Vertical Gravity Profile in a 10 m Atom Interferometer

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11th March 2020

Absolute gravimeters are used in geodesy, geophysics, and physics for a wide spectrum of applications. Stable gravimetric measurements over timescales from several days to decades are required to provide relevant insight into geophysical processes. Instrumental accuracy is established by the comparison with a reference apparatus. However, since no reference gravimeter of higher-order accuracy currently exists, absolute gravimeters participate in group comparisons led by the International Committee for Weights and Measures. The construction of stationary, large scale atom interferometers paves the way towards new absolute gravimetry references with a potential stability better than $1 \text{ nm/s}^2$ at 1 s integration time. At the Leibniz University Hannover, we are currently building such a very long baseline atom interferometer with a 10 m long interaction zone. The knowledge of local gravity and its gradient along and around the baseline is required to establish the instrument’s accuracy budget and enable transfers of gravimetric measurements to nearby devices for comparison and calibration purposes. We therefore established a control network for relative gravimeters and repeatedly measured its connections during the construction of the atom interferometer. We additionally developed a 3D model of the host building and studied the impact of mass changes due to hydrology on the gravity field around the reference instrument. The adjusted model fits the results of the latest gravimetric measurement campaign with 95\% confidence, opening the way for transfers of gravimetric measurements beyond the $10 \text{ nm/s}^2$ level.

Keywords: atom interferometry, gravity acceleration, gravimetry, gravimeter reference

1 Introduction

A variety of applications in geodesy, geophysics, and physics require the knowledge of local gravity $g$ (Van Camp et al., 2017). These applications include observing temporal variations of the mass distribution in the hydrosphere, atmosphere and cryosphere and furthermore the establishment and monitoring of height and gravity reference frames, the determination of glacial isostatic adjustment, and the realisation of SI units (Merlet et al., 2008; Liard et al., 2014; Schilling et al., 2017). The absolute value of gravity $g$ is usually measured by tracking the free fall of a test mass using a laser interferometer (Niebauer et al., 1993). The operation of an absolute gravimeter (AG), especially the combination of several instruments in a project, requires special consideration of the offset to true $g$ and the change thereof. In addition, the long-term stability of absolute gravimeters is of particular relevance when measuring small gravity trends. For example, the determination of the glacial isostatic adjustment (GIA) on regional scales of around 1000 km (Timmen et al., 2011) requires an instrument stable to the $20 \text{ nm/s}^2$ level over several years. Extending this effort by deploying several AGs also requires the knowledge of the bias of all the instruments involved (Olsson et al., 2019). The lack of a reference gravimeter for calibration purposes requires the participation in group comparisons. However, the development of stationary atom interferometers, which can be operated as gravimeters, may result in such a superior reference in the

\textsuperscript{1}Système International d’unités
future.

We start by discussing the typical approaches for monitoring the long-term stability of an AG and tracing the measurements back to the SI units (section 2). Then, after briefly describing the working principle of atomic gravimeters and the case for very long baseline atom interferometry (section 3), we present a gravity model for the Hannover Very Long Baseline Atom Interferometry (Hannover-VLBAI) facility, a new 10 m-scale baseline atom interferometer in commissioning at the Leibniz University Hannover (section 4). Finally, we present the micro-gravimetric surveys performed in the instrument’s site (section 5) to assess the accuracy of the gravity model (section 6). This paves the way towards systematics control in the atom interferometer and accurate transfers of measured $g$ values between the QG and classical AGs in a nearby laboratory.

## 2 Gravimeter offsets and SI traceability

Micro-g LaCoste FG5(X) or A10 (Niebauer et al., 2013) instruments represent the current state of the art in absolute gravimeters. They track the trajectories of freely falling corner cubes by means of laser interferometry to determine the local acceleration of gravity $g$. These types of absolute gravimeters are referred to as classical absolute gravimeters in the following text.

As described by the 2015 CCM-IAG Strategy for Metrology in Absolute Gravimetry (CCM-IAG, 2015), the direct way of tracing these absolute gravity measurements back to SI units goes through the calibration of their incorporated laser and oscillator to standards of length and time (Vitushkin, 2011). In high-accuracy instruments, the laser frequency is typically locked to a standard transition of molecular iodine (Chartier et al., 1993; Riehle et al., 2018). The time reference is usually given by a rubidium oscillator which needs to be regularly compared with a reference oscillator to ensure its accuracy as external higher-accuracy time sources are typically not available at measurement sites. In most cases, the oscillator’s frequency drift is linear ($<0.5$ mHz/month) and can therefore be accounted for in the instrument’s accuracy budget. However, Mäkinen et al. (2015) and Schilling and Timmen (2016) report on sudden jumps due to increased concentrations of gaseous helium (Riehle, 2004) when measuring near superconducting gravimeters. The impact of such frequency changes on the instrument’s accuracy can be as large as several tens of nm/s$^2$, if not identified. The frequency drift changes from linear to an exponential decrease after the helium event and may remain this way for years (Schilling, 2019). In the framework of the CCM-IAG AG metrology strategy, it is therefore necessary to validate the accuracy budget of individual gravity reference instruments by comparison with other reference instruments.

The equivalence of all gravity references is established by international comparisons in the framework of the CIPM MRA$^2$. Since no higher-order reference instrument is available, group comparisons are held in an approximately two year interval. There, the instruments operated by National Metrology Institutes (NMI) and Designated Institutes (DI) are used to determine the Key Comparison Reference Value (KCRV). The bias to the KCRV, or Degree of Equivalence (DoE) is then calculated for all individual instruments, including those without NMI/DI status participating in the so called pilot study, and is a measure for their accuracy.

Figure 1 shows the common participants, out of a total number of 35 gravimeters participating in the comparisons, to the last four KC held in Europe (Francis et al., 2013, 2015; Pálinkáš et al., 2017) and EURAMET.M.G-K3 (Falk et al., 2019). The participants are sorted by DoE of the first KC. The expanded uncertainty is given only for the last KC. Pilot Study (PS) indicates instruments of non NMI/DI institutions.

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$^2$Mutual Recognition Agreement of the Comité International des Poids et Mesures
around ±75 nm/s², and at a similar level for the most extreme cases of individual instruments. The individual KCs are linked by the so-called linking converter (typically around ±10 nm/s², Jiang et al., 2013) assuming that instrumental biases of the NMI/DI instruments remain small (Delahaye and Witt, 2002). Should this assumption not apply, this would introduce a shift in the international datum induced by a very small group of similar instruments. In Figure 1, the DoE of all but two participants in the last comparison (red markers) are below the previous comparison (green markers), in most cases more than 25 nm/s² and in some cases close to 50 nm/s². This is problematic since it changes measured g with respect to true gravity if these biases are applied in projects combining several AGs. Changing DoE of instruments and a non-zero linking converter can be explained by a variety of factors. For example, Olsson et al. (2016) show that a permanent change in the bias of a classical AG can occur during manufacturer service or unusual transport conditions (e.g. aviation transport). Also, Křen et al. (2017, 2019) identified, characterised and (partially) removed biases originating in the signal processing chain of FG5 gravimeters, e.g. due to cable length and fringe signal amplitude.

Quantum absolute gravimeters (QG), based on matter wave interferometry with cold atoms offer a fully independent design. They have demonstrated instabilities and inaccuracies at levels comparable to those from state of the art classical AGs by participating in KCs (Gillot et al., 2016) or common surveys with other instruments at various locations (Freier, 2017; Schilling, 2019). The availability of improved QGs as gravity references will enhance the stability of reference values obtained by key comparisons and therefore lead to a better international gravity datum.

3 Very long baseline atomic gravimetry

3.1 Atomic gravimetry

Atomic gravimeters use cold matter waves as free-falling test masses to measure absolute gravity. They exploit the coherent manipulation of the external degrees of freedom of these atomic test masses to realize space-time interferometers sensitive to inertial quantities and other forces. These techniques are for example used to perform precision measurements of fundamental constants (Rosi et al., 2014; Bouchendira et al., 2011; Parker et al., 2018), test fundamental physics (Schlippert et al., 2014; Rosi et al., 2017; Jaffe et al., 2017), sense small forces

\[ \Delta \phi = k_{\text{eff}} \cdot a T^2 \]  

where \(\hbar k_{\text{eff}}\) is the recoil transferred to the atomic wavepackets by the atom-light interaction processes, \(a\) the uniform acceleration experienced by the atoms during the interferometric sequence, and \(2T\) the total duration of the interferometer. The knowledge of the instrument’s scale factor \(k_{\text{eff}}T^2\) and the measurement of the phase \(\Delta \phi\) allow determining the projection of the acceleration \(a\) along \(k_{\text{eff}}\). When \(k_{\text{eff}}\) is vertical, such an instrument can therefore be used as a gravimeter, measuring the total vertical acceleration of the matter waves used as test masses.

The Mach–Zehnder light-pulse atom interferometer geometry works as follows. For each interferometric sequence, a sample of cold atoms is prepared in a time \(T_p\). Then, at

![Figure 2: Mach–Zehnder light-pulse atom interferometer geometry in a uniform acceleration field \(a\). At time \(t_0\), the atomic matterwave is put in a superposition of momenta \(p\) (-) and \(p + \hbar k_{\text{eff}}\) (--). The momenta are reversed at time \(t_0 + T\) to recombine the wavepackets with a last light pulse at time \(t_0 + 2T\). The populations in the two momentum classes after the last light pulse allow extracting the interferometric phase \(\Delta \phi\).](image-url)
time $t = t_0$, the first atom-light interaction pulse puts the matter wave in a superposition of quantum states with different momenta $p$ and $p + \hbar k_{\text{eff}}$, thus effectively creating two distinct semi-classical trajectories. At time $t = t_0 + T$, a second atom-light interaction process redirects the two atomic trajectories to allow closing the interferometer at time $t = t_0 + 2T$ with a third light pulse. Counting the population of atoms in the two momentum states provides an estimation of the interferometric phase $\Delta \phi$. Finally, the cycle of preparation of the cold atoms, coherent manipulation of the matter waves, and detection is repeated. Since the atom-light interaction imprints the local phase of the light on the matter waves, the above measurement principle can be interpreted as measuring the successive positions of a freely falling matter wave at known times $t_0$, $t_0 + T$, and $t_0 + 2T$. The reference frame for the measurement system is usually realized by a mirror retro-reflecting the light pulses, creating a light wave with well-defined equiphase fronts. Practically, the interferometric phase $\Delta \phi$ is scanned by accelerating the light wave at a constant rate $\alpha$, effectively tuning the differential acceleration between the matter waves and the light grating. Assuming that $k_{\text{eff}}$ and $a$ are parallel, the interferometric phase thus reads:

$$\Delta \phi = k_{\text{eff}} \left( a - \frac{\alpha}{k_{\text{eff}}} \right) T^2. \quad (2)$$

When $\alpha = k_{\text{eff}}a$, the interferometric phase vanishes independently of the interferometer’s duration $2T$, allowing to unambiguously identify this operation point. Also, the measurement of the acceleration $a$ amounts to a measurement of the acceleration rate $\alpha$ which can be traced back to SI units since it corresponds to frequency generation in the radiofrequency domain.

Assuming white noise at a level $\delta \phi$ for the detection of the interferometric phase, the instrument’s instability is given by:

$$\delta a(\tau) = \sqrt{2T + T_p} \cdot \frac{\delta \phi}{k_{\text{eff}} T^2} \cdot \frac{1}{\sqrt{\tau}} \quad (3)$$

In transportable devices, record instabilities have been achieved by Freier et al. (2016) with $\delta a = 96 \text{ nm}/\text{s}^2$ at 1 s. Commercial instruments like the Muquans AQG (Ménoret et al., 2018) reached instabilities of 500 nm/s$^2$ at 1 s with sample rates up to 2 Hz. The dominant noise source is vibrations of the mirror realizing the reference frame for the measurements.

The accuracy of such quantum gravimeters (QG) stems from the well-controlled interaction between the test masses and their environment during the measurement sequence. The main sources of inaccuracy in such instruments originate from uncertainties in the atom-light interaction parameters (e.g. imperfections of the equiphase fronts of the light grating), stray electromagnetic field gradients creating spurious forces, thus breaking the free-fall assumption, and knowledge of the inhomogeneous gravity field along the trajectories. Extensive characterization of these effects led to uncertainties in QGs below 40 nm/s$^2$, consistent with the results from CIPM key comparisons (Gillot et al., 2014) or common surveys with classical AGs (Freier et al., 2016).

3.2 Very Long Baseline Atom Interferometry

Very Long Baseline Atom Interferometry (VLBAI) represents a new class of ground-based atom interferometric platforms which extends the length of the interferometer’s baseline from tens of centimetres like in typical transportable instruments (Freier et al., 2016; Gillot et al., 2014) to multiple meters. According to equation [1], the acceleration sensitivity of a Mach–Zehnder type atom interferometer scales linearly with the length of the baseline ($\sim a T^2$). Therefore, an increase in the length of the baseline potentially enables a finer sensitivity for the atomic gravimeter through an increased scale factor $k_{\text{eff}} T^2$. A 10 m-long baseline instrument can for example extend the interferometric time $2T$ to 800 ms if the atoms are simply dropped along the baseline or up to 2.4 s if they are launched upwards in a fountain like fashion.

Using realistic parameters ($T_p = 3$ s, $\delta \phi = 10 \text{ mrad}$), equation [3] yields potential short-term instabilities for VLBAIs (1 s integration time):

$$T = 400 \text{ ms}: \quad \delta a = 8 \text{ nm}/\text{s}^2$$
$$T = 1.2 \text{ s}: \quad \delta a = 1 \text{ nm}/\text{s}^2 \quad (4)$$

competing with the noise level of superconducting gravimeters (Rosat and Hinderer, 2011; Rosat et al., 2018) while providing absolute values of the gravity acceleration $g$.

Nevertheless, the increased scale factor $k_{\text{eff}} T^2$ gained by the expanded baseline comes at the price of a stationary device with added complexity due to its size, and a vibration noise sensitivity magnified by the same scale factor as the gravitational acceleration for frequencies below $1/(2T)$. In particular, time- and space-varying electromagnetic and gravity fields along the free-fall trajectories of the matter waves have a direct impact on the accuracy and stability of the instrument, as the corresponding spurious forces depart from the assumptions of
equation (1), therefore leading to biases (D’Agostino et al., 2011) and impacting the instrumental height (Timmen, 2003).

3.3 The Hannover VLBAI facility

We introduce the Hannover Very Long Baseline Atom Interferometry (VLBAI) facility, an instrument developed at the newly founded Hannover Institute of Technology (HITec) of the Leibniz University Hannover, Germany. It builds on the concepts outlined in section 3.2 to provide a platform to tackle challenges in extended baseline atom interferometry. In the long term, it aims at tests of fundamental physics like for example the universality of free fall (Hartwig et al., 2015) but also other searches for new physics, and new methods for absolute gravimetry and gravity gradiometry (Schlippert et al., 2019).

The Hannover VLBAI facility is built around three main elements shown in figure 3:

1. Ultra cold samples of rubidium and ytterbium atoms are prepared in the two source chambers, allowing for both drop (max $T = 400$ ms) and launch (max $T = 1.2$ s) modes of operation. Advanced atom-optics promise enhanced free-fall times by relaunching the wavepackets during the interferometric sequence (Abend et al., 2016);

2. The reference frame for the inertial measurements is realized by a seismically isolated mirror at the bottom of the apparatus. The seismic attenuation system (SAS) uses geometric anti-spring filters (Wanner et al., 2012) to achieve vibration isolation above its natural resonance frequency of 320 mHz. The isolation platform is operated under high vacuum conditions to reduce acoustic and thermal coupling. The vacuum vessel containing the SAS is denoted VTS in sections 4-6;

3. The 10.5 m-long baseline consists of a 20 cm diameter cylindrical aluminium vacuum chamber and a high-performance magnetic shield (Wodey et al., 2019). The interferometric sequences take place along this baseline, in the 8 m-long central region of interest where the longitudinal magnetic field gradients fall below 2.5 nT/m.

In order to decouple the instrument from oscillations of the walls of the building, the apparatus is only rigidly connected to the foundations of the building. The
VTS (and SAS) and lower source chamber are mounted on a baseplate directly connected to the foundation. The baseline and upper source chamber are supported by a 10 m high aluminium tower, denoted as VLBAI support structure (VSS) in the following sections. The total footprint of the device on the floor is 2.5 m × 2.5 m. Traceability to SI units is ensured by locking the instrument’s frequency references to standards at the German NMI (PTB Braunschweig) via an optical link (Raupach et al., 2015). All heights are measured from the instrument’s baseplate. The altitude of this reference point in the German height datum is 50.545 m.

4 Environmental model

The VLBAI facility is implemented in the laboratory building of the Hannover Institute of Technology. The building consists of three floors (one underground, two above street level) and is divided in a technical part containing namely the climate control systems, and a section with the laboratories (see figure 4a). In the laboratory part, a so-called backbone gives laboratories access to the technical infrastructure and divides the building in two parts along its long axis. The backbone and southern row of laboratories have a footprint of 13.4 m × 55.4 m and are fully underground, approximately 5 m beneath the surface. The northern row of laboratories is fully above ground except for the gravimetry laboratory which is on an intermediate level, around 1.5 m below the street level and 3.4 m above the basement level (see figure 4a). The foundation of the building is 0.5 m thick except beneath the gravimetry laboratory, which has a separate 0.8 m foundation.

4.1 Physical model

Following the methods described by Li and Chouteau (1998), we discretise the HITec building into a model of rectangular prisms that accounts for more than 500 elements. The geometry is extracted from the construction plans, and we verified all the heights by levelling. The building is embedded in a sedimentary ground of sand, clay, and marl (2050 kg/m³). For the edifice itself, we include all walls and floors made of reinforced concrete (2500 kg/m³), the 7 cm to 13 cm thick liquid flow screed covering the concrete floors in the labs (2100 kg/m³), and the gypsum drywalls (800 kg/m³). We also incorporate the insulation material (150 kg/m³) and gravel on the roof (1350 kg/m³). We use a simplified geometry to model the large research facilities in the surroundings.

This is for example the case for the Einstein Elevator (Lotz et al., 2018), a free fall simulator with a weight of 165 t and horizontal distances of 32 m and 16 m to the VLBAI facility and gravimetry laboratory, respectively. Finally, we account for laboratory equipment, e.g. optical tables (550 kg each) according to the configuration at the time of the gravimetric measurement campaigns.

During the first measurements (2017), the interior construction was still in progress, and the laboratories were empty. By the time of the second campaign (2019), the building was fully equipped. The VLBAI support structure (VSS) and the vacuum tank (VTS) for the seismic attenuation system were in place. The VLBAI instrument (atomic sources, magnetic shield, 10 m vacuum tube) and seismic attenuation system were completed after the second campaign.

Due to their inclined or rounded surfaces, the VLBAI experimental apparatus and its support structure require a more flexible method than rectangular prisms to model their geometry. We apply the method described by Pohánka (1988) and divide the surface of the bodies to be modelled into polygonal faces to calculate the gravitational attraction from surface integrals. Contrary to the rectangular prisms method, there are only few restrictions on the underlying geometry. Most notably, all vertices of a face must lie in one plane and the normal vectors of all surfaces must point outward of the mass. For example, normal vectors of faces describing the outside surface of a hollow sphere must point away from the sphere and normal vectors on the inside surface must point towards the centre, away from the mass of the wall of the sphere. We extract the geometry of the VLBAI facility components from their tridimensional CAD model through an export in STL format. This divides the surface of the bodies into triangular faces, therefore ensuring planar faces by default. Moreover, the STL format encodes normal vectors pointing away from the object. Both prerequisites for the polygonal method by Pohánka (1988) are thus met. Using this method, the VSS (aluminium, 2650 kg/m³, total weight 5825 kg) consists of roughly 86 000 faces and the VTS and corresponding baseplates (stainless steel, 8000 kg/m³, total weight 2810 kg) contain 187 000 faces, mostly due to the round shape and fixtures of the VTS. As the overall computation time to extract the attraction of these components remains in the range of minutes, we do not need to simplify the models.

We use MATLAB to perform the numerical calcula-

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3 stereolithography or standard triangulation language
4 MATLAB Version 9.4.0.813654 (R2018a)
Figure 4: Views of HITec: cross-section (a) of the VLBAI laboratories with the gravimetric network of 2019 along two vertical profiles and area of interest (blue). The indicated groundwater variation (thick bar) refers to an average annual amplitude of 0.3 m. The thin bars indicated extreme low and high levels. The top view of HITec (b) shows the orientation of our coordinate system, the location of the VLBAI facility (blue) and the gravimetry lab including piers for gravimeters (light grey).

visions. As a cross-check, we implemented both the rectangular prisms and polyhedral bodies methods for the calculation of the attraction effect of the main frame of the HITec building. Both approaches agree within floating point numerical inaccuracy.

Finally, we include the effects of groundwater level changes, atmospheric loading, and solid Earth tides. Previous investigations in the gravimetry lab of a neighbouring building showed a linear coefficient of 170 nm/s² per meter change in the local groundwater table (Timmen et al., 2008). Two automatic groundwater gauges are available around the building: one installed during the construction work and the other with records dating back several decades. The effect of atmospheric mass changes is calculated using the ERA5 atmospheric model provided by the European Centre for Medium-Range Weather Forecasts and the methods described by Schilling (2019). Tidal parameters are extracted from observational time series. Other temporal gravity changes are not in the scope of this work.

4.2 Self-attraction results

Figure 5 shows the vertical component of the gravitational acceleration generated by the building, equipment, VSS and VTS. The VLBAI main axis is in the centre of the left plot ($x = 0$ m). The large structures around 5 m and 10 m correspond to the floor levels. Smaller structures are associated to, for example, optical tables or the VSS. The right panel of figure 5 highlights the attraction calculated for the main axis ($x = 0$ m) and for a second profile along $x = -1.8$ m and $y = 0$ m. The first profile shows a smooth curve except for the bottom 2 m, which are affected by the VTS. In this model, the part above 2 m on the main axis is empty space. The second profile passes through the floors, hence the zigzag features around 5 m and 10 m. While the main axis will later be occupied by the instruments baseline, the validation profile represents a location that will always remain accessible to gravimeters.

4.3 Effect of groundwater level changes

Based on the extensive groundwater level recordings from the gauge nearby the HITec building, we study the impact of groundwater level changes on gravitational attraction inside the building, specifically along the VLBAI main and validation profiles, as well as in the gravimetry laboratory.

Due to the layout of the building concerning the different basement levels, the change of the groundwater table

https://www.ecmwf.int
Figure 5: Calculated gravitational attraction from the building, large laboratory equipment, VSS and VTS in the xz-plane (left) and exemplarily on two profiles (right).

affects gravity in the VLBAI laboratories differently as in the gravimetry lab. Depending on the groundwater level, the foundation beneath the VLBAI laboratories can be partially within the groundwater table, whereas this is never the case for the gravimetry laboratory. As shown on figure 4a, the mean groundwater table is nevertheless below the level of the foundation below the VLBAI laboratories. Therefore, at certain points of the average annual cycle of amplitude 0.3 m, the groundwater table will rise only around the foundation of the VLBAI laboratories, whereas its level will still increase below the gravimetry laboratory. This effect is even more stringent for years where the average cycle amplitude is exceeded (around one in four years).

Figure 6 illustrates the different influence of the groundwater table level on gravity in the VLBAI and gravimetry laboratories. The change of gravity $\delta g_{gw}$ corresponding to groundwater level variations based on the existing time series is presented for different heights above the gravimetry pier and along the VLBAI main axis. As the groundwater level is always changing directly beneath the instrument piers in the gravimetry laboratory, we expect an almost linear change of gravity with changing groundwater level. The change of gravity is also almost independent of the height above the pier, as shown by the almost identical lines for $h = 0$ m directly on the pier and at $h = 1.4$ m, slightly over the instrumental height of the FG5X gravimeter. Therefore, AGs with various sensor heights, e.g., A-10 and FG5X, are affected in the same manner. The increase of $\delta g_{gw}$ is $38 \text{ nm/s}^2$ in an average year. This behaviour is different in the VLBAI laboratories. Once the groundwater level reaches the lower edge of the foundation, gravity will not increase linearly along the VLBAI main axis as the groundwater rises further. Moreover, in this situation, the effect has a different magnitude depending on the height in the room. In a year with the average amplitude of groundwater level variation (ca. $0.3$ m), $\delta g_{gw}$ will differ by $5 \text{ nm/s}^2$ between basement and the upper floor. In years exceeding the average groundwater variation, the difference between the basement and upper levels increases further. This effect is similar on the validation profile, to $1 \text{ nm/s}^2$.

These observations will be crucial when comparing AGs in the gravimetry laboratory to the VLBAI facility operated as a quantum gravimeter. Depending on the topology of the atom interferometer, the instrumental height of the VLBAI gravimeter changes and can introduce changes in the measured value of $g$ of more than $10 \text{ nm/s}^2$ as a result of the groundwater effect.

In order to track the effect of groundwater level changes more accurately, we plan to extend the findings of Timmen et al. (2008) by correlating periodic measurements on the validation profile in the VLBAI facility.
laboratories with the recordings of the two groundwater level gauges around the building. This should in particular allow us to take into account that, due to capillarity effects, the groundwater level will probably not sink uniformly below the foundation beneath the VLBAI laboratories once it reaches that level.

5 Gravimetric measurements

In June 2017 and August 2019, we performed surveys using relative gravimeters to verify our model from section 4 along the VLBAI main and validation profiles. This approach was already demonstrated in Schilling et al. (2017), in which the gravity field impact of a 200 kN force standard machine at the Physikalisch-Technische Bundesanstalt in Braunschweig was modelled. That model was verified with gravimetric measurements prior and after the installation of the force machine. The difference between the modelled impact and the measurement was within the uncertainty of the gravimeters used. For each measurement point, we measured its connection to at least another point and applied the step method with ten connections (Torge and Müller, 2012). A connection corresponds to one gravity difference observation between two points. Ten connections require five occupations of a measurement with a gravimeter. We measured most connections with at least two different instruments, reducing the outcomes to a mean instrumental height of 0.22 m above ground or platform.

We then performed a global least-squares adjustment using the Gravimetry Net Least Squares Adjustment software from the Institute of Geodesy (IFE) of the Leibniz University Hannover (GNLSA, Wenzel, 1985). In order to account for instrumental drift in the global adjustment, we treat each day and type of measurement independently and use a variance component estimation to weight the measurements in the global network adjustment.

5.1 2017 gravimetry campaign

We first mapped the gravity profile along the VLBAI profiles in June 2017, when the HITec building was still under construction and the VLBAI experimental apparatus not yet installed. Using the Scintrex CG3M-4492 (short CG3M) and ZLS Burris B-144 (B-114) spring gravimeters (Timmen and Gitlein, 2004; Schilling and Gitlein, 2015), we measured a total of 147 connections between seven positions spaced by ca. 2 m along the VLBAI main axis, nine positions on the validation profile, and two points outside of the building. We used scaffolding to access the measurement points on the main axis. However, although the scaffold was anchored against the walls, the uppermost platforms were too unstable to ensure reliable measurements. The B-114 was only able to measure on the bottom three positions, so the four upper levels were only occupied by the CG3M. We connected each point on the scaffold to another one on the same structure and to the closest fixed floor level, at a point part of the validation profile. As shown in figure 4a, the validation profile included measurements on the floor and on different sized tripods to determine the gradients.

The variance component estimation gives a posteriori standard deviations for the instruments of 50 nm/s² for the B-114 and 100 nm/s² and for the CG3M. The standard deviations for the adjusted gravity values range from 15 nm/s² to 42 nm/s² with a mean value of 28 nm/s². The standard deviations of the adjusted gravity differences vary from 21 nm/s² between fixed floor levels to 59 nm/s² between consecutive levels on the scaffold. The transfer of height from the upper floor to the basement through the intermediate levels on the scaffold showed a 2 mm discrepancy compared to the heights from levelling. We included the corresponding 2 mm · 3 nm/s²/mm = 6 nm/s² as a systematic uncertainty for the adjusted gravity values for the values measured on the scaffold. We also account for an 1 mm uncertainty on the measurement of the instrumental height.

5.2 2019 gravimetry campaign

We mapped the gravity profile along the VLBAI axes in a more extensive manner in Summer and Fall 2019. Most measurements were performed in one week of August 2019, adding two days in October and November 2019. We installed moveable platforms inside the VSS, installed in June 2019, and could measure on 16 levels on the main axis, spaced by 0.45 m to 0.95 m. The scheme for the validation profile did not change. The layout of the network is depicted on figure 4a. For this campaign, we used the CG3M, the Scintrex CG6-0171 (CG6), and ZLS Burris B-64 (B-64) spring gravimeters (Timmen and Gitlein, 2004; Schilling and Gitlein, 2015; Liu et al., 2019). Owing to the high mechanical stability of the VSS, measurements along the main axis were unproblematic for all instruments and the measurement noise was at a similar level on the moveable platforms and on the fixed floors. All but one position were oc-
ocupied with at least two gravimeters, amounting to 439 connections in the network adjustment.

The a posteriori standard deviations range from 15 nm/s² to 60 nm/s² with more than 50% below 30 nm/s². The higher standard deviations are a result of two days of measurements with the CG3M and connections to two particular positions outside of the area of interest of the VLBAI. The standard deviations of adjusted gravity differences in the network range from 7 nm/s² to 19 nm/s². This improvement, compared to the previous campaign, can be attributed to the stability of the VSS, the addition of the CG6 and the total number of measurements performed. The height of the moveable platforms inside the VSS was determined by a combination of levelling and laser distance measurement to two fixed platforms and the ceiling. For the height determination of the platforms, the uncertainty is 1 mm due to the laser distance measurement. We also account for an 1 mm uncertainty in the determination of the instrumental height above the platforms.

6 Combination of model and measurement

The measurement and model results along the VLBAI main and validation profiles are presented in figure 7. Figure 7a shows the total variation of gravity along the main axis. The plot is dominated by the normal decrease of gravity with height. The effect of the building can be better seen when removing the change of gravity with height and visualizing only the attraction effect of the building and laboratory equipment, as on figure 7b. There, the model corresponds to the configuration for the building and laboratory equipment, as on figure 7b. The effect of the building and walls, drywalls, etc. can be better seen when removing the change of gravity with height. The effect of the building is modified with a model of the soil surrounding HITec. As the density is only known to a certain degree, the Monte Carlo simulation also included the ground around HITec. The standard deviation of the simulation results for each gravimeter position is added to the measurements standard deviation by error propagation. The simulations’ standard deviations range from 10 nm/s² at the height of 4 m and increase to 35 nm/s² at the topmost position. This is also reflected in the increase in the standard deviations indicated by the errorbars in figure 7c.

The standard deviation of the measurements now consists of the following components:

\[
\sigma_{\text{obs}} = \sqrt{\sigma_{g}^{2} + \sigma_{h,\text{geo}}^{2} + \sigma_{z,\text{mod}}^{2} + \sigma_{\text{grad}}^{2}}. \tag{5}
\]

There, the standard deviation of the network adjustment is \(\sigma_{g}\). The contribution of the determination of the height of the gravimeter is \(\sigma_{h,\text{geo}}\). The result of the Monte Carlo simulations of the vertical component of geometric position of the central axis \(\sigma_{z,\text{mod}}\), and the modelling of the gravity gradient \(\sigma_{\text{grad}}\) are also attributed to the measurements.

The standard deviation of the model consists of the following components:

\[
\sigma_{\text{mod}} = \sqrt{\sigma_{\text{MC}}^{2} + \sigma_{h,\text{mod}}^{2}}. \tag{6}
\]

The standard deviation of the Monte Carlo simulations of the model density, e.g., in the heights of the gravimetric measurements, is \(\sigma_{\text{MC}}\). The standard deviation of the Monte Carlo simulations of the VLBAI central axis geometric positions horizontal component is \(\sigma_{h,\text{mod}}\).

Furthermore, a single parameter is estimated to reduce the gravity values from the magnitude of 9.81 m/s² to the order of magnitude of the model values for the
attraction. This parameter is the mean difference of observed minus computed results at the location of the observation in the area of interest. The measurements of 2017 are also corrected for the changes within the building with respect to 2019. No additional parameters were estimated to fit the measurements to the model or vice versa. The remaining signal should now contain the effect of the HITec on gravity.

In general, the 2017 measurements and the main axis model do not show a good agreement (see also Schilling, 2019) due to the instability of the scaffolding used as a platform (see also Greco et al., 2014). The agreement on the validation profile is better, and only the two topmost points do not agree with the model and simulation. These earlier measurements serve as a proof of concept and are given for the sake of completeness. The following discussion concerns only the results of the 2019 measurements.

The 2019 campaign provides a clear improvement considering the number of stations along the VLBAI main axis, the stability of the platforms in the VSS and therefore data quality. Consequently, the agreement between measurement and model is significantly improved. The measurement scheme on the validation profile remained unchanged compared to the 2017 campaign. Figure 7 shows the difference of the measurements and the model on the central axis. The area of interest for experiments in the VLBAI is approximately between 4 m and 13 m (see figure 3). Within this region, only the second-highest point is not within the simulation’s ±5% variations. The two tailed statistical test (α = 0.05) on the equality of model δgmod,i and measurement δgobs,i at point i according to

Null hypothesis:  δgome,i = δgobs,i − δgmod,i = 0
Alternative hypothesis:  δgome,i ≠ 0

Test statistics:  \( t_i = \frac{|δg_{ome,i}|}{\sqrt{σ^2_{obs,i} + σ^2_{mod,i}}} \)

passes for all but three points. The null hypothesis, considering the symmetry of the normal distribution, is rejected if \( t_i > N(0,1,1−α/2) \). The test fails for the points at \( h = 1.72 \text{ m}, 5.55 \text{ m} \) and 12.99 m.

The lowest point at \( h = 1.72 \text{ m} \), directly on the VTS, was challenging to measure, as the pump of the vacuum tank was active during the measurements causing high-frequency vibrations. As this position is outside of the experimental region of interest, no additional measurements were taken. The cause for the significant deviation from the model at \( h = 12.99 \text{ m} \), which was measured with only one gravimeter, is unknown. The height difference to the point above is only 0.16 m of free space,
so a real gravity variation appears unlikely. Treating this point as an outlier, and repeating the test after calculating the offset between adjusted gravity values and model without this measurement, the test also passes for the point at $h = 5.55$ m. All points on the validation profile pass the statistical test. The standard deviation of observations minus model is $20\,\text{nm/s}^2$ ($31\,\text{nm/s}^2$ if the second-highest point is included) for the central axis in the area of interest and $34\,\text{nm/s}^2$ on the validation profile.

The density of the different model components, chosen initially from technical documentation, are sufficient to generate a model which is identical to in situ measurements at a $95\%$ confidence level. Modelling a $5\%$ normally distributed variation of these densities results in a narrow range of possible model variations, which covers almost all measurements used to verify the model. We expect that using individual densities for each floor instead of one common density value for all concrete components in the building would improve the agreement between model and observations on the validation profile. Such extra modelling step should however be constrained not to deteriorate the model accuracy in the experimental region of interest.

As a final step, the VLBAI magnetic shield and vacuum system (Wodey et al., 2019, installed December 2019) will be added to the model. Comparable to the VSS and VTS, this device was designed using CAD, can be exported into the required format for our model and was built with known materials. While the assembly is significantly more complex, we expect the octagonal symmetry of the magnetic shield to simplify the numerical calculations and allow us to reach the same level of accuracy in the gravity model as for the VSS and VTS. It will however only be possible to check the quality of the extended model with measurements on the validation profile, as the main axis is obstructed by the instrument’s vacuum chamber. Nevertheless, the understanding of environmental variations (mostly hydrology) outlined in section 4.3 will render this possible with good accuracy. Due to the work associated with the installation of the VLBAI baseline components, this last model extension and its corresponding validation have not been done yet.

Extending our model with the VLBAI baseline components will allow us to connect gravimetric measurements along the validation profile and future data acquired by a VLBAI quantum gravimeter along its main axis in our adjusted gravimetric network. Since the measurement positions along the validation profile will remain free during operation of the VLBAI facility, this will for example enable comparisons of the VLBAI QG with FG5(X)-type classical AGs positioned in the VLBAI laboratories. In this specific setup, contributions of time variable gravity to the measurements are minimal for the VLBAI and instrument under test. Thus we expect to be able to transfer $g$ with an uncertainty below $10\,\text{nm/s}^2$ from the VLBAI baseline. Furthermore, creating a similar network including stations along the validation profile and in the HiTec gravimetry laboratory would permit gravimetric comparisons between the VLBAI QG and instruments operated on the gravimetric piers.

### 7 Conclusions

We established a gravimetric control network for the Hannover VLBAI facility, a novel 10 m-scale atom interferometer. The network consists of 439 connections measured by relative gravimeters. A least squares adjustment of the network results in a mean standard deviation of the adjusted gravity values of $9\,\text{nm/s}^2$. In addition, we developed a structural model of the building hosting the VLBAI facility and its surroundings. When compared, the model and the measurements agree with $95\%$ confidence, with standard deviations of the residuals of $20\,\text{nm/s}^2$ along the atom interferometer’s baseline, and $34\,\text{nm/s}^2$ on a second, parallel profile. Moreover, we gained insight on some dynamical aspects of the gravity field around the instrument, namely the effect of groundwater level variations.

We anticipate this gravimetric network to contribute to the assessment of the quantum gravimeter’s accuracy budget evaluation, but also to help determining the effective instrumental height ($g$-value reference position) and enable transfers of $g$ values from the atom interferometer’s baseline to the validation profile, accessible to mobile gravimeters for comparison and calibration purposes, beyond the $10\,\text{nm/s}^2$ level. Completing the model by including the VLBAI baseline, refining the description of the soil surrounding the host building, and including better estimates for the building material densities, we expect to open the possibility for gravity field measurement transfers and mobile instrument calibration at the $5\,\text{nm/s}^2$ level, almost an order of magnitude beyond the current state of the art from group comparisons. This paves the way towards the realization of a new gravity standard based on atom interferometry. Finally, the knowledge of the dynamical gravity field and its gradients is key to reaching new frontiers in funda-
mental physics tests with very long baseline atom interferometry.

Acknowledgements. The Hannover Very Long Baseline Atom Interferometry facility is a major research equipment funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). This work was supported by the DFG Collaborative Research Center 1128 “geo-Q” (project A02) and is supported by the CRC 1227 “DQ-mat” (project B07), Germany’s Excellence Strategy – EXC-2123 “QuantumFrontiers” – 390837967, and the computing cluster of the Leibniz University Hannover under patronage of the Lower Saxony Ministry of Science and Culture (MWK) and the DFG.

M. S., E. W., and C. S. acknowledge support from “Niedersächsisches Vorab” through the “Quantum-and-Nano-Metrology (QUANOMET)” initiative (project QT3) and for the initial funding of research in the DLR-SI institute. D. S. acknowledges funding from the German Federal Ministry of Education and Research (BMBF) through the funding program Photonics Research Germany (contract number 13N14875).

The VLBAI support structure was conceived by the engineering office Heinz Berlin (Wennigen, Germany) in collaboration with the VLBAI science team, and produced by Aljo Aluminium-Bau Jonuscheit GmbH (Berne, Germany).

We thank W. Ertmer for his vision and long lasting support on very long baseline atom interferometry and the acquisition of funding for the Hannover Institute of Technology. We are grateful to T. Frobøse and A. Wanner for their assistance during the installation of the vacuum tank and support structure.

Author contributions. M.S., É.W., L.T. planned geometric and gravimetric measurements, evaluated the data and prepared the initial draft. É.W., D.T., D.S., C.S., E.M.R. conceptualised VSS, VTS. É.W., D.T., K.H.Z. designed and built measurement platforms for VSS. M.S., É.W., L.T., D.T., K.H.Z. carried out the measurements. M.S. developed and implemented the gravity model. D.T., K.H.Z., D.S., C.S., E.M.R., J.M. provided critical input to the manuscript and approved the final version.

Data availability statement. Data of KC are available in the Key Comparison Database (https://www.bipm.org/kcdb) and cited literature. The datasets generated and analysed in this study are available from the corresponding author on reasonable request.

References

Abend, S., M. Gebbe, M. Gerseemann, H. Ahlers, H. Müntinga, E. Giese, N. Gaaloul, C. Schubert, C. Lämmerzahl, W. Ertmer, W. P. Schleich and E. M. Rasel (2016). “Atom-chip fountain gravimeter”. In: Phys. Rev. Lett. 117.20, 203003. doi:10.1103/PhysRevLett.117.203003

Alauze, X., A. Bonnin, C. Solaro and F. Pereira Dos Santos (2018). “A trapped ultracold atom force sensor with a μm-scale spatial resolution”. In: New Journal of Physics 20.8, 083014. doi:10.1088/1367-2630/aad716 arXiv:1807.05860 [physics.atom-ph]

Bouchendira, R., P. Claudé, S. Guellati-Khélifa, F. Nez and F. Briberen (2011). “New determination of the fine structure constant and test of the quantum electrodynamics”. In: Phys. Rev. Lett. 106.8, 080801. doi:10.1103/PhysRevLett.106.080801 arXiv:1012.3627 [physics.atom-ph]

CCM-IAG (2015). CCM – IAG strategy for metrology in absolute gravimetry - role of CCM and IAG. Last Update 2015-01-28. URL: http://www.bipm.org/wg/AllowedDocuments.jsp?wg=CCM-WGG (visited on 2019-08-05).

Chartier, J.-M., J. Labot, G. Sasagawa, T. M. Niebauer and W. Hollander (1993). “A portable iodine stabilized He-Ne laser and its use in an absolute gravimeter”. In: IEEE Transactions on Instrumentation and Measurement 42.2, pp. 420–422. doi:10.1109/11.1019.278595

D’Agostino, G., S. Merlet, A. Landragin and F. Pereira Dos Santos (2011). “Perturbations of the local gravity field due to mass distribution on precise measuring instruments: a numerical method applied to a cold atom gravimeter”. In: Metrologia 48.5, pp. 299–305. doi:10.1088/0026-1394/48/5/009

Delahaye, F. and T. J. Witt (2002). “Linking the results of key comparison CCEM-K4 with the 10 pF results of EUROMET.EM-K4”. In: Metrologia 39.1A, 01005. doi:10.1088/0026-1394/39/1a/5

Dutta, I., D. Savoie, B. Fang, B. Venon, C. L. Garrido Alzar, R. Geiger and A. Landragin (2016). “Continuous cold-atom inertial sensor with 1 nrad/√sec rotation stability”. In: Phys. Rev. Lett. 116.18, 183003. doi:10.1103/PhysRevLett.116.183003 arXiv:1604.00940 [physics.atom-ph]

Falk, R., V. Pálinkáš, H. Wziontek, A. Rülke and M. Val’ko (2011). “New determination of the fine structure constant and test of the quantum electrodynamics”. In: Phys. Rev. Lett. 106.8, 080801. doi:10.1103/PhysRevLett.106.080801 arXiv:1012.3627 [physics.atom-ph]

D’Agostino, G., S. Merlet, A. Landragin and F. Pereira Dos Santos (2011). “Perturbations of the local gravity field due to mass distribution on precise measuring instruments: a numerical method applied to a cold atom gravimeter”. In: Metrologia 48.5, pp. 299–305. doi:10.1088/0026-1394/48/5/009

D’Agostino, G., S. Merlet, A. Landragin and F. Pereira Dos Santos (2011). “Perturbations of the local gravity field due to mass distribution on precise measuring instruments: a numerical method applied to a cold atom gravimeter”. In: Metrologia 48.5, pp. 299–305. doi:10.1088/0026-1394/48/5/009

Delahaye, F. and T. J. Witt (2002). “Linking the results of key comparison CCEM-K4 with the 10 pF results of EUROMET.EM-K4”. In: Metrologia 39.1A, 01005. doi:10.1088/0026-1394/39/1a/5

Dutta, I., D. Savoie, B. Fang, B. Venon, C. L. Garrido Alzar, R. Geiger and A. Landragin (2016). “Continuous cold-atom inertial sensor with 1 nrad/√sec rotation stability”. In: Phys. Rev. Lett. 116.18, 183003. doi:10.1103/PhysRevLett.116.183003 arXiv:1604.00940 [physics.atom-ph]

Falk, R., V. Pálinkáš, H. Wziontek, A. Rülke and M. Val’ko (2019). “EURAMET.M.G-K3 key comparison final report”. In: unpublished DRAFT A Version 2.2.

Francis, O., H. Baumann, T. Volarik, C. Rothleitner, G. Klein, M. Seil, N. Dando, R. Tracey, C. Ulrich, S. Castelein, H. Hua, W. Kang, S. Chongyang, X. Songbo, T. Hongbo, L. Zhengyuan, V. Pálinkáš, J. Kostelecký, J. Mäkinen, J. Näränen, S. Gebbe, M. Gerseemann, H. Ahlers, H. Müntinga, E. Giese, N. Gaaloul, C. Schubert, C. Lämmerzahl, W. Ertmer, W. P. Schleich and E. M. Rasel (2016). “Atom-chip fountain gravimeter”. In: Phys. Rev. Lett. 117.20, 203003. doi:10.1103/PhysRevLett.117.203003

Alauze, X., A. Bonnin, C. Solaro and F. Pereira Dos Santos (2018). “A trapped ultracold atom force sensor with a μm-scale spatial resolution”. In: New Journal of Physics 20.8, 083014. doi:10.1088/1367-2630/aad716 arXiv:1807.05860 [physics.atom-ph]
Santos, P., Gillot, J. Hinderer, J.-D. Bernard, N. Le Moigne, B. Fores, O. Gitlein, M. Schilling, R. Falk, H. Wilmes, A. Germak, E. Biocati, C. Origlia, D. Iacovone, F. Baccaro, S. Mitzushima, R. De Plaen, G. Klein, M. Seil, R. Radinovic, M. Sękowski, P. Dykowski, I.-M. Choi, M.-S. Kim, A. Borreguero, S. Sainz-Maza, M. Calvo, A. Engfeldt, J. Ágren, R. Reudink, M. Eckl, D. van Westrum, R. Billson and B. Ellis (2015). “CCMG-K2 key comparison”. In: *Metrologia* 52.1A, 07009. DOI: [10.1088/0026-1394/52/1A/07009].

Freier, C. (2017). “Atom interferometry at geodetic observatories”. PhD thesis. Humboldt-Universität zu Berlin, Mathematisch-Naturwissenschaftliche Fakultät. DOI: [10.18452/17795].

Freier, C., M. Hauth, V. Schkolnik, B. Leykauf, M. Schilling, H. Wziontek, H.-G. Scherneck, J. Müller and A. Peters (2016). “Mobile quantum gravity sensor with unprecedented stability”. In: *8th symposium on frequency standards and metrology 2015* (Potsdam, Deutschland, 12th–16th Oct. 2015). Ed. by F. Riehle. Vol. 723. Journal of Physics: Conference Series. IOP Publishing, Bristol, p. 012050. DOI: [10.1088/1742-6596/723/1/012050]. arXiv: [1512.05660 [physics.atom-ph]].

Freymüller, J. T. and L. Sánchez, eds. (2016). *International symposium on Earth and environmental sciences for future generations*. IAG general assembly (Prague, Czech Republic, 22nd June–2nd July 2015). Vol. 147. International Association of Geodesy Symposia. Springer, Cham. ISBN: 978-3-319-69169-5. DOI: [10.1007/978-3-319-69170-1].

Gillot, P., O. Francis, A. Landragin, F. Pereira Dos Santos and S. Merlet (2014). “Stability comparison of two absolute gravimeters: optical versus atomic interferometers”. In: *Metrologia* 51.5, pp. L15–L17. DOI: [10.1088/0026-1394/51/5/115]. arXiv: [1406.5134 [physics.geo-ph]].

Gillot, P., B. Cheng, A. Imanaliev, S. Merlet and F. Pereira Dos Santos (2016). “The LNE-SYRTE cold atom gravimeter”. In: *Proceedings of the European Physical Society on Enhancement and Research* (EFTF) (York, UK, 4th–7th Apr. 2016). IEEE. DOI: [10.1109/eftf.2016.7477832].

Greco, F., V. Iafolla, A. Pistorio, E. Fiorenza, G. Currenti, R. Napoli, A. Bonaccurso and C. D. Negro (2014). “Characterization of the response of spring-based relative gravimeters during paroxysmal eruptions at Etna volcano”. In: *Earth, Planets and Space* 66.1. DOI: [10.1186/1880-5981-66-44].

Hartwig, J., S. Abend, C. Schubert, D. Schlippert, H. Ahlers, K. Posso-Trujillo, N. Gaaloul, W. Ertmer and E. M. Rasel (2015). “Testing the universality of free fall with rubidium and ytterbium in a very large baseline atom interferometer”. In: *New Journal of Physics* 17.3. DOI: [10.1088/1367-2630/17/3/035011]. arXiv: [1503.01213 [physics.atom-ph]].

Jaffe, M., P. Haslinger, V. Xu, P. Hamilton, A. Upadhye, B. Elder, J. Khoury and H. Müller (2017). “Testing sub-gravitational forces on atoms from a miniature in-vacuum source mass”. In: *Nature Physics* 13.10, pp. 938–942. DOI: [10.1038/nphys4189]. arXiv: [1612.05171 [physics.atom-ph]].

Jiang, Z., V. Pálinkaš, O. Francis, H. Baumann, J. Máňken, L. Vitvuskin, S. Merlet, L. Tisserand, P. Jousset, C. Rothleitner, M. Becker, L. Robertson and E. F. Arias (2013). “On the gravimetric contribution to watt balance experiments”. In: *Metrologia* 50.5, pp. 452–471. DOI: [10.1088/0026-1394/50/5/452].

Kasevich, M. A. and S. Chu (1991). “Atomic interferometry using stimulated Raman transitions”. In: *Phys. Rev. Lett.* 67.2, pp. 181–184. DOI: [10.1103/physrevlett.67.181].
Pálinkaš, V., O. Francis, M. Valko, J. Kostelecký, M. Van Camp, S. Castelein, M. Bilker-Koivula, J. Näränen, A. Watlet, B. Meurers, O. Olsson, P.-A., K. Breili, V. Pohánka, V. Ophaug, H. Steffen, M. Bilker-Koivula, B. Ellis and B. Lucero (2017). “Regional comparison of absolute gravimeters, EURAMET.M.G-K2 key comparison”. In: Metrologia 54.1A, 07012. DOI: 10.1088/0026-1394/54/1A/07012

Riehle, F., J. Hartwig, H. Albers, L. L. Richardson, C. Meiners, R. J. Rengelink, C. Schubert, A. Roura, W. P. Schleich, W. Ertmer and E. M. Rasel (2019). “Proof mass interferometry for inertial sensing and tests of fundamental physics”. In: Proceedings of the eighth meeting on CPT and Lorentz symmetry (Indiana University, Bloomington, USA, 12th–16th May 2019). Ed. by R. Lehnert. DOI: 10.1142/11655 arXiv: 1909.08524v1 [physics.atom-ph]

Riehle, F., P. Gill, F. Arias and L. Robertsson (2018). “The CIPM list of recommended frequency standard values: guidelines and procedures”. In: Metrologia 55.2, pp. 188–200. DOI: 10.1088/1681-7575/aa3a02

Rosi, G., F. Sorrentino, L. Cacciapuoti, G. M. Tino (2014). “Sensitivity limits of a Raman atom interferometer as a gravity gradiometer”. In: Phys. Rev. A 89.2, 023607. DOI: 10.1103/PhysRevA.89.023607 arXiv: 1312.3741 [quant-ph]

Schilling, M. and O. Gitlein (2015). “Accuracy estimation of the IIE gravimeters Micro-g LaCoste gPhone-98 and ZLS Burris Gravity Meter B-64”. In: IAG 150 years. IAG scientific assembly in Postdam, Germany, 2013 (Postdam, Deutschland, 1st–6th Sept. 2013). Ed. by C. Rizos and P. Willis. Vol. 143. International Association of Geodesy Symposia. Springer, Cham, pp. 249-256. ISBN: 978-3-319-24603-1. DOI: 10.1007/978-3-319-24603-1_29

Schilling, M. and O. Gitlein (2017). “The gravity field in force standard machines”. In: Proceedings of the IMEKO TC3, TC5, TC22 Joint Conference (Helsinki, Finland, 30th May–1st July 2017). DOI: 10.15488/3073

Schillpert, D., J. Hartwig, H. Albers, L. L. Richardson, C. Schubert, A. Roura, W. P. Schleich, W. Ertmer and E. M. Rasel (2019). “Quantum test of the universality of free fall”. In: Phys. Rev. Lett. 120.20, 203002. DOI: 10.1103/PhysRevLett.120.203002 arXiv: 1406.4979 [physics.atom-ph]

Schilling, M., L. Timmen and R. Kumme (2017). “The gravity field in force standard machines”. In: Proceedings of the IMEKO TC3, TC5, TC22 Joint Conference (Helsinki, Finland, 30th May–1st July 2017). DOI: 10.15488/3073

Schilling, M., L. Timmen and R. Kumme (2017). “The gravity field in force standard machines”. In: Proceedings of the IMEKO TC3, TC5, TC22 Joint Conference (Helsinki, Finland, 30th May–1st July 2017). DOI: 10.15488/3073

Schilling, M., L. Timmen and R. Kumme (2017). “The gravity field in force standard machines”. In: Proceedings of the IMEKO TC3, TC5, TC22 Joint Conference (Helsinki, Finland, 30th May–1st July 2017). DOI: 10.15488/3073

Schillpert, D., C. Meiners, R. J. Rengelink, C. Schubert, D. Tell, E. Wodey, K. H. Zipfel, W. Ertmer and E. M. Rasel (2019). “Quantum test of the universality of free fall”. In: Phys. Rev. Lett. 112.20, 203002. DOI: 10.1103/PhysRevLett.112.203002 arXiv: 1406.4979 [physics.atom-ph]
Wanner, A., G. Bergmann, A. Bertolini, T. Fricke, H. Lück, C. M.
Mow-Lowry, K. A. Strain, S. Gossler and K. Danzmann (2012).
“Seismic attenuation system for the AEI 10 meter Prototype”.
In: Classical and Quantum Gravity 29.24, 245007. doi: 10.1088/0264-9381/29/24/245007.

Wenzel, H.-G. (1985). “Schwerenetze”. In: Geodätische Netze in
der Landes- und Ingenieurvermessung II: Vorträge des Kontakt-
studiums Februar 1985 in Hannover. Ed. by H. Pelzer. Konrad
Wittwer, Stuttgart, pp. 457–486.

Wodey, É., D. Tell, E. M. Rasel, D. Schlippert, R. Baur, U. Kiss-
ing, B. Kölliker, M. Lorenz, M. Marrer, U. Schläpfer, M. Wid-
mer, C. Ufrecht, S. Stuiber and P. Fierlinger (2019). “A scalable
high-performance magnetic shield for Very Long Baseline Atom
Interferometry”. In: arXiv: 1911.12320v2 [physics.ins-det]

Zhou, M.-K., Z.-K. Hu, X.-C. Duan, B.-L. Sun, L.-L. Chen, Q.-Z.
Zhang and J. Luo (2012). “Performance of a cold-atom gravim-
eter with an active vibration isolator”. In: Phys. Rev. A 86.4,
043630. doi: 10.1103/PhysRevA.86.043630