Characterizing the GPS Satellite Antenna Phase- and Group-Delay Variations Using Data from Low-Earth Orbiters: Latest Results

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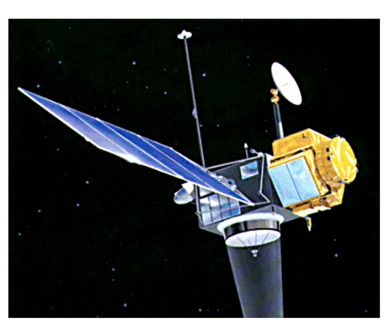
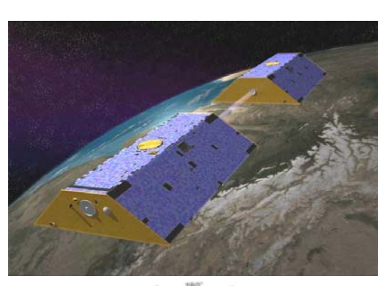
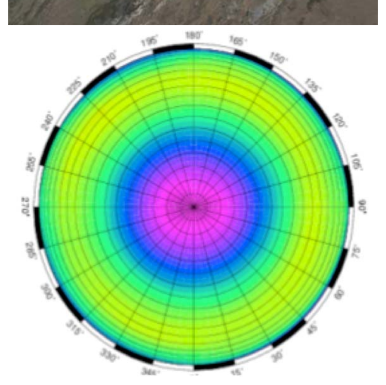
Abstract Designed to support navigation, the L-band antenna arrays on the GPS satellites are significantly larger and more complex than the simple receiver antennas used in geodetic applications. The phase- and group-delay variations attributed to the GPS satellite antennas are difficult to model, and remain among the limiting sources of error for the most demanding GPS geodetic problems, such as determination of the terrestrial reference frame (TRF). We have developed techniques for estimating the GPS satellite antenna phase- and group-delay variations using tracking data from low-Earth orbiters (LEOs). We describe updated estimates that are based on combinations of data from the GRACE (2002–present) and TOPEX/Poseidon (T/P, 1992–2005) missions. These satellites offer a number of substantial advantages for developing antenna calibrations. The scale (mean height) and origin of the orbit solutions are well determined (at the cm level or better) from dynamical constraints, thus obviating the need for a TRF constraint in solving for the antenna calibrations. In addition, there is no tropospheric delay to confound interpretation of the LEO measurements. In both cases, the multipath environment is also favorable: the GRACE receiver antenna is a choke ring embedded in the surface of a clean spacecraft with a simple profile, while the T/P antenna is mounted on a 4-m boom above the spacecraft bus. Together, the T/P and GRACE missions provide a unique opportunity to observe and compare antenna calibrations for current as well as legacy GPS satellites. We provide updated comparisons of our antenna phase variation models to the International GNSS standard (based on ground data), and present new estimates of the antenna group-delay variations for use with pseudorange data. Finally, we apply our latest antenna calibrations in realizing the terrestrial reference frame from GPS alone. Current comparisons of our GPS-based TRF (1999-2012) with ITRF2008 show 0.2-mm/yr agreement in scale rate and better than 1-mm/yr agreement for origin rate (3D). We discuss possible origins of a remaining scale bias.

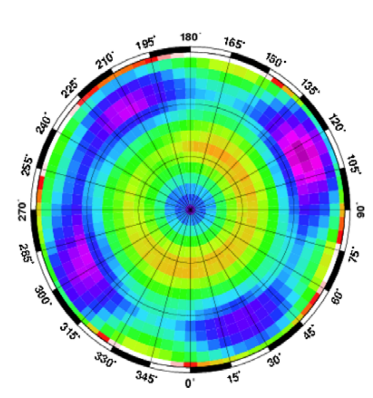
LEO-Based Calibrations of GPS Transmit Antennas



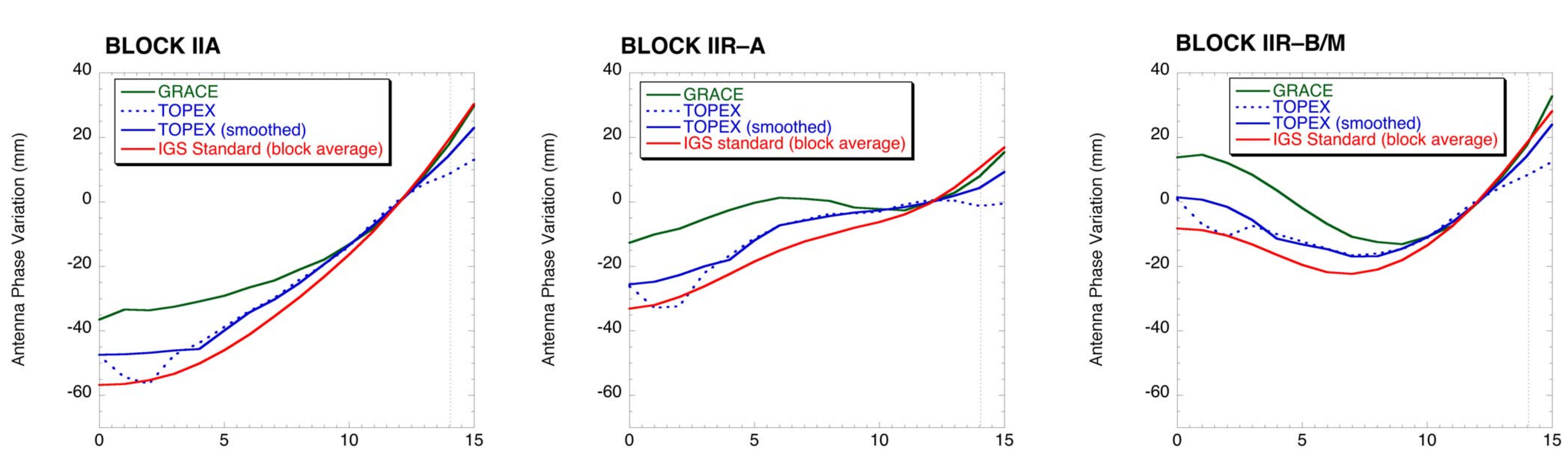


- Treat LEO as "reference antenna in space"
- Choose candidate missions to minimize multipath
  - GRACE (2002–pr.)
  - TOPEX/POSEIDON (1992–2005)
- Use Precise Orbit Determination (POD) to provide constraints
  - Scale constraint from dynamics (GM)
  - No a-priori constraint to TRF (use fiducial-free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



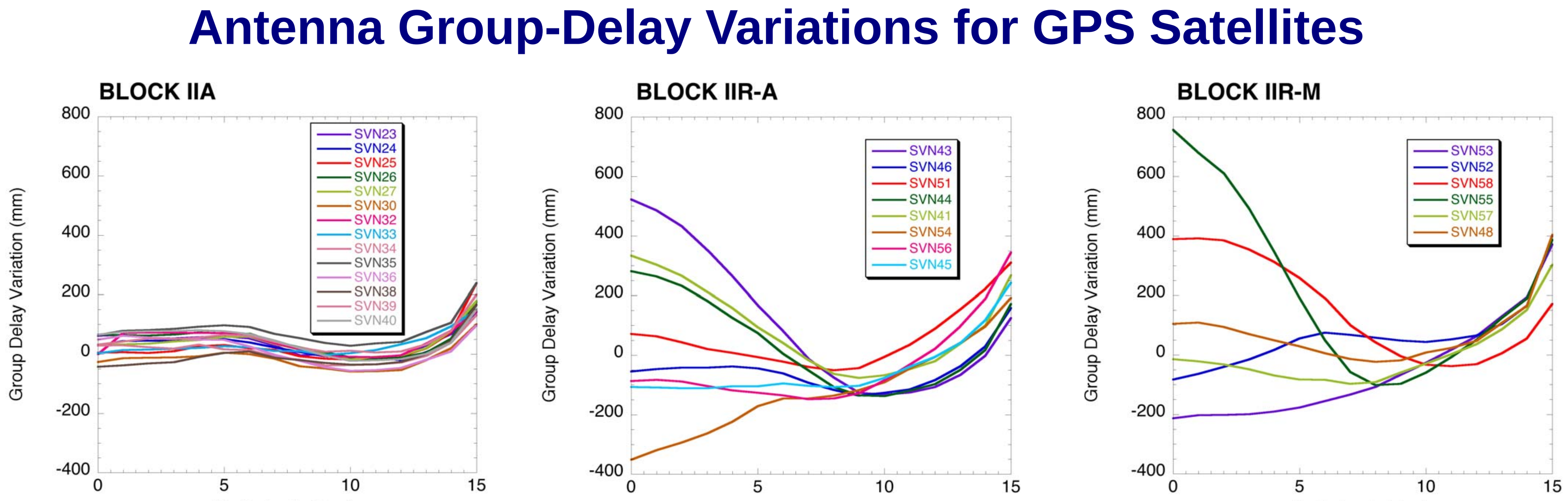


Antenna Phase Variation Estimates for GPS Satellites



- GRACE = Use GRACE APV (from pre-launch anechoic measurements) as reference
- TOPEX = Use TOPEX APV (from pre-launch test range measurements; Dunn and Young, 1992) as reference
  - GRACE still needed to provide connection to Block IIR satellites
  - Smoothed version of TOPEX a-priori APV map attempts to remove high-frequency variations from test-range measurements
- IGS Standard = Block averages of IGS08 transmitter calibrations (e.g., Schmid et al., 2007)

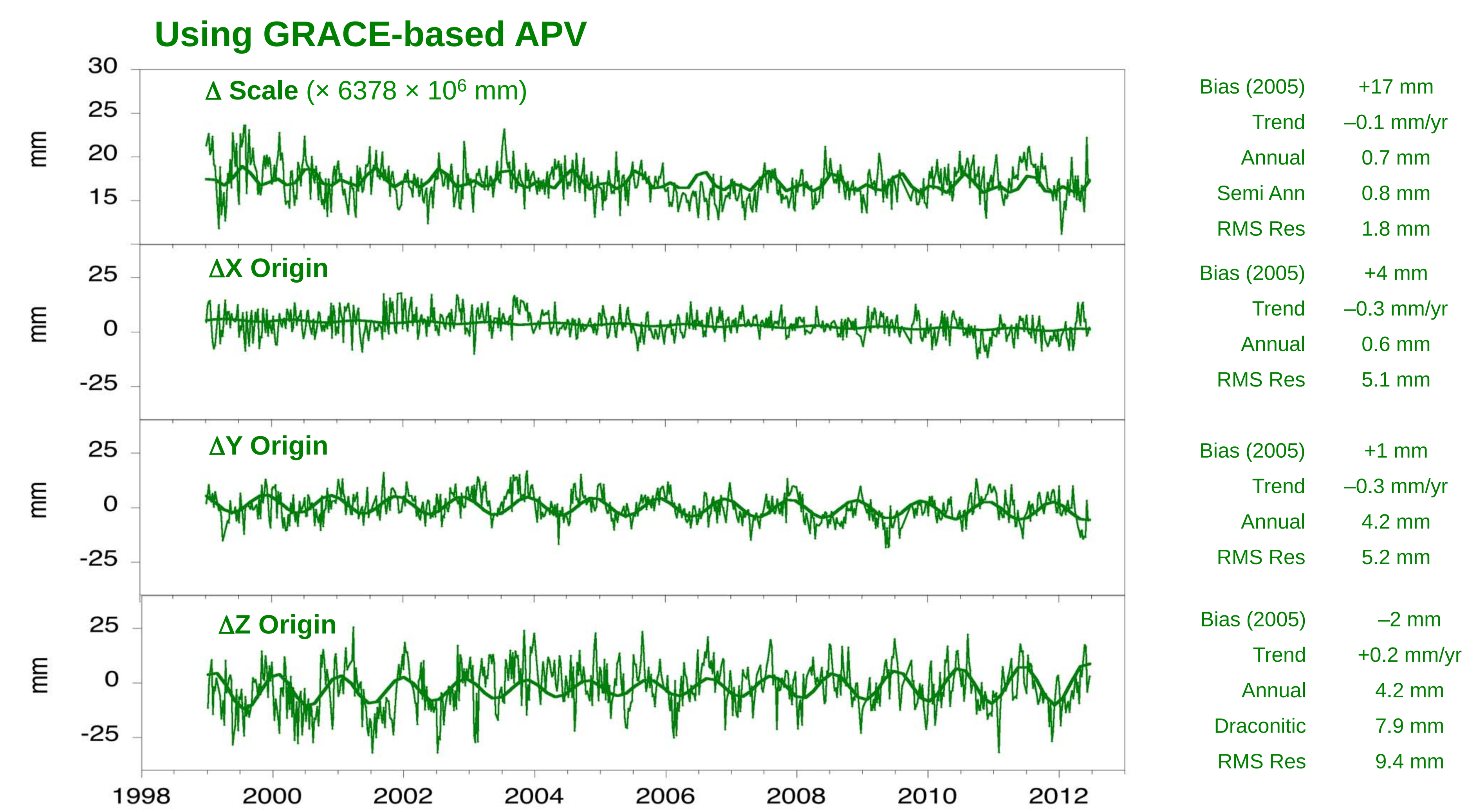
Antenna Group-Delay Variations for GPS Satellites

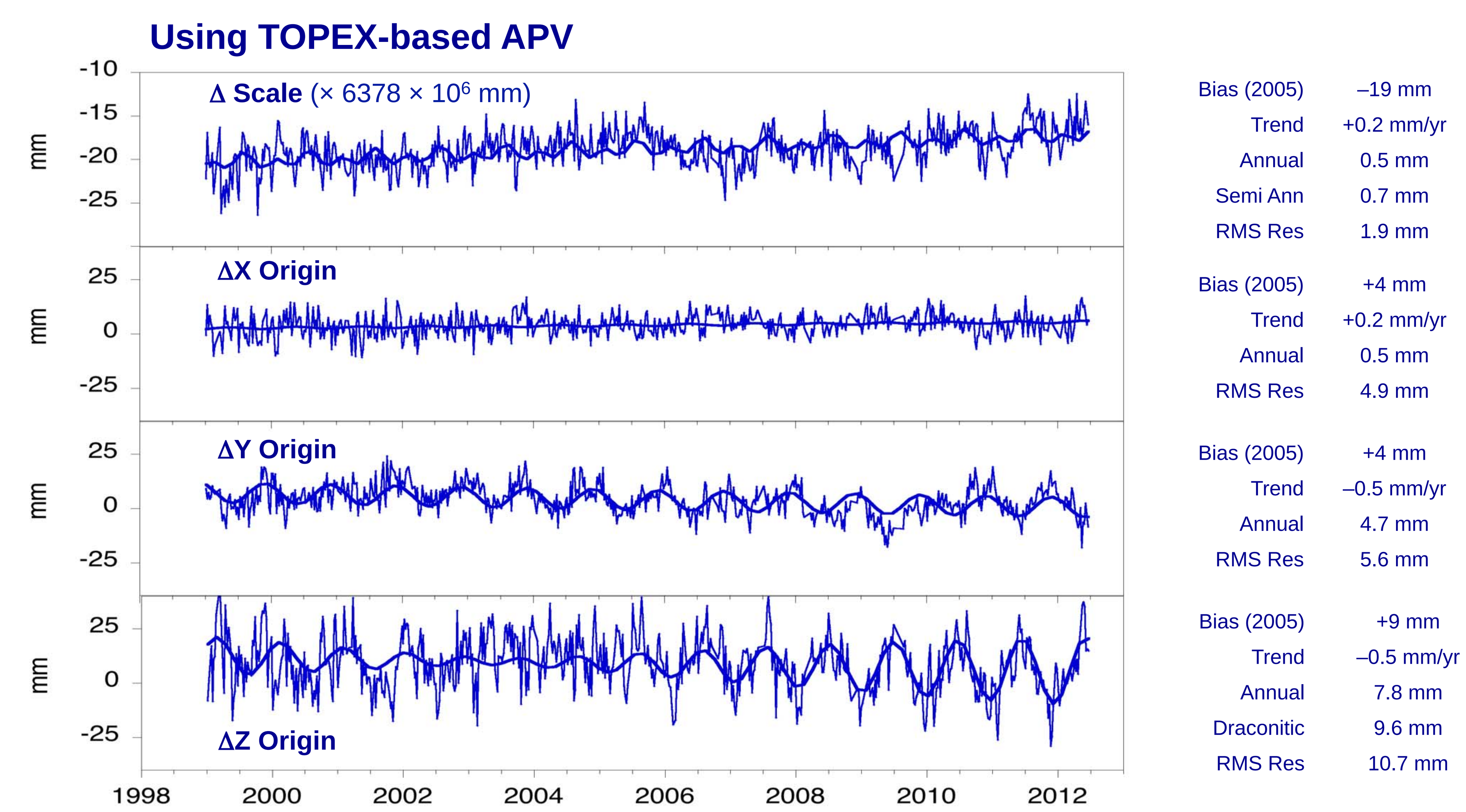


- GRACE-based estimates of transmitter group delay variations can be used to correct ionosphere-free pseudorange
  - Results show important satellite-to-satellite variations for Block IIR
- Early attempts to derive TOPEX-based estimate of Block II/IIA group delay unsuccessful
  - Yield large elevation-dependent variation consistent with 24-m offset from Block II/IIA center of mass.
  - GPS Demonstration Receiver (GPSDR) ASIC error (SNR-dependent) and TOPEX code multipath are candidate explanations.

GPS Terrestrial Reference Frame vs. IGS08

The LEO-based estimates of GPS APV are used to realize the TRF using a ~14-yr time series of 9-day global network solutions (40 stations + GPS constellation) centered on each GPS week. The solutions are "fiducial free", ensuring independence from ITRF/IGS08. The resulting TRF shows excellent agreement with IGS08:

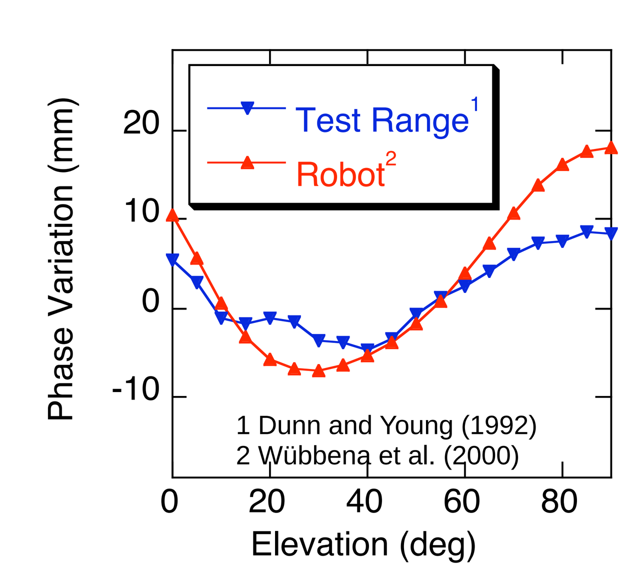




Scale Bias vs. IGS08: Impact of Antenna Model Pairings

Two subsets of the weekly network solutions (in 2004 and 2010) were used to quantify the sensitivity of the scale bias (vs. IGS08) to the APV model pairings (receiver/transmitter). The two candidate models for the ground receiver antennas (all choke rings) are depicted in the bottom right panel. In terms of scale bias, the best agreement with IGS08 (~1-cm level at the Earth's surface) is obtained using TOPEX as the reference antenna in space (bold-faced entries).

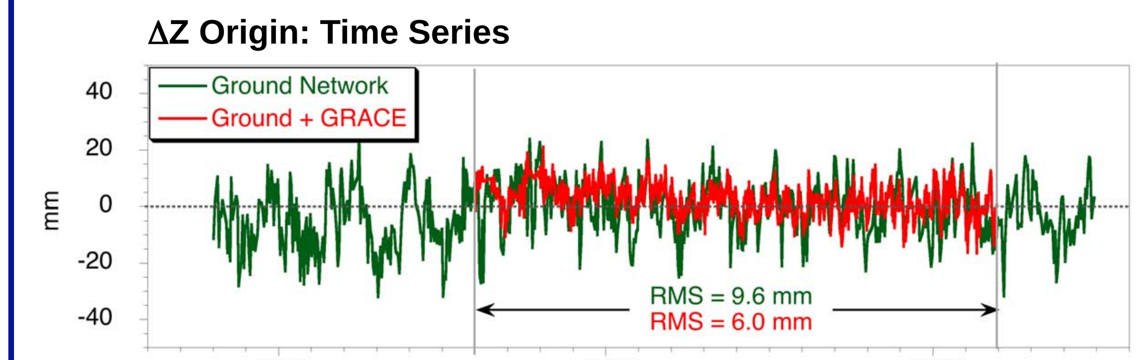
Reference Antenna for Transmitter APV	Ground Antenna APV	Year	No. of Weekly Solns.	Δ Scale vs. IGS08	
				σ (mm)	Mean (mm)
GRACE	Test Range[1]	2004	12	1.7	+17
GRACE	Test Range[1]	2010	45	1.6	+18
TOPEX	Test Range[1]	2004	12	1.1	–19
TOPEX	Test Range[1]	2010	45	1.8	–17
TOPEX smoothed	**Test Range[1]**	**2010**	**45**	**1.8**	**–12**
GRACE	Robot[2]	2004	12	1.8	+45
TOPEX	**Robot[2]**	**2004**	**12**	**1.0**	**+10**
TOPEX smoothed	Robot[2]	2010	45	1.7	+17



Impact of GRACE LEO Data on Realization of the TRF

Data from LEOs can also be included directly in the network solutions to improve recovery of the TRF. Adding GRACE to the 40-station ground network significantly reduces systematic errors at the draconitic harmonics, particularly for the Z component of the geocenter.

ΔZ Origin: Time Series



ΔZ Origin: Periodogram