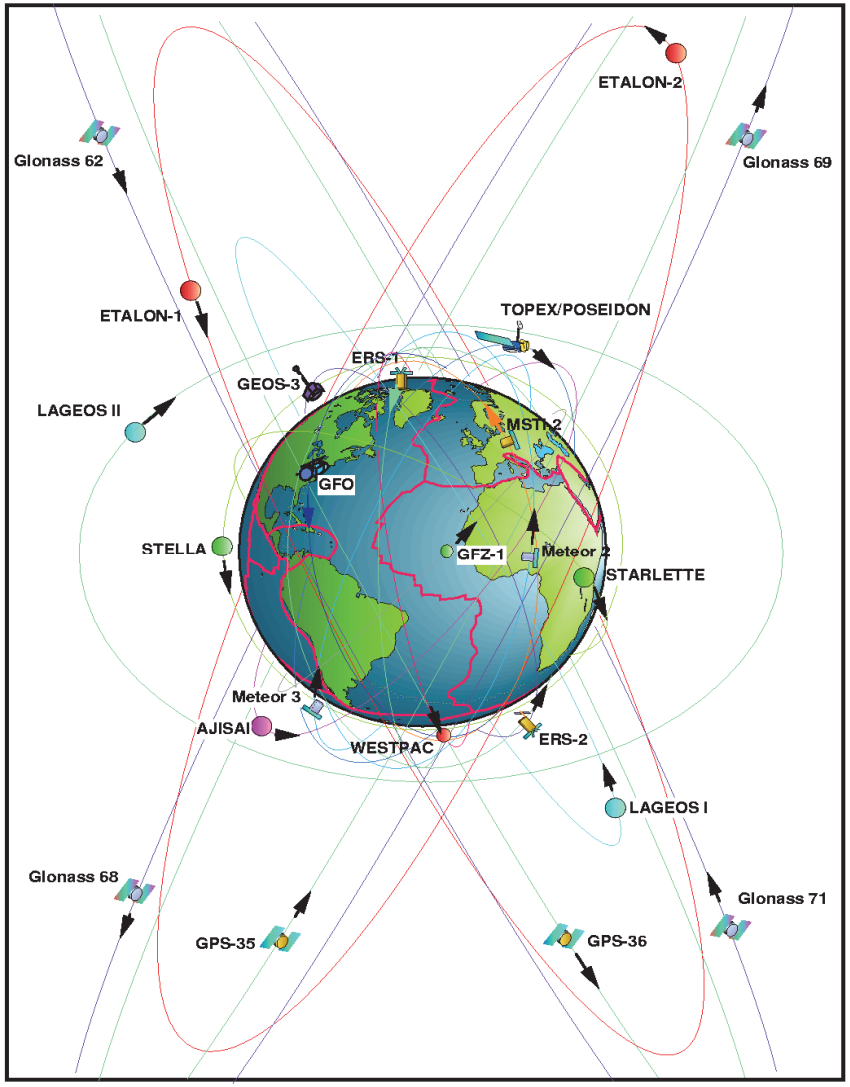
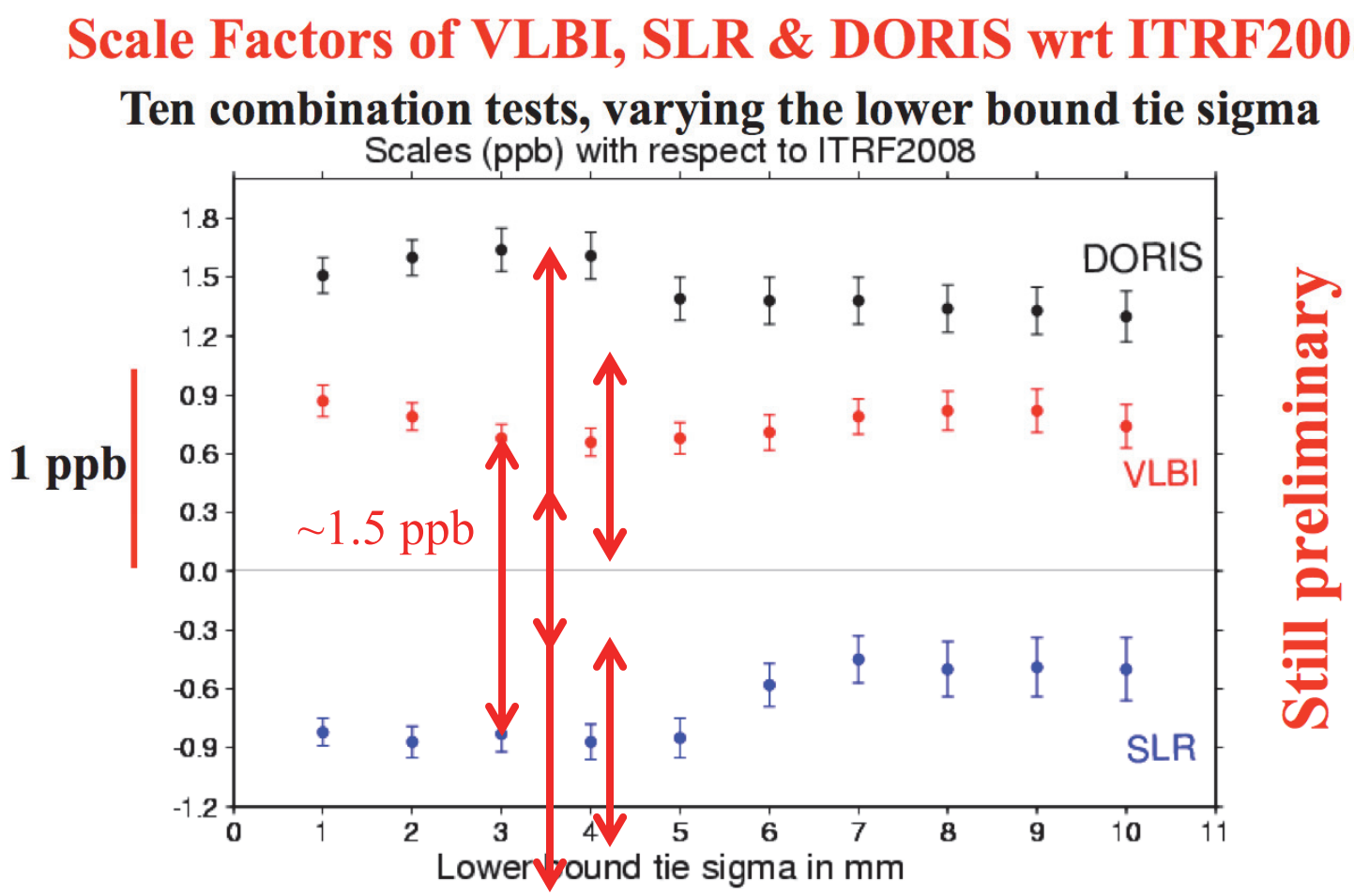
The Scale of the Terrestrial Reference Frame from VLBI and SLR

J. C. Ries
Center for Space Research
The University of Texas at Austin

IERS Unified Analysis Workshop
Pasadena, CA
27-28 June 2014



Why is there a persistent scale difference between SLR and VLBI?



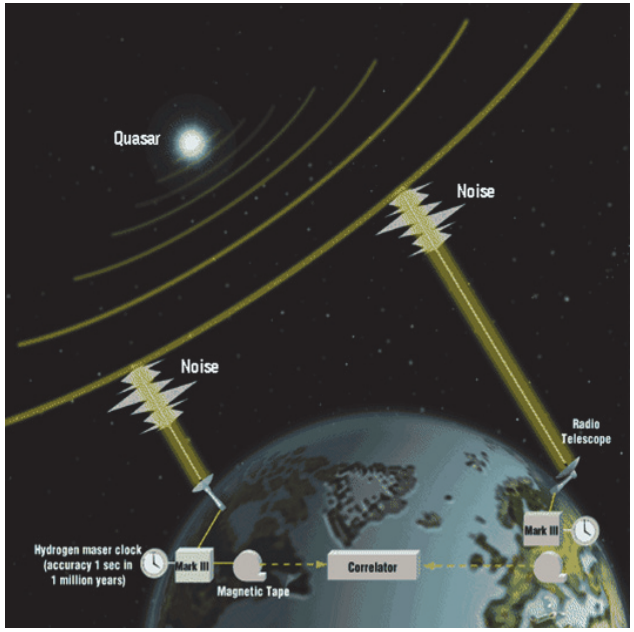
Scale & Terrestrial Reference Frame (VLBI)

- The scale from VLBI is in theory determined only by the speed of light
  - The 'speed of light' depends on a correct modeling of relativity; is the 1991 consensus model correct? (relativistic contribution from Earth's mass to coordinate time transformation is 0.7 ppb)

$$t_{v_2} - t_{v_1} = \frac{\Delta T_{grav} - \frac{\hat{K}\cdot\vec{b}}{c}\left[1 - \frac{(1+\gamma)U}{c^2} - \frac{|\vec{V}_\oplus|^2}{2c^2} - \frac{\vec{V}_\oplus\cdot\vec{w}_2}{c^2}\right] - \frac{\vec{V}_\oplus\cdot\vec{b}}{c^2}(1 + \hat{K}\cdot\vec{V}_\oplus/2c)}{1 + \frac{\hat{K}\cdot(\vec{V}_\oplus+\vec{w}_2)}{c}}$$

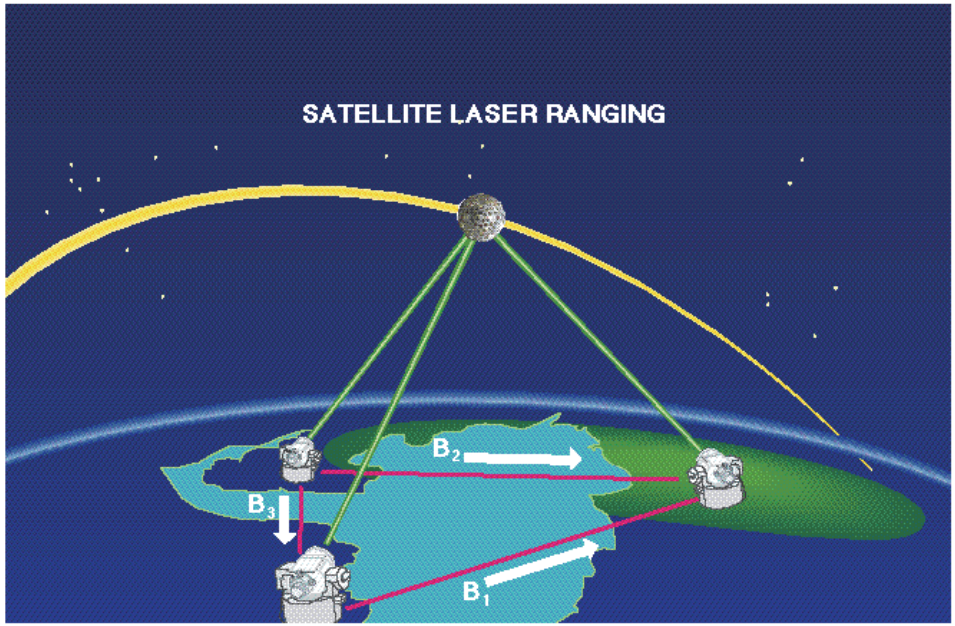
- In practice, troposphere estimation is required for radiometric techniques, which is highly correlated with station height and thus scale
  - What is the uncertainty in the zenith delay estimates? 1 mm, 3 mm…?

- Including gravitational antenna deflection might increase scale disparity further



Scale & Terrestrial Reference Frame (SLR)

- The SLR scale is ultimately determined from the speed of light, orbital dynamics and the LAGEOS center of mass model (➔GM)
- GM is usually held fixed; is the uncertainty in GM a limiting factor in the SLR scale?

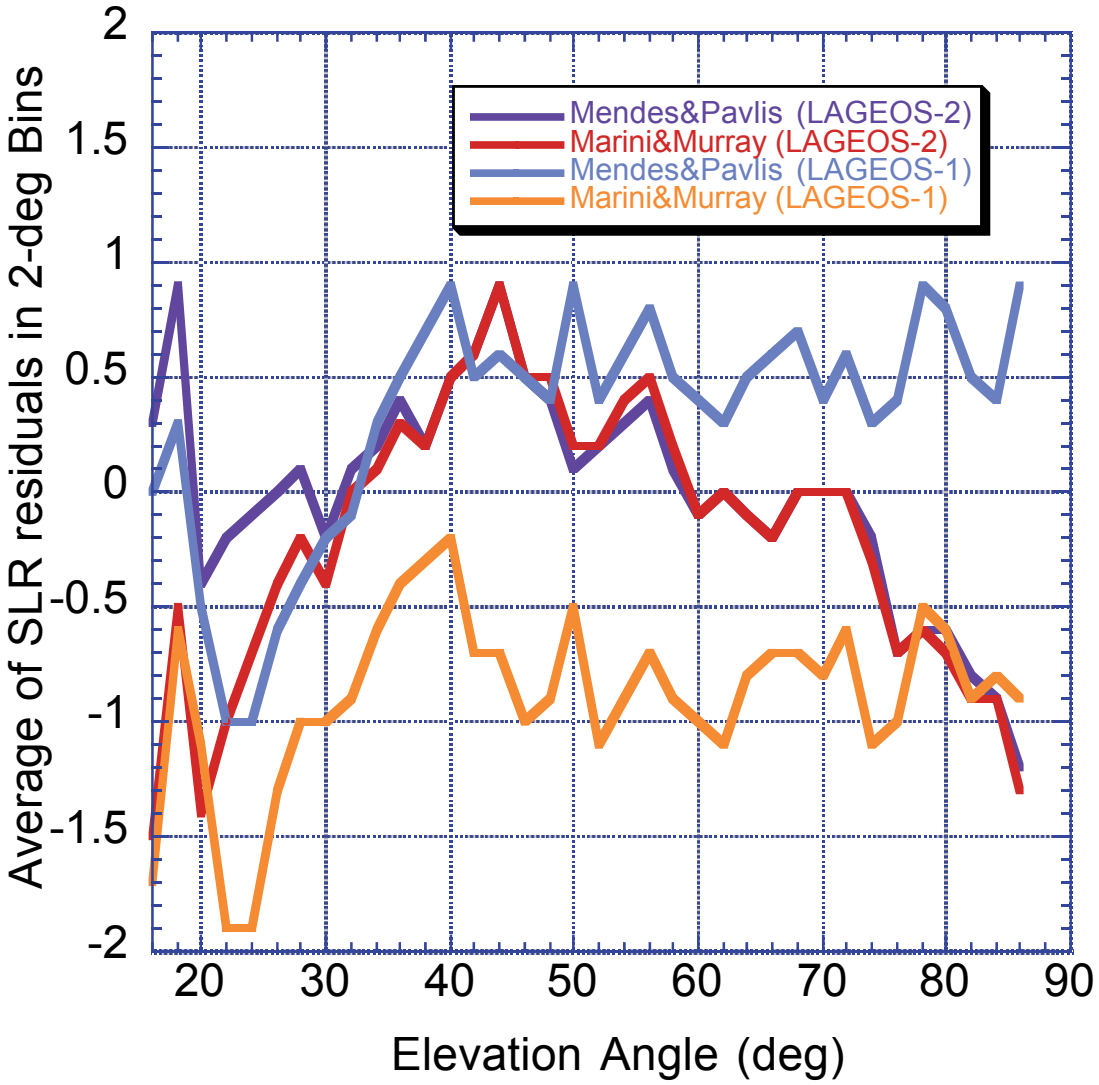


- In 1992, GM estimated using 5 years of LAGEOS-1 data to determine value currently in use (based on CoM = 251 mm)
  - Must simultaneously estimate orbit, GM and all station heights to avoid locking in apriori scale
  - GM = 398600.4415 ± 0.0008 km^3/s^2 (TDT or TT value)
  - Assumed 2 cm biases plus a 'quesstimate' for troposphere error (0.2% or ~4-5 mm in zenith delay)

Can we reduce uncertainty?

- In 2005, looked at updated tropospheric refraction model (Mendes et al., 2002; Mendes & Pavlis, 2004)
- Used 12 years of SLR data from LAGEOS-1 and LAGEOS-2 and considered 1 cm biases for each station (almost certainly pessimistic for better sites)
  - GM = 398600.4415± 0.00016 km^3/s^2 (using M&M refraction)
    - LAGEOS-1/2 differ by only 0.00013 (0.3 ppb), but most systematic errors are common
    - This uncertainty includes only random error (including bias)
- Repeated experiment with new refraction GM = 398600.4416± 0.00016 km^3/s^2 (0.3 ppb change)
  - Change in terrestrial scale was only ~1.5 mm
  - Note that 1 ppb change in GM leads to 0.8 ppm change in TRF scale

SLR Tropospheric Refraction Model Comparison for LAGEOS-1/2



All accepted SLR data for LAGEOS-1 and LAGEOS-2 since late 1992 (launch of L-2)

Residuals in 2 deg elevation bins, computing weighted average (only bins with > 1000 pts; most have 20000 to 30000 pts)

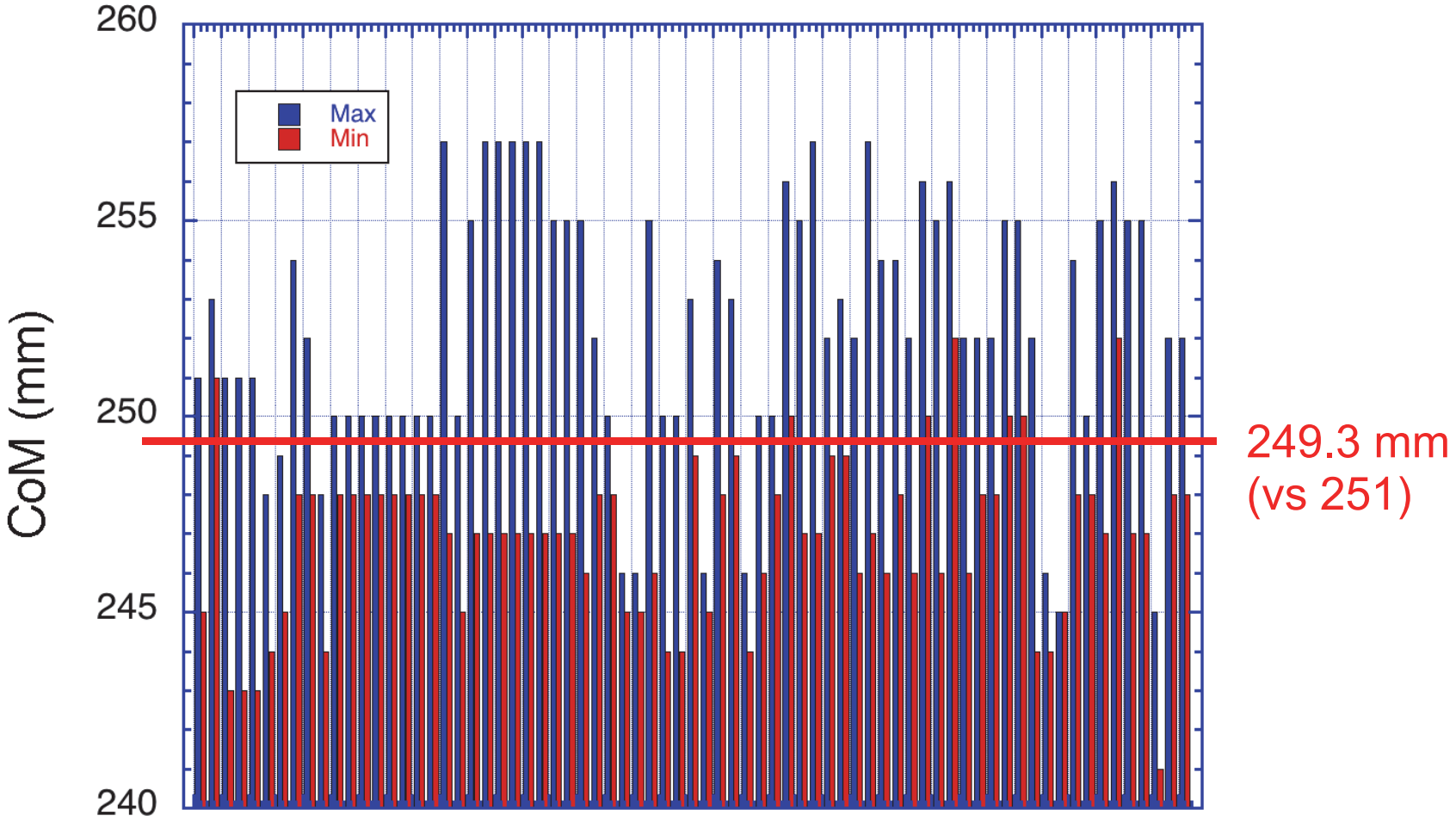
Significant variance reduction for Lageos-1 residuals

No change for Lageos-2

GM estimation from SLR (total error estimate)

- Assuming that errors in M&P are below the 1-mm level (zenith delay), contribution to GM error estimate appears to be small
- Consider contribution to error estimate from CoM model errors
  - It is easy to demonstrate that each 3 mm of CoM error leads to 1 ppb error in GM (for LAGEOS…differs by satellite altitude)
  - At the time, ~4 mm in the CoM uncertainty seemed reasonable, if not a bit pessimistic
- Total uncertainty estimate for GM is thus dominated by CoM uncertainties
  - GM = 398600.4416 ± 0.0004 km^3/s^2 (adopting M&P model)
  - Change was too small to justify changing GM, though the uncertainty could be reduced from 2 ppb to 1 ppb
- With 20 years of LAGEOS data and in light of new modeling for LAGEOS CoM, how is the estimate of GM affected? Can the uncertainty be further reduced?

Station Dependent CoM model



- GM = 398600.4417 (standard CoM) vs 398600.4416 (new CoM)
  - Uncertainty ~0.0002 (0.5 ppb) assuming 2 mm uncertainty for CoM

Conclusions (1)

- Any determination of GM must include consideration of all systematic errors
  - All parameters (orbit, GM,and station heights) need to be free to adjust to avoid building in apriori scale
  - Troposphere refraction model error seems to be small
  - Center of mass offset model uncertainty dominates
- Using 20 years of L1/L2 data and allowing for the possibility of a persistent range bias of up to 5 mm in every station (probably still pessimistic for best stations), we get
  - Standard CoM: 398600.4417 ± 0.0003 km^3/s^2
  - Station-dependent CoM: 398600.4416 ± 0.0002 km^3/s^2
    - Assumes ~2 mm uncertainty in new CoM model; assuming 1 mm uncertainty might be overly optimistic (at this level, effect of possible biases becomes comparable)

Conclusions (2)

- New estimate of GM would increase scale of SLR by only ~0.2 ppb (and scale uncertainty due to GM is reduced to ~0.4 ppb)
  - Other effects must be contributing to ~1.5 ppm disparity between VLBI and SLR
- Scale offset between VLBI and SLR has persisted in spite of considerable improvements in data and analysis
  - Should re-examine VLBI consensus model (now 23 years old) to see if some small term has been overlooked
  - Concerned about effect of adding model for gravitational deflection (possibly increasing scale disparity)
  - SLR scale does not seem to be significantly biased due to GM error; can SLR analysis be improved in some other way?