Time-Variable Gravity Analysis Using Satellite-Laser-Ranging as a Tool for Observing Long-Term Changes in the Earth’s Systems

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Zonal Rate Solutions - What’s is happening?

Zonal gravity rate and long period tide solutions. All values are x10\(^{-11}\)

<table>
<thead>
<tr>
<th>Study</th>
<th>(\dot{J}_2)</th>
<th>(\dot{J}_3)</th>
<th>(\dot{J}_4)</th>
<th>(\dot{J}_5)</th>
<th>(\dot{J}_6)</th>
<th>18.6-yr Tide C(_{2,0}) Amp. (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheng, et al. [1989]</td>
<td>-2.5±0.3</td>
<td>1.2</td>
<td>-0.1±0.3</td>
<td>0.3±0.6</td>
<td>1.5±1.5</td>
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</tr>
<tr>
<td>Nerem &amp; Klosko [1996]</td>
<td>-2.8±0.3</td>
<td>1.6±0.4</td>
<td>0.2±1.5</td>
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<tr>
<td>Cazenave, et al. [1996]</td>
<td>-3.0±0.5</td>
<td>-1.8±0.1</td>
<td>-0.8±1.5</td>
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<tr>
<td>Cheng, et al. [1997]</td>
<td>-2.7±0.4</td>
<td>0.5</td>
<td>-1.3±0.5</td>
<td>-1.4±1.0</td>
<td>2.1±0.6</td>
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<td>From GGG2000:</td>
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<tr>
<td>Base - Data through 1997</td>
<td>-3.0±0.4</td>
<td>0.3</td>
<td>-0.9±0.4</td>
<td>1.4±1.0</td>
<td>1.3±0.4</td>
<td>-1.0±0.6</td>
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<tr>
<td>Use only LAGEOS-1, Starlette, and Ajisai</td>
<td>-2.7±0.5</td>
<td>0.1</td>
<td>-0.9±0.5</td>
<td>0.1±1.6</td>
<td>1.2±0.5</td>
<td>-0.5±0.9</td>
</tr>
<tr>
<td>Use weight LAGEOS-1 2x</td>
<td>-3.1±0.5</td>
<td>0.3</td>
<td>-0.8±0.2</td>
<td>1.2±1.0</td>
<td>1.3±0.3</td>
<td>-0.8±0.5</td>
</tr>
<tr>
<td>Assume 2 m SLR weight</td>
<td>-2.0±0.3</td>
<td>0.9</td>
<td>-0.8±0.3</td>
<td>-2.7±1.0</td>
<td>1.9±0.4</td>
<td>1.2±0.7</td>
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<tr>
<td>Estimate only (\dot{J}_2) - (\dot{J}_5)</td>
<td>-2.4±0.2</td>
<td>0.2</td>
<td>-0.9±0.4</td>
<td>0.1±0.6</td>
<td>1.3±0.4</td>
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<tr>
<td>Estimate only (\dot{J}_2) - (\dot{J}_4)</td>
<td>-2.5±0.2</td>
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<tr>
<td>Revised Base – Data through 1997</td>
<td>-3.0±0.3</td>
<td>0.2</td>
<td>-0.5±0.4</td>
<td>1.6±0.8</td>
<td>0.8±0.4</td>
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<tr>
<td>+1998-1999</td>
<td>-0.9±0.3</td>
<td>0.5</td>
<td>1.1±0.4</td>
<td>-0.5±0.9</td>
<td>-0.7±0.4</td>
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<tr>
<td>+2000</td>
<td>-0.6±0.5</td>
<td>0.5</td>
<td>1.8±0.5</td>
<td>-2.2±0.6</td>
<td>-1.4±0.4</td>
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<td>+1998-2000</td>
<td>-0.2±0.3</td>
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The lumped \(J_{\text{odd}}\) rates were computed using the following relation derived from this study:

\[
J_{\text{odd}} = J_3 + 0.864 \ J_5
\]
Yearly Zonal Solutions

- Somewhere around 1996-1997 there is a distinct change in the yearly zonal averages
- Zonal rate solution tests show that this change is not attributable to any spacecraft
  - Changes in the Lageos-1 “anomaly” during this period can not be the cause

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<td>80-93</td>
<td>-3.3</td>
<td>0.8</td>
<td>-0.7</td>
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<td>0.7</td>
<td>-0.7</td>
</tr>
<tr>
<td>80-00</td>
<td>-2.1</td>
<td>0.7</td>
<td>-0.6</td>
</tr>
<tr>
<td>96-00</td>
<td>4.4</td>
<td>2.6</td>
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Slopes of weighted linear fits to the recovered zonal time series

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Satellite Derived Geopotential Series

- Uses Lageos-1, Lageos-2, Starlette, Stella, Westpac, Ajisai, TOPEX/POSEIDON (T/P), GFZ-1, Etalon-1, and Etalon-2 SLR tracking data, and the DORIS tracking of T/P

- Data weights were based on those resulting from the calibration of long-period gravity rate and seasonal phase/amplitude solutions of Cox et al. [2000b]
  - ~1-2 m overall for the SLR, relative DORIS/SLR weight matches the POEs

- Data were aggregated into nominal 60-day (pre 92) and 30-day (post 91) periods
  - 30-day periods correspond to three T/P repeat cycles
  - Lageos-1/2 and Etalon-1/2 30-day arcs, Lageos-1 are 90 days in 1979
  - 10-day arcs for the rest

- Tides:
  - The Sa, Ssa, at nominal equilibrium values
  - The 18.6 yr, and 9.3 year tides from the comprehensive solutions
  - The rest of the tides are from the EGM96 solution, with Schrama/Ray background.

- No \textit{a priori} gravity rates were applied, consequently trends should appear in the plots

- No \textit{a priori} atmospheric gravity was applied - results will contain the effects of atmospheric mass perturbations
Timeline of Precise Satellite Tracking Data

Satellite Tracking Data

- Lageos-1
- Starlette
- Ajisai
- Etalon-1
- Etalon-2
- Lageos-2
- T/P SLR/DORIS
- Stella
- GFZ-1
- Westpac
- Champ
- Jason-1
- Grace

Year:
- 1976
- 1978
- 1980
- 1982
- 1984
- 1986
- 1988
- 1990
- 1992
- 1994
- 1996
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
• The atmospheric inter-annual variation amplitude is \( \sim 5 \times 10^{-10} \)
• The atmospheric inter-annual rate alternates between +/- \( 3 \times 10^{-10} \), as large as the long term observed rate
(Observed J2 - Atmosphere), and Ocean and Ice

- Red: (Observed-NCEP IB)-annual
- Black: Pre 1997 fit, slope = $-2.8 \times 10^{-11}$ per year
- Blue: GSL inferred J2 change
- Purple: T/P SSH inferred J2 change
- Green: Greenland+West Antarctica [Zwally et al., 2001]
Observed J3 and Atmosphere
Observed J3 - Atmosphere

Observed J3 - NCEP (2D,IB)

- Observed-NCEP
- Observed-NCEP, -annual, 1 Yr filter
- Linear Fit

J3 (x1e10)

(Observed J3 - Atmosphere), and Ocean and Ice

- Red: (Observed-NCEP IB)-annual
- Black: Linear fit, slope = 0.9x10^{-11} per year
- Blue: GSL inferred J3 change
- Purple: T/P SSH Inferred J3 change
- Green: Greenland+West Antarctica [Zwally et al., 2001]
Observed J4 and Atmosphere

The observed C4,0 does exhibit the same post 97 deviation the C2,0 does
(Observed J4 - Atmosphere), and Ocean and Ice

- Red: (Observed-NCEP IB)-annual
- Black: Linear fit, slope = -0.1 \times 10^{-11} per year
- Blue: GSL inferred J4 change
- Purple: T/P SSH Inferred J4 change
- Green: Greenland+West Antarctica [Zwally et al., 2001]
Observed J2 - What could change the slope?

- First guess: Ice
  - In order to overshadow PGR, Greenland would lose about 500 Gt annually, for a net GSL rate of ~ +1.4 mm/yr
  - Greenland and W. Antarctica implied gravity rates derived from radar altimetry [Zwally, 2001]
    - Ice height-derived GSL for Greenland: -.22 mm/yr
    - Ice height-derived GSL for West Antarctica: -.08 mm/yr
  - Greenland result matches Ice mass balance inferences from inverse solutions using gravity zonals, pole rates and GSL rate
  - Have the wrong sign to explain the deviation
  - East Antarctica?
    - Would need to contribute ~2 mm/yr to GSL, depending on the scenario
  - Glaciers?
    - Using Meier’s 1984 numbers, a sea level contribution of ~2 mm/yr is needed
- If it is Ice, where is the change in GSL?
Observed J2 - What could change the slope?

- **Atmosphere**
  - 2D computations based on NCEP do not explain it
    - Excellent annual agreement with J3, implying that the general handling of the data is correct
  - What of 3D computations?
    - Differences between 2D and 3D computations are also too small
      - Effect on J2 is only about \(2 \times 10^{-10}\), with little interannual variation
      - Effect on J3 near zero

- **Water impoundment**
  - Really large dams can cause a jump of \(0.2 \times 10^{-10}\) in J2, but it’s not enough

- **Hydrology**?
  - Lack of data…presently
J2 Atmospheric Gravity - 2D vs 3D

2D vs. 3D Atmospheric J2

Date


J2 x1E10

3D
2D
Difference
Observed J2 - What could change the slope?

- Core or mantle?
  - Mantle acts too slow
  - Core was assumed to be small
    - W. Kuang of UMBC reviewed his models...under some assumptions changes as large as ~0.5x-11 per year are possible
      - How probable? Remains to be seen... More work

- Ocean
  - Timing of onset corresponds with last big ENSO event
  - T/P SSH data implies changes that are consistent and comparable to the observed gravity changes
The Core and $J_2$

$J_2$ signals ($10^{10}$) from geodynamo simulations. Time scale is non-dimensional, but is of the order of decades.

Figure Courtesy of W. Kuang (NASA GSFC)
Sea Surface Temperature and Height EOF/PC
The ECCO assimilation mode ocean model bottom pressure contribution to $J_2$

The ECCO model run incorporates the TOPEX/POSEIDON altimeter data
• Correlation is 0.65 with a 12 month delay in the observed series
• Implication that ENSO events buildup may be observable
• Error bars on monthly observations exceed $1 \times 10^{-10}$
Atmosphere and S_{2,1}?
Conclusion

- Significant interannual signals at the $1 \times 10^{-10}$ level for C2,0 and C3,0
  - Differences in temporal data distribution, weighting, and technique will likely effect results of long-term rate estimation
  - Strong inter-annual periodicity requires long temporal baselines in order to try and recover decadal (and longer) rates
  - Need to improve accounting for mass exchange
    - $\Rightarrow$ Need to account for atmosphere to assess surface mass transport

- Apparent Environmental signals present in more than just Zonals
  - ENSO in S2,2?
  - Atmospheric Mass in 2,1 terms

- Large change in $J_2$ rate
  - Short term deviation or something more?
  - Not atmosphere
  - Ice Melting scenarios large enough to explain this produce far too much GSL change
  - Ocean?
    - $\Rightarrow$ Changes consistent with extratropic SST and SSH changes