Recent Advances in Realizing the Terrestrial Reference System from GPS

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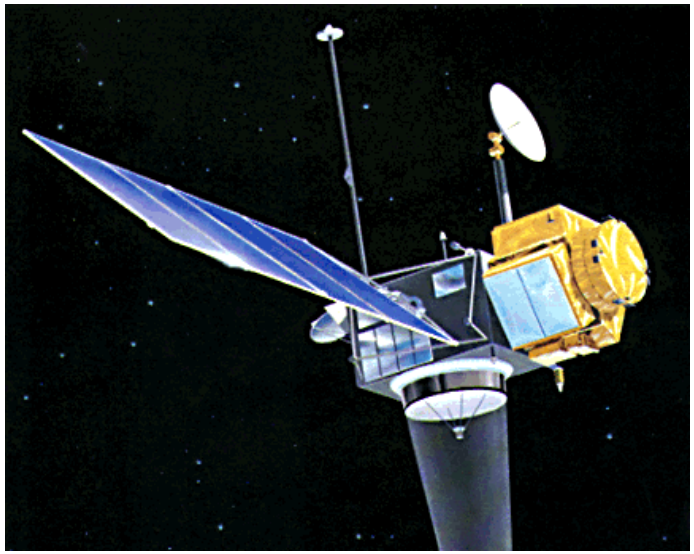
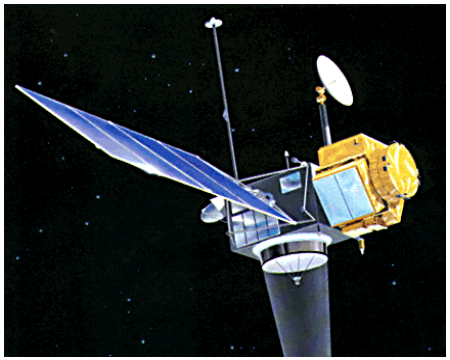
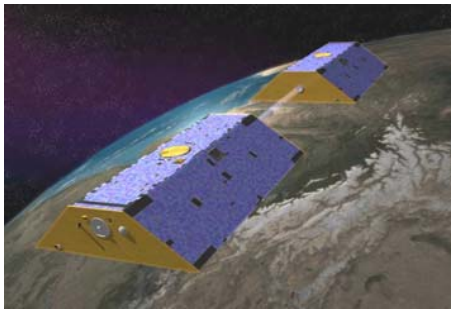
Motivation

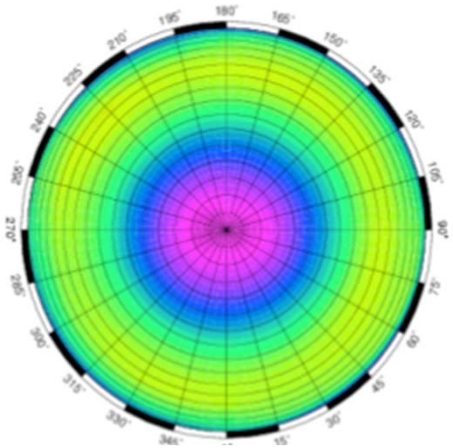
- Realize the terrestrial reference frame (TRF) using GPS alone.
  - What is the potential contribution of GNSS data in a multi-technique combination?
  - What are the strengths and weaknesses of GPS?
  - What are the uncertainties in current realizations of the ITRF?
- Foundation of a “GPS-only frame” is accurate modeling of antenna phase variations (APV).
  - All participants in network, but especially the GPS transmit antennas.
  - APV models should be independent of any extant TRF.



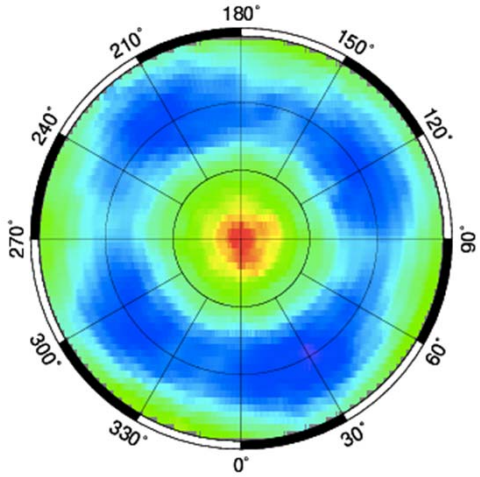
Calibrating the GPS Transmit Antennas Using Data from Low Earth Orbiters (LEO)







- **Treat LEO as "reference antenna in space"**
- **Choose candidate missions to minimize multipath**
  - TOPEX/POSEIDON (1992–2005)
  - GRACE (2002–pr.)
- **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
- **Adopt pre-launch antenna APV calibrations of LEO antenna**
  - e.g., anechoic, antenna test range



Pre-launch LEO APV Calibration

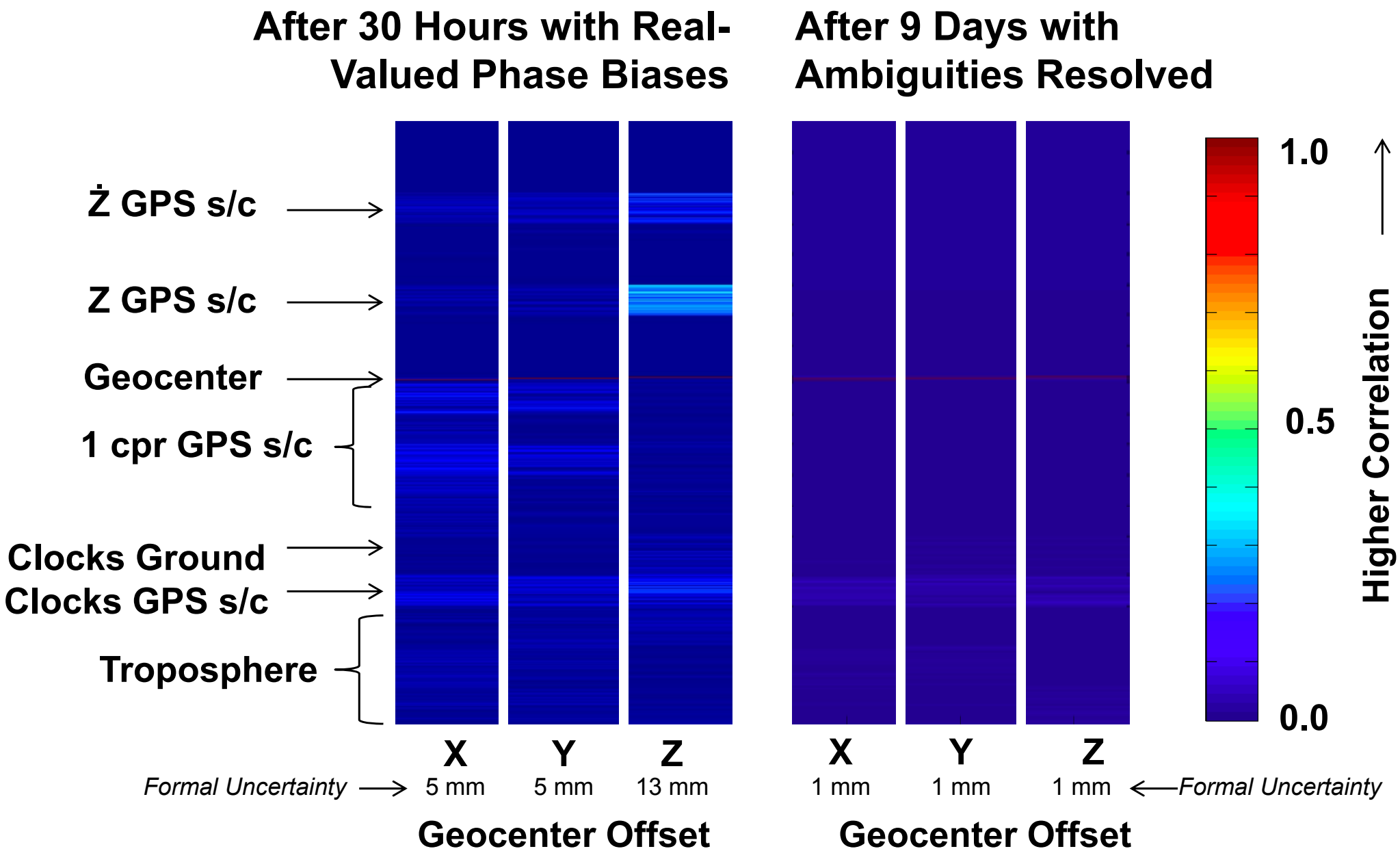
Estimated GPS Transmit Antenna APV

Realizing the TRF from GPS: Nominal Longarc Network Solution Strategy

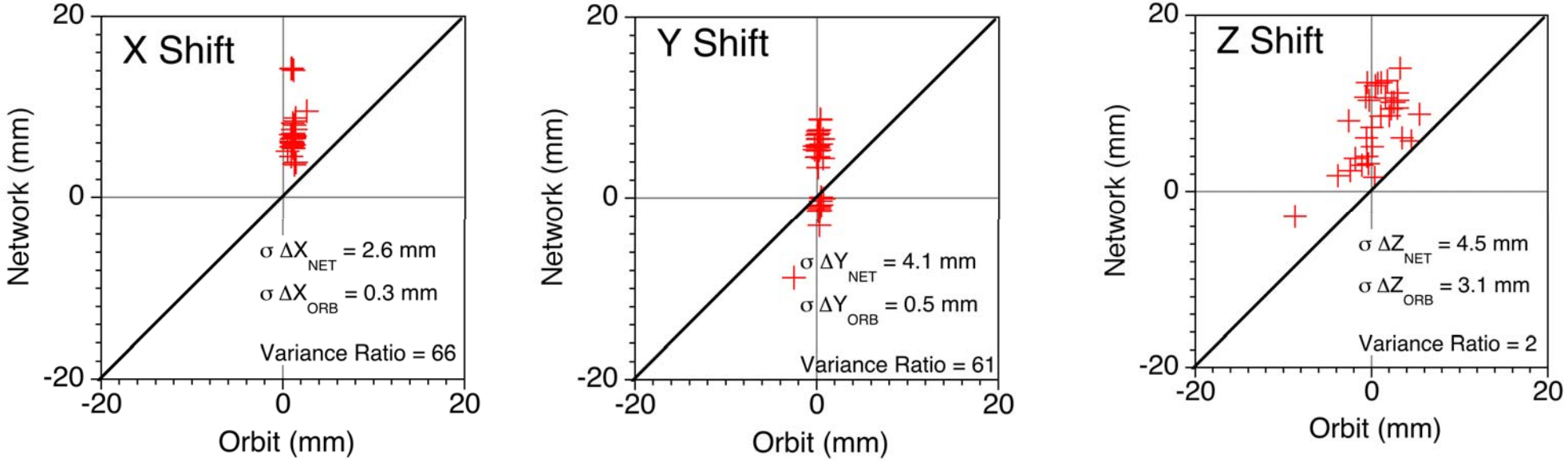
Element	Selection
Time span	1995–2012 (~17 yrs.)
Orbit Arc Length	9 days, centered on GPS week (2-d overlap)
Number of Terrestrial GPS Stations	40 (selected from stations with choke rings to improve homogeneity)
Transmitter Antenna Calibration Model	TOPEX-referenced GPS APV model: Block averages for all five GPS s/c antenna types: I, II/IIA, IIR-A, IIR-B/M, IIF
Ground Receiver Ant. Calibration Model	IGS standard
A priori uncertainty on station positions	1 km ("fiducial free", Heflin et al., 1992)
Tracking data	5-min decimated LC (1-cm σ), smoothed PC (1 m σ)
GPS Satellite POD Strategy	Two-tiered strategy: –For well modeled satellites: 1 cpr CL accelerations updated every ~36 hr as colored noise (τ = 7 d); –For poorly modeled satellites: standard JPL ISGAC approach (more aggressive stochastics).
Phase ambiguities	Integer resolution
Earth orientation parameters	2-hr (random-walk) updates to X, Y pole and UT1–UTC.

- Internal (GPS) TRF compared to $ITRF2008_{IGb08}$ using 7-param. Helmert transform.
  - Also called "network shift" approach.

Long-arc Strategy Reduces Correlations Impacting TRF Parameters

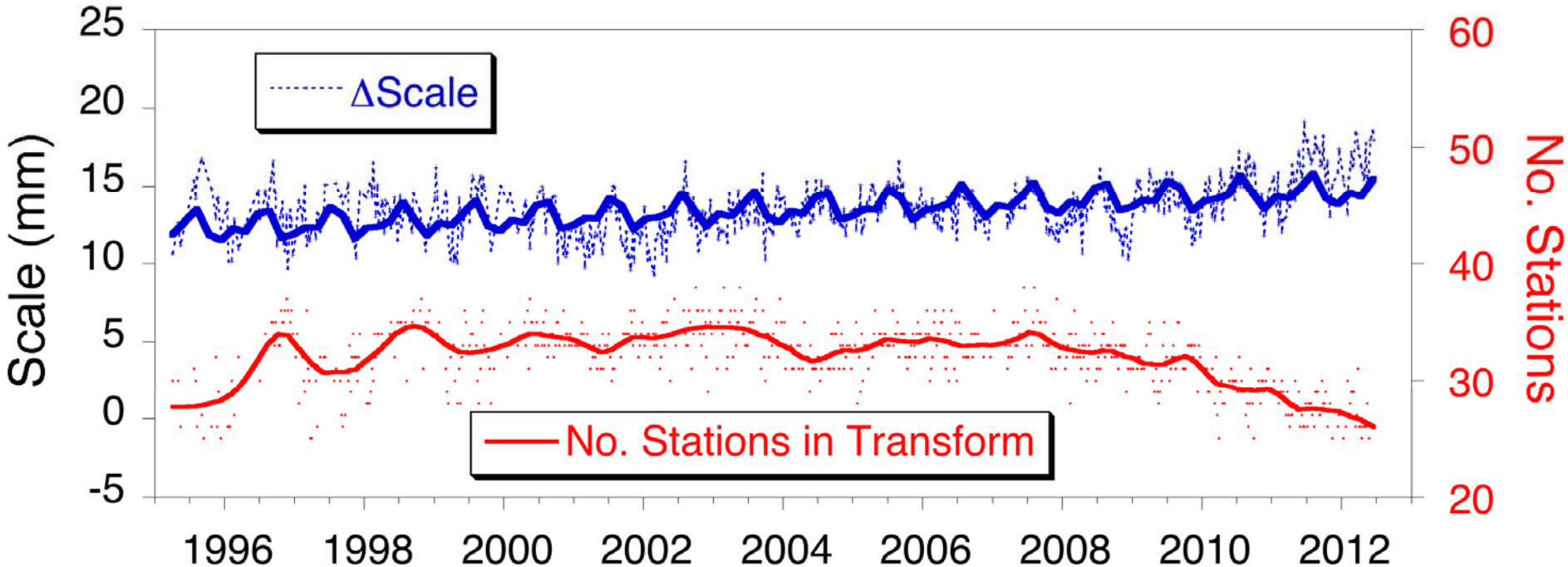


Correlation of Origin Shift? Orbit vs. Network



- **Over 30 candidate solution strategies used to assess uncertainty of origin**
  - Based on single 9-d test solution (March 2011).
  - Illustrates sensitivity to different troposphere, POD, antenna phase variation models.
- **Fiducial-free longarc GPS orbit solutions well centered.**
  - Based on Helmert transforms to IGS combined orbit solution
  - Sub-mm repeatability in equatorial (XY) plane (few mm along Earth spin axis)
- **Ground network solutions show higher variance in origin shift.**
  - Based on Helmert transforms to IGS08 frame.
  - Repeatability of 3–5 mm, despite large inflation of variance vs. orbit shift.

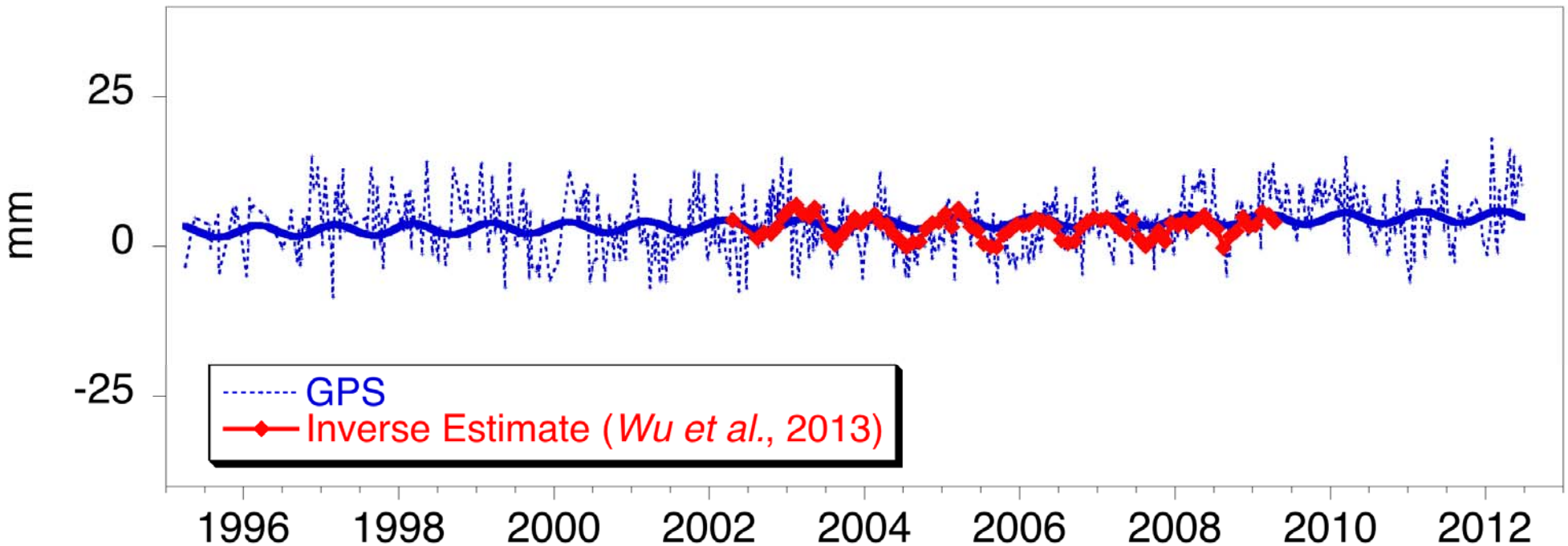
ΔScale (vs. $ITRF2008_{IGb08}$)



- **Weekly repeatability of 1.4 mm**
- **Stability crucial for studies of global sea level change**
- **Drift of +0.1 mm/yr (0.02 ppb/yr)**
- **Scale bias of +14 mm (~2 ppb)**
  - Affected by choice of antenna models
  - Ensemble local effects (e.g., multipath) also contribute

Bias (2005)	**+14 mm**
Trend	**+0.1 mm/yr**
Annual	**0.8 mm**
Semi Ann	**0.6 mm**
RMS Res	**1.4 mm**

ΔX Origin (vs. $ITRF2008_{IGb08}$)

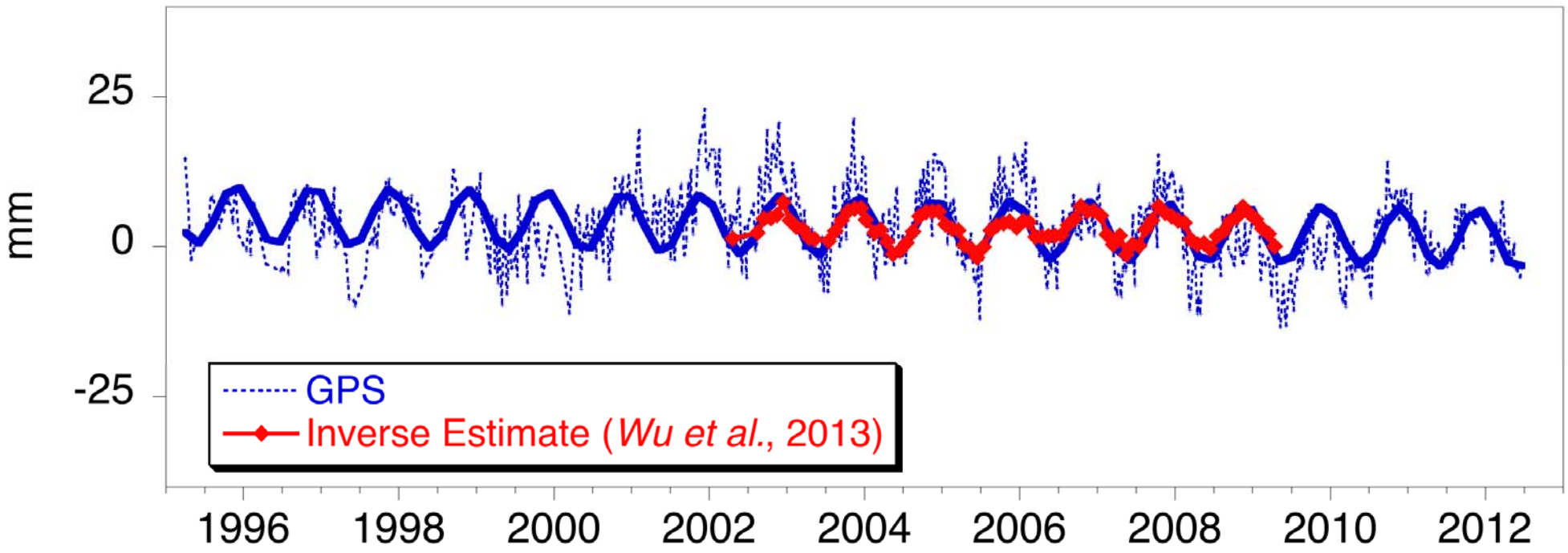


- **Best determined component**
- **Offset of +4 mm at 2005.0 epoch**
- **Drift of 0.2 mm/yr**
- **Annual geocenter motion:**
  - In phase with independent estimate
  - GPS amplitude 1-mm smaller

Bias (2005)	**+4 mm**
Trend	**+0.2 mm/yr**
Annual	**1.0 mm**
RMS Res	**4.4 mm**

Wu, X., et al. (2013): Geocenter Motion and Degree-1 Surface Mass Variations – Reconciling Results from Direct SLR Determination and Inverse Estimation, GRACE Science Team Meeting.

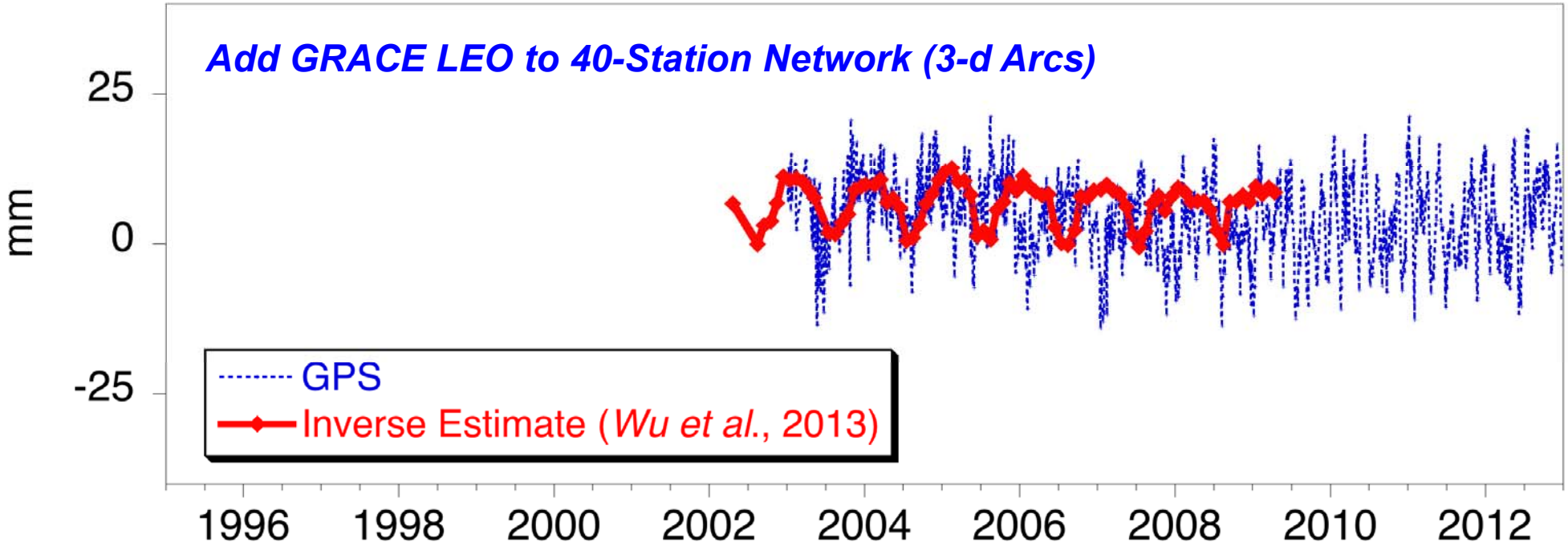
ΔY Origin (vs. $ITRF2008_{IGb08}$)



- **Offset of +3 mm at 2005.0 epoch**
- **Drift of –0.2 mm/yr**
- **Annual geocenter motion:**
  - In phase with independent estimate
  - GPS amplitude 2-mm larger

Bias (2005)	**+3 mm**
Trend	**–0.2 mm/yr**
Annual	**4.9 mm**
RMS Res	**4.9 mm**

ΔZ Origin (vs. $ITRF2008_{IGb08}$)



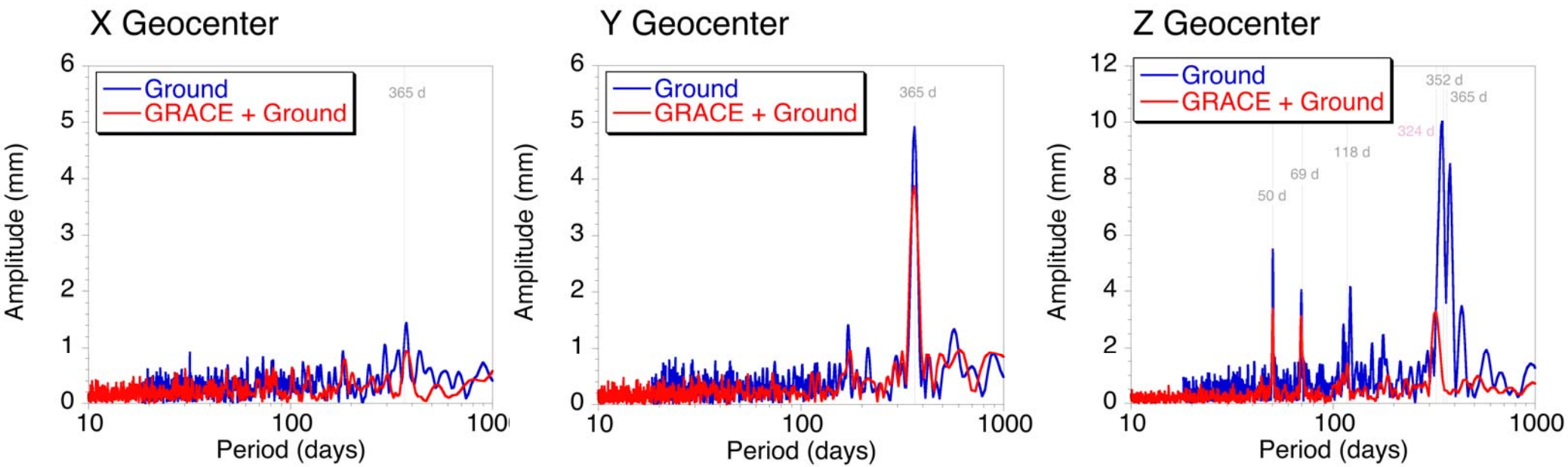
- Centering on spin (Z) axis more difficult.
- Prone to systematic GPS measurement errors (esp. draconitic + overtones).
- Despite larger periodic errors, long-term stability is excellent.
- Inclusion of LEO (i.e., GRACE) leads to dramatic improvement.

Bias (2005)	+5 mm
Trend	–0.4 mm/yr
Annual	—
Draconitic	—
RMS Res	6.3 mm

Summary

- New TRF realization from GPS alone
  - Spans nearly two decades (1995–2012) and includes all (5) GPS satellite blocks.
  - Uses LEO-referenced GPS s/c APV models that are independent of frame.
  - Uses long (9-d) arc solution strategy designed to reduce correlations in GPS data.
- Long-term stability of GPS origin and scale competitive with current ITRF
- Scale drift of 0.1 mm yr^{-1} vs. $ITRF2008_{IGb08}$ (1995–2012)
  - Offset ~2 ppb (~1 cm) sensitive to ant. calibrations & unmodeled multipath.
- Origin drift (3D) of 0.3 mm yr^{-1} vs. $ITRF2008_{IGb08}$ (1995–2012)
  - Offset of 5 mm in equatorial plane.
  - Offset of 7–17 mm along spin axis, depending on strategy.
- Agreement of annual geocenter motion with independent estimate:
  - Favorable in equatorial plane for both phase and amplitude
  - Poor along spin axis (dominated by draconitic variations)
- Inclusion of GRACE in network significantly improves TRF origin (esp. Z)
  - Origin offset (3D) of 6 mm vs. ITRF2008 (2003–2012)
  - Origin drift (3D) of 0.4 mm yr^{-1} vs. ITRF2008 (2003–2012)
- Long-arc (9-d) GPS orbit solutions ~2 cm lower than IGS combined orbit
  - Based on 2010–2012 comparisons
  - May lead to further reduction in SLR bias (~2 cm) for GPS35/36

Next Steps: Additional LEO Data



- **Main benefit of LEO data is improved Z geocenter.**
- **Inclusion of GRACE data significantly reduces GPS draconitic errors.**
  - Introduces signal at ~324 d (due to GRACE beta prime period?)
  - Underscores importance of using multiple LEOs where possible.
- **Processing of additional LEO data underway:**
  - Dual-frequency data TOPEX/Poseidon (1993) help to anchor TRF solutions, and overcome early station distribution problems.
  - Beginning in 2000, CHAMP data are available.
  - Jason-1 (2002–2006) and OSTM/Jason-2 (2008–pr.) provide data from orbits complementary to GRACE.