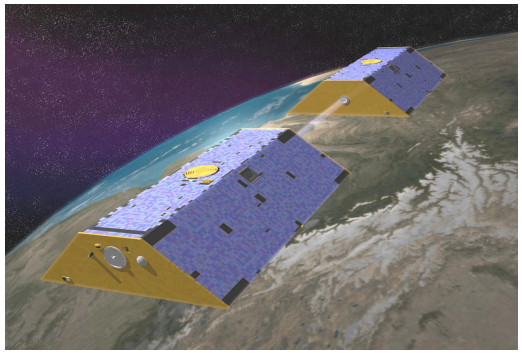
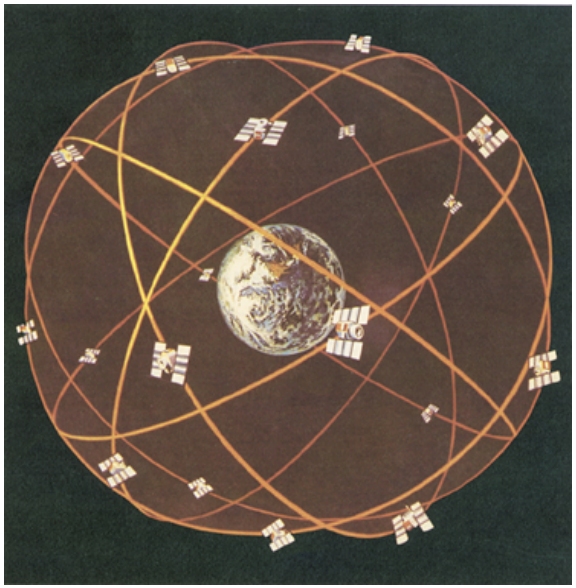
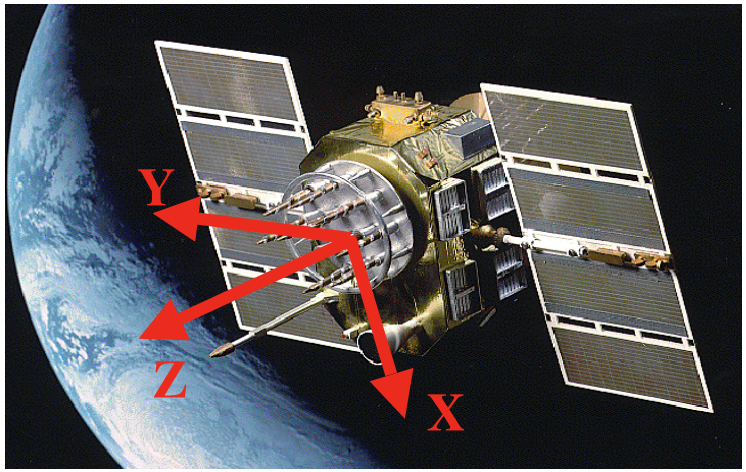


Calibrating the GPS Satellites Transmit Antenna

Yoaz Bar-Sever, Willy Bertiger, Sung Byun, Shailen Desai, Bruce Haines, George Hajj

Jet Propulsion Laboratory

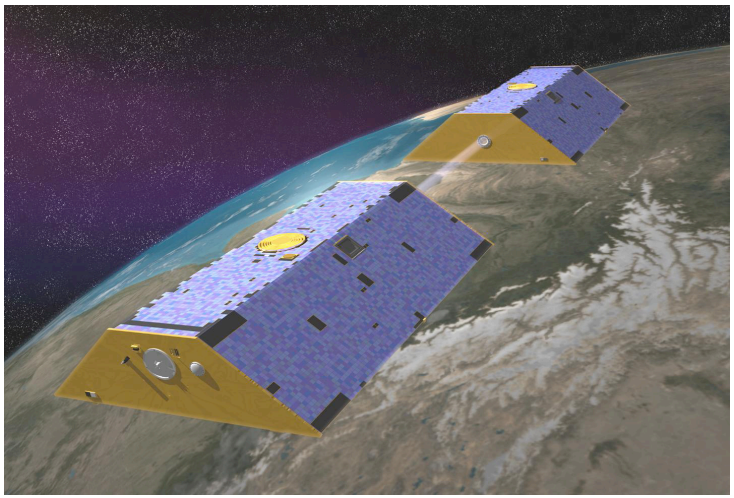




JPL's Approach for the GPS Transmit Antenna Phase Center Map

JPL's approach for deriving complete antenna phase and pseudorange patterns:

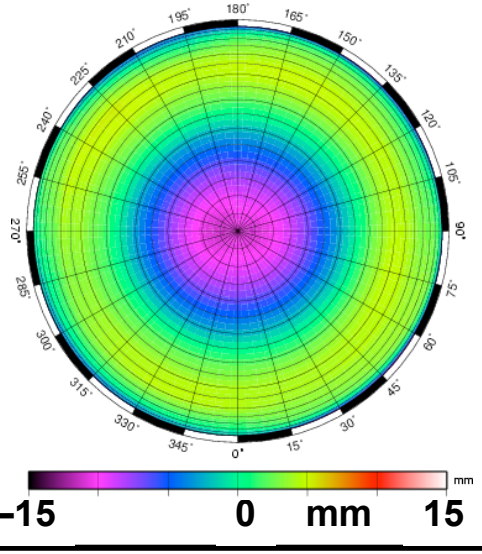
- Use residual stacking approach [Hurst and Bar-sever, 1998]
- Use extra-atmospheric reference antennas; Choose reference antenna on a well-modeled (electromagnetically and dynamically) spacecraft
- Use iterative approach to calibrate all antennas (transmit and receive)
- Validate and assess the derived maps with objective performance metrics

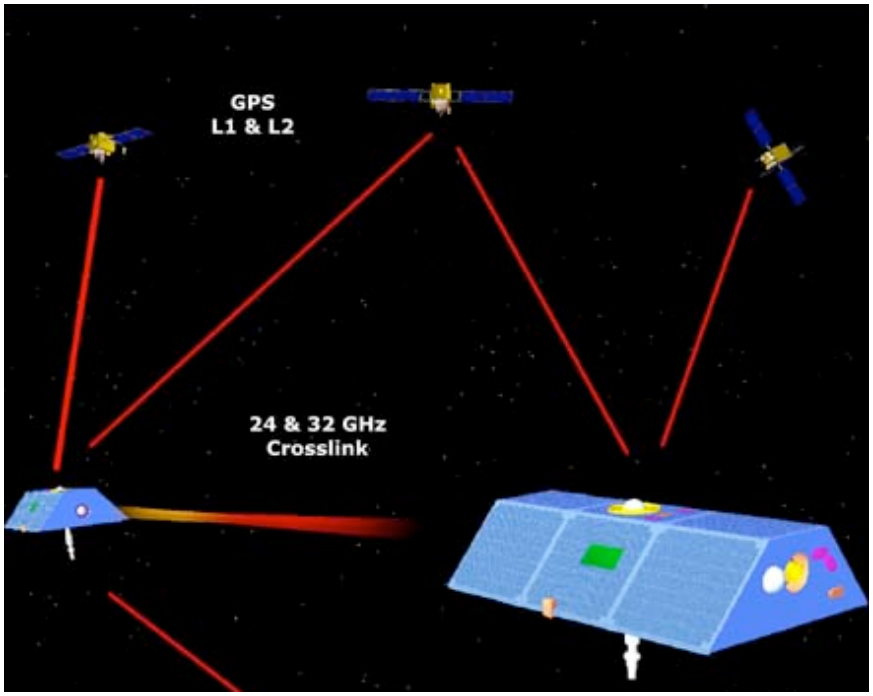


- GRACE advantages:
  - Scale (mean height) can be determined at cm level from dynamical POD constraint (GM)
  - Clean spacecraft produce low multipath, and facilitates modeling of surface forces
  - Long-duration measurements (2002–) with dense global coverage (89.5° inclination)

GRACE Processing

- Daily precise orbit solutions spanning two years (2003–04)
  - One s/c at a time
- Dynamical POD to preserve link between scale and GM
  - C_D and 1 *cpr* acc. reset every rev. per UT/CSR approach
- GPS ephemeris and clock offsets fixed to precise values (JPL/IGSAC)
- GRACE antenna *a priori* PCV model from anechoic chamber:

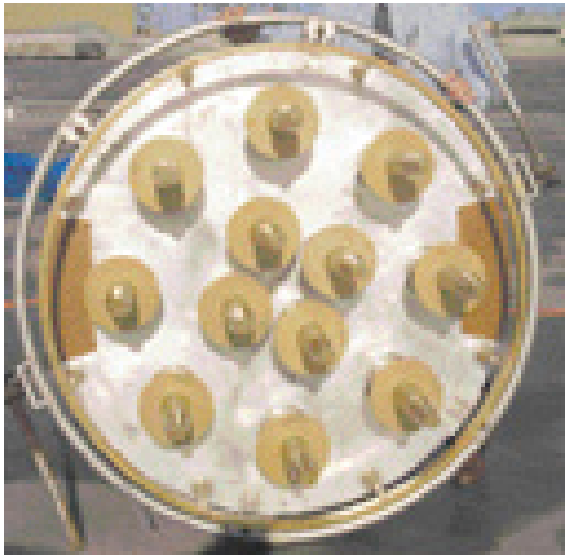




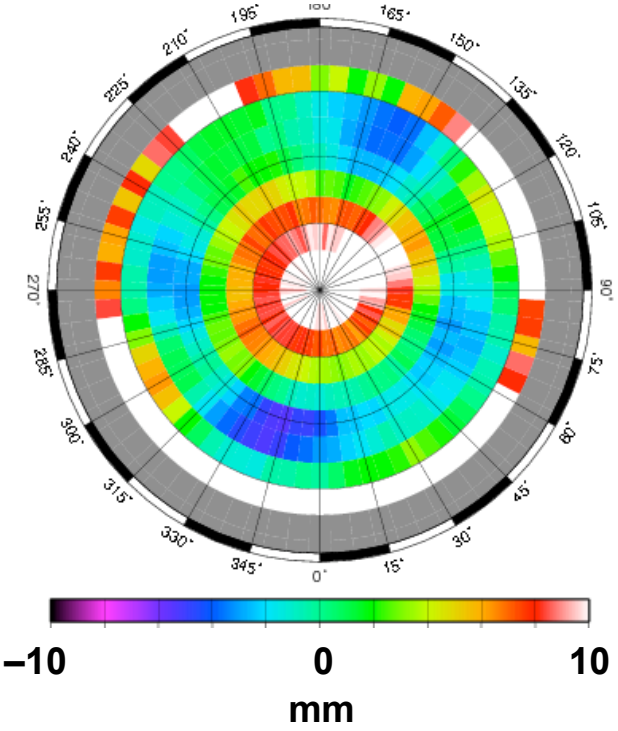
- 5-min GPS data
  - Carrier (LC) only and carrier + code (LC + PC) solutions performed.
- Postfit residuals binned according to az/el of transmitters.
  - Iterate until converged (8X)

Phase-Center Variation (PCV) Maps Reveal GPS Antenna Elements

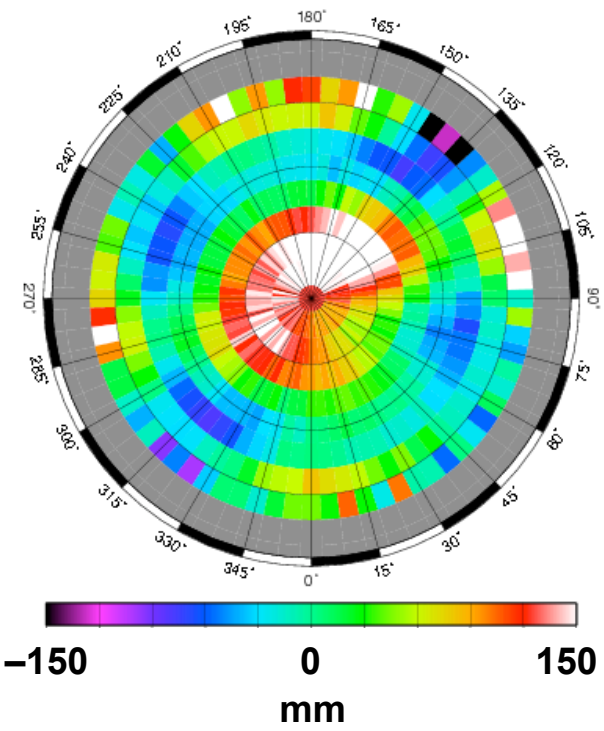
GPS Block IIA Antenna Array
(Mader and Czopek, 2002)



GPS Block IIA Carrier (LC) PCV
(Mean Offsets Removed)



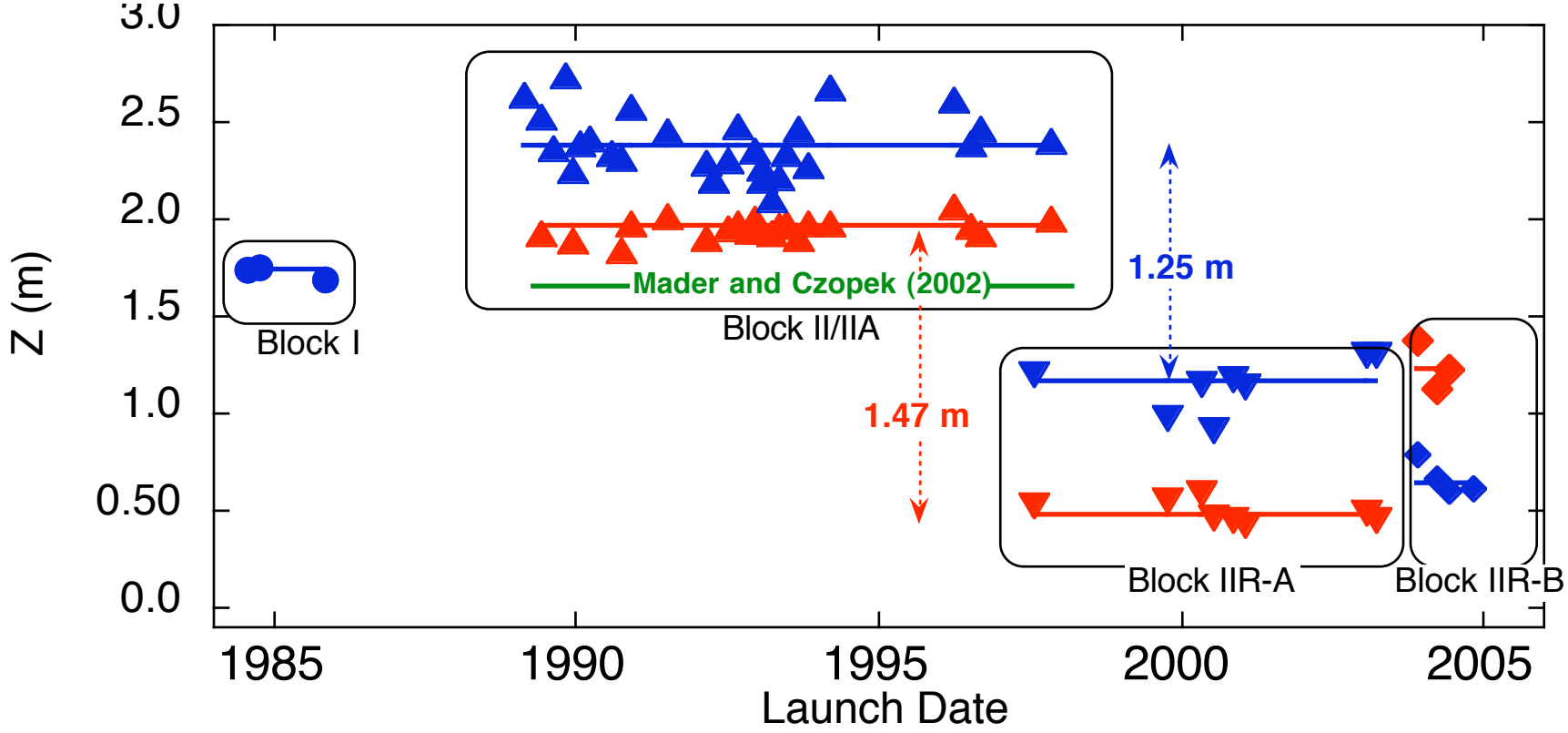
GPS Block IIA Code (PC) PCV
(Mean Offsets Removed)



Extract phase center offset from az/el map through least squares fit of:
C - X sin el cos az **- Y** sin el sin az **- Z** cos el

GPS Nadir (+Z) Phase Center Offsets

GRACE-based Vs. Ground-based (IGS test) Solutions



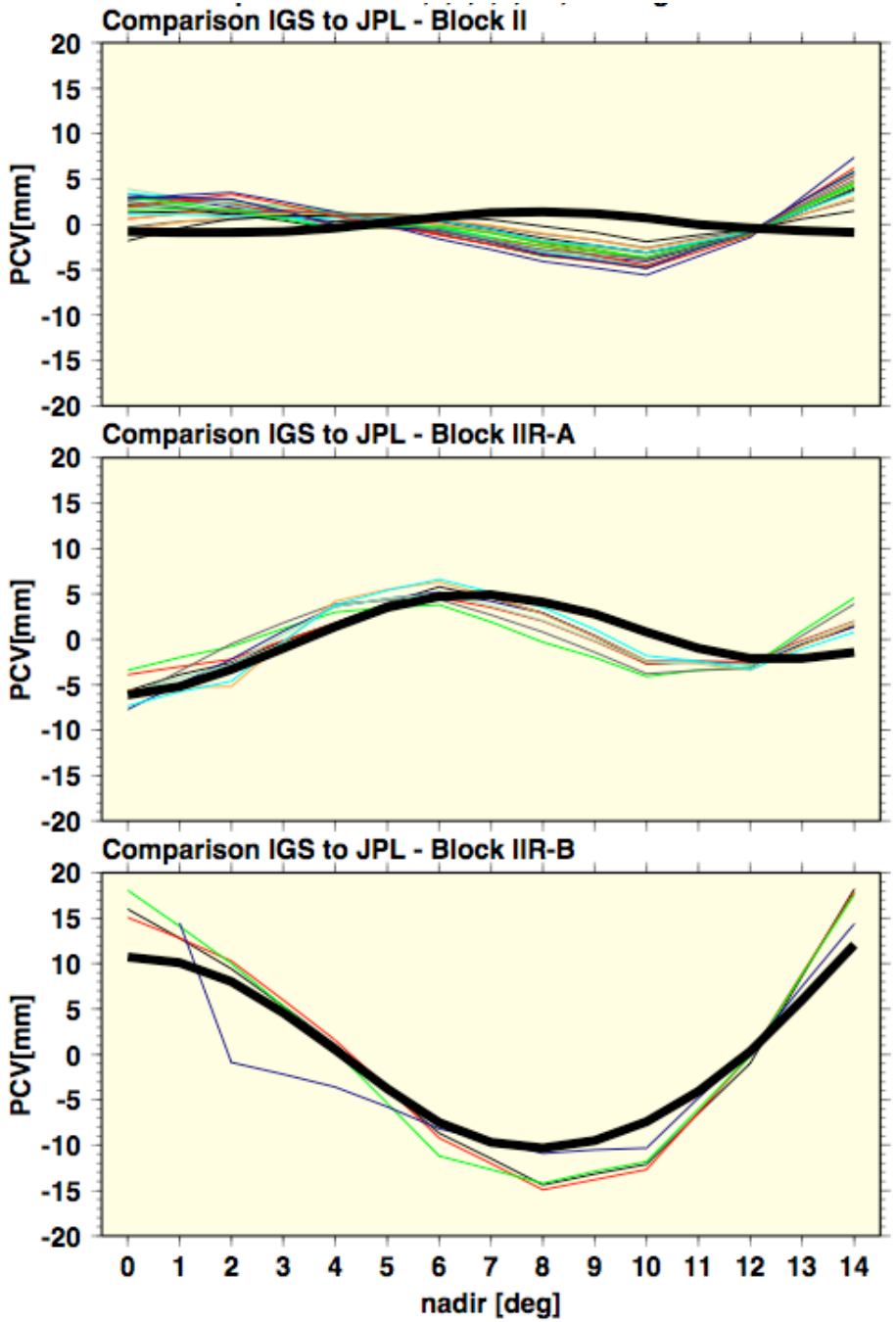
▲	GRACE[1] Block II/IIA:	+1.96 ± 0.05 m	● Ground[2] Block I:	+1.73 ± 0.03 m
▼	GRACE[1] Block IIR-A:	+0.49 ± 0.06 m	▲ Ground[2] Block II/IIA:	+2.40 ± 0.16 m
◆	GRACE[1] Block IIR-B	+1.24 ± 0.13 m	▼ Ground[2] Block IIR-A:	+1.14 ± 0.14 m
			◆ Ground[2] Block IIR-B:	+0.67 ± 0.09 m

1 From fitting of map to A – Bcos ϕ, where ϕ is the off- nadir angle and B is the phase-center offset in the Z direction.

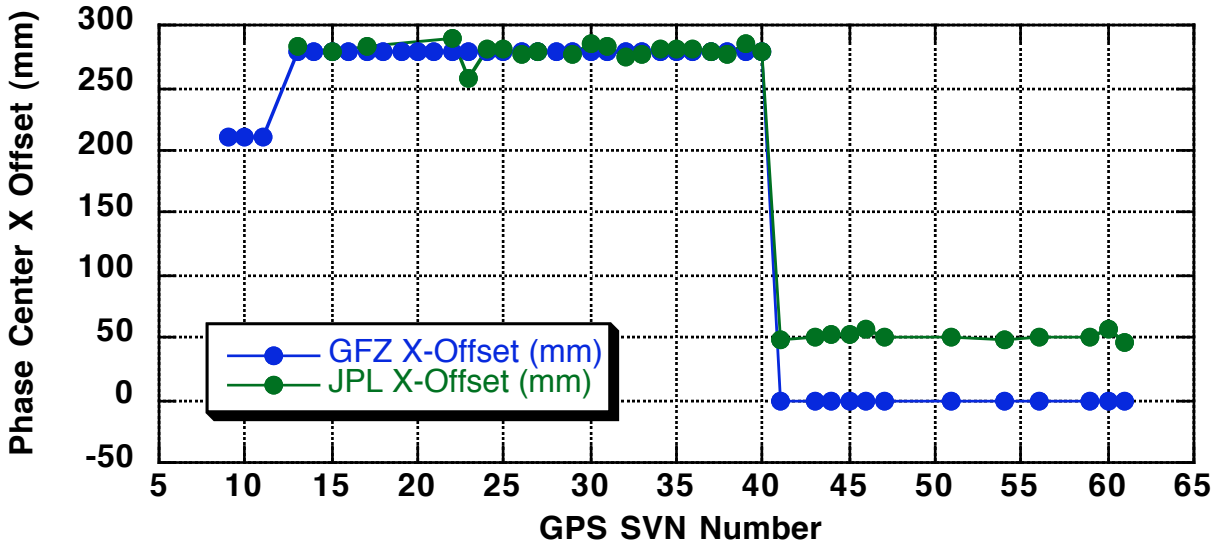
2 TUM/GFZ Ground Network (IGb00) Solution (igs_test05.atx, Schmid and Gendt, 2005)

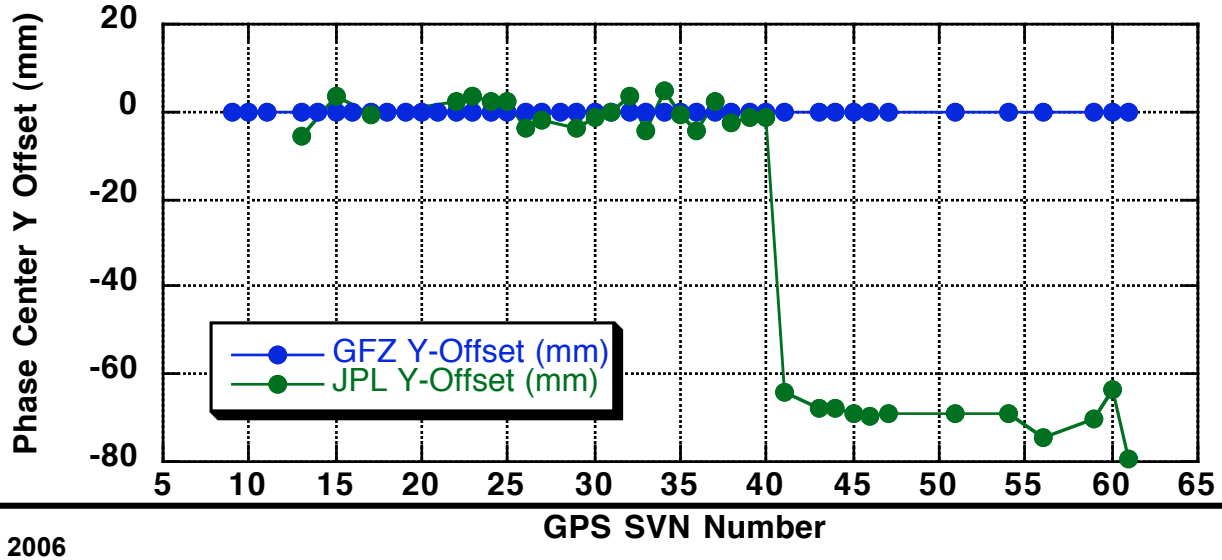
Comparisons with the JFZ/TUM Transmitter Maps

JFZ/TUM



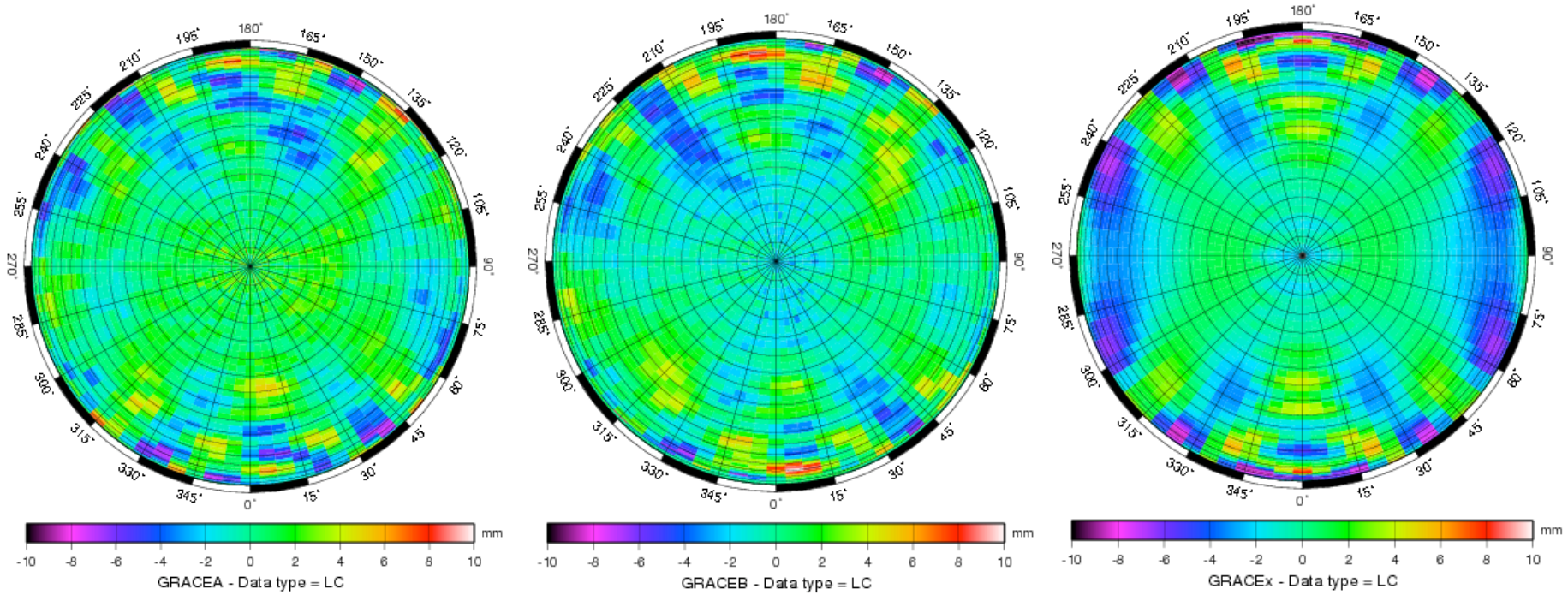
X and Y Offsets





Closure: Phase Calibration Maps for GRACE

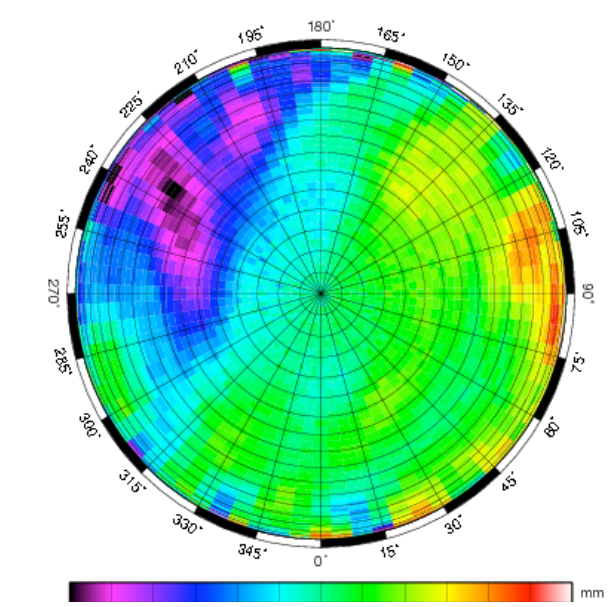
After construction of the GPS transmitter maps, maps for any receiver can be derived using the same residual stacking approach



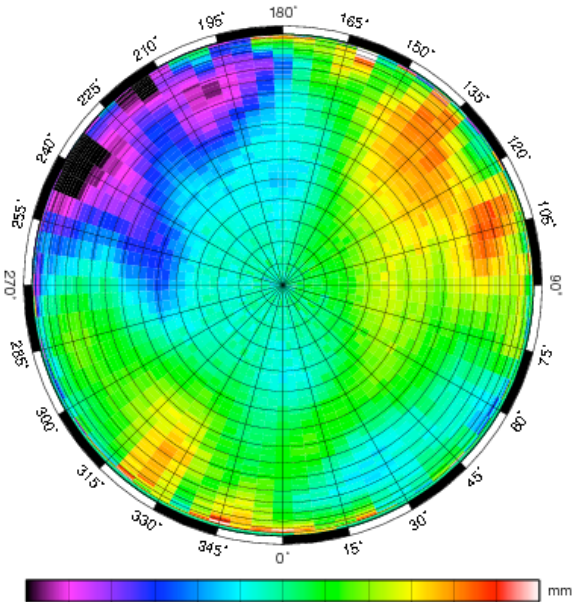
GRACEA	GRACEB	GRACE
Correction to Apriori	Correction to Apriori	Multipath Simulator
Anechoic Chamber Map	Anechoic Chamber Map	(scaled by 0.5)

Closure: Pseudorange Calibration Maps for GRACE

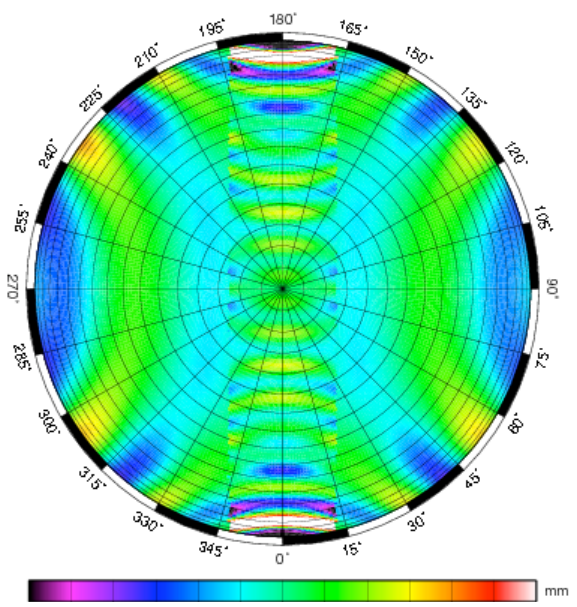
- **In contrast to the phase (LC) residuals, GRACE pseudorange (PC) residuals do not show good agreement with multipath simulator**
- **However, similarity of the two GRACE maps suggests fidelity**



GRACE-A



GRACE-B



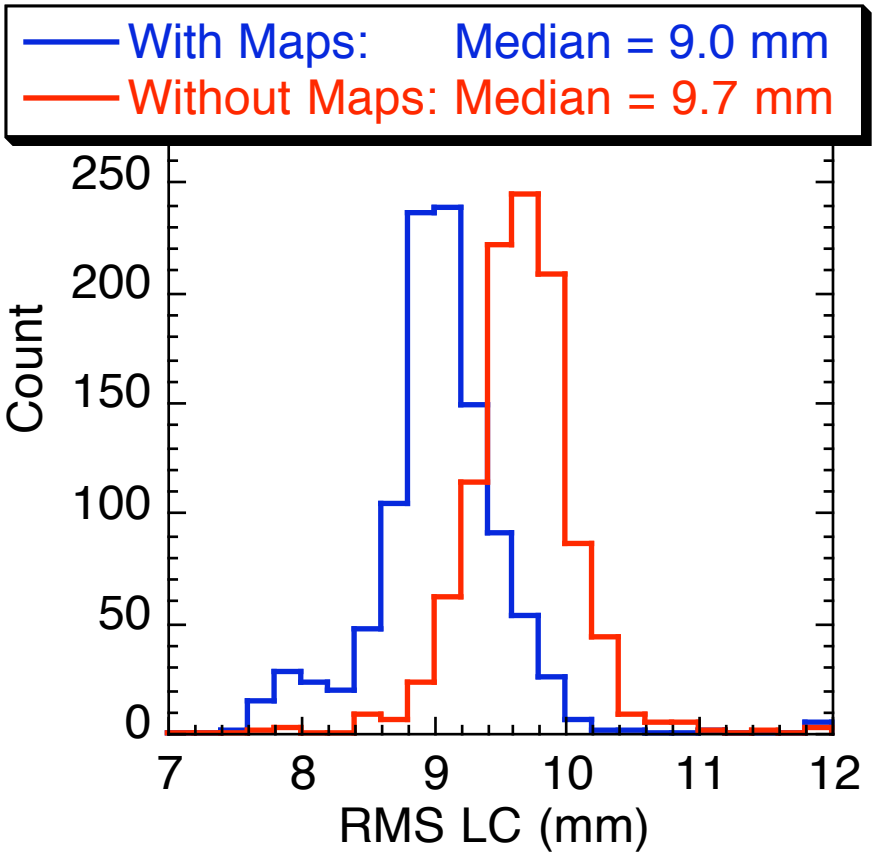
GRACE Multipath Simulator[1]

1 Byun, S., G. Hajj and L. Young, *Radio Science* 37(6), 2002

Jason-1 Precise Orbit Determination Tests:

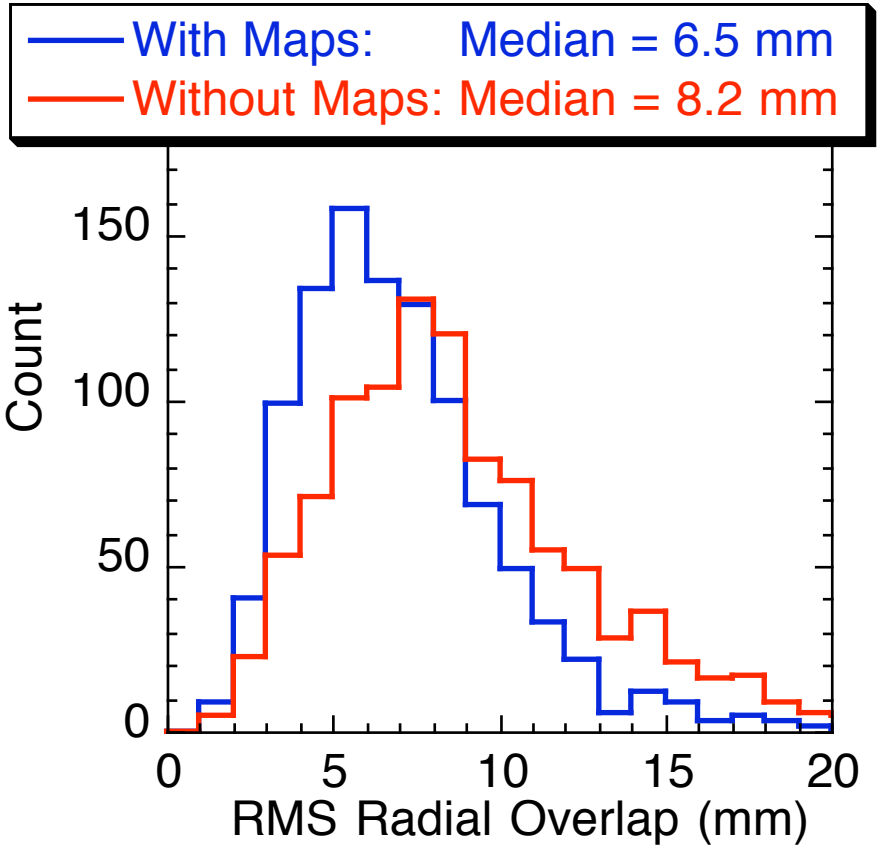
Three Years (2002–2004) of Daily Solutions

Carrier-Phase (LC) RMS Postfit Residual (Daily)



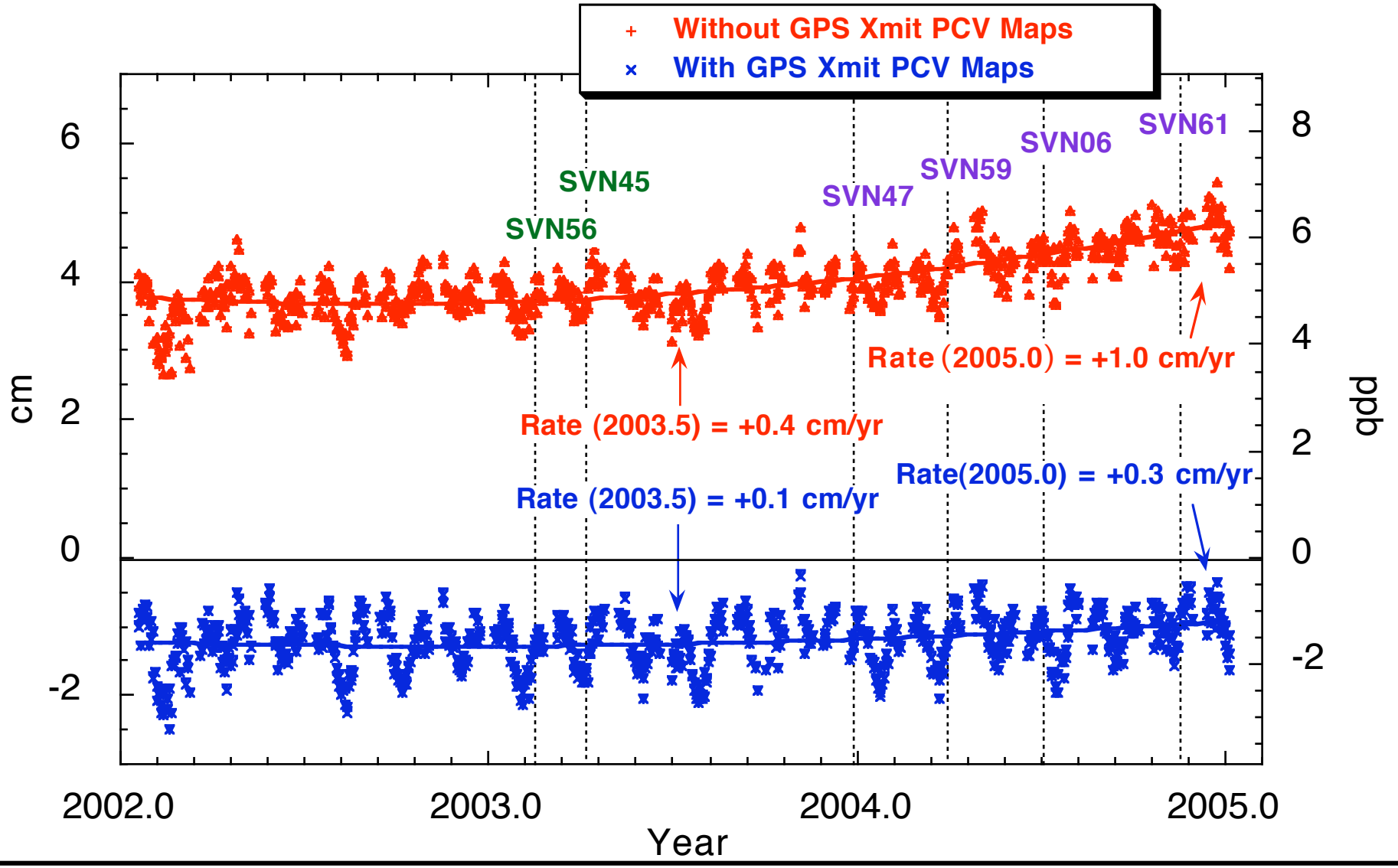
RMS Radial Overlap

30-hr Solutions Overlapping by 6 hr



High Elevation SLR Range Biases: 14 mm² variance reduction for 1813 passes

GPS Transmitter PCV Maps Explain Anomalous Estimated Radial Antenna Offsets for Jason-1



Ground Antenna Maps and GPS Orbit Determination

Ground sites maps were determined empirically using residual stacking technique

- Precise point positioning residuals with JPL Final (Flinn) orbits
- 365 days in 2004
- JPL (GRACE-based) transmitter maps
- 7 deg elevation angle cutoff

GPS orbit determination was carried out for 2 5-day arcs in January 2005

- 26 ground sites
- Fiducial free technique
- For each day compute Helmert transformation to the IGS Combined orbits

GPS Orbit Determination Performance

RMS Phase Residuals (mm)

Rx Map \ Tx Map	None	IGS	JPL (GRACE)
None	6.1, 7.2	6.1, 7.1	5.9, 7.0
IGS (Robot)		5.9, 7.0	6.0, 7.1
JPL (Empirical)			5.6, 6.7

RMS Pseudorange Residuals (cm)

Rx Map \ Tx Map	None	IGS	JPL (GRACE)
None	45.6, 54.7	45.6, 54.7	45.1, 54.3
IGS (Robot)		45.6, 54.8	45.1, 54.3
JPL (Empirical)			44.6, 52.7

Green is Best Red is Worst

1D RMS difference from IGS Combined (cm)

Rx Map \ Tx Map	None	IGS	JPL (GRACE)
None	5.8, 5.9	4.5, 4.8	5.3, 5.5
IGS (Robot)		4.3, 4.6	5.3, 5.4
JPL (Empirical)			5.2, 5.4

Z-shift relative to IGS Combined (cm)

Rx Map \ Tx Map	None	IGS	JPL (GRACE)
None	3.5, 3.8	2.2, 3.0	3.2, 3.5
IGS (Robot)		1.2, 1.5	2.3, 1.9
JPL (Empirical)			2.9, 3.2

Conclusions

- GPS phase-center variation (PCV) maps developed from GRACE data
  - Describe complete phase-center correction with respect to s/c center-of-mass
  - Available for all GPS s/c flying in 2003–2004 time frame.
  - Available for both ionosphere-free carrier phase (LC) and pseudorange (PC)

    ftp://sideshow.jpl.nasa.gov/pub/gipsy_products/Antenna_Maps
- Basic validation of PCV maps yields promising results
  - Inferred Block IIA nadir (Z+) offset (+2.0 m for LC) yields better agreement with number from field measurements (+1.7 m; *Mader and Czopek*, 2002).
  - Residual systematic errors (GRACE LC residuals) agree with multipath predicts.
- PCV maps significantly reduce heretofore unexplained Jason-1 errors
  - Reduce scale error (as revealed in estimated antenna offset) from +5.1 to –1.5 ppb (+3.9 to –1.2 cm)
  - Reduce scale rate (2002–2004) from +0.47 to +0.13 ppb/yr (+3.6 to +1.0 mm/yr)
  - Improve Jason-1 POD (better tracking residuals, overlaps)
- Consistent ground antenna maps derived, improving GPS POD stats