Characterization of an Atom Interferometer Gravimeter with Classical Sensors for the Use in Geodesy and Geophysics

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Motivation

- Absolut Gravimetry is dominated by laser interferometers with falling corner cubes

- In recent years a number of Atom Interferometer (AI) gravimeters have been developed
  - AOSense & $\mu$Quans: commercial quantum gravimeter
  - LNE Syrte: Cold Atom Gravimeter
  - IQ LUH: in development (QUANTUS modification)

- HU Berlin: Gravimetric Atom Interferometer (GAIN)
  - Characterization by comparison with SCG and AG
Agenda

- Motivation
- Atom interferometry
- Geodetic Observatory Wettzell 2013: GAIN + GWR SCG
- Onsala Space Observatory 2015: GAIN + GWR SCG + FG5X
- Summary and Conclusion
Atom interferometry

simplified observation eq.

\[ P_{F=2} = \frac{1}{2} [1 - \cos(\Delta \Phi)] \]

\[ \Delta \Phi = k_{eff} g T^2 \]
Atom interferometry

$g$-experimental sequence

1. Magneto-Optical-Trap $\rightarrow$ preparation of atoms
2. State selection
3. Light – atom interaction
4. Detection of state populations
5. Tip/tilt mirror $\rightarrow$ vertical alignment and Coriolis
6. Vibration isolation

cycle rate of $g$-measurement: 1.5 s
November 2013

Two weeks of measurements

In parallel to SG-30

Determination of scale factor with $4 \times 10^{-4}$ uncertainty

Calibration with FG5: $1 \times 10^{-3}$ [Francis and van Dam., (2002), van Camp et al., (2015)]

Difference to $g_{ref}$: $62 \pm 64 \text{ nm s}^{-2}$

Error budget dominated by magnetic effect

Hysteresis of vibration isolation revealed
Onsala Space Observatory 2015: GAIN + GWR SCG + FG5X

Four week campaign in February

- OSG-054 and GAIN: precision → almost 4 weeks of recordings
- FG5X-220 and GAIN: absolute accuracy → switch of positions after 4 days

Improvements of GAIN after Wettzell

- Magnetic shielding of MOT → quicker setup of instrument → removal of systematic effect
- Readjustment of vibration isolation
- Post-correction for residual vertical mirror movement [Le Gouët et al., (2008)]
Onsala Space Observatory 2015: GAIN + GWR SCG + FG5X

AGU Fall Meeting
San Francisco | 14–18 December 2015
Difference of GAIN and OSG-054 from 30 minute averages.
OSO 2015 vs. Wettzell 2013

Difference GAIN – SCG (RMS: 3 nm s\(^{-2}\)/6 nm s\(^{-2}\)).
OSO 2015 vs. Wettzell 2013

Allan deviation of GAIN – SCG.

Allan deviation [g] vs. averaging time [s]

- Blue dots: Onsala
- Red dots: Wettzell

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Pillar AC ($\sigma = 5 \text{ nm s}^{-2}$) and AA ($\sigma = 9 \text{ nm s}^{-2}$) with the $\bar{g}$ of each pillar subtracted.
RMS of Seismometer vs. AG (FG5X-220 from 4.2.-12.2. and GAIN from 7.2.-12.2.).
Summary and Conclusion

Results GAIN

- Continuous operation with minor down time
- Improvement of sensitivity to $< 1 \times 10^{-10} g$
- Difference to FG5X-220 mean $g$-result $32 \pm 39 \text{ nm s}^{-2}$
- Error budget dominated by wavefront aberration
  [Schkolnik et al. (2015)]
- Confirmation of SCG scale factor with uncertainty $2.6 \times 10^{-4}$
Summary and Conclusion

Results FG5X-220

- Measurements under unfavorable conditions due to microseismic activity

- Results fit to land-uplift determined with previous FG5 Measurements [Timmen et al. (2015)]

- Currently no indication for orientation dependent instrumental effect → improvement over FG5-220 [Gitlein, (2009)]
Summary and Conclusion

Next Steps

- Comparison with SCG essential for characterization of AI sensitivity and identification of instrumental effects
- Reduction of systematic effect
- Participation in international comparison of absolute gravimeters
Thank you for your attention

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Van Camp, M., Meurers, B., de Viron, O., Forbriger, T.:
Optimized strategy for the calibration of superconducting gravimeters at the one per mille level.

Francis, O., van Dam, T.:
Evaluation of the precision of using absolute gravimeters to calibrate superconducting gravimeters.

Gitlein, Olga:
Absolutgravimetrische Bestimmung der Fennoskandischen Landhebung mit dem FG5-220.
Wissenschaftliche Arbeiten der Fachrichtung Geodäsie und Geoinformatik Nr. 281, (2009)

Le Gouët, J., Mehlstäubler, T.E., Kim, J., Merlet, S., Clairon, A., Landragin, A., Pereira Dos Santos, F.:
Limits to the sensitivity of a low noise compact atomic gravimeter.

Niebauer, T. M., Sasagawa, G. S., Faller, J. E., Hilt, R., Klopping, F.:
A new generation of absolute gravimeters

Schkolnik, V., Leykauf, B., Hauth, M., Freier, C., Peters, A.:
The effect of wavefront aberrations in atom interferometry.

Timmen, L., Engfeldt, A., Scherneck, H.-G.:
Observed secular gravity trend at Onsala station with the FG5 gravimeter from Hannover.
Annex: ambiguity solution

Fringes with different $T$ from scanning $\alpha$: $\Delta \Phi = (k_{eff} g - \alpha) \cdot T^2 + \Delta \phi_L$
Annex: Microseismic activity recorded by OSG-054

Time derivation of 1 Hz SCG data.
Annex: Error budget

GAIN systematic error budget for the 2nd campaign. Values for the 1st campaign are denoted with an asterisk. The bias was subtracted from gravity measurements.

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>Bias [nm s$^{-2}$]</th>
<th>Error [nm s$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raman Wavefronts</td>
<td>$-28$</td>
<td>$\pm 22$</td>
</tr>
<tr>
<td>Coriolis Effect</td>
<td>0</td>
<td>$\pm 15$</td>
</tr>
<tr>
<td>Magnetic Field Effects</td>
<td>0</td>
<td>$\pm 10$</td>
</tr>
<tr>
<td>RF Groupdelay</td>
<td>0</td>
<td>$\pm 10$</td>
</tr>
<tr>
<td>Self Gravitation</td>
<td>19</td>
<td>$\pm 5$</td>
</tr>
<tr>
<td>Ref-Laser Frequency</td>
<td>$-12</td>
<td>-10*$</td>
</tr>
<tr>
<td>Sync. Vibrations</td>
<td>0</td>
<td>92*</td>
</tr>
<tr>
<td>AC Stark Shift (1PLS)</td>
<td>0</td>
<td>$\pm 5$</td>
</tr>
<tr>
<td>Rb Background Vapor</td>
<td>5</td>
<td>$\pm 3$</td>
</tr>
<tr>
<td>AC Stark Shift (2PLS)</td>
<td>0</td>
<td>$\pm 2$</td>
</tr>
<tr>
<td>Vertical Alignment</td>
<td>0</td>
<td>1*</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$-16</td>
<td>77*$</td>
</tr>
</tbody>
</table>
Annex: Absolute gravity comparisons

<table>
<thead>
<tr>
<th>First Campaign</th>
<th>Gravity</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nm s$^{-2}$</td>
<td>nm s$^{-2}$</td>
</tr>
<tr>
<td>GAIN gravity value</td>
<td>9 808 369 285</td>
<td>±61</td>
</tr>
<tr>
<td>meas. height correction</td>
<td>400</td>
<td>±10</td>
</tr>
<tr>
<td>Reference value</td>
<td>9 808 369 623</td>
<td>±18</td>
</tr>
<tr>
<td>Difference GAIN–Ref.</td>
<td>62</td>
<td>±64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second campaign</th>
<th>Gravity</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nm s$^{-2}$</td>
<td>nm s$^{-2}$</td>
</tr>
<tr>
<td>GAIN gravity value</td>
<td>9 817 158 312</td>
<td>±32</td>
</tr>
<tr>
<td>meas. height correction</td>
<td>727</td>
<td>±10</td>
</tr>
<tr>
<td>Reference value</td>
<td>9 817 159 023</td>
<td>±20</td>
</tr>
<tr>
<td>Difference GAIN–Ref.</td>
<td>32</td>
<td>±39</td>
</tr>
</tbody>
</table>

Comparison of absolute gravity values. The vertical gravity gradient was determined previous to GAIN measurements.