Accuracy and Stability of a Terrestrial Reference Frame Realized from GPS Data

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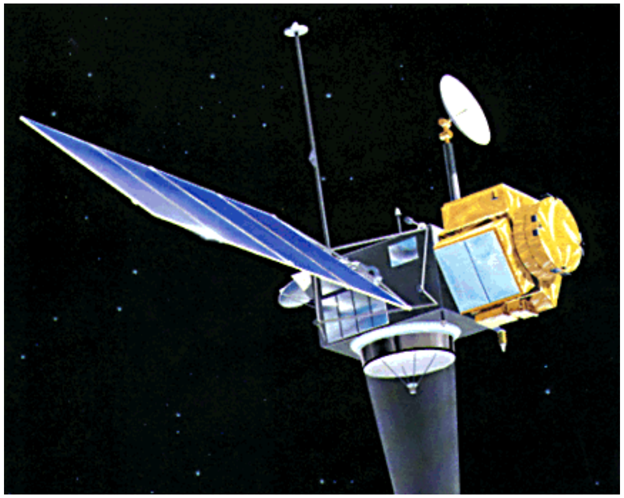
December 7, 2012

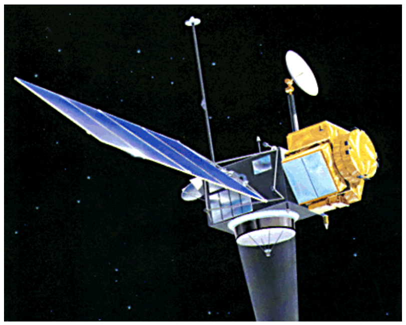
AGU Fall Meeting, San Francisco CA

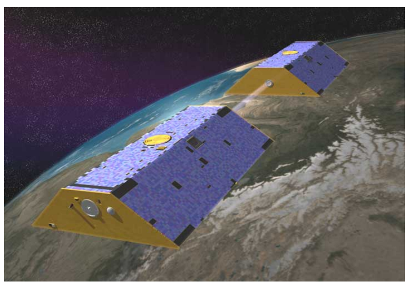
Motivation

- 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.

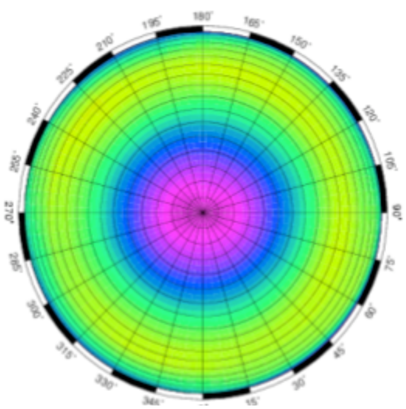


Calibrating the GPS Transmit Antennas Using Data from Low Earth Orbiters (LEO)

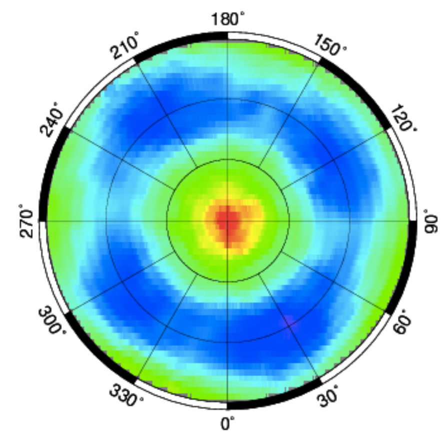




- **Treat LEO as "reference antenna in space"**
- **Choose candidate missions to minimize multipath**
  - TOPEX/POSEIDON (1992–2005)
  - GRACE (2002–pr.)
- **Use Precise Orbit Determination (POD) to provide constraints**
  - Scale constraint from dynamics (GM)
  - No a-priori constraint to TRF (use fiducial-free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



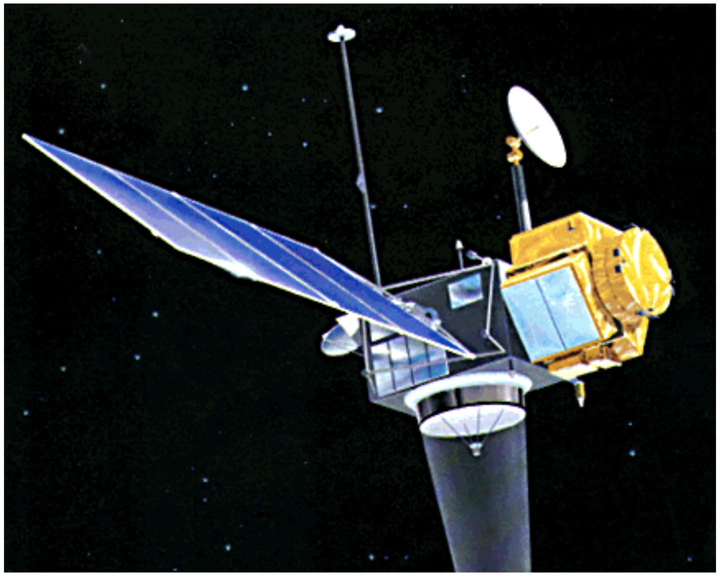
Pre-launch LEO APV Calibration

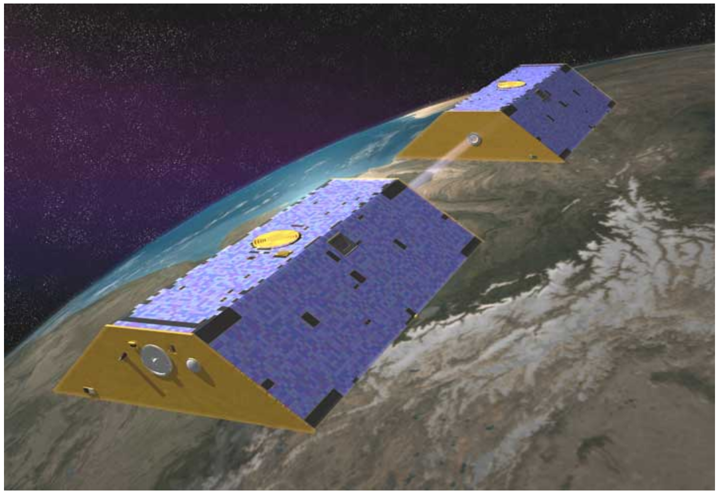


Estimated GPS Transmit Antenna APV

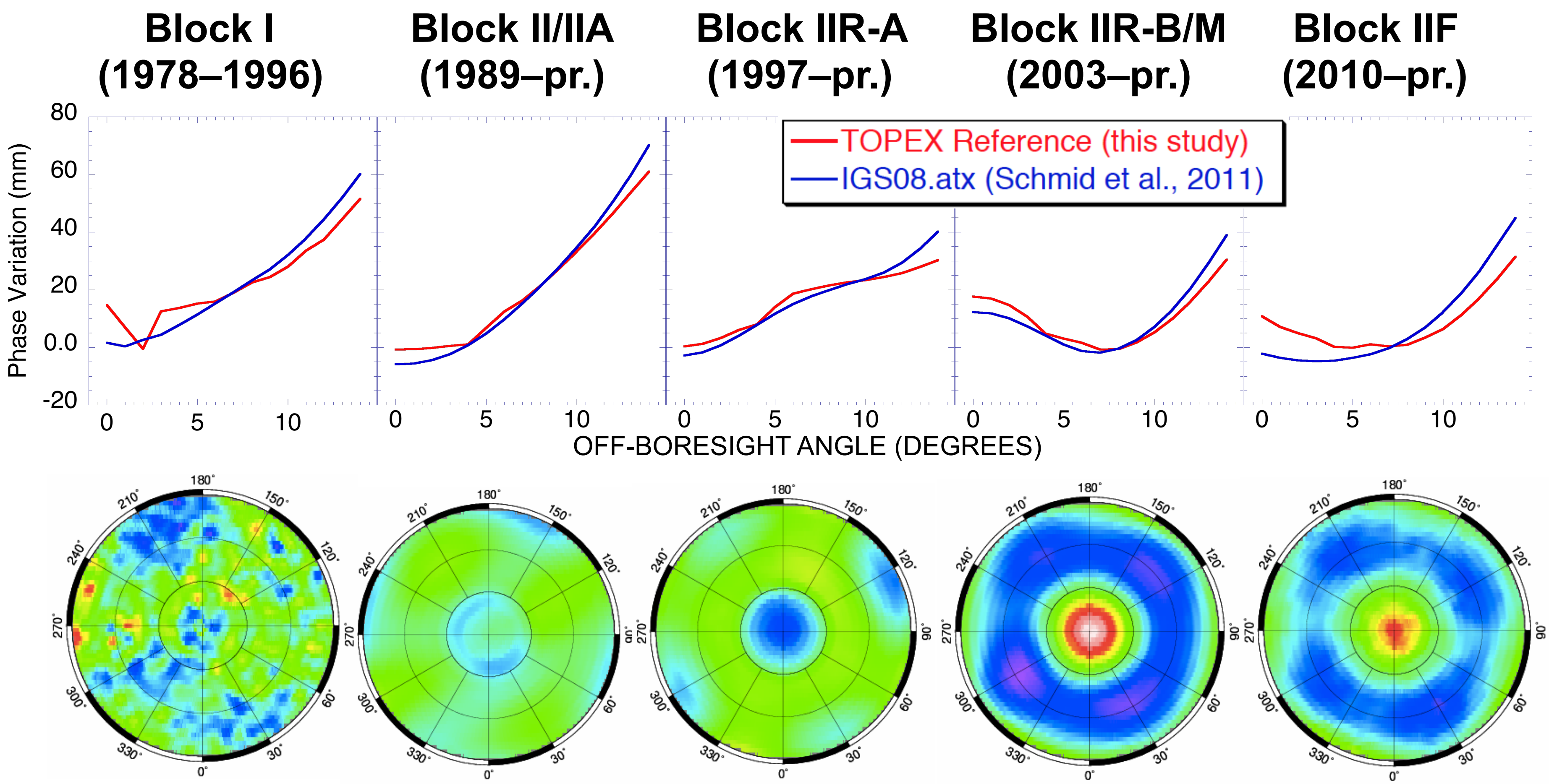
GPS Transmitter Antenna Phase Variations (APV) from TOPEX/POSEIDON (T/P) and GRACE

- Combine results from T/P (1993) and GRACE (2003–2008)
  - Perform daily dynamical POD using carrier phase (LC) only
  - Save daily normal equations and combine after-the-fact
  - Estimate block-average APV for each GPS satellite antenna type (I, II/IIA, IIR-A, IIR-B/M, IIF).
- Treat T/P as reference antenna
  - Capitalize on low phase multipath
    - Choke ring on 4-m boom
  - Use test-range measurements (Dunn and Young, 1992) as *a priori*.
    - Polynomial smoothing in elevation
  - Allow only azimuthal adjustments to T/P APV
    - GRACE APV adjusted
  - Exploit satellites (Block IIA) tracked commonly by both GRACE and T/P.
    - Provide means of communicating TOPEX reference to modern (IIR/IIF) satellites.





Antenna Phase Variations for GPS Satellite Blocks



- Note highly contrasting APV patterns for different satellite blocks.
- Against the backdrop of the evolving GPS constellation, mismodeled APV will manifest as scale instability (cf. Zhu et al., 2003; Ge et al, 2005).

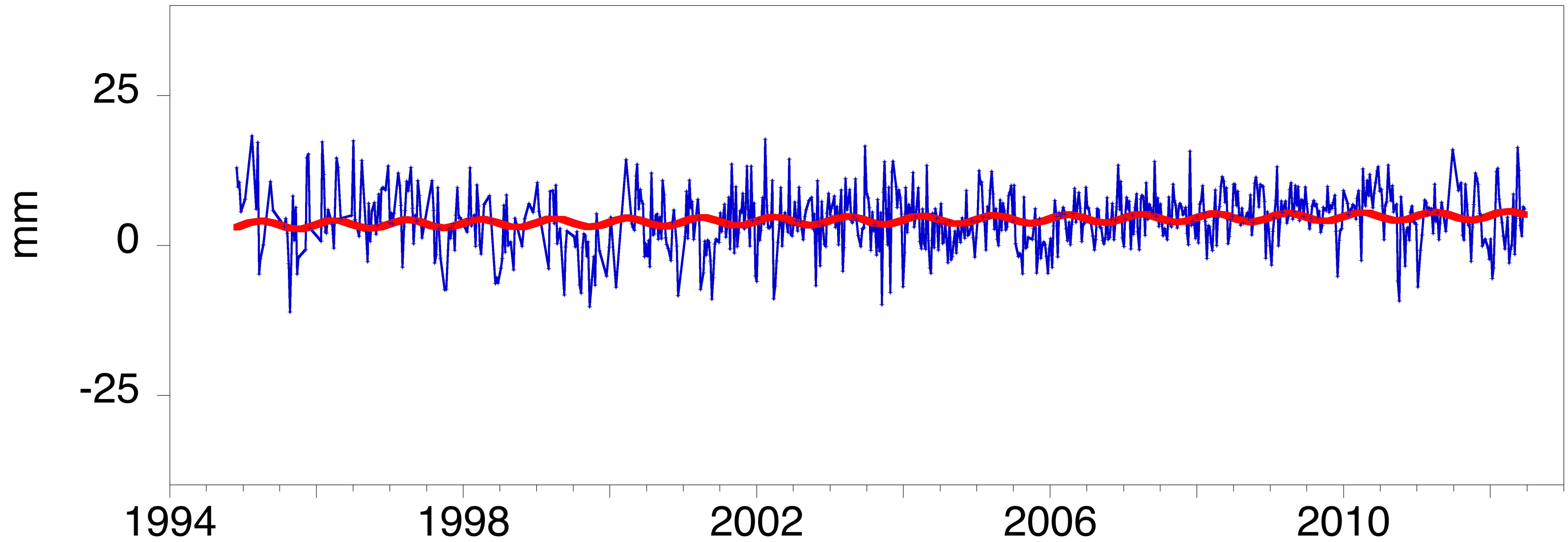
Realizing the TRF from GPS: Longarc Network Solution Strategy

Element	Selection
Time span	1994–2012 (~18 yrs.)
Orbit Arc Length	9 days, centered on GPS week (2-d overlap)
Number of Terrestrial GPS Stations	40* (selected from stations deploying TurboRogue-style 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	JPL Ant. Test Range (*Young and Dunn,* 1992)
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	1 cpr UVW accelerations (U along sun-s/c vector); updated every 12 hrs. as random walk
Phase ambiguities	Integer resolution
Earth orientation parameters	Daily (random-walk) updates to X and Y pole. UT1 fixed to Bulletin A.

* 40 qualifying stations not generally available for 1997 and earlier

- Internal (GPS) TRF compared to $ITRF2008_{IGS08}$ using 7-param. Helmert transform.
  - Also called "network shift" approach
  - Origin shift (3D) and scale difference expose TRF errors in both (GPS and ITRF) frames.

ΔX Origin (vs. $ITRF2008_{IGS08}$)

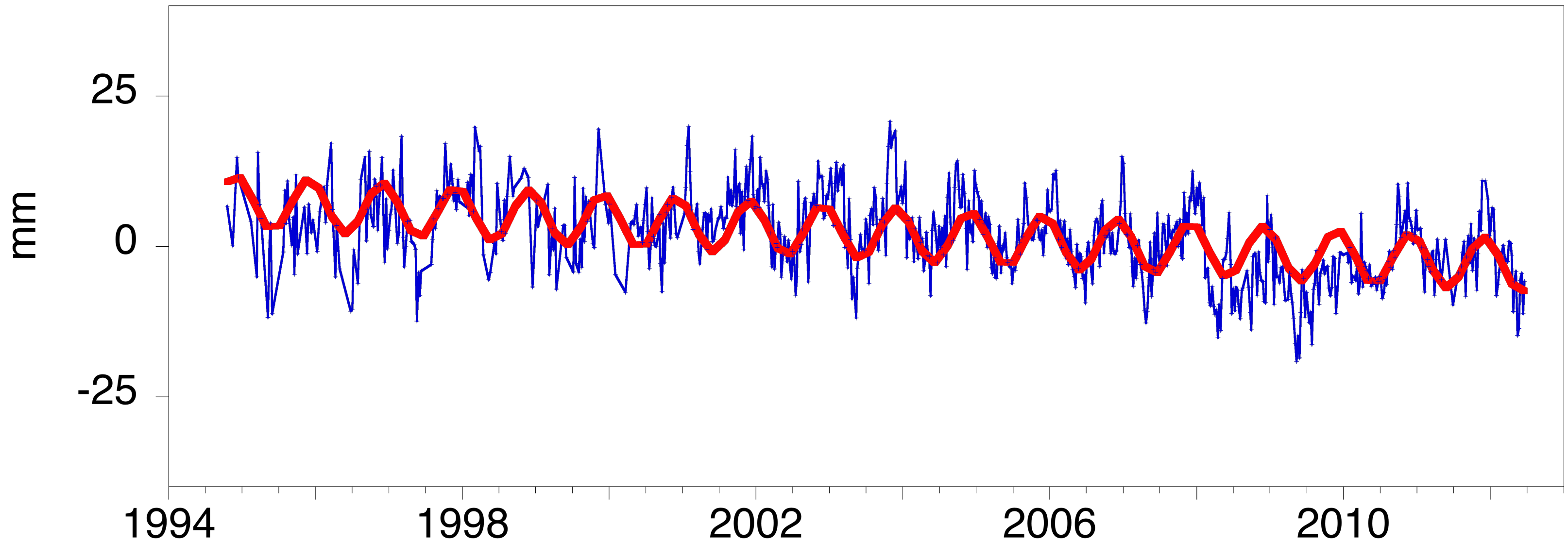


- **Bias < 5 mm**
- **Best repeatability on this (X) axis**
  - < 5 mm for weekly solutions
- **Negligible drift (0.1 mm/yr)**
- **Annual geocenter variation < 1 mm**
  - Smaller than consensus estimates of ~2 mm (e.g., Wu et al., 2012)

Bias (2005)	+4 mm
Trend	+0.1 mm/yr
Annual	0.8 mm
RMS Res	4.8 mm

Wu et al., Geocenter motion and its geodetic and geophysical implications, J. Geodynamics 58, 44– 61, 2012

ΔY Origin (vs. ITRF2008$_{IGS08}$)

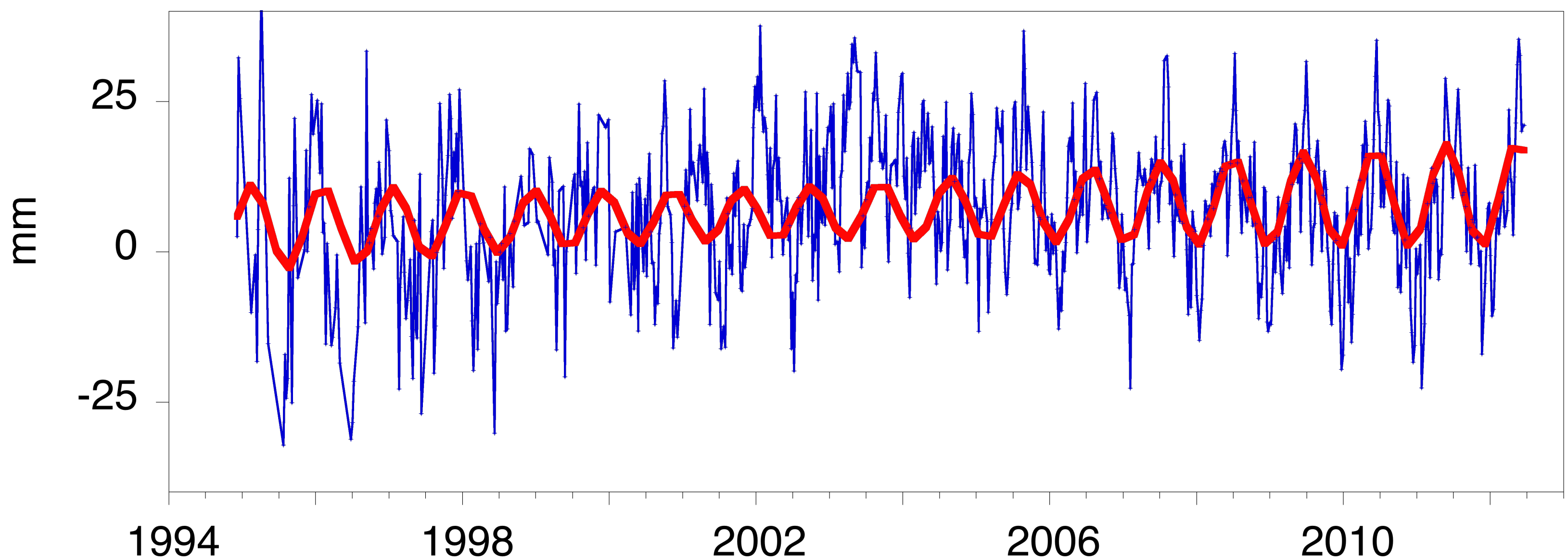


- **Negligible bias (~1 mm at epoch)**
- **Drift < 1 mm/yr**
  - But pattern is not linear
- **Annual geocenter variation: 4 mm**
  - Peaks in late November
  - Consistent with consensus estimate

Bias (2005)	**+1 mm**
Trend	**–0.6 mm/yr**
Annual	**4.4 mm**
RMS Res	**5.4 mm**

*Wu et al., Geocenter motion and its geodetic and geophysical implications, J. Geodynamics 58, 44– 61, 2012

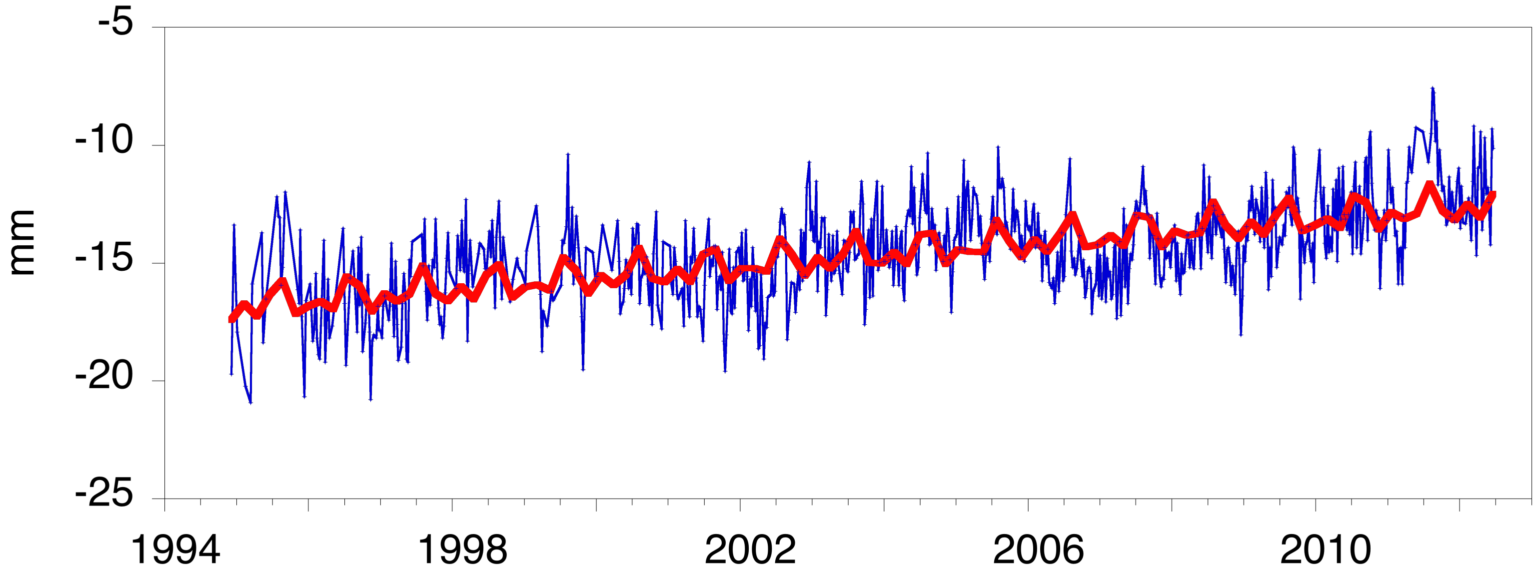
ΔZ Origin (vs. $ITRF2008_{IGS08}$)



- **Centering on spin (Z) axis more difficult**
  - Weekly repeatability > 1 cm
- **Prone to systematic GPS measurement errors (e.g., at draconitic year)**
- **Despite larger errors, bias and stability are excellent**
- **Annual geocenter variation: 2 mm**

Bias (2005)	**+7 mm**
Trend	**+0.3 mm/yr**
Annual	**2.4 mm**
Draconitic	**6.7 mm**
RMS Res	**11.4 mm**

ΔScale (vs. $ITRF2008_{IGS08}$)

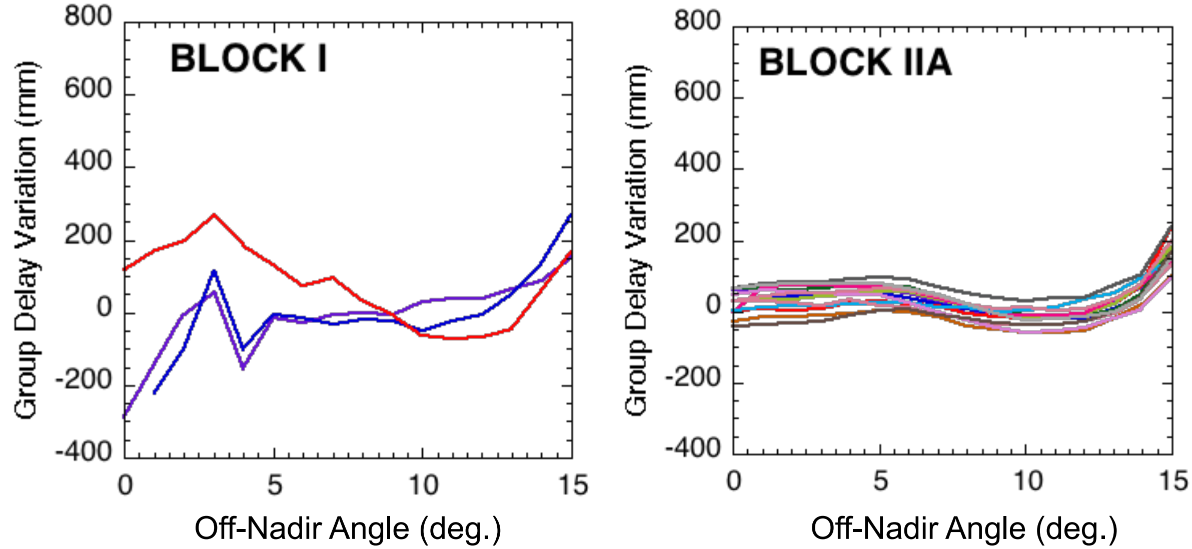


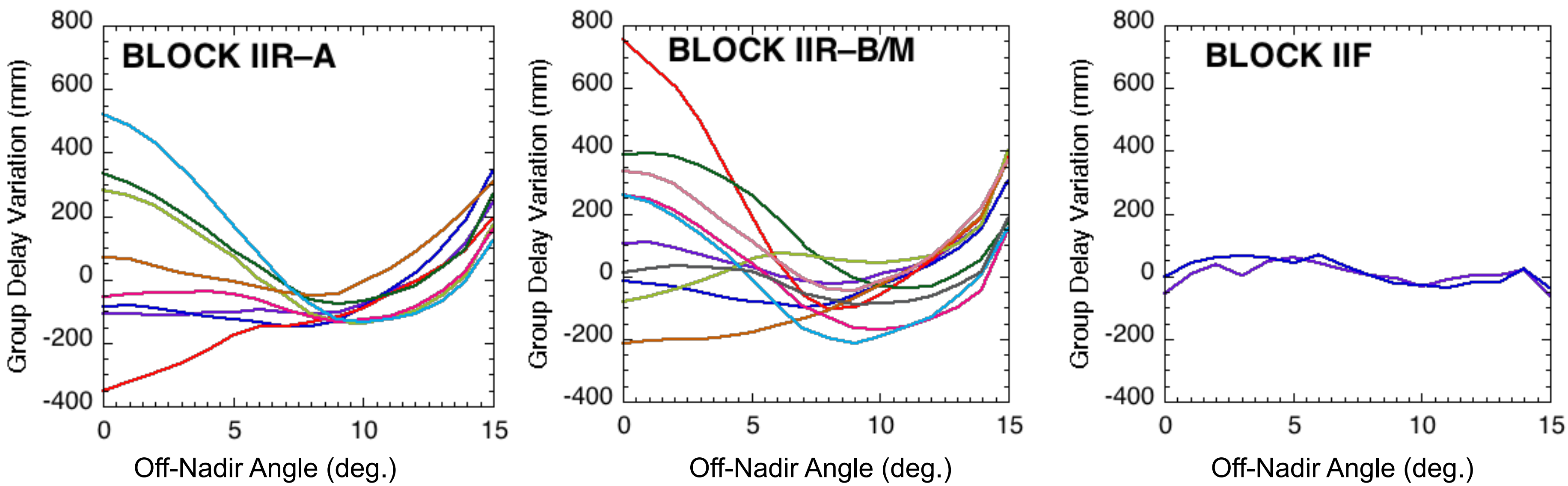
- **Scale stability crucial for studies of global sea level change**
- **Repeatability (weekly) of 1.6 mm**
- **Drift of +0.2 mm/yr (0.04 ppb/yr)**
- **Scale bias of –14 mm (~2 ppb)**
  - Affected by choice of model for ground (choke ring) antenna
  - Ensemble local effects (e.g., multipath) also contribute

Bias (2005)	**–14 mm**
Trend	**+0.2 mm/yr**
Annual	**0.5 mm**
Semi Ann	**0.6 mm**
RMS Res	**1.6 mm**

Next Steps: Group Delay Variations

- **Use GRACE as reference antenna**
  - Embedded antenna preferred for group delay
- **Block IIRs show important satellite-specific variations.**
  - Legacy (Block II/IIA) satellites more consistent.

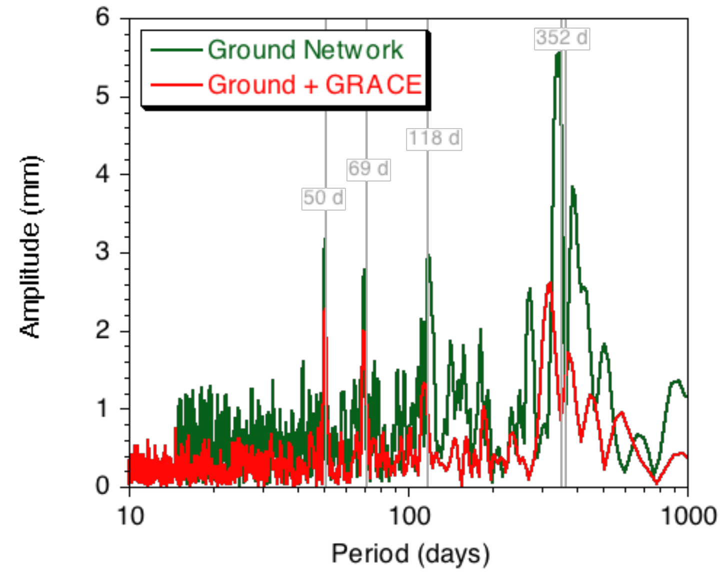




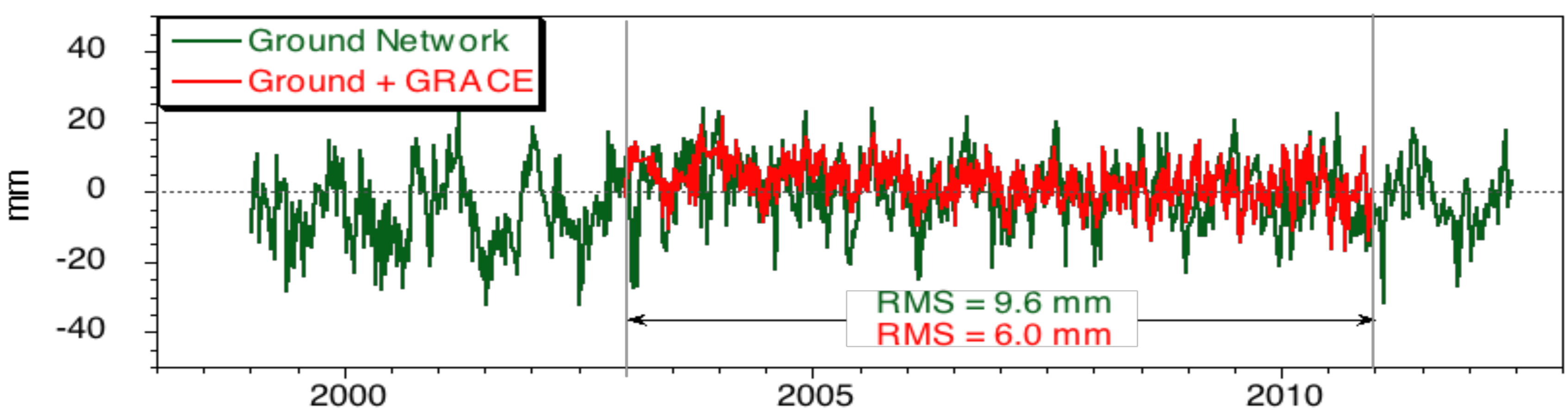
Next Steps: Add LEO Data in Network Solutions

- Adding GRACE to the 40-station ground network significantly improves TRF.
  - Reduced systematic errors at the draconitic harmonics.
  - Particularly for the Z component of the geocenter.
- Candidate missions include T/P, Jason 1/2 and CHAMP.

Periodogram of ΔZ Origin (vs. IGS08)



Time Series of ΔZ Origin (vs. IGS08)



From Haines et al. 2011, Fall AGU

Summary

- New TRF realization from GPS alone
  - Spans nearly 18 years (1994–2012) 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.
- Scale stability of 0.2 mm yr^{-1} vs. $ITRF2008_{IGS08}$ (1994–2012)
  - Scale offset ~2 ppb (~1 cm) sensitive to ant. calibrations & unmodeled multipath.
- 3D origin stability of 0.7 mm yr^{-1} (cf., Collilieux et al., 2010)
  - But some non-linear patterns (esp. in Y & Z).
  - May include actual (secular) geocenter motion in addition to frame error.
- 3D origin offset of 9 mm
- Excellent overall agreement with $ITRF2008_{IGS08}$
  - Consistent with estimated errors for state-of-the-art TRF (e.g., Altamimi et al., 2011, Wu et al, 2011; Argus, 2012).
  - Exception is scale offset.
- Future plans:
  - Incorporate models for antenna group-delay variations (for pseudorange data).
  - Systematically incorporate LEO data in network solutions.
  - Continue investigations of scale bias (e.g., new ground/test range measurements).

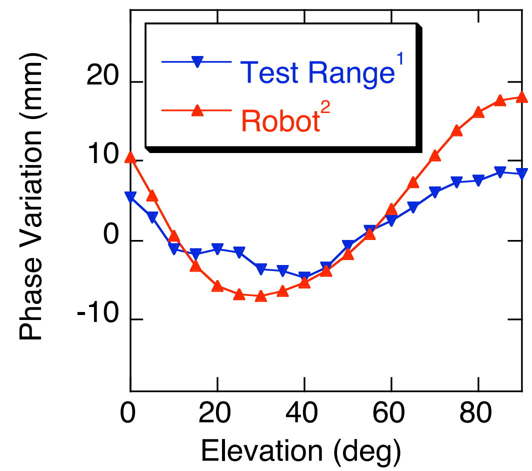
Scale Bias: Impact of Antenna Model Pairings

- Choice of ground antenna calibration model (test range vs. robot) impacts scale by ~3 cm (> 4 ppb).

Reference Antenna for Transmitter APV	Ground Antenna APV	Year	No. of Weekly Solns.	Δ Scale vs. IGS08	
				σ (mm)	Mean (mm)
TOPEX[1]	Test Range[1]	2004	12	1.1	–19
TOPEX[1]	Test Range[1]	2010	45	1.8	–17
TOPEX smoothed	Test Range[1]	2010	45	1.8	–12
TOPEX[1]	Robot[2]	2004	12	1.0	+10
TOPEX smoothed	Robot[2]	2010	45	1.7	+17

1 Dunn and Young (1992)
2 Wübbena et al. (2000)

APV for Ground Antenna (AOAD/M_T Choke Ring)



APV for TOPEX antenna