Realization of Terrestrial Reference Frame at the observation level using space geodetic techniques

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Session 2 - Building Global GNSS-Based Reference Frames

Jet Propulsion Laboratory
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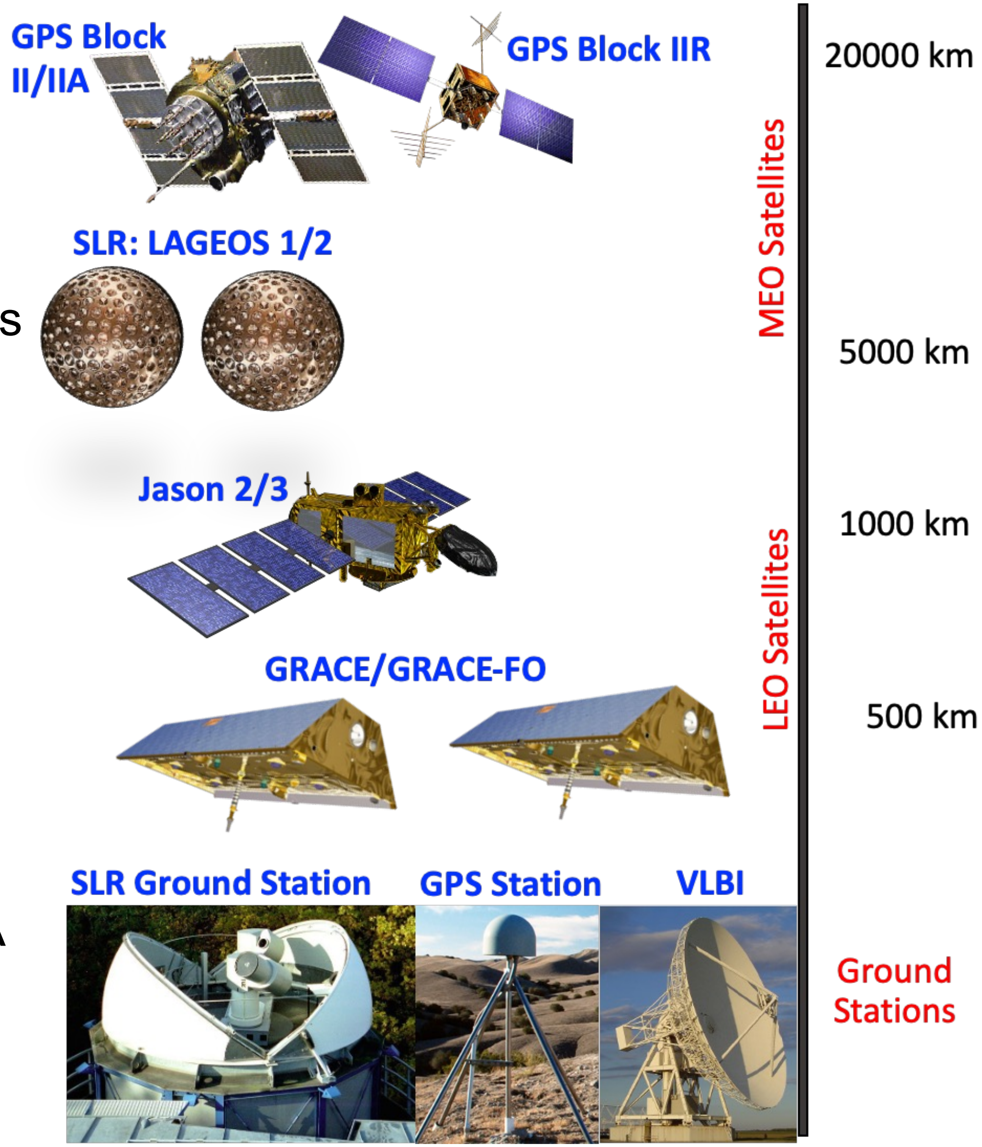
Observation-Level Terrestrial Reference Frame

- Combines 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
  - De-couples frame estimates from systematic GPS draconitic errors
  - Improves observability and coverage relative to ground network
- Uses single software system (GipsyX) for all techniques
  - Ensures consistent standards.
- Products unified with the frame
  - Precise orbits for strategic LEOs, time variable gravity & EOP
  - Independent of ITRF releases and associated cadence (few years)
- Reduces burden on infrastructure and processing
- Reflects key aspects of GRASP mission concept, proposed to NASA (2011 & 2015), and the recent announced GENESIS ESA mission.



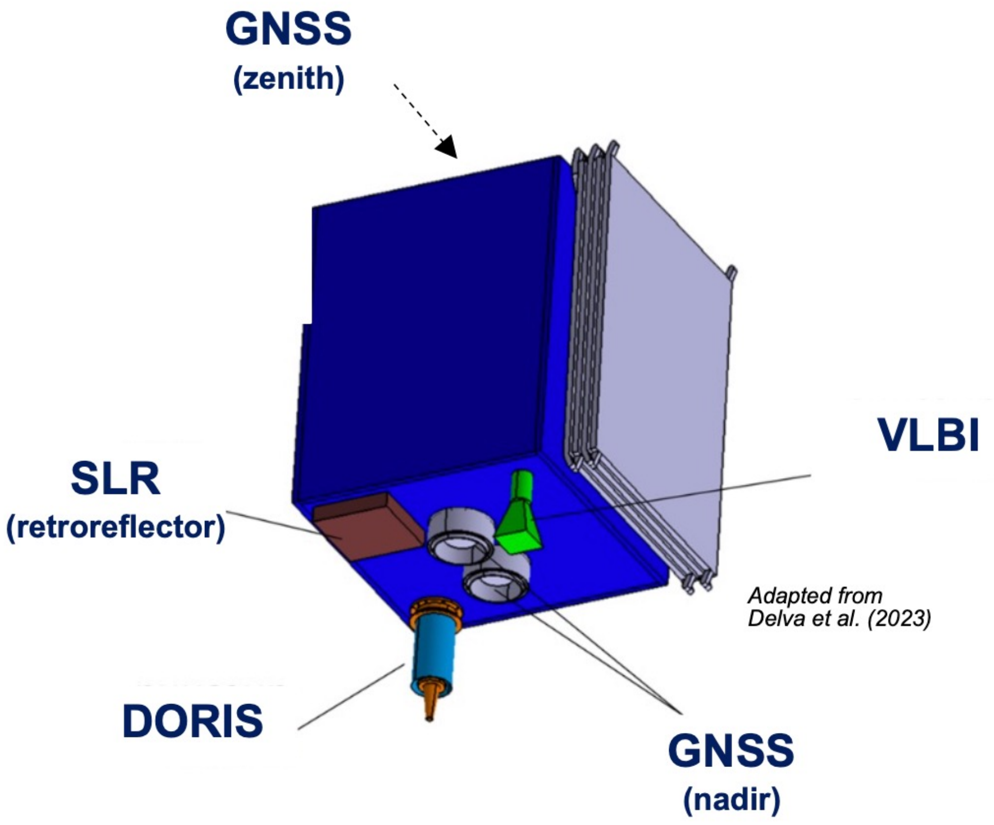
Space Ties Link Geodetic Techniques

GENESIS (ESA)

- Dedicated Mission
- 6000 km orbit, planned 2028 launch
- Space Ties for all Geodetic Techniques

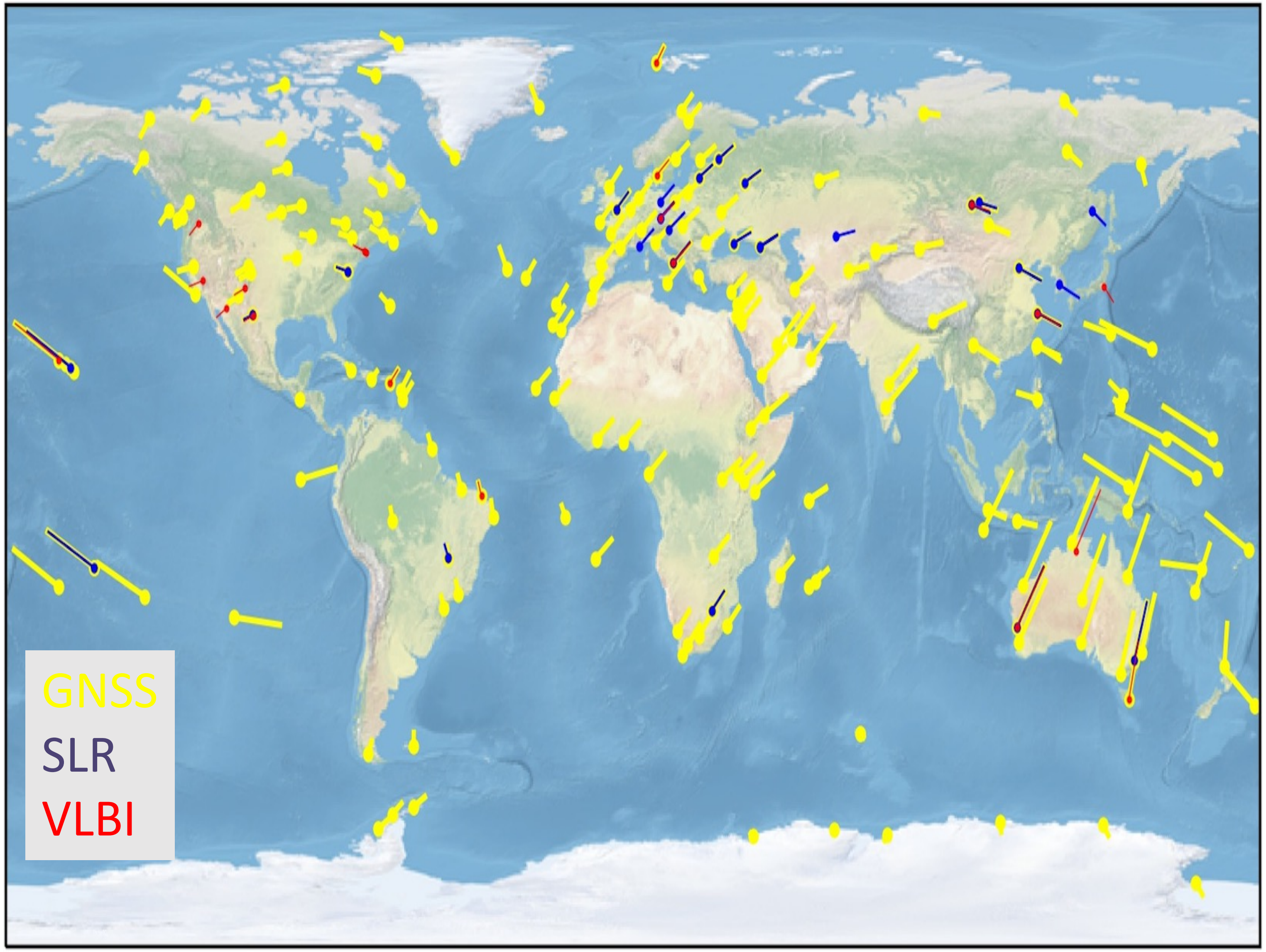
Observation level TRF (JPL)

- No dedicated mission →
  Observations of opportunity
- Space Ties for all Geodetic Techniques (except VLBI)



Realization of Observation-Level Terrestrial Reference Frame

Horizontal Velocity Field (Plate Tectonics)



- 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 500 stations.
  - Mostly GNSS (388), but also many SLR (47) and VLBI.

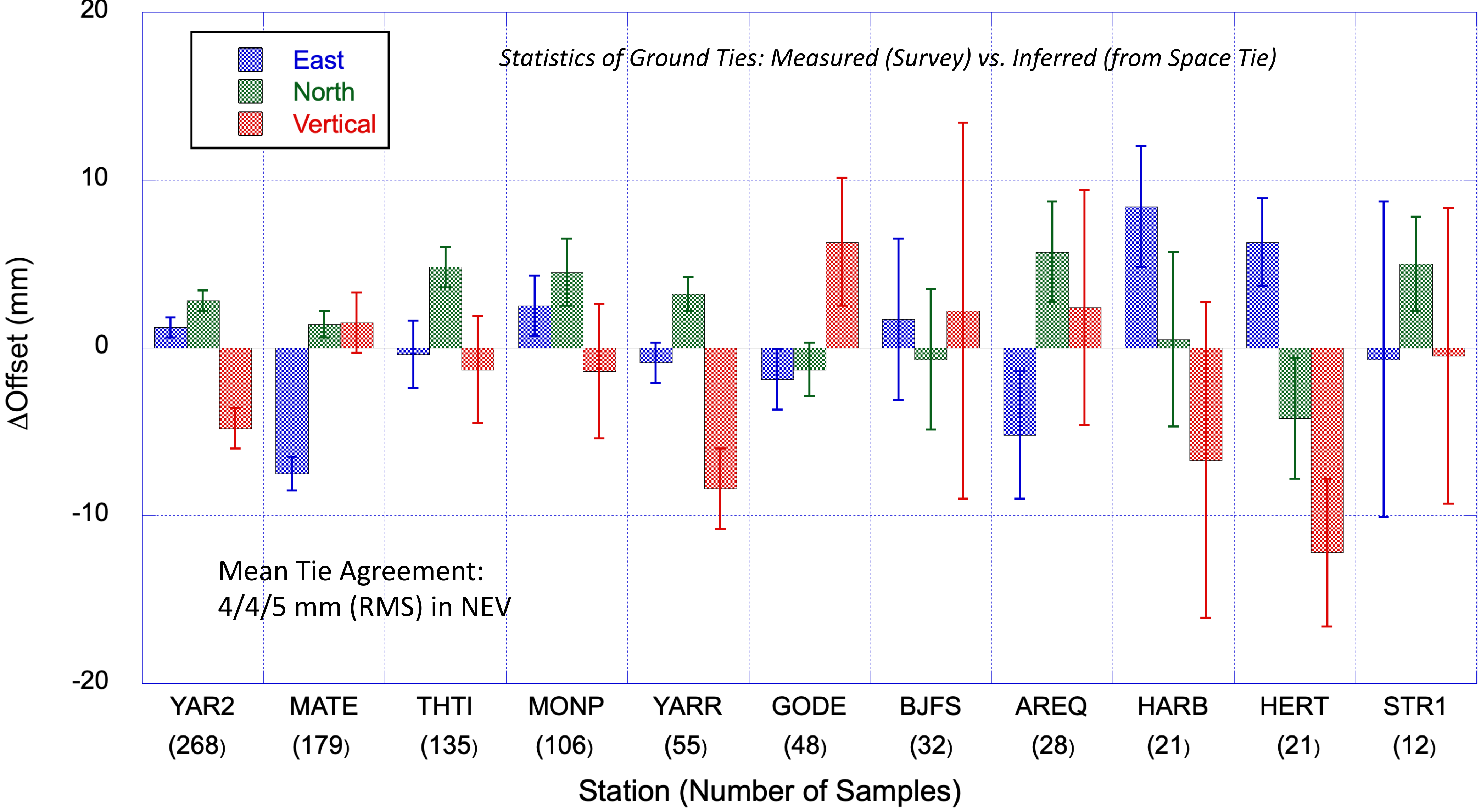
In the plot (left)

Linear and annual motions for:

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

New Solution Demonstrates Strong Potential of Space Ties

Ground Ties Between GNSS & SLR Accurately Recovered with No Prior Information



- Error bars represent $\pm 2\ s_x$ where s_x = standard error of the mean.
- Ties with 3D formal errors > 20 mm (from network solution) removed.

How Does Observation-Level Frame Compare to ITRF2020?

- Testing contribution of different geodetic techniques: GPS-Only, GPS+SLR, GPS+SLR+VLBI
- Geocenter offset : All techniques are competitive to ITRF2020
- Long-term stability: All techniques are indistinguishable from ITRF2020 (0.0–0.3 mm yr^{-1} per component).
- Scale: GPS-only poor agreement with ITRF2020

Geocenter and scale offset (mm) at 2015.0

Solution	Offset in mm at Epoch (January 1, 2015)			
	δX	δY	δZ	δScale
GPS Only (Ground + LEO)	–0.58 ± 0.67	–1.49 ± 0.66	–0.69 ± 0.83	+6.01 ± 0.63
GPS + SLR	+0.15 ± 0.37	–1.78 ± 0.34	+0.43 ± 0.55	+2.32 ± 0.52
GPS + SLR + VLBI	+0.05 ± 0.34	–1.83 ± 0.31	+1.11 ± 0.51	+2.82 ± 0.41

Relative Drift (mm yr^{-1})

Solution	Rate in mm yr^{-1}			
	δX	δY	δZ	δScale
GPS (Ground +LEO)	+0.06 ± 0.05	+0.32 ± 0.05	–0.09 ± 0.11	–0.12 ± 0.06
GPS + SLR	+0.14 ± 0.04	+0.24 ± 0.04	–0.09 ± 0.10	–0.22 ± 0.05
GPS + SLR + VLBI	+0.11 ± 0.04	+0.18 ± 0.04	+0.02 ± 0.09	–0.05 ± 0.05

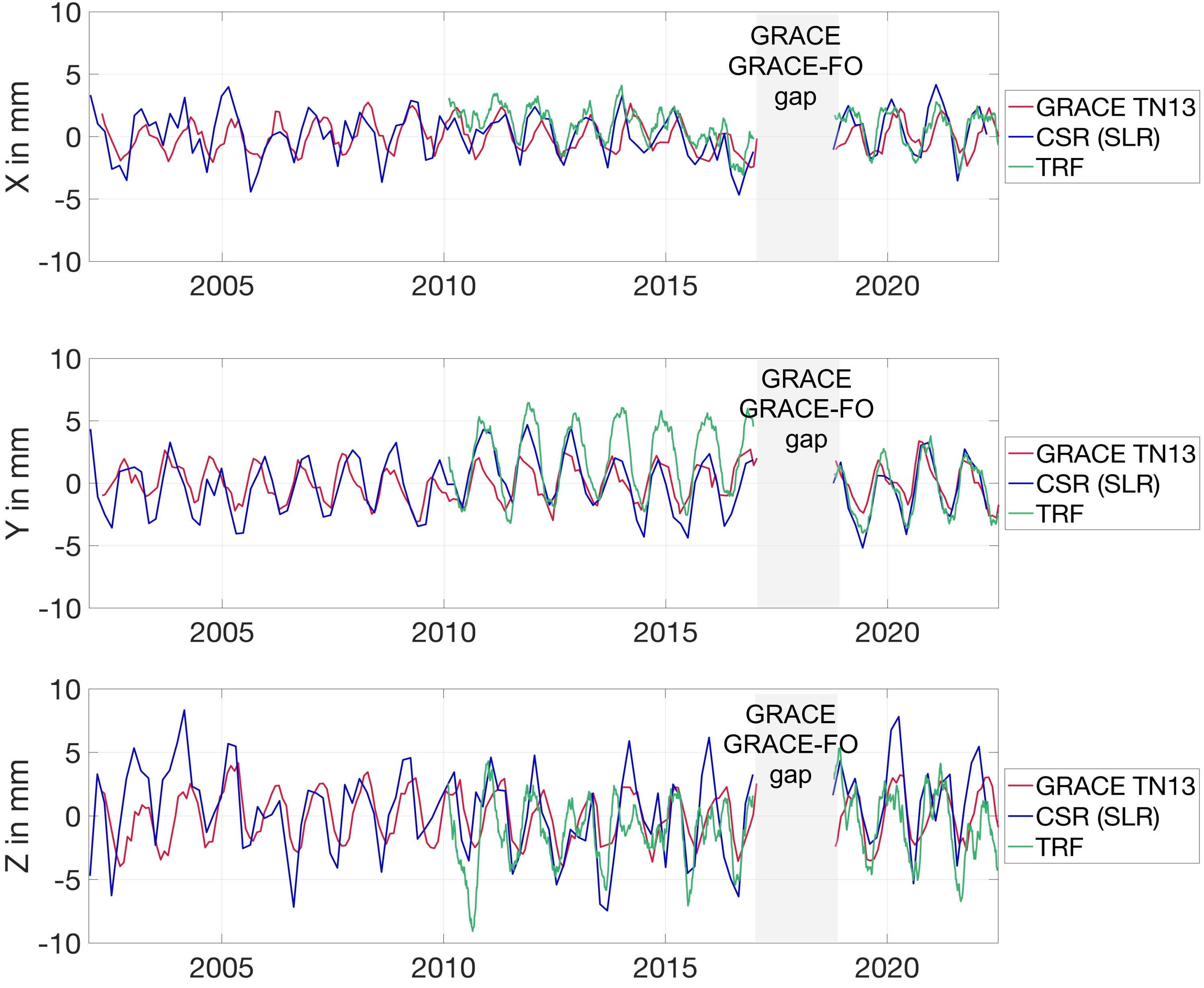
Annual Geocenter Motion (Degree-1 Gravity)

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

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

- Equatorial **Y** component
  - Excellent agreement in amplitude (3 m 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.

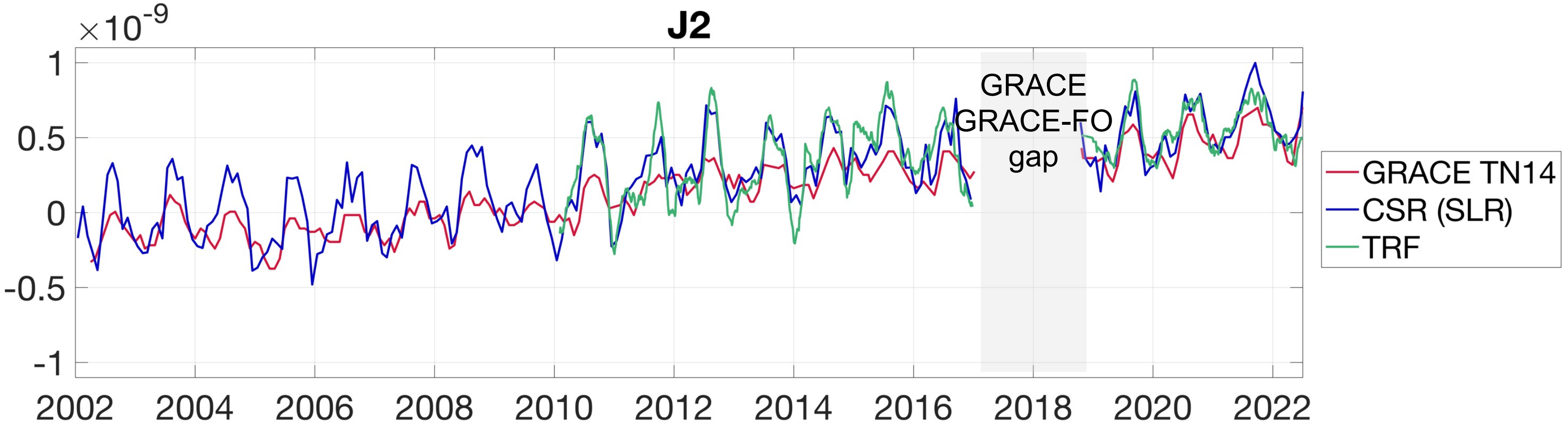


Time Variable Gravity

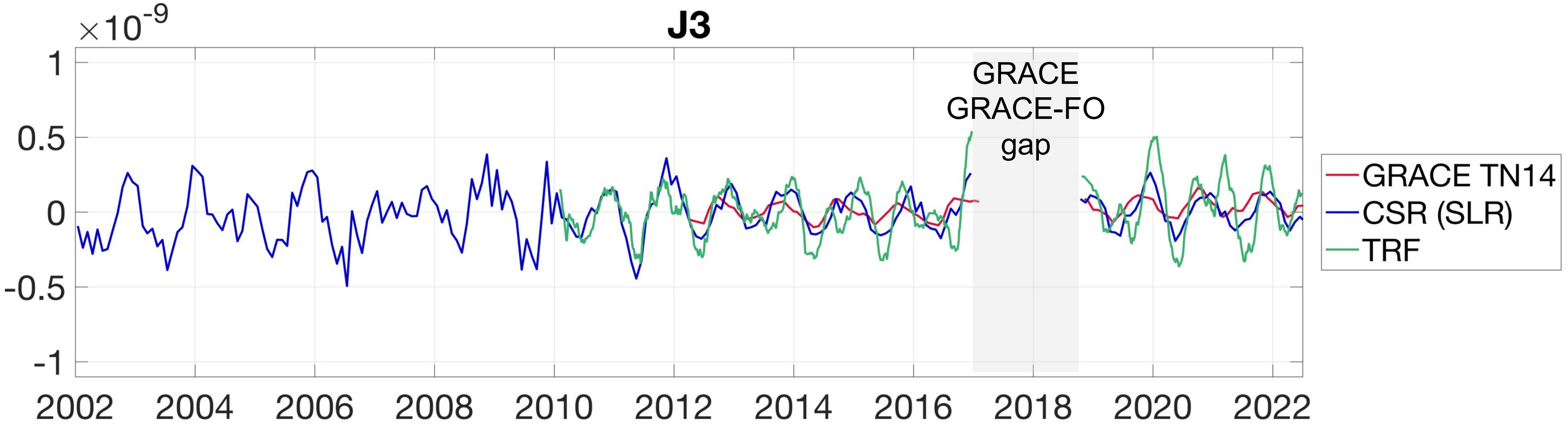
Fundamental frame parameters & low degree gravity field: Unified

- Observation-level frame (TRF) vs:
  - GRACE TN14 (*Loomis et al., 2020)*
  - CSR SLR (*Ries, 2016*)

J2: Inclusion of SLR (esp. LAGEOS) → Significantly improves recovery of *J2.*

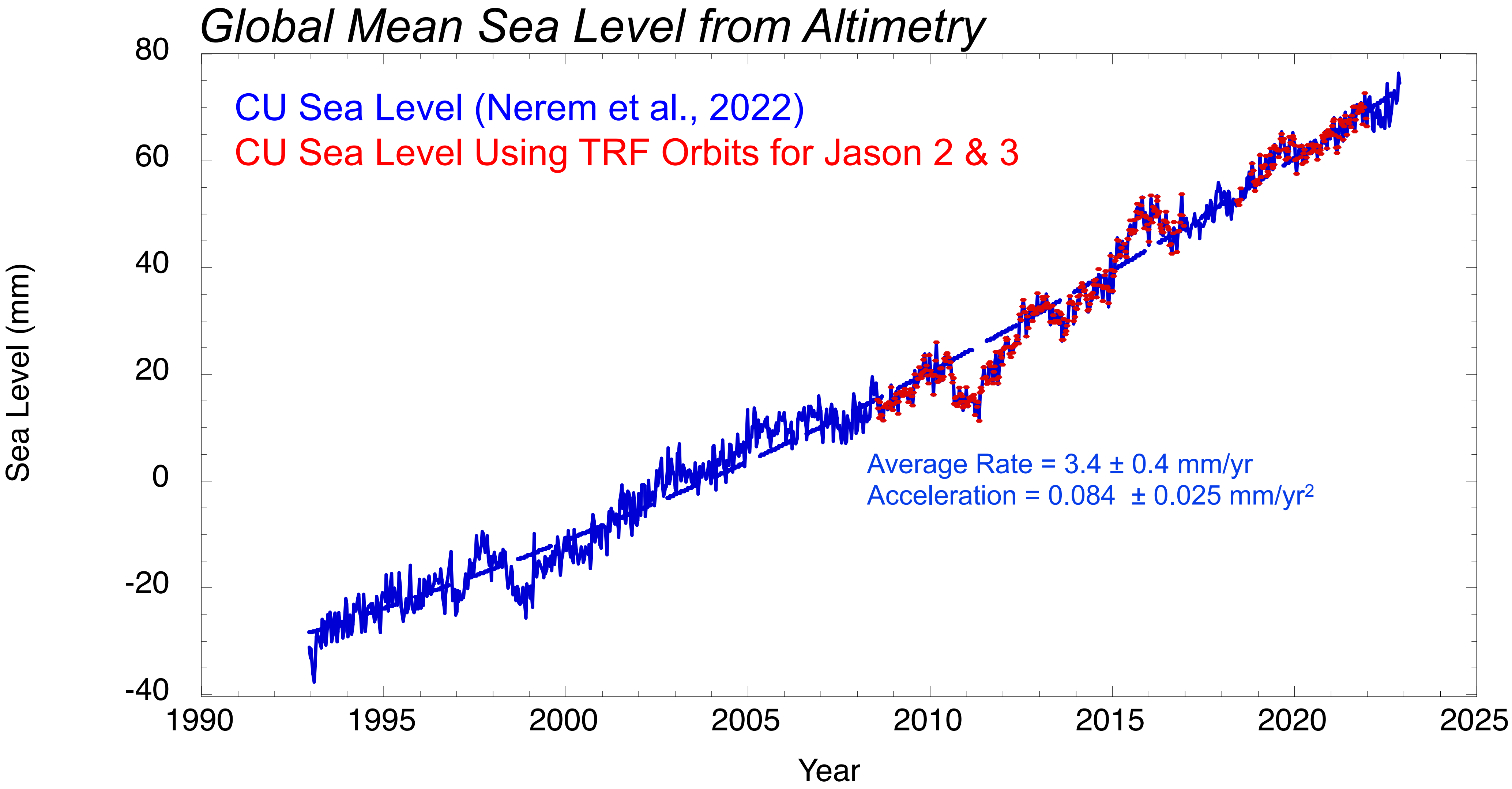


J3: In family with competing solutions. Addition of LARES expected to improve the amplitude of the annual cycles.



How Does Experimental TRF Impact Sea Level?

- Jason-2 & 3 orbit solutions are taken directly from TRF GPS-only network solutions.
- Differences with conventional (IGb14) GPS-only orbits are projected onto global sea level record.
- Results suggest negligible impact on estimates of global sea level rate.



Summary

Hallmarks of new Observation Level TRF

- Combines three techniques (GPS, SLR and VLBI) at the observation level + strategic LEOs
- Uses space ties to connect satellite geodetic techniques.
- Advantages: Light infrastructure | immune to frame aging | unified geodetic byproducts.

TRF performance

- Indistinguishable from ITRF2020 in terms of long-term stability.
- Shows significant benefit of LAGEOS/SLR for low-degree gravity (*J2*).
- Impact of observation level frame on global & regional sea level: fully competitive with ITRF.

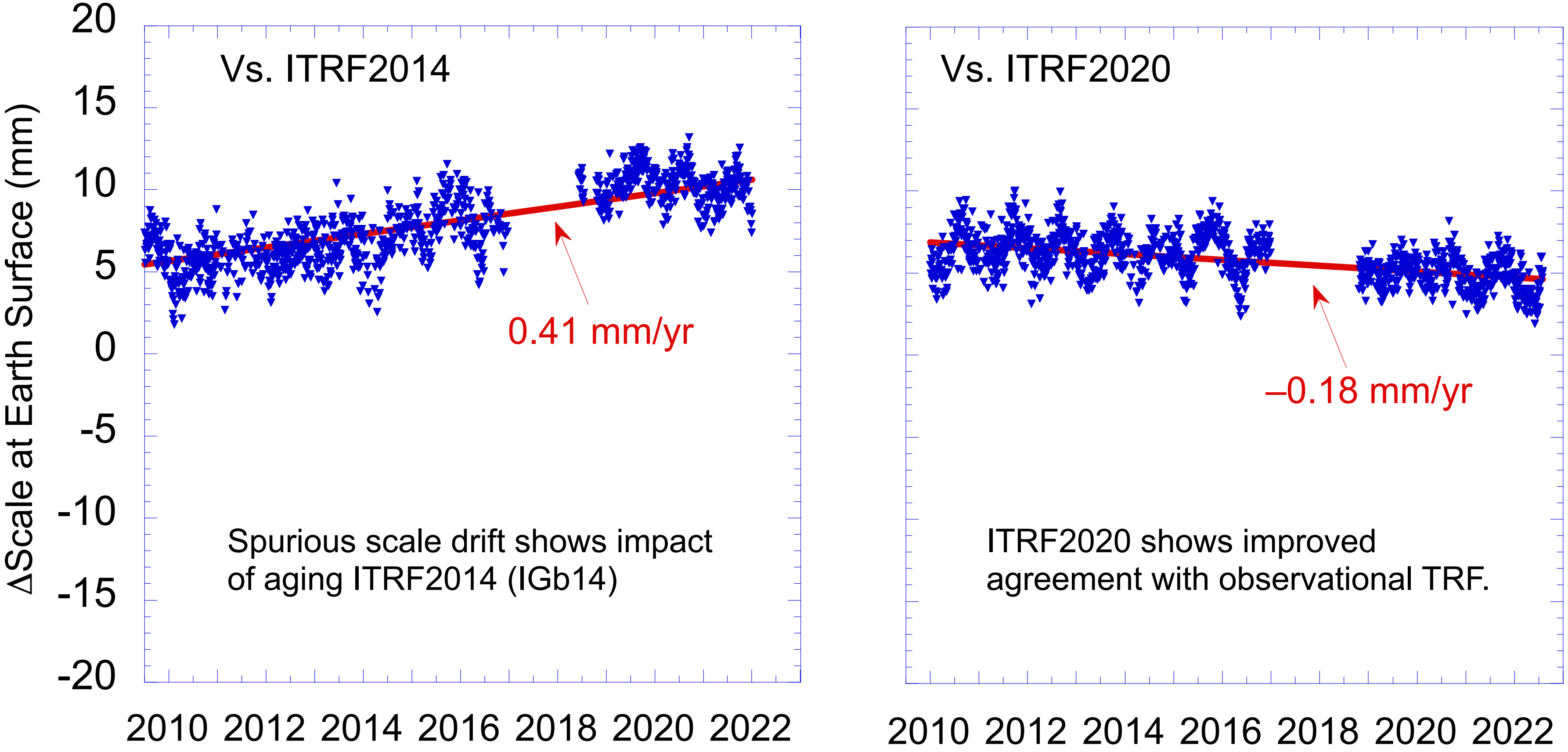
Future work

- Test routine production
- Explore enhancements: GRACE KBR, Multi GNSS, addl. strategic LEOs (Sentinel-6).

Supplementary Material

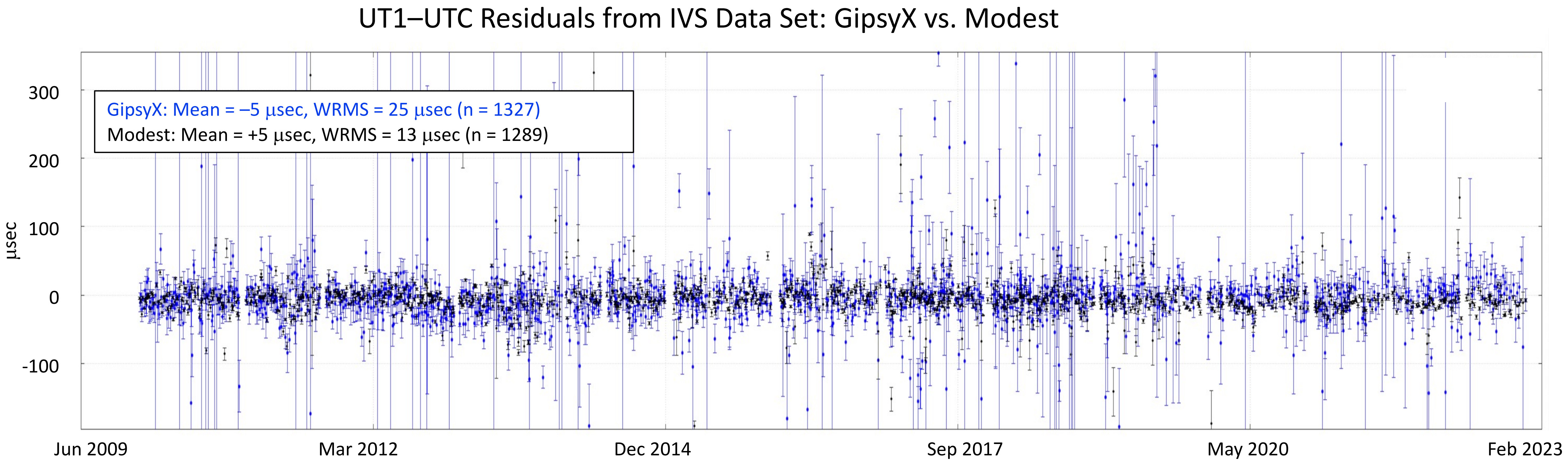
Evolution of Scale vs. ITRF

Stable TRF scale revealed signs of aging in ITRF2014



Earth Orientation Parameters

- In Alvord Solutions, Polar motion and UT1–UTC estimated using a random walk model with 2-hr updates.
- Inclusion of VLBI (for selected arcs) enables estimates of absolute UT1 (vs. UT1 variations from GPS).
- GipsyX estimates for UT1–UTC from VLBI approaching results from legacy (Modest) software.



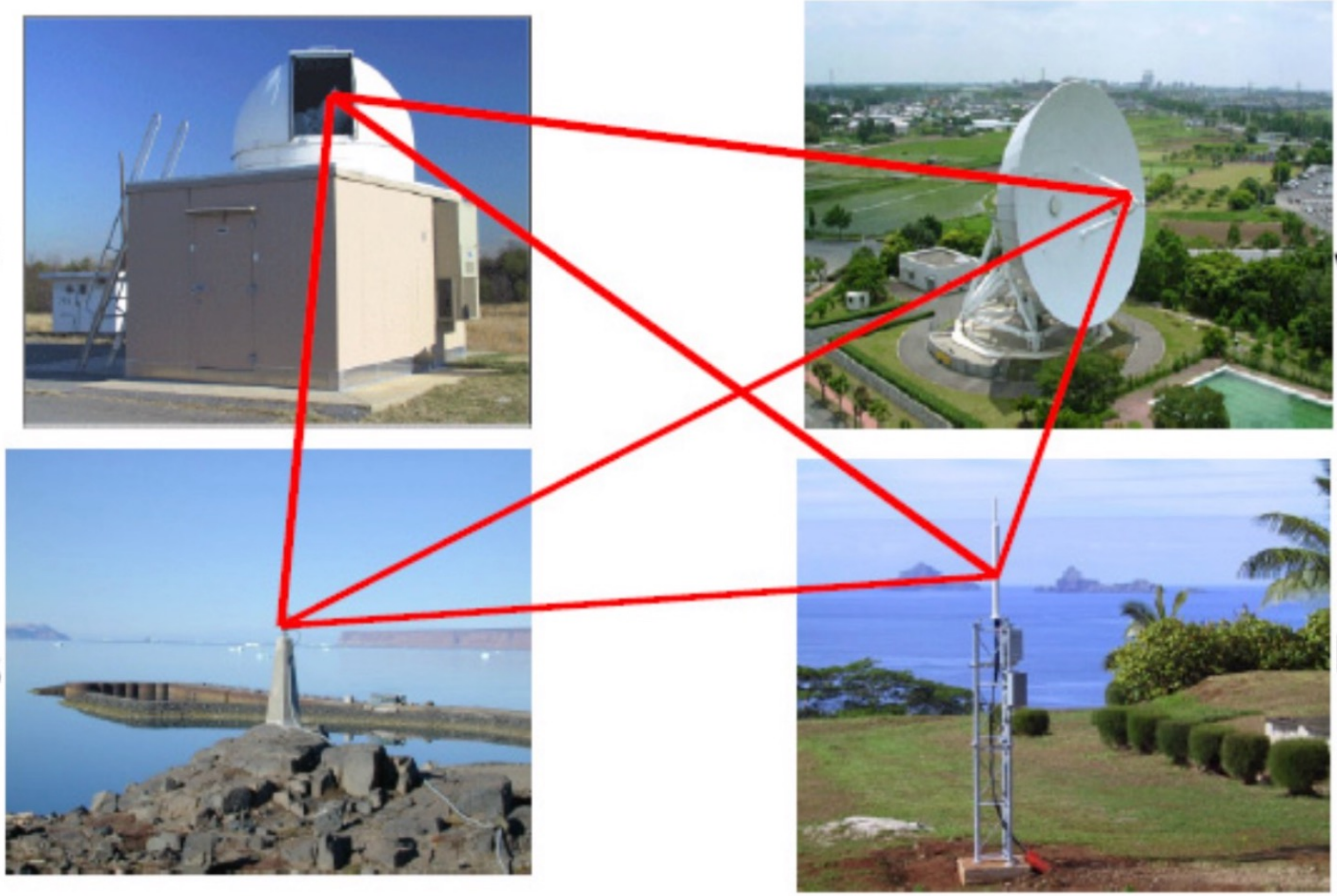
Current Practice:
Ground Survey Ties Link Geodetic Techniques

Measurement Reference Points

Survey Benchmark

SLR/LLR

VLBI

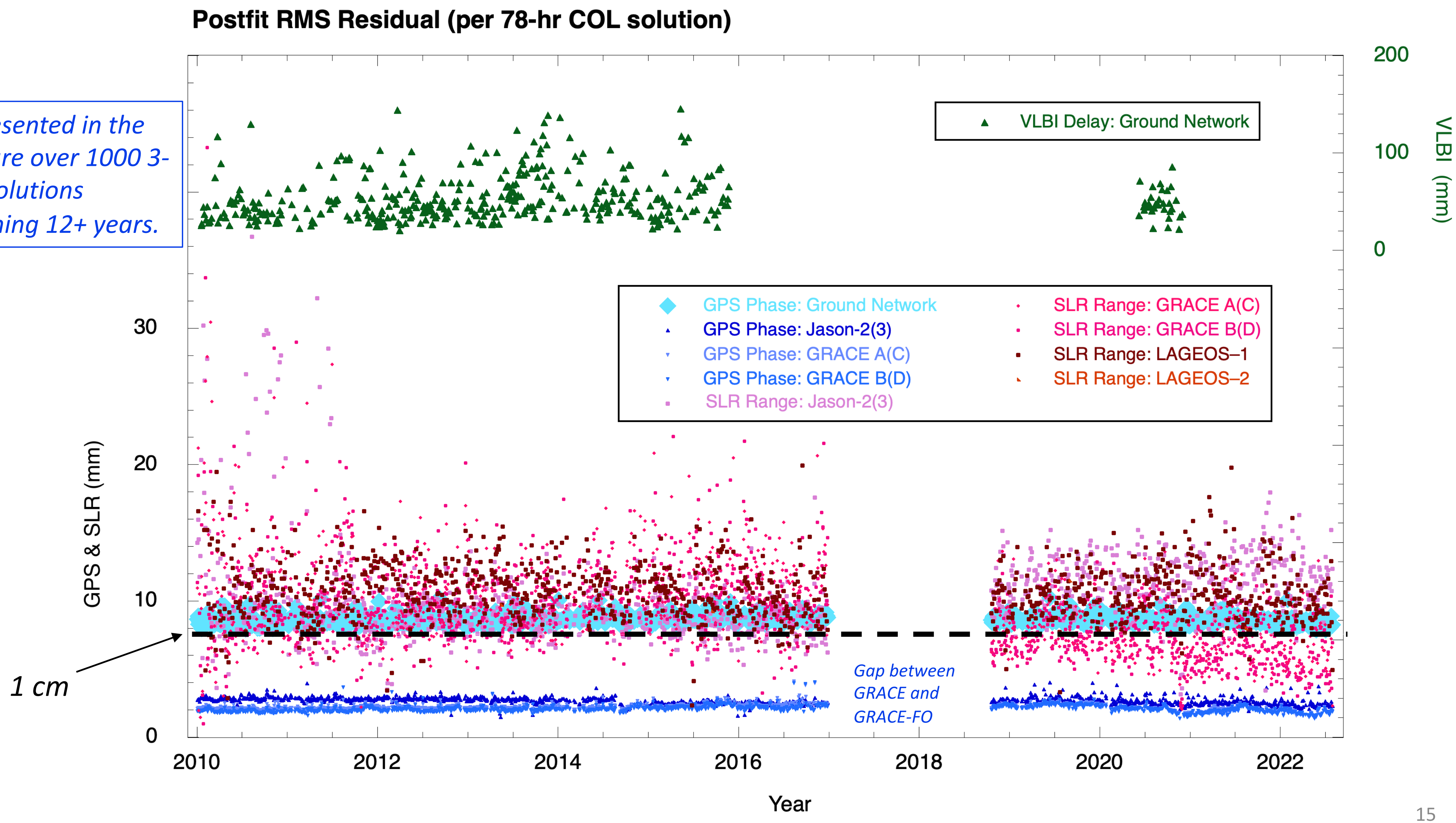


GNSS

DORIS

Tracking Residuals From a Global Combination at the Observation Level

Represented in the plot are over 1000 3-day solutions spanning 12+ years.

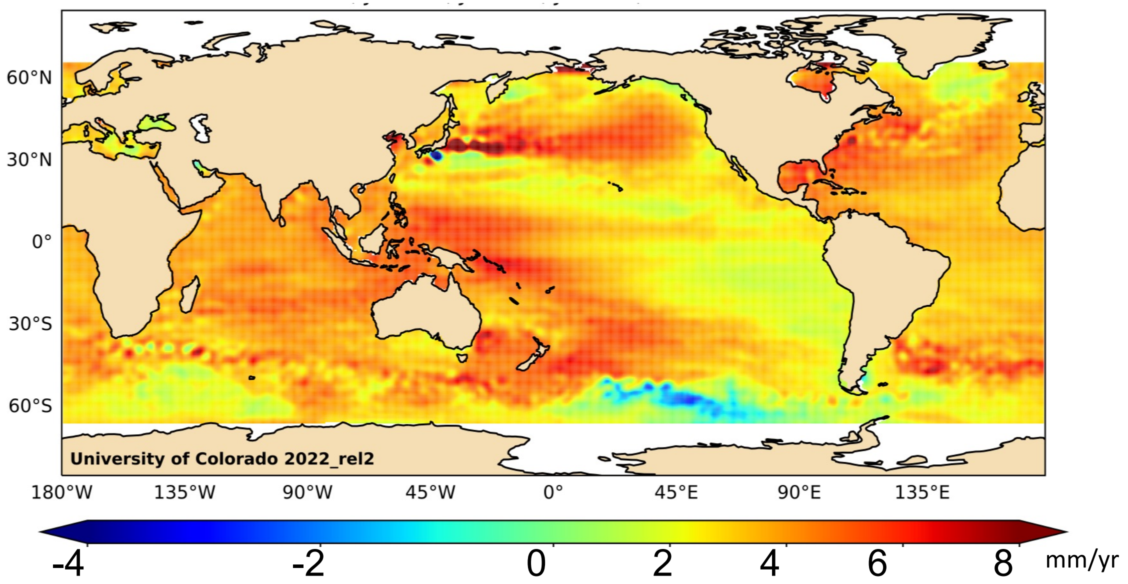


Consistency between Alvord and ITRF in Recovering Regional Sea Level Trends from Jason

Sea Level Trend Map (CU, Nerem et al.)

Global Statistics:

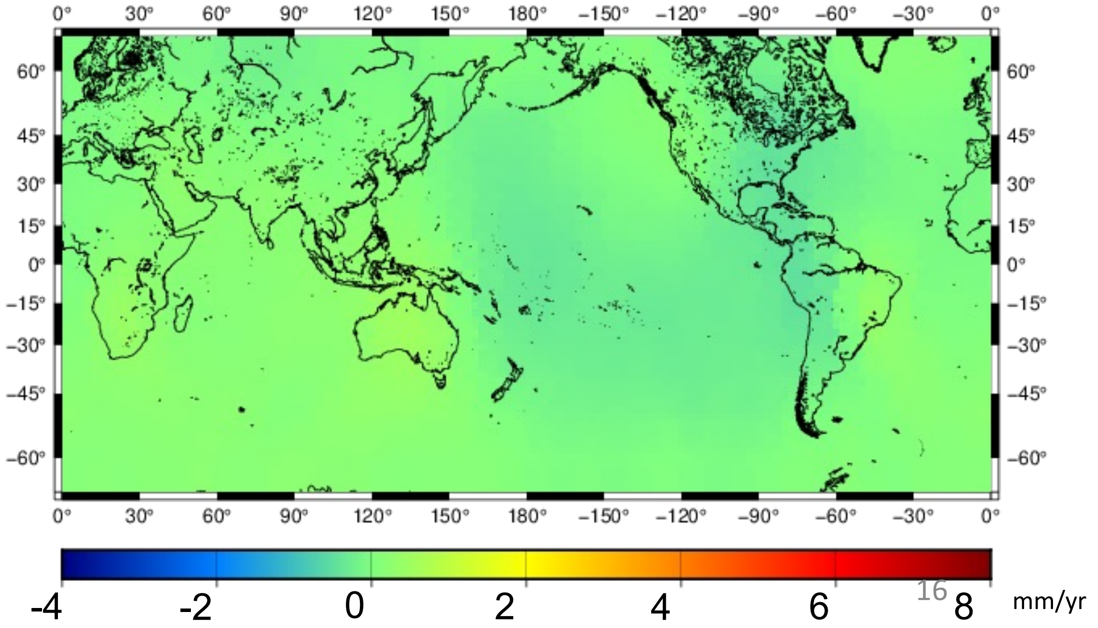
Mean = +3.32 mm yr^{-1}
σ = 1.35 mm yr^{-1}
Min = –10.16 mm yr^{-1}
Max = +20.66 mm yr^{-1}



TRF Differences (Alvord vs. ITRF)

Global Statistics:

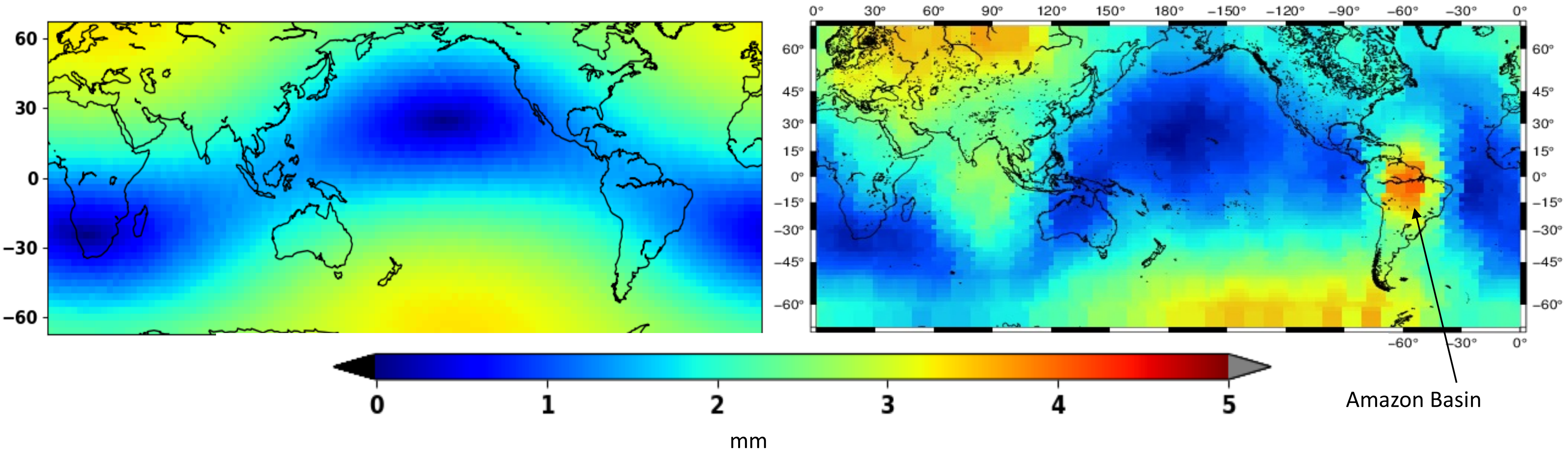
Mean = –0.02 mm yr^{-1}
σ = 0.20 mm yr^{-1}
Min = –0.48 mm yr^{-1}
Max = +0.51 mm yr^{-1}



Annual Amplitude of Jason Orbits Differences (Alvord vs linear ITRF): Reveal Impact of Annual Geocenter Motion on Sea Level

Model Amplitude
For Jason Orbits From Model of Annual Geocenter Motion (Desai et al., 2018)

Observed Amplitude (2010–2022)
For Jason Orbits From Differences of Alvord & ITRF



- Hemispheric signal depicts expected pattern of annual geocenter motion, with the Alvord Jason orbits following the quasi-instantaneous TRF.
- Regional patterns in South America (Amazon Basin) and Southeast Asia (Monsoons) reflect time-variable gravity at shorter wavelengths.