Terrestrial Reference Frame from GPS: New Perspectives from Low-Earth Orbit

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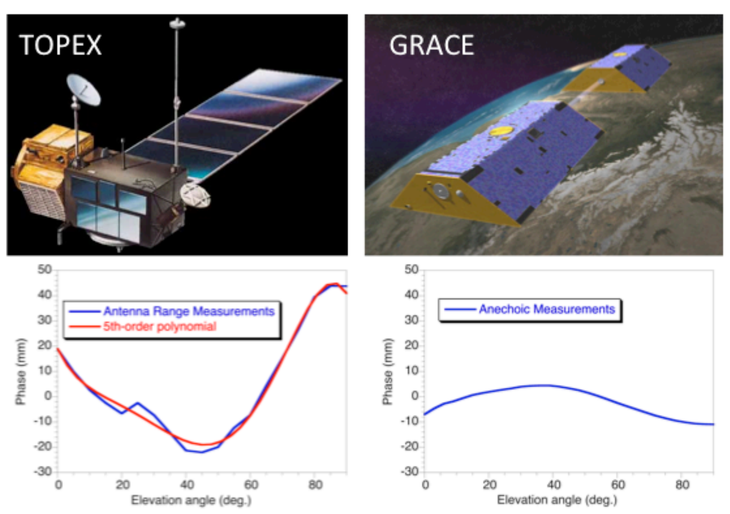
Abstract Data from Global Navigation Satellite Systems (GNSS) play vital roles in both realizing and disseminating the International Terrestrial Reference Frame (ITRF). Driven by both economy and convenience, geodetic-quality GNSS receivers have been dispersed throughout the globe and provide the only basis of measurement at many of the sites underlying the ITRF. Through site collocations, GNSS systems also provide crucial survey ties between the tracking systems supporting other space-geodetic techniques (SLR, VLBI and DORIS). Due to misgivings about the absolute geocentric accuracy of the GPS system at the mm- to cm-level, however, GPS data have been excluded from direct determination of both the origin and scale of the ITRF. We review recent advances in determining the origin and scale of the TRF based on GPS data alone. These advances have been made possible by the emergence of new techniques that leverage data from GPS receivers on low-Earth orbiters (LEO), either to improve characterization of the GPS transmitter antenna patterns, or to supplement terrestrial data in network solutions. The results help lay the groundwork for a potential expansion of the role of GPS in defining and maintaining the ITRF at the level necessary to support the most demanding applications (e.g. measuring global sea-level change).

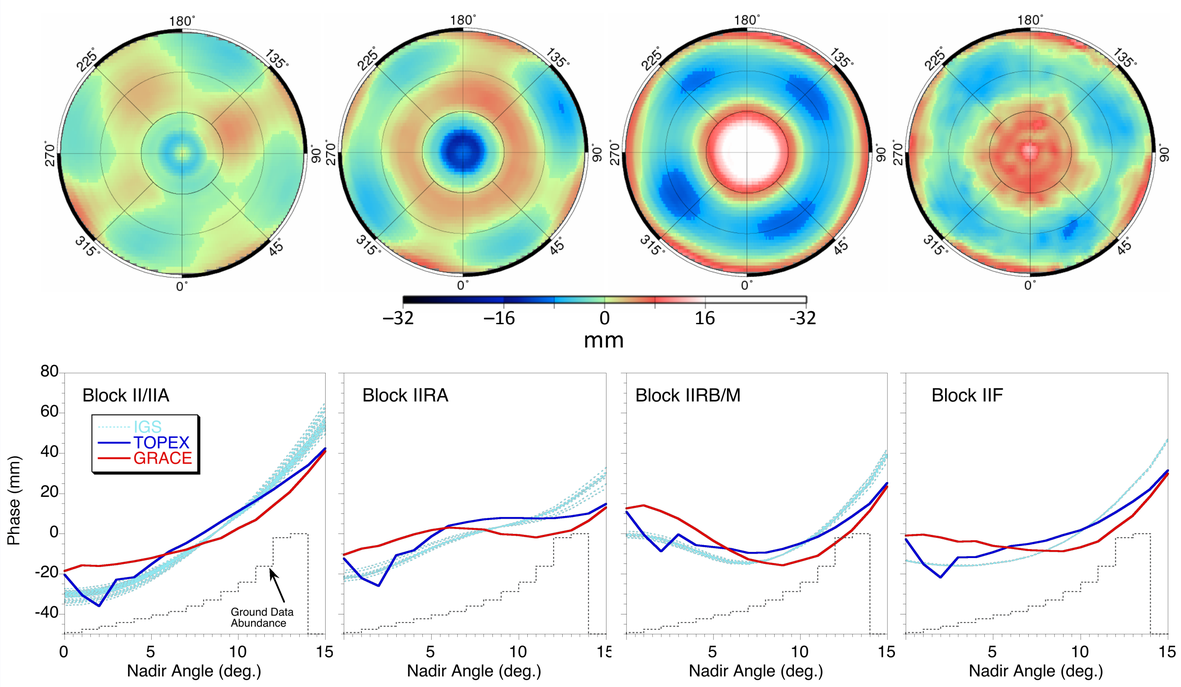
Based on ~17 years of data (1997–2013), our current GPS-defined frame agrees with ITRF2008 to 0.03 ppb/yr and 0.4 mm/yr in terms of scale and origin (3D) rate respectively. We have recently updated our estimates of the GPS transmitter antenna phase variations using data from the GRACE and TOPEX/Poseidon missions, and have also performed new network solutions directly incorporating LEO data from the GRACE mission. We describe the impacts of these evolutions on the TRF realization.

LEO-Based Calibrations of GPS Transmit Antennas



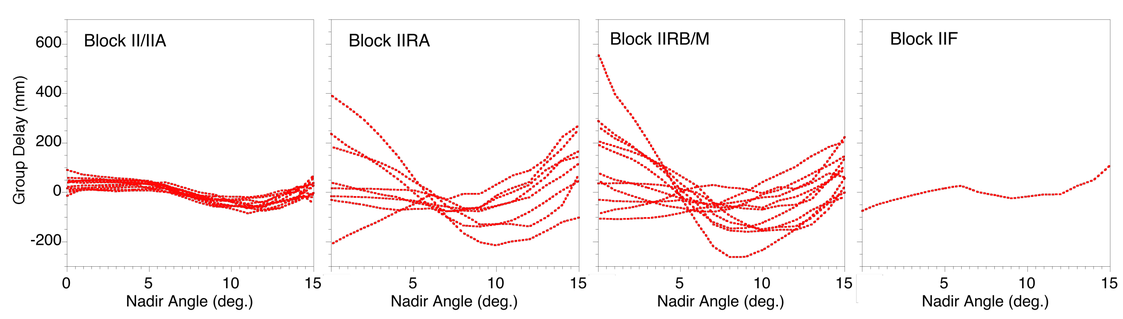
- Treat LEO as "reference antenna in space"
- Choose candidate missions to minimize multipath
  - GRACE (2002–pr.)
  - TOPEX/Poseidon (1992–2005)
- Use Precise Orbit Determination (POD) to provide constraints
  - Scale constraint is gravitational (GM)
  - No a-priori constraint to TRF (use fiducial-free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

Antenna Phase Variations for GPS Satellites



- TOPEX = Use TOPEX APV (from pre-launch test range measurements; Dunn and Young, 1992) as reference
- GRACE = Use GRACE APV (from pre-launch anechoic measurements) as reference
- IGS Standard = IGS08 calibrations from terrestrial data (e.g., Schmid et al., 2007)

Antenna Group-Delay Variations for GPS Satellites



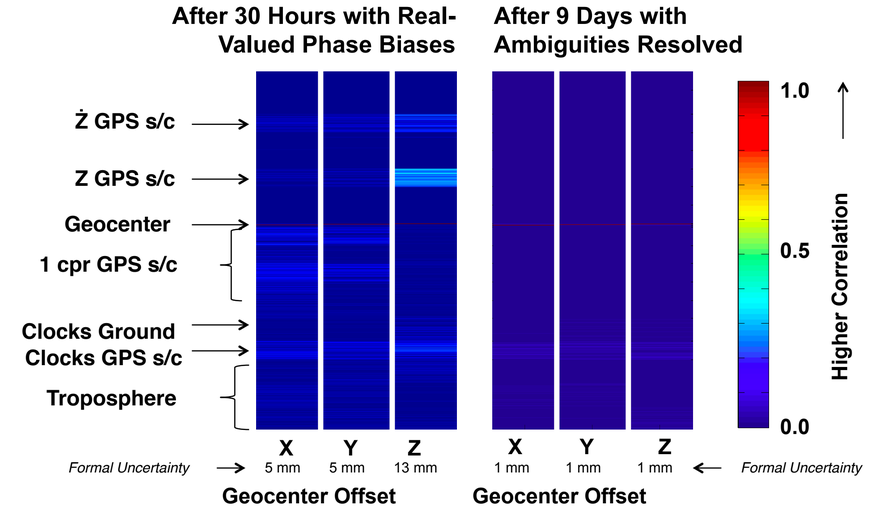
- GRACE-based estimates of transmitter group delay variations can be used to correct ionosphere-free pseudorange
- Results show important satellite-to-satellite variations for Block IIR
- Block IIF result based on SVN62 only, but early results from newer launches hint at similar patterns.

Long-Arc Estimation Strategy

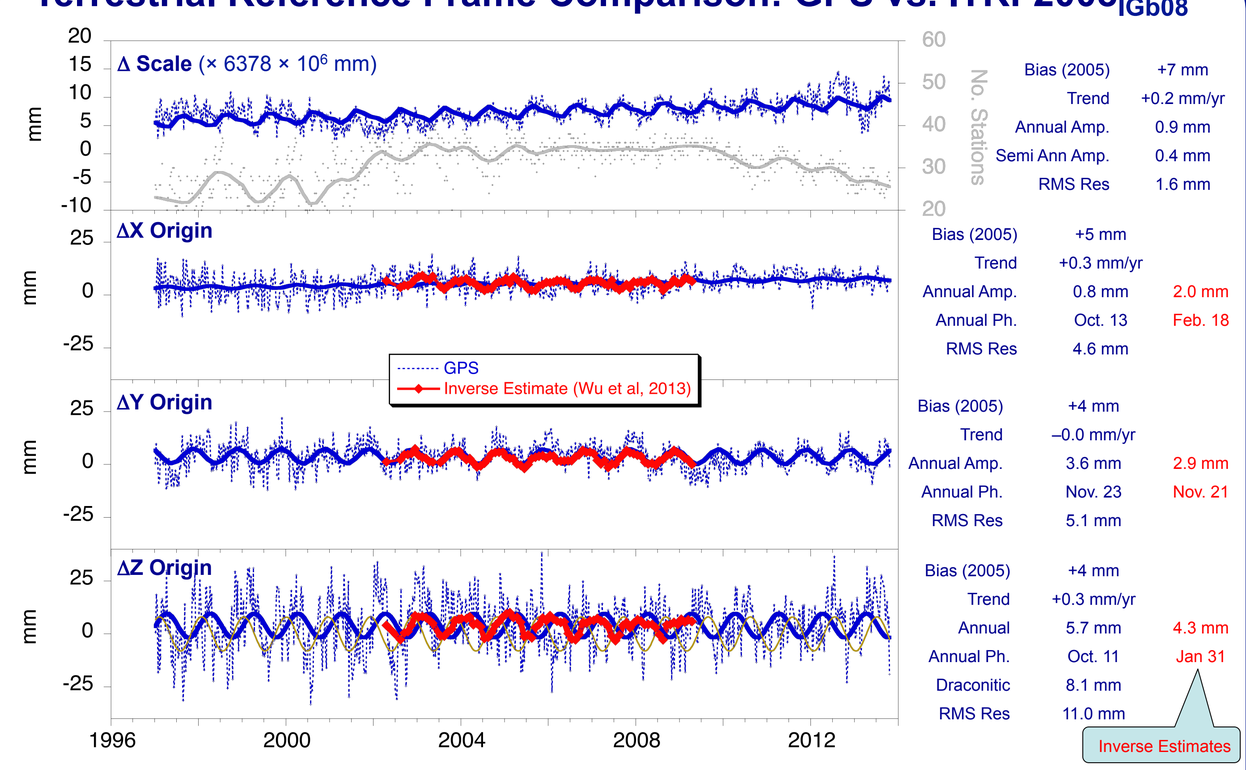
Element	Selection
Time span	1997–2013 (~17 yrs.)
Orbit Arc Length	9 days, centered on GPS week (2-d overlap)
Number of Terrestrial GPS Stations	40 (selected from stations with Dorne Margolin-style choke-ring antennas to improve homogeneity)
Transmitter Antenna Phase Variations	Block averaged estimates from LEO data. Elevation dependence from average of TOPEX and GRACE; azimuthal variations from GRACE.
Transmitter Antenna Group-Delay Variations	Block averaged estimates for II/IIA and IIF. Satellite-specific estimates for IIR (all from GRACE).
Ground Receiver Ant. Calibration Model	Antenna Test Range (Dunn and Young, 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 accelerations in solar (UV) coordinates updated every ~36 hr as colored noise (τ = 7 d). Solar radiation pressure coefficient and Y bias as constant per 9-d arc, with GSPM13 background model.
Phase ambiguities	Integer resolution
Earth orientation parameters	2-hr (random-walk) updates to X, Y pole and UT1–UTC.

Internal (GPS) TRF from long-arc strategy (above) compared to $ITRF2008_{IGb08}$ using Helmert transform ("network shift" approach).

- Correlations among estimated parameters (e.g., clocks, orbital params., troposphere) can hinder recovery of TRF from GPS data (Kuang et al., 1996; Rebischung et al., 2013).
- Long-arc strategy effective at reducing these correlations.



Terrestrial Reference Frame Comparison: GPS vs. $ITRF2008_{IGb08}$

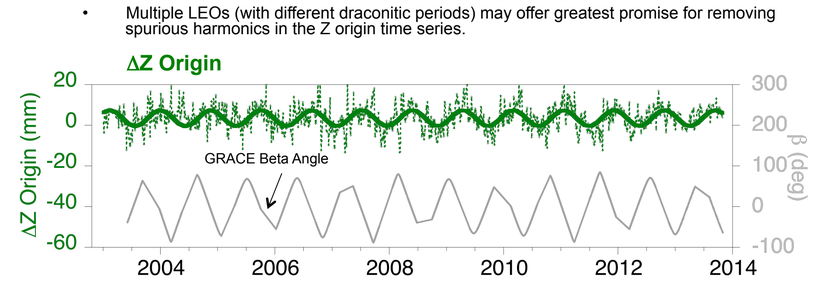


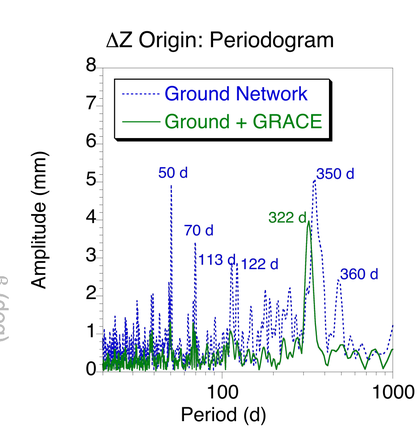
- Scale and scale rate agree to 1 ppb and 0.05 ppb/yr respectively.
  - Absolute scale (bias) sensitive to various antenna calibrations at level of 1–3 ppb.
- 3D Origin and origin rate agree to 8 mm and 0.4 mm/yr respectively.
- Annual geocenter motion compares favorably with independent data.
  - ~ 1 mm agreement in amplitude for all three coordinates.
  - Excellent alignment of phase for Y, but X and Z phase shifted by ~1 season (GPS earlier).

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.

Impact of GRACE LEO Data on Realization of the TRF

- Based on 3-d arcs with 40 ground stations + GRACE
- Largest impact on Z origin
  - Improves repeatability (from 10.8 to 5.9 mm)
  - Significantly reduces errors at GPS draconitic annual period (~352 d) and overtones, but…
  - Systematic errors correlated with GRACE beta angle emerge (~322 d).
  - Multiple LEOs (with different draconitic periods) may offer greatest promise for removing spurious harmonics in the Z origin time series.





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