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

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“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”)
- Combination of several global solutions
- Solution of regional station positions including 3+ global stations
- 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
    \[ T(\Omega) = \sum_{n,m,\Phi} T_{nm}^\Phi Y_{nm}(\Omega) \]
  - Height
    \[ H(\Omega) = \sum_{n,m,\Phi} h_n' \cdot \frac{3\rho_S}{(2n+1)\rho_E} T_{nm}^\Phi Y_{nm}(\Omega) \]
  - 2-D Lateral
    \[ L(\Omega) = \sum_{n,m,\Phi} l_n' \cdot \frac{3\rho_S}{(2n+1)\rho_E} T_{nm}^\Phi \nabla Y_{nm}(\Omega) \]
  - Geoid
    \[ N(\Omega) = \sum_{n,m,\Phi} (1 + k_n') \cdot \frac{3\rho_S}{(2n+1)\rho_E} T_{nm}^\Phi Y_{nm}(\Omega) \]
Load to degree 6 (GPS & Model)

Estimated Load
- GPS

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

Water-equivalent depth of load (mm)

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!
Estimated scale as part of Helmert transformation has significant ($\alpha=0.01$) 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 $\alpha=0.0002$
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
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
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](http://www.nbmg.unr.edu/staff/geoff.htm)