Observing Absolute Gravity Acceleration in the Fennoscandian Land Uplift Area

Arbeitskreis Geodäsie/Geophysik 2006, Worpswede, 17. bis 20. Oktober

Anders Celsius 1743: 13 mm/year decrease of sea level since 1731; evaporation or a hole in the bottom.

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and
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1. Gravimetric Determination of the Fennoscandian Uplift
2. Absolute Gravimetry
3. The Current Project
4. Summary / Conclusion

The Celsius seal rock with water level marks
Gravimetric Determination of the Fennoscandian Land Uplift
- approaches in Geophysics and Geodesy -

- isostatic uplift since the glacial maximum (18 ka BP);
- geophysical modeling with unknowns (geometry of ice sheets, Earth model parameters, lateral rheological variations);
- for recent land uplift: complementary data from geodesy and oceanography.

Apparent land uplift model NKG2005LU according to Ågren & Svensson 2006 (geodetic levelling, mareographs, rel.gravimetry, GPS + geophys. modelling)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{H}_u \approx 9.0 \text{ mm/yr}$</td>
<td>Ekman 1996</td>
<td></td>
</tr>
<tr>
<td>$\dot{H}_c \approx 1.2 \text{ mm/yr}$</td>
<td>Nakiboglu &amp; Lambeck 1991</td>
<td></td>
</tr>
<tr>
<td>$\dot{g} / \dot{h} \approx -0.2 \mu\text{Gal/mm}$</td>
<td>Ekman &amp; Mäkinen 1996</td>
<td></td>
</tr>
<tr>
<td>$N_0 \approx 0.6 \text{ mm/yr}$</td>
<td>“</td>
<td></td>
</tr>
<tr>
<td>$\dot{h}_0 \approx 10.8 \text{ mm/yr}$</td>
<td>“</td>
<td></td>
</tr>
<tr>
<td>$\dot{g} \approx -2.0 \mu\text{Gal/yr}$</td>
<td>“</td>
<td></td>
</tr>
</tbody>
</table>
Gravimetric Determination of the Fennoscandian Land Uplift
- GRACE: satellite gravimetry with area measurements -

GRACE
• temporal geoid change: ±2 to 3 mm for a phenomenon of 600 km extension (Tapley et al. 2004).

Synergy with terrestrial methods:
• Fennoscandian land uplift is a measurable signal for GRACE;
• interference with mass variations due to oceanography, land hydrology and atmospheric processes;
• combination with hydrological, atmospheric and geodetic measurements are inevitable.

geodetic “Ground-Truth” is required
Gravimetric Determination of the Fennoscandian Land Uplift
- absolute gravimetry: terrestrial point measurements -

FG5:
Determination of absolute gravity acceleration by free-fall experiments (drops) using laser interferometry.

\[ z \approx \frac{1}{2} gt^2 \]

Assumption:
- single error sources
  - setup uncertainty and small temporary offsets of absolute gravimeter,
  - soil moisture / ground water,
  - atmosphere (residual effect),
  - ocean and Baltic Sea (residual eff.) effect the final result (linear trend) after many station determinations only randomly (→ averaging effect).

instrumental errors
gravitational “noise” \( s(AG) \)

project idea: since 2003, yearly occupations of the stations

goal: \( s(\dot{g}) = < \pm 2 \, \mu \text{Gal} \) for a 5 years time span
In addition and complementary to other geodetic measurements, terrestrial absolute gravimetry has the following positive characteristics:

- monitoring of gravity changes caused by subsurface mass redistributions or by vertical displacements;
- accuracy of absolute gravity net is independent of geographical extension and of scale of gravity range;
- independent validation method for GPS, VLBI, SLR, and superconducting gravimetry;
- combined with geometrical methods, vertical surface deformations and subsurface mass movements can be separated.
Absolute Gravimetry
- accuracy and precision -

FG5-220 (Univ. Hannover)

Repeatability control at station Hannover

Instrumental offset control by comparisons

<table>
<thead>
<tr>
<th>Date</th>
<th>Station</th>
<th>FG5-220 compared with</th>
<th>Diff. [nm/s²]</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 03</td>
<td>Bad Homburg (BH)</td>
<td>mean</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>April 05</td>
<td></td>
<td>&quot;</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>April 06</td>
<td></td>
<td>&quot;</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Mar+Apr04</td>
<td>Ås</td>
<td>FG5-226</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>May 04</td>
<td>Vaasa AB</td>
<td>FG5-221</td>
<td>14</td>
<td>Simult.</td>
</tr>
<tr>
<td>May 04</td>
<td>Metsäh. AB</td>
<td>FG5-221</td>
<td>-3</td>
<td>Simult.</td>
</tr>
<tr>
<td>May 04</td>
<td>Metsäh. AC</td>
<td>FG5-221</td>
<td>44</td>
<td>Simult.</td>
</tr>
<tr>
<td>Oct 04</td>
<td>Onsala AS</td>
<td>FG5-226</td>
<td>-23</td>
<td>Simult.</td>
</tr>
<tr>
<td>Oct 04</td>
<td>Onsala AS</td>
<td>FG5-221</td>
<td>3</td>
<td>Simult.</td>
</tr>
<tr>
<td>Oct 04</td>
<td>Onsala AN</td>
<td>FG5-226</td>
<td>-14</td>
<td>Simult.</td>
</tr>
<tr>
<td>Oct 04</td>
<td>Onsala AN</td>
<td>FG5-221</td>
<td>15</td>
<td>Simult.</td>
</tr>
</tbody>
</table>

mean (excl. BH) r.m.s. 7 ± 21

Int. Comparison of Absolute Gravimeters in Walferdange (Luxemb.), Nov. 2003:
dg (FG5-220 - mean(15 instr.)) = -19 nm/s² (Francis et al. 2006)

FG5-220 accuracy: ±2 . . . ±3 μGal
Absolute Gravimetry
- merge with relative gravimetry -

a) transmission of g-value along the vertical

b) connecting safety points

c) measuring the effect of human-caused mass redistributions, e.g. building conversion

±1 ... ±2 μGal
(for differences of up to 10 mGal)
The Current Project  
- project realization -

**Keys:**

- planning panel: NKG working group “Geodynamics”
- close cooperation between four FG5-expert teams (2003: BKG, FGI, IfE, since 2004: FGI, IfE, UMB);
- continuous GPS at almost all stations (BIFROST);
- geod. levelling between abs.gravity points and eccenters (control of local variations, direct connection to GPS);
- integration of already existing geodetic data sets (e.g. Wilmes et al. 2004, Kuo et al. 2004);
- comparison with GRACE.

**Products:**

1. temporal changes of gravity and **the gravity disturbances** at the measurement locations,
2. area model for gravity disturbances and for geoid changes.
Conversion of gravity and height changes

Change of gravity disturbance:

\[ \dot{h} = 1.0 \text{ cm} \]
\[ g_{t2}(h_2) - g_{t1}(h_1) = -2.0 \mu\text{Gal} \]
\[ \frac{\partial g}{\partial h} = -3.0 \frac{\mu\text{Gal}}{\text{cm}} \]
\[ \delta g = +1.0 \mu\text{Gal} / \Delta t \]

Geoid change:

\[ \dot{N} = \frac{R}{4\pi \gamma} \iiint_{\sigma} H(\psi) \left( \dot{g} + \frac{2\gamma}{r} \dot{h} \right) d\sigma \]

gravity disturbance

Apparent land uplift [mm/yr], after Ekman 1996
Due to lateral heterogeneous Earth’s properties and other (minor) tectonic phenomena: no radial symmetrical uplift behaviour.

Absolute gravimetric observation system with a dense and regular station distribution.
Complementarity of Gravimetric Techniques

models for temporal mass variations (short-term, daily to yearly):
- ocean/sea, atmosphere,
- land hydrology (continental water storage)

Terrestrial gravimetry, geometrical methods:
Abs.grav./SCG, GPS

Sat. gravimetry:
GRACE, follow-ups

Secular mass movements in the recent past:
models for isost. land uplift, sea level change, ice mass balance, etc.

Point measurement → validation / testing → area measurement

Terrestrial gravimetry, geometrical methods:
Abs.grav./SCG, GPS

Sat. gravimetry:
GRACE, follow-ups

Combining

Validation / testing → point measurement

Providing measured constraints → area measurement

SCG: stationary determination of short-term gravity changes
FG5: transportable determination of long-term gravity changes
Summary and Conclusions

• more than 30 absolute gravimetry stations in Fennoscandia recently observed;

• occupied stations: 22 (2003), 24 (2004), 30 (2005);

• four FG5 absolute gravimeter are employed to increase the reliability and accuracy of the whole network and to achieve a proper number of station occupations every year;

• accuracy of a single station determination: $\pm 2 \ldots \pm 3 \text{ µGal}$;

• with GRACE, a new appreciation of processes in the system Earth has arisen which requires the interaction with ground based measurement techniques;

• the absolute gravity net is designed as a long-term monitoring system;

• with the implementation of a long-term reference frame, future gravimetric datum problems can be avoided (establishment of a few reference stations with SCG, GPS, GW monitoring, frequent abs. grav. measurements by different groups).
Acknowledgments

Thank’s to all involved colleagues from the project partners:

Danish National Space Center (DNSC), Copenhagen

Department of Mathemat. Sciences and Technology, University of Environmental and Life Sciences, Ås

Federal Agency for Cartography and Geodesy (BKG), Frankfurt

Finnish Geodetic Institute, Masala

Lantmäteriet, Gävle

Onsala Space Obs., Chalmers Univ. of Technology

Statens Kartverk, Hønefoss
Absolute Gravimetry
- accuracy and precision: site and instrument stability -

Quantitative estimation of the site stability and the instrument’s stability

Systematic errors are not considered:
instrumental offset, misaligned verticality, floor recoil, etc.
Absolute Gravimetry
- accuracy and precision: setup uncertainty -

Gravity differences at ~120.0 cm height (sensor) between two points measured by absolute and relative gravimetry.

Parallel registration in Bad Homburg / BKG.

<table>
<thead>
<tr>
<th>Location</th>
<th>AB-AC (dg)</th>
<th>AS-AN (dg)</th>
<th>BA-AA (dg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metsähovi</td>
<td>1.9</td>
<td>7.7</td>
<td>34.9</td>
</tr>
<tr>
<td>Onsala</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bad Homburg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comparison with absolute gravimetry:
\[ dg(\text{abs}) - dg(\text{rel}) \]

<table>
<thead>
<tr>
<th>Year</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>1.9</td>
</tr>
<tr>
<td>2004</td>
<td>-1.6</td>
</tr>
<tr>
<td>2005</td>
<td>-0.3</td>
</tr>
<tr>
<td>2006</td>
<td>1.9</td>
</tr>
<tr>
<td>2007</td>
<td>0.2</td>
</tr>
</tbody>
</table>

R.m.s. discrepancy: ±1.6 µGal (setup uncertainty)

→ several setups during a station determination to minimize the instrumental setup uncertainties (floor-recoil, azimuth dependency: Coriolis force / attrition, electrostatic, …)
The Current Project “Absolute Gravimetry to Observe the Fennoscandian Land Uplift” - project realization -

Denmark: absolute gravimetry with measurement tent and camper

Finland: gravimeter transportation with bars

Norway: new station Ålesund
Gravimetric Determination of the Fennoscandian Land Uplift
- conversion of measured land uplift of geoid change -

From Hotine (1969): formula for the conversion of temporal gravity and height changes to geoid changes:

\[
\dot{N} = \frac{R}{4\pi\gamma} \int_H \dot{H}(\psi) \left( \dot{g} + \frac{2\gamma}{r} \dot{h} \right) d\sigma,
\]

mit \( H(\Psi) = \left( \sin \frac{\Psi}{2} \right)^{-1} - \ln \left( 1 + \left( \sin \frac{\Psi}{2} \right)^{-1} \right). \)

\( \dot{N} \): temporal geoid changes,
\( \dot{h} \): ellipsoidal height changes,
\( \dot{g} \): gravity changes,
\( \gamma \): normal gravity,
\( R \): mean Earth's radius,
\( r \): radius of the computation point P,
\( \Psi \): spherical distance between P and surface element \( d\sigma \).

- combination of gravimetry and GPS is needed,
- accuracy of both measurement types should be in accordance to each other, e.g. ±2 µGal und ±1 cm.