A GPS-Based Terrestrial Reference Frame from a Combination of Terrestrial and Orbiter Data

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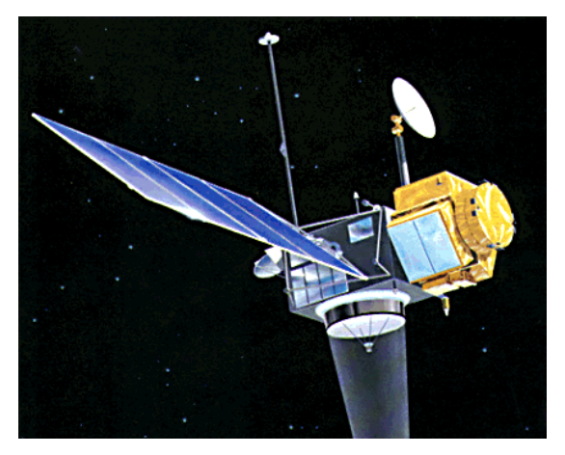
Abstract

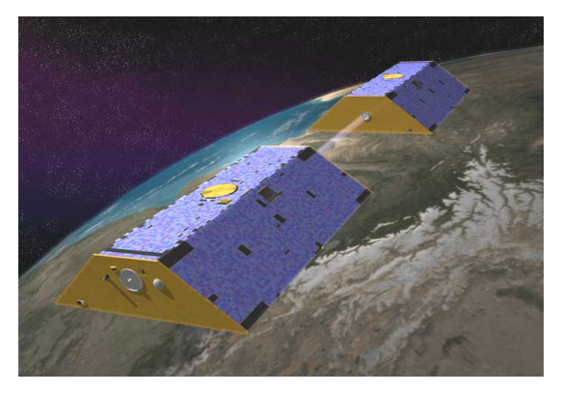
The terrestrial reference frame (TRF)—as realized by the global network of space-geodetic observatories—provides the foundation for many fundamental measurements of the changing Earth system. The accurate monitoring of sea-surface height, ice sheet thickness and land motion all depend on the fidelity of the TRF. We describe new realizations of the TRF based on precision GPS tracking data collected on the ground and in low-Earth orbit (LEO). Satellites in LEO offer a number of substantial advantages for developing a TRF. The perspective afforded by GPS receivers in orbit is unmatched in terms of both spatial and temporal coverage. In addition, the scale (mean height) of the orbit solutions is well determined (cm-level) from dynamical constraints, and there is no troposphere signal to confound interpretation of the measurements.

We use GPS data from the TOPEX/POSEIDON (1992–2005) and GRACE (2002–present) missions to enable derivation of the TRF. These missions were selected due to their precision orbit determination (POD) capabilities, and to their favorable multipath environments. Building on our prior work, we use data from these satellites to derive improved estimates of the antenna phase variations (APV) of the GPS satellite antennas. APV models for these large, complex antennas remain among the limiting sources of error for the most demanding global geodetic problems such as TRF realization. These antenna calibrations are then applied in realizing the TRF from GPS alone. The TRF is based on a combination of ground and GRACE data for the period 2002–2010, processed in multi-day solutions.

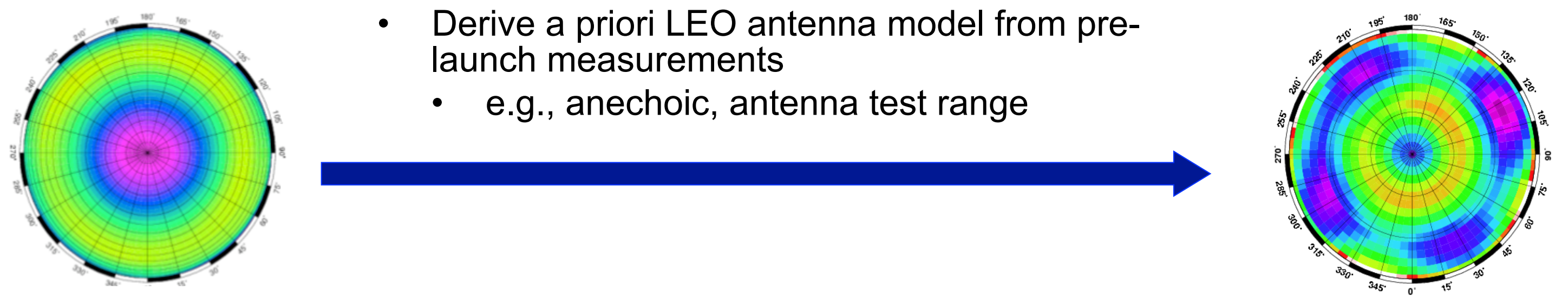
Current results indicate that the inclusion of GRACE data significantly improves the stability of the TRF along the spin (Z) axis. In particular, the repeatability of individual (3-d) determinations (with respect to ITRF2008) is improved from 9 to 6 mm. We present updates of this GPS-derived frame, and characterize the efficacy of the GRACE (LEO) data in reducing systematic GPS errors, such as those occurring at the draconitic (352-d) period. Finally, we discuss the implications of these results for the proposed GRASP mission, which will provide a space-based platform of singular accuracy for the collocation and exploitation of the tracking systems underlying GGOS.

LEO-Based Calibrations of GPS Transmit Antennas





- Treat LEO as "reference antenna in space"
- Choose candidate missions to minimize multipath
  - GRACE (2002–pr.)
  - TOPEX/POSEIDON (1992–2005)
- Use Precise Orbit Determination (POD) to provide constraints
  - Scale constraint from dynamics (GM)
  - No a-priori constraint to TRF (use fiducial-free GPS products)
  - No troposphere
- Derive a priori LEO antenna model from pre-launch measurements
  - e.g., anechoic, antenna test range



Candidate Reference Frame Strategies

- Use GPS s/c antenna phase variation (APV) models from LEO
  - GRACE vs. TOPEX
- Use 40 well-distributed stations with choke-ring antennas
  - TurboRogue-inspired design (with Dorne-Margolin Element) common in global geodetic network
  - Improves homogeneity among GPS stations for TRF realization
  - Use choke-ring APV model from JPL test range (Dunn and Young, 1992)
- Use GRACE-A data in network solution
  - Capitalize on improved observability afforded by LEO platform
- Use long-arc solutions to better capitalize on dynamical constraints
  - 9 days (ground network) or 3 days (ground + GRACE)
- Use fiducial-free network/POD strategy (Heflin et al., 1992)
- Loose (1-m) a priori constraint on all stations
  - Internal (GPS) TRF compared to ITRF2008(IGS08) via 7 parameter transformation

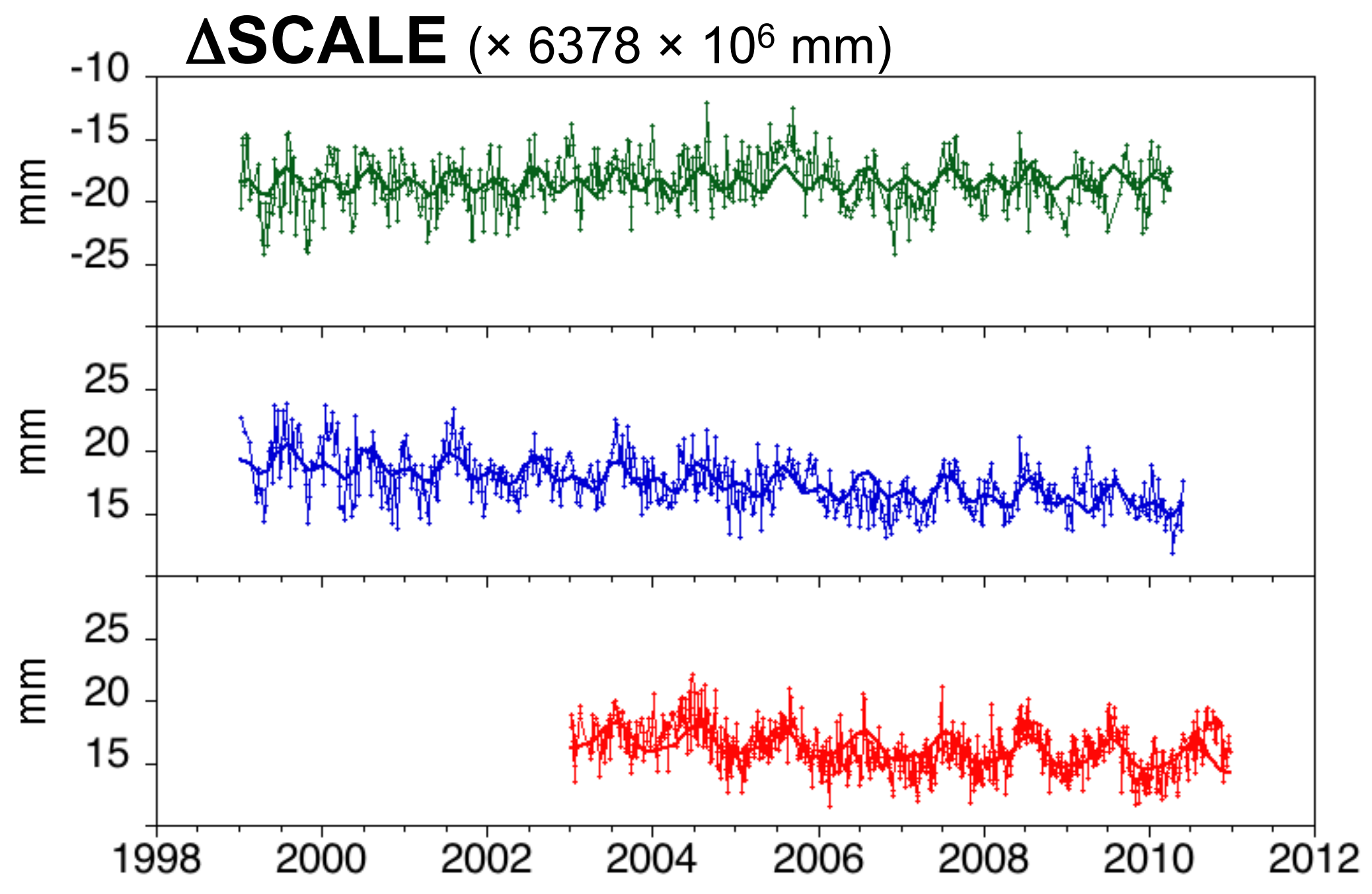
Newest Strategy Features GRACE Data In Network Solution

	Ground Network TOPEX-based APV	Ground Network GRACE-based APV	Ground Network + GRACE LEO GRACE-based APV
Orbit Arc Length	9 days, centered on GPS week	9 days, centered on GPS week	3 days
Number of Terrestrial GPS Stations	40 (choke rings only)	40 (choke rings only)	40 (choke rings only)
Number of Low-Earth Orbiters	None	None	One (GRACE-A)
Transmitter Antenna Calibration Model	TOPEX-based APV maps	GRACE-based APV maps	GRACE-based APV maps
Ground Receiver Antenna Calibration Model	JPL Ant. Test Range *Young and Dunn* (1992)	JPL Ant. Test Range *Young and Dunn* (1992)	JPL Ant. Test Range *Young and Dunn* (1992)
LEO Receiver Antenna Calibration Model	n/a	n/a	Anechoic Chamber
GPS Satellite POD Strategy	1 cpr UVW; Random Walk	1 cpr UVW; Random Walk	1 cpr UVW; Random Walk
LEO POD Strategy	n/a	n/a	1 cpr HCL; Colored Noise Const. HCL (5-min updates)

Reference Frame: Comparisons to ITRF2008

- Candidate GPS-derived frames are independent of ITRF
  - GPS s/c antenna calibrations (APV) derived through dynamical POD: no constraint to TRF
- GPS-based frames compared to ITRF2008/IGS08 via 7-parameter transformation
  - Computed for each (multi-day) solution
  - Long-term stability captured in time series of individual transforms
- TRF rates agree at 0.5 mm yr^{-1} level (1σ, each component).
- TRF offsets agree at 5-mm level (1σ, each component).
  - Exception is scale bias (impacted by mean APV errors).

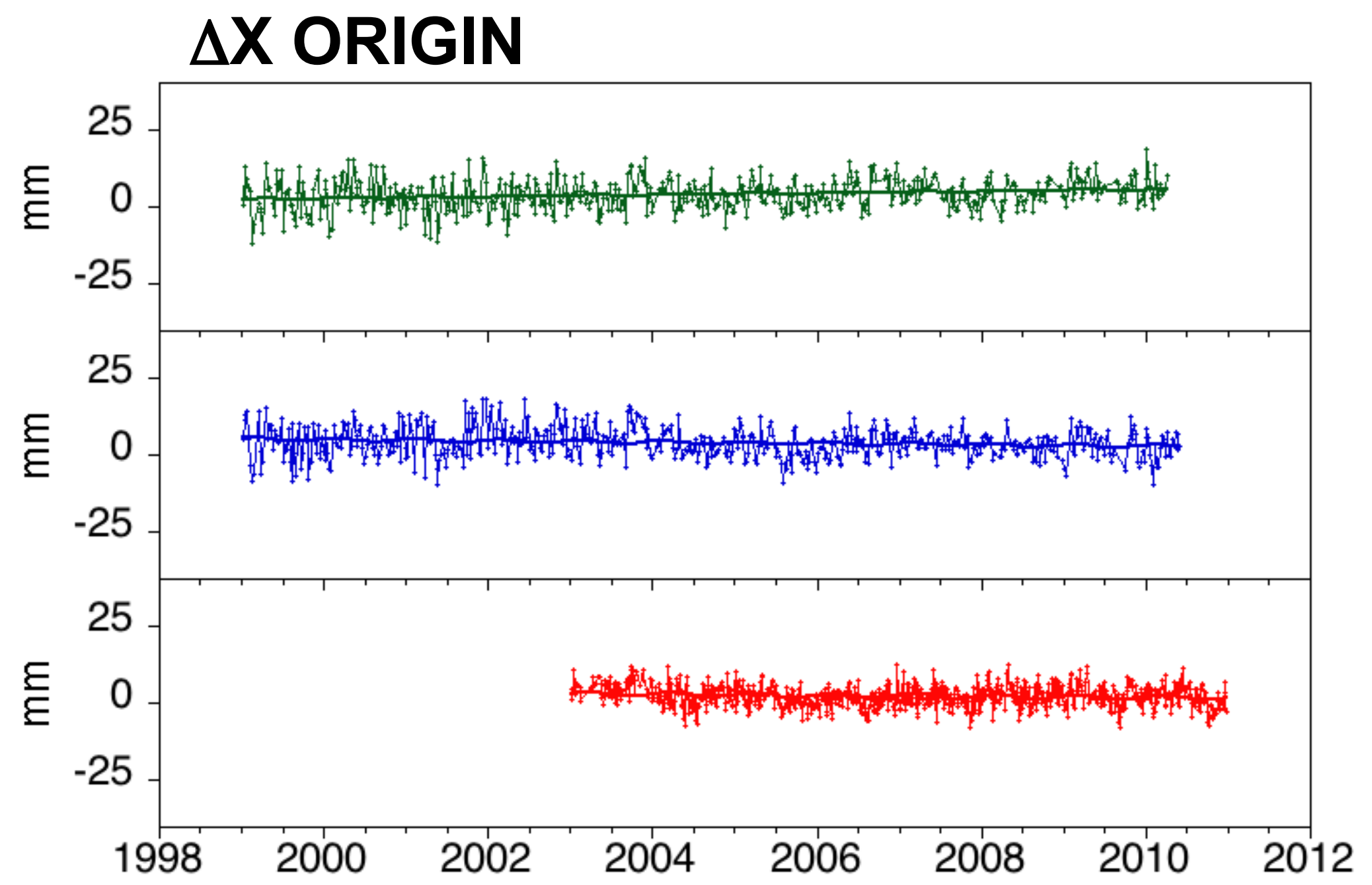
🟩 **40-station ground network +** TOPEX-based APV for GPS satellite antennas
🟦 **40-station ground network +** GRACE-based APV for GPS satellite antennas
🟥 **40-station ground network + GRACE +** GRACE-based APV for GPS satellite antennas



Bias (2005) –18 mm
Trend +0.0 mm/yr
Annual 0.4 mm
Semi Ann 0.8 mm
RMS Res 1.9 mm

Bias (2005) +17 mm
Trend –0.3 mm/yr
Annual 0.8 mm
Semi Ann 0.8 mm
RMS Res 1.7 mm

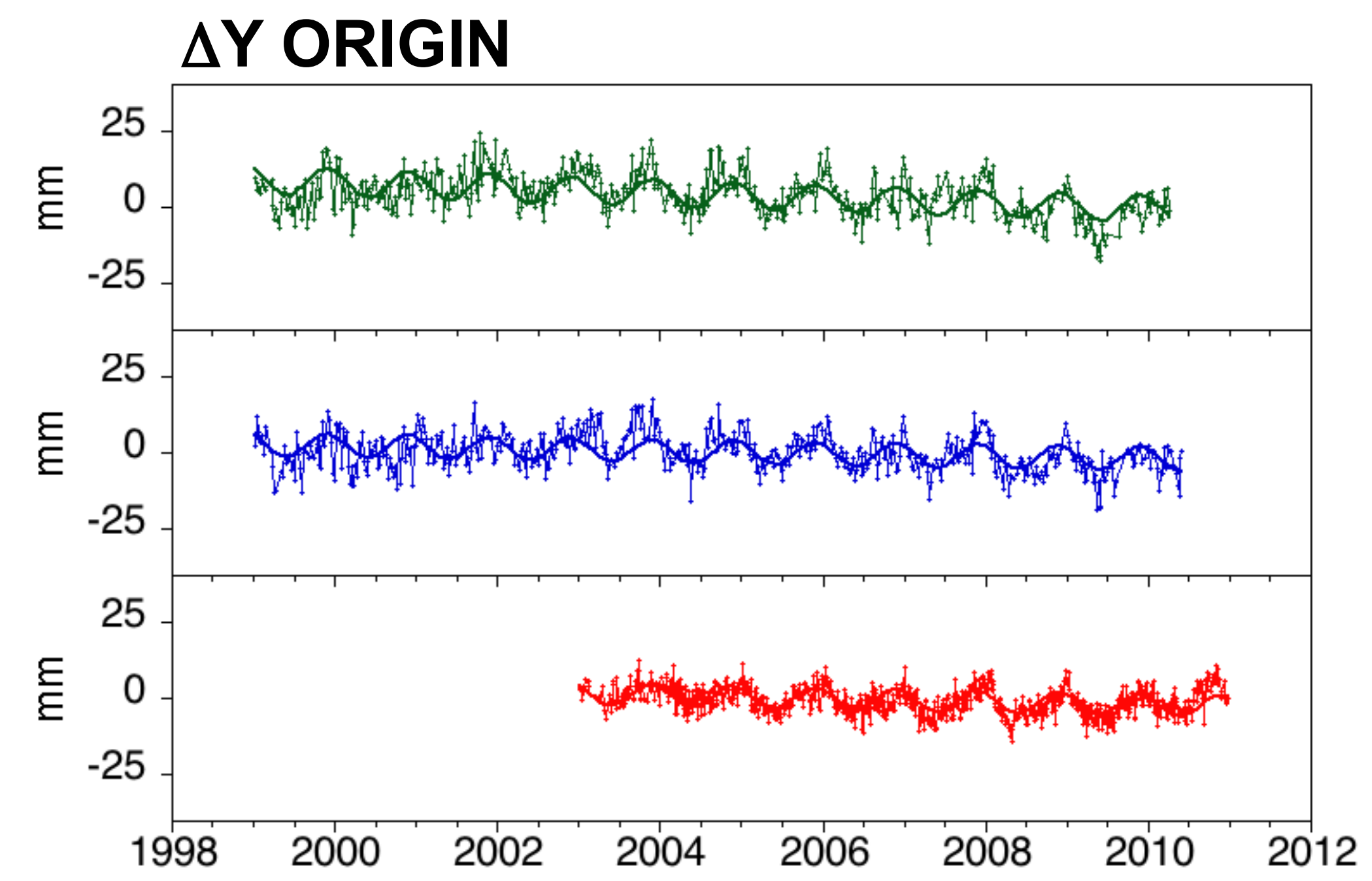
Bias (2005) +17 mm
Trend –0.2 mm/yr
Annual 1.1 mm
Semi Ann 0.3 mm
RMS Res 1.5 mm



Bias (2005) +4 mm
Trend +0.3 mm/yr
Annual 0.3 mm
RMS Res 4.9 mm

Bias (2005) +4 mm
Trend –0.2 mm/yr
Annual 0.5 mm
RMS Res 5.0 mm

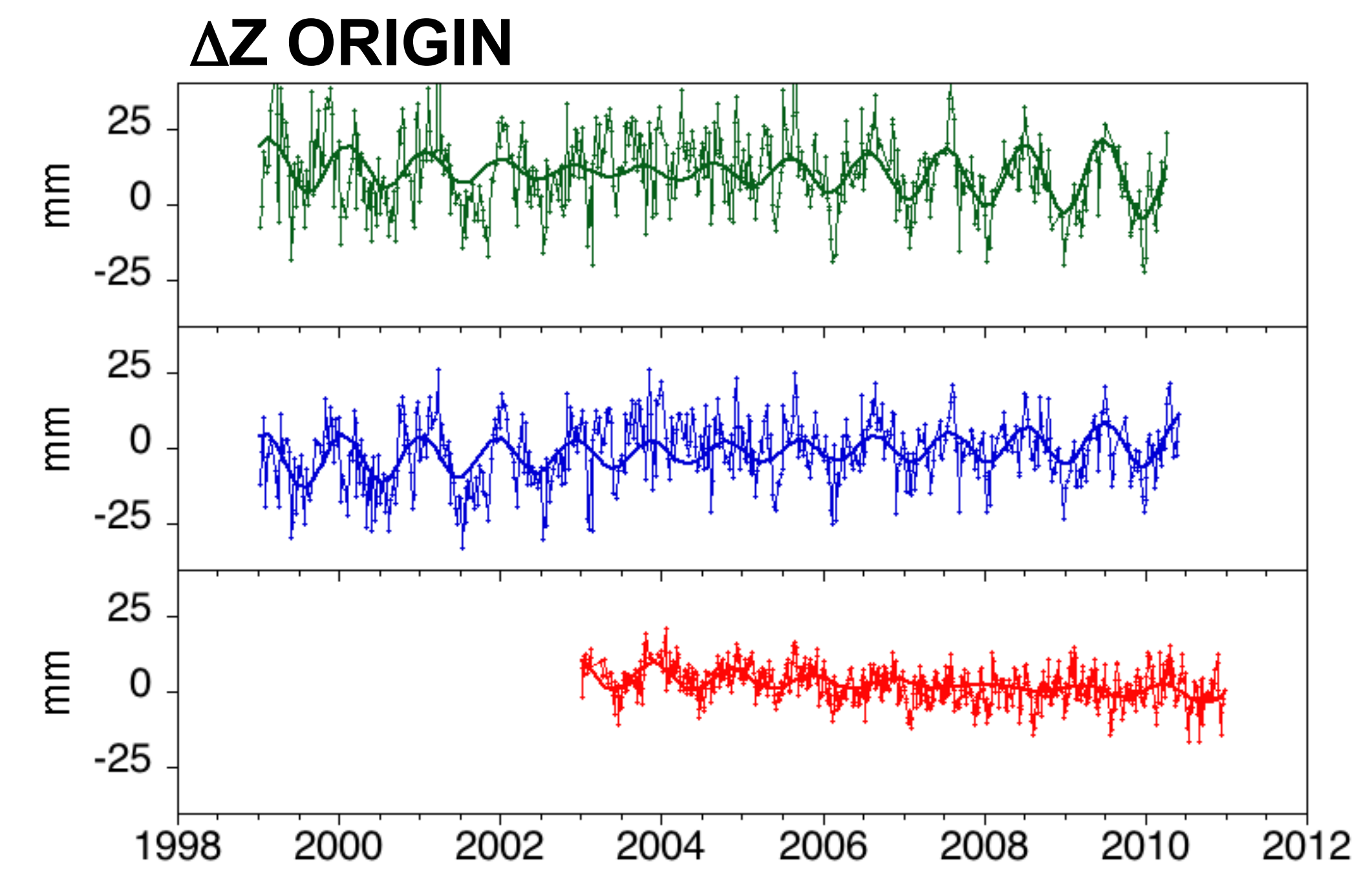
Bias (2005) +3 mm
Trend –0.2 mm/yr
Annual 0.7 mm
RMS Res 3.5 mm



Bias (2005) +4 mm
Trend –0.8 mm/yr
Annual 4.5 mm
RMS Res 5.6 mm

Bias (2005) +0 mm
Trend –0.4 mm/yr
Annual 3.9 mm
RMS Res 5.2 mm

Bias (2005) +0 mm
Trend –0.5 mm/yr
Annual 3.4 mm
RMS Res 3.5 mm



Bias (2005) +10 mm
Trend –0.4 mm/yr
Annual 8.1 mm
Draconitic 10.1 mm
RMS Res 11.2 mm

Bias (2005) –1 mm
Trend +0.6 mm/yr
Annual 4.7 mm
Draconitic 8.2 mm
RMS Res 9.7 mm

Bias (2005) +4 mm
Trend –0.8 mm/yr
Annual 4.7 mm
Draconitic 4.1 mm
RMS Res 5.0 mm

Annual Geocenter Motion

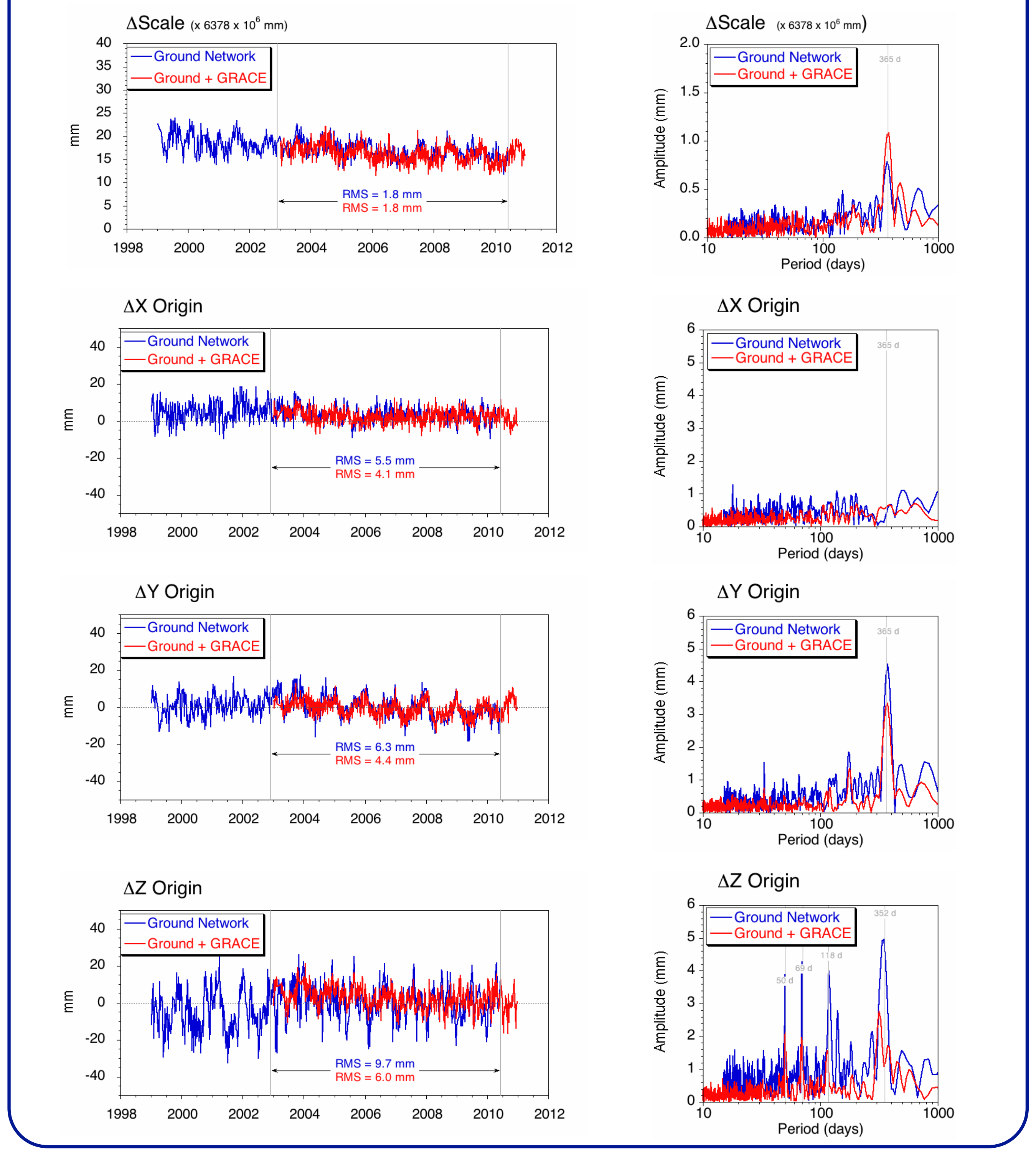
- Good overall agreement with independent (e.g. SLR, Inversion) estimates
  - Exception is strategy using TOPEX-based APV (Z component)
  - Amplitude of X geocenter smaller than competing estimates.
- New GRACE-based long-arc techniques improve Z geocenter from GPS
  - Need sufficient data for simultaneous estimation of draconitic and annual.

Data	ΔX_g		ΔY_g		ΔZ_g		**Years**
	Amp mm	Phase day	Amp mm	Phase day	Amp mm	Phase day	
SLR: 5 satellites *(Cheng et al., 2010)*	3.2 ± 0.4	33 ± 3	2.6 ± 0.2	306 ± 2	4.3 ± 0.3	31 ± 2	*2002-2010*
GPS GRACE LEO *(Kang et al., 2009)*	3.0 ± 0.2	32 ±14	2.4 ± 0.2	353 ± 14	4.0 ± 0.3	288 ± 16	*2003-2007*
Inversion *(Wu et al., 2006)*	1.8 ± 0.1	49 ± 4	2.7 ± 0.1	329 ± 2	4.2 ± 0.2	31 ± 3	*2002-2009*
Model *(Collilieux et al., 2009)*	2.1	28	2.1	342	2.7	49	*1993-2006*
GPS Longarc with T/P-based APV *(this study)*	0.3 ± 0.3	98 ± 66	4.5 ± 0.3	335 ± 4	8.1 ± 1.0	122 ± 7	*1999-2010*
GPS Longarc with GRACE-based APV *(this study)*	0.5 ± 0.3	46 ± 35	3.8 ± 0.3	329 ± 5	4.7 ± 0.8	92 ± 10	*1999-2010*
GPS Longarc with GRACE-based APV + GRACE LEO Data *(this study)*	0.7 ± 0.2	81 ± 14	3.4 ± 0.1	332 ± 5	4.7 ± 0.5	19 ± 6	*2003-2010*

Table Adapted from Wu et al. (this meeting): Abstract G31C-02

Impact of GRACE LEO Data

- Improves repeatability in all components vs. ITRF2008/IGS08
- Largest impact on Z component of origin
  - Significantly reduces variability linked to GPS draconitic year (352 days × n^{-1} where n = 1, 3, 5, 7)



GRASP Mission Proposal

- Leverages geodetic results (e.g., TRF, APV) from GRACE, T/P missions
- Collocates GNSS, SLR, DORIS and VLBI on one spacecraft
  - Simple, compact spacecraft, supremely calibrated on the ground
  - High LEO (elliptical) orbit to simplify modeling of surface forces
- Main scientific aim: meet GGOS goals for accuracy of TRF to support measurements of sea level and global change.