Geocenter motion excited by large-scale mass redistribution

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Definition of Geocenter

Center of Figure (CoF)

Center of Mass (CoM)

Geocenter = CoM w.r.t. CoF
Measurement of geocenter motion from SLR

Measuring loading deformation which includes degree-1 components

Measuring gravity variations which does not include degree-1 components

SLR is the best technique to measure geocenter motion at present

Observed deformation - gravity-derived deformation
= degree-1 deformation = Geocenter motion
Objective of this study

- To derive geocenter motion from SLR observation using our original software package “c5++”
- To assess our “c5++” solution by comparing with CSR solution
- To investigate driving sources of recent long-term geocenter motion
SLR analysis software: **CONCERTO 5++ (c5++)**

(Otsubo et al, 1994; Hobiger et al., 2013)

Implement up-to-date geophysical models and TRF

- IERS Conventions 2010
- EGM 2008 model
- ITRF 2008
- etc
Strategy of SLR data analysis

- Arc length is 3 days
- Empirical acceleration (constant and one-per-rev) is estimated at 1.5 days interval
- 60 days -average geocenter motion is calculated
Results: Geocenter motion from c5++
Geocenter motion from CSR (provided by Dr. Ries)
Scatter plot: c5++ solution vs. CSR solution

X axis
Correlation = 0.61

Y axis
Correlation = 0.82

Z axis
Correlation = 0.83
Long-term geocenter motion: c5++ solution

2-year moving average

- **X direction**
- **Y direction**: Shift in trend around 2000
- **Z direction**

Time (year): 1994 to 2014
Long-term geocenter motion: CSR solution

2-year moving average

X direction

Y direction

Z direction

Shift in trend around 2000
Trend shift in $\Delta J_2$ from SLR observation

Melting of polar ice sheets change the trend in $\Delta J_2$

(Cheng et al., JGR 2013)
Main sources of mass redistribution in 2000s

Linear mass trend in 2003-2013 from GRACE gravimetry

- Glacial Isostatic Adjustment
- Ice loss
- Sea-level rise

cm/yr

-16.0 -6.0 -2.4 -0.8 0.8 2.4 6.0 16.0
Estimation of mass-driven geocenter motion

1. Polar ice sheets
   Ice thickness variations from ICESat altimetry from 2003 Oct. to 2009 Sep.

2. Sea level rise
   Solve sea-level equation using ice mass variations from ICESat

3. Glacial Isostatic Adjustment
   Theoretical values by Greff-Lefftz (JGR 2000)
1. Polar ice sheets: Antarctica

Linear trend in ice thickness from ICESat (2003-2009)

Total mass change in Antarctica

Ice loss rate of ~100 Gt/yr

Assumes ice density as 700 kg/m$^3$ for ablation area, 300 kg/m$^3$ for accumulation area
1. Polar ice sheets: Greenland

Linear trend in Ice thickness from ICESat (2003-2009)

Total mass change in Greenland

Assumes ice density as 700 kg/m$^3$ for ablation area, 300 kg/m$^3$ for accumulation area
2. Sea level rise

Sea level equation [e.g. Métivier et al., EPSL 2010]

\[
h_{SL}(\theta, \varphi, t) = \frac{\rho_{l}}{g_{o}} \Phi(\theta, \varphi) * h_{l}(\theta, \varphi, t) + \frac{\rho_{OC}}{g_{o}} \Phi(\theta, \varphi) * h_{SL}(\theta, \varphi, t)^{SL} + C(t)
\]

Sea level rise by polar ice mass variations

Total sea level variation by polar ice mass variations

Sea level rise of ~1 mm/yr
3. Glacial Isostatic Adjustment

Theoretical estimation by Greff-Lefftz (JGR 2000)

GIA-driven geocenter motion depends on viscosity of lower mantle and upper mantle

Here, we pick up the average values of the right figure:

\[ X_g = 0.1 \pm 0.05 \text{ mm/yr} \]
\[ Y_g = -0.1 \pm 0.1 \text{ mm/yr} \]
\[ Z_g = 0.2 \pm 0.2 \text{ mm/yr} \]
Results: Estimated geocenter motion

X axis
- ICE: -0.17 mm/yr
- SEA: -0.15 mm/yr
- GIA: 0.10 mm/yr

Y axis
- ICE: 0.37 mm/yr
- SEA: -0.05 mm/yr
- GIA: -0.10 mm/yr

Z axis
- ICE: -0.56 mm/yr
- SEA: -0.17 mm/yr
- GIA: 0.20 mm/yr
Results: Comparison between SLR and estimation

**X axis**
- SLR (c5++): -0.04 mm/yr
- SLR (CSR): -0.04 mm/yr
- ICE+SEA+GIA: -0.22 mm/yr

**Y axis**
- SLR (c5++): +0.22 mm/yr
- SLR (CSR): +0.53 mm/yr
- ICE+SEA+GIA: +0.22 mm/yr

**Z axis**
- SLR (c5++): -0.60 mm/yr
- SLR (CSR): -0.84 mm/yr
- ICE+SEA+GIA: -0.53 mm/yr
# Results: Linear rates of geocenter motion

<table>
<thead>
<tr>
<th></th>
<th>X axis (mm/yr)</th>
<th>Y axis (mm/yr)</th>
<th>Z axis (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SLR (c5++)</strong></td>
<td>-0.04 ± 0.08</td>
<td>+0.22 ± 0.02</td>
<td>-0.60 ± 0.03</td>
</tr>
<tr>
<td>**SLR (CSR)</td>
<td>-0.05 ± 0.04</td>
<td>+0.53 ± 0.04</td>
<td>-0.84 ± 0.08</td>
</tr>
<tr>
<td><strong>ICE+SEA+GIA</strong></td>
<td>-0.22 ± 0.06</td>
<td>+0.22 ± 0.10</td>
<td>-0.53 ± 0.24</td>
</tr>
<tr>
<td><strong>ICE</strong></td>
<td>-0.17 ± 0.02</td>
<td>+0.37 ± 0.01</td>
<td>-0.56 ± 0.14</td>
</tr>
<tr>
<td><strong>SEA</strong></td>
<td>-0.15 ± 0.02</td>
<td>-0.05 ± 0.01</td>
<td>-0.17 ± 0.01</td>
</tr>
<tr>
<td><strong>GIA</strong></td>
<td>+0.10 ± 0.05</td>
<td>-0.10 ± 0.10</td>
<td>+0.20 ± 0.20</td>
</tr>
</tbody>
</table>
Summary

- Recent large-scale mass redistributions move geocenter to south by ~0.5 mm/yr and 135E direction by ~0.3 mm/yr
- Mass losses in polar ice sheets are the main sources of recent geocenter motion
- SLR observation roughly agrees with the estimated results
- Our X component solution appears to be noisy (currently being investigated)
Future works

- To include contributions from ice mass variations in mountain glaciers using ICESat altimetry data
- To examine contributions of massive earthquakes using dislocation theory

Thank you for your attention!
Significance of precise geocenter determination

• Construction of Terrestrial Reference Frame (TRF)

• Precise determination of crustal velocity field

• Construction of global geoid model
Estimation of mass-driven geocenter motion

Computational formula of geocenter motion [e.g. Munekane, JGR 2007]

\[ X_g = R \sqrt{3} \left( \frac{1 - \frac{h_1' + 2l_1'}{3}}{1 + k_1'} \right) \Delta C_{11} \]

\[ Y_g = R \sqrt{3} \left( \frac{1 - \frac{h_1' + 2l_1'}{3}}{1 + k_1'} \right) \Delta S_{11} \]

\[ Z_g = R \sqrt{3} \left( \frac{1 - \frac{h_1' + 2l_1'}{3}}{1 + k_1'} \right) \Delta C_{10} \]

\( X_g, Y_g, Z_g: \)
Geocenter motion

\( \Delta C_{10}, \Delta C_{11}, \Delta S_{11}: \)
dimensionless Stokes' coefficients of geopotential

\( R: \) Radius of the Earth

\( k_1', h_1', l_1': \)
load love and Shida number of degree-1 components
Map of SLR stations

**Annual variation**

Atmosphere (ECMWF model)
Ocean (ECCO model)
Land water (GLDAS model)
Geocenter motion estimated from geophysical fluid models
Phasor diagram of annual components

$$\text{Amplitude of Sine}$$

$$\text{Amplitude of Cosine}$$

**X axis**

**SLR (CSR)**

$$1.79 \pm 0.34 \text{ mm}$$

**SLR (c5++)**

$$2.37 \pm 0.49 \text{ mm}$$

**Fluid model**

$$3.85 \pm 0.29 \text{ mm}$$

**Y axis**

**SLR (CSR)**

$$0.72 \pm 0.35 \text{ mm}$$

**SLR (c5++)**

$$1.54 \pm 0.31 \text{ mm}$$

**Fluid model**

$$2.91 \pm 0.30 \text{ mm}$$

**Z axis**

**SLR (CSR)**

$$5.17 \pm 0.69 \text{ mm}$$

**SLR (c5++)**

$$6.02 \pm 0.68 \text{ mm}$$

**Fluid model**

$$6.84 \pm 0.31 \text{ mm}$$