Gravity field modelling for the Hannover 10 m atom interferometer

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Interferometry with cold atoms and lasers

- Atom interferometry is a versatile tool in
  - Fundamental physics (e.g. test of GR)
  - Geodesy and Geophysics (improving sensors e.g. for Earth observation)
- Current developments
  - Gravimeters (for air, sea, land deployment)
  - Inertial sensors (for navigation and accelerometry)
  - Demonstrator missions in microgravity / space (e.g. (BEC)CAL, MAIUS, QUANTUS)

This work focuses on combining classical gravimetry with a large-scale atom interferometer for

- Determination of the AI error budget
- Realising a gravimetric reference

Atom interferometry concept

Cold atoms as test masses in an interferometer

Leading order phase shift $\Delta\Phi$

$$\Delta\Phi = \mathbf{k}_{\mathrm{eff}} \cdot \mathbf{a}T^2$$

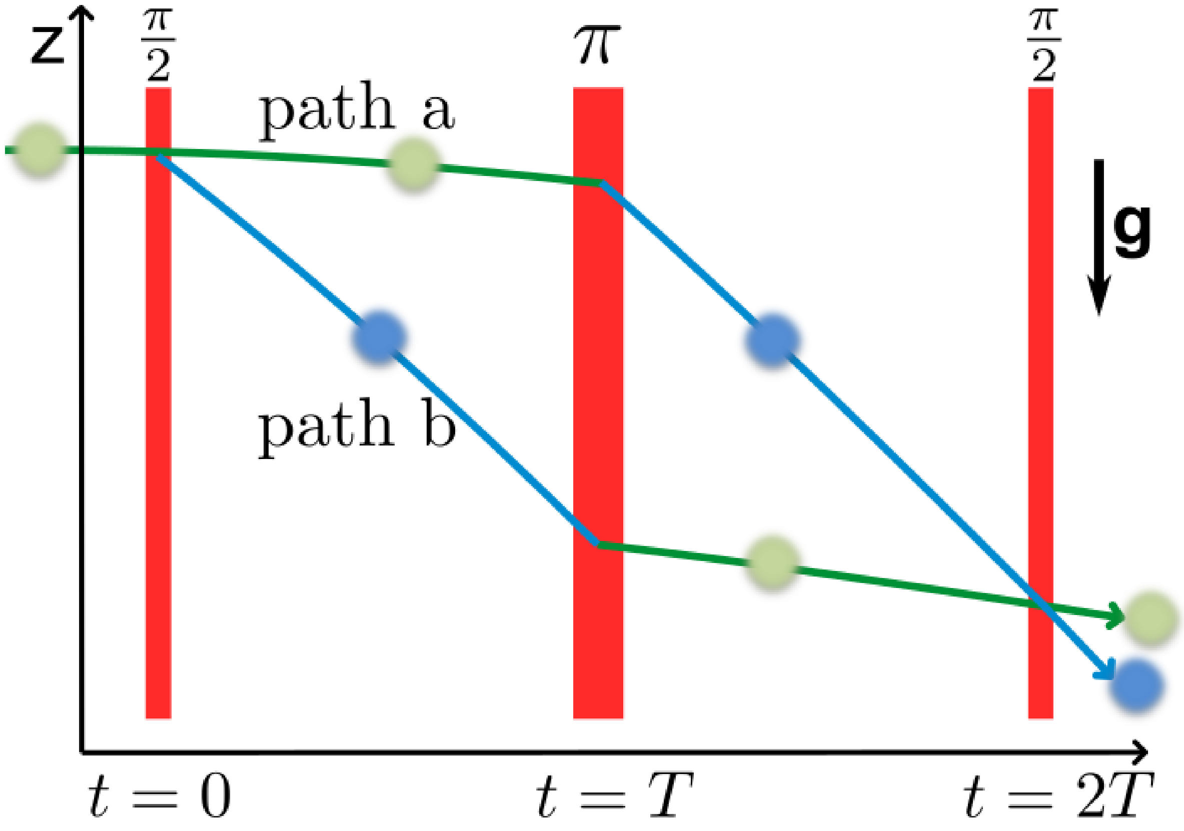
Gravimeter / VLBAI: $\mathbf{k}_{\mathrm{eff}} \parallel \mathbf{g}$

$$\Delta\Phi = k_{\mathrm{eff}} \left(g - \frac{\alpha}{k_{\mathrm{eff}}} \right) T^2$$

Frequency chirp α (partly) compensates acceleration of atoms

Measurement: population *P* of atoms per state

$$P_{|e\rangle} = \frac{1}{2} \left(1 - \cos \Delta\Phi\right)$$

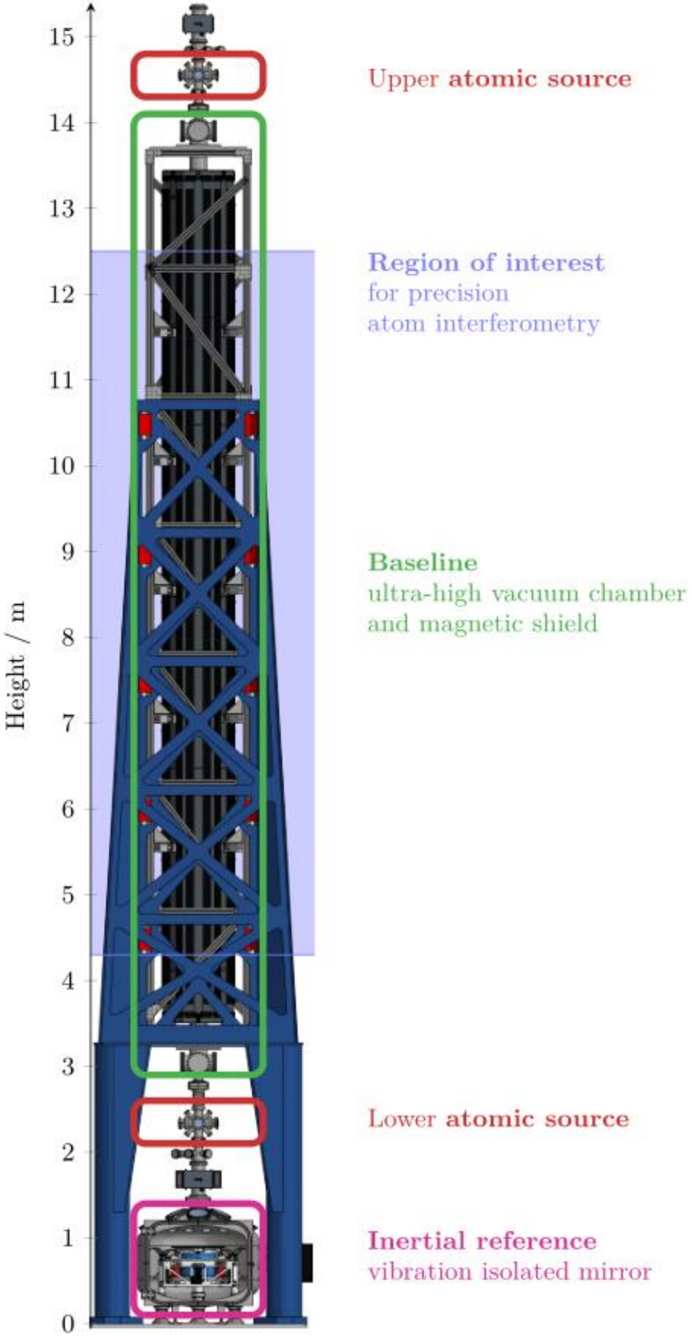


Mach-Zehnder light-pulse atom interferometer

Very Long Baseline Atom Interferometry

- Atomic sources: Rb and Yb
  - Drop: $T=400\ \mathrm{ms}$
  - Launch: $T=1.2\ \mathrm{s}$
- Baseline: 10 m magnetic shield and vacuum system [Wodey2020]
- Region of interest: defined by magnetic field gradient
- Inertial reference: based on gravitational wave detector vibration isolation [Wanner2012]

The Very Long Baseline Interferometry facility is part of the Hannover Institute of Technology (HITec) [Schlippert2020].

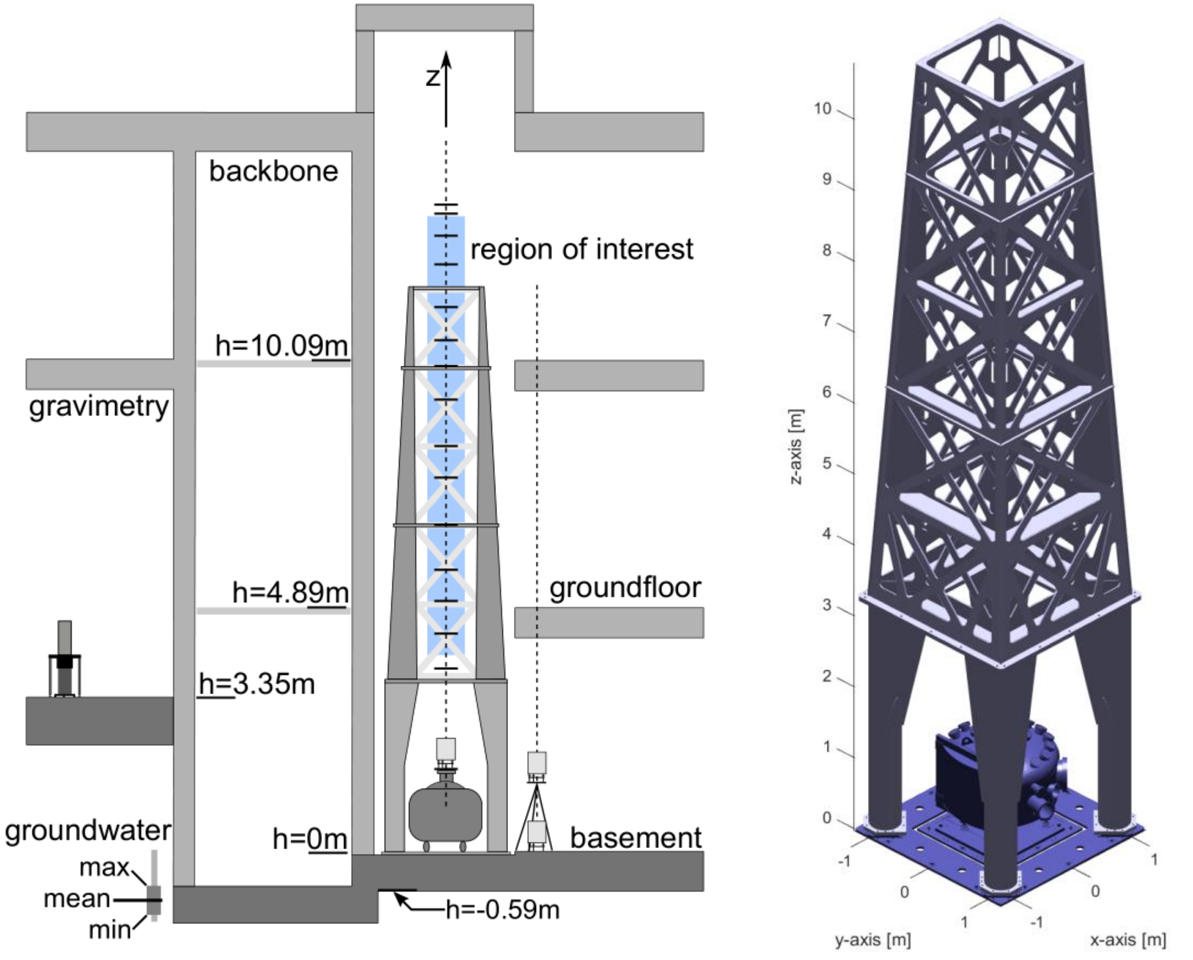


Model of HITec

Model includes

- Building (concrete, drywall, insulation…)
- Equipment
  - Support structure (VSS) ≈ 5800 kg
  - Baseplate and vacuum tank (VTS) ≈ 2800 kg
  - Optical tables ≈ 600 kg (some nm/s²)
  - Einstein Elevator ≈ 160 t (some 10 nm/s²)
- Environment
  - Basements for estimation of groundwater effect and gradient

Heights refer to the baseplate and are verified by levelling.



HITec cross-section (not to scale) with gravity network and VLBAI support structure with vacuum tank for inertial reference

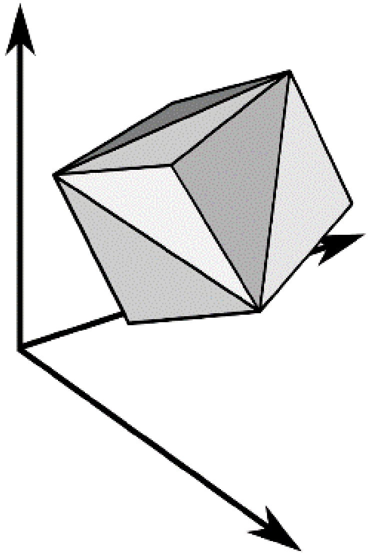
Model of HITec

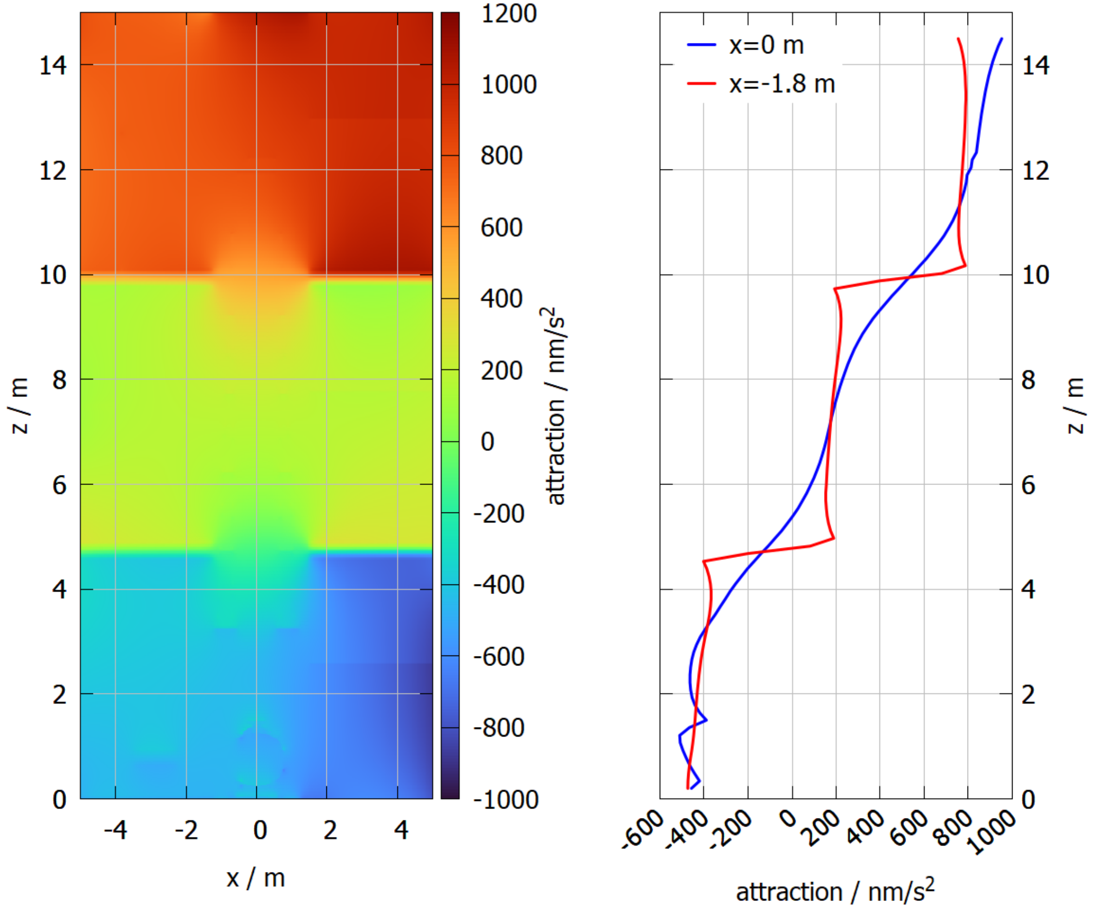
HITec Building

- Rectangular prisms (>500 Elements)

VLBAI: VSS and VTS

- Polyhedral bodies of uniform density
- Triangular mesh of surface,
  e.g. export from CAD
- Calculate attraction [Pohanka1988]





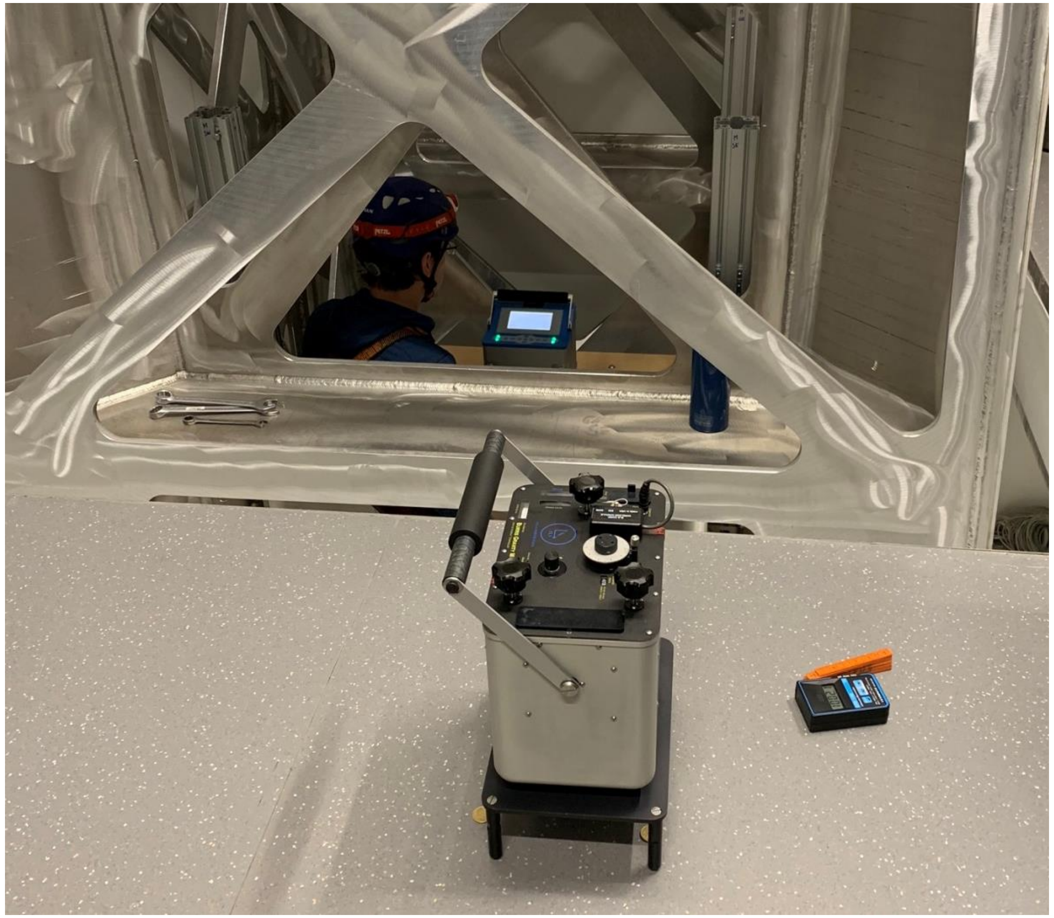
Gravitational attraction of building, laboratory equipment, VSS and VTS in the xz-plane and on two vertical profiles

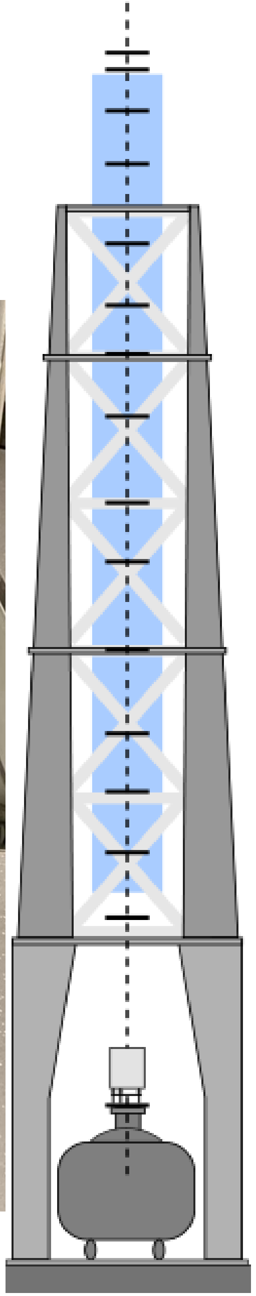
See also [Schilling2020]

Gravimetric network 2019

- Three gravimeters
  - Scintrex CG3M-4492, CG6-0171, ZLS B-64
  - 16 levels on VLBAI main axis
  - 9 levels on secondary profile
  - 439 gravity differences

- Least squares adjustment
  - Adjusted *g*: $\bar{\sigma}_g = 9\ \mathrm{nm/s^2}\ (7 - 19\ \mathrm{nm/s^2})$
  - Single gravity tie: $\sigma_{dg} = 15 - 60\ \mathrm{nm/s^2}$





Monte Carlo simulations

Density of building materials and surrounding soil
- ±5% variation of density of each element
- Normal distribution
- 50000 runs

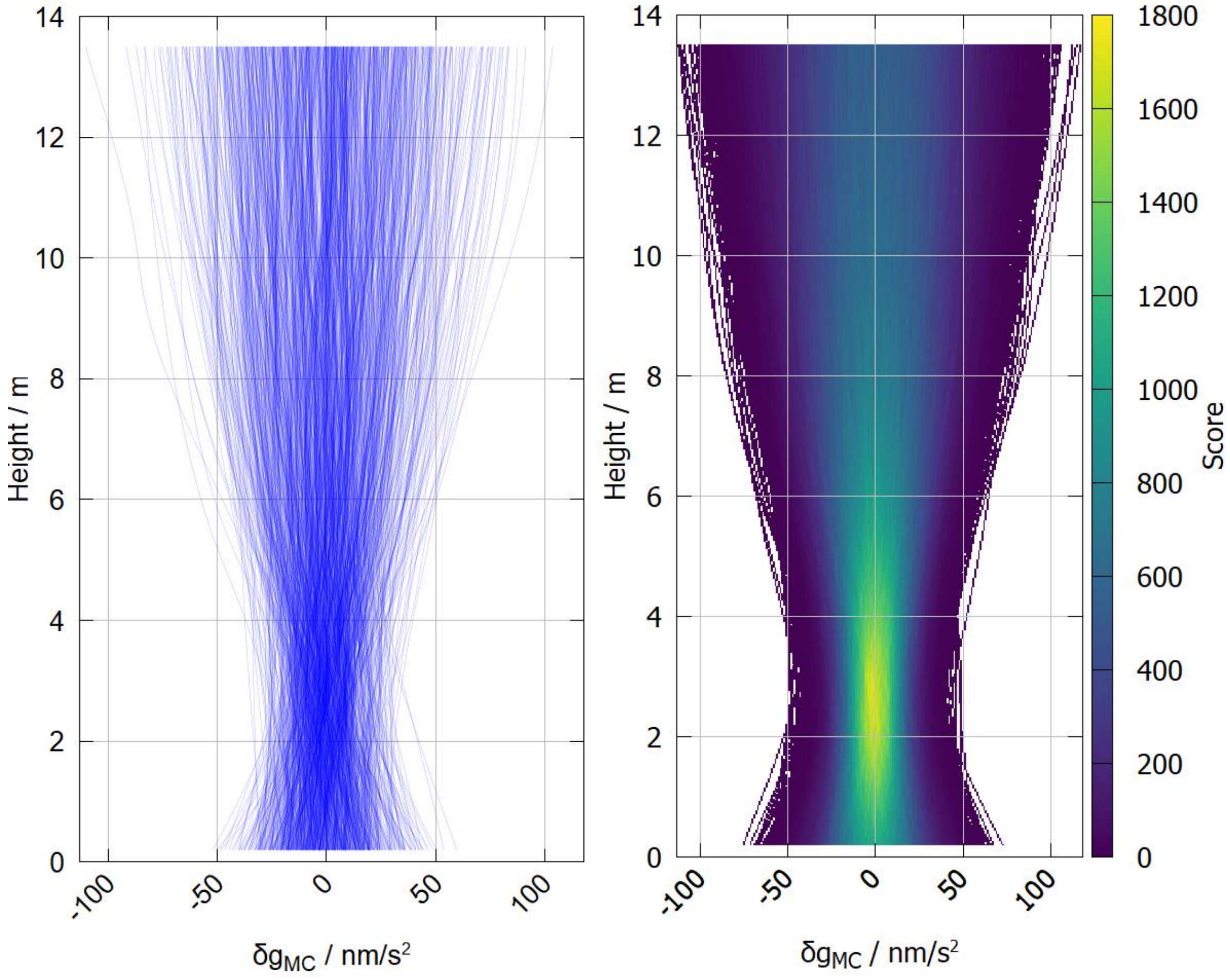
No simulation for VSS/VTS density

Position of VLBAI main axis and gravimeter
- Horizontal position ±3 cm
- Vertical position ±2 mm

Standard deviations of model and observations

$$\sigma_{\mathrm{mod}} = \sqrt{\sigma^2_{\mathrm{MC}} + \sigma^2_{\mathrm{hz,mod}}}$$

$$\sigma_{\mathrm{obs}} = \sqrt{\sigma^2_{\mathrm{g}} + \sigma^2_{\mathrm{h,geo}} + \sigma^2_{\mathrm{z,mod}} + \sigma^2_{\mathrm{grad}}}$$



Subset (left) and heatmap (right) of <u>all</u> density-simulations with respect to model-density

Results 2019: main axis

$$\sigma_{\text{mod}} = \sqrt{\sigma^2_{\text{MC}} + \sigma^2_{\text{hz,mod}}} \approx 6 - 11\,\text{nm/s}^2$$

$$\sigma_{\text{obs}} = \sqrt{\sigma^2_{\text{g}} + \sigma^2_{\text{h,geo}} + \sigma^2_{\text{z,mod}} + \sigma^2_{\text{grad}}} \approx 14 - 36\,\text{nm/s}^2$$

Statistical test 95% confidence level

$$\text{Null hypothesis: } \delta g_{\text{omc},i} = \delta g_{\text{obs},i} - \delta g_{\text{mod},i} = 0$$

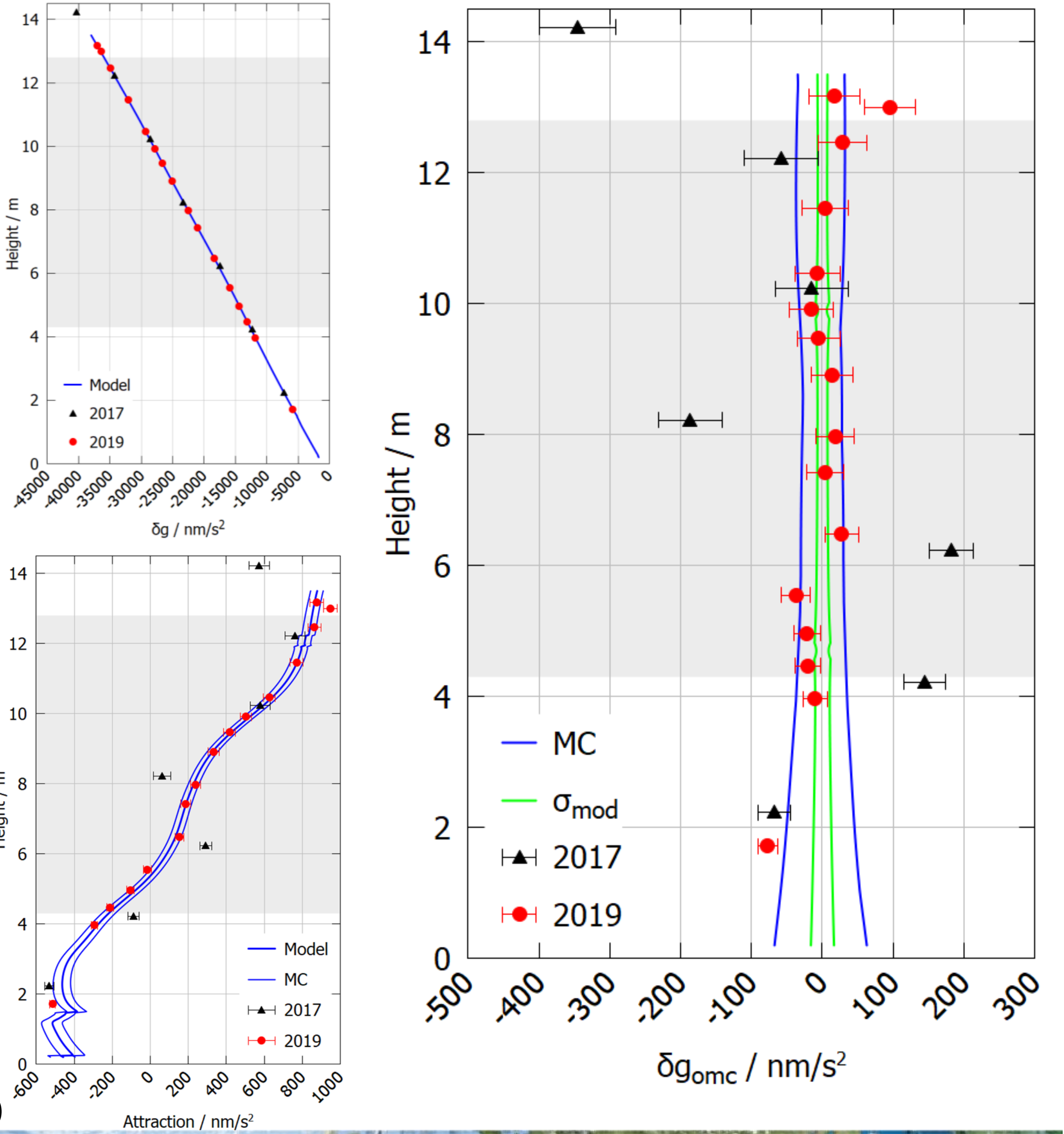
$$\text{Alternative hypothesis: } \delta g_{\text{omc},i} \neq 0$$

$$\text{Test statistics: } t_i = \frac{|\delta g_{\text{omc},i}|}{\sqrt{\sigma^2_{\text{obs},i} + \sigma^2_{\text{mod},i}}}$$

$$\text{Rejection criteria: } t_i > N_{(0,1,1-\frac{\alpha}{2})}$$

Test fails for points at 1.72 m and 12.99 m.
→outside of region of interest

$$\sigma_{\text{residuals}} = 20\,\text{nm/s}^2$$



Total gravity change (top left), gravitational attraction (bottom left) and gravity residuals (right)

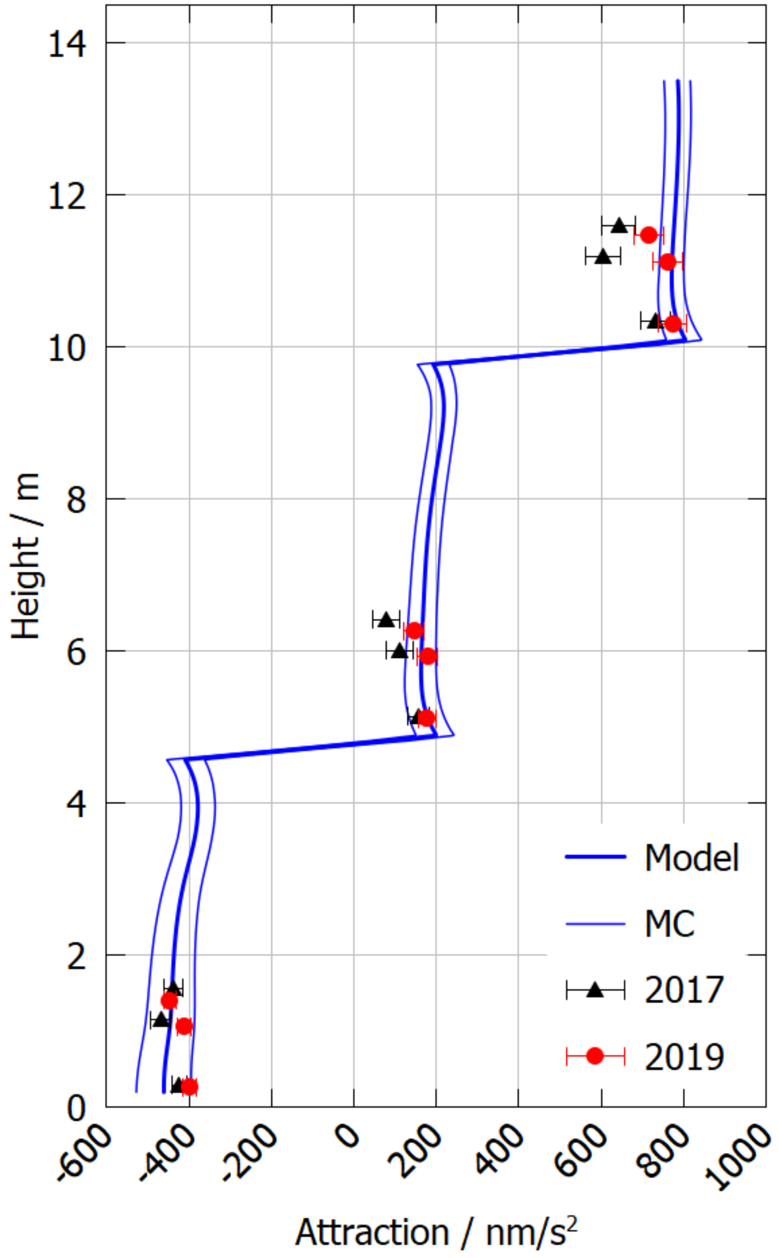
Results 2019: secondary axis

- Results of 2017 show better match compared to main axis
- 2019: statistical test passed
- $\sigma_{\text{residuals}} = 34\ \text{nm/s}^2$

Also used as constraint, e.g. improvement on main axis do not degrade results on secondary axis.

To do improving current model:

- Estimate more diverse densities (building)
- More complex geometry (soil around building)



Conclusions and outlook

- Modelling of local gravity field demonstrated
- Verification with gravimetric methods
- Agreement on 95% confidence level

Delivery of baseline
December 2019

Next steps

- Add VLBAI-baseline to model
- Gravimetric measurements for verification
- Characterisation of temporal gravity changes (e.g. groundwater level variations)
- Determine ‘transfer function’ between main and secondary axis

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