Laser Ranging to GNSS & LPOD2005

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SLR Tracking of GNSS Constellations

50 Years of Satellite Geodesy and Geodynamics

Metsovo, Greece
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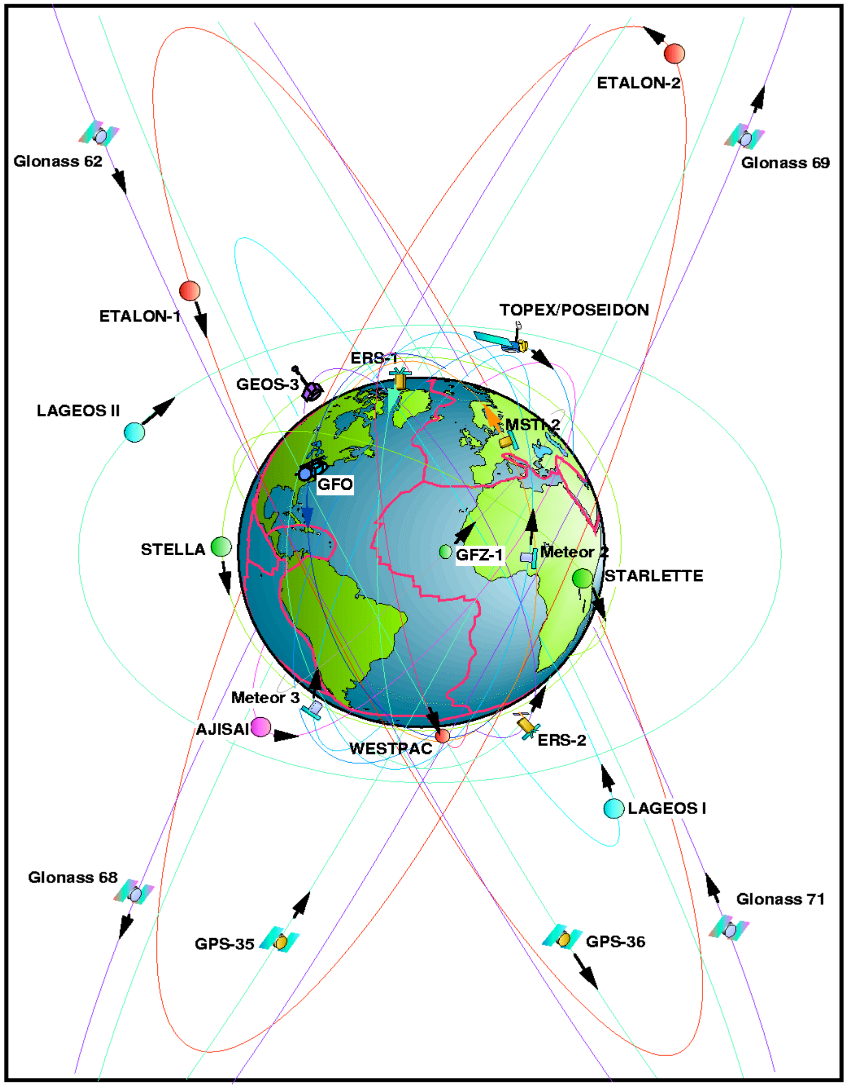
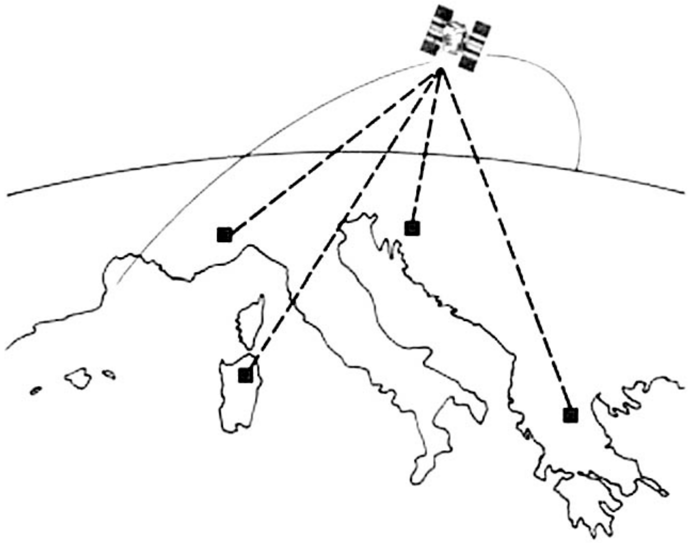


GPS, SLR and VLBI in the TRF

- SLR and VLBI determine the 'backbone' of the TRF in terms of its origin, scale and absolute orientation (wrt celestial frame)

- However, due to its dense geographic coverage, GPS is practically the only disseminator of that TRF to most users
  - For example, ocean tide gauges are rarely co-located with SLR or VLBI

- GPS forms the 'web' that helps separate the local motions from the global frame components



Why do we use different techniques?

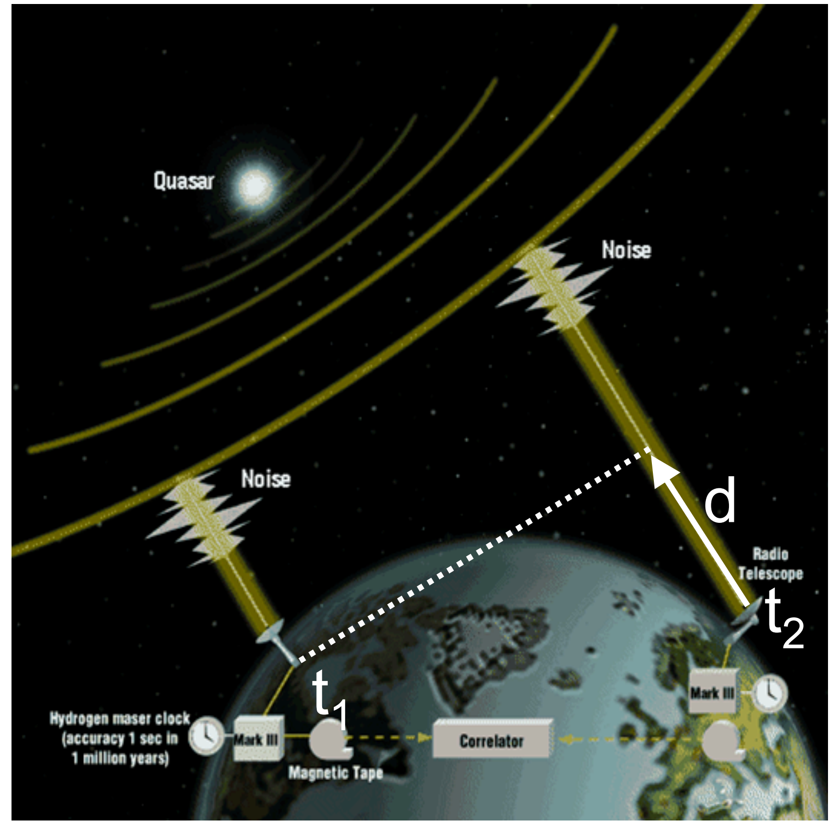
- Each technique has fundamentally different observations with unique contributions to the TRF
- Where they overlap, they can provide cross validation and increased accuracy (or uncover a discrepancy)
- The current precision for determining the TRF scale is sufficient that a discrepancy between SLR and VLBI at the ppb level is probably significant

TECHNIQUE **Signal** **Source** **Obs. Type**	**VLBI** **Microwave** **Quasars** **Time difference**	**SLR** **Optical** **Satellite** **Two-way absolute range**	**GPS/DORIS** **Microwave** **Satellites** **Range change**
Celestial Frame UT1	**Yes**	No	No
Polar Motion	**Yes**	Yes	**Yes/**Yes
Scale (absolute lengths)	**Yes**	**Yes**	Yes
Geocenter (origin)	No	**Yes**	Yes
Geographic Density	No	No	**Yes**

Yes means has strong capability
Yes means some capability exists

Scale & Terrestrial Reference Frame (1)

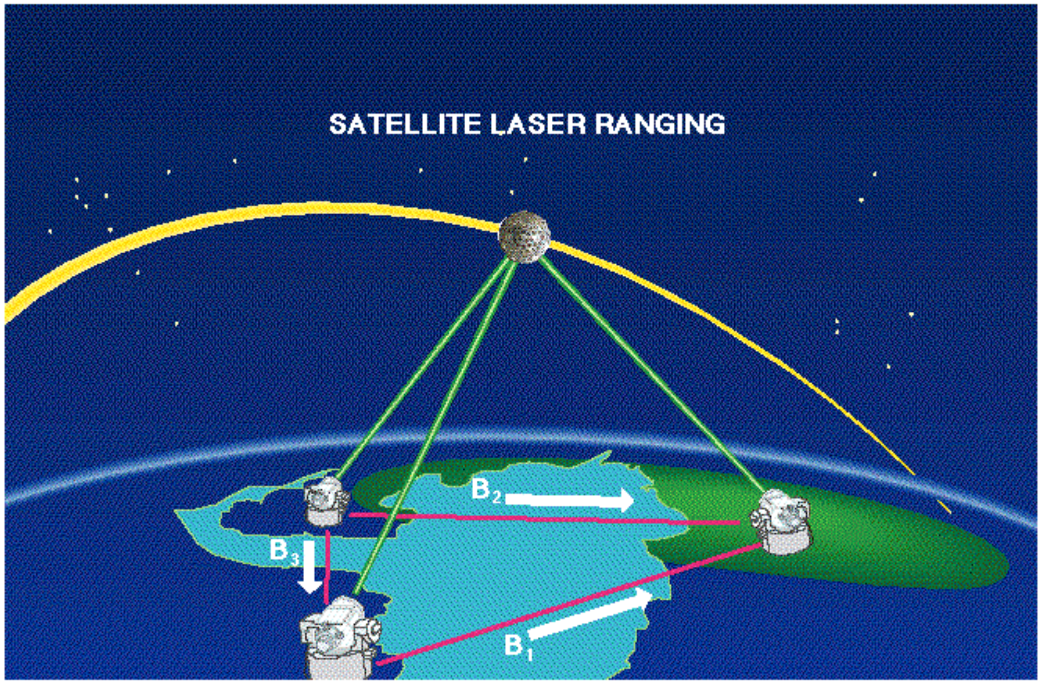
- A scale change is the uniform increase or decrease of all distances
  - 1 ppb change in scale ⇒ ~6 mm change in station height
- VLBI determines the absolute distance vectors kinematically
- There are no dynamics involved and there is no connection to Earth's mass center
- Earth's mass enters only through a relativistic time delay correction



$$d = c\,(t_2 - t_1) + \text{corrections}$$

Scale & Terrestrial Reference Frame (2)

- SLR measures station location indirectly through an intermediate target
- Satellite orbital period is related to orbital radius and Earth's mass (GM)
- Laser ranging provides absolute orbital height and curvature, so we can estimate orbit, station heights, biases and GM simultaneously (radiometric biased-range measurements cannot and must depend on SLR-based GM)



GM estimation from SLR (1)

- In 1992, GM estimated using 5 years of LAGEOS-1 data to determine value currently still in use
  - GM = 398600.4415 ± 0.0008 km^3/s^2 (TDT value)
    - GM (SI) = GM (TDT) * $(1+L_G)$ = 398600.4418
  - Considered 2 cm biases plus a ‘quesstimate’ for troposphere error (0.2% or ~4-5 mm in zenith delay)
    - Possible systematic error in Murini & Murray model was a concern
    - Did not consider contribution of Center of Mass (CoM) offset errors
- Recently, we estimated GM using 12+ years of SLR data from LAGEOS and LAGEOS-2
  - GM = 398600.44163 ± 0.00042 km^3/s^2 (± 1 ppb)
  - ‘Formal’ error = 0.00004 km^3/s^2 (0.1 ppb)
    - ‘Formal’ error estimate already includes 4-6X increase in the apriori SLR data standard deviation to try to better reflect systematic errors

GM estimation from SLR (2)

- Considering a 1 cm bias (average bias over the whole data span) for each station increased uncertainty to 0.00027 (~ 0.7 ppb)
  - Estimating or not estimating biases changed the GM solution by less than the estimated uncertainty (solution is very robust)
- Atmosphere refraction contribution estimated to be < 0.2 ppb
  - Compared estimates using Mendes & Pavlis refraction model to standard Marini & Murray model
  - Difference in GM was only 0.3 ppb, about the same size as the difference between the LAGEOS and LAGEOS-2 estimates
  - Assuming most of the difference is error in the older M&M model, refraction errors might be assumed to contribute no more than 0.1-0.2 ppb to the uncertainty in GM (or scale)

GM estimation from SLR (3)

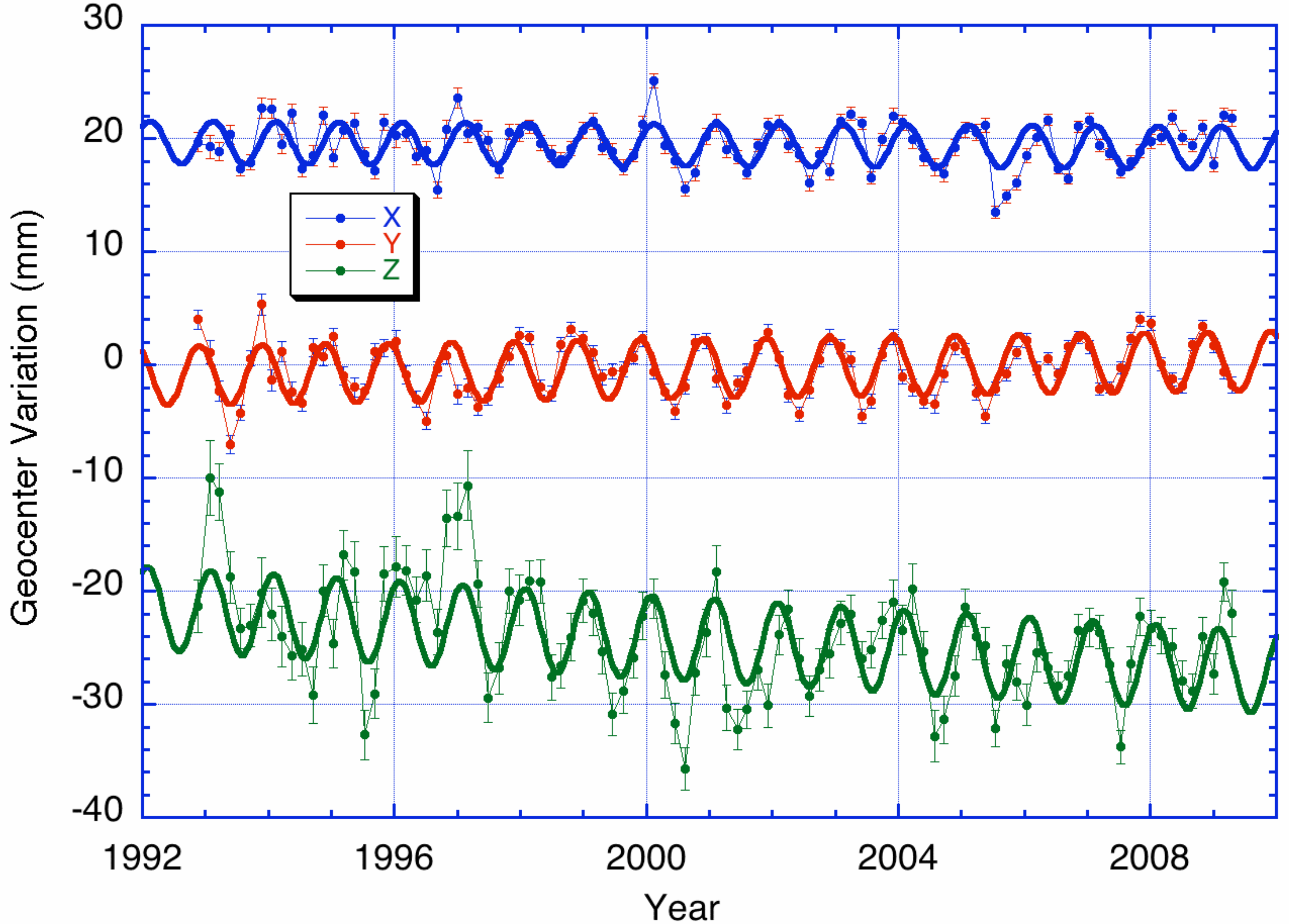
- CoM model was identified as likely ‘tall pole’ in error budget
  - Using ‘guesstimate’ of 4 mm error in the CoM correction led to an increase of the estimated error in GM to 0.00042 (~1 ppb)
  - ITRF2005 scale issue motivated more careful analysis of impact of CoM model errors on GM, for LAGEOS and other satellites

Satellite (A in Earth radii)	CoM Error required for 1 ppb error in GM
Starlette (~1)	1 mm
LAGEOS (~2)	3 mm
GPS (~4)	~8 mm (extrapolated)

- Low satellites are much too sensitive to CoM errors
- Laser ranging to GNSS satellites could provide a better GM estimate (feeding back to the lower satellites), but the CoM has to be known very well to improve on current accuracy

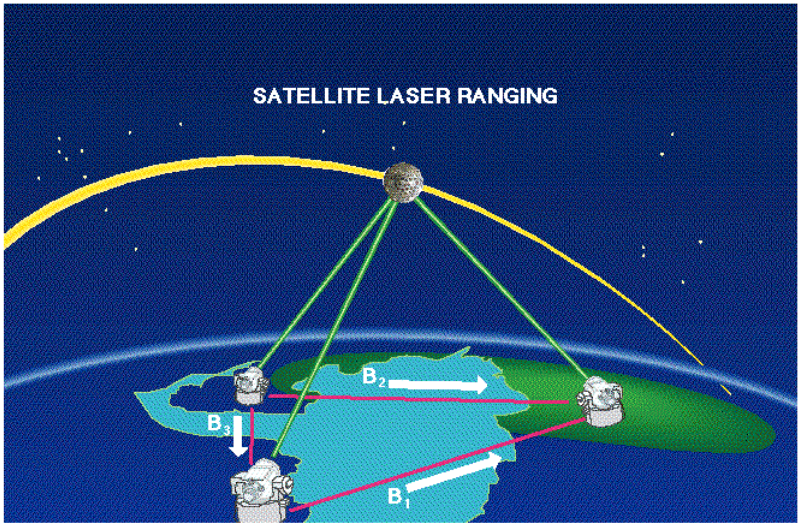
SLR provides most accurate tie to origin

60-day geocenter estimating translation only;
LAGEOS1+LAGEOS-2, LPOD2005, est. biases



GPS Issues - Orbit Verification

- GPS orbit quality is estimated at the few to several cm level
- As GPS system and data analysis evolves, cm-level orbit accuracy can be validated only with SLR tracking to GPS satellites (assuming precise center-of-mass and LRA phase center knowledge)

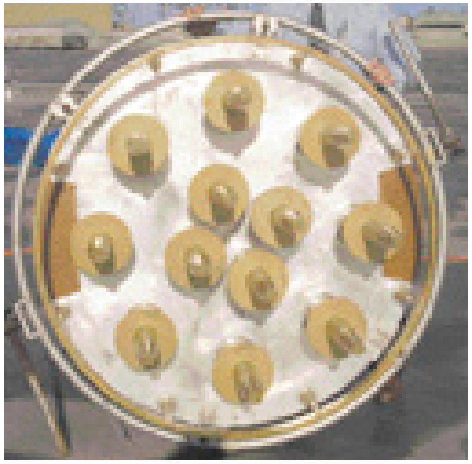


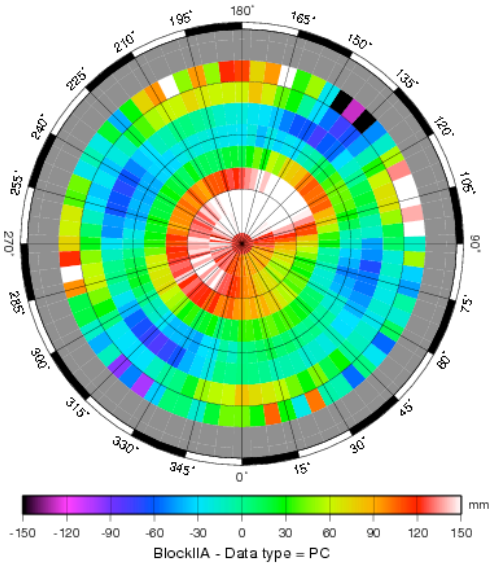
- Progress towards closure of SLR bias for GPS orbits as force modeling has improved demonstrates the value of an independent means of orbit accuracy assessment

GPS Issues - Phase center / Orientation

- Considerable effort ongoing to improve GPS transmit antenna phase center models; knowing precisely the orbit accuracy and center-of-mass offset is an essential part of this analysis

- Laser ranging is sufficiently precise (and accurate) to discriminate if the spacecraft orientation or center-of-mass offset modeling is incorrect





GPS Issues - Phase center

- This technique was applied to the Jason-1 altimeter satellite
- We were able to adopt a more accurate CoM correction for Jason-1 based on SLR analysis
- The correction in the Z direction indicated by GPS was incorrect (now known to be due to GPS phase center errors discussed in previous slide)

Estimated correction to Jason-1 center-of-mass from analysis of GPS and SLR residuals (Fall AGU, 2002)

	Delta-X (mm)	Delta-Z (mm)
JPL GPS	-15	-43
CSR GPS	-13	-34
NASA GPS	-15	-40
GPS average	-14	-39
NASA SLR	-13	3

Conclusions: SLR on GPS can…

- Provide ‘co-location in space’ to provide a direct tie between the SLR and GPS techniques to increase the robustness of the reference frame determination
- Provide quality assurance of GPS orbits and help verify spacecraft orientation and antenna phase center models
- Help resolve issues of absolute scale, but very good center-of-mass knowledge is critical
- Help compare and calibrate reference frames determined by other GNSS systems with retro-reflectors (GLONASS and Galileo)
- Facilitate the continued utility of GPS for advanced science and civil applications; there are undoubtedly applications we have not even thought of

Laser station coordinates for Precision Orbit Determination consistent with ITRF2005 (LPOD2005)

or

An Idiot's Guide to Processing SLR

Processing SLR is not Easy

- SLR, because it attempts to be a precise and accurate measure of absolute range, requires a considerable care to achieve the best results
- Those of us in the SLR analysis working group have a long history of tracking the large and small problems (there are many), and so have built our systems to accommodate them.
- New users of SLR data, however, do not necessarily have a clear description of all the problems and issues that need to be addressed.
- For example, a problem encountered for the altimeter satellite orbit determination (Topex/Poseidon, Jason-1 and Jason-2) was the lack of a clear consensus on what the modeling for the DORIS and SLR coordinates should be.
- This led to the development of DPOD2000 (based on ITRF2000) and later, DPOD2005 (based on ITRF2005), and now also LPOD2005 for laser tracking

New Reference Frame: ITRF2005

LAGEOS-1/2 SLR residual RMS for 1992-2005 using 60-day arcs*, GGM02C, Mendes/Pavlis refraction model, 17-station 'core' network

	ITRF2000	ITF2005	ITRF2005 (scaled)
SLR RMS (mm)	**13.3 / 12.5**	**12.6 /12.3**	**12.0 / 11.4**
Variance Decrease (mm^2)	**-**	**18 / 5**	**33 / 26**
SLR Mean (mm)	**1**	**3**	**<1**
YARAG Mean (mm)	**3**	**6**	**<1**

* 60-day arcs used for geocenter estimation

Performance for Jason-1

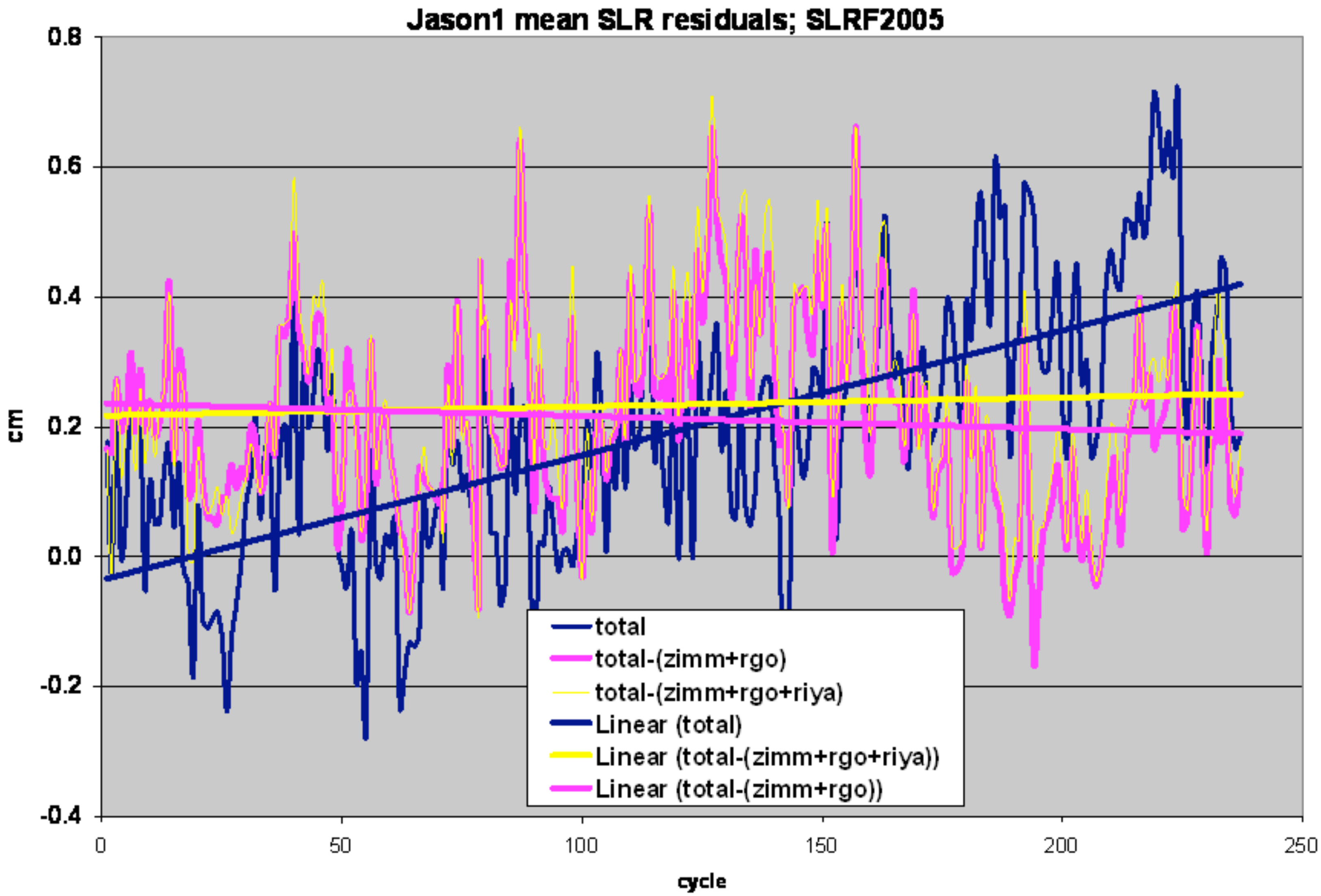
Average over Cycles 1-90, EIGEN-GL04C gravity model

	ITRF2000	ITF2005	ITRF2005 (scaled -1.2 ppb,
SLR RMS (mm)	**15.5**	**15.7**	**15.4**
SLR mean (mm)	**<1**	**3.5**	**<1**
DORIS RMS (mm/s)	**0.354**	**0.352**	**0.351**
DORIS mean station height error (mm)	**4**	**3**	**2**
Alt. crossover Mean/RMS (mm)	**-1.4 / 59.0**	**-1.4 / 59.0**	**-1.4 / 59.0**

However, looking at data in 2008, degraded performance observed in 2008 for important sites such as Zimmerwald, Ajaccio, RGO, Arequipa

From F. Lemoine et al., OSTST meeting 10-12 Nov 2008)

SLR Mean Residuals with SLRF2005



Rationale for LPOD2005

- Need reference set of laser ranging station coordinates for POD for T/P and Jason-1 reprocessing, as well as for Jason-2
  - Must be good enough for high-precision orbit determination
  - Identify major bias problems and data that should not be used
    - Example: RGO (12 mm bias starting 2/10/07}
    - Example; Arequipa (do not use data between 6/23/01-3/24/02)
- Like DPOD2005 for DORIS, LPOD2005 based on ITRF2005
  - Starts with SLRF2005 (ITRF2005+ITRF2000+new stations)
  - Proposse alternative coordinates where tests reveal problems
    - Example: use Arequipa velocity from GPS for DORIS and SLR
- **Not intended to be cutting-edge SLR analysis; only 'good enough' for robust SLR-based POD**

Current (V14) and all past versions of LPOD2005 available at
ftp://ftp.csr.utexas.edu/pub/jason/models/coords

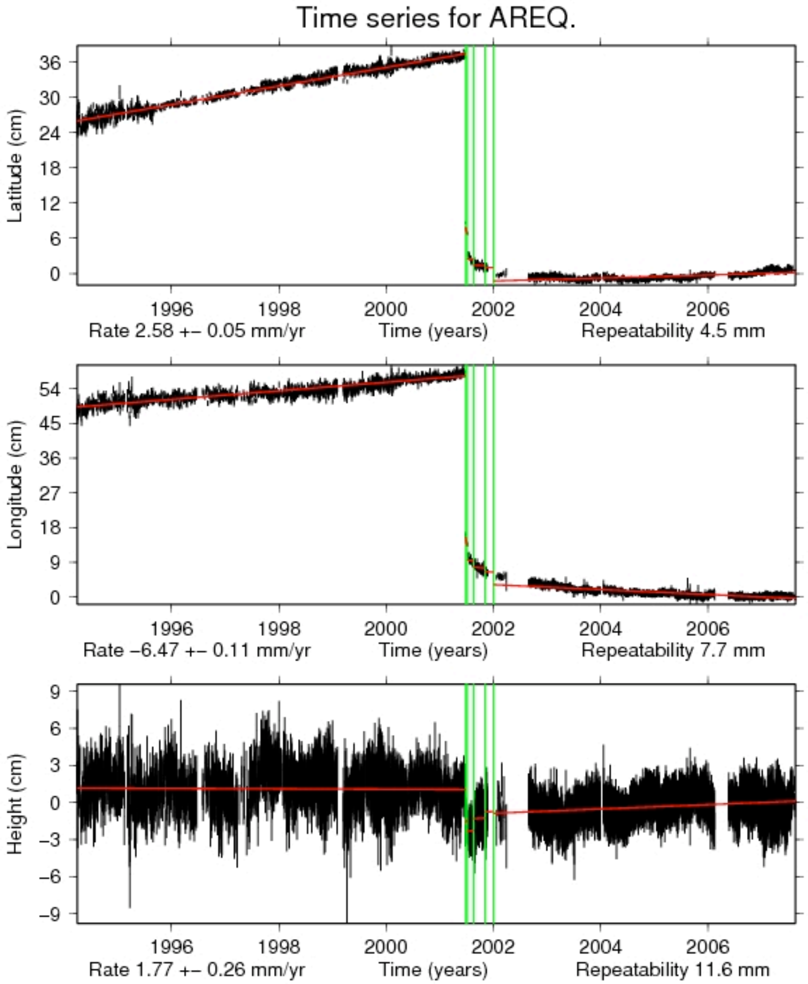
Example: Arequipa (7403)

- Use GPS velocity after earthquake and post-seismic deformation
- Appears to stabilize to near-linear motion around March 2002
  - Data between July 21, 2001 and ~March 24, 2002 should not be used (or downweight…a lot)
- Following DPOD2005, use two linear velocity segments to represent motion after March 24, 2002

See http://www.ipgp.jussieu.fr/~willis/DPOD2005.htm

- Estimate separate SLR positions consistent with velocity

http://sideshow.jpl.nasa.gov/mbh/all/AREQ.html

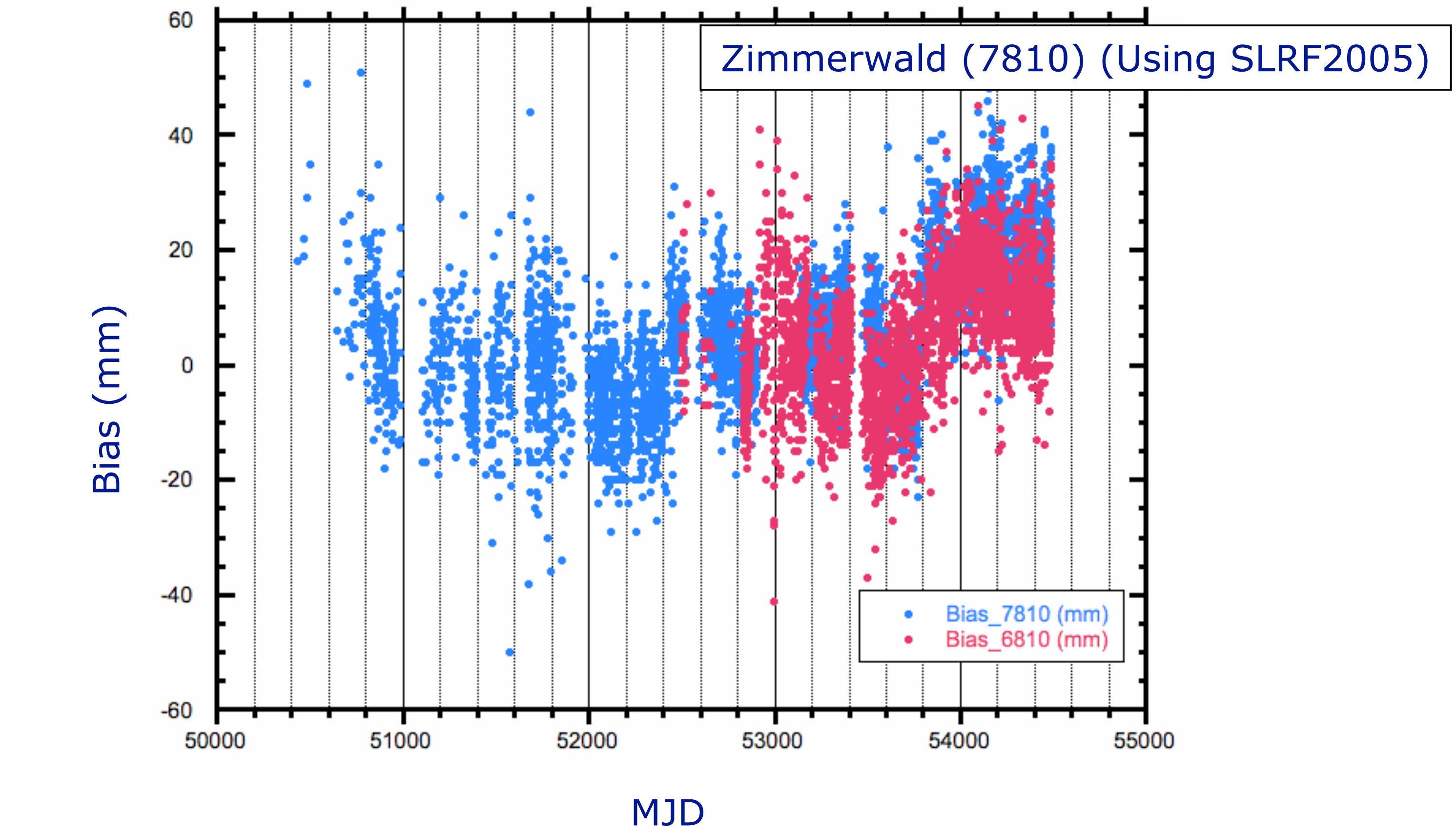


Other Examples

- Riyadh (7832)
  - Vertical velocity seems too large in ITRF2005/SLRF2005 (bias issues?)
  - Shows up more clearly when extrapolated to recent epochs
  - Used previous velocity (ASI) and re-estimated position
- San Juan (7406)
  - Updated velocity from ASI based on more data; re-adjusted position
  - Data editing: exclude all data prior to May 5, 2006
- Ajaccio (7848)
  - Poor fits with ITRF2005 (5.5 cm vs 1.5 from previous coordinates)
  - Velocity taken from previous ASI estimate; position re-estimated (< 1 cm)
  - Used over 500 passes of Starlette data (little LAGEOS data to work with)
- Burnie (7370)
  - New station; preliminary position from Starlette (over 200 passes)
  - Plate model velocity may not be accurate but should hold up till next TRF
  - 1.5 cm performance on LAGEOS-1 for few passes available

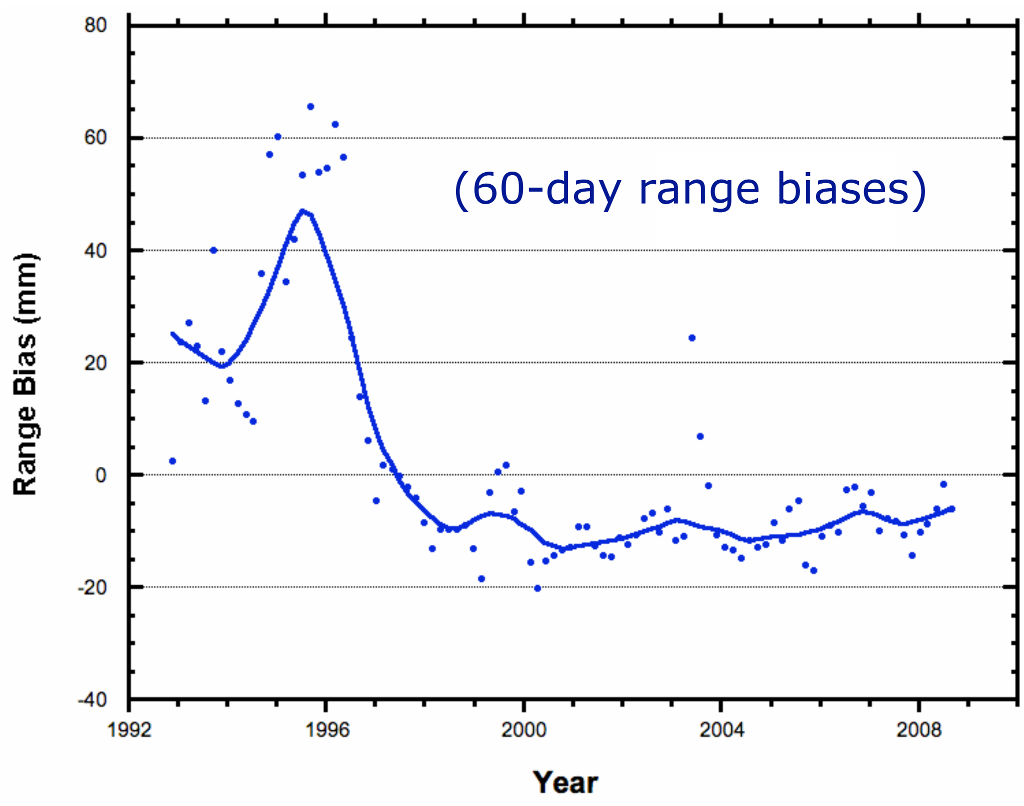
Bias Issues Affecting Coordinates

- Zimmerwald (7810)
  - Bias history affected ITRF2005 position estimate
  - Adopted ILRS AWG bias model and readjusted position; results good



Bias Issues (cont.)

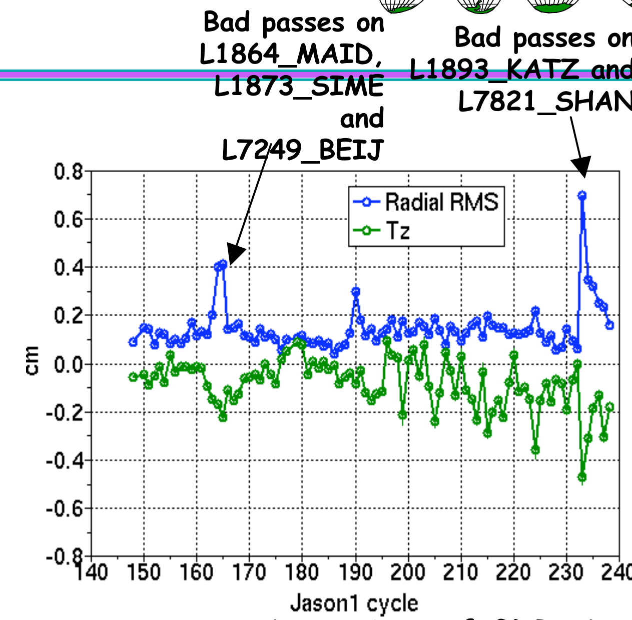
- Wettzel (8834) new in Version 11
  - Bias problems throughout data span affected velocity estimate
  - Adopted approximate bias model and VLBI velocity; readjusted position (9-10 mm performance in 2008 for LAGEOS-1/2)
  - However, recommend routinely estimating bias (arc-by-arc) for all data (biases for L1/L2 differ from Starlette/Stella by 7-10 mm)



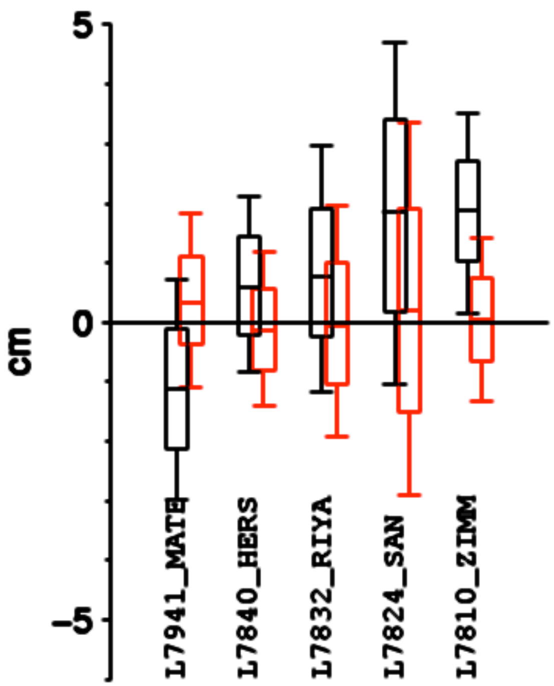
From Cerri et al., OSTST meeting 10-12 Nov 2008)

Known problems – SLRF2005

- The LPOD2005 solution is now available and corrects biases/coordinates of some important stations
- Test performed on Jason-1 cycles 138-239, with fixed station biases

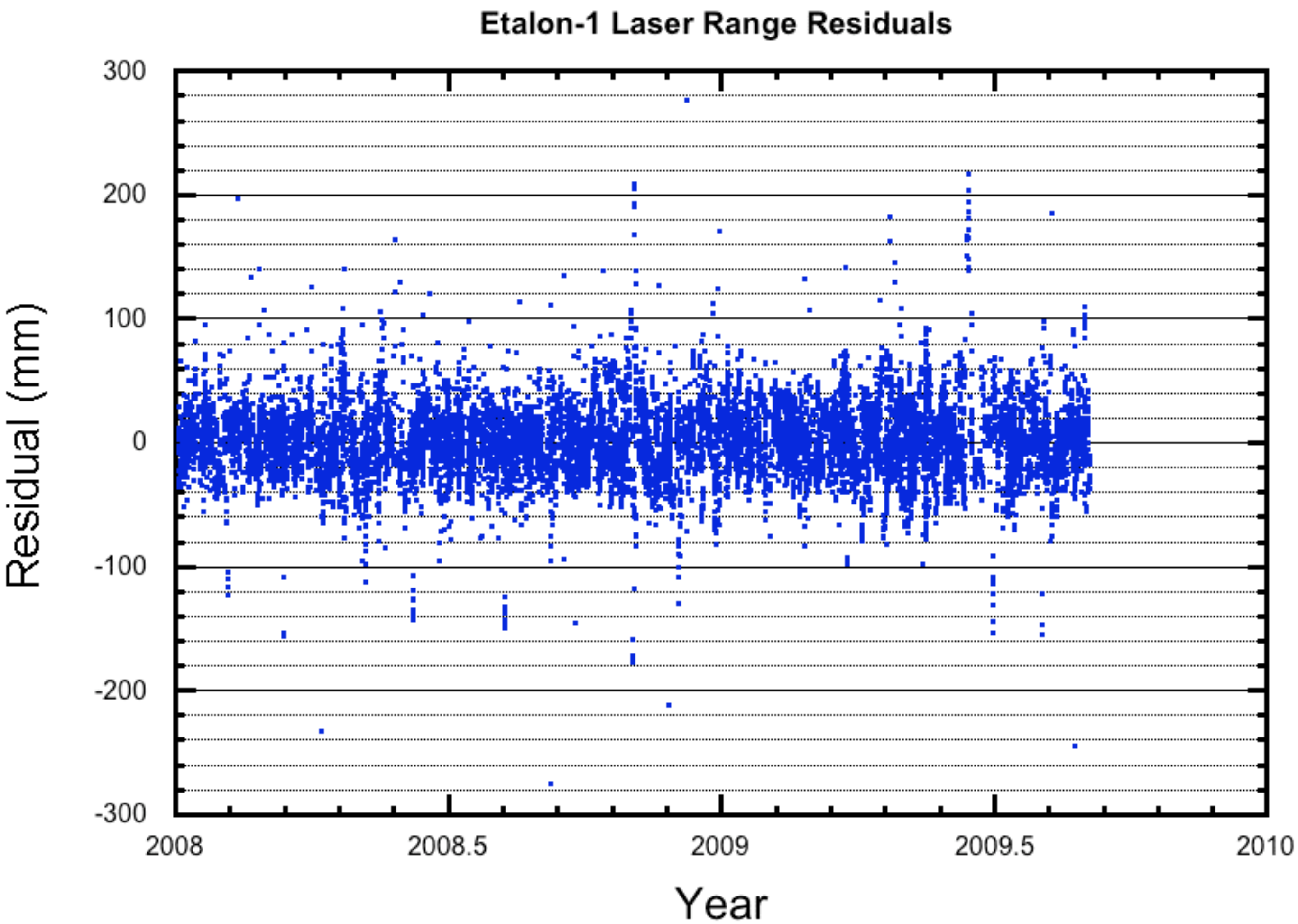


Comparison of GDR-C reprocessed orbits wrt LPOD05 test orbits



- The impact is small but not negligible
  - Bias on some stations was solved for on GDRC orbit and compensated for SLRF05 errors (ex. 7810ZIMM)
  - Biases should still be solved for some stations
- The operational POE will switch soon to LPOD2005

Etalon-1 SLR Residuals using LPOD2005



SLR residuals for 2008-2009 after editing

RMS: 26 mm

Mean: 0.5 mm

Precision: 4-12 mm (slightly worse than for lower satellites)

Dynamical modeling was conservative:

28-day arcs
7-day 'drag'
14-day 1-cpr

CoM: 576 mm for all sites

Summary

- LPOD2005 attempts to modify SLRF2005 minimally but still provide good SLR-based POD performance
  - Bias issues are an ongoing concern; not a static problem
- Users must still decide on appropriate station weighting and be vigilant in data editing
  - Have confidence in the station coordinates and edit data that is obviously inconsistent
- Feedback encouraged

ftp://ftp.csr.utexas.edu/pub/jason/models/coords