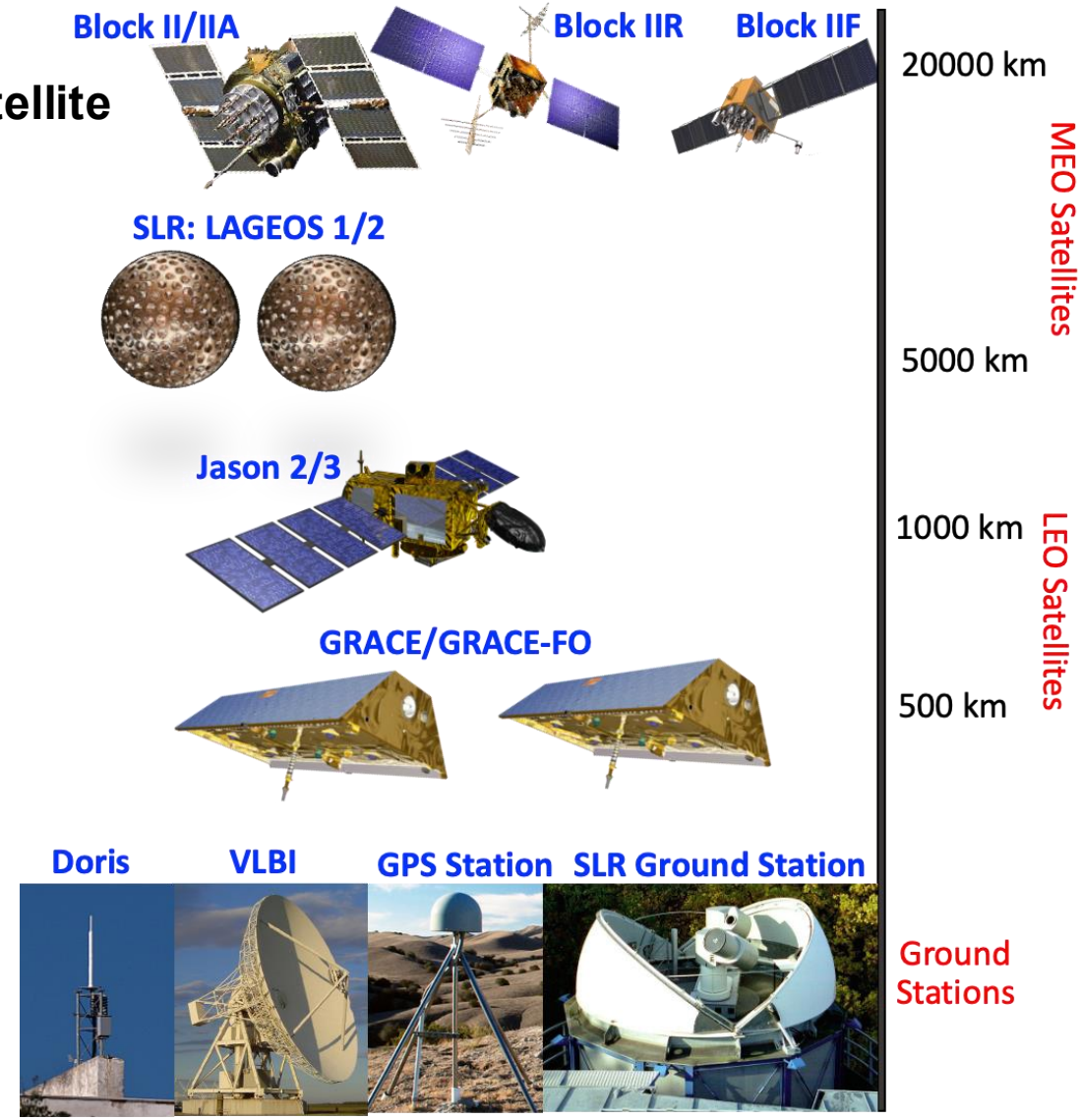
~47 DORIS ground stations per day

Weight prescription: 0.5 mm/s

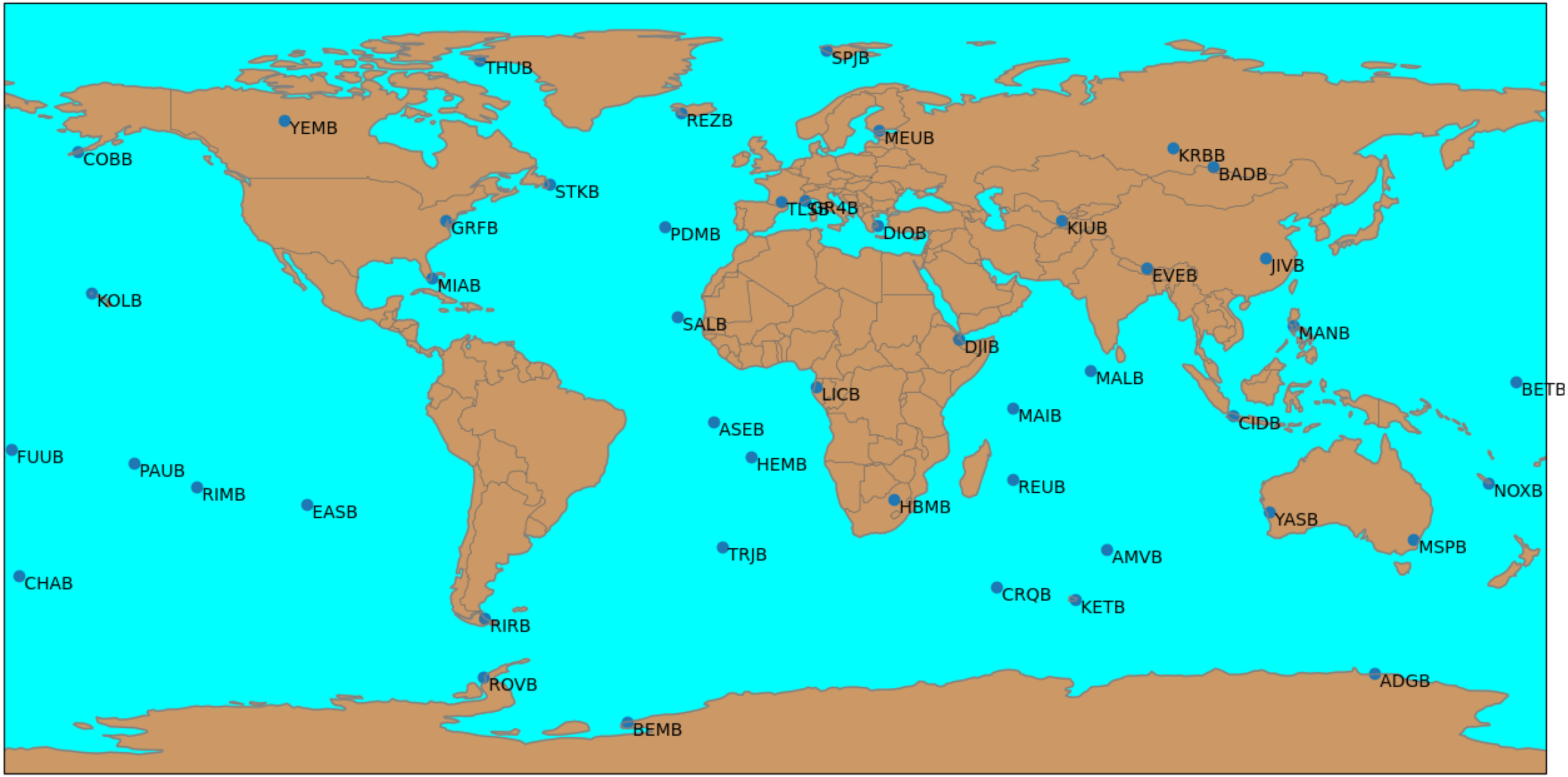
3.25 d between 04/2019 - 07/2019

Four technique

GPS + SLR + VLBI + DORIS

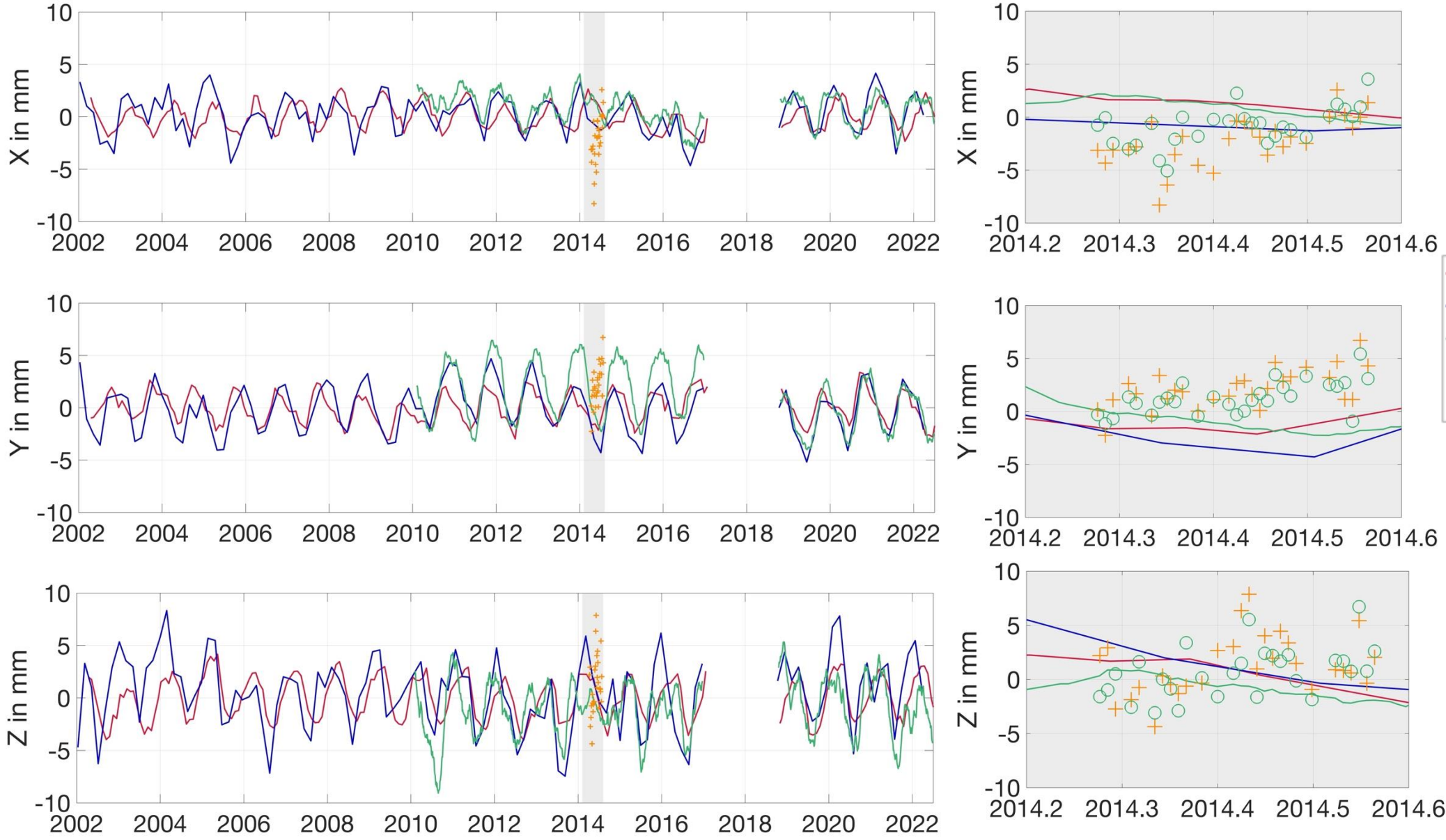


DORIS stations



Annual Geocenter Motion

First results including 47 DORIS sites show high level of agreement for geocenter



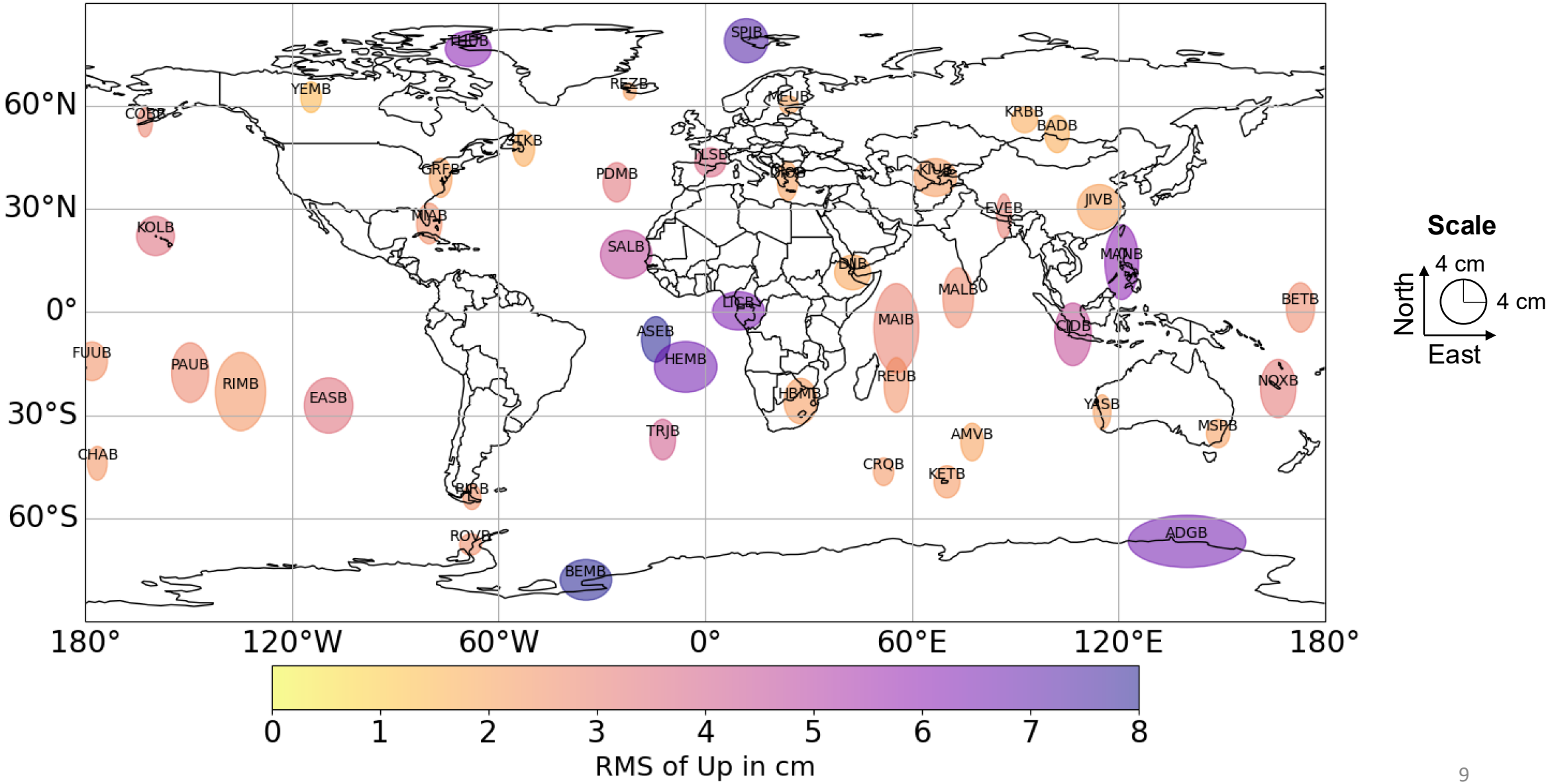
TN13: Sun et al. 2016

CSR: Ries, 2016

TRF-3tech: Haines et al. 2024

RMS of the differences of DORIS station positions vs ITRF2020

DORIS sites show cm level agreement for positions relative to ITRF2020

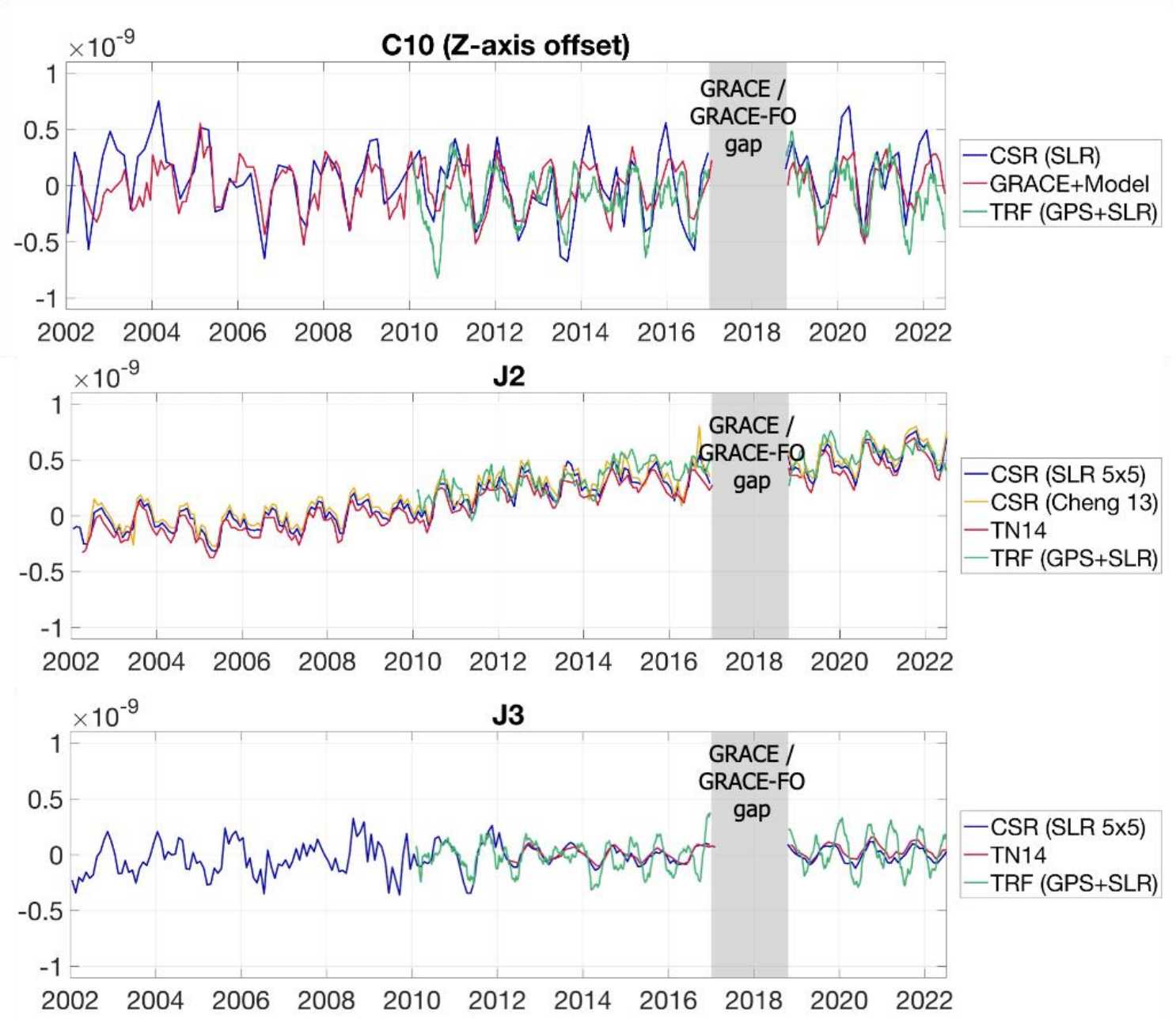


Data strength allows for reliable recovery of low-degree gravity

From the Haines et al., 2024 realization

J2: Input and parametrization choices drive differences among different solutions.
TRF: SLR significantly improves J2 recovery (compared to a GPSonly solution).

J3: In family with competing solutions. Addition of LARES expected to improve the amplitude. (soon!!!)



Peidou et al., 2025; EGU

Recent Updates

GPS: Support of all available blocks

New SLR satellites

LARES 1 and 2 → Low Degree Gravity Field Coefficients

New LEOs

Sentinel 3A, 3B, 6A, 6B, SWOT, Swarm A/B/C

Increased number of GNSS stations: 120

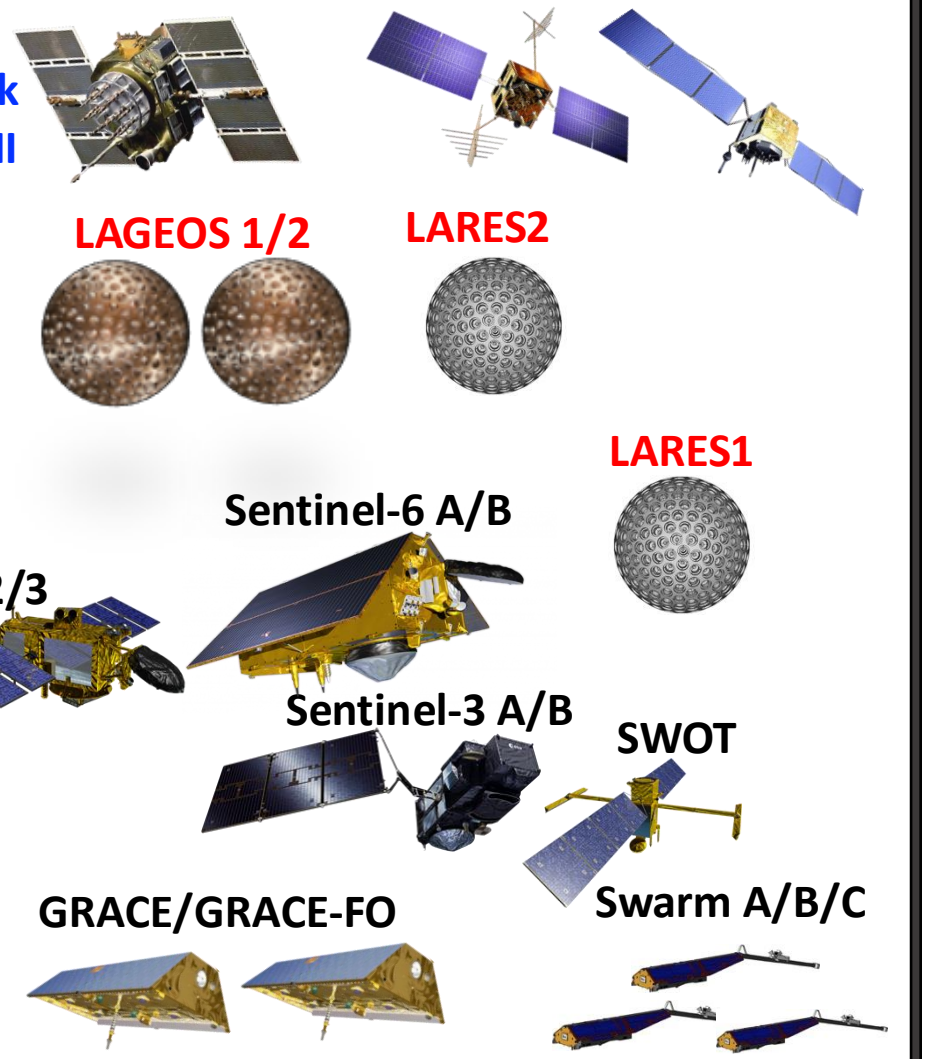
SLR processing: Legacy data (before 2009)

Updated models

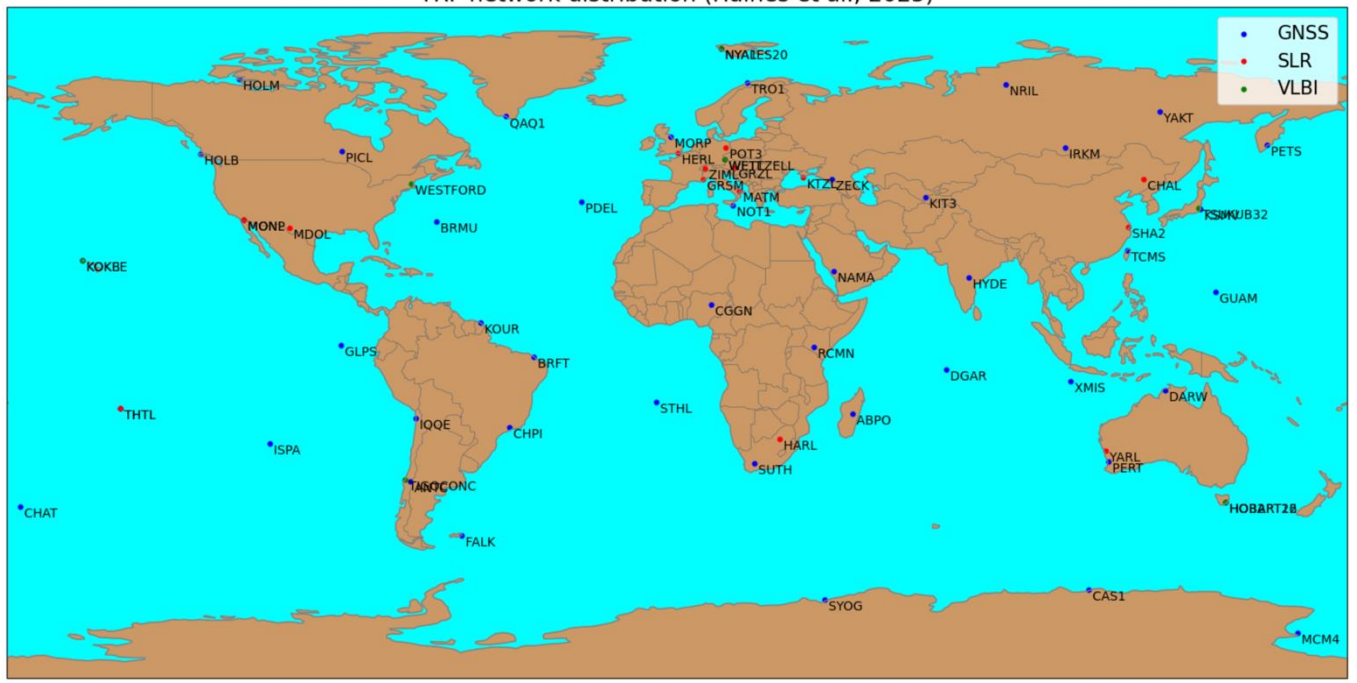
Troposphere

Gravity Field

Framework ready to process Galileo



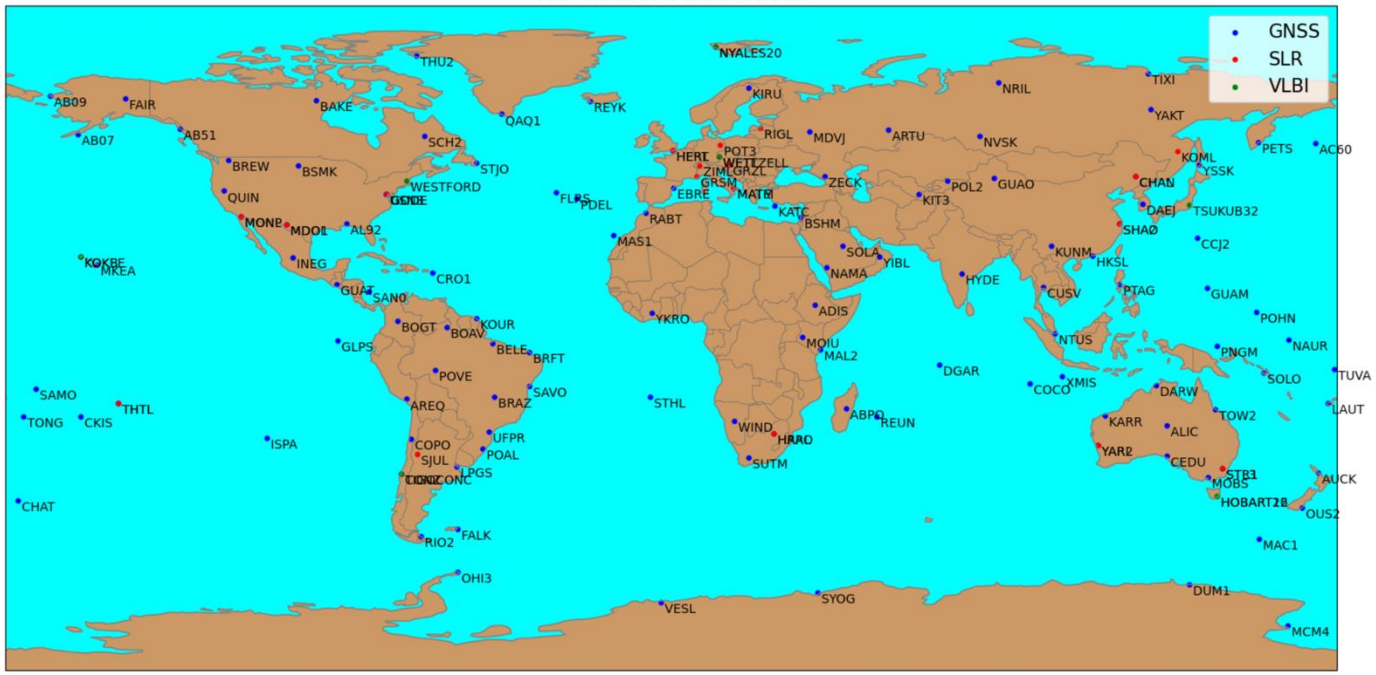
TRF network distribution (Haines et al., 2025)



Haines et al., 2025

GPS 46
SLR 15
VLBI 8

TRF network distribution



New Implementation

GPS 120
SLR 19
VLBI 8

Four technique reference frame realization at the observation level

GPS | SLR | VLBI | DORIS

JPL's GipsyX → First software capable to process observations from the four core geodetic platforms

On-going efforts:

- Trade studies on each technique's strength
- Optimize DORIS and VLBI data editing
- Background modeling / Parametrization

Integrating observations for TRF realization enables new science

Global Mean Sea Level

Low degree gravity field recovery

Data strength, spatial coverage and unequal spacing → favor recovery of low-degree gravity coefficients

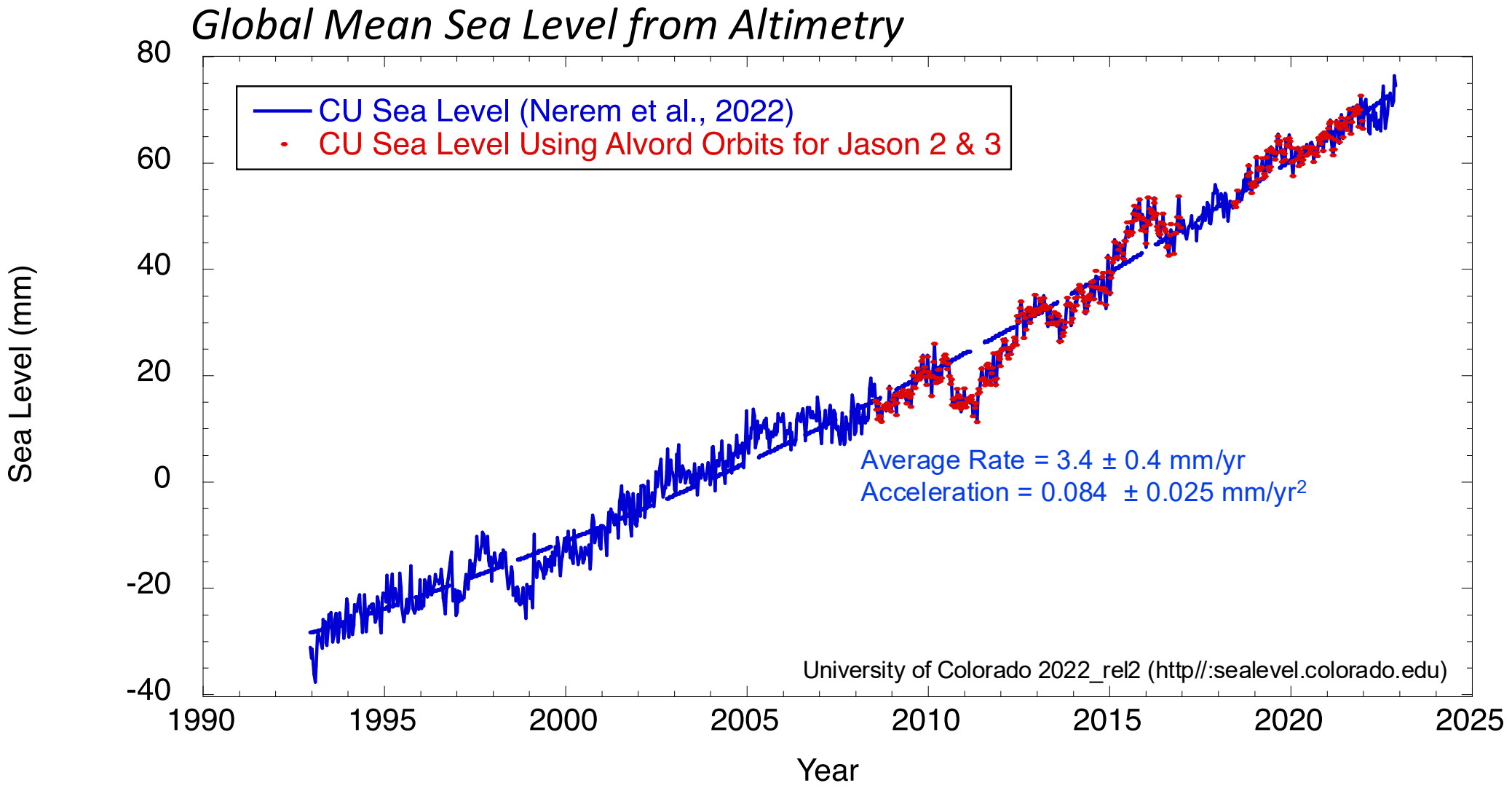
Geodynamic Modeling

Mega-Earthquakes: Measuring fingerprints on Earth Orientation Parameters (EOP).

Model Validation/Enhancement: Assist Ice sheet system modeling to constrain mantle rheology and mass distribution.

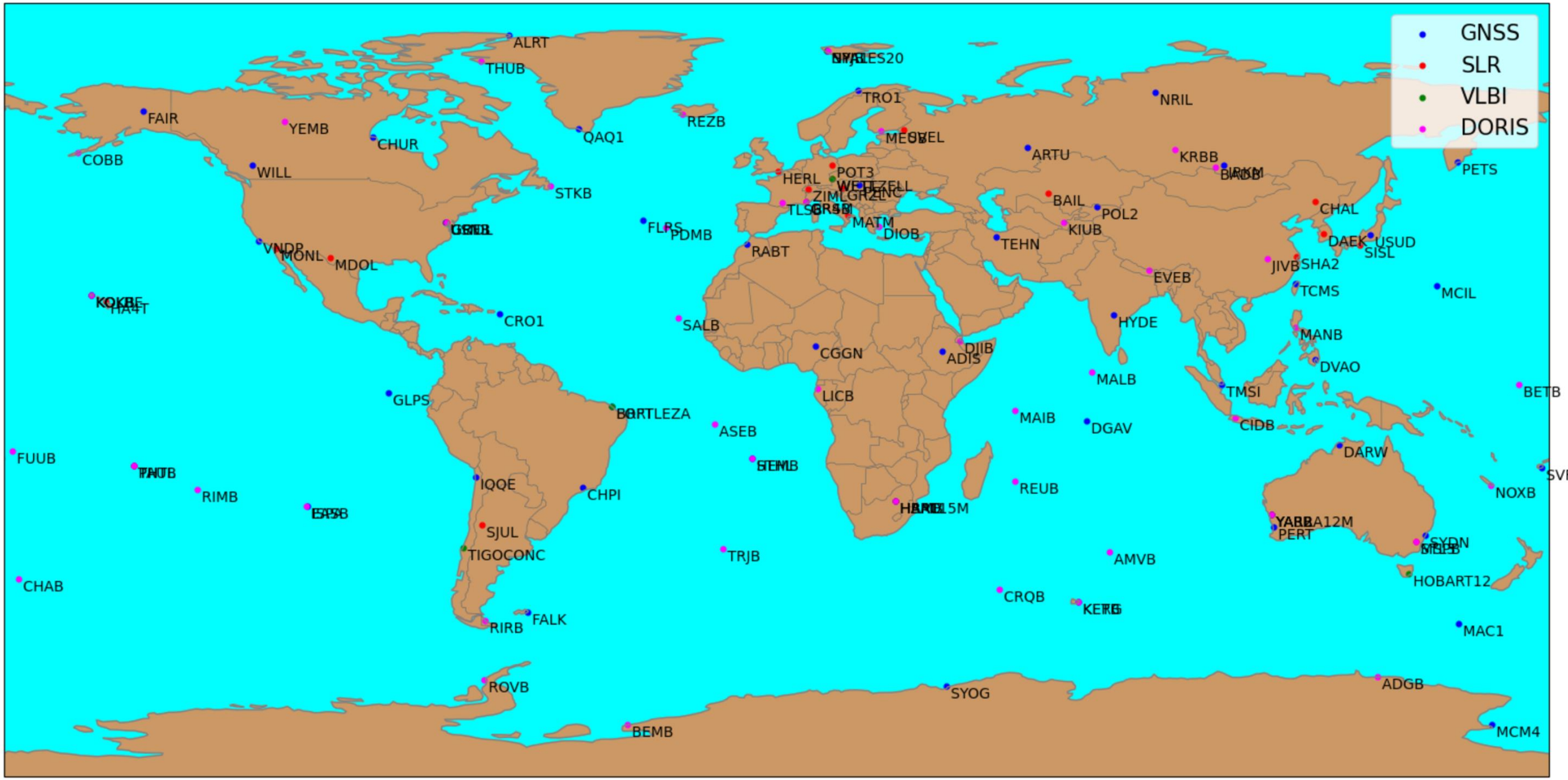
How Does TRF Impact Sea Level?

- Jason-2 & 3 orbit solutions are taken directly from Alvord GPS-only network solutions.
- Differences with standard (GDR) orbits are projected onto global sea level record.
- Results suggest negligible impact (0.02 mm/yr) on estimates of global sea level rate.

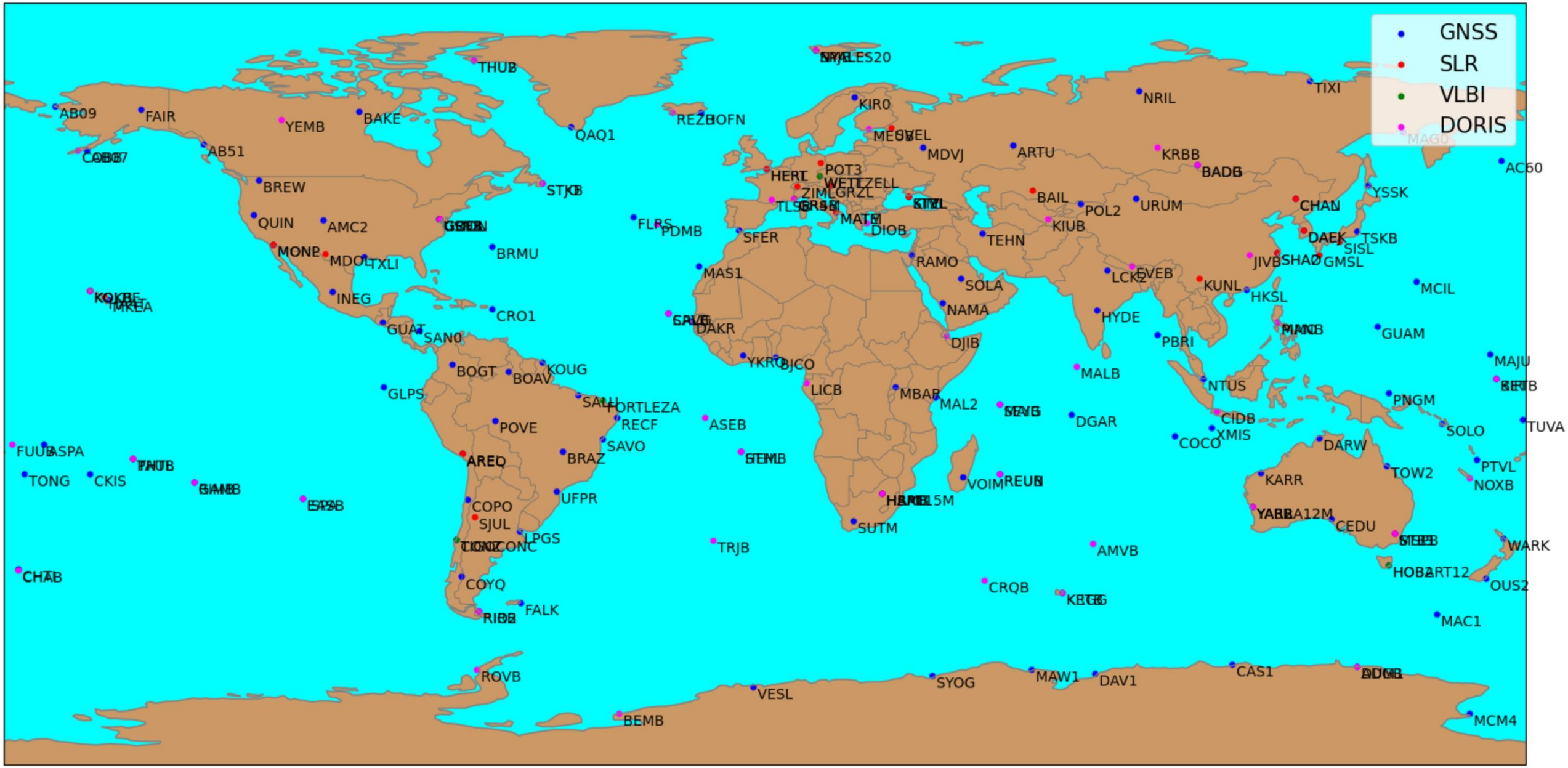


Supplementary Material

TRF network distribution 2014-04-15 - before modernization



TRF network distribution 2014-04-15



DORIS residuals

DORIS observations are processed at 10 sec data-rate.

80% of the residuals range within $\pm$ 0.5 mm/s