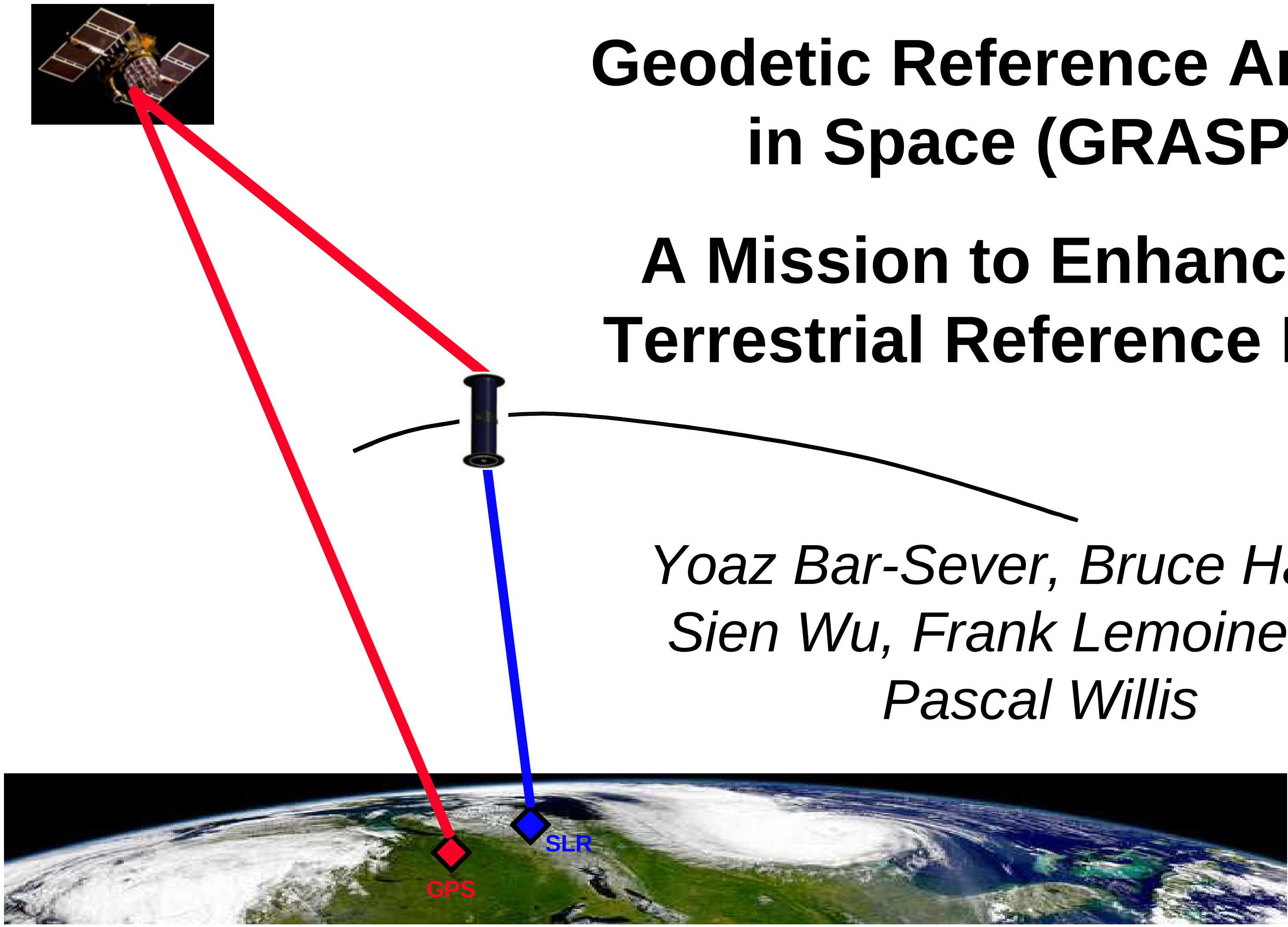
Geodetic Reference Antenna in Space (GRASP):

A Mission to Enhance the Terrestrial Reference Frame

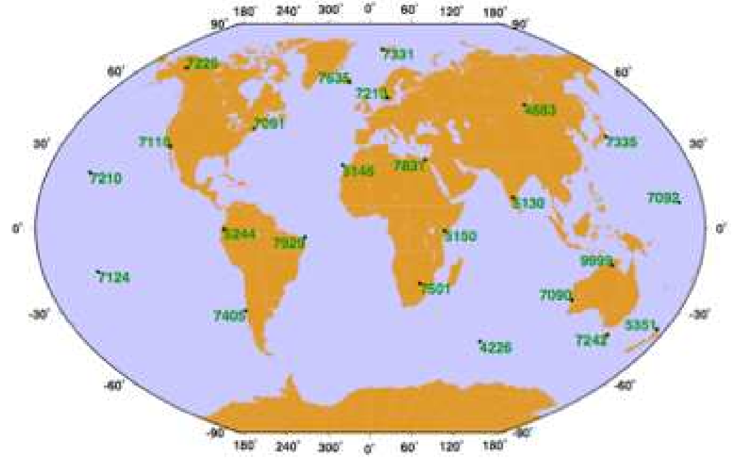


Yoaz Bar-Sever, Bruce Haines, Sien Wu, Frank Lemoine, and Pascal Willis

Key Aspects of the TRF

Definition

- Based on a sub-set of ‘super’ sites
- Primarily from VLBI (orientation, scale), SLR (geocenter, scale), and to lesser extent from GPS and DORIS
- Cost of super-sites limits network size
- **Challenge: accurate local ties**



Proposed NASA network of 24 Super Sites (VLBI+SLR+GPS)

Densification

- Primarily with GPS, DORIS
- **Challenge: TRF transfer**

Access

- Primarily with GPS
- **Challenge: accurate GPS ephemeris and antenna models**

The IGS Network in 2008

Problem: Determination of Local Ties

Local ties are extremely hard to measure

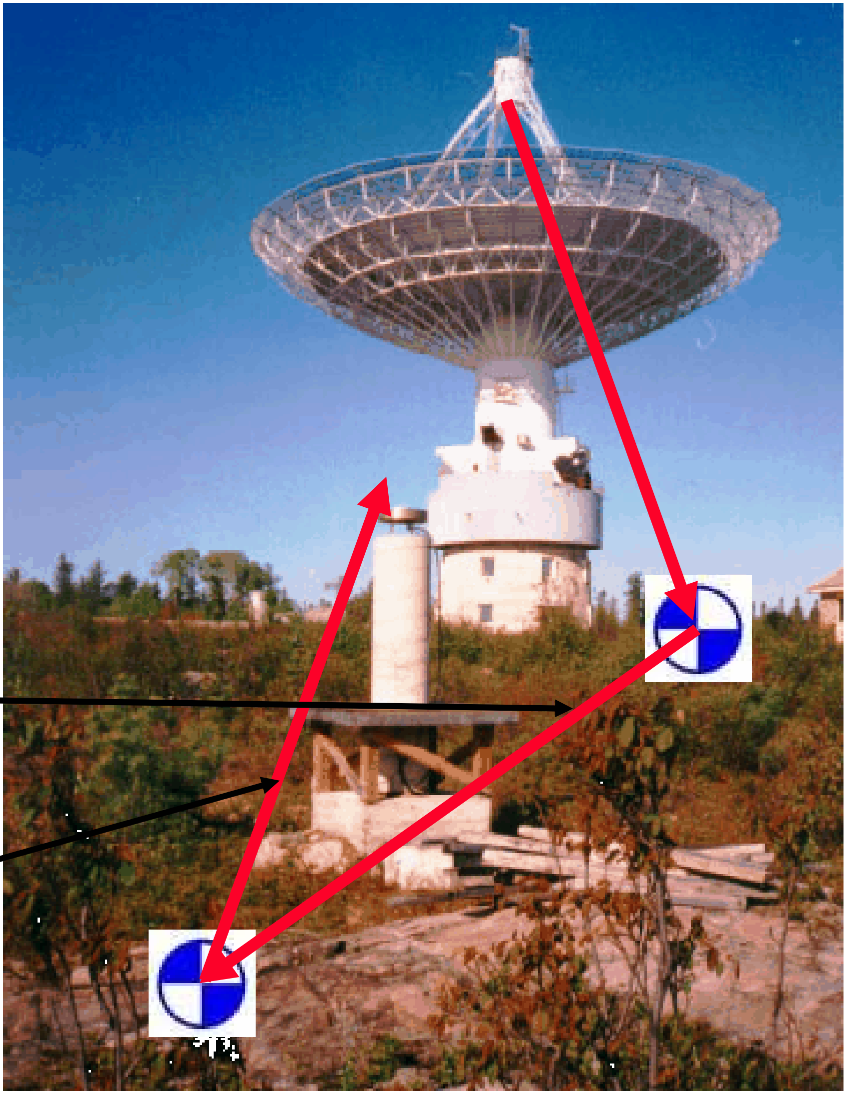
- Require careful surveying
- Continuously changing due to ground motion and environmental changes
- Eccentricities to RF phase center are ill defined and subject to highly variable multipath

σ^2**(tie) =** σ^2**(ecc1) +** σ^2**(markers) +** σ^2**(ecc2)**

Ties between physical markers are relatively easy to survey

Eccentricities (between physical marker and phase center) are potentially intractable at cm level

Presently, the transfer of TRF across techniques is critically dependent on poorly determined local ties



Algonquin Radio Observatory

Problem: Determining the GPS Ground Antenna Phase Variations

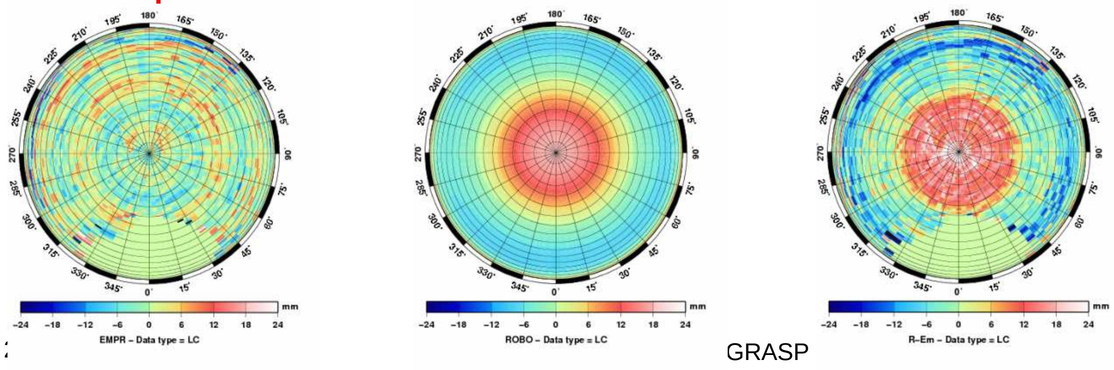
Three basic approaches: anechoic chamber, Robot calibration, and empirical in-situ estimation

- Robot-calibrated APV maps were adopted by the IGS as standard for ground GPS sites; most antennas and radomes have been calibrated
- Test range (mimicking anechoic chamber) calibrations conducted at JPL for Dorne Margolin choke ring antenna (Young and Dunn, 1992)
- The JPL in-situ empirical approach is based on stacking of months of post-fit residuals (from point-positioning or network solution)
  - **Accounts for local multipath and temporal variability**
  - **Accounts for as-is hardware (antenna and radome pair)**
  - **Uses the transmit antennas as reference (which could be uncertain)**

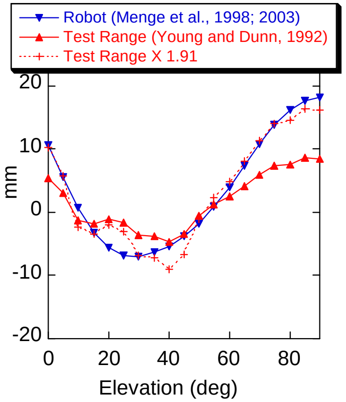
The Geo++ Robot

Phase center offset values can differ by several cm between empirical and other approaches

- Systematic phase center offset aliases into TRF Scale



TurboRogue Choke Ring Ant. Phase Variation (LC, mm)

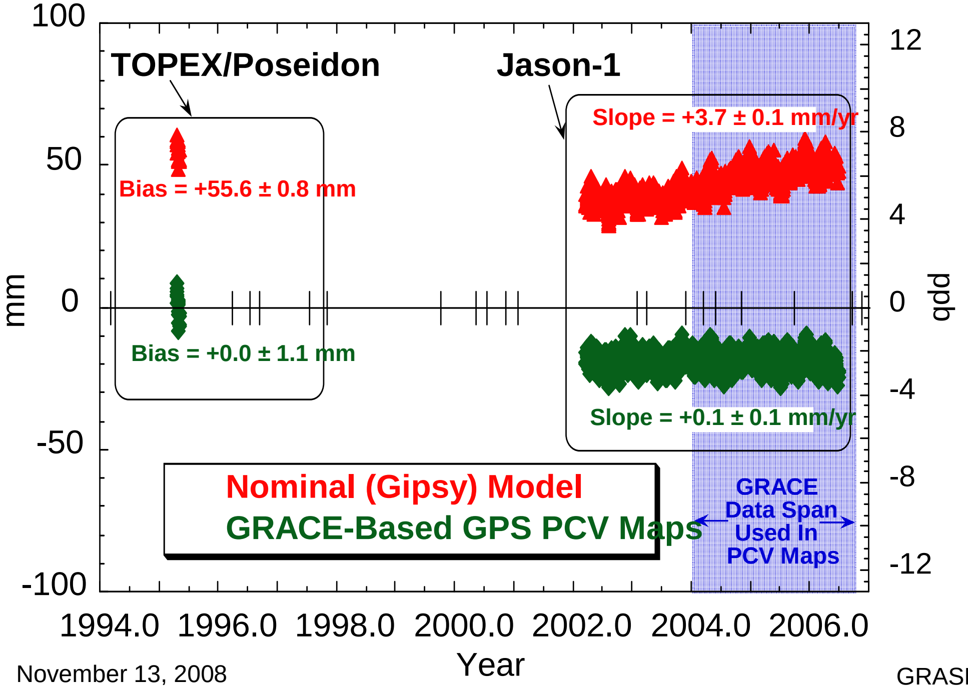


Problem: Determining the Antenna Phase Variations of the GPS Satellites (1/2)

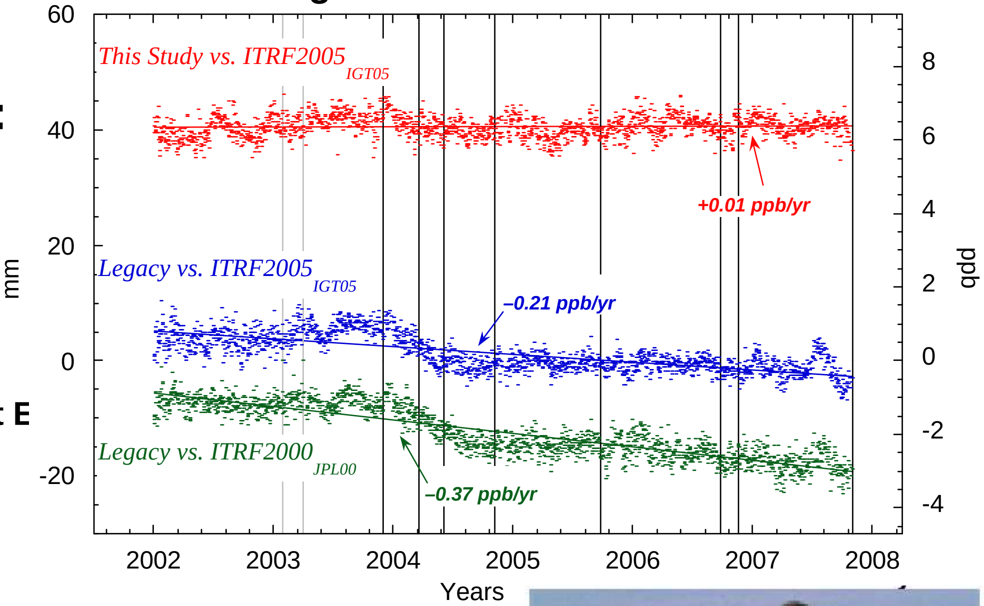
Uncertainties in GPS transmit antenna phase variations (APV) are among the limiting sources of error in global, GPS-based geodesy. Apparent root cause of:

- Drift in GPS realization of TRF Scale
- Bias in Topex GPS antenna position
- Drift in Jason GPS antenna position

Time Series of T/P and Jason-1 Radial Antenna Offset E



TRF Scale from GPS Alone (2002–2007): Agreement with ITRF2005



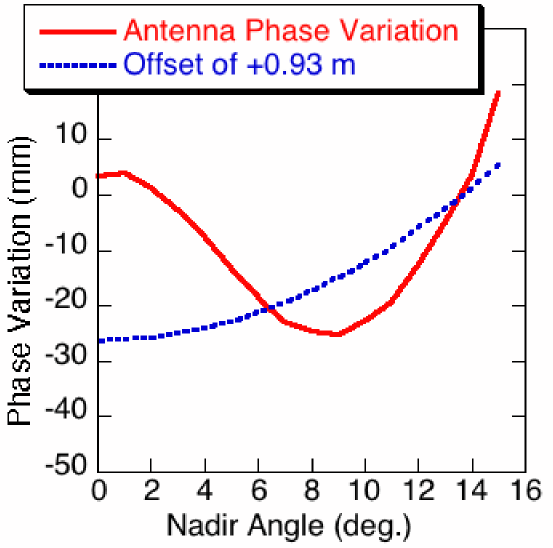
GPS Block IIA Antenna (Mader and Czopek, 2002)

Problem: Determining the Antenna Phase Variations of the GPS Satellites (2/2)

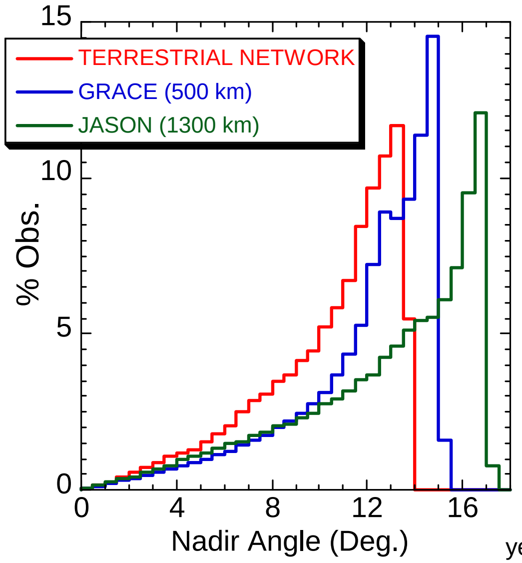
Estimation of GPS transmit APV from ground observations is problematic:

- Sensitivity to tropospheric delay biases: 0.005 m global trop bias => 0.28 m offset
- High correlation with receiver APV, which are uncertain due to local multipath and diversity of hardware
  - **Robot- or anechoic chamber-based antenna calibrations do not capture the conditions in-situ**
  - **High likelihood of global systematic error because of common monument types**
- Dependent on the TRF; IGS selected antenna offset to maintain the TRF Scale
- Narrow field of view limits utility for space applications

Block IIR-B APV



Sampling of GPS Transmitter Beam Pattern

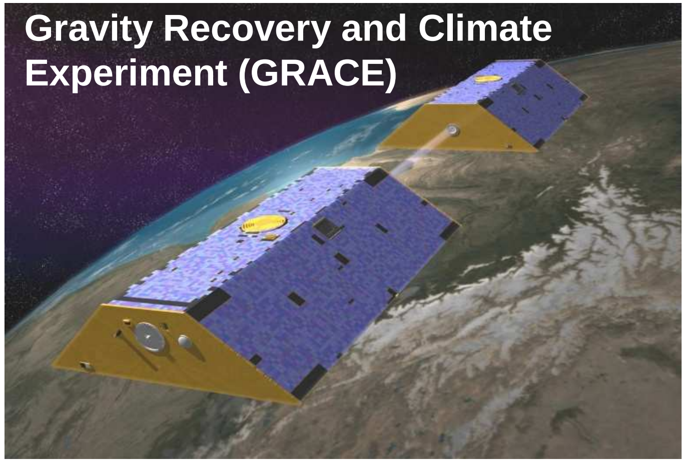


The Solution for GPS APV Determination: Reference Antenna in Space

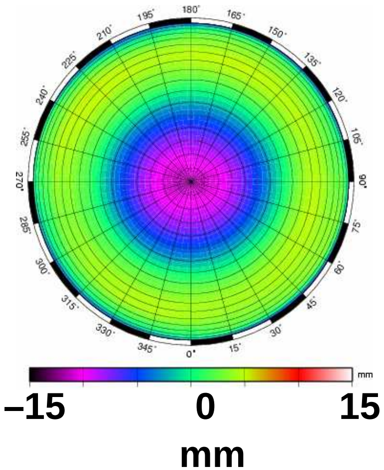
GRACE mission (2002–) was used as orbiting geodetic lab for recovering GPS transmitter APV maps using post-fit residuals stacking approach

GRACE advantages:

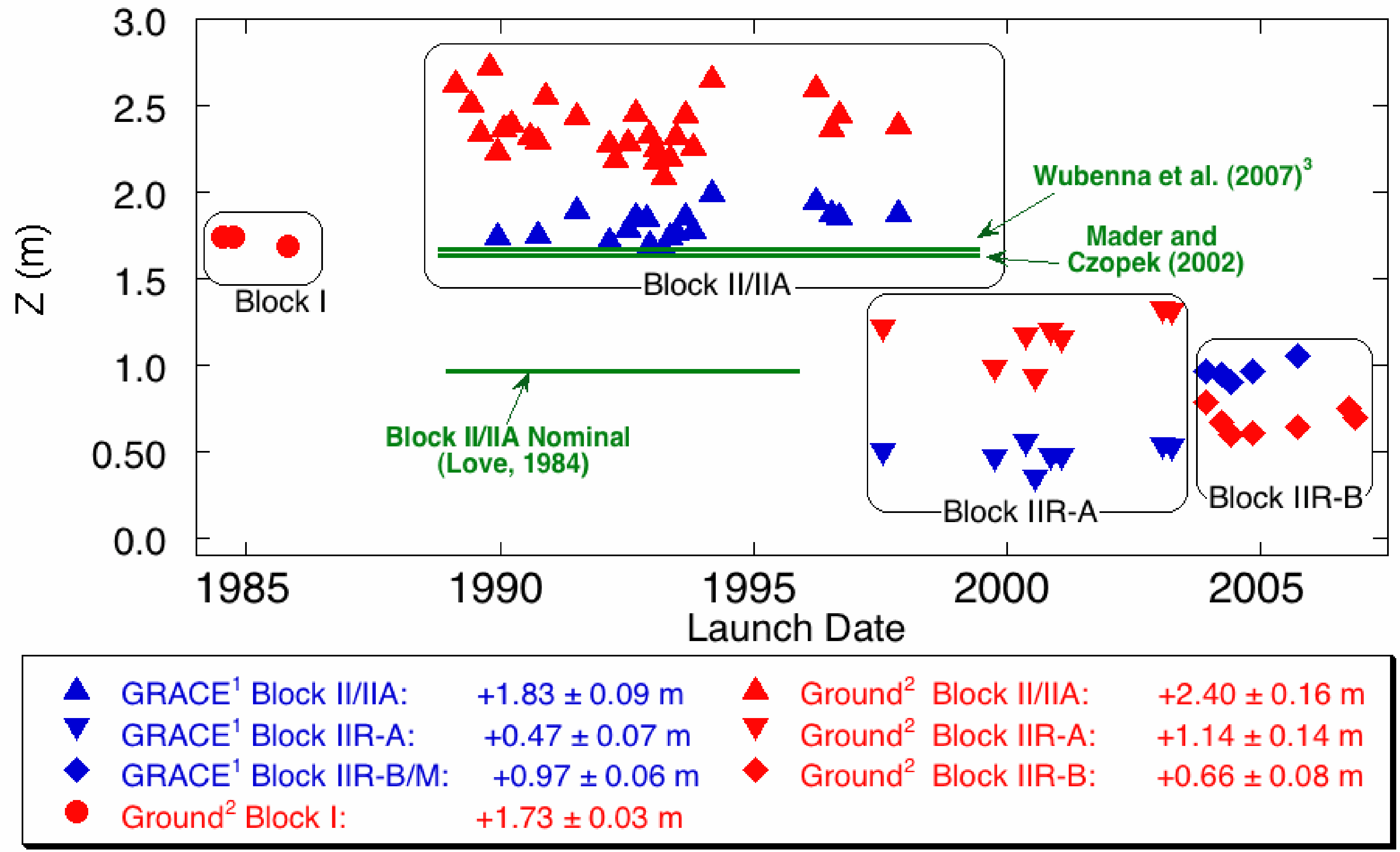
- Scale (mean height) can be determined at cm level from dynamical POD constraint (depends only on GM, and independent of the TRF).
- Clean spacecraft and simple attitude laws facilitate modeling of surface forces.
- Pre-fight APV is high fidelity due to low multipath environment
- Simple and fixed geometry enables modeling of residual multipath
- Long-duration measurements (2002–) with dense global coverage (89.5° inclination).
- 500 km altitude implies no troposphere to confound APV interpretation.
- 500 km altitude enables sampling of GPS antenna beam pattern beyond Earth's limb.



GRACE *a priori* antenna phase variation model from anechoic chamber



GPS Nadir (+Z) Phase Center Offsets
GRACE- Vs. Ground-based (IGS) Solutions



Summary of the Experience with GRACE-Based APV Maps

Basic validation of APV maps yields promising results

- Inferred Block IIA nadir offset (+1.8 m for LC) yields good agreement with recent robot test (+1.7 m; *Wubenna et al*, 2007) and rooftop test (+1.7 m; *Mader and Czopek*, 2002)
- Residual systematic errors (GRACE LC residuals) agree with multipath predicts.

APV maps significantly reduce scale errors in kinematic POD of Jason-1 and T/P

- Reduce **Jason-1 scale rate** (2002–06) from +0.48 to **–0.03 ppb/yr** (+3.7 to –0.2 mm/yr)
- Reduce **Jason-1 scale bias** from +5.6 ppb to **–3.0 ppb** (+43 to –23 mm)
- Reduce **T/P scale bias** in 1995 test data from +7.3 to **–0.6 ppb** (+56 to –4.5 mm)

APV maps significantly stabilize TRF scale realized in global network solution.

- **+0.01 ppb/yr wrt to ITRF2005** (2002-2007) using GRACE maps & IGS ground maps together.
- Testifies to ability of GPS alone to determine TRF scale rate over 6-yr span.

6 ppb bias in TRF scale using GRACE maps & robot-based ground maps together.

- Consistent with smaller transmit PCO (Z+) from GRACE-based technique.
- Use of Choke ring APV from JPL antenna test range decreases bias to +1 ppb (< 1 cm).

The Next Step: Geodetic Reference Antenna in Space (GRASP)

The GRACE Reference approach has a number of weaknesses at present:

- Pre-flight calibration of the GRACE GPS antenna was carried out in isolation from the spacecraft and consequently does not include multipath
- There were no pre-flight pseudorange APV calibrations
- The satellite orbit is very low, susceptible to dynamics mismodeling, which compromises the link to GM, and the realization of scale
- Environmental variations (eg, due to solar cycle) may alter the satellite dynamics modeling and lead to scale instability
- The SLR/GPS baseline onboard is not known at the mm level
- Cannot use the spacecraft to collocate other techniques: DORIS, VLBI
- GRACE has already exceeded its designed lifetime!

These shortcomings could be addressed with a dedicated mission: GRASP

- **Collocate all the geodetic techniques on one spacecraft to sub-mm**
- **Ground calibrate all sensors to sub-mm**
- **Design spacecraft and orbit to facilitate sub-mm POD**

An ideal platform with which to overcome the limitation of present day technology for determining, densifying, and accessing the terrestrial reference frame

GRASP Mission Concept

Collocate all geodetic techniques on one spacecraft: GNSS, DORIS, SLR, VLBI

Design spacecraft to be super clean, stable, modelable, and calibratable at the sub-mm level

- No moving parts, no fuel, no shadowing/secondary reflections, no thermal imbalance, no thermal expansion, small enough to fit in anechoic chamber,…

Fly at high LEO or MEO

- Eliminates atmospheric drag mismodeling and reduces gravity mismodeling
- Increases VLBI and SLR observability and consistent with VLBI antenna slew rate

Supreme pre-launch calibration

- Put the whole spacecraft in anechoic chamber to calibrate all RF sensors to sub-mm
- Measure baselines among sensors phase centers to sub-mm level

JPL Team-X GRASP Mission Design

2500 km altitude

- No disposal necessary (no disposal is possible since there is no fuel)
- Common observability across 8,000 km baseline
- 2.3 hr orbit period accommodates VLBI slew rate
- High nadir angle sampling of GPS APV
- Challenging radiation environment

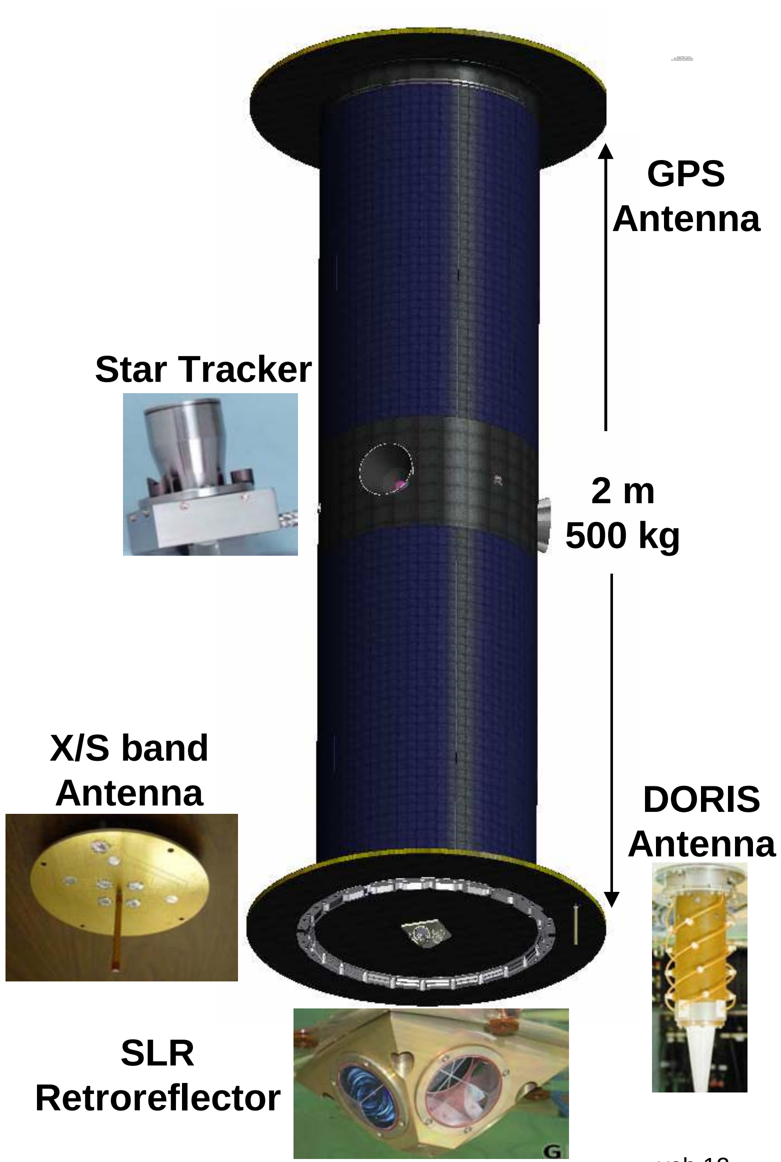
Sun-synchronous (near polar) orbit

- Good sampling of all ground sites, GPS satellites

Gravity-gradient spacecraft

- Attitude measured with star trackers
- High ballistic coefficient (lots of lead)

==> Simple spacecraft; simple instruments



Broad GNSS Benefits

Absolute reference antenna for consistent calibration of all GNSS antennas, ground and space

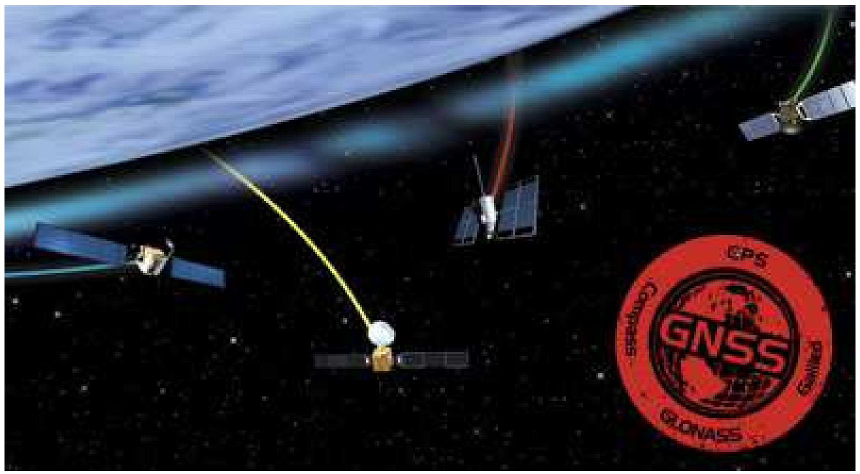
- **Factor of 3.5** improvement is determination of GPS antenna radial offset with GPS data alone; **factor of 8** improvement with SLR data
- Acutely needed as GNSS antennas, frequencies, and signals proliferate
- Broad GNSS system-wide improvements due to better antenna models
- GNSS satellite APV sampling fully consistent with high LEO missions, such as Jason, and will improve GNSS-based orbit determination of LEOs

GRASP directly improves GNSS orbit determination and ground positioning due to exquisite dynamics (10 times better than Jason) and outstanding observation geometry

- **Factor of 3** improvement in GPS POD

Enhances GNSS contributions to the TRF through geocenter and scale (GNSS-based scale determination not shown here**)**

- **Factor of 10** improvement in Geocenter determination with GPS data alone



New Perspectives on TRF Definition and Transfer

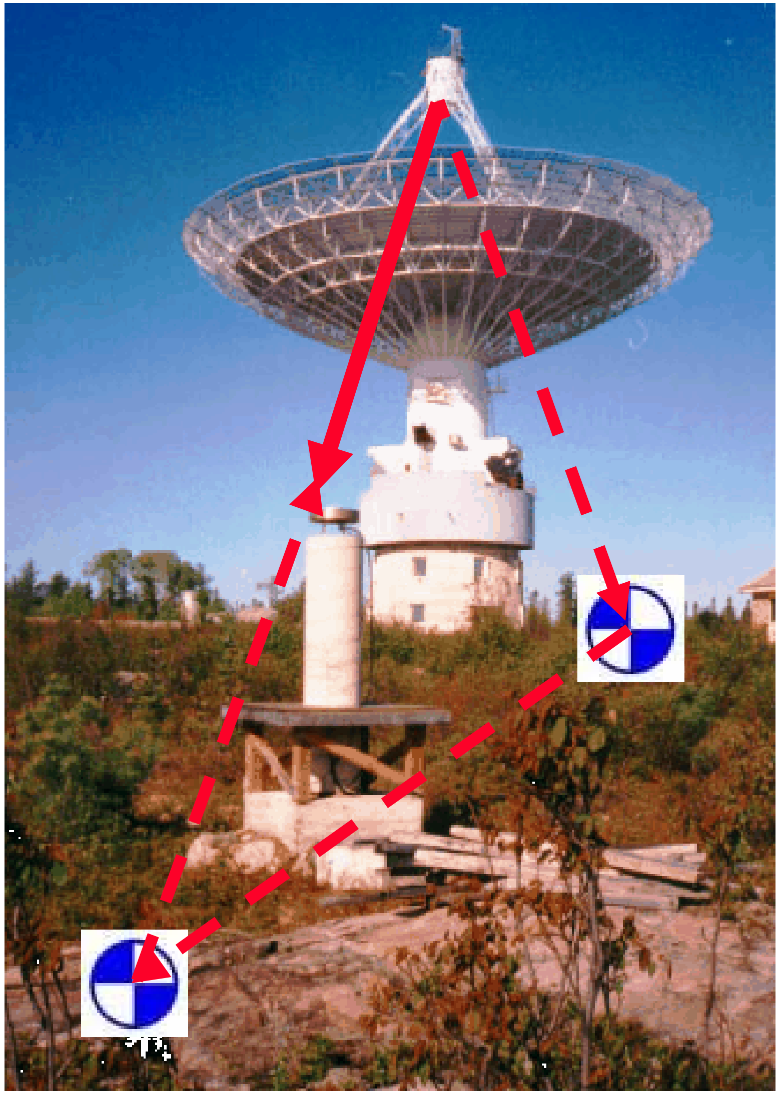
Enables phase-center to phase-center reference frame transfer between the key geodetic techniques

- **Few mm accuracy** in just 7 days
- Reduces or eliminates the need for ground collocation, and for local tie surveys
- Enables **unlimited densification** of the TRF through GNSS
- With local surveying can determine true local eccentricities

Enables more consistent combination of the diverse geodetic techniques

- GRASP provides consistent scale, tied to GM, for all techniques
- Improve the definition of the TRF with increased contributions from GNSS

Stable platform and long-term presence ensures long-term stability of the TRF



New Cross Technique Synergy

Improve positioning of VLBI and Deep Space Network Tracking sites will improve deep space navigation and planetary science

- Enhance TRF-CRF closure tests with VLBI
- Improved deep space navigation by improving DSN antenna locations
- GRASP also offers the ideal target to calibrate DSN range measurements

Broad benefits to DORIS from collocation with all geodetic techniques

- Higher orbit implies more ground beacons visible simultaneously
- May enable better synoptic mapping of ionosphere (mostly side views)
- Densification (e.g., DORIS, GPS) could benefit troposphere recoveries.

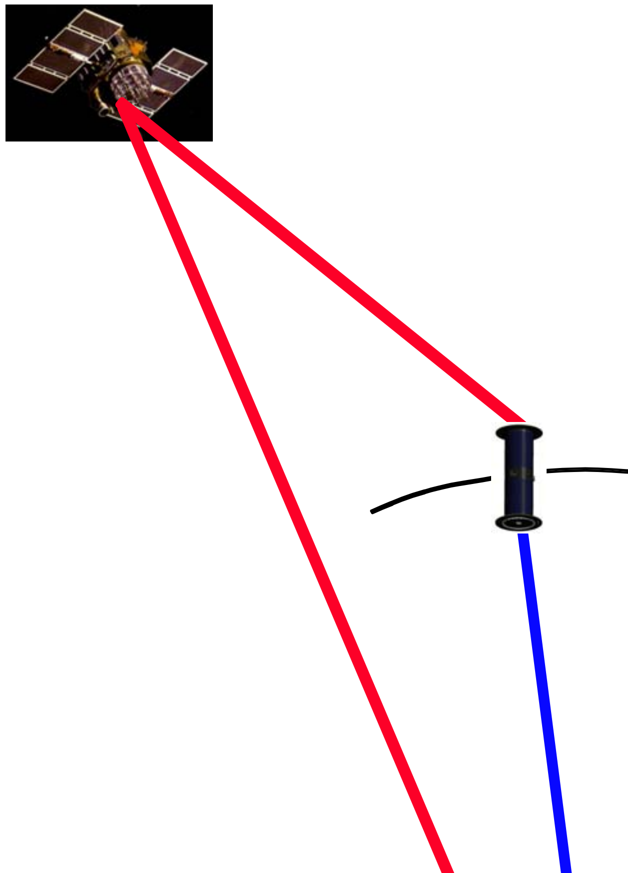
=> Looking for partnership with CNES on the development of GRASP

Fresh approach to geodesy will bring together the disparate geodetic communities as never before, and energize the unified modeling campaign, consistent with GGOS goals

Backup Slides

GRASP Simulations
(SLR can serve as proxy for VLBI)

Grand network solution with 66 GPS sites, 11 SLR sites, 29 GPS sats, 1 GRASP; 7 day arc



Scenario #1: GNSS-based reference frame enhancements

- GPS-only tracking of GRASP
- Calibration of GPS transmit antenna
- GPS orbit determination

Scenario #2: SLR to GPS reference frame transfer

- GPS and SLR tracking of GRASP
- Fix SLR sites and estimate GPS sites
- Calibration of GPS transmit antenna
- GPS orbit determination

Scenario #3: GPS to SLR reference frame transfer

- GPS and SLR tracking of GRASP
- Fix GPS sites and estimate SLR sites

Sample Detailed Simulation Setup (GIPSY)

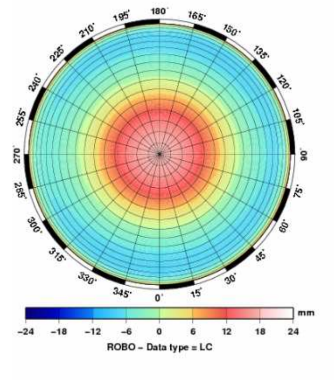
Constellation: 29 GPS satellites

MEO: 2500-km polar orbit

SLR Stations: 11 stations

GPS Stations: 66 stations

Data Types: To GPS stations: ion-removed GPS pseudorange (40 cm) & carrier phase (5 mm) + Robot APV maps for LC (& x100 for PC)
To GRASP: ion-removed GPS pseudorange (10 cm) & carrier phase (2.5 mm)
SLR to/from GRASP: (1 cm)



Data Span: 7 days

Data Sampling: once every 5 minutes

Estimated Geodetic Parameters:

GPS transmitting antenna phase centers (10 cm each component)

GPS tracking station location (20 cm each component) —SLR stations fixed
(or) SLR station location (20 cm each component) —GPS stations fixed
(or) geocenter (1 km) — all stations fixed

Other Estimated Parameters:

GRASP and GPS epoch states (1km; 1m/sec)

GRASP process-noise force (0.1nm/sec^2 each direction)

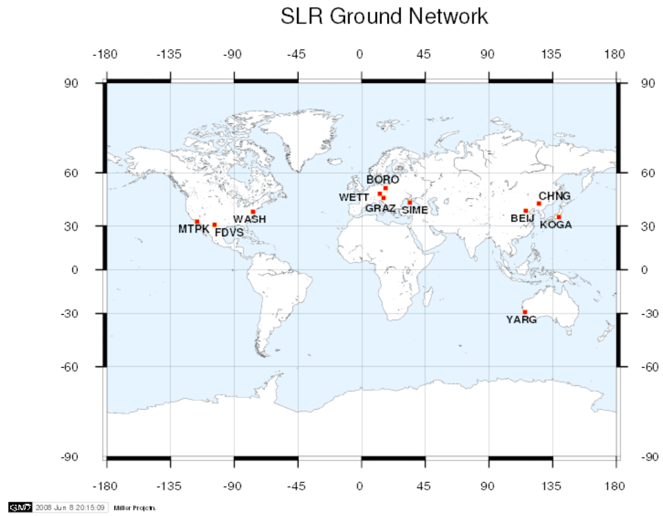
GPS X & Z solar scales as process noise (1%)

GPS Y force as process noise (0.01nm/sec^2)

GPS and ground clocks as white noise

GPS tracking site zenith troposhere delays as random walk

Phase biases



7-Parameter Transformation:

with stacov for GPS stations —SLR stations fixed

(or) with stacov for SLR stations —GPS stations fixed

Simulation Results
(Combined Random and Systematic Errors)

Scenarios \ Performance Metrics	GPS Orbit mm	GPS Ant Z Offset mm	GRASP Orbit mm	Geo-center mm	GPS Site Position mm	SLR Site Position mm	Helmert Trans. mm
0) Ground GPS Data Only (No GRASP): Fixed ground sites, estimate GPS orbits, phase offsets, geocenter	20.7 H 13.5 C 22.2 L	113.6	N/A	2.9 X 2.6 Y 59.4 Z	N/A	N/A	N/A
1) GPS Data Only from Ground and GRASP: Fixed ground sites, estimate GPS orbits, phase offsets, geocenter	7.4 H 7.2 C 7.4 L	30.9	0.9 H 0.6 C 2.4 L	2.2 X 0.9 Y 5.6 Z	N/A	N/A	N/A
2) SLR -> GPS Ref. Transfer: GPS and SLR Data, fixed SLR sites, estimate GPS orbits, phase offsets, and GPS sites	8.4 H 8.7 C 7.9 L	14.1	0.7 H 0.7 C 1.9 L	2.7 X 1.3 Y 1.4 Z	2.9 X 3.7 Y 0.9 Z	N/A	0.4 Ry 2.0 Tz 4.5 Sc
3) GPS -> SLR Ref. Transfer: GPS and SLR Data, fixed GPS sites, estimate GPS orbits, and SLR sites	8.3 H 7.1 C 7.4 L	N/A	0.7 H 0.6 C 2.0 L	0.8 X 0.8 Y 0.7 Z	N/A	0.1 X 0.2 Y 0.1 Z	0.4 Ry 0.4 Tz 0.3 Sc

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DSN Navigation Requirements

Tracking Error Source (1 sigma Accuracy)	units	current capability	2005 reqt	2010 reqt	2020 reqt	2030 reqt
Doppler/random (60s)	mm/s	0.03	0.05	0.03	0.03	0.02
Doppler/systematic (60s)	mm/s	0.001	0.05	0.003	0.003	0.002
Range/random	m	0.3	0.8	0.5	0.3	0.1
Range/systematic	m	1.1	0.6	2	2	1
Delta-VLBI	nrad	2.5	5	2	1	0.5
Troposphere zenith delay	cm	0.8	1	0.5	0.5	0.3
Ionosphere	TECU	5	5	5	3	2
Earth orientation (real-time)	cm	7	30	5	3	2
Earth orientation (after update)	cm	5	5	3	2	0.5
Station locations (geocentric)	cm	3	3	2	2	1
Quasar coordinates	nrad	1	1	1	1	0.5
Mars ephemeris	nrad	2	-	3	2	1