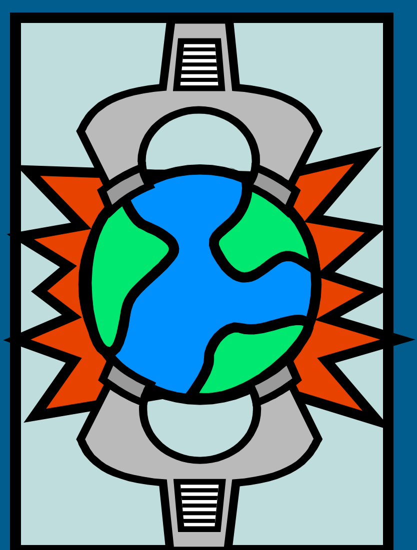
Relationships between mass redistribution, station position, geocenter, and Earth rotation: Results from IGS GNAAC analysis



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Introduction

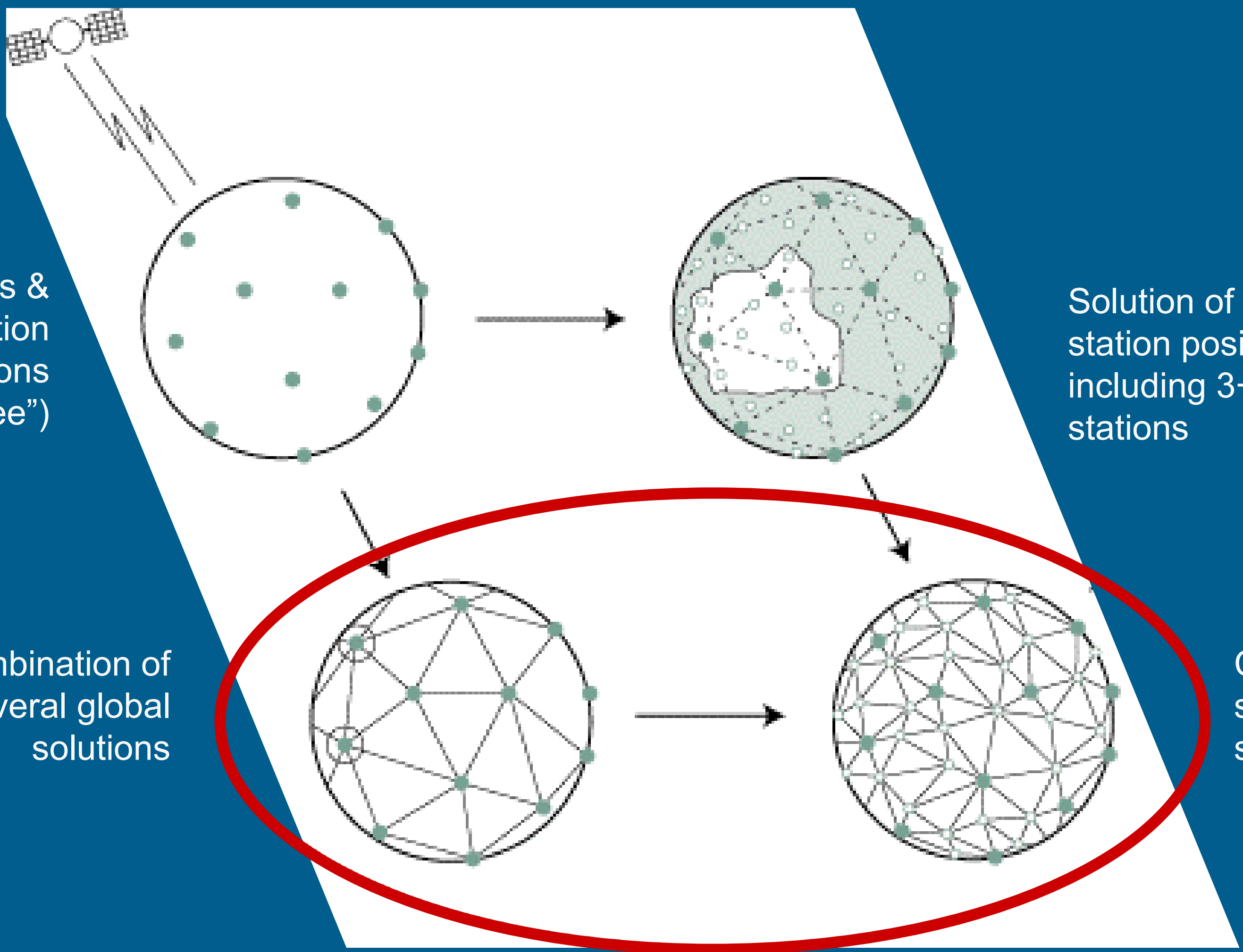
- **"Three Pillars of Geodesy"**
  1. **Earth's geometric shape**
  2. **Earth's gravity field**
  3. **Earth's orientation in space**

- All are connected by Earth's response to mass redistribution
  - Earth's shape dominated by surface mass loading (0.1-10 yr)
- Effects of (seasonal) loading:
  - (Seasonal) variation in IGS station coordinate time series
  - Degree-0: *apparent* (seasonal) scale in IGS network
    - *biased* Helmert transformations, hence *frame-related errors*
  - Degree-1: *real* (seasonal) motion of solid Earth center of mass
    - several mm common-mode signal in GPS coordinate time series
    - theory predicts that this is not simply a translation
  - Degree-2: *real* (seasonal) polar motion from moment of inertia

IGS GNAAC analysis since 1995: polyhedron construction (weekly)

Solution of orbits & global station positions ("fiducial-free")

Solution of regional station positions including 3+ global stations

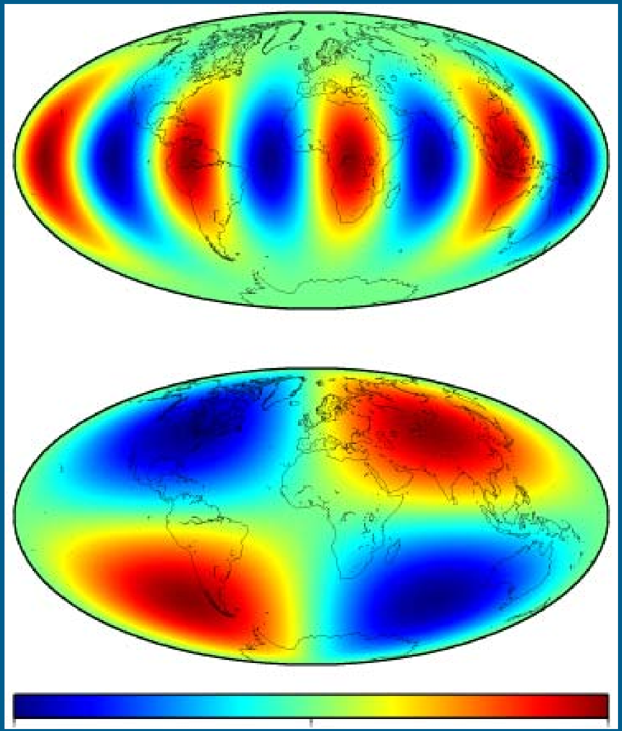


Combination of several global solutions

Combination of several regional solutions

Physical Love-Shida model

- Earth deformation & geoid height all depend on surface mass distribution by load Love numbers (LLNs) within spherical harmonic expansions
  - Total load $$T(\Omega) = \sum_{n,m,\Phi} T_{nm}^{\Phi} Y_{nm}^{\Phi}(\Omega)$$
  - Height $$H(\Omega) = \sum_{n,m,\Phi} h'_n \frac{3\rho_S}{(2n+1)\rho_E} T_{nm}^{\Phi} Y_{nm}^{\Phi}(\Omega)$$
  - 2-D Lateral $$\mathbf{L}(\Omega) = \sum_{n,m,\Phi} l'_n \frac{3\rho_S}{(2n+1)\rho_E} T_{nm}^{\Phi} \nabla Y_{nm}^{\Phi}(\Omega)$$
  - Geoid $$N(\Omega) = \sum_{n,m,\Phi} (1 + k'_n) \frac{3\rho_S}{(2n+1)\rho_E} T_{nm}^{\Phi} Y_{nm}^{\Phi}(\Omega)$$



Load to degree 6 (GPS & Model)

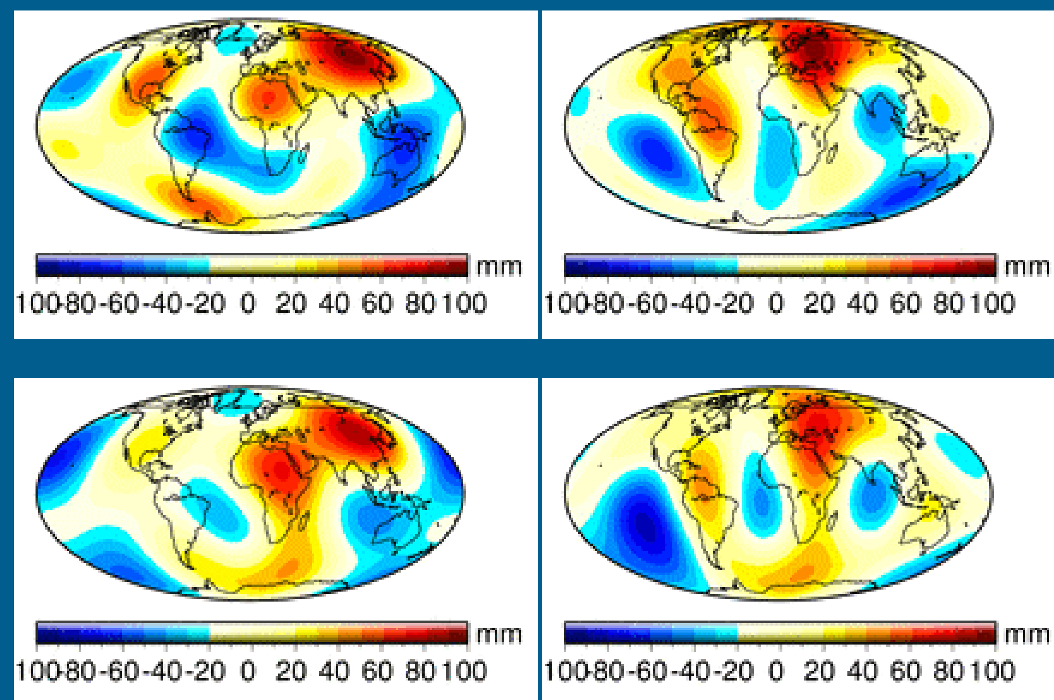
Water-equivalent depth of load (mm)

Estimated Load

- GPS

Modeled Load

- Soil moisture, snow depth: Milly et al.
- Atmosphere: NCEP/NCAR reanalysis + inverted barometer
- Ocean circulation: ECCO



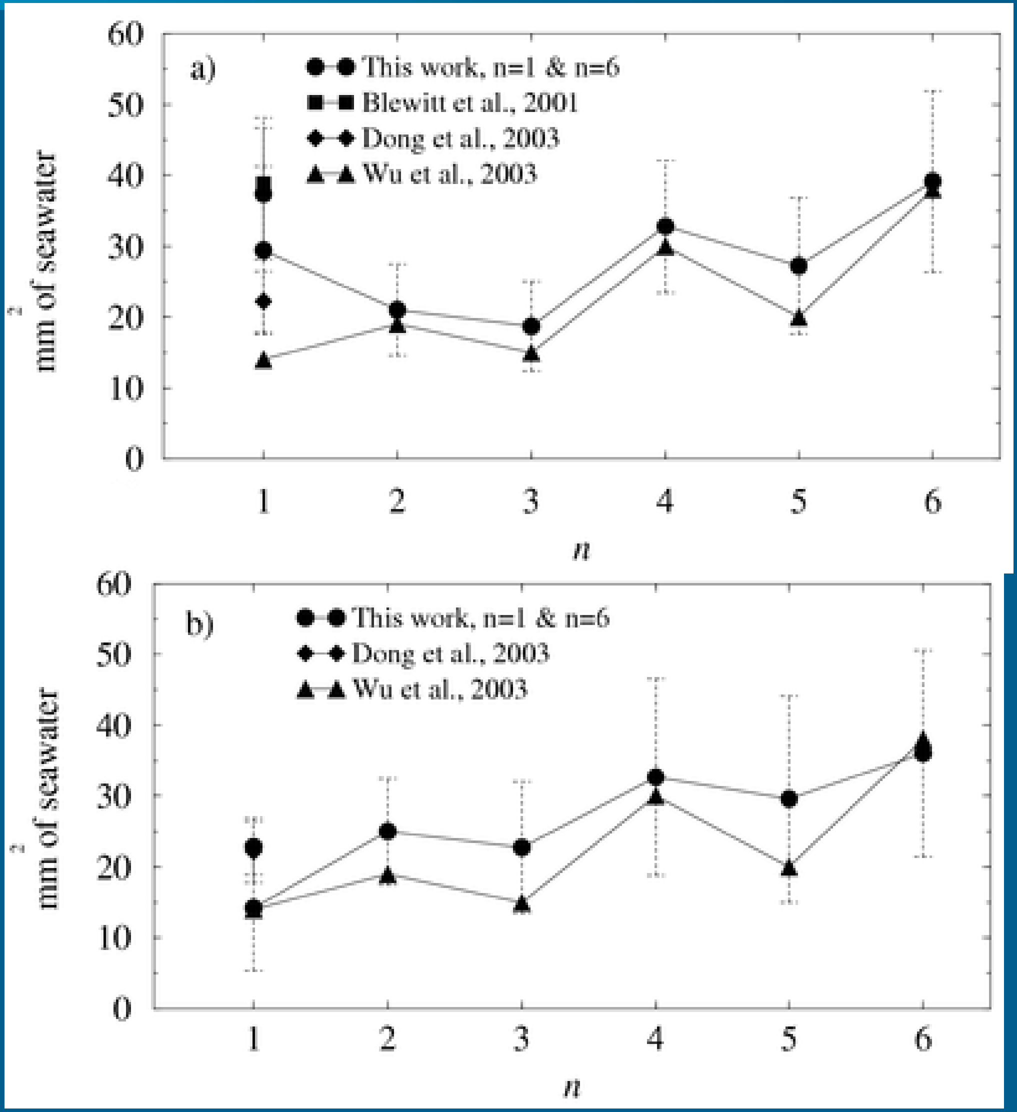
Annual Cosine **Annual Sine**

Deg-0: Total mass

- Conservation of surface mass implies
  - degree-0 load = 0
  - average change in Earth radius = 0
- Problem of network scale
  - Scale change = degree-0 deformation
  - …and GPS scale is defined by the speed of light
  - Therefore variation in network scale ought to be **zero**
  - But scale often used in 7 or 14-parameter transformation
  - So why include scale in Helmert transformations?
    - to remove systematic error in orbit models, etc.?
    - or (incorrectly), to remove apparent scale due to real loading signals that are aliased by the non-uniform IGS network?
    - can lead to frame errors and can bias the load signal

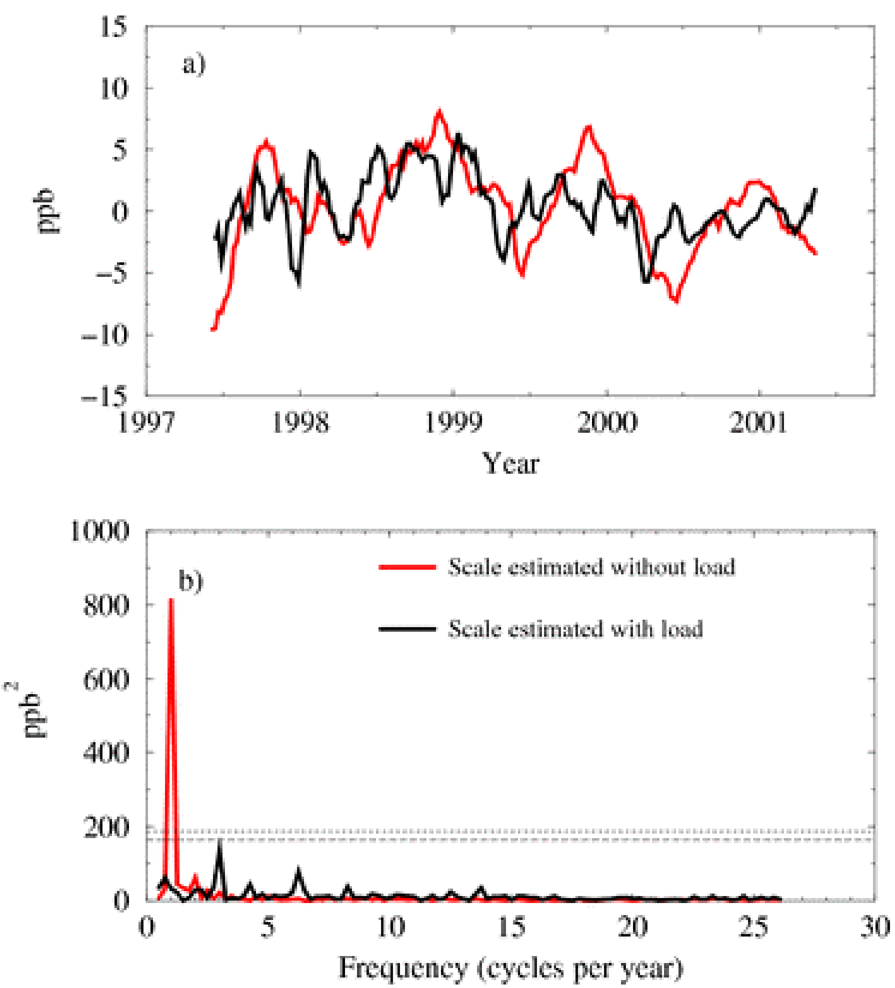
Effect of removing scale on load

- Top plot
  - Two step estimation - remove scale parameter
    - Dong et al., 2003, n=1
    - Wu et al, 2003, n=6
  - One step estimation – **No** scale parameter removed
    - Blewitt et al., 2001, n=1
    - This work, n=1, n=6
  - Poor agreement for deg-1
- Bottom plot
  - Two step estimation – Both groups remove scale parameter first
  - Good agreement for deg-1
  - But degree-1 now more sensitive to truncation!



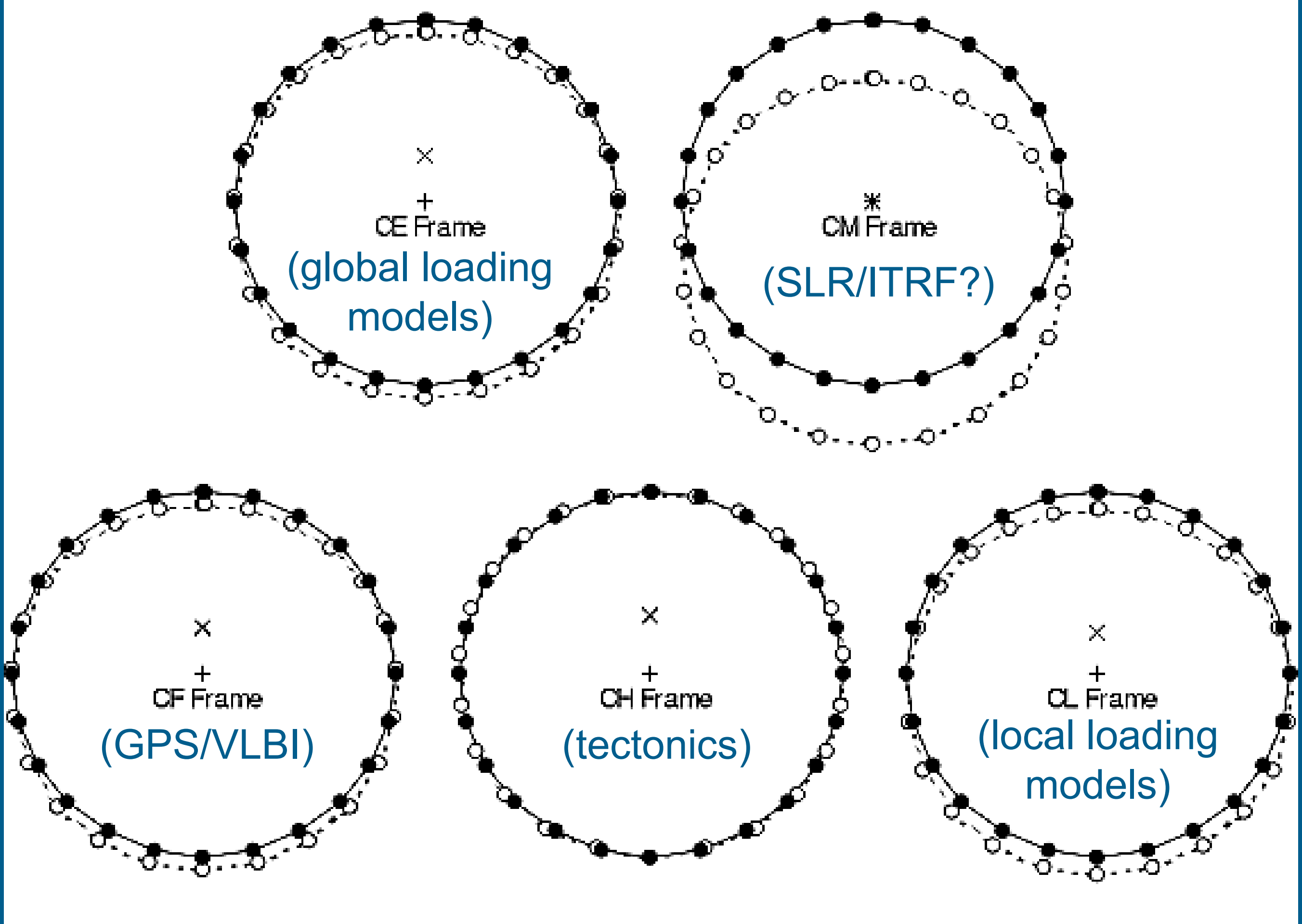
Effect of load estimation on scale

- Estimated scale as part of Helmert transformation has significant (α=0.01) annual signal: 3.2 ppb
- Simultaneous estimation of scale + load coefficients eliminates annual scale signal !
- …and load parameters are unaffected by simultaneous scale estimation!
- **Helmert parameters should be simultaneously estimated with load coefficients !**



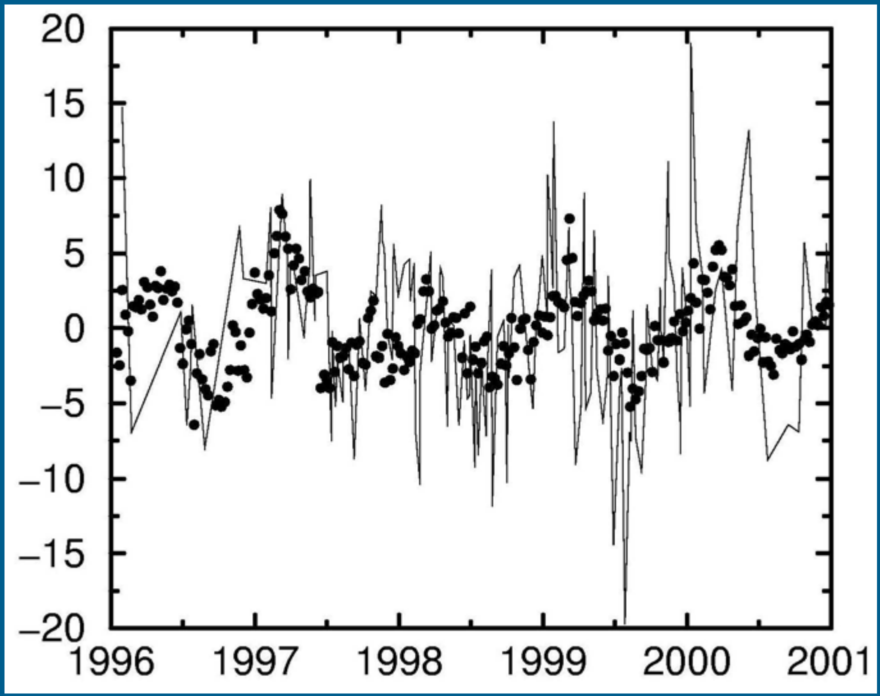
Deg-1: Center of mass & origin

- Degree-1 displacements appear differently in various frames



Deg-1: Independent confirmation

- GPS degree-1 deformation estimated every week
- Used to predict baseline length variations on VLBI baselines *not used in the GPS analysis*
  - Plot shows Westford-Gilcreek baseline
  - Dots from GPS “model”
  - Lines from VLBI observations
  - Correlation significant α=0.0002

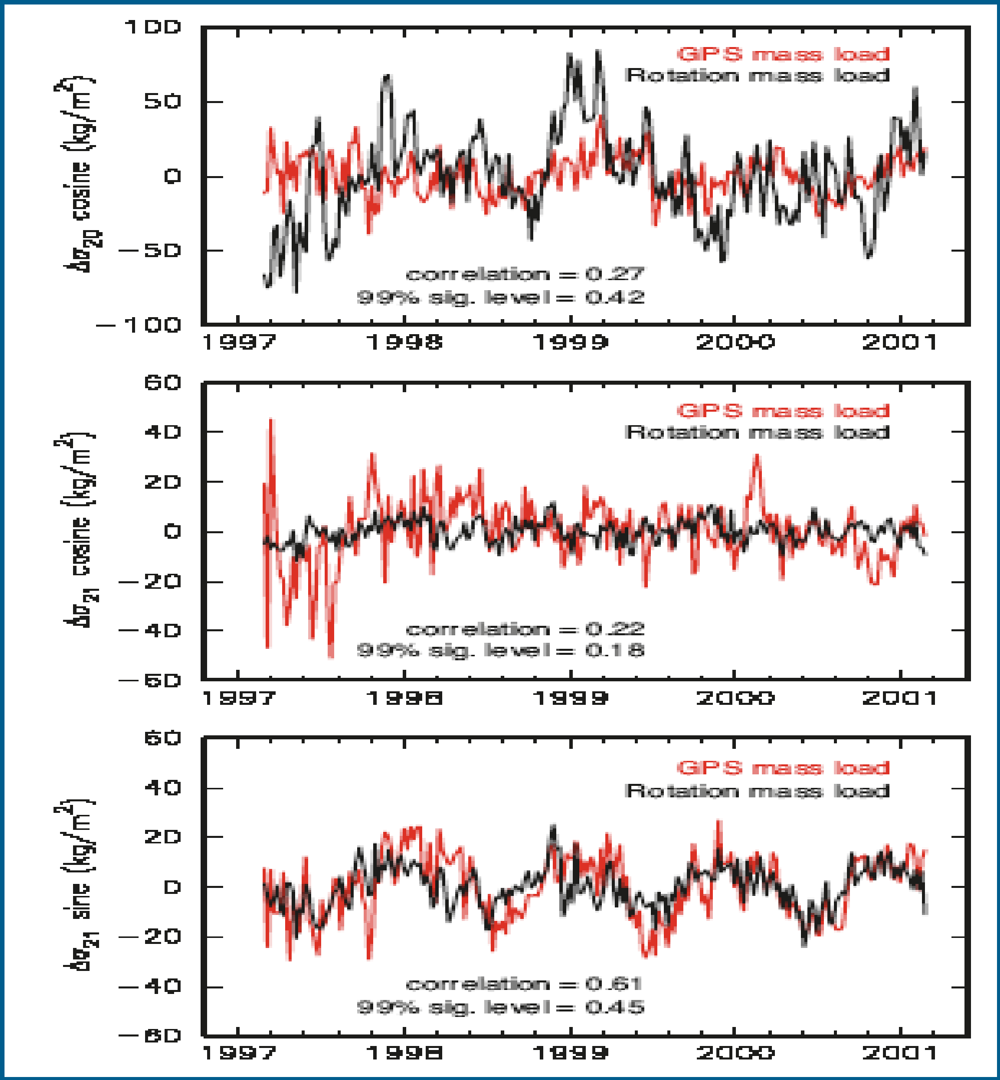


Deg-2: Earth rotation consistency

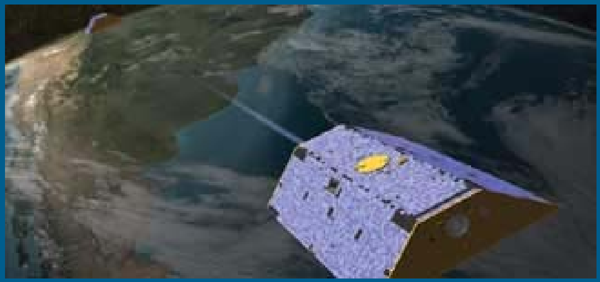
- Angular Momentum of Surface Fluids
  - Motion & Mass: angular velocity & moment of inertia
- Use Earth rotation measurements to test the GPS-inferred mass load
  - Degree-2 coefficients related to Earth's inertia tensor and hence to changes in Earth's rotation
  - Changes in (2,0) mass load coefficient cause length-of-day to change
  - Changes in (2,1) mass load coefficients cause the Earth to wobble as it rotates (excites polar motion)
  - Compare Earth rotation changes predicted by GPS-derived mass load coefficients to observed changes
  - after removing tidal and motion effects (winds and currents) from observed changes

Results: Degree-2 & Earth rotation

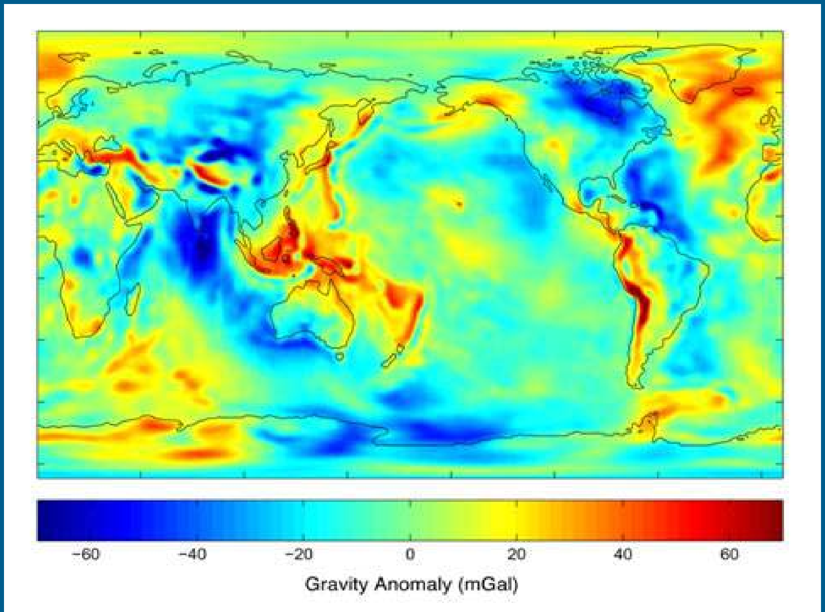
- Poor correlation with LOD excitation residual
  - Motion model error is believed to dominate
  - Mass load series exhibits less variability, is likely to be more accurate
- Significant correlation with polar motion excitation
  - Particularly so for the y-component which has a large seasonal cycle
  - Motion model error is believed to be very small



Consistency with gravity field



- GRACE experiment…
  - Monthly gravity fields, 2002–2007



- and SLR also gives
  - geocenter
  - and low-degree gravity field
- GPS gives
  - geocenter
  - and surface geometry
- Relationship between
  - geometry (surface height)
  - and gravity (geoid height)

$$H_{nm}^{\Phi} = \frac{h_n'}{1+k_n'} N_{nm}^{\Phi}$$

  - Hence invert for LLN ratio with no explicit knowledge of load

Constraints on Earth's elasticity

- GPS degree-1/GPS geocenter:

$$\frac{h_1'}{1+k_1'} = -0.20 \pm 0.01$$

- GPS degree-1/SLR geocenter:

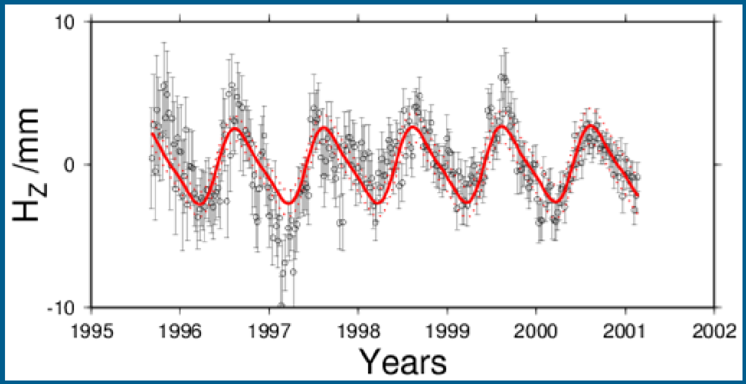
$$\frac{h_1'}{1+k_1'} = -0.21 \pm 0.02$$

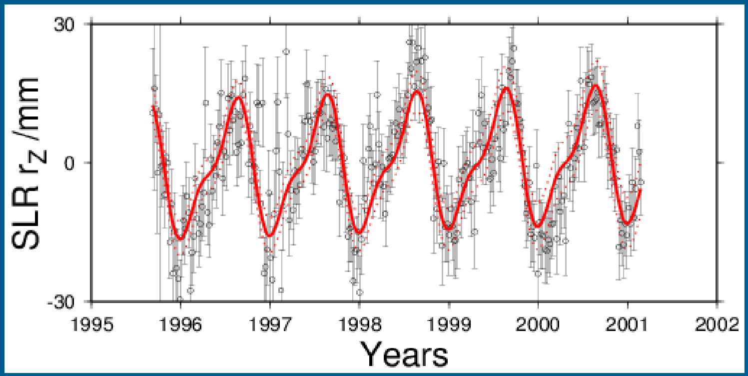
  - Earth Model (PREM): -0.25

- At degree-2:

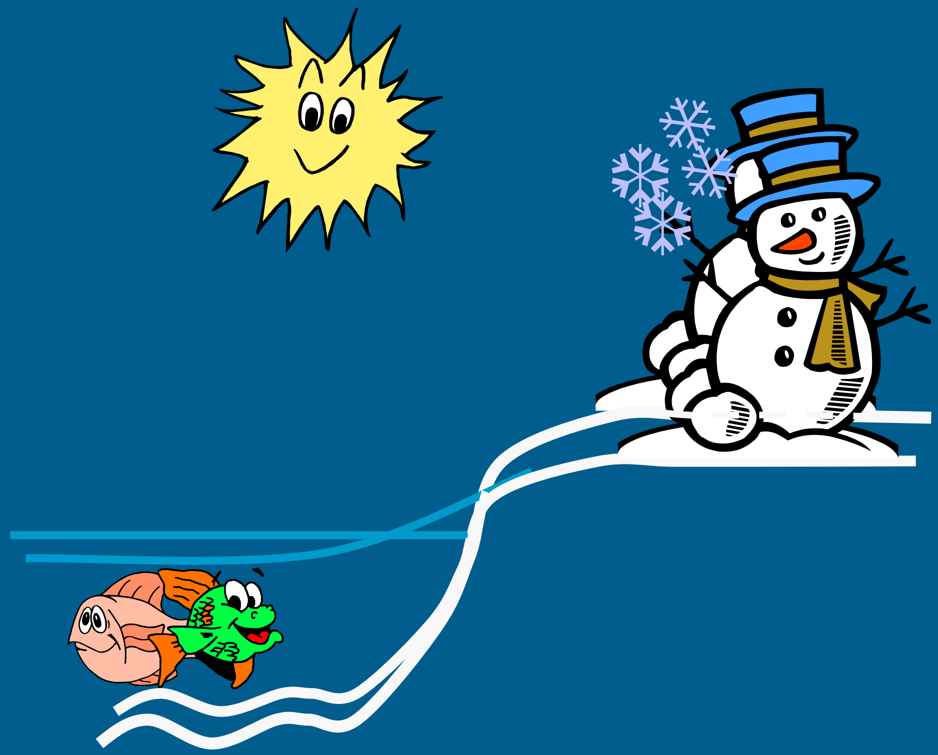
$$\frac{h_2'}{1+k_2'} = -0.81 \pm 0.15$$

  - Earth Model (PREM): -1.4



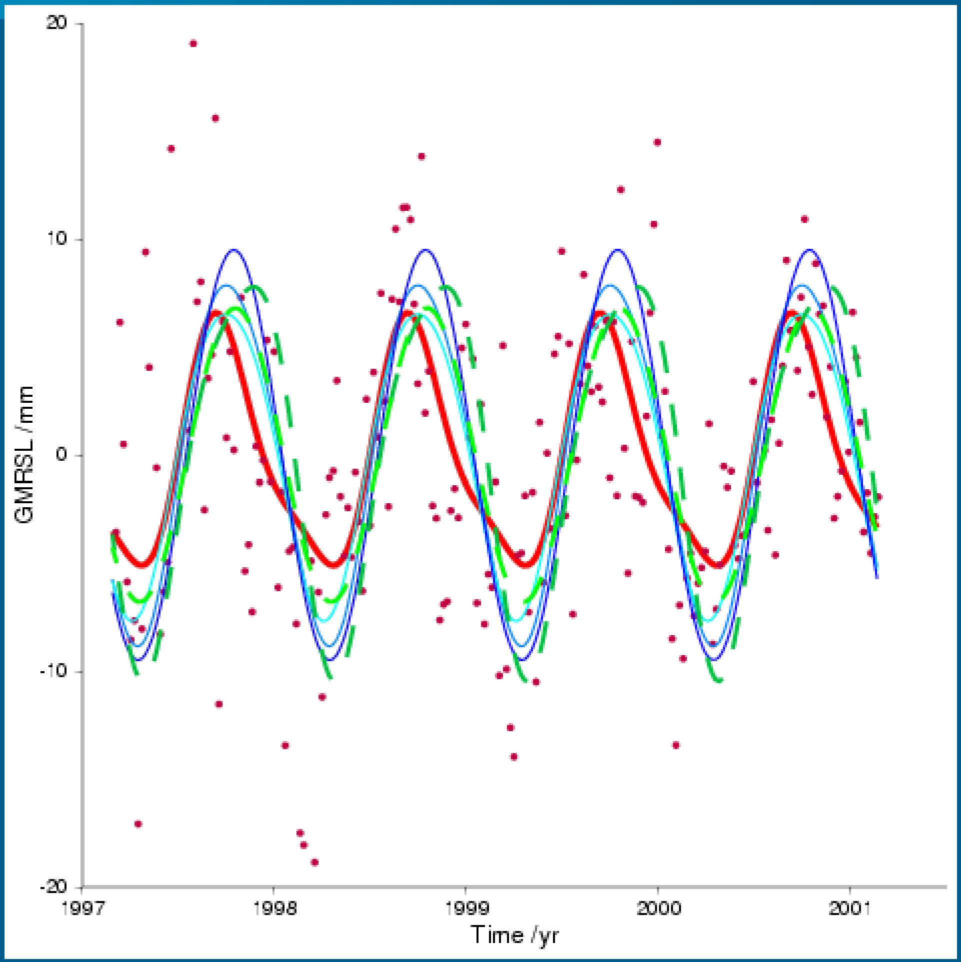


Self-consistent mass redistribution



Non-steric global mean sea level

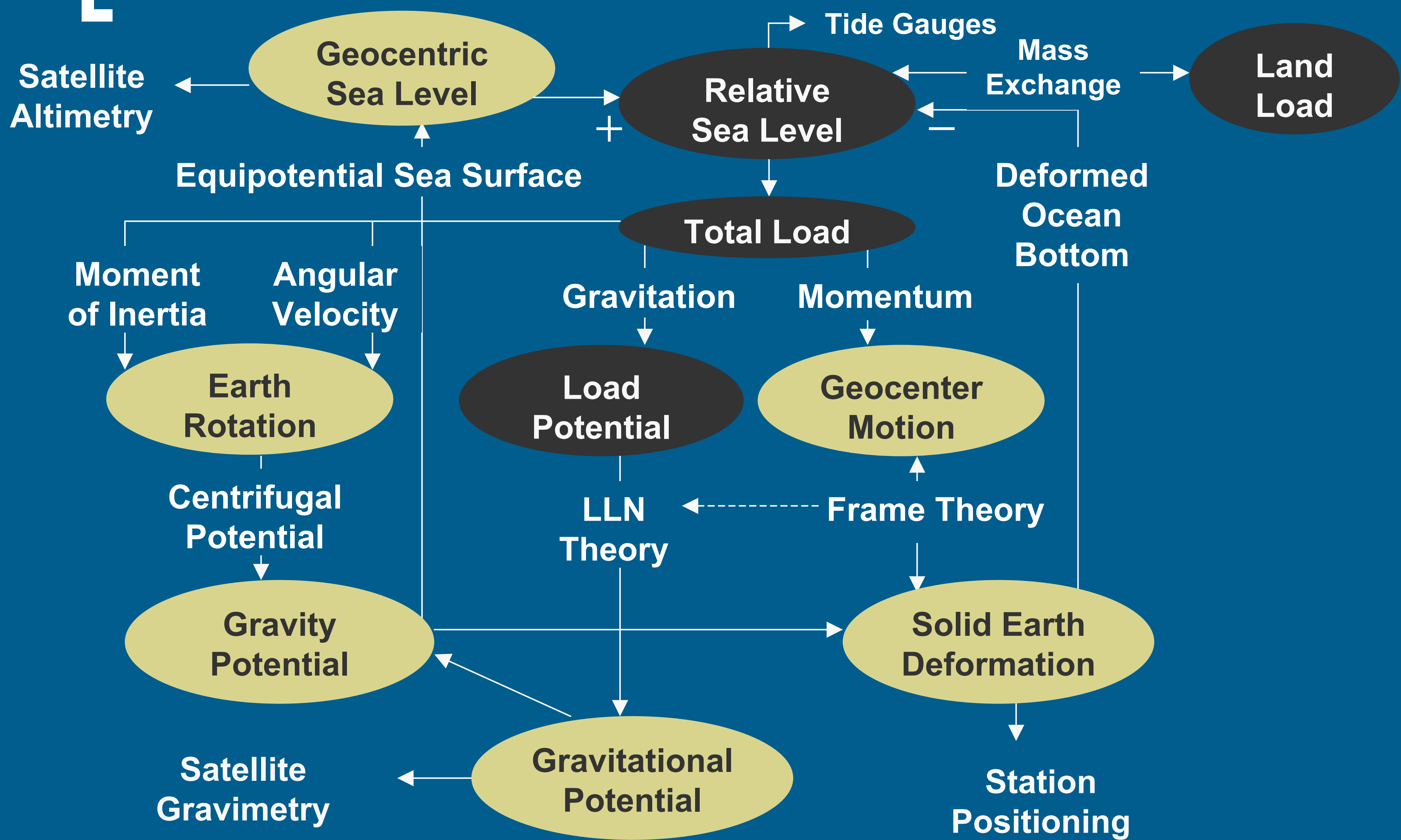
- GPS weekly results
  - 11.7 mm peak-to-peak max on 10 Sep
- Compare with seasonal models derived from:
  - hydrological models
  - TOPEX altimetry
  - with various assumptions
- Ocean heat budget?



Prospects: Physical assimilation

- Consider 3 Levels of Data Assimilation:
  - Station coordinate level
  - Kinematics level
  - Physical (dynamics) level
- Physical level has the potential
  - To enforce consistency in Earth system
  - To combine GPS, VLBI, SLR, GRACE, Jason, tide gauge data, surface gravity, Earth rotation,…
  - But it requires careful treatment of reference frames and consistency within and between models
  - assimilation should clarify our thinking and should help to resolve problems in models and data

"Grand Unified Geodesy"



Conclusions: What can IGS do to improve Global GPS Science?

- IGS GNAAC analysis has demonstrated the physical connections between coordinates, loading, gravity, sea level, & Earth rotation
- IGS can incrementally improve current products by improving:
  - station distribution: uniformity, density, and stability
  - station configuration: uniformity and stability
  - station data & metadata: accuracy and availability
  - duration of IGS network: 20+ years!
- **PROPOSAL: IGS should adopt a new product:**
  - spherical harmonic coefficients (weekly)
  - simultaneously estimated Helmert parameters (to ITRF)
  - This will create an important physical connection to other types of observations, and to other IAG Services & scientific communities
- **It will be back to the "good old days" in global GPS geodesy!**
  - **by taking IGS to the next level - *dynamics***

Our recent publications on this…

- **Some PDFs at: http://www.nbmg.unr.edu/staff/geoff.htm**

  - Gross, R., G. Blewitt, P. Clarke, D. Lavallee, Degree-2 harmonics of the Earth's mass load estimated from GPS and Earth rotation data, *Geophys. Res. Lett.* (in press, 2004)
  - Blewitt, G., Fundamental ambiguity in the definition of vertical motion, in *The State of GPS Vertical Positioning Precision: Separation of Earth Processes by Space Geodesy*, European Center for Geodynamics & Seismology (in press, 2004).
  - Blewitt, G., Clarke, P.J., D. Lavallee, and K. Nurutdinov, Application of Clebsch-Gordan coefficients and isomorphic frame transformations to invert Earth's changing geometrical shape for continental hydrological loading and sea level's passive response, in *Proc. of the IUGG 2003 General Assembly* (in press, 2004)
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  - Blewitt, G., Self-consistency in reference frames, geocenter definition, and surface loading of the solid Earth, *Journ. Geophys. Res., Vol. 108(B2)* 210, doi: 10.1029/2002JB002082, 2003.
  - Lavallee, D., and G. Blewitt, Degree-one Earth deformation from very long baseline interferometry, *Geophys. Res. Lett., Vol 29(20),* doi:10.1029/2002GL015883, 2002.
  - Blewitt, G., D. Lavallée, P. Clarke, and K. Nurutdinov, A new global mode of Earth deformation: Seasonal cycle detected, *Science*, *294*, 2342–2345, 2001.