Terrestrial Reference Frame from Combined Precise Orbit Determination of GPS, GRACE, and LAGEOS

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Outline

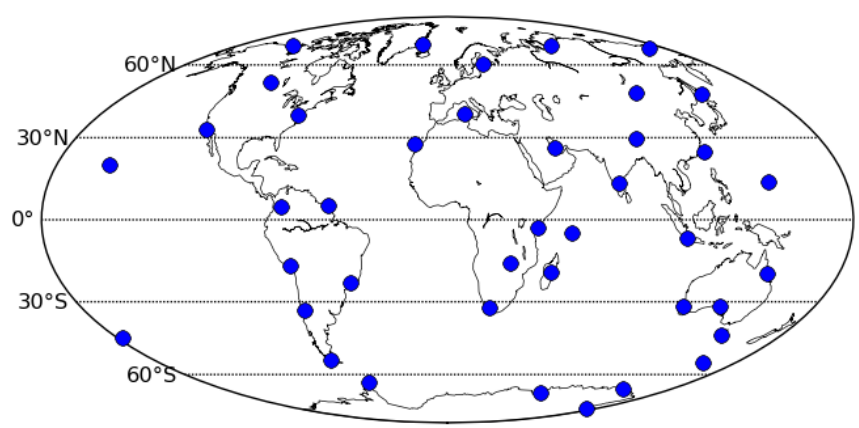
- Introduction
- Orbit determination strategy
- Antenna calibrations
- Evaluate three solutions
  - GPS
  - GPS + GRACE
  - GPS + GRACE + LAGEOS
    - Combining GPS and SLR at measurement level
- Summary and conclusions

Introduction

- Goal is to realize accurate and stable terrestrial reference frame (TRF) from GPS and low Earth orbiters (LEO)
- Approach
  - Perform precise orbit determination (POD) of GPS constellation
  - Include GRACE-A
  - Then add SLR tracking to LAGEOS-1/2, combining techniques at measurement level
- Processing utilizes multi-day arcs, GRACE-based transmit antenna calibrations, very different estimation strategy vs. JPL's operational POD and IGS contribution
- Careful to generate solutions independent of ITRF
  - Can validate TRF realizations relative ITRF/IGb08

Ground Network

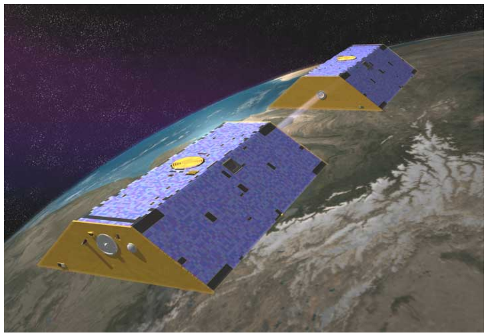
- Desire homogeneous stations for TRF realization
  - Limit to sites with choke-ring antennas
  - TurboRogue-inspired design is common in global geodetic network
- Check daily data quality metrics (e.g. phase breaks, postfit residual statistics) and remove poor quality sites
- Select approximately 40 stations
  - Half in each hemisphere
  - Improves Z-origin

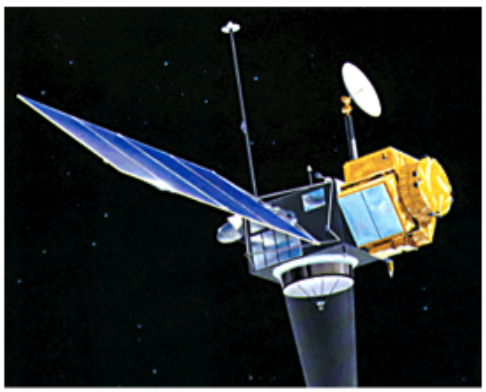


POD Strategy

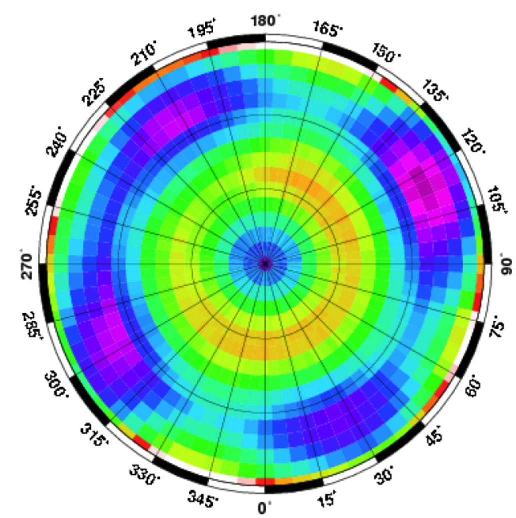
	JPL Ops/IGS	Long-Arcs TRF
Orbit Arc	30 hours (centered at noon)	3 days (capitalize on dynamics)
Number of GPS Stations	80	~40
Elevation Angle Cutoff	7 deg	10 deg
Albedo Model	Applied	Applied
Transmitter Antenna Calibration Model	IGS standard APV maps	Topex/GRACE-based APV maps
Receiver Antenna Calibration Model	IGS standard APV map	JPL Antenna Test Range (Young and Dunn, 1992)
Pole Position	X, Y offset and rate per arc	X, Y offset as random walk (daily update)
UT1-UTC	Rate per arc	Not estimated
1 and 2 CPR Empirical Accelerations	Not estimated	UVW coordinates as random walk

LEO-Based GPS Transmitter Antenna Calibrations





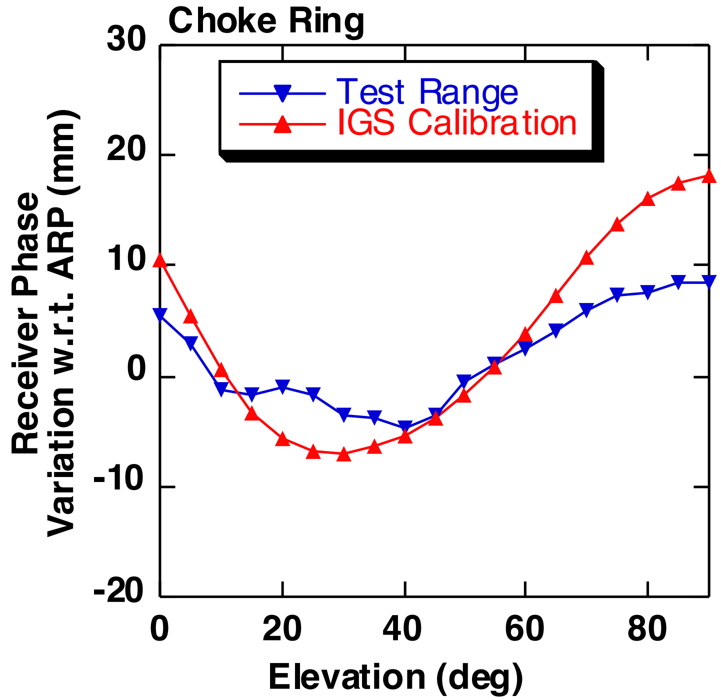
- Estimate calibrations in tandem with TOPEX/GRACE orbit determination
- LEOs above troposphere, low multipath
- GRACE anechoic chamber calibration is reference
- No constraint to ITRF as POD is fiducial-free
- Scale from satellite dynamics
- Calibrations derived for Block II/IIA/IIR



TYPICAL GPS APV (LC)

See poster by Haines et al., "The Terrestrial Reference Frame from GPS: New Perspectives from Low-Earth Orbit" for additional antenna calibrations.

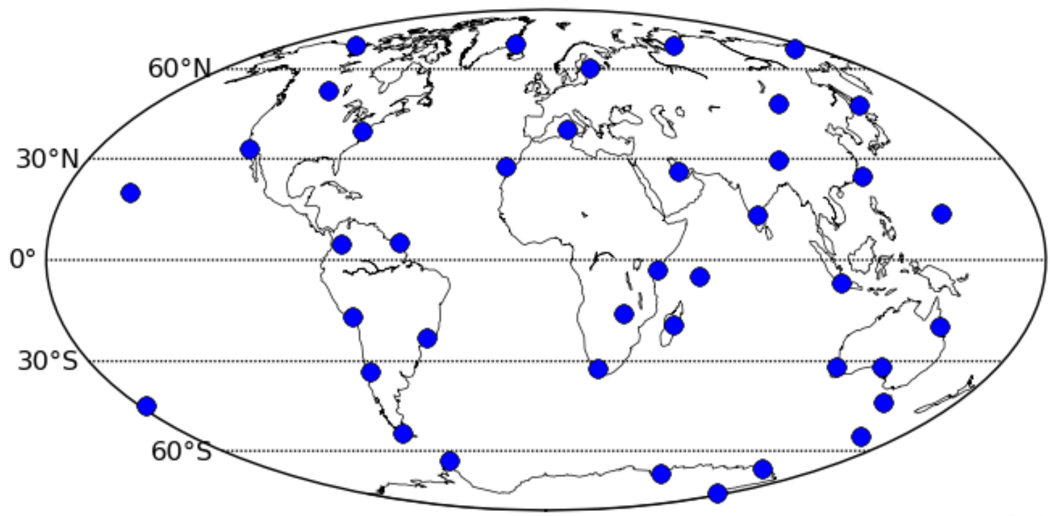
Test Range Choke-Ring Antenna Calibration



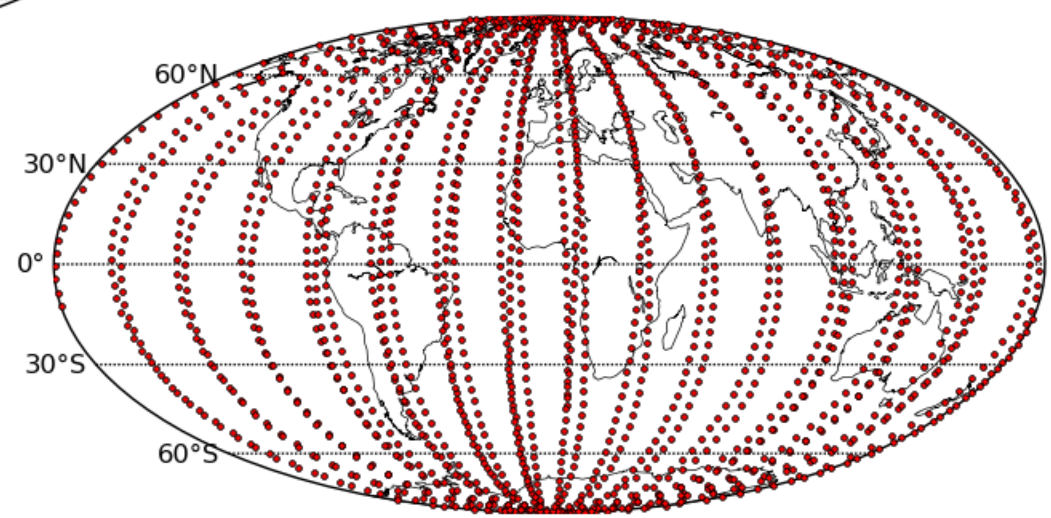
- JPL test range calibration (Young and Dunn, 1992)
- Comparison to IGS robot calibration for AOAD/M_T shows:
  - 2-mm agreement in estimated LC phase center offset
  - 4-mm RMS difference in LC antenna phase variation (APV)
  - Similar APV patterns, but factor of 2 difference in amplitude
- Test range APV more coherent with GRACE-based GPS APV

GRACE Improves Observation Geometry

- **LEO in polar orbit provides coverage over oceans and both hemispheres**

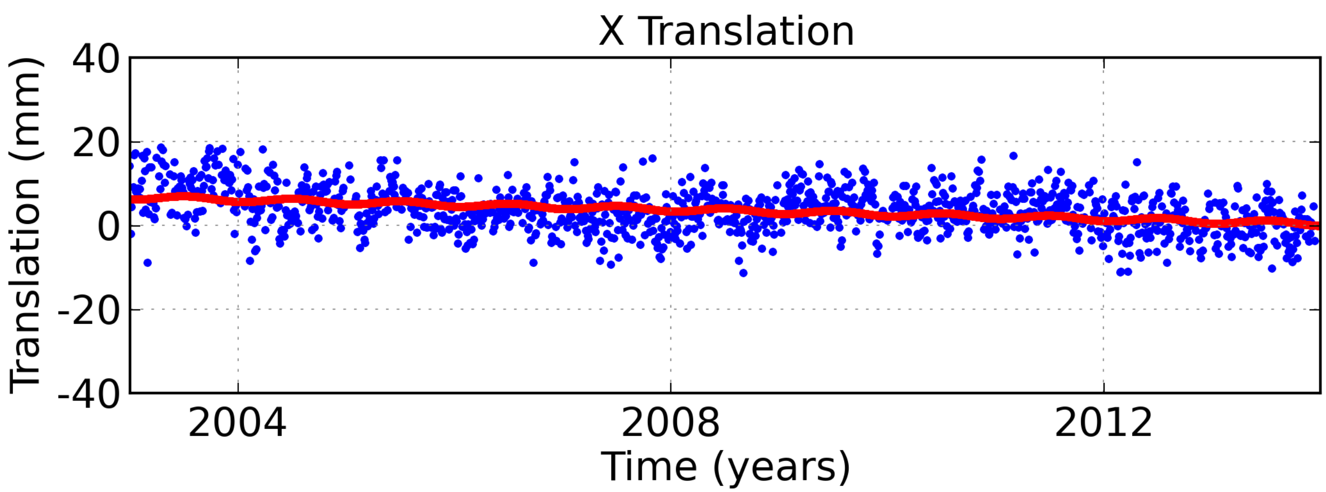


1-Day GRACE-A Ground Track



TRF from GPS: X-Origin

GPS | **GPS+GRACE-A**

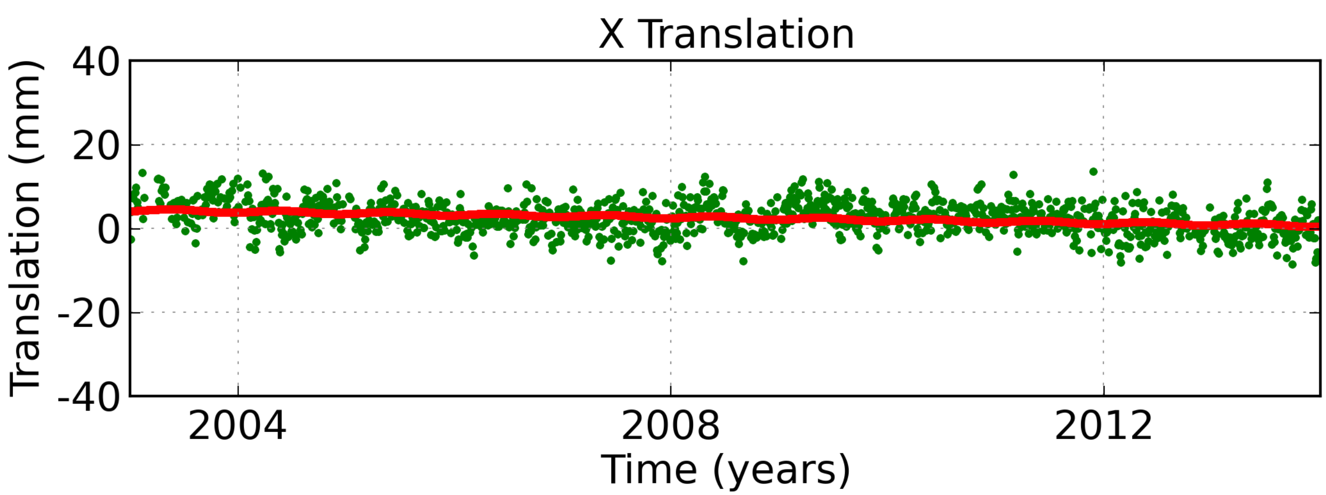


Bias: 5.6 mm

Trend: -0.6 mm/yr

Annual: 0.5 mm

Postfit: 5.5 mm RMS



Bias: 3.7 mm

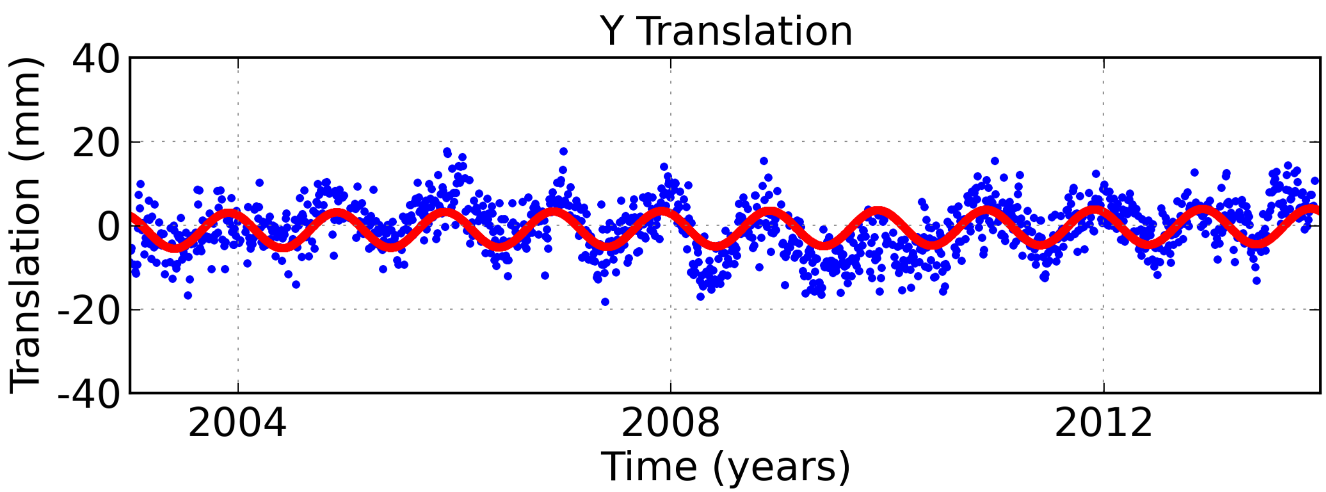
Trend: -0.3 mm/yr

Annual: 0.3 mm

Postfit: 3.9 mm RMS

TRF from GPS: Y-Origin

GPS | **GPS+GRACE-A**

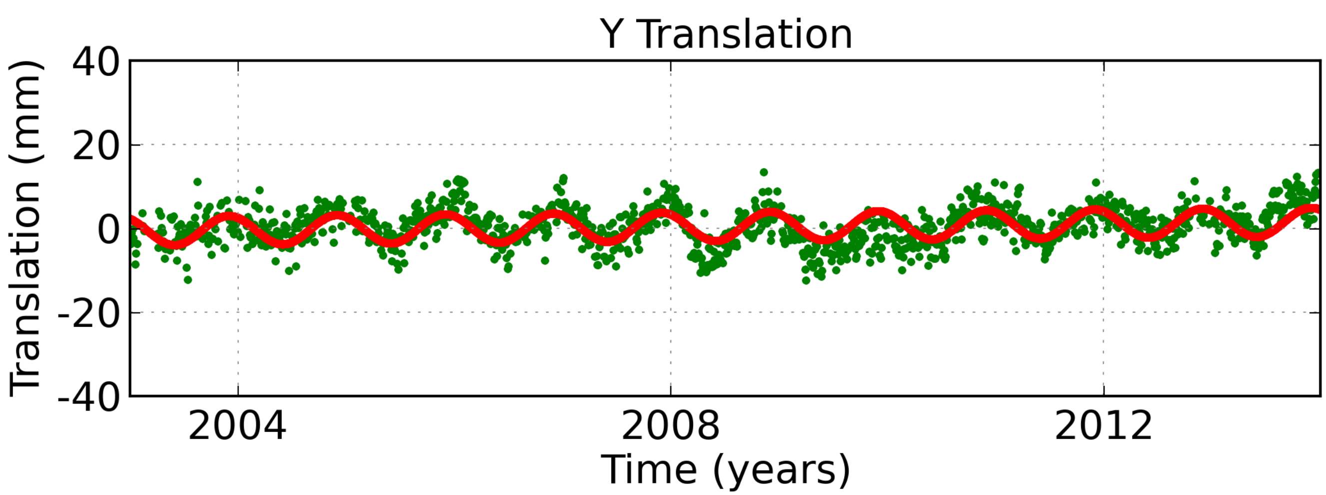


Bias: -1.1 mm

Trend: 0.1 mm/yr

Annual: 4.3 mm

Postfit: 7.1 mm RMS



Bias: -0.2 mm

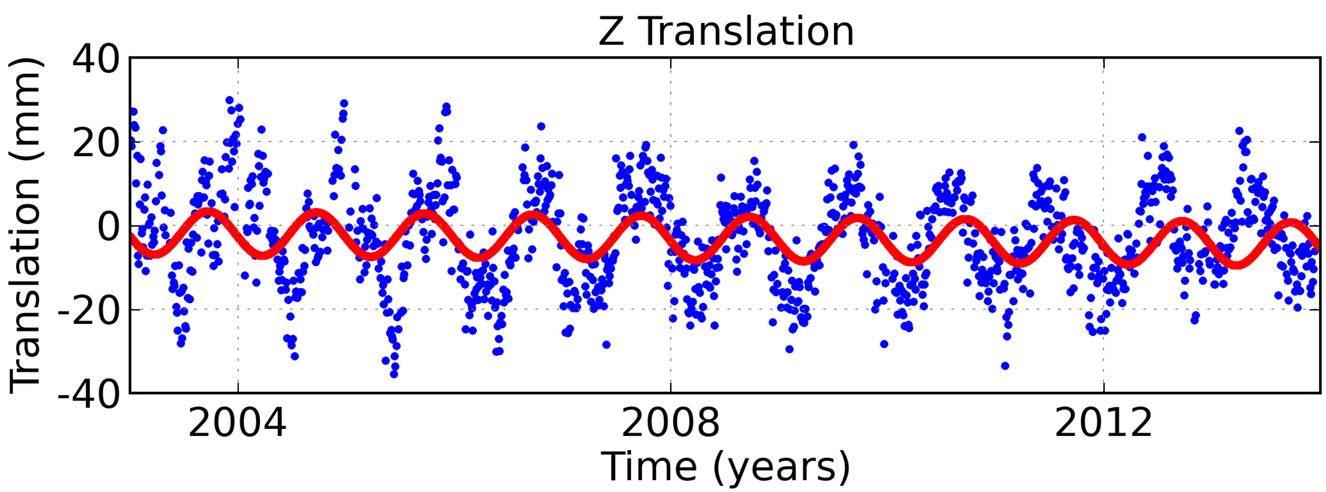
Trend: 0.2 mm/yr

Annual: 3.4 mm

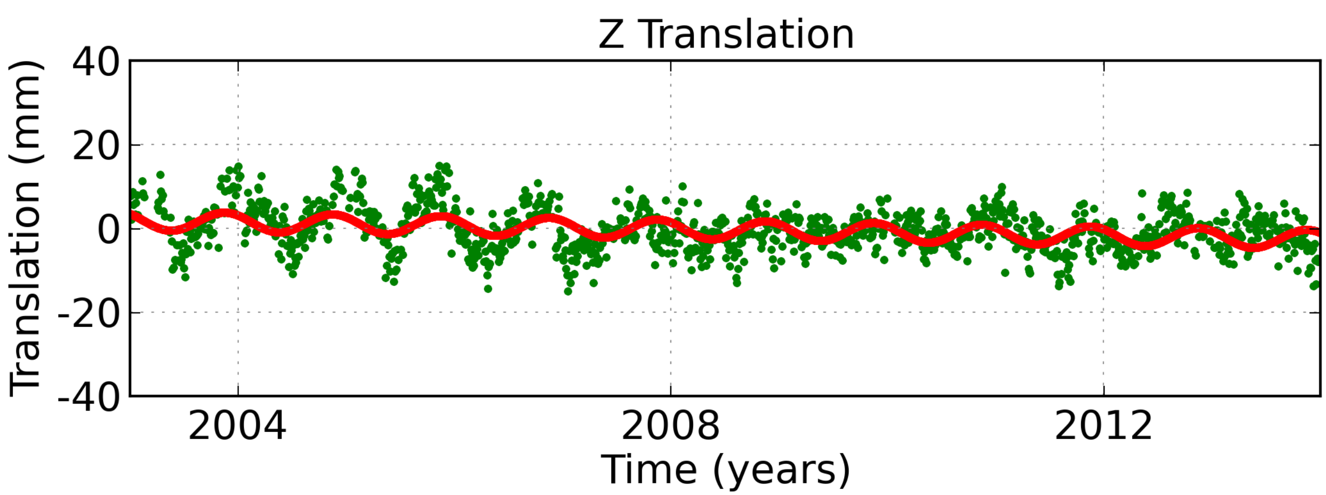
Postfit: 5.4 mm RMS

TRF from GPS: Z-Origin

GPS ■ **GPS+GRACE-A** ■



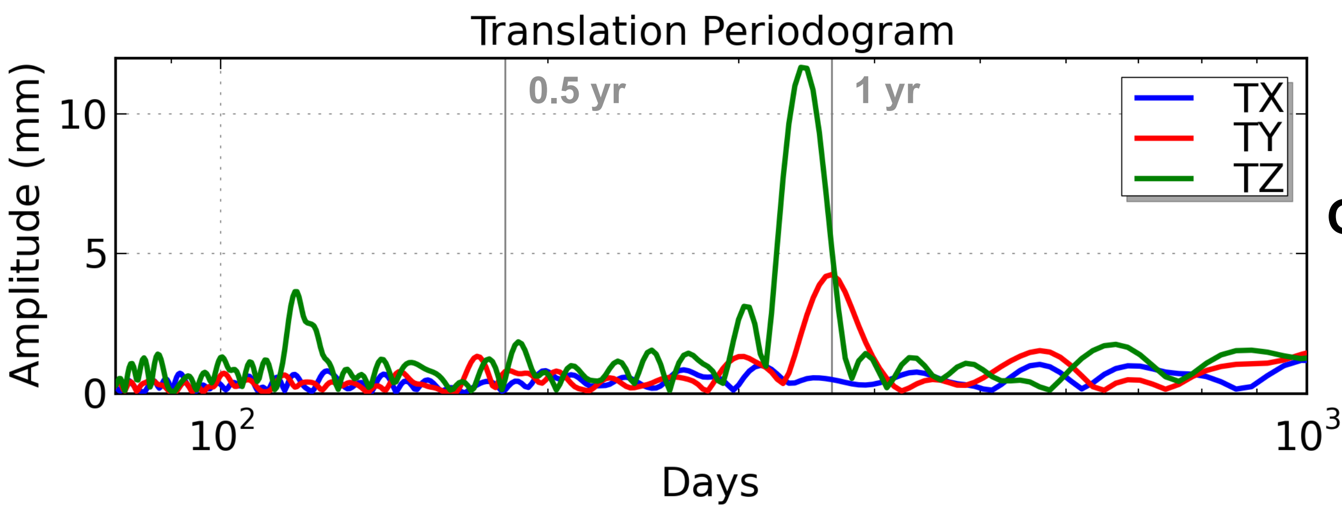
Bias: -2.2 mm
Trend: -0.3 mm/yr
Annual: 5.2 mm
Postfit: 12.4 mm RMS



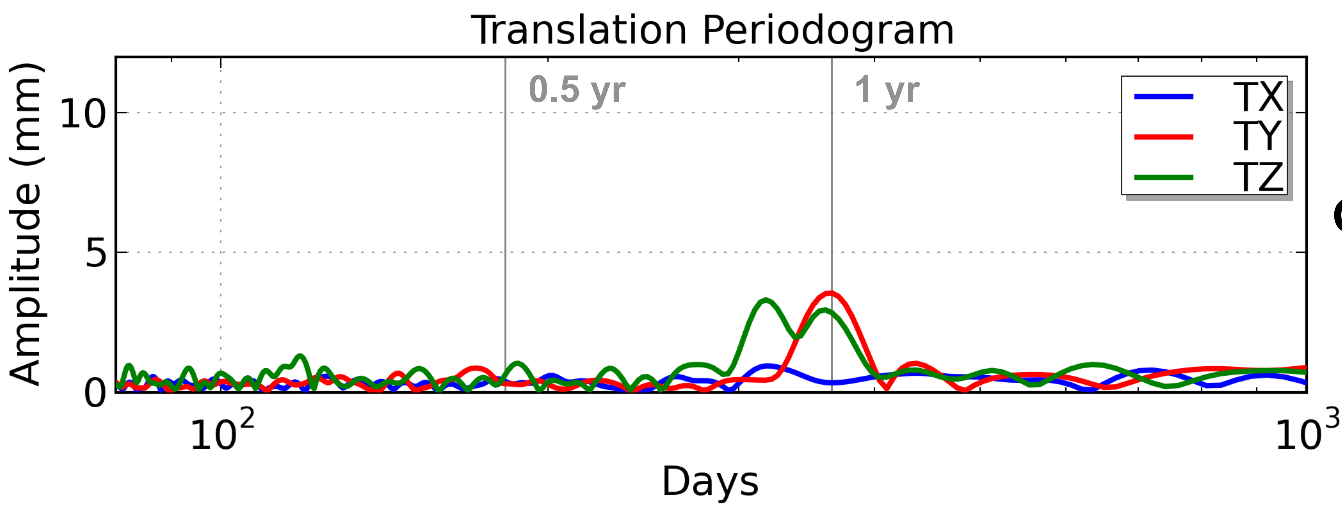
Bias: 1.1 mm
Trend: -0.4 mm/yr
Annual: 2.2 mm
Postfit: 5.5 mm RMS

TRF from GPS: Translation Periodogram

- LEO reduces TZ signal at GPS draconitic (~354 days)



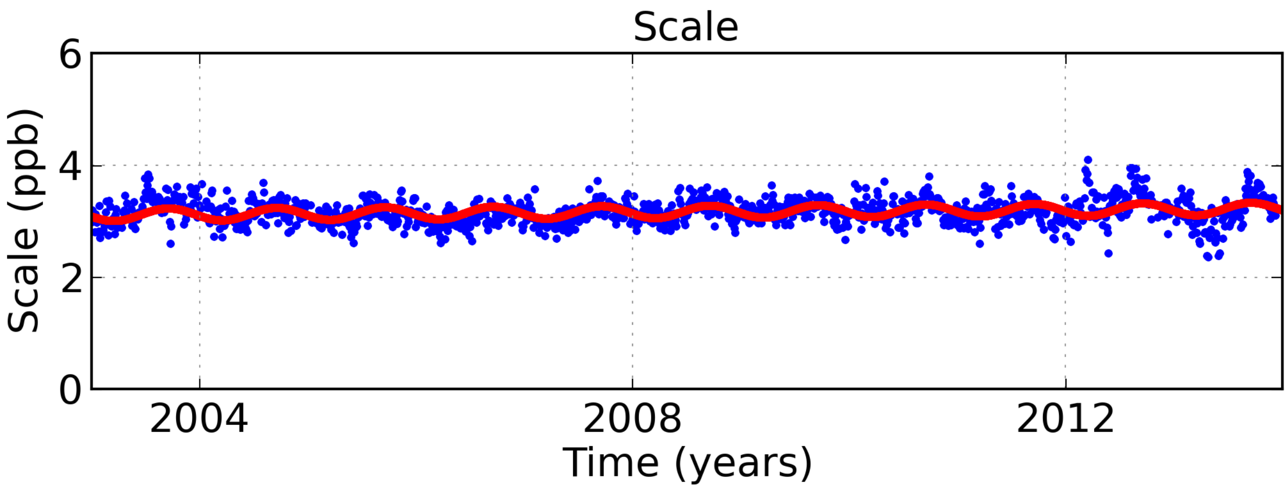
GPS only



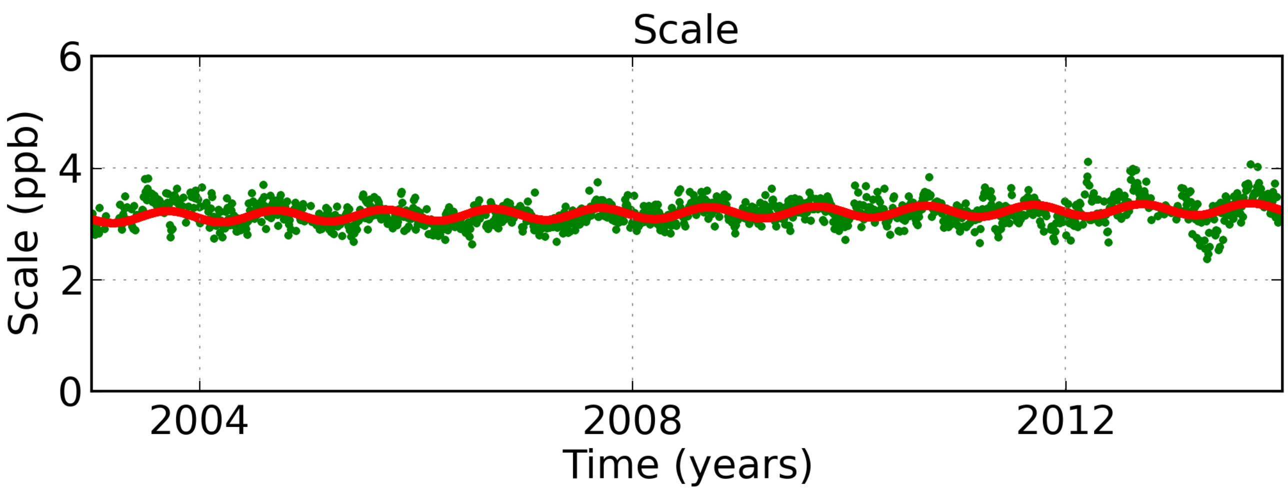
GPS + GRACE-A

TRF from GPS: Scale

GPS (blue) **GPS+GRACE-A** (green)



Bias: 3.1 ppb
Trend: 0.01 ppb/yr
Annual: 0.1 ppb
Postfit: 0.2 ppb RMS



Bias: 3.1 ppb
Trend: 0.01 ppb/yr
Annual: 0.1 ppb
Postfit: 0.2 ppb RMS

Adding LAGEOS

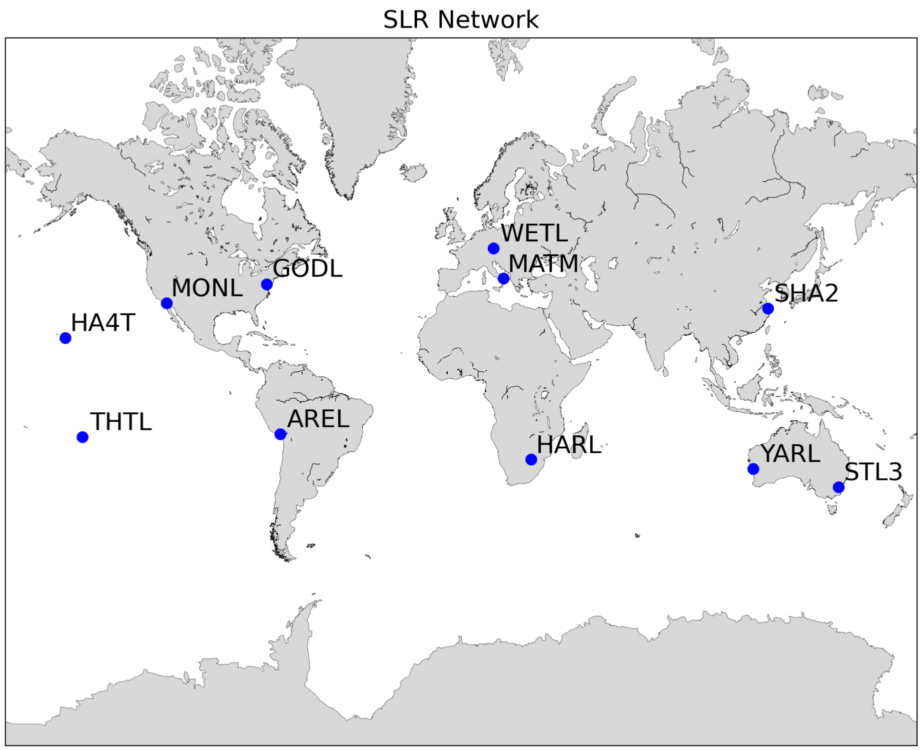
- Tried using SLR to GRACE-A and fixing space tie
  - Few measurements, orbit more kinematic
- Use LAGEOS-1 and -2 instead
  - Simple satellite, straightforward dynamics
  - Circular orbit at ~5700 km altitude
  - Priority mission for SLR tracking

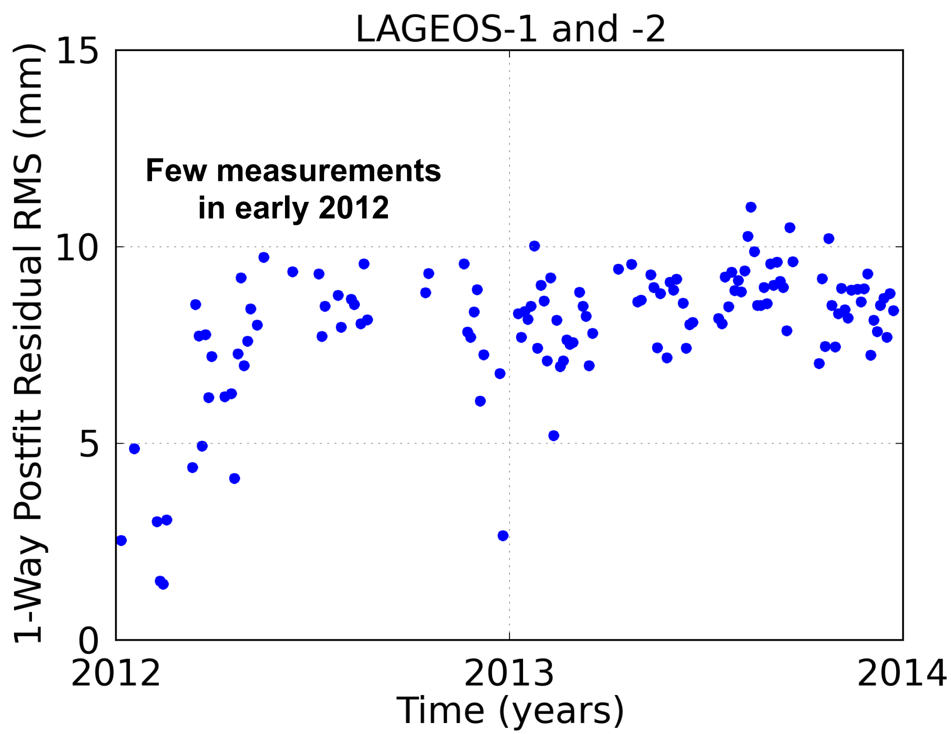
[NASA / ILRS]

- Constrain surveyed tie vectors at GPS-SLR collocations
- Challenges
  - Getting used to SLR metadata and new data format (CRD)
  - Very few SLR measurements
    - Typical 3 day run with 40 GPS and 4-8 SLR stations contains 700,000 GPS LC/PC measurements and 200-1000 SLR normal points

Combined GPS + SLR Solutions (1/2)

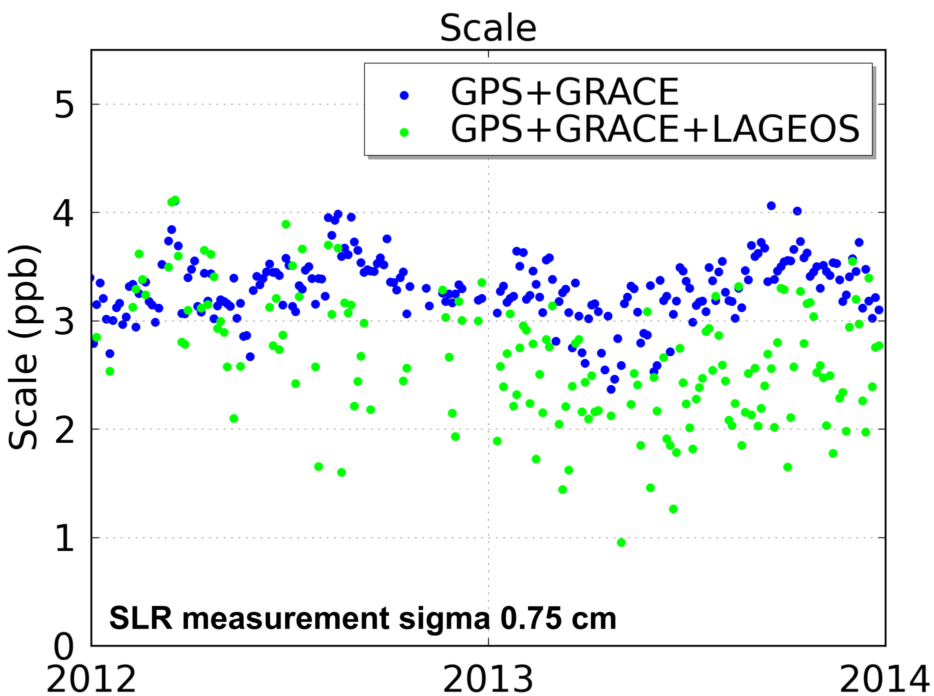
- Include data from up to 11 SLR stations in 3-day GPS + GRACE-A solutions
  - All station positions estimated (1 km apriori sigma)
  - Constrain tie vectors between GPS and SLR monuments to relate the two techniques
- Reasonable postfit residuals, ignoring SLR station biases for now

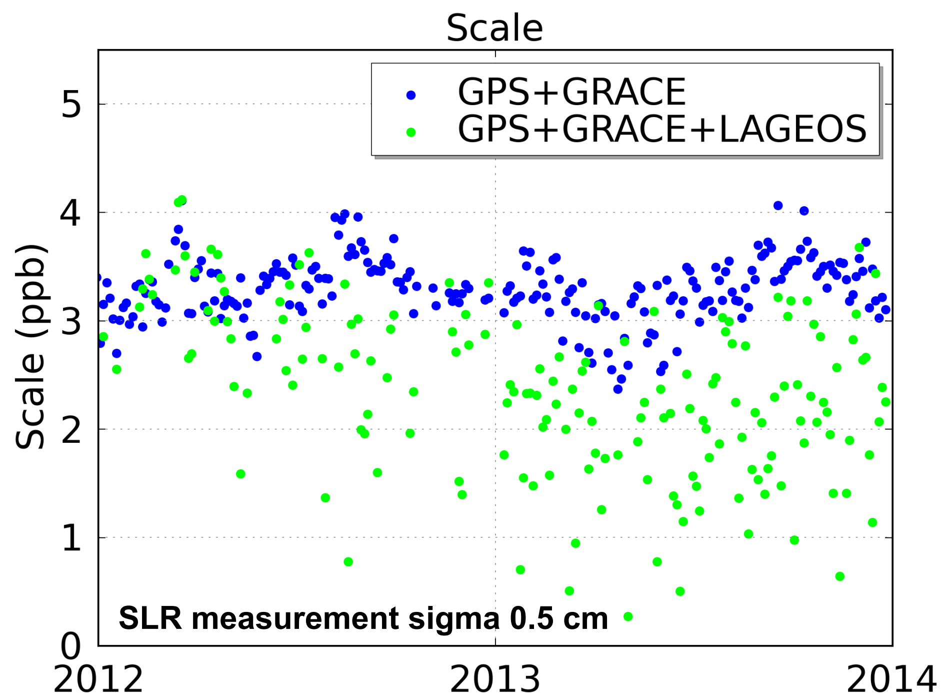




Combined GPS + SLR Solutions (2/2)

- Adding SLR tracking yields favorable impact on scale bias, but scatter increases





	GPS	**SLR**
Measurement sigma	1 cm (LC)	0.75 cm
Scale bias 2013-2014	3.26 ppb	2.43 ppb

	GPS	**SLR**
Measurement sigma	1 cm (LC)	0.5 cm
Scale bias 2013-2014	3.26 ppb	2.07 ppb

Summary and Conclusions

- Terrestrial reference frame realized from GPS
  - GPS only
    - 3D origin offset < 7 mm, rate < 1 mm/yr
    - Scale bias 3.1 ppb, rate 0.01 ppb/yr
  - GPS + GRACE-A
    - 3D origin offset < 4 mm, rate < 1 mm/yr
    - Scale bias 3.1 ppb, rate 0.01 ppb/yr
- Combined GPS and SLR tracking to LAGEOS-1/2
  - Apply GPS-SLR collocation tie vector constraints
  - SLR reduces scale bias, but increases scatter
  - Working to include additional tracking stations, Etalon-1 and -2 satellites (~20,000 km altitude)