Vertical Motion from Satellite Altimetry and Tide gauges

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NTNU Trondheim, Wednesday June 23 2004
Motivation to study vertical motion

⇒ Sea level change observations rely on tide gauge records

⇒ Tide gauge records are affected by vertical motion of the land surface

⇒ GPS sites are sparsely distributed and only short term data is available

⇒ Glacial Isostatic Adjustment (GIA) predicts vertical motion
  → ..., but insufficiently known Earth parameters.
  → ..., but no accurate spatial and temporal ice loading history.
  → ..., but is affected by non-GIA related vertical motion, e.g. tectonics, mantle dynamics.
  → and is thus not very accurate for regional/local applications.
What can we do?

⇒ Combination of tide gauge records and altimetry (Kuo et al., 2004, Nerem et al, 2002)

⇒ Study gravity to separate GIA, tectonics and mantle dynamics.

⇒ Assimilate vertical motion in GIA models.

⇒ Study GIA at the former ice margin, where sensitivity is distinct (Mitrovica et al., 1994).
Laurentide ice sheet

Glaciation and deglaciation cycles and southern extension of the Laurentide ice sheet (Karrow et al, 2000). maximum southern extent is reaching the Ohio river. Ice margin is crossing the Great Lakes.
Ice history data provided by Jim Fastook (pers. communication, 2002). Ice thickness at snapshots 20 ka BP (left), 10 ka BP (center), and 6 ka BP (right).
ICE4G predicted vertical motion in North America (Peltier, 2001).
Absolute gravity, tide gauge and GPS stations around the Great Lakes.
Combination of tide gauge and altimetry data

⇒ Topex-Poseidon cycles 4-330 from PO.DAAC, about 10 years
  → Corrected for instrumental, environmental and geophysical effects (Benada, 1997) except IB correction.

⇒ Great Lakes daily (or 6-min) tide gauge data from 27 NOAA CO-OPS and 23 Canadian MEDS station. Tide gauge records time span is 40 to 141 years.
Satellite altimetry tracks of the Missions Jason, ICESat, EnviSat, GFO-1, Topex, ERS1/2 and GEOSAT.
Lake surface gradient obtained from Topex data May-August 2002 with ICESat tracks.
Method

Rate of relative sea level change can be expressed as follows (all functions of lat/lon):

\[
\begin{align*}
\dot{S}_{tg} &= -\dot{U} + \dot{T} + \dot{D} + \dot{S}_{var} + \dot{S}_{res}, \\
\dot{S}_{alt} &= \dot{T} + \dot{D} + \dot{S}_{var} + \dot{S}_{res} + \dot{S}_{drift}, \\
\dot{S}_{gps} &= -\dot{U} = \dot{S}_{gia},
\end{align*}
\]

where \(\dot{U}\) is the rate of vertical motion, \(\dot{T}\) is the thermal expansion signal, \(\dot{D}\) indicates the signal due to recent deglaciation, \(\dot{S}_{var}\) is the annual and inter-annual sea level variability, and \(\dot{S}_{res}\) denotes the residual sea level change signal. TG is defined free of errors, all errors are in \(\dot{S}_{drift}\).

\[-\dot{U} = \dot{S}_{tg} - \dot{S}_{alt} - \dot{S}_{drift}\]
The uplift rates $\dot{U}$ are estimated using the differences of the time series between tide gauge data and altimetry data. Results accepted if correlation $\geq 0.9$.

$$\dot{U} = \frac{\sum_n (A_n - \overline{A})(B_n - \overline{B})}{\sqrt{\sum_n (A_n - \overline{A})^2} \sqrt{\sum_n (A_n - \overline{A})^2}}$$

Network adjustment using least squares.

⇒ Gauss-Markov model with stochastic contraint.

⇒ Input: Slope of the difference of two tide gauge stations.

⇒ Output: Relative vertical motion between tide gauges.
Performance check with GPS in Fennoscandia

Kuo, Shum, Braun and Mitrovica, GRL, 2004
Performance check in Alaska

Blue error bars: Nerem and Mitchum, 2002
Green error bars, Kuo et al., 2004
Vertical motion comparison Great Lakes

⇒ Combination of tide gauge and altimetry

⇒ Tide gauge only analysis (Mainville, 2003)

⇒ USGS GPS velocities and JPL global velocities

⇒ Mitrovica GIA model ($L_M = 120, U_M = 1 \times 10^{21}, L_M = 10 \times 10^{21}$, Milne et al., 2001)

⇒ Mitrovica GIA model ($L_M = 120, U_M = 1 \times 10^{21}, L_M = 3 \times 10^{21}$)

⇒ ICE4G-VM2 (Peltier, 2001)

⇒ ICE3G (Tushingham and Peltier, 1992)
Vertical motion from TG/Altimetry, ICE4G-VM2 as background.
+ Mainville TG analysis (2003)
+ USGS GPS (large diamonds) and JPL velocities
+ Mitrovica ($LM = 120\text{km}, UM = 1 \times 10^{21} \text{Pas}, LM = 10 \times 10^{21} \text{Pas}$)
Mitrovica ($LM = 120km, UM = 1 \times 10^{21} Pas, LM = 3 \times 10^{21} Pas$)
Vertical motion vs. station #
Vertical motion vs. latitude
GPS solutions in the Great Lakes

Vertical motion rates determined by GPS strongly depends on data time span and processing software. Only a limited number of CGPS available.
<table>
<thead>
<tr>
<th>mm/yr</th>
<th>NGS</th>
<th>USGS</th>
<th>JPL</th>
<th>NRCAN</th>
<th>PARK</th>
<th>This study</th>
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<td>0.47</td>
<td>3.43</td>
<td>0.8</td>
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<td>-1.43 ± 0.49</td>
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<td>DET1</td>
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<td>-0.53</td>
<td>2.4</td>
<td>-0.1</td>
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<td>0.45 ± 0.13</td>
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<td>-1.21</td>
<td>0.9</td>
<td></td>
<td>0.11 ± 0.12</td>
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<td>MIL1</td>
<td>-3.45</td>
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<td>-6.48</td>
<td>-1.6</td>
<td></td>
<td>-0.05 ± 0.07</td>
</tr>
<tr>
<td>SAG1</td>
<td>-1.25</td>
<td>0.07</td>
<td>-1.89</td>
<td>-0.3</td>
<td></td>
<td>-0.18 ± 0.49</td>
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<tr>
<td>STB1</td>
<td>0.95</td>
<td>1.9</td>
<td>-3.01</td>
<td>-0.7</td>
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<td>-1.28 ± 0.07</td>
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<td>-2.07</td>
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<td>-0.5</td>
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<td>0.78 ± 0.12</td>
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<tr>
<td>YOU1</td>
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<td>2.17</td>
<td>5.86</td>
<td>0.9</td>
<td></td>
<td>-0.39 ± 0.20</td>
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</table>
### Vertical motion statistics

Table 1: Mean difference between Model and TG/Alt Observation. UM/LM in $10^{21} Pas$, LT in km.

<table>
<thead>
<tr>
<th>#</th>
<th>Model/Observation</th>
<th>Mean difference mm/yr</th>
<th>Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>Mitrovica LT=120 UM=1 LM=10</td>
<td>1.702</td>
<td>± 1.453</td>
</tr>
<tr>
<td>m2</td>
<td>Mitrovica LT=120 UM=1 LM=3</td>
<td>0.269</td>
<td>± 1.055</td>
</tr>
<tr>
<td>m3</td>
<td>ICE4G-VM2 LT=120 UM=.5 LM=3</td>
<td>0.259</td>
<td>± 0.785</td>
</tr>
<tr>
<td>m4</td>
<td>ICE3G LT=120 UM=1 LM=2</td>
<td>0.170</td>
<td>± 0.720</td>
</tr>
<tr>
<td>m5</td>
<td>Mainville TG analysis</td>
<td>-0.256</td>
<td>± 0.502</td>
</tr>
</tbody>
</table>
Assimilating vertical motion data in a forward model based on ICE3G loading history and systematic variation of the UM and LM viscosity and LT and UM/LM boundary results in best fit model:

\[
\begin{align*}
LT &= 120\text{km}, \\
UM/LM \text{ boundary} &= 660\text{km}, \\
UM &= 0.5 \times 10^{21}\text{Pas}, \\
LM &= 1 \times 10^{21}\text{Pas}.
\end{align*}
\]
Another approach - Gravity

⇒ Remove non-GIA uplift components before constraining Earth parameters.

⇒ Gravity can be studied to infer the contribution of incomplete rebound.

⇒ Absolute gravity measurements can be converted to vertical motion, in case it is due to GIA (Wahr, 1995).

⇒ What percentage of the gravity signal (-34 mGal)/vertical motion is caused by GIA?
  - Simons and Hager (1997) estimate about 50% is due to incomplete rebound.
  - Patrick Wu (2002) estimates even less (25%) based on GIA modeling including ambient stress.
  - Gravity correlation studies (see also Poster by Potts et al. SS03 !!TODAY!!) explain 75% by incomplete rebound.
Terrain-correlated gravity anomalies over free air gravity. This includes incomplete GIA, terrain effects, and crustal thickness variations. Remaining signal must be related to mantle dynamics, tectonics and/or model errors.
Decomposition using spherical wavelets

Free-air-gravity

ICE4G

Highly accurate vertical motion has been derived from the combination of tide gauge and altimetry data.

Comparison with independent analysis of tide gauge, GPS and GIA model predictions lead to a mean difference of $0.25 - 1\text{mm/yr} \pm 0.7 - 1\text{mm/yr}$.

Results fit best with GIA models with $LT=120$ km, $UM = 0.5 - 1 \times 10^{21} \text{Pas}$, $LM = 1 - 3 \times 10^{21} \text{Pas}$.

Gravity correlation analysis explains 75% of the signal by incomplete rebound.

GIA modeling will be extended to 3-D radially symmetrical, self-gravitating, viscoelastic models including variation of the ice loading.
history.

⇒ More GPS and absolute gravity data will further constrain solution.

⇒ Multi-mission altimetry and longer time span will stabilize vertical motion estimates.