Abstract

Atom interferometers have demonstrated high sensitivities in measurements of accelerations, rotations and different physical constants. In this article, we present the mobile instrument GAIN (Gravimetric Atom Interferometer) which allows to utilize this potential for high precision on-site measurements of the local gravitational acceleration. Important influences and systematics arising from both the experimental realization as well as the environment and possibilities to distinguish between them are reviewed. In addition, we give a compact overview of other established gravimeters and discuss the performance of GAIN in the context of several comparison campaigns.
1 Introduction

After the first experimental realizations of atom interferometers in the 1990s [1, 2, 3, 4] several experiments have proven atom interferometry to be a highly sensitive tool for the determination of physical constants such as the fine structure constant [5, 6] and the gravitational constant [7, 8, 9] as well as in the field of testing general relativity [10, 11, 12]. Beside their applications in fundamental physics atom interferometers have demonstrated the measurement of rotations and accelerations with high precision and accuracy, leading to a new generation of gyroscopes, gravity gradiometers and absolute gravimeters [13, 14, 15]. By now their sensitivities compete with other state-of-the-art instruments, which in the case of gravimeters are based on springs/mass-systems or macroscopic falling test masses. They will be referred to as classical gravimeters hereafter to clearly emphasize the different physical principles. Lately efforts have been started to reduce atom interferometers in size and mass while increasing their stability to allow for measurements outside of physics laboratories to make them a viable alternative to classical gravimeters.

There are a number of interesting applications for gravimeters, e.g., in the field of geodesy [16]. Modern gravimeters measure relative changes and the absolute value of local acceleration due to gravity, \( g \), to within one part per billion or better. At this level of sensitivity several position and time dependent influences can be observed, ranging from tidal effects to mass redistributions above and below the surface of the Earth. As \( g \) changes with height, absolute measurements are a way to define and control the vertical height datum and offer a method independent from geometric methods, e.g., Global Navigation Satellite Systems (GNSS) and leveling, to determine height changes. Measurements at tide gauges allow the separation of sea level changes and land surface shifts. Post-glacial rebound causing land uplift, e.g., in Fennoscandia, has been observed using absolute gravimetry [17]. Subsurface mass variations (geophysical as well as man made processes) can also be monitored. They include, e.g., changes of the ground-water table which more and more becomes matter of public interest, especially in dry regions. Besides high resolution point-wise gravimetry to resolve temporal variations, the increasing importance of GNSS in height determination requires dense spatial coverage with precise and homogeneous gravity measurements to guarantee a sufficiently accurate reference surface (geoid).

In this paper, in sec. 2 we first give a short introduction into the working principle of atom interferometry followed in sec. 3 by a description of the Gravimetric Atom Interferometer (GAIN), which was developed at the Humboldt University of Berlin. It integrates a highly sensitive atom interferometer for gravity measurements in a mobile set-up and includes sub-systems for the suppression of environmental vibrations and systematic offsets arising from the rotation of the Earth (Coriolis effect). A characterization of its sensitivity and stability was undertaken during measurement campaigns with classical state-of-the-art gravimeters which are presented in sec. 4. The most typical gravity signals are briefly illustrated in sec. 5 while the results of the campaigns are discussed in sec. 6.
Figure 1: Mach-Zehnder type atom interferometer sequence under the influence of gravity. The atoms are split, reflected and recombined by a combination of beam-splitter and mirror pulses. The lines indicate the classical trajectories of the atoms, which are either in the upper (dashed line) or lower (solid line) internal state.

2 Principle of atom interferometry

The atom interferometer presented here is based on interfering ensembles of $^{87}$Rb atoms in an atomic fountain configuration. We use stimulated Raman transitions between two hyperfine ground states to implement the beam splitters and mirrors. As these have been discussed in great detail elsewhere \[2, 14\] we here only give a brief description.

The atoms are subjected to two counter-propagating light fields with a frequency difference that equals the hyperfine splitting between the two hyperfine ground states. During a transition, atoms change both their internal and momentum state by means of absorption from one light field and stimulated emission into the other light field with an associated momentum change $\hbar k_{\text{eff}} = \hbar (|k_1| + |k_2|)$. The transition probability depends on the length and intensity of the Raman pulse and can be adjusted to implement a beam splitter ($\pi/2$) pulse which creates an equal superposition of excited and ground state, or a mirror ($\pi$) pulse with a transition probability of 1. Figure 1 shows a Mach-Zehnder type $\pi/2 - \pi - \pi/2$ pulse sequence used to split, reflect and recombine the atomic wave packets. The phase difference between paths A and B can be separated into three distinct parts.

$$\Delta \Phi = \Delta \Phi_{\text{path}} + \Delta \Phi_{\text{light}} + \Delta \Phi_{\text{split}}$$  \hspace{1cm} (1)

The first contribution is caused by the free evolution of the atomic wave packets between the interferometer pulses and vanishes under the assumption of a homogeneous gravitational field. The third term depends on the splitting of the atomic wave packets during the interferometer sequence and is also small under typical experimental conditions. The second term, which is due to the atom-light interaction, gives the largest phase contribution in our atom inter-
ferometer. Whenever an atom changes its state, the local Raman laser phase \( \phi_i = \pm (k_{\text{eff}} z_i - \omega_{\text{eff}} t_i) \) is imprinted onto the wave function, with a sign depending on the initial state. Adding up the contributions for all three pulses as depicted in fig. 1 leads to a phase difference

\[
\Delta \Phi = (\phi_1 - \phi_2^A) - (\phi_2^B - \phi_3)
\]

(2)

which can be read out at the output port using state dependent detection, making use of the fact that the relative population \( P_2 \) of the upper state depends on \( \Delta \Phi \) in the following manner

\[
P_2 = \bar{P} + C \cos \Delta \Phi
\]

(3)

with the offset \( \bar{P} \) and the fringe contrast \( C \).

2.1 Atom Interferometers as Gravimeters

When combining the local Raman laser phase \( \phi_i \) at the atomic positions in the laboratory frame with eq. (2), one finds that the observed interferometer phase is given by

\[
\Delta \Phi = (k_{\text{eff}} g - \alpha) T^2 + \phi_l
\]

(4)

with the local gravitational acceleration \( g \) and the time \( T \) between interferometer pulses. Equation (4) additionally includes a RF-frequency chirp \( \alpha \approx -2\pi \times 25 \text{MHz/s} \) which is applied to one of the Raman lasers and cancels the time-varying Doppler-shift of the atoms due to the gravitational acceleration. It thus keeps the Raman lasers on resonance during all pulses and also relaxes the requirement on the pulse timing accuracy. The phase offset \( \phi_l \) is applied to the last Raman pulse and can be used in conjunction with \( \alpha \) to null the phase difference \( \Delta \Phi \). To distinguish a zero phase from other multiples of \( 2\pi \), the interferometer time \( T \) can be changed.

Equation (4) describes the atom interferometer very well at the targeted accuracy of \( \Delta \Phi / \Phi = 10^{-10} \) and only needs to be modified to account for gravity gradients and finite length Raman pulses. It also shows that in order to design a sensitive gravimeter it is desirable to increase the time between pulses since the sensitive scales quadratically with \( T \). During the measurements presented here we operated our interferometer with \( T = 260 \text{ms} \), corresponding to a phase shift of \( \Delta \Phi \approx 1.5 \times 10^7 \) caused by Earth’s gravitational acceleration.

At our targeted accuracy of better than \( 10 \text{nm/s}^2 \), gravity gradients can not be neglected any more. The first term \( \Delta \Phi_{\text{path}} \) in eq. (4) causes significant phase shifts at this level and needs to be evaluated. This can be done by calculating the classical action along each interferometer path as described in [14] and yields the measured gravity value \( g_m \) in the presence of a linear gravitational gradient \( \gamma \)

\[
g_m = \frac{\Delta \Phi}{k_{\text{eff}} T^2} = g_0 + \gamma \left( \frac{7}{12} T^2 + \bar{v} T + z_0 \right) + ...
\]

(5)

with an initial height \( z_0 \), gravitational acceleration \( g_0 \), and the average velocity between both interferometer paths \( \bar{v} \).

Note that this result is identical up to first order in \( \gamma \) to what is obtained by calculating the measured gravity value \( g_m = (z(2T) - 2z(T) - z(0)) / T^2 \) from
the free fall of a macroscopic test mass in a falling corner cube gravimeter as in eq. (10). The quantum nature of the atom indeed does not play a significant role at this level of precision as the same result can also be obtained by simply modeling the atoms as point particles measuring the local laser phases $\phi_i$ during the three Raman pulses.

This changes when evaluating eq. (5) up to second order in $\gamma$. The splitting of the wave packets during the interferometer sequence then starts to play a role and the associated term $\Delta\Phi_{\text{split}}$ in eq. (1) enters in $g_m$. The associated terms are, however, exceedingly small for our experimental parameters and can safely be ignored in our gravimeter measurements, compare [14]. For a more detailed description of higher order phase shifts and also relativistic effects in atom interferometry, see [18].

3 The mobile atom-interferometer GAIN

The atom-interferometer GAIN [19] was designed with the goal of performing high precision gravity measurements outside of physics laboratories on sites of interest from the geodetic point of view. To accomplish this goal GAIN consists of a vacuum system mounted in a mobile trolley and two 19” electronic racks, one dedicated to the laser system while the other one mostly contains the control electronics. These sub-parts will be discussed below. Further subcomponents of the setup, including the vibration isolation system as well as the Tilt- and Coriolis Compensation system, are presented in chapters 3.4, 3.5 and 3.6. A photograph of GAIN after arriving at the Geodetic Observatory Wettzell is shown in fig. 2.

Figure 2: The mobile atom interferometer GAIN at the Geodetic Observatory Wettzell, Germany.
3.1 Experimental procedure

Each measurement starts with trapping some $10^8$ rubidium 87 atoms emitted by a dispenser during 600 ms in a Magneto-Optical-Trap (MOT). The MOT is in a 1-1-1 configuration, i.e., all three axes are tilted by an angle of $\cos \alpha = 1/\sqrt{3}$ to the vertical. Once the loading is complete we switch off the MOT coils and 5 ms later the atoms are launched using the moving molasses technique at a upward velocity of 4.05 m/s. By ramping down the cooling laser intensity and increasing the detuning we cool the atoms adiabatically to about 3 $\mu$K [20]. To ensure that all atoms are in the F=2 hyperfine ground state after launch, repumper light is present during the complete launching sequence. To increase the interferometer contrast and to ease the analysis of systematic effects we select only a narrow velocity distribution in vertical direction of the atoms by applying a long low-intensity Gaussian Raman pulse, transferring the appropriate atoms from the F=2, $m_F=0$ into the F=1, $m_F=0$ hyperfine ground state. This will select a narrow velocity distribution along the Raman beam axis corresponding to an effective temperature of 13 nK in one dimension. The remaining atoms in the F=2 state are eliminated from the measurement cycle during state selection by a blow away light pulse resonant to the F=2 $\rightarrow$ F’=3 transition. Additionally we apply a microwave $\pi$ pulse for the clock transition to start the interferometer in the F=2 state. The microwave pulse also removes unwanted residual population of the $m_F \neq 0$ states.

When the well prepared atomic sample enters the magnetically shielded interferometer zone, it is subjected to the three Raman pulses separated by $T = 260$ ms. Our Raman beams enter the vacuum chamber from the top with the same linear polarization. By inserting a $\lambda/4$ waveplate between vacuum chamber and bottom mirror we ensure an orthogonal polarization for the retro-reflected beam relative to the incident beam. Due to the selection rules Raman transitions are only allowed for orthogonal linear or orthogonal circular polarization. During the interferometer, the difference in frequency between both Raman beams is chirped at $\alpha = d\omega/dt \approx 2\pi \times 25.1$ MHz/s to compensate for the Doppler shift of the atoms. When the atoms enter the detection zone the relative population of the atoms in the $F = 2$ state is determined by collecting the fluorescence light perpendicular to the detection beam on a photo-multiplier tube (PMT). During a first light pulse only atoms in the F=2 state contribute to the signal. Afterwards, the atoms in $F = 1$ are optically pumped to the $F = 2$ state and the fluorescence light of all atoms is detected during a second light pulse (fig. 3b). By fitting the population in the F=2 state to the eqs. (3) and (4) we deduce a value for the gravitational acceleration. During the measurement a slow feedback loop corrects the chirp rate and the phase of the last laser pulse to ensure that the interferometer always operates on the slopes of the central fringe and tracks its maximum.

3.2 Vacuum system

Our setup is based on a cold atom fountain, doubling the available interrogation time and reducing systematic effects due to a symmetrical parabolic atom path compared to a release type atom interferometer, i.e., an interferometer where the atoms are simply released from the MOT and dropped with an initial vertical velocity of $v_0 = 0$ [13]. The vacuum chamber (see fig. 3) consists of three major
parts: the MOT chamber for loading, cooling and launching $^{87}\text{Rb}$ atoms, the detection chamber that is also used for state selection, and the interferometer tube where the atoms are split and recombined. These parts are made of titanium alloy because of its low density, good vacuum properties and low electrical conductivity that reduces stray magnetic fields produced by eddy currents from switching off the MOT coils. The interferometer tube is additionally shielded by three layers of a nickel-iron alloy with high magnetic permeability (Mu-metal) to suppress environmental magnetic fields while a precision wound coil inside the tube creates a well defined quantization axis. Optical access is provided by a variety of high quality windows with indium sealing. The vacuum is maintained by a 201/s ion pump and a titanium sublimation pump, which is activated about once in three months. With this setup we reach an ultimate pressure of $2 \times 10^{-10}$ mbar. During operation of the rubidium dispenser the pressure increases to the $1 \times 10^{-9}$ mbar range. The complete package is mounted in a transportable cage setup with dimensions of $193 \text{ cm} \times 82 \text{ cm} \times 127 \text{ cm}$ and a total mass of about $160 \text{ kg}$.

Figure 3: Interferometer set-up: Atoms are cooled and launched in the MOT chamber and their internal state is prepared on their way upwards. The interferometer sequence is applied while the atoms are inside a magnetic shield with both Raman beams entering from the top and being retro-reflected by a mirror below the chamber. Due to the Doppler shift, only one pair of these four beams is in resonance and drives the stimulated Raman transition. Three Raman pulses form a Mach-Zehnder type interferometer (a). On their way downwards the internal state of the atoms is determined by fluorescence detection (b). (c) shows the mirror for the Raman beams mounted on a Tip/Tilt table on top of an active vibration isolator.
3.3 Laser system

Our laser system was designed to be mobile (i.e., easily transportable by a small truck) and robust to perform gravity measurements in less than a day after arriving at a new gravity measurement site. These sites are usually inside a building with a relative stable environment. Temperature variations lower than one Kelvin allow for continuous measurements longer than 24 hours, while stronger temperature fluctuations require a more frequent readjustment of a few critical components and relocking of the lasers. A detailed description of the first version of our laser system can be found in [21]. Since then we made some critical changes and will here give a brief overview of the current status.

We use four different laser sources all frequency stabilized to a dedicated reference laser. This large number of lasers, one for each function, provides maximum flexibility for extensions. One dedicated Raman laser module permits complex Raman pulse sequences undisturbed by the frequency tuning of the cooling and detection lasers. To increase the stability of the laser system to ease adjusting and to keep the possibility for future updates, the system consists of several modules connected by optical fibers and will be presented in the following.

As laser sources we use two different types of laser diodes. For cooling, repumping and detection we use distributed feedback (DFB) laser diodes [EYP-DFB-0780-00080] with a linewidth about 1 MHz, while for the reference and Raman lasers we use external cavity diode lasers (ECDL) with an interference filter for coarse wavelength selection based on a design developed at SYRTE [22] and using Sharp GH0781JA2C laser diodes. The ECDLs have an output power of up to 50 mW and a linewidth of less than 100 kHz. As the output power of these diodes is not sufficient for our needs, we use two tapered amplifiers [EYP-TPA-0780-01000] to amplify the Raman lasers to one Watt of output power each and one additional amplifier [custom-made at the Ferdinand-Braun-Institut] for cooling.

The reference laser is stabilized to 40 MHz below the $^{85}\text{Rb F}=3 \rightarrow \text{F'}=4$ transition using the modulation transfer spectroscopy technique [23]. This transition gives an error signal with the highest amplitude and the steepest slope. The error signal is used for stabilization of the laser frequency via a fast path using the laser diode’s current and a slow path using the piezo voltage of the lasers cavity. We measured a locking bandwidth of 300 kHz limited by electronics and cable lengths. For gravity measurements the reference laser frequency drift should be lower than the desired experiment drift, which is lower than $5 \times 10^{-10}$ in our case. For this reason we perform an additional spectroscopy on the cold atoms in the vacuum chamber during long term measurements to determine the actual frequency for post correction.

For cooling and repumping the DFB laser diodes are offset locked to the reference laser. For this purpose a small part of the light power from each diode is split and overlapped with the reference light on a fast photo diode resulting in beat frequencies of about 1000 MHz for the cooling and 5080 MHz for the repumper light. These frequencies are divided down by a factor 10 and 256 respectively. Comparing the signal’s zero-crossings to a reference frequency provided by a Direct Digital Synthesizer (DDS) with a digital phase-frequency detector (PFD) gives an error signal that we use for frequency stabilization with a bandwidth of 200 kHz. By changing the DDS output we are able to
reach any desired frequency. A layout of the cooling modules is shown in fig. 4. The cooling and repumping light are coupled to polarization maintaining fibers. The repumping light is directly guided to the switching and distribution module, while the cooling light is amplified in a dedicated amplifier module. This module includes a 2 Watt tapered amplifier as well as a high power optical isolator. Behind the isolator the light is coupled into two fibers with an efficiency of 60 percent, leading to 980 mW in total behind the fibers. Due to our fountain setup, the 3 upper MOT beams need to be red detuned by 3 MHz, whereas the three lower MOT beams need to be shifted closer to the resonance. Instead of shifting the frequency with an acousto-optic modulator (AOM) in a double-pass configuration, we use a single-pass setup with short beam paths. With proper alignment the fiber coupling loss between the AOM operated at 80 MHz and at 77 MHz is negligible. While the lower MOT light is only shifted in frequency in a dedicated module the upper MOT beams are additionally overlapped with the repumper light in a switching module also providing outputs for the detection and blowaway beams. Behind the switching modules the MOT beams are split in a home-made 1:3 fiber splitting module based on commercial components. Due to the use of dedicated fiber coupled modules the cooling system is very stable. Even after long transportation in a truck and resetup only minor adjustments are needed. In the lab, continuous operation over a period of 4 months without touching the system or beam distribution has been achieved.

While the required performance of the frequency stabilization is easy to achieve for the cooling module, this is not the case for the interferometer beams. In order to induce optical Raman transitions between the hyperfine ground states, a fixed phase relation and a frequency difference of $\approx 6.835$ GHz is required. We use light of two ECDLs amplified to 1 Watt each using two separate tapered amplifiers and overlapped in an intra module optical fiber (see below) with the same polarization. To absorb detrimental spontaneous emission from the amplifier, the light passes a rubidium vapor cell for filtering. Behind the fiber an AOM is used for fast switching and pulse-shaping of the Raman pulses. While the Raman master is stabilized in a similar way as the cooling and repumping lasers, the Raman slave is stabilized in phase and frequency with respect to the Raman master. For this phase lock, the light is overlapped on a fast photo diode.
Figure 5: Layout of Raman laser module. Optical isolators, lenses and some mirrors are not shown for clarity.

after the intra-module optical fiber so that all noise sources that are not common to both beams can be compensated for by the phase lock. In addition, the intra-module fiber ensures a constant spatial phase front on the photo diode. The beat signal is mixed down using an ultra low noise 6735 MHz reference resulting in a 100 MHz signal that is phased locked onto a DDS reference with a PFD. An additional high frequency control path for the laser diode current is implemented via a N-channel FET as a voltage to current converter and an additional lag-lead compensation circuit. The achieved locking bandwidth is slightly above 4 MHz [24, 21]. A layout of the Raman module is shown in fig. 5

3.4 Vibration isolation stage

Relative motions of the optical components can have a large detrimental effect on the interferometer phase noise and have to be considered in order to design a gravimeter with a high sensitivity to $g$. Due to the retro-reflection scheme used for the Raman beams, the relative phase between those two beams only depends on movements of the retro-reflection mirror, which acts as an inertial reference for the gravity measurement.

As stated by the equivalence principle, it is impossible to distinguish locally between accelerations of this inertial reference and uniform gravitational fields. In gravimeters with a continuous mode of operation this problem is usually circumvented by low-pass filtering the sensor signal under the assumption that environmental vibrations become negligible at frequencies well below 0.1 Hz. This does not work well for most absolute gravimeters and in particular for the atom gravimeter presented here, due to the inherently sampled form of measurement. The Nyquist theorem then states that it is impossible to distinguish or remove high frequency signals above the Nyquist frequency from low frequency signals after sampling. Furthermore, large vibrations corresponding to more than one fringe will irreversibly degrade the output because of the non-linear nature of the interference fringes. The vibration isolator therefore acts as a low-pass filter
to prevent aliasing and keeps the output signal within one well-known fringe. The frequency dependence of the vibration induced phase noise is given by the atom interferometer sensitivity function \[25\] and shows that efficient isolation of sub-Hertz frequencies is particularly important. Since commercially available vibration isolators did not fulfill this requirement sufficiently, we constructed a custom isolator \[26, 19\] following the ideas given in \[27\]. Another vibration isolator published in \[28\] is also very similar to our setup.

Our system is based on a commercial vibration isolator table 50BM-10 by MinusK with a mechanical spring system to decouple vertical ground motions and an inverse pendulum mechanism for horizontal vibration isolation \[29\]. Both vertical and horizontal resonance frequency are tunable down to 0.5 Hz \[1\], which means that frequencies below 1 Hz essentially pass through the isolator unchanged and only higher frequencies are attenuated. To improve the platform performance for low frequencies one could lower the mechanical resonance frequency. This, however, would require prohibitively large springs and is not an option.

To achieve the above mentioned goals while keeping the small footprint of the platform we implemented an active feedback system \[26, 19\]. An accelerometer measures residual accelerations on the isolator platform and passes them through a feedback filter into voice coil actuators which exert a force between the platform top and base, which effectively lowers the resonance frequency of the passive platform. Since the atom interferometer is only sensitive to vibrations along the vertical propagation axis of the Raman beams we implemented the active system only in the vertical axis. We use a Guralp CMG-3VL single axis seismometer to measure the residual vibrations on the platform top with sufficient fidelity. The output signal is proportional to acceleration within the bandwidth of 0.003 Hz to 100 Hz and passes through a digital loop filter implemented on a NI compactRIO system. The filtered signal is converted to a current which drives two voice coils built directly into the platform \[26\]. Particular care was taken to align the sensitive axis of the accelerometer vertically and to place it directly under the retro-reflecting mirror in order to minimize the influence of cross-axis coupling and tilt modes of the isolation platform.

By properly adjusting the feedback filter parameters we achieve an effective resonance frequency of 50 mHz. The error signal of the closed feedback loop is shown in fig. \[9\] and indicates that the system effectively removes the mechanical resonance of the platform at 0.5 Hz and suppresses frequencies above approximately 0.1 Hz by one order of magnitude. The corresponding reduction in the atom interferometer phase noise also supports these findings: Before implementing the active isolation system we were limited to interferometer times \(T \leq 40\) ms in the noisy environment of our university building in order to keep the output signal within a well defined fringe. The active system allows us to increase \(T\) to 260 ms which overall increased the sensitivity of the atom gravimeter per launch from \(\Delta g/g \approx 7 \times 10^{-6}\) to \(\Delta g/g \approx 2 \times 10^{-8}\) for a single measurement.

### 3.5 Coriolis effect and compensation

Due to the imperfect alignment of the atomic fountain, the atoms always have a non-vanishing transverse velocity component. The trajectory of the atoms

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1 The smallest achievable horizontal resonance frequency of our platform was lowered from 1.5 Hz to 0.5 Hz by using custom elements made by the manufacturer.
Figure 6: Top: Vibrations on the isolator platform as indicated by the feedback sensor error signal. The vibrations on the floor were measured simultaneously with a second seismometer and demonstrate the expected reduction of seismic noise on top of the isolator. Bottom: Magnitude of the isolator transfer function obtained from the same data set, indicating an effective resonance frequency of around 50 mHz.

during the interferometer sequence thus spans a non-zero area and gives rise to an additional phase shift due to the Sagnac effect [14, 30]. This makes the interferometer sensitive to the rotation of Earth and induces a gravity offset given by

\[ \Delta g = 2 \Omega \cdot (v_0 \times \hat{v}_{\text{rec}}) \]

(6)

with the Earth's rotation rate \( \Omega \), the atomic velocity \( v_0 \) and the normal vector \( \hat{v}_{\text{rec}} \) in the direction of the photon recoil. By assuming an Earth rotation rate of \( \Omega = 73 \, \mu \text{rad s}^{-1} \) and the latitude of Berlin (52°) this can be simplified to

\[ \Delta g_C \approx 90 \, \mu \text{rad/s} \cdot v_{\text{EW}} \]

(7)

at our location where \( v_{\text{EW}} \) is the atom velocity in East-West direction. To achieve a targeted accuracy of 5 nm/s², \( v_{\text{EW}} \) would have to be smaller than 60 \( \mu \text{m/s} \), which is very hard to achieve in our experimental setup. We therefore use a Piezo driven Tip/Tilt stage (PI S-330 closed-loop) shown in fig. 7 to rotate the retro-reflecting mirror with a constant rate during the interferometer sequence, following an idea from [31]. The additional rotation effectively cancels out the rotation of the Earth and significantly relaxes the requirements on the fountain alignment. Switching the Tip/Tilt system on and off yields a relative gravity offset \( \Delta g_C \approx 100 \, \text{nm/s}^2 \), which corresponds to a horizontal velocity of \( v_{\text{EW}} = 1 \, \text{mm/s} \). The remaining uncertainty with the Tip/Tilt system enabled is determined by the quality of the alignment between the mirror’s and Earth’s...
rotation axes. By assuming an orientation error of less than 3° and under the assumption that \( v_{NS} = v_{EW} \), we arrive at a residual error of less than 5 nm/s² due to rotations, which is within our current targeted accuracy. To further reduce this effect in the future, the horizontal velocity could be minimized using a scheme shown in [14].

3.6 Tilt Alignment

The atom interferometer is only sensitive to the gravity component along the effective wave vector of the Raman beams. Since the quantity of interest of a gravimeter measurement is the absolute magnitude of \( g \) at a given location, careful alignment of the measurement axis has to be ensured. To achieve a targeted accuracy of 5 nm/s², the angle between \( k_{eff} \) and the vertical axis needs to be smaller than \( \sim 20 \mu \text{rad} \). The sensitive axis of the atom interferometer is influenced by both the Raman telescope and the retro-reflection mirror. Any misalignment relative to each other and relative to the vertical will reduce the magnitude of \( k_{eff} \) and the projection onto the vertical. To avoid the effort needed to align both components independently with high accuracy, we first stabilize their relative alignment by means of an autocollimator setup: The retro-reflected Raman beam is coupled back into the optical fiber through the Raman telescope by adjusting the Piezo Tip/Tilt mirror position. We measure the coupling efficiency with a photo-diode at the far end of the fiber next to a polarizing beam splitter cube (PBS), compare fig. 5. Since incoming and reflected light have perpendicular polarization in our optical setup they get deflected to opposing output ports of the PBS. The Tip/Tilt angle of the mirror is adjusted to yield a maximum coupling efficiency during the 2nd Raman pulse, see fig. 7. Due to the rotation of the Tip/Tilt mirror (see section 3.5), this angle changes between the pulses which results in a reduced coupling efficiency. Any imbal-
ance in the coupling efficiency between the first and last pulse indicates a slight misalignment and can be used to automatically correct the Tilt angle through a feedback loop. To achieve the same tilt stabilization along the perpendicular rotation axis, we apply three additional off-resonant Raman pulses during the MOT loading phase and simultaneously rotate the Tip/Tilt mirror along that axis. Even though the additional pulses occur while the MOT is switched on, we did not find any mutual interference.

The above method allows us to control the relative alignment between both Raman beams with an accuracy of a few µrad, which is more than sufficient to reach the desired accuracy. It also does not need any additional optics in the optical path of the Raman beams, does not affect the interferometer, and avoids systematic errors in the alignment.

Due to the active stabilization scheme, only the vertical alignment of one “effective” beam has to be ensured. This can be done by scanning the beam tilt during a gravity measurement and fitting the residual gravity signal to the vertical component. This is equivalent to analyzing the correlation between experiment tilt and residual gravity as detailed in [19] and yields the vertical tilt position with an uncertainty of less than 5 µrad, which again is well within the requirements for our absolute accuracy.

4 Classical gravimeters and their applications

In the following section, we describe the principles of state-of-the-art relative and absolute gravimeters. An in depth discussion can be found in textbooks aimed at the geodetic and geophysical community like [32] and [33].

4.1 Mechanical spring gravimeters

Spring gravity meters, employing quartz or metal-alloy springs, are a versatile tool in relative gravimetry. They can be used for point measurements in local gravity networks determining the gravity difference between the locations of the network (e.g., Scintrex CG-5, ZLS Burris Gravity Meter [34]). Microgravimetric measurements in support of absolute gravimetry are also common. These include the measurement of horizontal and vertical gradients of gravity and the establishment of control points in the vicinity of the absolute gravity station [16]. These instruments can also record the change of gravity for extended periods of time at a single position. The Micro-g LaCoste gPhone is specifically build for the recording of gravity time series [35].

Figure 8 shows the two principles implemented in modern mechanical spring based gravimeters. Independent from the technical realization, the spring has to obey Hooke’s law, so the elongation of the spring Δl is proportional to a change of gravity Δg. The equilibrium condition for the vertical spring balance is

\[ mg = k (l - l_0) \]  

with the spring constant k and the lengths of the spring l and l₀ with and without load. The change of length of a 10 cm spring has to be determined to 1 nm to achieve a precision of 100 nm/s² [36]. The equilibrium of the general spring lever balance in fig. 5 depends on the torques exerted by the gravitational force.

14
and spring forces \[ mga \sin (\alpha + \delta) = k (l - l_0) \frac{d}{l} \sin \alpha. \] (9)

The highest mechanical sensitivity is achieved when \( \alpha + \delta = 90^\circ \) and \( \alpha \approx 90^\circ \) (astatization). To fulfill this condition within the worldwide range of gravity the upper spring mount is not fixed but can be moved. For the same sensitivity of the instrument as stated for the vertical spring, the movement of the mass \( m \) has to be measured with a precision of 2 \( \mu \)m [36]. Modern instruments use electronic feedback systems to compensate the displacement of the mass \( m \) and keep \( m \) in the zero position. Obviously, the change of the spring constant \( k \) and variations of the length of the spring due to aging or environmental influences directly affect the measured gravity changes. The first effect can be calibrated by regular comparisons of measured gravity differences between absolute measurements. The last effect is known as instrumental drift. All spring gravimeters are affected by drift even though the sensor is housed in a pressure tight oven keeping a constant temperature and internal air pressure (also preventing buoyant forces). The linear drift in the order of a few 1000 nm/s\(^2\) per day is listed in [37] for several vertical spring gravimeters (Scintrex CG-3 and CG-5). For a stationary continuously recording spring lever gravimeter (gPhone-054) [35] reports a drift of 100 nm/s\(^2\) per day four weeks after installation and 50 nm/s\(^2\) per day after 14 weeks. After 14 weeks the drift remains at 50 nm/s\(^2\) per day. In addition to the linear drift component smaller drift components of higher order are also common. However, these are highly dependent on the instrument and a general statement cannot be made. Due to the non-linear components of the drift a distinction between small gravity signals, e.g., changes in hydrology with a few tens nm/s\(^2\), and instrumental drift in recorded gravity time series is often not possible. In local gravity networks, consisting of pointwise measurements, the instrumental drift can be determined by repeated occupations of the same station. In this case an accuracy of 10 nm/s\(^2\) to 20 nm/s\(^2\) for repeatedly measured gravity differences can be achieved with either type of spring gravimeter, as reported in [10, 38]. A more elaborate discussion of instrumental effects can be found in [36].

4.2 Superconducting gravimeters

The Superconducting gravimeter (SG) is the most sensitive and stable spring type relative gravimeter. The mechanical spring is replaced by a magnetic
levitation of a superconducting sphere in the field of superconducting, persistent current coils \[39, 40\]. By the perfect stability of supercurrents, the typical drift problem of mechanical spring type gravimeters is almost completely solved. The SG shows only a low and almost linear instrumental drift, providing unequaled long-term instrumental stability. Due to the design of the magnetic levitation, large displacements of the sphere for small changes in gravity enable highest sensitivity. The SG provides uniquely low noise in a large frequency range, from periods above the microseismic background noise up to interannual signals. Measurements of the diurnal and semi-diurnal Earth tides with a year long record yield amplitudes at the various frequencies to within 0.01 nm/s².

Both, the wires of the coils and the sphere of the sensor unit are made of pure niobium, which is superconducting below temperatures of 9.2 K. To ensure a stable superconducting state, the unit is placed inside a vacuum can, which is enclosed by a magnetic shield made of mu-metal to avoid influences of stray magnetic fields, and is dipped into a dewar filled with liquid helium. Since the boiling point of helium depends on the atmospheric pressure, the temperature of the sensor unit must be regulated to achieve the required stability of 1 mK.

The superconducting hollow sphere as the basic element of the sensor measures typically 2.54 cm in diameter and weighs about 5 g. It is levitated by the magnetic forces induced by the currents trapped into two superconducting coils and the secondary currents induced on the surface of the sphere. Both coils are located along the vertical axis, which allows to adjust the force gradient independent of the position of the sphere. The levitated sphere is moved from its initial position by gravity changes or inertial accelerations. Its displacement is measured by a capacitance bridge formed by three plates made of aluminum enclosing the sphere with a gap of 1 mm. Normally the sensor is operated in feedback to increase the linear dynamic range. The feedback force to hold the sphere in the null position is derived from the low pass filtered signal of the capacitance bridge and is applied as current to an additional superconducting coil. This voltage represents the gravity signal and is recorded by a high precision digital voltmeter. A schematic diagram of the sensor is shown in fig. 9.

The voltage must be scaled by a calibration factor which can only be determined by comparison with known accelerations. A common approach is to compare the tidal variations recorded by another gravimeter, e.g., an absolute gravimeter. The combination of repeated absolute gravity measurements with the continuous SG time series enables further to separate the SG instrumental drift from long term changes and to check the stability of absolute gravimeters \[41\].

To measure the magnitude of the gravity acceleration, the sensor must be precisely aligned in direction of the vertical. A tilt compensation system is used to keep this alignment during operation. The signals of two tiltmeters perpendicular to each other located inside the dewar are used to drive thermal levellers mounted between the dewar and the support posts which smoothly compensate tilts without causing artificial accelerations.

A refrigeration system is used to absorb the heat flowing in from the room temperature. The efficiency of current cooling systems allows to reliquefy helium gas in a closed-cycle system. The insignificant loss of helium allows a long-term, uninterrupted operation. To avoid signal disturbances due to coldhead vibrations, the coldhead is mounted separately from the dewar and is mechanically connected only by a thin diaphragm to prevent gas exchange. Figure 9 shows
4.3 Laser interferometer absolute gravimetry

Modern absolute gravimeters (AG) measure the absolute value of $g$ by observing time and distance of a free falling object by means of a laser interferometer and a precise clock. The most common AG is the Micro-g LaCoste FG5 [42] and its latest development the FG5X. For $g$ measurements a typical procedure would be 50 free fall experiments (drops) every 30 minutes or 100 drops every 60 minutes with a time of 10 s between drops. These sets of 50 or 100 drops would be repeated for 8 to 12 hours, often over night due to lower man made microseisms (e.g., traffic). Depending on the location this 8 to 12 hour cycle would be repeated two or three times. Between cycles the instrument setup is repeated to identify setup errors. With the A-10 gravimeter Micro-g LaCoste offers a more rugged version for field measurements. There are a few independent developments, e.g., the IMGC-2 [43] which operates by the rise and fall principle, analog to the fountain principle in fig. 3 of GAIN, but with a macroscopic object.

Figure 10a shows a schematic of the FG5 Gravimeter. The main components are the dropping chamber (vacuum chamber), the interferometer (including the laser and timing system), and the super spring (inertial reference and seismic isolation) [44]. The evacuated dropping chamber houses the corner cube, which acts as a test mass for the free fall experiments. The length of the drop is 20 cm for the FG5 and 30 cm for the FG5X corresponding to a 0.2 s and 0.25 s time in free fall. The corner cube is located inside a cart which is accelerated along with it during free fall and lifts it back into the upper position afterwards. The cart also minimizes the air drag acting on the test mass. Residual atmosphere inside the cart is moved along with the test mass and parts of the cart act as barrier during free fall against the remaining air inside the dropping chamber. The inertial reference of the interferometer is placed inside the super spring [45], which...
serves the same purpose as the vibration isolation described in sec. 3.4. The super spring uses a combination of springs and an electronic feedback system to achieve a period of about 60 s. Between dropping chamber and super spring including the interferometer base is no mechanical connection and both parts of the FG5 have separate tripods. This way vibrations caused by the dropping mechanism are not directly transferred into the super spring.

The interferometer of the FG5 is a Mach-Zehnder configuration (fig. 10b) with a WEO Model 100 iodine stabilized helium-neon laser [46]. The laser light enters the interferometer base via fiber-optic cable, where the light is split and one beam travels to the photo detector while the second beam is sent upward where it is reflected in the falling corner cube. The reflected beam travels downward into the inertial reference corner cube where it is reflected back into the interferometer base. In the interferometer base the beam is directed to the photo detector and recombined with the reference beam. The photo detector then digitizes the analog fringe signal. Depending on the instrument and configuration by the user approximately 600 or 1200 (FG5 and FG5X) equidistant time-distance pairs of fringe signal zero-crossings are evaluated in a least square adjustment. Taking into account the vertical gradient in gravity $\gamma$ the observation equation is [16]

$$z(t) = z_0 \left(1 + \frac{1}{2} \gamma t^2\right) + v_0 \left(t + \frac{1}{6} \gamma t^3\right) + \frac{1}{2} g_0 \left(t^2 + \frac{1}{12} \gamma t^4\right).$$

The time $t$ has to be corrected for the finite speed of light and the initial parameters velocity $v_0$ and position $z_0$ are adjustment unknowns. The vertical gravity gradient $\gamma$ is either measured using relative gravity measurements at different heights along the plumb line or the free air gradient (30.86 nm/s$^2$ per cm) is used. The required accuracy for the time and distance measurements are 0.1 ns and 0.2 nm to achieve an accuracy of 10 nm/s$^2$. Timing is kept with a rubidium oscillator, which is regularly compared with a frequency normal of higher order. The largest impact on the distance measurement is the air gap modulation [42].

\[3\] Reference [16] contains an additional term $\frac{\gamma t^4}{4} z_0$ which is due to an error in the series expansion and can be ignored. The formula printed here is the corrected version.
The light travels in the atmosphere within the interferometer and super spring but enters the evacuated dropping chamber through an optical window. Vibrations of the dropping chamber and the optical window change the path length the laser travels under atmospheric conditions versus the path length the laser travels in vacuum. Due to different refractive indexes this changes the measured distances to the falling corner cube. Other effects on AG measurements include Coriolis effect, vertical alignment, imperfections of the optical elements, self attraction, and floor recoil. The total uncertainty is estimated at 11 nm/s^2. The complete error budget of the FG5 is discussed in [42]. AGs are regularly compared at international (ICAG) or European (ECAG) meetings and the instruments, a majority of FG5, some A-10, and a few independent developments, agree within a few tens of nm/s^2 [47]. The operational aspects and long term experiences of AGs are discussed in [46].

5 Modeling of temporal gravity variations

The gravity at a given location is influenced by a variety of effects. In the following section, we describe the time variable changes due to Earth tides, atmosphere, ocean loading and hydrology. This can only be a short overview and we refer to geodesy textbooks and comprehensive articles, e.g., [36, 48, 37], for an extended discussion of the subject.

5.1 Earth tides

The gravitational accelerations produced by the sun, the moon and to a lesser extend by other celestial bodies are only completely compensated in its center of mass by centrifugal accelerations due to the orbital motion of the Earth around the barycenter. Because of the spatial extension of the Earth, the gravitational accelerations are slightly position dependent, whereas the orbital accelerations are constant within the Earth and on its surface. The difference between both forces are the tidal accelerations [49]. Figure 12 shows the measurements of GAIN and modeled Earth tides for 6 days. Due to the Earth’s rotation the tidal accelerations are changing with time at a fixed location. Fortnightly and monthly tides are caused by the moon, whereas semi-annual and annual periods are caused by the movement of the Earth around the sun. The variation of the orbital inclination of the moon causes a modulation of the amplitude of lunar tides with a period of 18.6 years. The longest period is around 20,941 years [50]. The total amplitude is latitude dependent and can reach more than 2500 nm/s^2 from peak to peak. The tidal acceleration of the sun amounts to 46 % of the lunar tides. The largest tides next to moon and sun are caused by the planet Venus with a maximum effect of 5.88 × 10^{-2} nm/s^2 [49]. Figure 11 shows the tidal accelerations $b_t$ for the Earth–moon system, where $b_t$ is the result of the orbital acceleration $b_0$ of the Earth around the barycenter of the Earth–moon system and the gravitational acceleration of the moon $b$ at $P$ on the Earth surface. Applying Newton’s law of gravitation using the mass of the moon $M_m$ and the distances $r_m$ and $l_m$ of the moon to the center of gravity and to $P$ the resulting tidal acceleration on a rigid (not deformable) and oceanless Earth is
Although the tidal acceleration at \( P \) could be computed by accumulating the effects of all two-body systems for the Earth and the relevant celestial bodies using eq. (11), it is more convenient to expand the tidal potential into spherical harmonics assuming a rigid Earth, yielding tidal potential catalogs. These are basically tables of amplitudes, phases and frequencies of individual tidal waves. One of the most comprehensive tidal potential catalogs is HW95 [51] which contains 12,935 partial tides.

Since the real Earth is not a rigid body, it reacts with deformations to tidal forces which reach up to 40 cm at mid latitudes [16]. The elastic response of the Earth to these forces is computed by convolving the tidal potential with transfer functions for a nonrigid Earth [52, 53, 54]. The transfer function is expressed as a set of amplitude factors \( \delta_i = \frac{A_{ei}}{A_{ti}} \) which express the ratio between the amplitudes of tidal forces for an elastic \( A_{ei} \) versus a rigid \( A_{ti} \) Earth and respective phase delays \( \Delta \Phi_i \) for each distinct wavegroup \( i \). The transfer function can be calculated theoretically for a spherical or ellipsoidal, hydrostatically prestressed Earth model with constant rotation, assuming elastic properties for mantle and core [52] or even taking mantle inelasticity into account [54]. The parameters \( \delta_i \) and \( \Delta \Phi_i \) can be independently determined by tidal analysis [55] of gravimetric time series of several months to years length. However, ocean tide loading effects are superimposed and can only be separated by an appropriate ocean model.

5.2 Gravity effects due to mass redistribution and loading

Besides the Earth’s tides as the major source of temporal gravity variations, mass changes on and above the Earth’s surface are inducing changes in the gravity acceleration. Not only a change of the direct Newtonian attraction is caused by mass redistributions, but also deformation of the Earth’s shape due to the change in the surface load. The latter splits up into a change in the vertical position of the gravimetric sensor (free air effect) and a secondary perturbation of the gravity potential, as a result of a mass redistribution inside the Earth (indirect effect). Assuming a radially symmetric, self-gravitating Earth, these effects can be computed by convolution of the surface mass load with a kernel function, the Green’s function of the normal stress surface loading problem [56, 57, 58]. The so-called load Love numbers \( h'_n, l'_n, \) and \( k'_n \) characterize the elasticity of the crust-mantle structure. The point load of the mass element \( dm \)
generates the vertical displacement

\[ du = \frac{a}{M_E} \sum_{n=0}^{\infty} h_n'(\cos \theta) \, dm \]  

(12)

and the gravity change

\[ \delta g = \frac{2g}{a} du + \frac{g}{M_E} \sum_{n=0}^{\infty} (n - (n - 1) k_n') P_n(\cos \theta) \, dm \]  

(13)

where \( a \), \( g \) and \( M_E \) denote the mean radius, gravity and mass of the Earth and \( P_n \) are the Legendre polynomials. The distance \( \theta \) is measured as an angle along a great circle. These equations must be integrated over the whole Earth’s surface. Since the mass load \( dm \) is given by numerical models with finite resolution, the integration is replaced by the sum of discrete surface elements. For masses in the vicinity of the computation point the point load approach is no longer valid. Either the grid must be refined by interpolation or replaced by a detailed local model. The part of the Newtonian mass attraction effect from the near field can also be computed using elementary bodies for which an analytical solution of the integral exists.

Major sources of surface mass changes and loading effects are the ocean tides, atmospheric mass redistributions, continental water storage changes and non-tidal ocean mass variations. Ocean tide loading results from variation of the ocean masses due to tidal forces and is superimposing the tidal deformation of the solid Earth at the same frequencies, resulting in deviations of amplitudes and phases of the respective tidal waves \[57\]. Therefore tidal models obtained from analysis of gravimetric time series already include this effect, whereas theoretically derived Earth tide models must be complemented. The gravity effect is obtained by convolution of the amplitudes and phases of an ocean model with the the Green’s functions in eqs. \([12] \) and \([13] \) and amounts up to 10 % of the effects of the solid Earth close to the coast and up to 2 % at continental regions. Since these models are limited to the main tidal waves an interpolation into the complete tidal spectrum using admittance factors is necessary to correct precise gravity measurements adequately.

Similarly, mass changes in the atmosphere are causing both, direct Newtonian mass attraction effects as well as changes in the surface load. This effect can be computed efficiently by a linear relationship to the surface air pressure \( p \) \[59\]

\[ g_{Atm} = m_{Atm} \left( p - p_0(h) \right) \]  

(14)

where \( p_0 \) is the height dependent reference pressure in accordance with the standard atmosphere ISO 2533 and \( m_{Atm} \) is the admittance factor. Despite the factor \( m_{Atm} \) is frequency dependent, up to 95 % of the effect can be modelled with a constant value of typically 3.0 nm/s²/hPa. Higher accuracy can be reached if the three dimensional density distribution is taken into account using detailed atmospheric models \[60, 61\]. Atmospheric gravity effects amount up to 400 nm/s².

A further influence are continental water storage changes. At global scale loading and attraction effects are caused, although with much lower amplitude not exceeding 30 nm/s². However, local mass changes in the vicinity of the gravimetric sensor are dominating \[62, 63\] and may have significant impact on gravity observations, exceeding 100 nm/s² at specific locations.
5.3 Influence of the Earth’s rotation

For a body rotating about its axis of the main moment of inertia a suitable excitation may result in a displacement of the figure axis with respect to the rotation axis. After excitation, the figure axis oscillates around the rotation axis. Such variations of the geocentric position of the Earth’s rotation axis (polar motion) perturbs the centrifugal force and cause deformation within the Earth. Neglecting fractional variations in the rotation rate, a first order perturbation in the centrifugal potential \( V \) is given by

\[
\Delta V(r, \theta, \lambda) = -\frac{\Omega^2 r^2}{2} \sin 2\theta (m_1 \cos \lambda + m_2 \sin \lambda),
\]

where \( \Omega \) is the mean angular velocity of the Earth’s rotation, \( m_1, m_2 \) describe the time-dependent offset of the instantaneous rotation pole from the mean (pole coordinates), while \( \theta, \lambda \) and \( r \) denote the co-latitude, longitude and radial distance of the location [64, 65]. The effect is dominated by the 14-month Chandler wobble and annual variations. The resulting long period gravity variation is less than 50 nm/s\(^2\) in amplitude. The effect of the oceans response to these forces (ocean pole tide) doesn’t exceed 2% of the gravity the pole tide and can be neglected for most applications [66].

6 Measurement campaigns

The local gravitational acceleration is subject to temporal variations with a magnitude of a few 1000 nm/s\(^2\) (\( \approx 10^{-7}g \)) during a day mainly due to the tidal effects described in sec. 5. In order to resolve changes caused by other environmental effects, e.g., by hydrology and mass transportation below the surface of the Earth which typically are on the 10 nm/s\(^2\)-level or smaller, the major effects have to be removed. A characterization of an instrument at this level can best be realized by measurements performed by different instruments in parallel. Thus, instrumental drifts and instabilities can be distinguished from environmental influences. For classical absolute gravimeters there are regular comparison campaigns like the European Comparison of Absolute Gravimeters (ECAG) [47] where small differences between individual instruments can be identified.

We performed comparison measurements between the atom interferometer GAIN and three different types of classical state-of-the-art gravimeters including the portable spring-type gravimeter gPhone-98, the high precision stationary superconducting gravimeter SG-30, and the portable falling corner cube gravimeter FG5X-220. While the first two types are designed to resolve relative gravity changes with high resolution, the main purpose of the latter instrument is to determine the absolute value of gravity (see sec. 4).

6.1 Comparison between GAIN and the gPhone-98

During the first comparison in December 2012 the gPhone, a mechanical spring-based gravimeter, was operated by the Institut für Erdmessung (IfE) next to the GAIN sensor. Variations of the gravitational acceleration were observed over a period of two weeks and a selection of the data taken by the GAIN instrument is shown in fig. 12. The time curve is mainly influenced by tidal effects.
with a changing amplitude from day to day. The solid black line represents the tidal effect calculated with the help of the software T-Soft [67] and local parameters determined by the IfE. Figure 13 shows residuals of both instruments corrected for tides and atmospheric influences. Data taken by the gPhone was additionally corrected for a linear drift of 102 nm/s² per day. Drifts of higher order are typically much smaller and therefore are neglected on this timescale. Both signals are averaged over 30 minutes and yield standard deviations of 7 and 9 nm/s² for the GAIN interferometer and the gPhone, respectively. This scattering is slightly higher compared to other gPhone measurements due to the noisy environment on the 2nd floor of our university building. Residual variations of 20 nm/s² in the GAIN signal on a daily timescale might be due to Raman intensity fluctuations, which were not stabilized during this measurement.

6.2 Comparison between GAIN and the SG-30

Superconducting gravimeters offer the highest sensitivity today, substantially exceeding that of spring-type gravimeters. They come with much lower drift rates of 50 nm/s² per year and less after the decay of initial run-in effects. A direct comparison between the SG-30 and the GAIN instrument, which had been improved in the meantime, was performed at the Geodetic observatory Wettzell, operated by the Federal Agency for Cartography and Geodesy (BKG), in the South of Germany in October 2013. During a time period of two weeks the short term sensitivity and long term stability were analyzed. In addition, absolute gravity measurements are performed on a regular basis with FG5 gravimeters at the same location. By combining these observations, the relative changes recorded with SG-30 are transformed into an absolute reference function, which will be used to compare the absolute values acquired from GAIN.

This campaign also allowed us to demonstrate the mobility of the GAIN instrument, as it was transported over 600 km and reassembled within a few
days. By optimizing the workflow for the instrumental set-up, the time for reassembling could be shortened to less than a day after return transport. This includes connecting the different subsystems and a complete alignment of the experiment.

Figure 14 shows a selection of four days of residual gravity data measured by GAIN (dots with error-bars) and by the lower sensor of the superconducting gravimeter SG-30 which is installed at the station (black curve). All data is averaged over 30 minutes. In the upper figure the data is only corrected for tidal effects illustrating a remaining signal of environmental effects at the 10 nm/s²-level, which is dominated by atmospheric mass redistribution. In the lower figure atmospheric effects are removed as well. At the level of the remaining variations not all environmental influences can be completely calculated with theoretical models. Therefore, the difference between both signals has to be analyzed for a more detailed investigation of instrumental properties. First results show that no unexpected long term drift between both instruments and thus no drift of the GAIN sensor was observable. Here, the well-known linear drift of the SG-30 was removed. Statistical uncertainties at the low $10^{-10}g$-level or below for integration times of one day could be observed. The complete analysis is still in progress.

6.3 Aiming at absolute accuracy - comparison with the FG5X-220

The atom interferometer relates accelerations to frequency chirps and changes in state population at its output ports via eqs. 4 and 5. Thus, the absolute value of the gravitational acceleration can be determined with high absolute accuracy using precise frequency references. For a comparison of the absolute
values the state-of-the-art classical gravimeter FG5X-220 was used. During a measurement campaign on the ground floor of our physics institute in Berlin the GAIN and the FG5X sensors (the latter operated by the IfE) measured the local gravitational acceleration. The atom interferometer was operated at its standard repetition rate of 0.7 Hz while the FG5X performed 50 free fall experiments with a 10 s drop interval per hour continuously for 3 days, which is not the standard mode of operation. The scatter between data sets, which were averaged over 60 minutes, was 8 and 29 nm/s$^2$ for the GAIN and FG5X sensors respectively.

Table 1: Overview of systematic effects which have already been compensated in the presented data and their typical relative magnitude without cancellation and remaining uncertainty after suppression. This table does not allow to state a total uncertainty since further effects still have to be investigated.

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>typical effect [nm/s$^2$]</th>
<th>uncertainty after suppression [nm/s$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Stark shift</td>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>Coriolis effect</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>Wave fronts</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Vertical alignment</td>
<td>50</td>
<td>$&lt; 0.3$</td>
</tr>
<tr>
<td>Laser-lock offset</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Self attraction</td>
<td>19</td>
<td>1</td>
</tr>
</tbody>
</table>

*The repetition rate and measurement time of the FG5X is typically kept low due to life-time limitations, which are inherent to the mechanical design of the instrument.*
Table 2: Properties of classical gravimeter types and the atom interferometer GAIN in seismic quiet environments. (1) Falling corner cube instruments are typically only used during short periods for continuous measurements because of life-time limitations. (2) The accuracy for the GAIN sensor is the targeted value.

<table>
<thead>
<tr>
<th></th>
<th>Noise [nm/s²/√Hz]</th>
<th>Drift [nm/s²/day]</th>
<th>Accuracy [nm/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring/Mass System [37]</td>
<td>20</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>Superconducting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravimeter [69]</td>
<td>1-3</td>
<td>&lt;0.15</td>
<td>-</td>
</tr>
<tr>
<td>Falling Corner Cube [47, 42]</td>
<td>300-500(1)</td>
<td>-</td>
<td>≈20</td>
</tr>
<tr>
<td>Atom Interferometer</td>
<td>150</td>
<td>-</td>
<td>5(2)</td>
</tr>
</tbody>
</table>

A detailed evaluation of the absolute values is still in progress, since the characterization of the GAIN sensor is incomplete by now. Some main systematic effects, the influence of the Coriolis effect of the Earth, the AC-Stark shift and the vertical alignment, have already been sufficiently controlled and suppressed. In addition, the highly symmetrical atomic fountain configuration minimizes further known effects such as offsets due to residual Zeeman shifts or due to the two photon light shift [68]. An overview of systematic effects that were already considered in our analysis is given in table 1.

We expect that a careful characterization will reduce remaining uncertainties and lead to a level of absolute accuracy which is comparable to the FG5X within the next year. Similar other atom interferometers have already demonstrated uncertainties of only 34 nm/s² to 70 nm/s² and agreements with classical absolute gravimeters within 24 nm/s² to 70 nm/s² [14, 47].

7 Conclusion and Outlook

We have presented an atom interferometer optimized for mobility and high precision gravity measurements and compared its performance during several test campaigns with other state-of-the-art gravimeters which we have briefly introduced. Some main characteristics of the different gravimeter types are summarized in table 2. In conclusion, we showed that the sensitivity of the GAIN interferometer is similar to the mobile spring gravimeter gPhone-98 and superior to the absolute gravimeter FG5X-220. Only the stationary superconducting gravimeter SG-30 offers a significantly higher resolution.

While we have already suppressed several systematic effects (see table 1) and demonstrated drift free measurements over a few weeks, a detailed characterization of the remaining systematics is expected to lead to an absolute accuracy comparable to the best classical absolute gravimeters in the near future. Thus, the atom interferometer will combine the ability to perform long term registrations at a high sensitivity with a drift free operation and an absolute measurement in one instrument.
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