The Special Role of SLR for Inter-Technique Combinations

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- G&G: **G**eometry and **G**ravity
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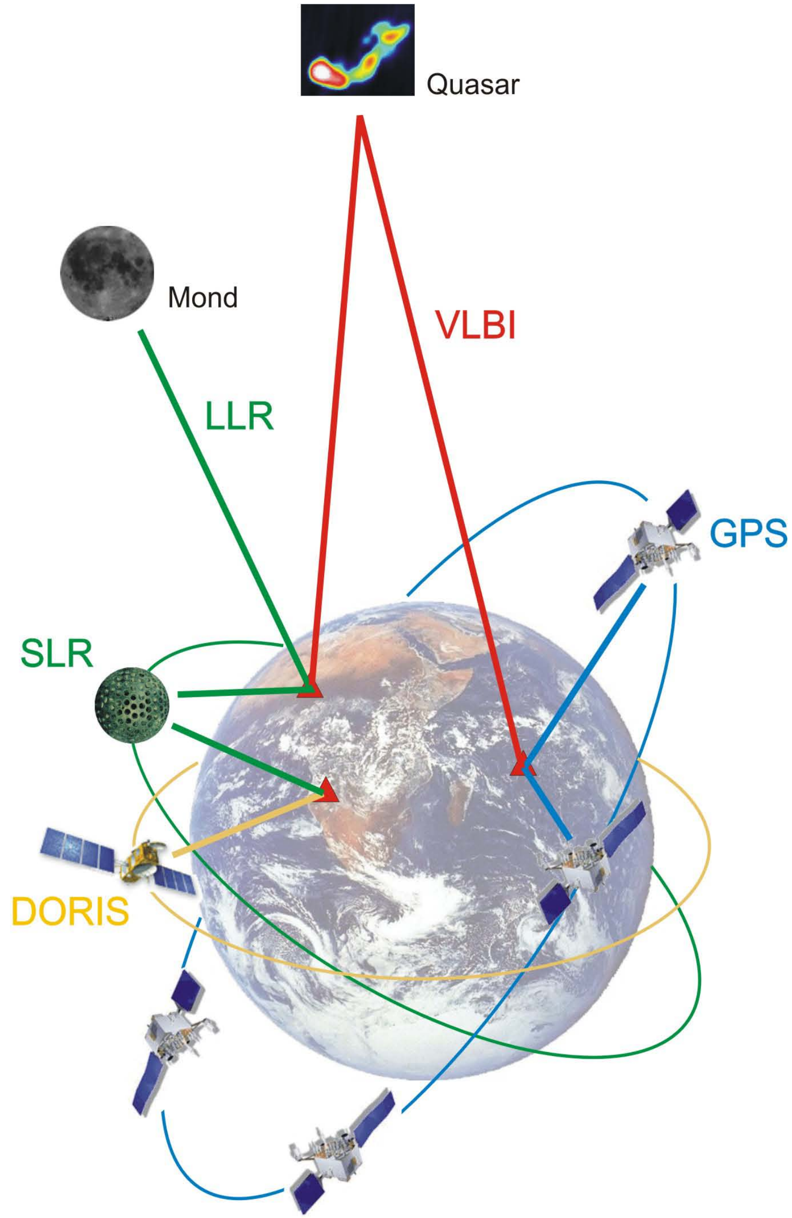
Introduction: Vision of a Rigorous Combination



- Make use of the **strengths** of the individual observation techniques
- Profit from **co-location** of instruments (sites and satellites)
- Ensure **consistency** between all techniques
- Differ between technique-specific systematic **biases** and genuine geodetic/geophysical **signals**
- **Final goal**: All common parameters of all observing techniques are rigorously combined as consistent input to the IGGOS project

Parameter Space for Combination

Parameter Type	VLBI	GPS/ GLON.	DORIS/ PRARE	SLR	LLR	Alti- metry
Quasar Coord. (ICRF)	X					
Nutation	X	(X)		(X)	X	
Polar Motion	X	X	X	X	X	
UT1	X					
Length of Day (LOD)		X	X	X	X	
Sub-Daily ERPs	X	X				
ERP Ocean Tide Amplitudes	X	X		X		X
Coord.+Veloc.(ITRF)	X	X	X	X	X	(X)
Geocenter		X	X	X		X
Gravity Field		X	X	X	(X)	X
Orbits		X	X	X	X	X
LEO Orbits		X	X	X		X
Ionosphere	X	X	X			X
Troposphere	X	X	X			X
Time/Freq. Transfer	(X)	X		(X)		

Major SLR Contributions (rows Nutation through LEO Orbits)

Solutions and Statistics (S&S)

CONT'02 VLBI Campaign

- DGFI: **VLBI** solutions
- TUM : **GPS** solutions
- TUM : **SLR** solutions (L1+L2)

October 17-30, 2003, continuous VLBI

SLR: few observations but also few parameters (no clocks, no troposphere, no ambiguities,…)

CONT'02	SLR	VLBI	GPS
# Obs.	5'195	46'682	5'935'760
# Coord.	81	24	459
# EOP	75	75	75
# Tropos.	0	1'554	26'726
# Orbits	30	0	3'770
# Ambig.	0	0	43'238
# Clocks	0	1'164	---
# Param.	186	2'817	74'268

Wavelength and Water Vapor (W&W)

SLR is the only technique observing at optical wavelengths:

- SLR is in a **unique situation** concerning atmospheric refraction
- Troposphere **dispersive** for SLR, but not for microwaves
- Two-frequency laser ranging (mainly **validation tool** ?)
- Dry delay can be modeled with pressure data at the site
- Wet delay is quite small

All other techniques (GPS, VLBI, DORIS, altimetry, InSAR, …):

- Suffer from the **same tropospheric refraction effects**
- Suffer from **similar ionospheric refraction effects**
- Have tropospheric refraction as the or a **major error source**

Only SLR can help to detect biases (e.g. due to atmosphere mismodeling) common to all other techniques

Wavelength and Water Vapor (W&W)

Influence of water vapor e on SLR/LLR (Marini-Murray):

$$\delta\rho^{SLR}_{trp,wet}(z=0) \approx 0.000141 \cdot e$$

Influence of water vapor on GPS/VLBI/DORIS (Saastamoinen):

$$\delta\rho^{Micro}_{trp,wet}(z=0) \approx 0.002277 \cdot \left(\frac{1225}{T} + 0.05 \right) \cdot e \approx 0.0096 \cdot e$$

Ratio of Microwave/SLR: $$\frac{\delta\rho^{Micro}_{trp,wet}(z=0)}{\delta\rho^{SLR}_{trp,wet}(z=0)} \approx 68$$

Wet delay: GPS/VLBI/DORIS up to 40 cm; SLR up to 6 mm

Troposphere zenith delay parameters — weakening the solutions — have to be estimated for microwave techniques, but not for SLR

Clocks and Correlations (C&C)

Estimation of clock parameters:

- **SLR**: the only technique, where in general **no clock corrections** have to be estimated
- **GPS**: receiver and satellite clock parameters for every epoch
- **VLBI**: receiver clock corrections about every hour (between stations)
- **DORIS**: clock biases have to be estimated too

Estimation of clock parameters degrades the height quality

Exceptions for SLR:

- Estimation of a **range bias** for an SLR station: corresponds to a **receiver clock correction** in GPS/VLBI/DORIS
- Estimation of a **time biases** for an SLR station

Estimation of range biases should be avoided to the extent possible

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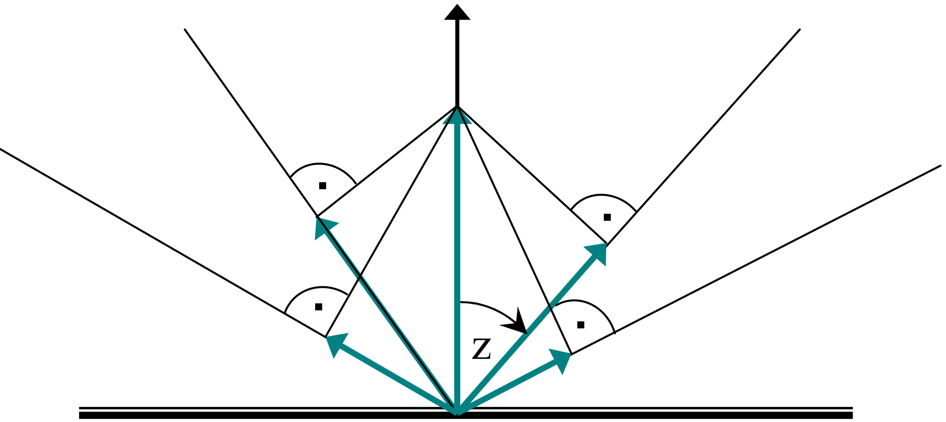
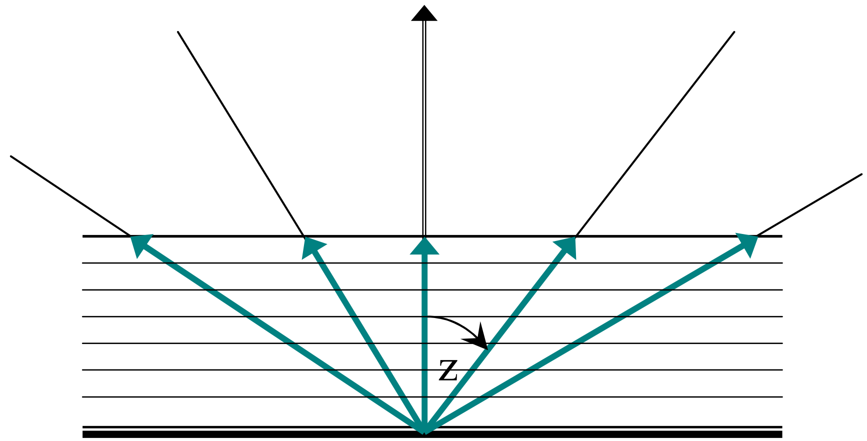
Parameter Zenith-Dependence

Station Height



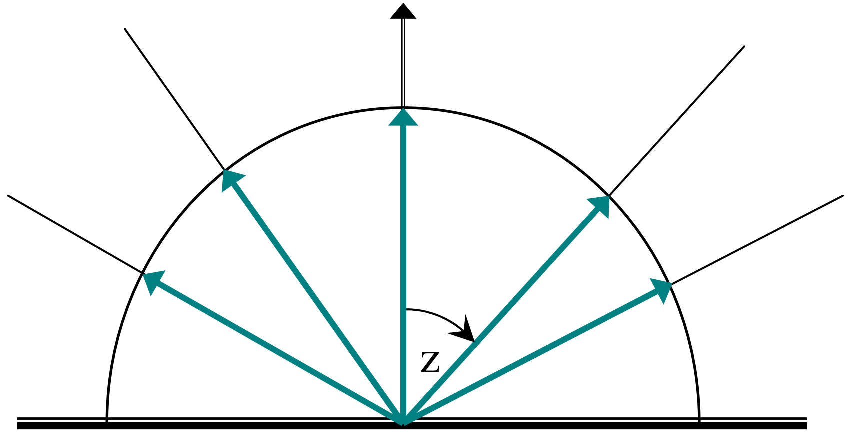
$$\delta\rho_h(z) = \cos(z)\cdot\delta\rho_h(0)$$

Zenith Troposphere Delay



$$\delta\rho_{trp}(z) = \frac{1}{\cos(z)}\cdot\delta\rho_{trp}(0)$$

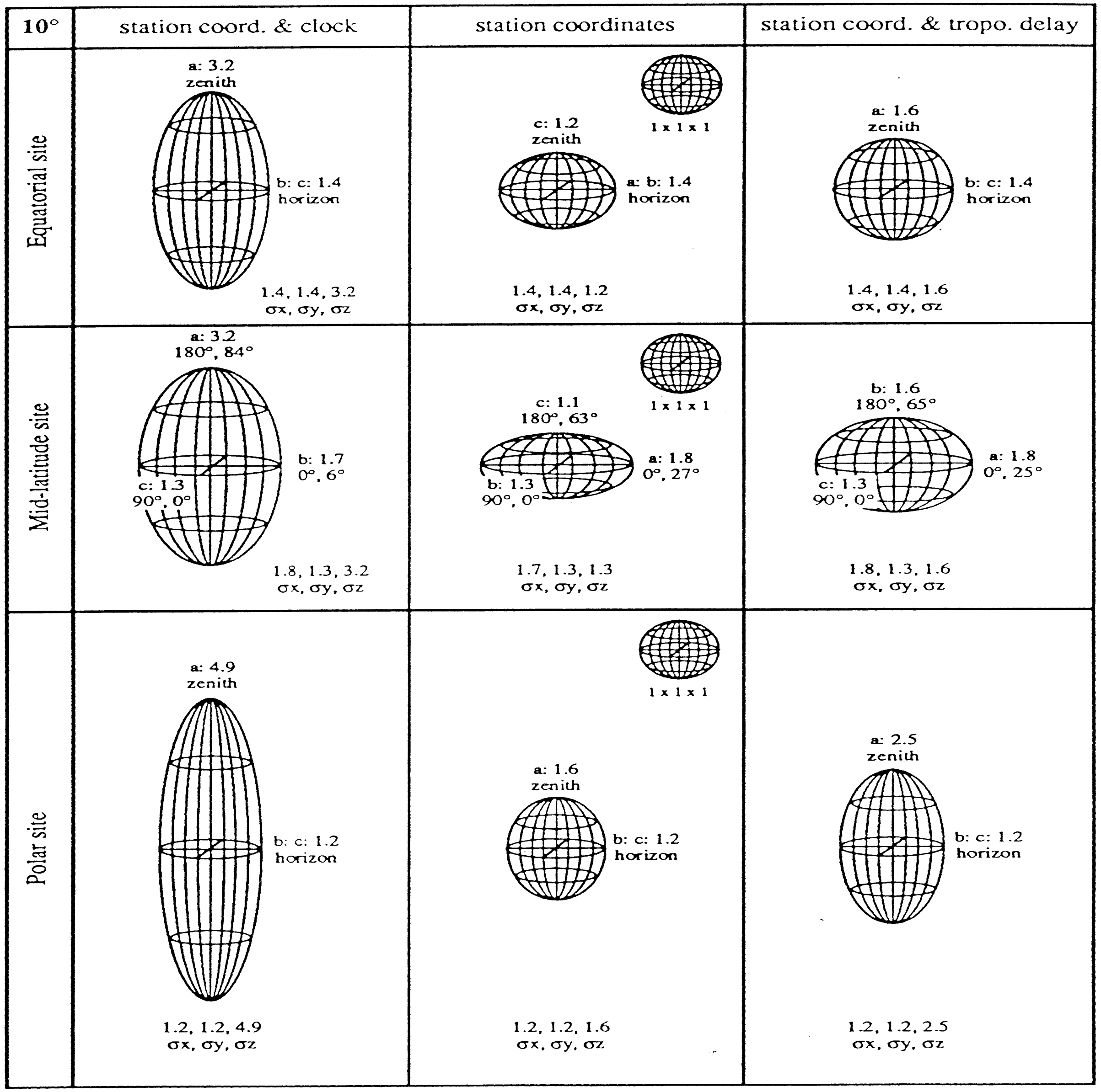
Clock Correction



$$\delta\rho_{clk}(z) = \delta\rho_{clk}(0) = c\cdot\delta t_R$$

Correlation: Height, Clocks, Troposphere

Coord. + Clock | **Coord. only** | **Coord.+Tropo.**

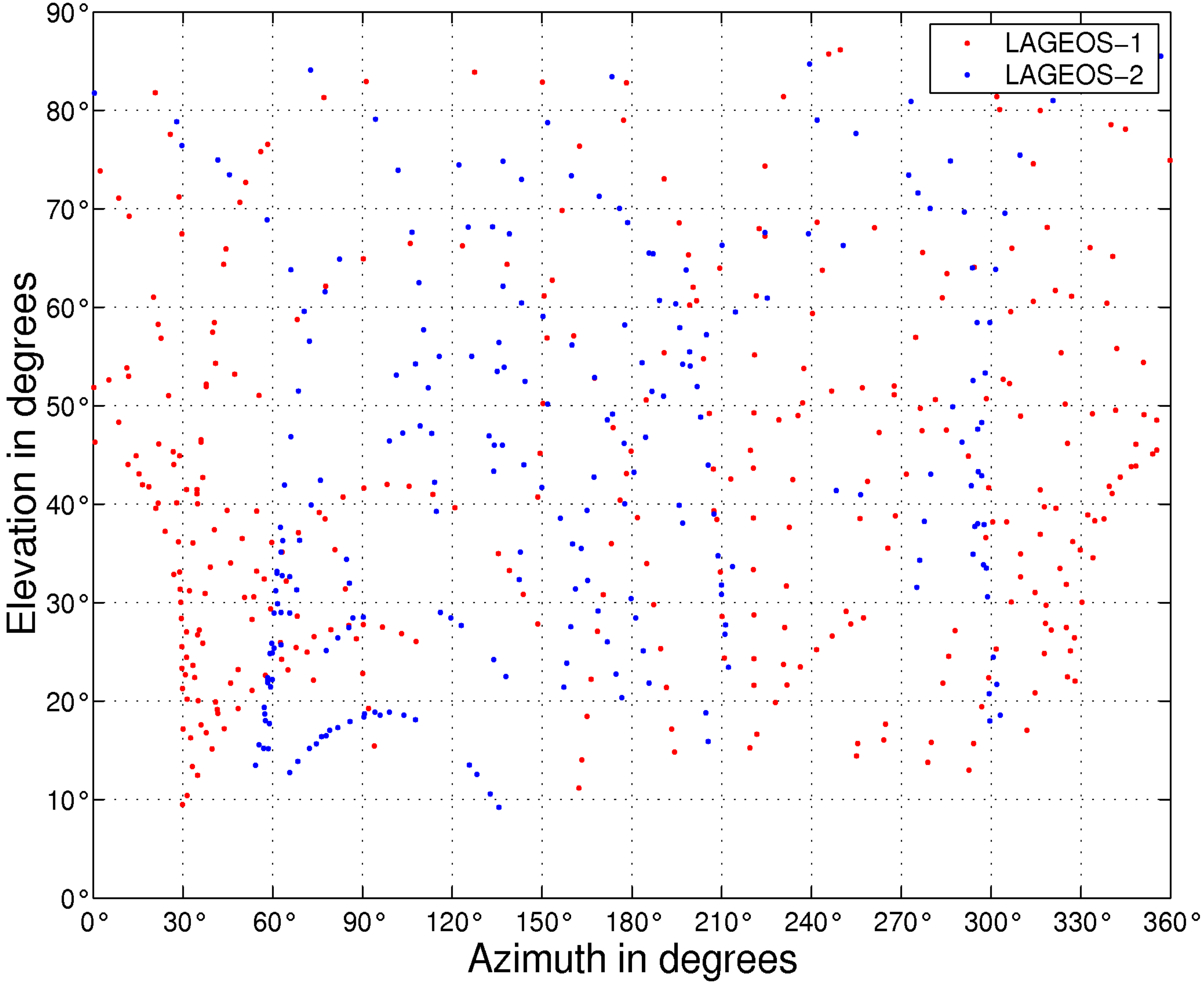


- Influence of clock and troposphere estimation on station height (Santerre)
- Extreme correlations between height, clock, and troposphere zenith delay
- No problem for SLR: heights should be perfect

z_{max}	$\sigma 1_h / \sigma 0_h$	Cor(h,trp)
70	13.78	-0.964
75	9.23	-0.943
80	6.13	-0.907
85	3.94	-0.830

Observation Geometry

LAGEOS–1/2 SLR observations from Graz, days 290–303/2002



Nice observation geometry for good stations (14 days)

Well-suited for height determination

SLR very important for absolute height estimation

Estimation of range biases should be avoided to the extent possible

Antennas and Absolute Scale (A&A)

Characteristics of GPS receiver and satellite antennas:

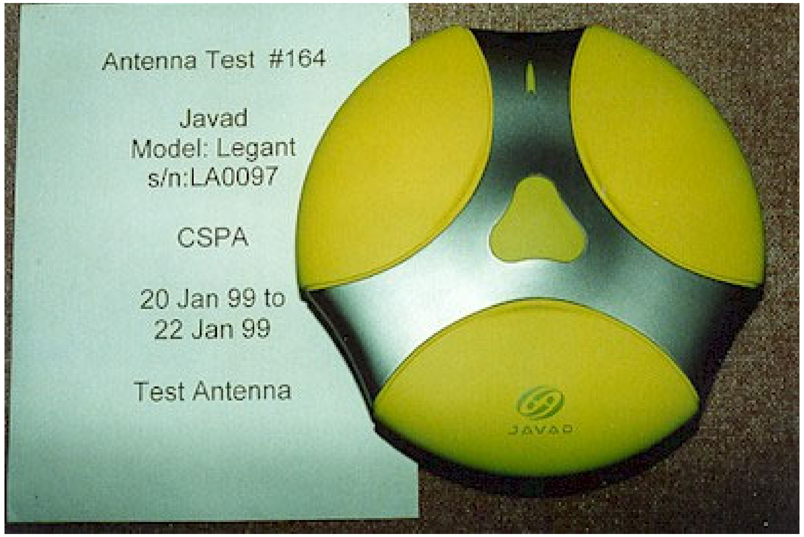
- Not accurately known, changing with elevation and azimuth
- GPS results dependent on **elevation cut-off**
- Large systematic effects due to **antenna phase center** corrections (receiver and satellite antennas)
- Many changes of GPS receiver/antenna equipment (jumps in height)
- GPS is too much affected by systematic effects to allow accurate **absolute height** and **absolute scale** determination in the global network and for ITRF.

VLBI telescopes:

- VLBI telescopes are huge and heavy structures
- VLBI **telescope deformation** may bias results (elevation dependence?)

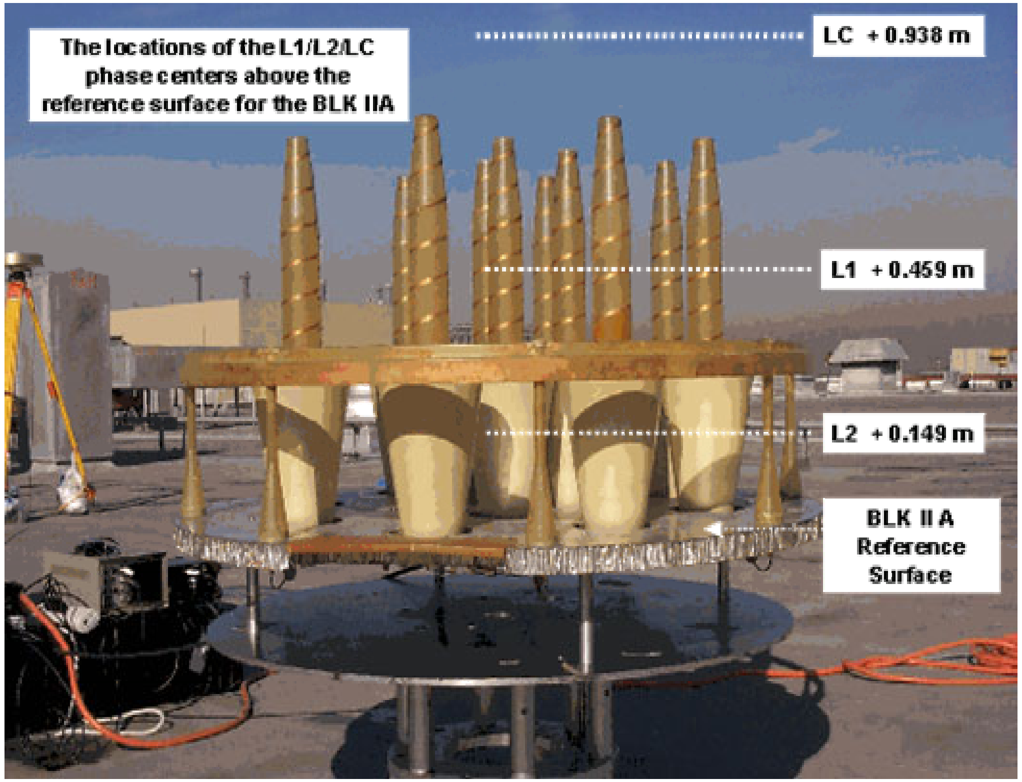
SLR: no such antenna problems (deformation should be small, no phase center variations): well-suited to define scale of ITRF; but calibration has to be very accurate and reliable.

Antenna Phase Center Corrections

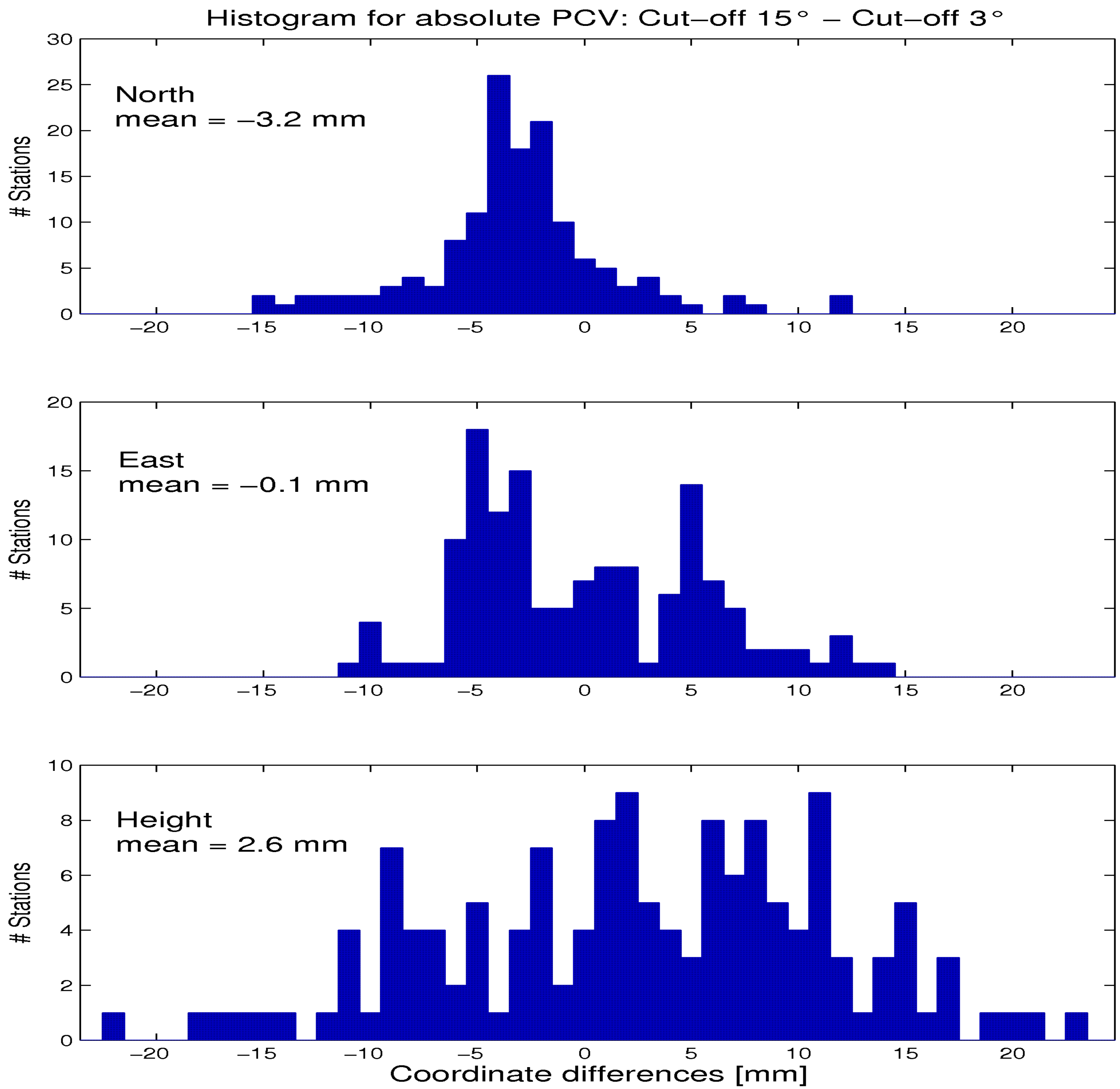


Antenna phase center variations:

- GPS receiver antenna
- GPS satellite antenna

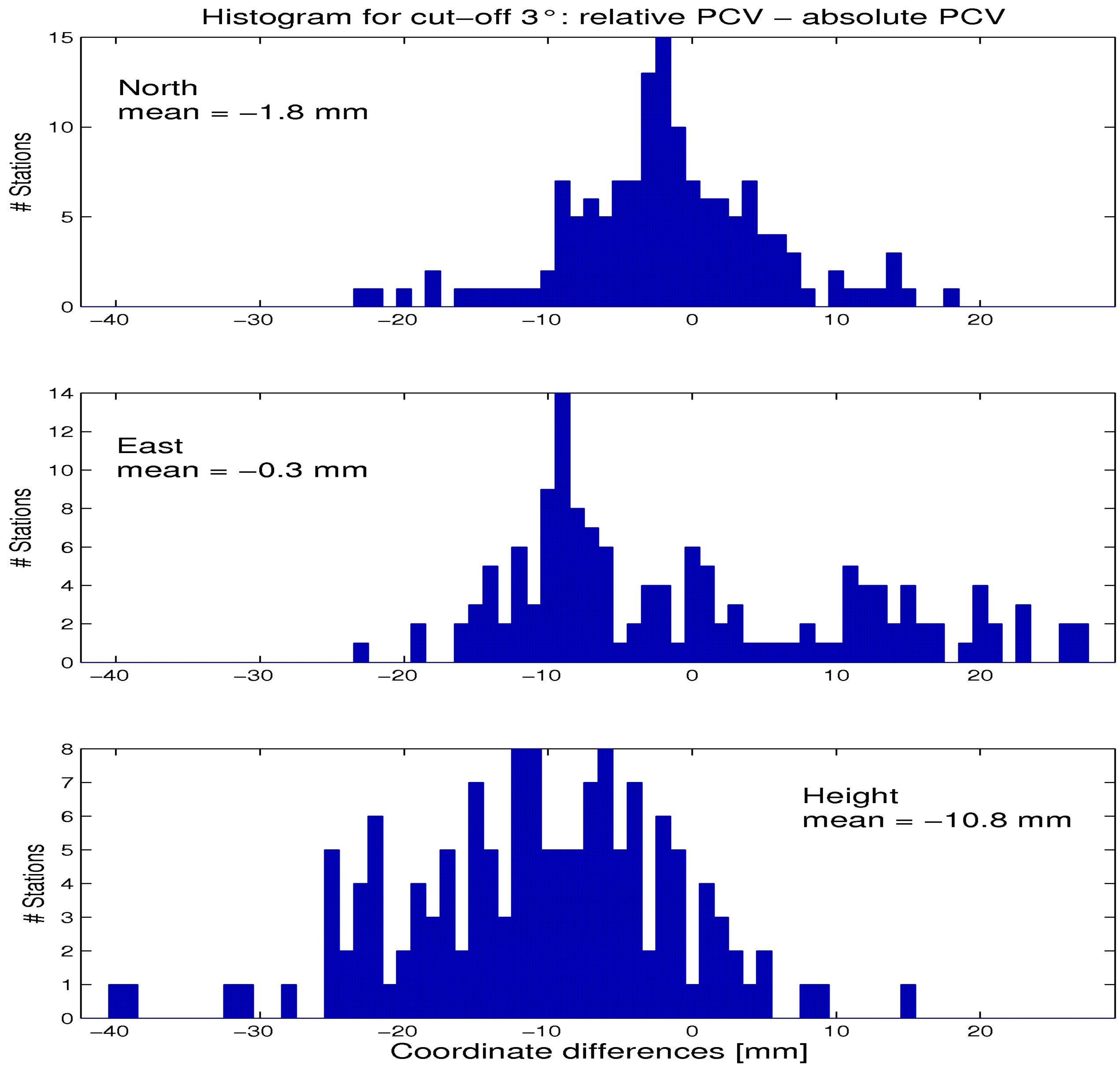


GPS: Elevation Cut-Off Effect



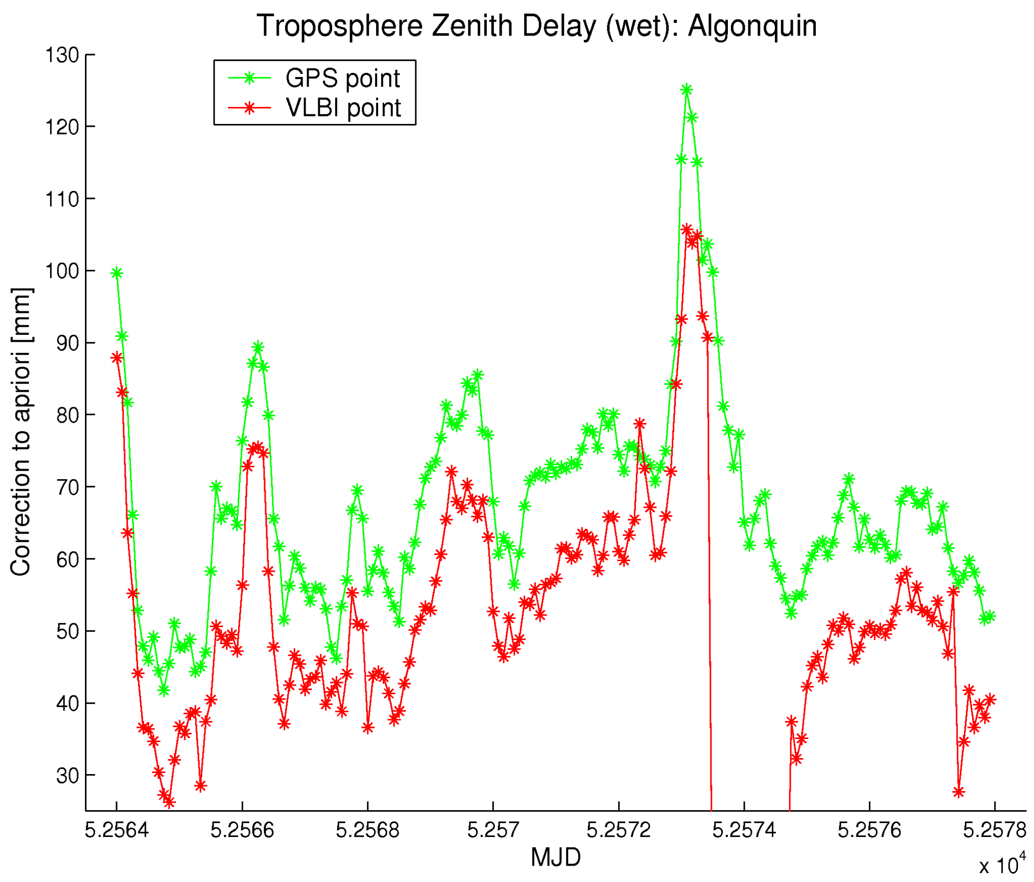
- Change of station coordinates due to a change in **elevation cut-off angle**
- Most up-to-date **absolute phase center variations** used for receivers (robot measurements) and satellites (global estimation)
- **Antennas are a critical error source !**

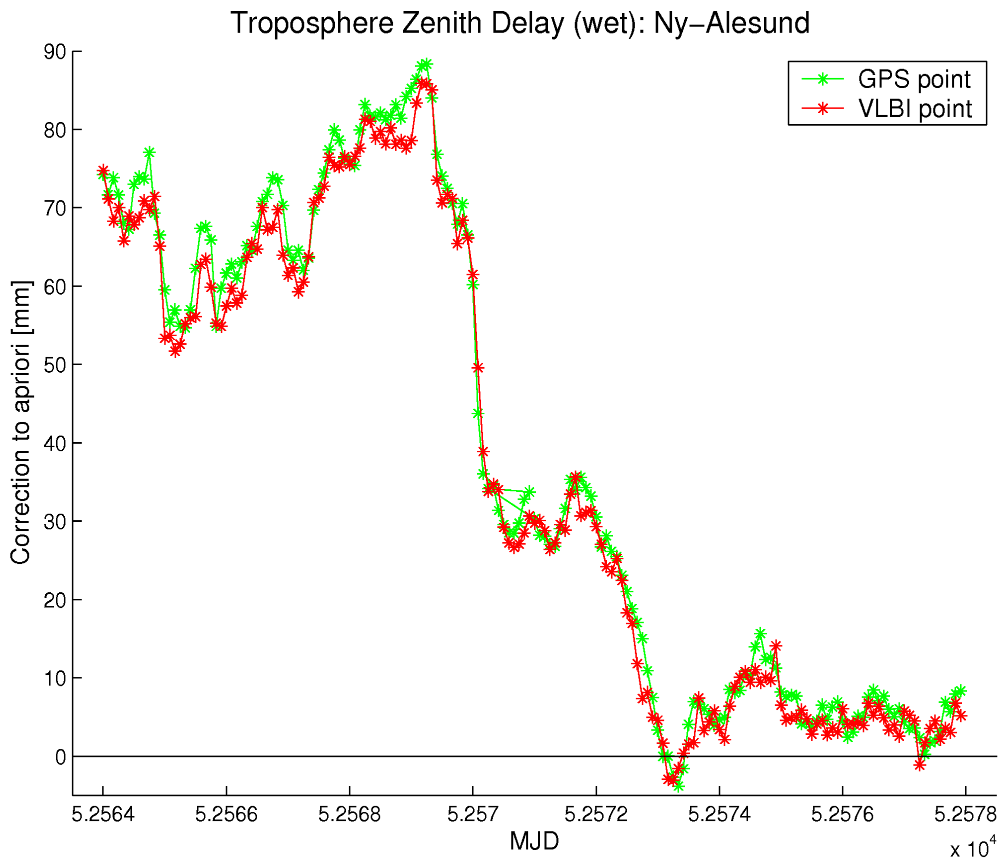
GPS: Absolute-Relative Antenna Patterns



- Change from **relative** (now in use) to **absolute** antenna information (to be used by IGS in future)
- Absolute phase center variations only derivable with fixed ITRF scale.
- Systematic change in scale to ITRF (several mm)

Comparison of GPS & VLBI Troposphere



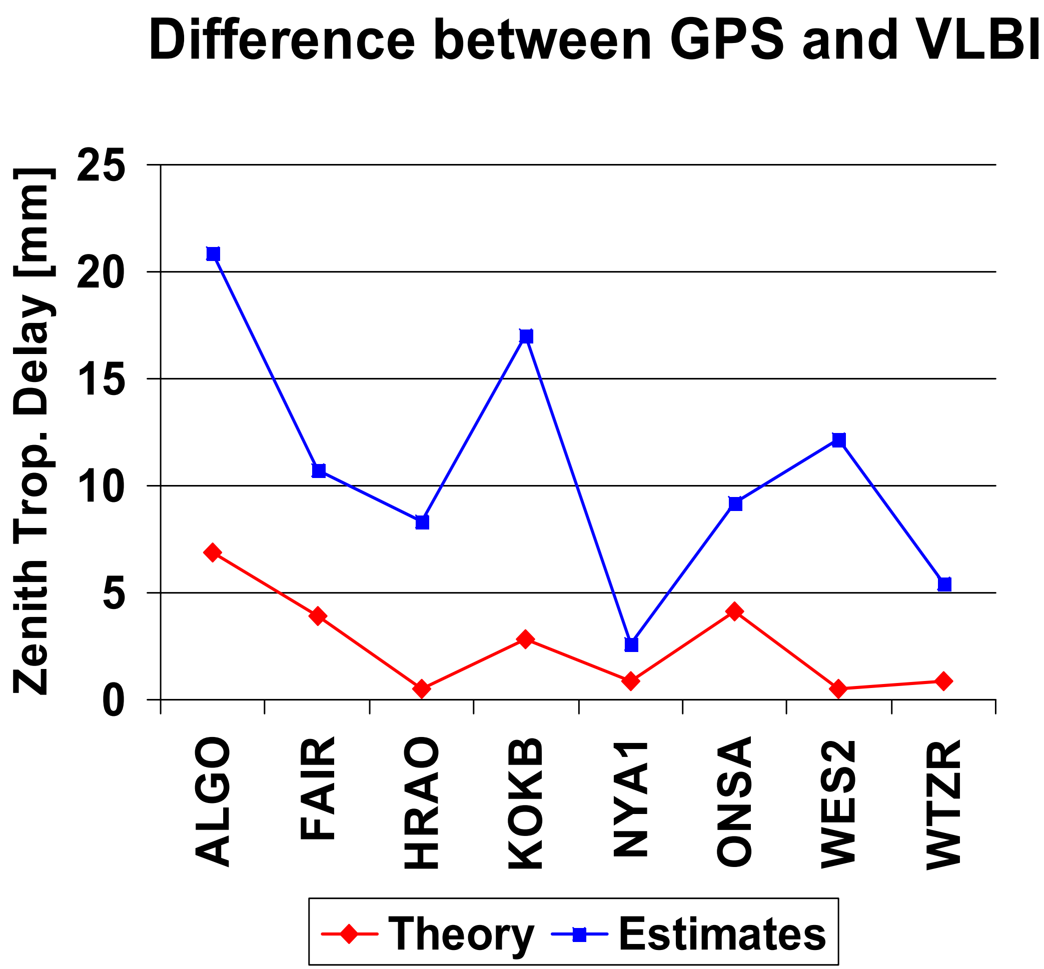


- CONT'02 Campaign (14 days)
- Very nice agreement in temporal variations, but **large systematic biases** between VLBI and GPS, indicating some unmodeled effects

Comparison of GPS & VLBI Troposphere

Station	ΔHeight (local tie) [m]	ΔZTD Theory [mm]	ΔZTD Estim. [mm]
ALGO	23.11	6.9	14.0
FAIR	13.08	3.9	6.8
HRAO	1.54	0.5	7.8
KOKB	9.24	2.8	14.2
NYA1	3.07	0.9	1.7
ONSA	13.71	4.1	5.1
WES2	1.75	0.5	11.7
WTZR	3.10	0.9	4.5

ΔHeight = 10m → ΔZD ≈ 3mm



Rotation and Rotation Rates (R&R)

One-to-one relation between changes in **UT1-UTC, Δε, Δψ** and changes in the orbital elements **Ω, i, u_0** (ρ=1.0027379):

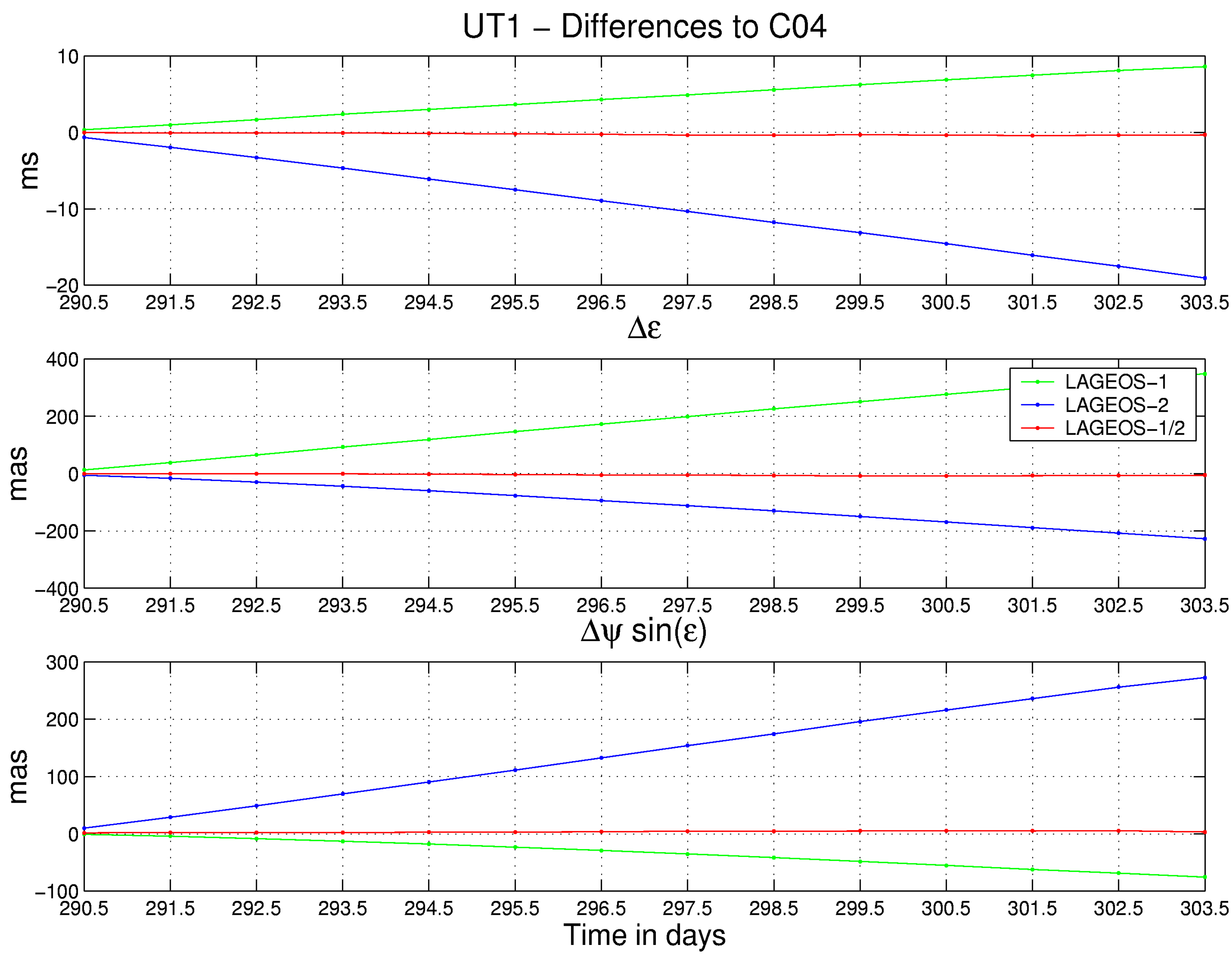
$$
\begin{aligned}
\Delta(\mathrm{UT1{-}UTC}) &= -(\Delta\Omega + \cos i \cdot \Delta u_0)/\rho \\
\delta\Delta\epsilon &= \cos\Omega \cdot \Delta i + \sin i \sin\Omega \cdot \Delta u_0 \\
\delta\Delta\psi \cdot \sin\epsilon_0 &= -\sin\Omega \cdot \Delta i + \sin i \cos\Omega \cdot \Delta u_0
\end{aligned}
$$

→ UT1-UTC and nutation offsets cannot be estimated together with orbital elements

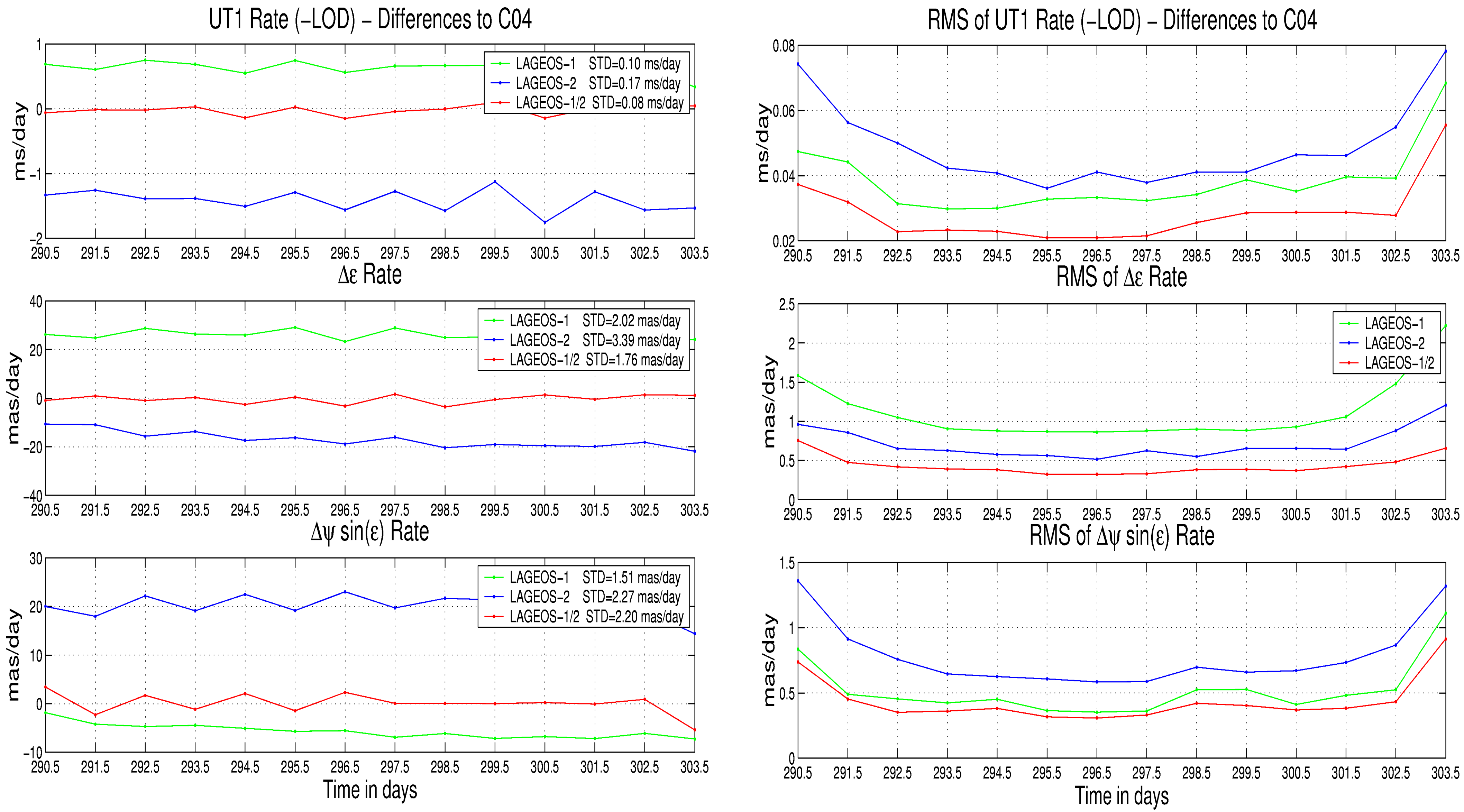
$$
\begin{aligned}
(\mathrm{UT1{-}\dot{U}TC}) &= -\mathrm{LOD} = -(\dot\Omega + \cos i \cdot \dot u_0)/\rho \\
\Delta\dot\epsilon &= \cos\Omega \cdot \dot i + \sin i \sin\Omega \cdot \dot u_0 \\
\Delta\dot\psi \cdot \sin\epsilon_0 &= -\sin\Omega \cdot \dot i + \sin i \cos\Omega \cdot \dot u_0
\end{aligned}
$$

→ LOD and nutation rates can be estimated by satellite techniques; quality of orbit model is crucial (changes of elements with time)

UT1-UTC and Nutation from SLR

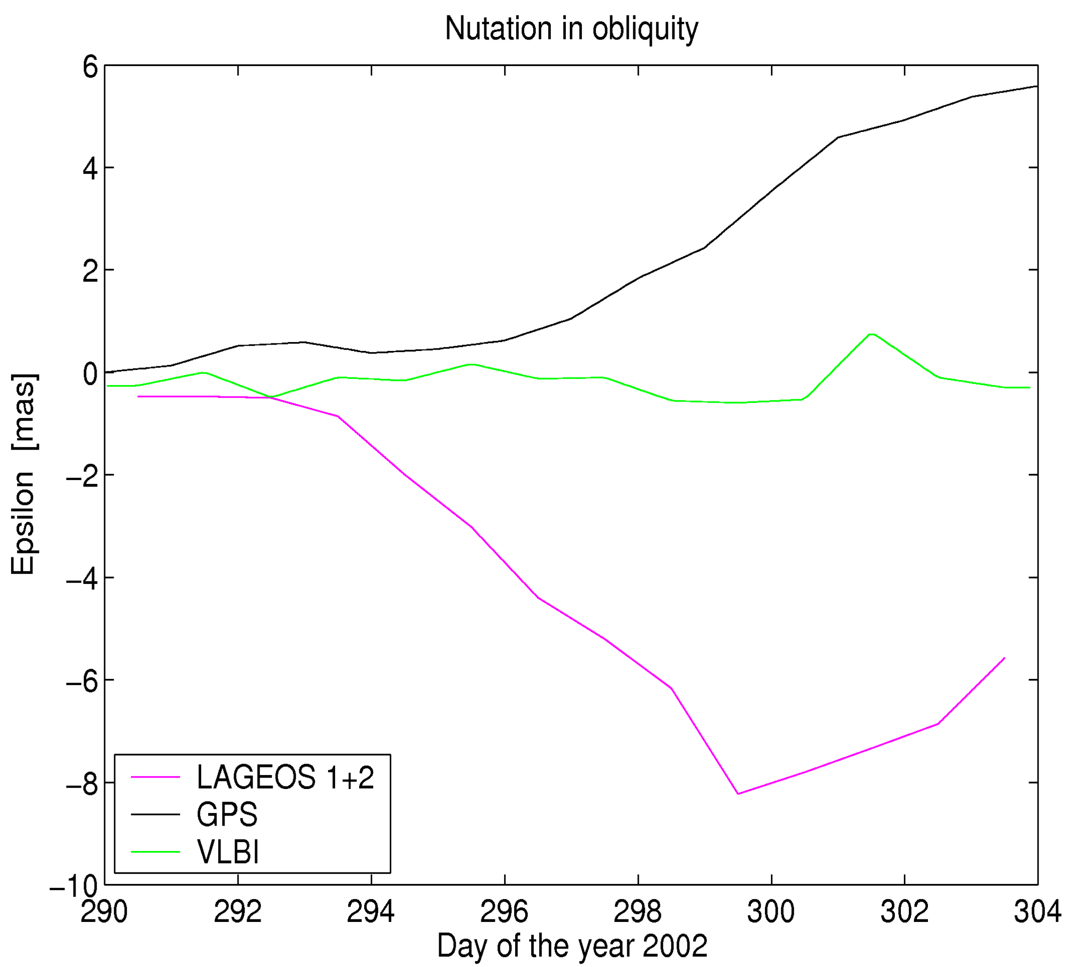


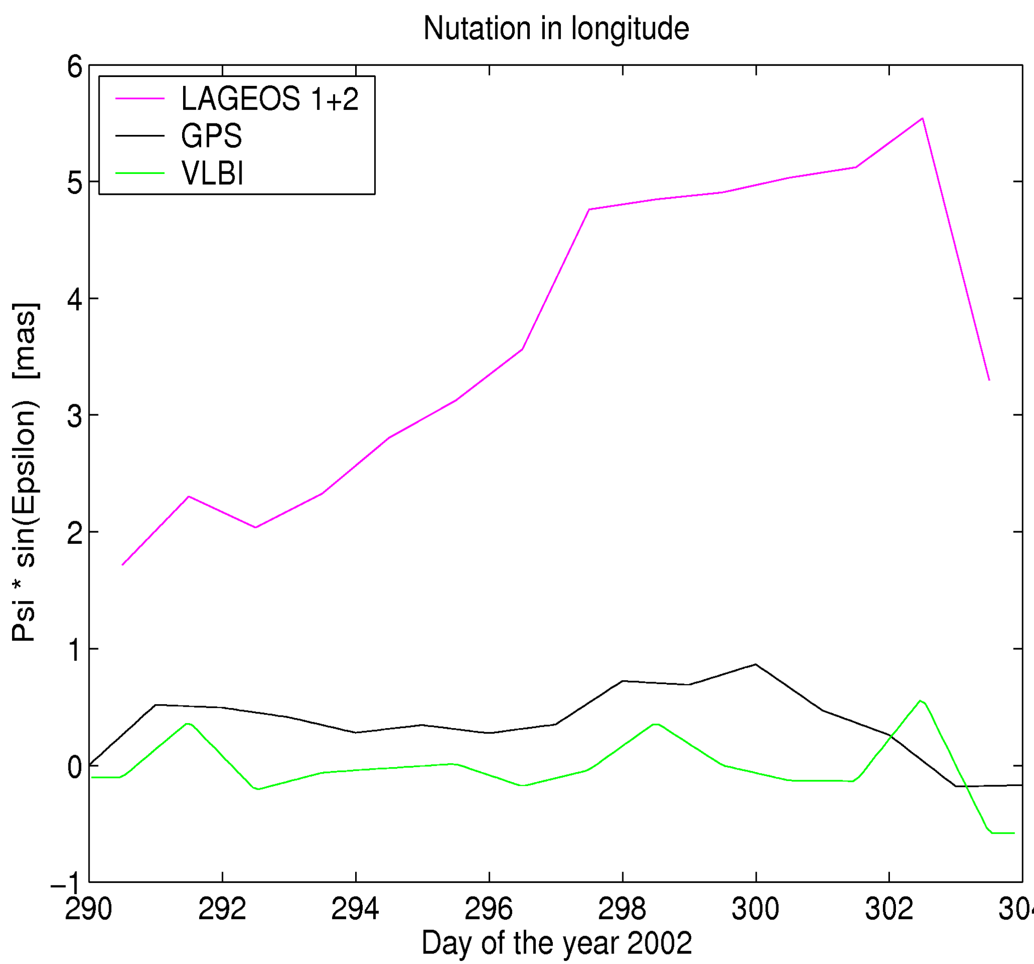
LOD and Nutation Rates from SLR



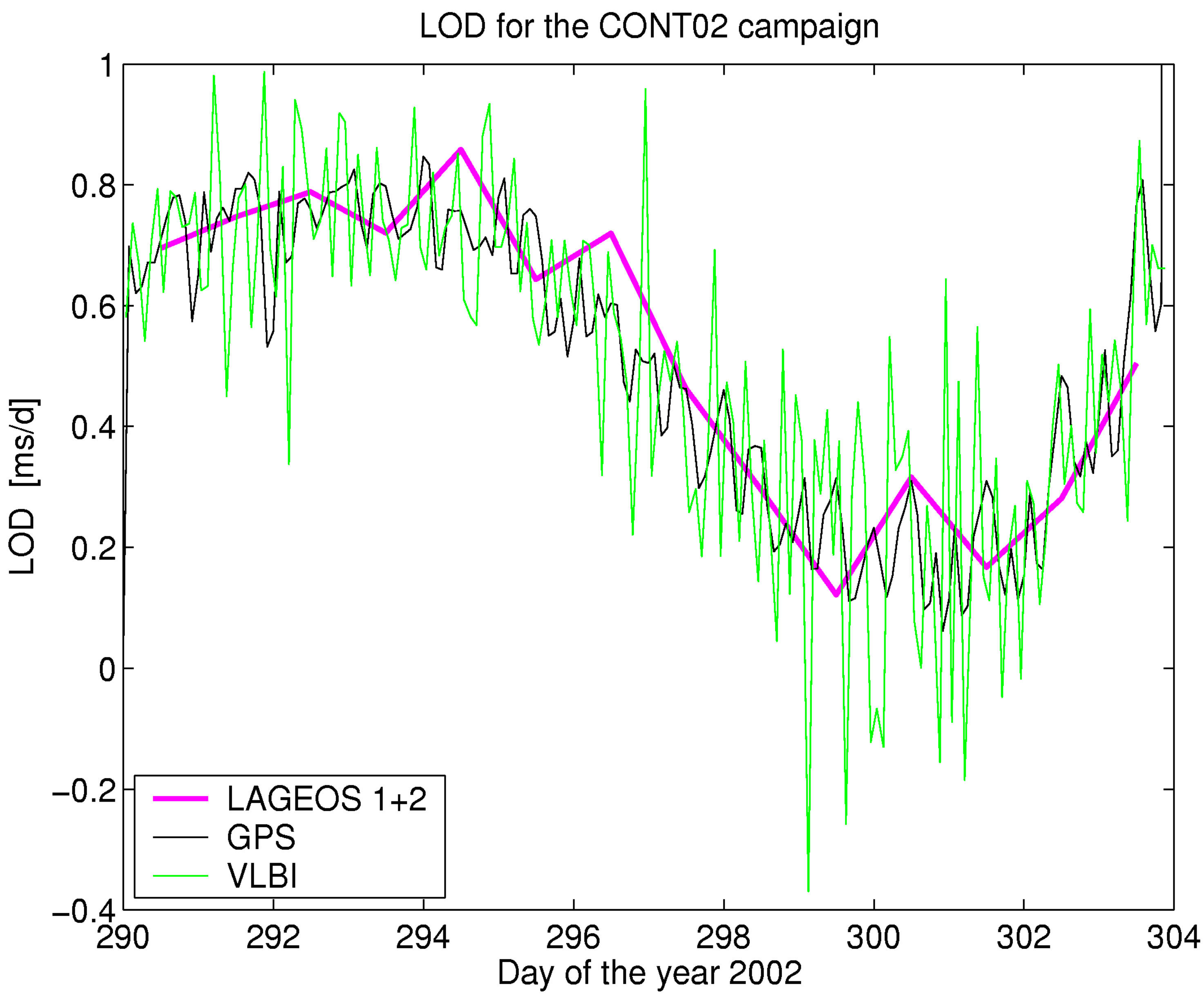
Nutation from SLR, GPS, and VLBI

- Comparison of nutation during the CONT'02 Campaign (14 days)
- SLR results similar to those of GPS (at least in obliquity)



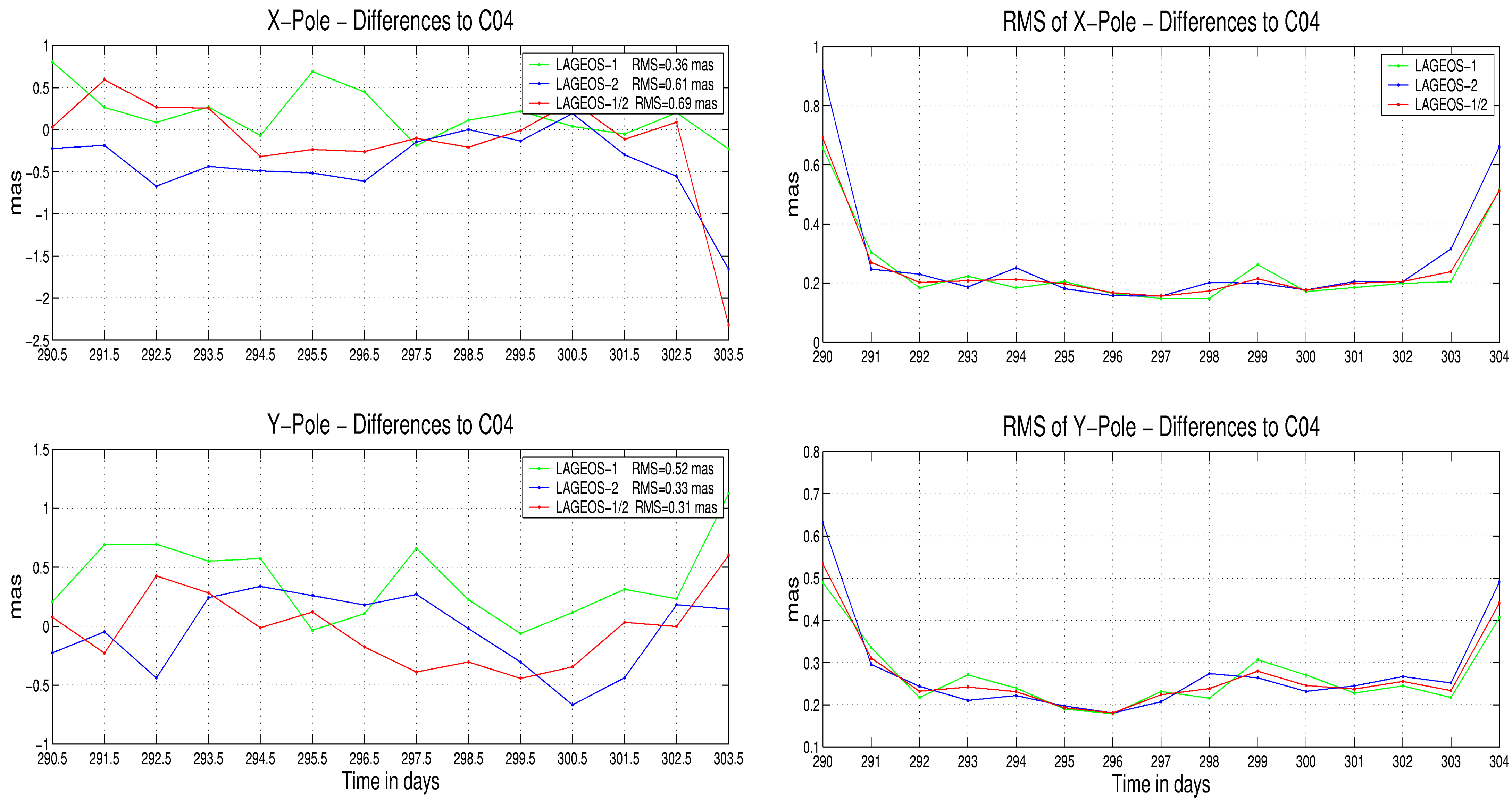


LOD from SLR, GPS, and VLBI



- CONT’02 Campaign (14 days)
- Subdaily LOD from GPS and VLBI
- Daily values from SLR (Lageos 1 + 2)

X- and Y-Pole from SLR



CONT'02 Campaign

Geometry and Gravity (G&G)

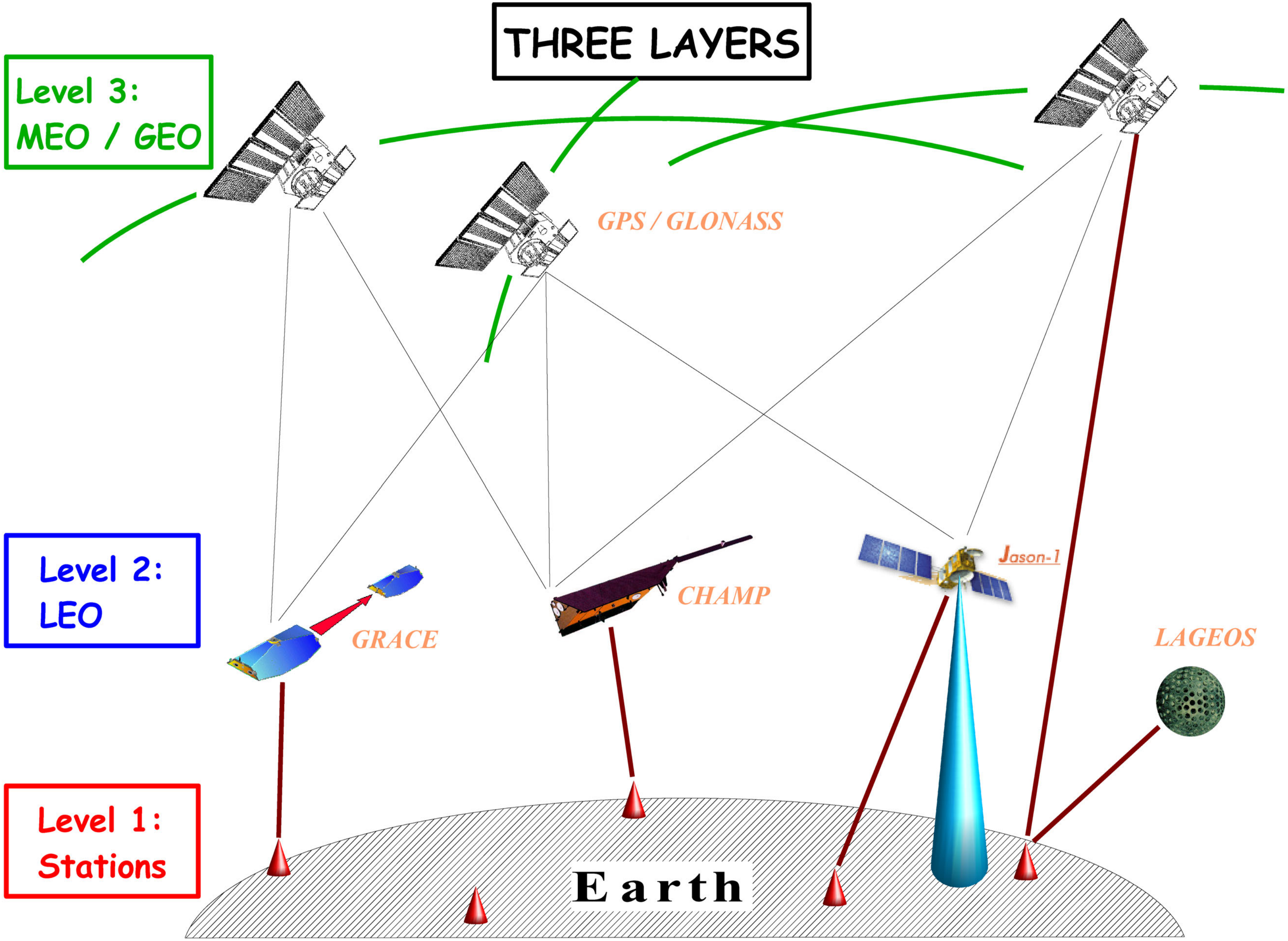
SLR is one of the major techniques to establish a link between geometry, Earth rotation, and gravity (three pillars of geodesy):

- Geocenter: relation between origin of ITRF and low order harmonics coefficient $\mathbf{C_{01}}$, $\mathbf{C_{11}}$, $\mathbf{S_{11}}$ of the Earth's gravity field
- Principle axes of inertia tensor: relation between Earth rotation, orientation of the gravity field ($\mathbf{C_{21}}$, $\mathbf{S_{21}}$, $\mathbf{S_{22}}$), and ITRF orientation
- Help to distinguish between "matter terms" and "motion terms" (gravity "feels" only "matter", Earth rotation "matter" and "motion")

SLR as a link between 3 pillars: very important for the IGGOS integration concept and for IERS reference frame definitions

Gravity field variations due to exactly the **same Earth processes** (e.g., from geophysical fluids) as Earth rotation and deformation (geometry)

Three Layers of Objects



Orbits and „Observed-Computed“ (O&O)

Validation of GNSS orbits (GPS, Glonass, Galileo, …):

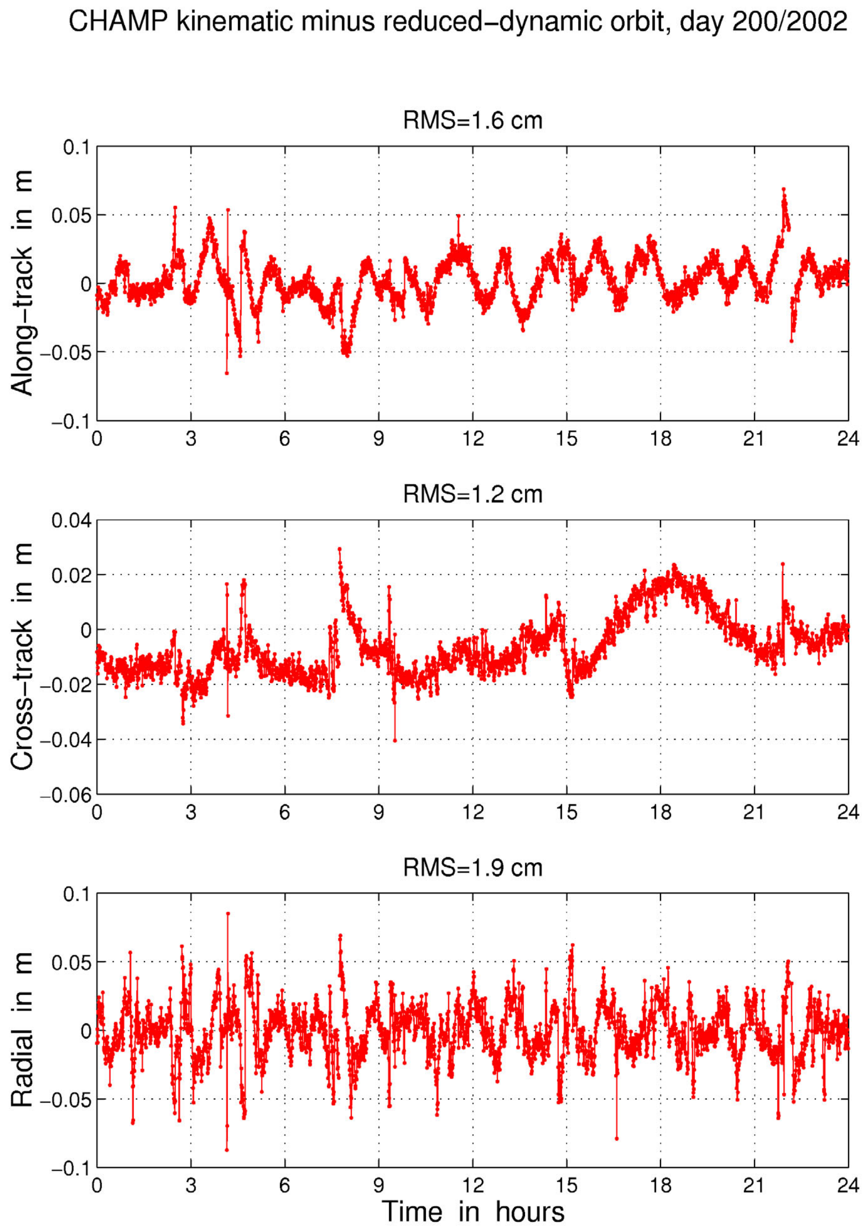
- SLR measurements are successfully used to validate GNSS orbits
- **Systematic bias** of about **4-5 cm** (!) between GPS orbits from microwave and SLR observations — reason still unclear
- May become important for **Galileo** satellites, too

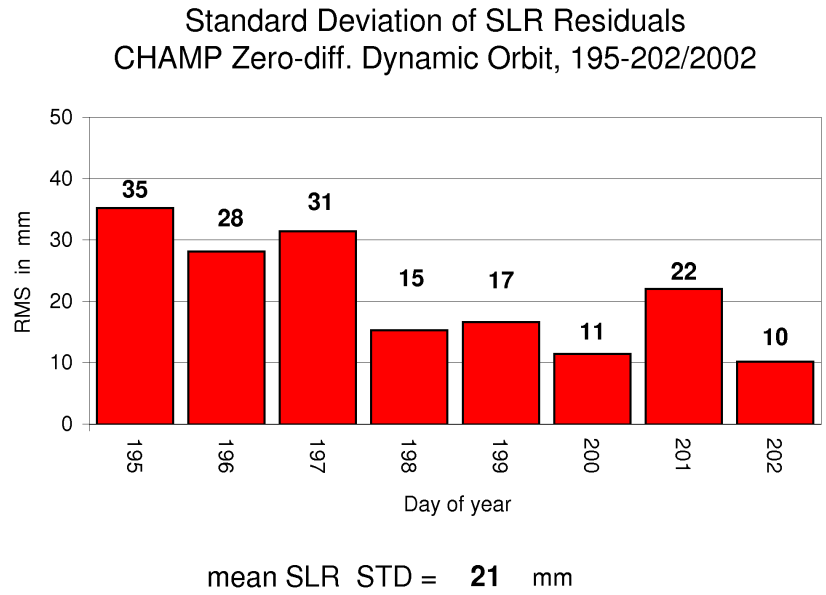
Validation of Low Earth Orbiter (LEO) orbits:

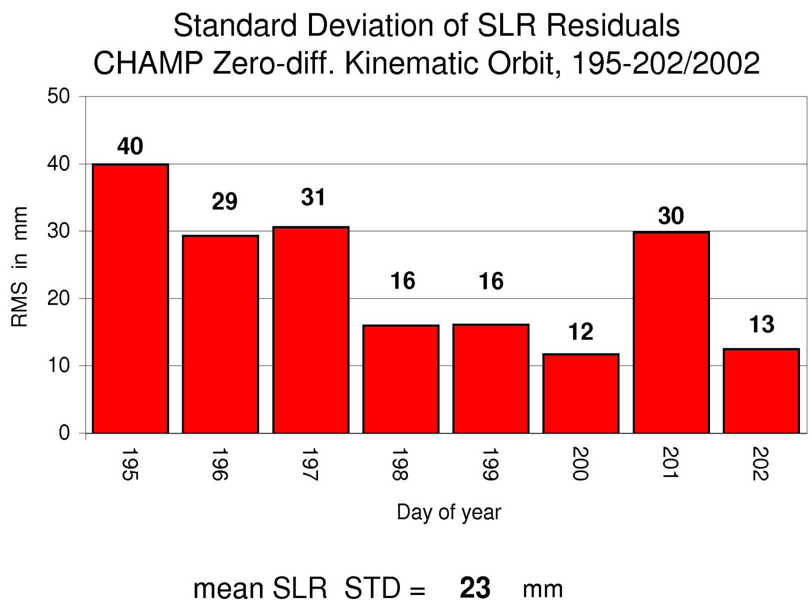
- Much progress in **precise orbit determination** (POD) of **LEOs** thanks to validation with SLR “observed-computed” (O-C)
- Evaluation of different **strategies** (kinematic, reduced-dynamic, …) and **software packages** and **parameterizations**
- SLR “O-C” values allow detection of **systematic orbit errors**

SLR observations are extremely valuable for POD studies; POD becomes ever more crucial for new satellite missions

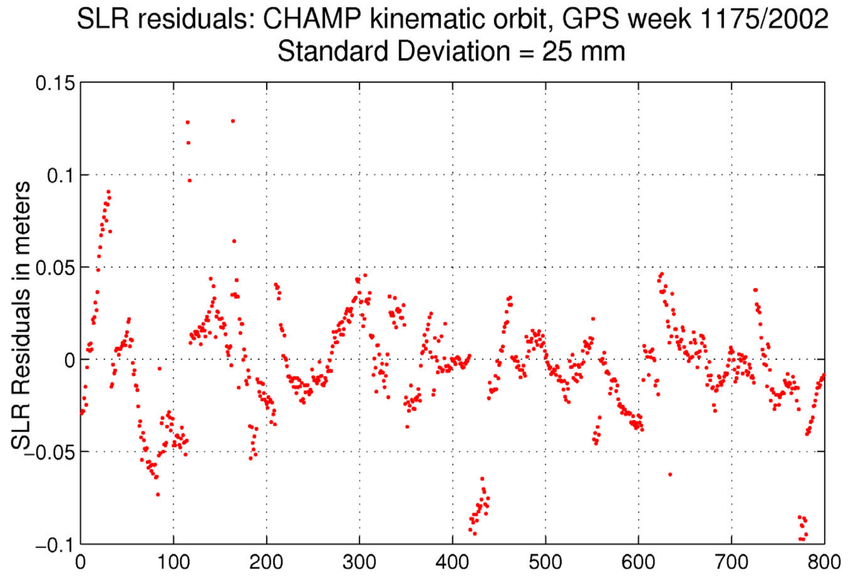
SLR Validation of CHAMP GPS Orbits

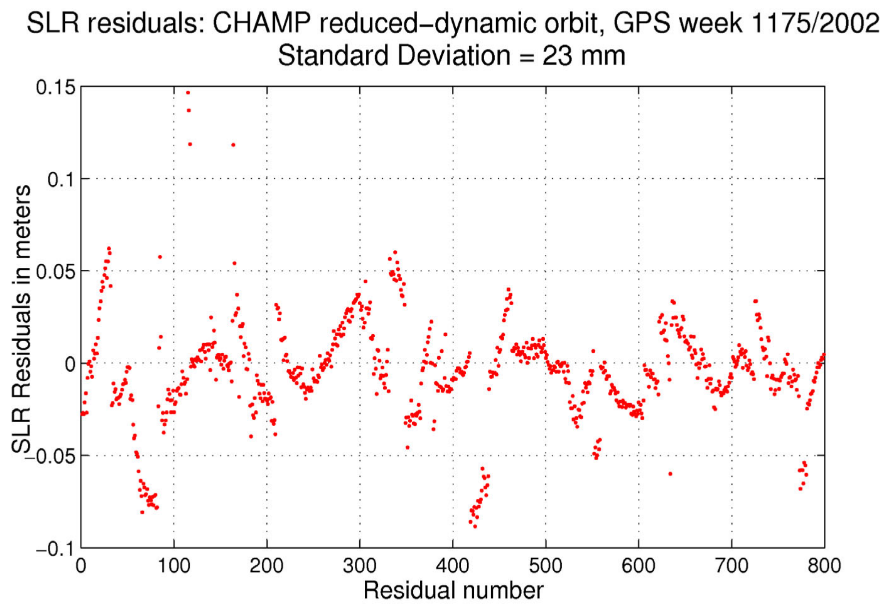






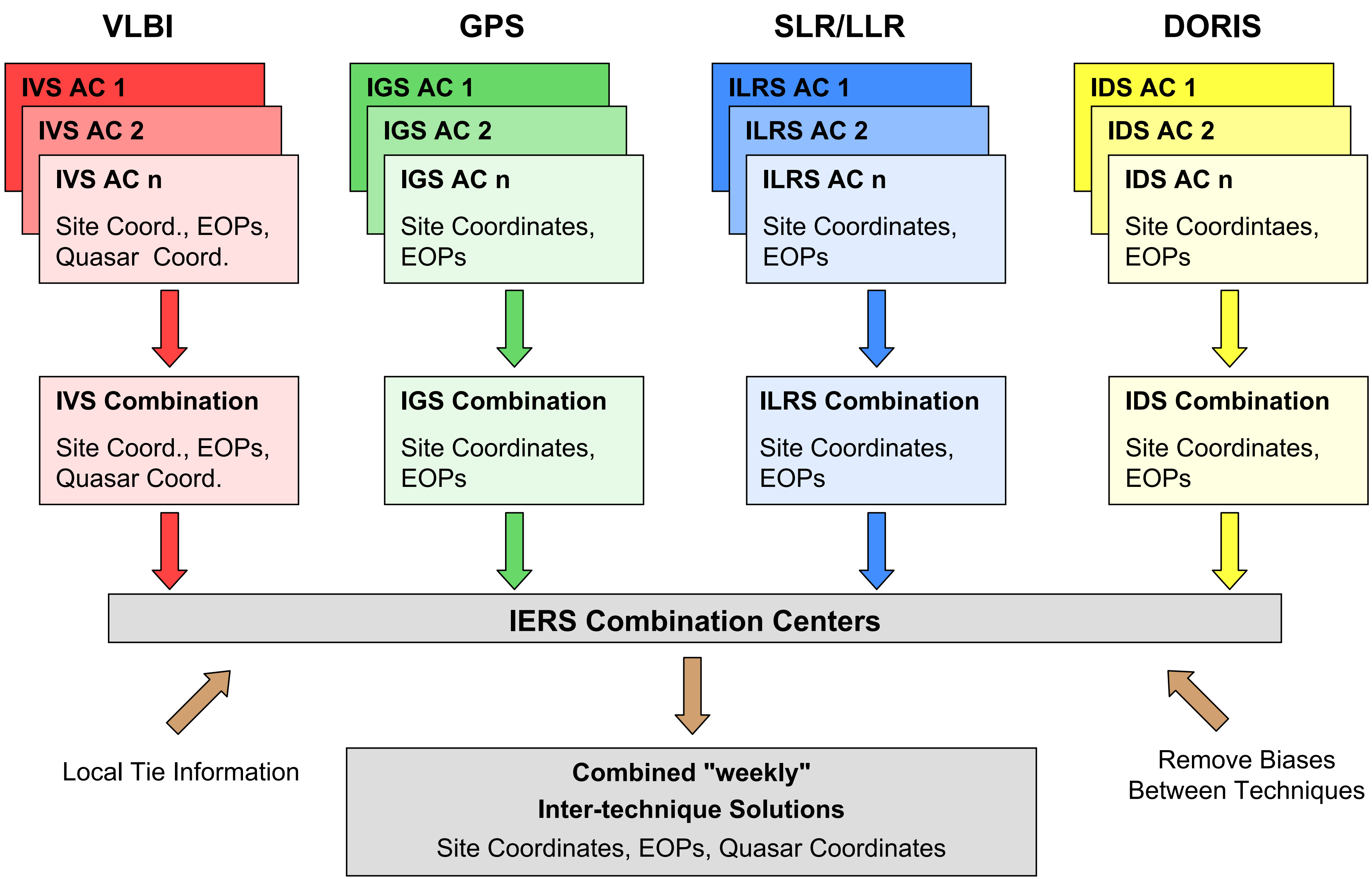
CHAMP Orbits: Observed-Computed





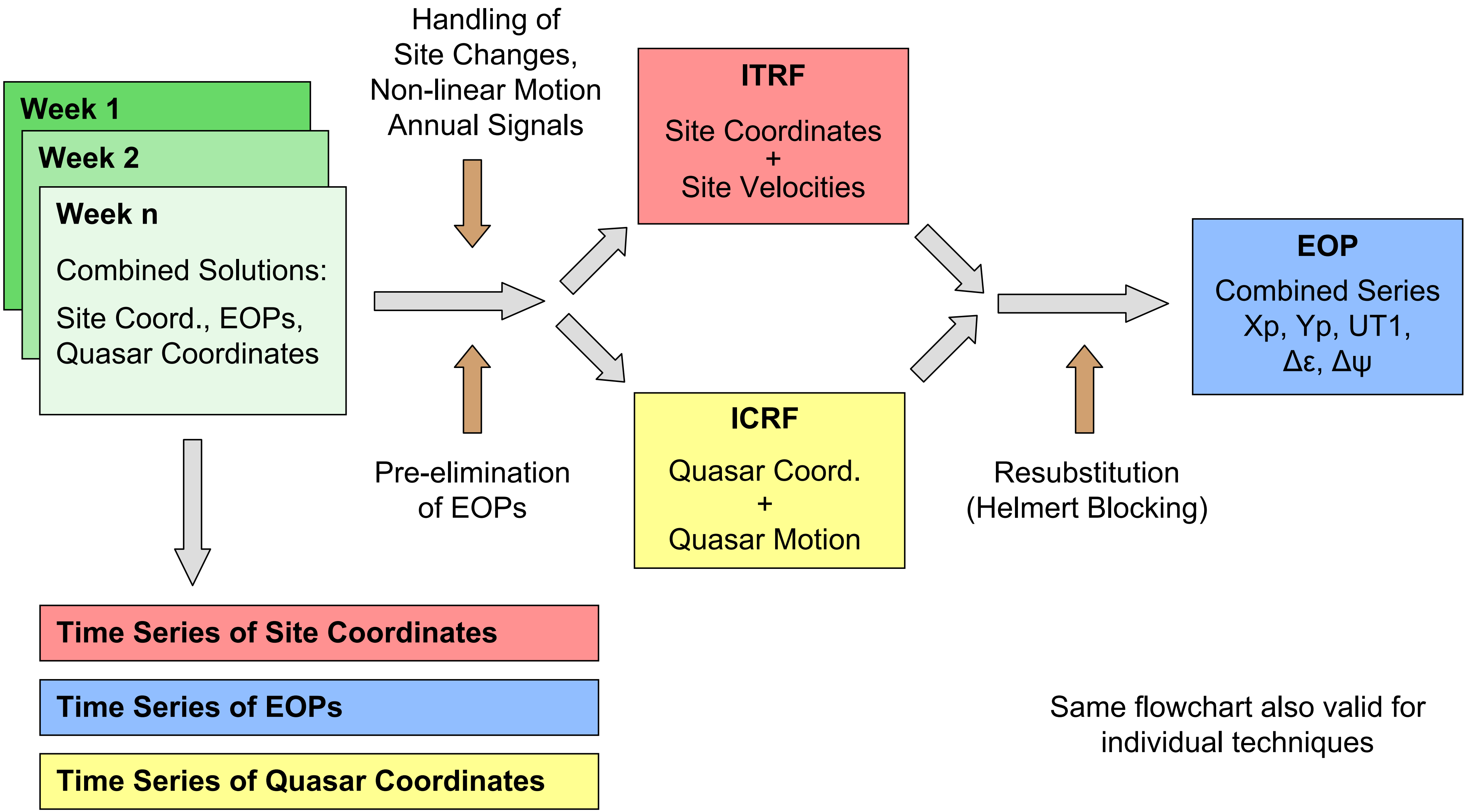
- SLR “O-C” values (or residuals) still show **significant systematic trends** for individual passes
- Similar behavior of **kinematic** and **reduced-dynamic** orbit residuals
- Detailed analysis of the residuals may give information on **model deficiences**, e.g.:
  - GPS polarization effect
  - Relativistic corrections
  - Higher order ionospheric corrections
  - Orbit parameterization …

Future Combination: "Weekly" SINEX Solutions



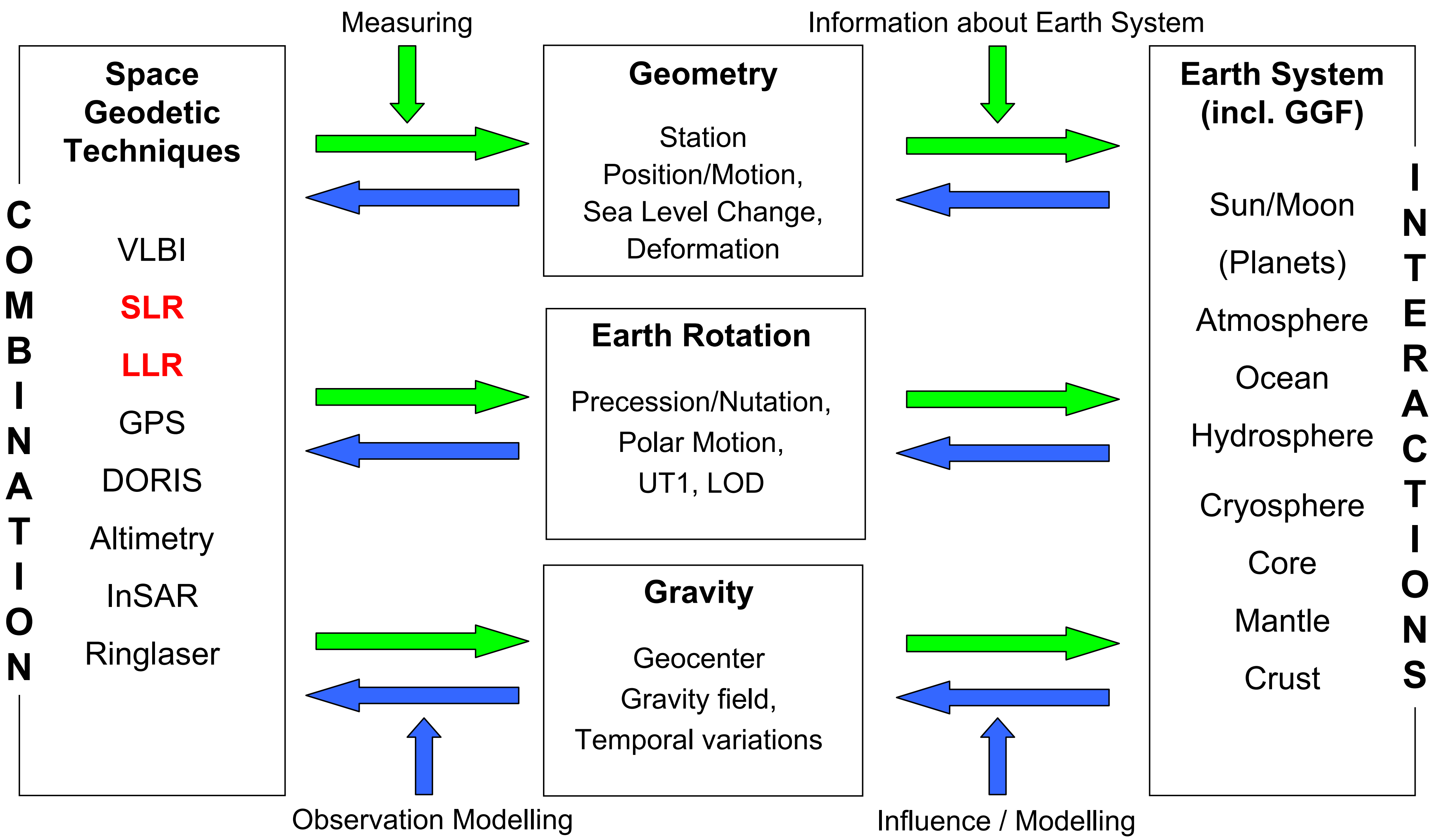
Future Combination: Multi-Year Solutions

(Fully Consistent Set of ITRF/EOPs/ICRF)



Same flowchart also valid for individual techniques

Measuring and Modeling the Earth System



Conclusions

- SLR has few observations, but also few parameters to estimate
- SLR is the only optical technique (unique to assess atmosphere biases)
- No troposphere estimation necessary for SLR (correlations, biases)
- No clock correction estimation necessary for SLR (correlations, biases) → good heights
- No big antenna problems → absolute scale, heights
- Important link between gravity, Earth rotation, and geometry
- SLR O-C crucial for progress in POD

SLR is a unique partner in the goal of a rigorous combination of the space geodetic techniques (IERS and IGGOS)

The individual techniques should feel as a part of a larger whole with a common goal rather than working in competition

Interlinked, the techniques are much stronger and it is more difficult to isolate and cut individual techniques