Estimating the gravity field impact on a 10 meter atom interferometer

G43B-1061

M. Schilling[1] D. Schlippert[2] C. Schubert[2] E. Wodey[2] C. Meiners[2] W. Ertmer[2] E.M. Rasel[2] J. Müller[1]

[1]Institut für Erdmessung and [2]Institut für Quantenoptik Leibniz Universität Hannover

Abstract

A large variety of scientific experiments as well as common applications require more and more precise knowledge of gravity g, its derived quantities, and their change in time. For several phenomena the effect on g can be modelled for any given location, e.g., Earth tides and the redistribution of mass in the ocean and the atmosphere. Considering the desired sensitivity of future instruments, these models have to be evaluated for their suitability. The gravitational effect of the instrument itself is typically either neglected or determined once and assumed to be stable. Local changes in gravity, e.g., changes in the groundwater table at a laboratory, are often neglected. The vertical gradient in gravity is assumed to be linear and stable in time and, depending on the size of the experiment, this often is a valid assumption. In case of the Very Long Baseline Atom Interferometer [1, VLBAI], a 10 m vertical atom interferometer currently being installed at Leibniz Universität Hannover/HITec with the scope of precise gravity, gravity gradient measurements and tests of the universality of free fall, higher order corrections have to be estimated. This is especially relevant, since the instruments extends over three floors, experiencing non-linear gravity variations when passing the concrete floor of the building. Additionally, the impact of the instrument itself and its supporting structure has to be evaluated. Since the VLBAI has the potential to serve as a reference providing g for the comparison with classical gravimeters in the future, a transfer of g from the effective measuring height of the atom interferometer to a location accessible with an absolute gravimeter is required. Thus, changes in the local gravity field have to be investigated for their effect on the gradient within the instrument.

Very Long Baseline Atom Interferometer (VLBAI) see G43B-1060

The VLBAI extends the baseline of current atom interferometers, e. g., transportable gravimeters or experiments designed for micro-gravity, from some cm or dm to 10 m. In its initial phase of operation the atoms of two atomic species are dropped from the top of the instrument. In a later phase atoms will also be launched from the bottom, increasing the time in free fall. The main applications and research goals are in geodesy and fundamental physics [1]:

- absolute gravimetry with $1 \times 10^{-9}\,\mathrm{m\,s^{-2}}$ accuracy
- gradiometry with better than $5 \times 10^{-10}\,\mathrm{s^{-2}}$ accuracy
- quantum test of the universality of free fall (UFF)/Eötvös ratio at 7×10^{-13} level

In the gravimeter and the UFF test, gravity gradients have to be modelled at a level of $<3 \times 10^{-7}\,\mathrm{s^{-2}}$.

HITec - Hannover Institute of Technology

The Hannover Institute of Technology (HITec) is a research building, currently under construction at Leibniz Universität Hannover. It is focused on basic and applied research in the fields of quantum physics and geodesy. The VLBAI atomic fountain is one of three major large-scale facilities. The Einstein Elevator for experiments in micro-gravity and a fibre drawing system for space qualified applications are the other two.

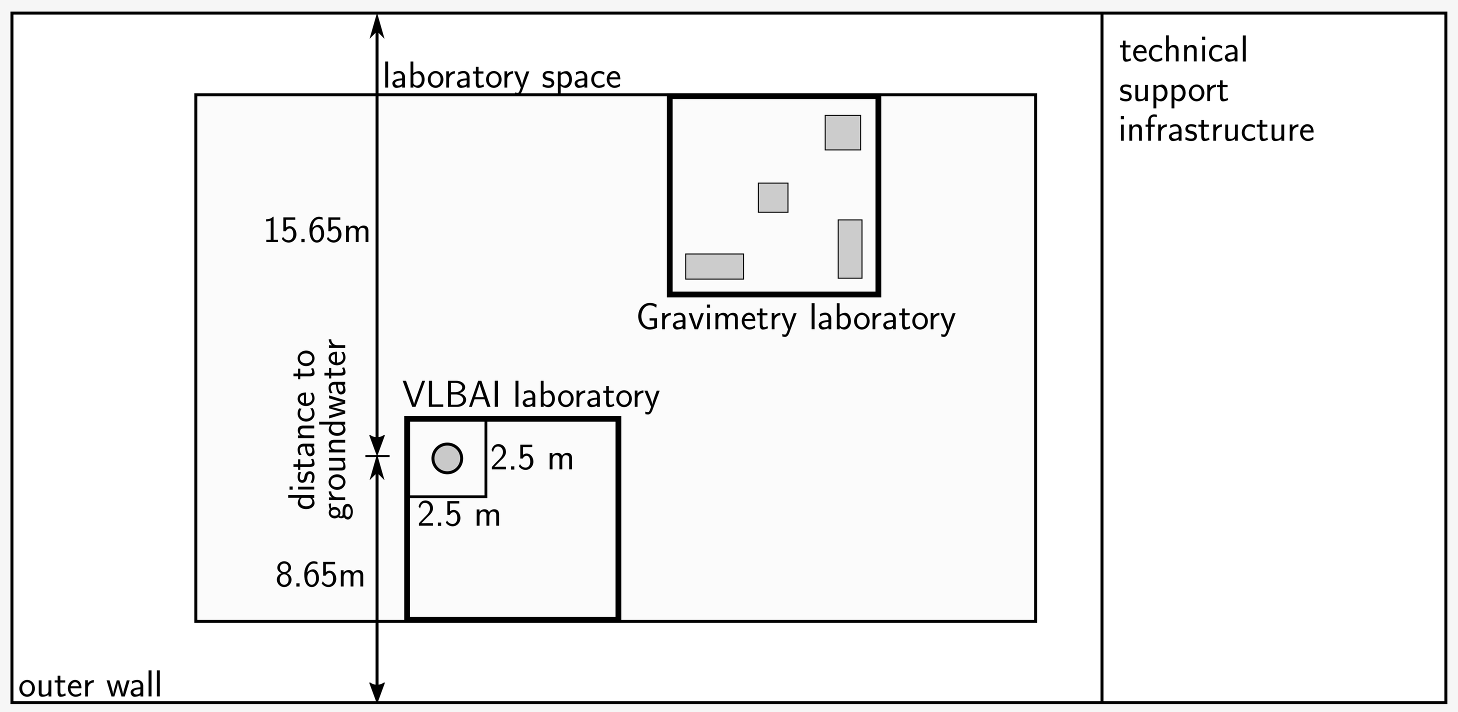
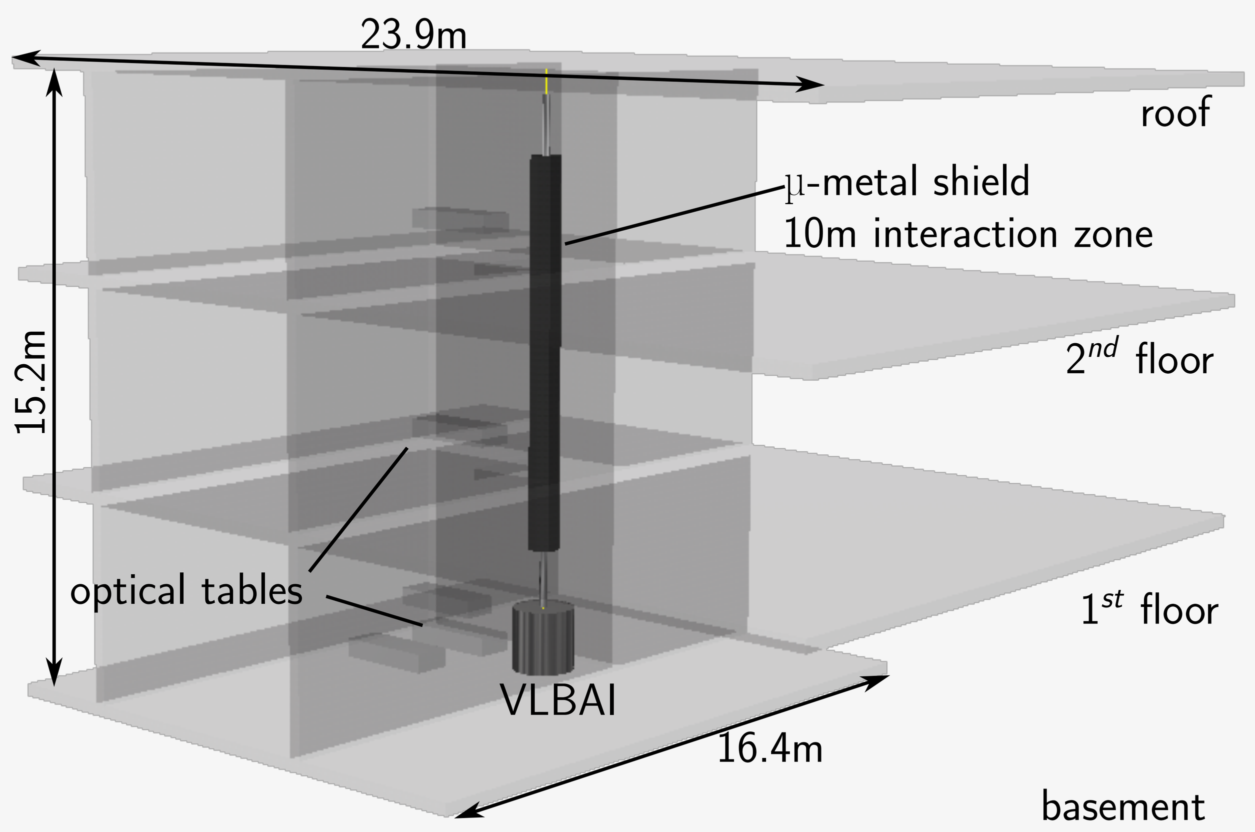


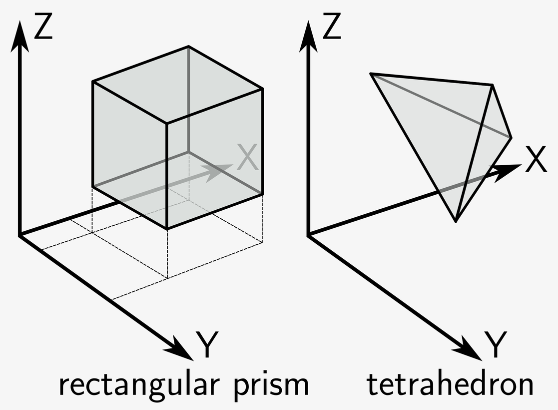
Fig. 1: Schematic view of HITec with location of VLBAI and gravimetry laboratories with dedicated pillars.

The basement level is 4.85 m below the surface and within the groundwater table. The average amplitude of seasonal groundwater change is 30 cm with a maximum of 60 cm. Earlier work found a pore volume of 30 % corresponding to a change in gravity of $130\,\mathrm{nm\,s^{-2}}$ for a 1 m water layer [5].

Simplified model of HITec and VLBAI



The main goal is the calculation of attractions and gradients along the VLBAI main axis.



Gravitational effects are modelled by rectangular prism [2]:

- concrete shell of building with dimensions according to construction plan
- optical tables with weight/dimension from available laboratory equipment

Gravitational effects are modelled by polyhedral bodies [3]:

- established methods used to generate tetrahedra from polyhedral bodies
- complex geometry and density of materials of VLBAI instrument from current design

Gravitational Attraction

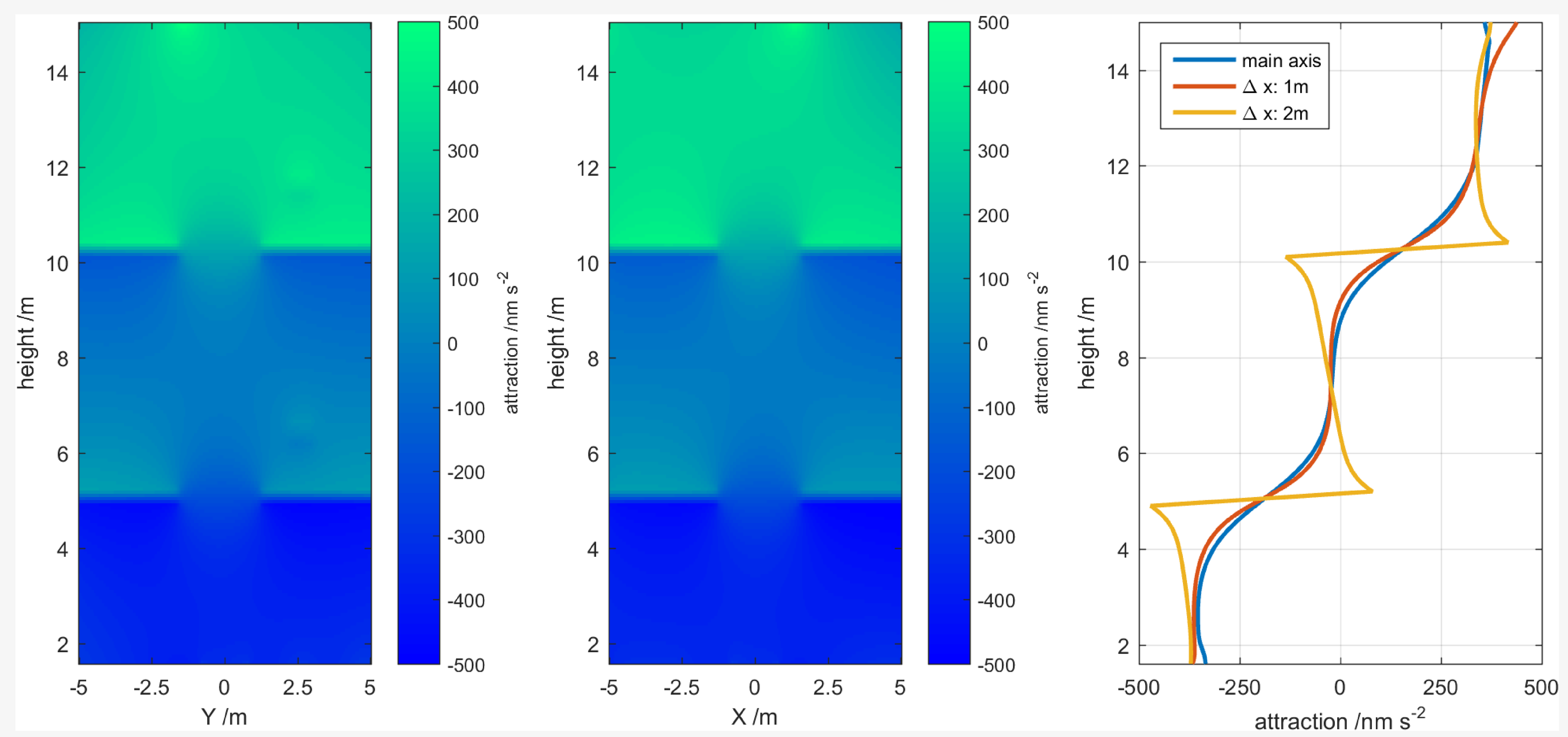


Fig. 2: Gravitational attraction of the complete model in the near-field of the VLBAI.

Figure 2 *left* and *center* show the attraction in the YZ-plane and XZ-plane respectively. The structures in the figure are caused by the concrete floor and optical tables in the YZ-plane. On the *right* only the effect on the central axis and in a distance of 1 m and 2 m in X direction is shown. The effect in a distance of 1 m is within $\pm 20\,\mathrm{nm\,s^{-2}}$ except for the last meter. The steps in 2 m distance result from the position of the calculation point inside a floor.

The location of VLBAI inside the building is fixed, so the effect of the building can be determined once. However, Laboratory equipment can be rearranged. The effect of the optical tables (400 kg each) is $2.5\,\mathrm{nm\,s^{-2}}$ at a distance of 2.2 m. Moving these tables to a distance of 1.25 m increases the effect to $4.5\,\mathrm{nm\,s^{-2}}$, which is above the aspired absolute accuracy.

Gradients

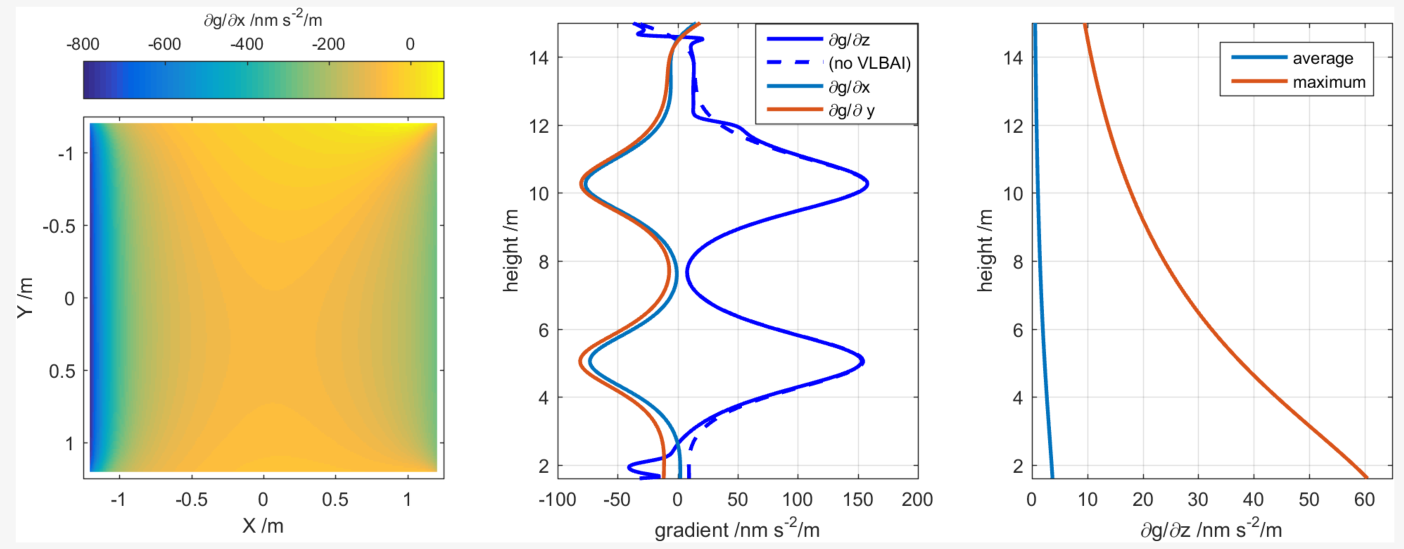


Fig. 3: Horizontal and vertical gradients in gravity.

Figure 3 *left* shows the horizontal gradients in X direction in the opening of the first floor. The centre of the plot is the VLBAI main axis. The vertical and horizontal gradients on the VLBAI main axis are shown in the *centre*. The blue and the dashed blue lines are the vertical gradients. The dashed line is the gradient without the VLBAI itself. The light blue and the red line are the horizontal gradients. The largest gradients, positive and negative, are calculated for the parts of the main axis, when the first and second floor is passed. In the *right* plot the influence of groundwater level changes on the vertical gradient is shown. The blue/red line corresponds to the average/maximum amplitude of groundwater level changes during one year.

Gravimetric Methods

As shown in the *centre* plot of figure 3, the vertical gradients reaches up to $150\,\mathrm{nm\,s^{-2}\,m^{-1}}$. This is the effect of the model only and it cannot be separated from the overall gradient, which is easily measured using relative gravimeters [4]. Figure 2 shows the attraction along the main axis and 1 m away, the closest a relative gravimeter can be deployed.They are almost identical. This suggests the gradient can be monitored next to the VLBAI and compared to VLBAI measurements once it is operational.

Conclusions

- Local gravity affects experiments in the VLBAI.
- A first model of HITec and the VLBAI for attraction and gradients is demonstrated.
- The modelled effects are in an order of magnitude that can be verified with gravimetry.

→ The combination of modelling and gravimetry should be used for testing and experiments in the VLBAI.

Next steps (depending on construction progress)

- Implement local gravity network with connection to existing absolute measurements

Acknowledgements

The authors would like to thank the DFG Sonderforschungsbereich (SFB) 1128 Relativistic Geodesy and Gravimetry with Quantum Sensors (geo-Q) for financial support.

References

[1] J. Hartwig, S. Abend, C. Schubert, D. Schlippert, H. Ahlers, K. Posso-Trujillo, N. Gaaloul, W. Ertmer, and E. M. Rasel. Testing the universality of free fall with rubidium and ytterbium in a very large baseline atom interferometer. *New Journal of Physics*, 17(3):035011, 2015.

[2] X. Li and M. Chouteau. Three-dimensional gravity modeling in all space. *Surveys in Geophysics*, 19(4):339–368, 1998.

[3] V. Pohanka. Optimum expression for computation of the gravity field of a homogeneous polyhedral body. *Geophysical Prospecting*, 36(7):733–751, 1988.

[4] L. Timmen. Absolute and relative gravimetry. In G. Xu, editor, *Sciences of Geodesy - I*, chapter 1. Springer, Berlin – Heidelberg, 2010.

[5] L. Timmen, O. Gitlein, J. Müller, G. Strykowski, and R. Forsberg. Absolute gravimetry with the Hannover meters JILAg-3 and FG5-220, and their deployment in a Danish-German cooperation. *Zeitschrift für Geodäsie, Geoinformation und Landmanagement*, 133:149–163, 2008.

Created with LaTeX beamerposter

Leibniz Universität Hannover
Institut für Erdmessung
Schneiderberg 50
30167 Hannover | Germany

AGU Fall Meeting | San Francisco | USA
December 12th – 16th 2016

Manuel Schilling
schilling@ife.uni-hannover.de