Reaching the Intrinsic Noise of an Absolute Quantum Gravimeter

Mayana Teloi, Mouhamad Haidar Lakkis, Anthony Amorosi, Laura Antoni-Micollier, Camille Janvier, Vincent Ménoret, Pierre Vermeulen, Peter Rosenbusch, and Christophe Collette

Over the past decades, gravimeters with different working principles have been developed, such as superconducting gravimeters, spring gravimeters or gravimeters based on optical interferometry [1]. Their ability to measure local changes in gravitational acceleration with very high sensitivity makes these instruments widely used in fundamental physics, geodesy and geophysics [2]–[4]. Recently, quantum gravimeters based on matter wave interferometry have demonstrated some of the best resolutions and stabilities [5].

Background on Absolute Gravimeters

Absolute gravimeters are sensors that measure the value of gravity through the free-fall of a proof mass that constitutes an inertial frame. In quantum gravimeters, the proof mass are ultra-cold atoms whose acceleration is measured by matter wave interferometry. Three pulses of two counter-propagating laser beams imprint their phase on the atomic wavefunction, allowing the deduction of the vertical acceleration. Because the counter-propagating laser beams are typically formed by reflection off a mirror, vibrations of the mirror impact the laser phase experienced by the atoms, thereby introducing noise to the gravity measurement. In many locations, this is the dominant noise source, because human activity and natural effects cause ground vibrations whose frequency range coincides with the gravimeter's sensitivity [6].

Absolute quantum gravimeters are discrete instruments, sensitive to slowly varying signals, thus polluted by low frequency ground vibration. Therefore, efforts are made on ground isolation at low frequencies, below 10 Hz. Three main isolation strategies are used: passive and active isolation platforms and the ground vibration compensation. The passive solution consists of a spring-mass damping system which is mostly efficient above its resonance frequency, as it acts as a low-pass filter. Because of the architecture and the working principle, it is difficult to reach low resonance structures, making these tables mostly suited for high-frequency ground isolation, typically above 5 Hz. The passive solution provides a partial ground mitigation to the atomic interferometer as it reduces in particular high frequency (> 1 Hz) propagating noise. It does not cover low frequencies in the gravimeter bandwidth that fall in the range up to 1 Hz. To extend the isolation towards the gravimeter bandwidth, passive stages are mounted with actuators and sensors that allow the resonance frequency to be tuned with adequate control strategies. This active platform solution allows better isolation in the bandwidth of interest but is limited to the laboratory environment. Since a gravimeter is also an instrument for field measurement and should be transportable, a more convenient solution is the use of an external sensor. The ground vibration strategy merges an auxiliary sensor with the quantum gravimeter. The auxiliary sensor measures seismic acceleration of the reference mirror during gravity measurement and evaluates its impact on the gravimeter signal in real-time or in post-processing. This technique is more compact but performances are tightly linked to the sensor dynamics and resolution, making it less robust than an active platform isolation [5].

In regards to these strategies, we applied the active isolation method to an absolute quantum gravimeter mounted on a home-made platform. The aim is to assess the impact of ground vibration reduction on gravity measurement using an absolute gravimeter. For that purpose, the study was performed on the Absolute Quantum Gravimeter (AQG Exail A04). This instrument is a drift- free absolute gravimeter with a long-term stability of 10 nm/s^2. To mitigate noise from ground vibrations, the AQG employs a real-time vibration compensation system. It is based on a built-in classical accelerometer (Nanometrics Titan) that records high frequency accelerations and feeds back to the laser phase. Thanks to this compensation system the gravimeter performs without dedicated vibration isolation equipment even in challenging environments such as inner city and upper-floor locations [4] or even under volcanic tremor [7]. The AQG reaches a sensitivity of typically 700 nm/s^2 at 1 s at an inner-city location (commonly subject to important ground vibrations) and typically 500 nm/s^2 at 1 s at a quiet site [4]. Although already remarkable, these numbers show that further optimization of the built-in vibration compensation system could bring even better sensitivity.

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The purpose of this paper is to test the gravimeter in a lowest-noise environment and thereby evaluate the potential sensitivity gain. To do so, the gravimeter is placed on an actively isolated table illustrated in Fig. 1 with the aim to reduce the seismic noise. This paper will explain the impact of the seismic noise on the gravity measurement. The experimental architecture and vibration isolation table control strategy are presented, and gravity data obtained with the active isolation are discussed.

The main goal of gravimeters is to measure low frequency gravity signal coming from local density variations due to hydrology, seismic waves, mass variation around the instrument and many other sources described in [1]. However, ground vibrations are indistinguishable from a change of the value of gravity, introducing noise to the measurement. Therefore, we need a way to isolate the gravimeter from ground accelerations to access the gravity signals of interest.

To isolate gravimeters from the noise part, it is important to understand how this noise enters the measurement process. In cold-atom gravimeters, atoms are in free-fall inside a vacuum chamber, so they are decoupled from the environment. The atom free-fall is measured with a laser retro- reflected from a mirror that interacts with the atoms. The planes of phase of the laser are the reference frame attached to the instrument. The final measurement gives the acceleration of this reference frame with respect to that of the free-falling atoms, considered as purely inertial. Ground vibrations are transmitted through the instrument mechanical structure to the mirror and thus to the laser phase. As a consequence, any motion of the mirror $\delta_z(t)$ induces an unwanted phase shift ϕ_{mirror} in the atom interferometer described by:

$$\begin{aligned}\Delta\phi &= \phi_1 - 2\phi_2 + \phi_3 + \phi_{mirror} \\ &= k_{eff}\, gT^2 + k_{eff}\, \delta_z(t)\end{aligned} \tag{1}$$

where ϕ_i are the atomic phase shifts induced by the laser pulse i, $k_{eff} = 4\pi/\lambda$ is the laser effective wave vector with $\lambda = 780$ nm the laser wavelength, and T = 60 ms is the time between two laser pulses [4].

To reduce the mirror noise contribution $k_{eff}\, \delta_z(t)$, Exail's AQG comes with a built-in classical accelerometer (Nanometrics Titan) that is sensitive to high frequency vibrations. In order to study the AQG vibration compensation system and search for other potential noise sources, we reduced the amplitude of the ground motion by placing the AQG on an actively controlled platform, described in the next section.

Experimental Set-up

Active Isolation

The active isolation set-up is composed of a passive stage placed on three isolators (Yuanda Tech), each containing a voice coil. Above the hexagonal platform are mounted three vertical inertial sensors [9]. The actuators and sensors are placed in a collocated way to assure better stability. The sensors are sealed inside vacuum bells at a pressure of 10 mbar to remove the air around the proof masses. In each sensor, the mass displacement is read-out by an optical interferometer that allows a resolution of $10^{-13}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 1 Hz to be achieved [10]. A laser source (Koheras Adjustik X15) with 1550 nm wavelength is used to feed the sensors. Their signal is then sent to the acquisition system (Scalexio - DSpace). The sensors' signals are processed and controlled within the acquisition system. At the output of the controller, the analog control signal is passed through a homemade current amplifier and injected into the voice coil actuators [9].

The feed-back loop is schematized in Fig. 2. The AQG is placed at the center of the table with the real-time vibration compensation system based on hybridization with the built-in accelerometer active, and aligned perpendicular to the table. The three vertical inertial sensors, in purple, measure the relative vertical displacement y between their proof masses and the table. In each sensor, this displacement is measured by an optical interferometer.

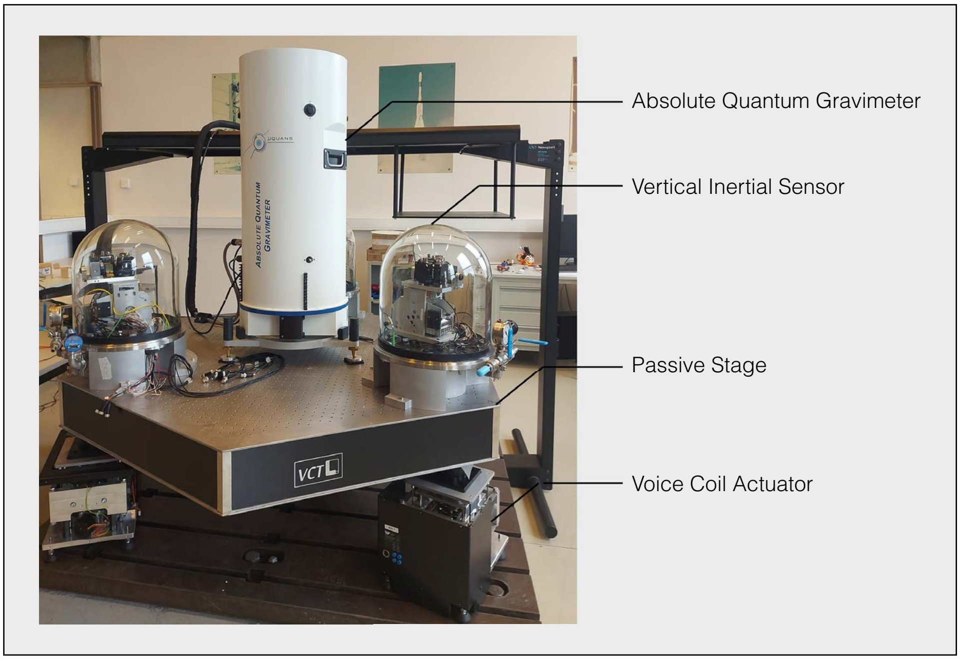

Fig. 1. Photo of the experimental set-up: The Absolute Quantum Gravimeter is placed at the center of an active isolation platform on two rubber patches. Three inertial vertical sensors are mounted under vacuum bells to reduce air fluctuations. Three voice coil actuators are placed under the sensors.

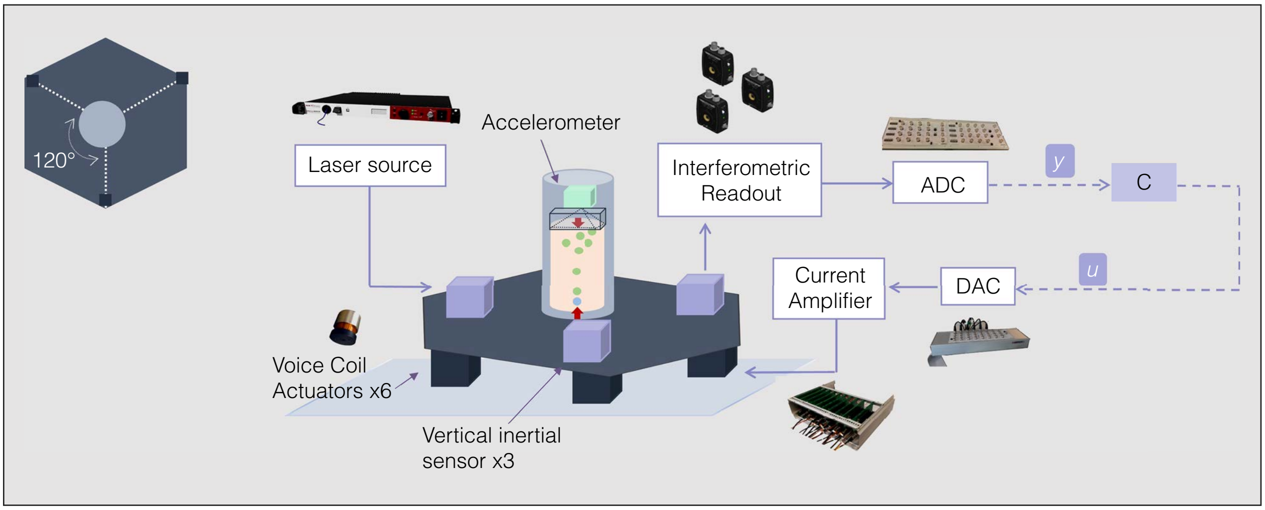

Fig. 2. Signal processing scheme for the active seismic isolation.

Processing the optical interference fringes reveals the displacement which is then fed to the control loop *C*. Because of their positioning, the sensors are also sensitive to rotations θ_x and θ_y which are thus fed to the controller along with the vertical direction. At the end of the numerical operations, the control input signal *u* is passed through an analog-to-digital converter in order to operate the voice coils via a homemade current amplifier [9]. A top view of the hexagonal table with the actuator positions is schematized in the outer left.

In this configuration, the isolation bandwidth ranges from 0.1 to 10 Hz. The upper boundary is fixed by the architecture, since high frequency flexible modes of the structure must be avoided. The lower boundary is set by tilt-to-horizontal-coupling, because, at low frequencies, the inertial sensors do not differentiate rotation from translation [9].

The AQG functions in a cyclic manner with one cycle lasting 540 ms. Its measurement bandwidth is thus below 1 Hz [4]. Therefore, we optimize the isolation platform controller to the range 0.1 to 1 Hz. The control strategy implemented is based on a virtual sensor fusion approach (VSF). It combines a physical inertial sensor at low frequencies and a virtual inertial sensor at high frequencies. This method allows a better isolation in the bandwidth of interest to be achieved, while bypassing stability issues induced by high frequency modes [11].

The ground isolation measurements are shown in Fig. 3. The graph displays the power spectral density of the vertical acceleration as measured by the AQG built-in Titan accelerometer when the AQG is placed directly on the ground with two rubber patches (pink) and as measured by one of the home-built sensors on the table when the AQG is placed on the table and the controller is active (brown). To obtain the amount of vibration mitigation, the two curves are divided and presented in the lower plot (purple). (It is different from the transmissibility because the two measurements were obtained at different times and with two different sensors.). The Low (NLNM) and High (NHNM) Peterson Seismic Models are superimposed for reference (black).

From 0.1 to 0.5 Hz, the home-built sensor indicates vibrations below the Titan nominal resolution (blue) [8]. Here, the virtual sensor fusion algorithm performs well with an isolation factor extending from 10 to 100. Above 1 Hz, the attenuation factor ranges from 0.1 to 100. The impact of the ground vibration reduction on the gravity measurement is discussed in the following section.

Gravity Measurement

The performance of the AQG was assessed with the platform controller on, creating thereby an extremely calm environment. The evaluation was carried out during the night of 15 September 2023 for approximately 12 h. Because the goal of this study is to observe the influence of seismic noise on the gravimeter output, all contributions to gravity known to vary in time are removed: The AQG software uses ancillary sensors and available data to correct the raw gravity signal for

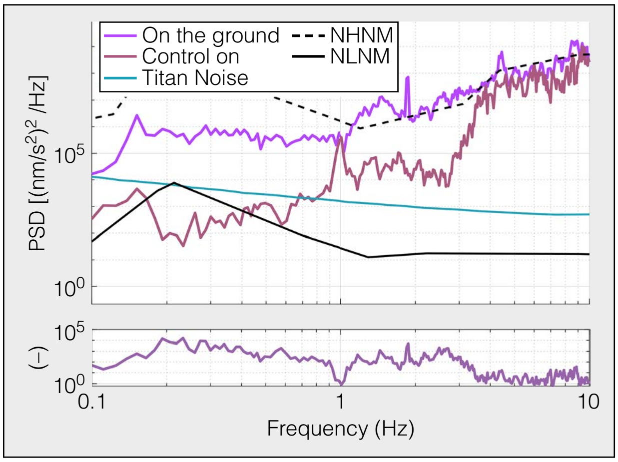

Fig. 3. (a) Power spectral densities of the ground acceleration measured by the AQG internal accelerometer and the platform's sensors under different conditions. (b) Reduction in acceleration noise obtained by dividing the square roots of the values reported in the "on the ground curves" and "control on" point by point.

instrument verticality, polar motion, atmospheric pressure and instrumental parameters such as magnetic field [4]. It also subtracts tidal effects via a Tsoft script [12]. The resulting gravity values g_{corr} are segmented into two-hour bunches. Two segments from 19:30 to 21:30 (brown) and from 21:30 to 23:30 (dashed-blue) are presented in Fig. 4 and Fig. 5. These graphs give the residual fluctuations g_{res} with the mean g_0 removed:

$$g_{res} = g_{corr} - g_0 \tag{2}$$

Fig. 4 shows that for frequencies <0.04 Hz the active vibration isolation attenuates the noise on g_{res} by a factor 3 with respect to the measurement with the AQG placed on the ground at Liège. Another reference measurement is made with the AQG at the Membach, Belgium geophysical station. The two measurements without active isolation in Liège (pink) and in Membach (green) exhibit a small peak around 0.15 Hz. This is the spectral signature of micro-seismic noise. The low-frequency difference in the gravity signal recorded at these two sites is due to the measurement conditions. The measurement in Liège is performed in the laboratory within the university during a normal academic day, while the one taken in Membach is set in a cavern with low seismic noise. This comparison highlights that ground vibrations affect the gravity signal and that these are the dominant noise in Absolute Quantum Gravimeters.

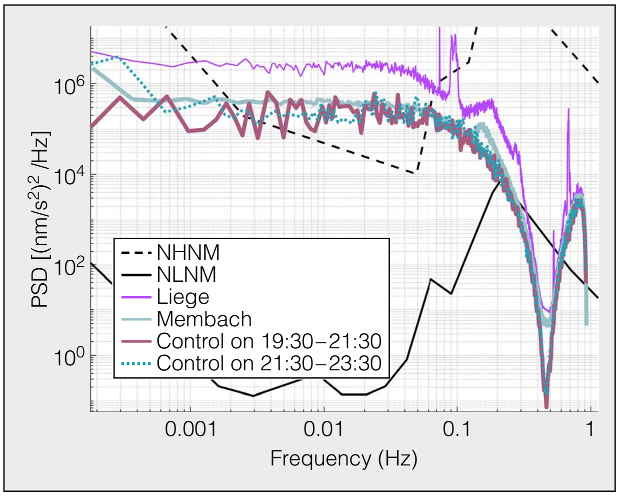

Fig. 4. Power spectral density of the gravity residuals g_{res} from measurements in Liège and Membach.

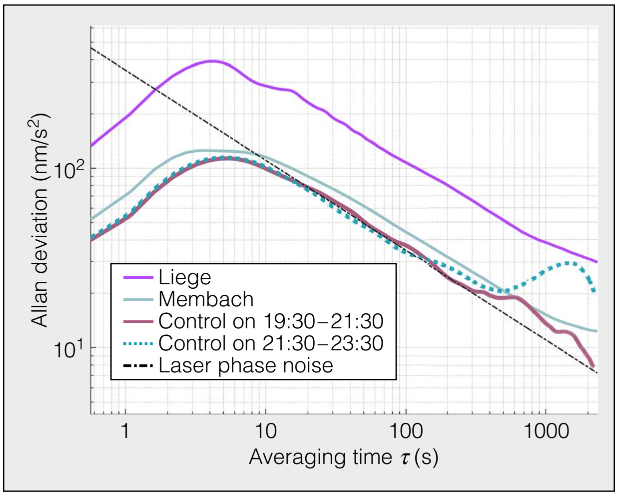

Fig. 5. Allan deviation of the gravity residuals g_{res} from measurements in Liège and Membach.

Fig. 5 shows the same data as Fig. 4 plotted as Allan deviation $\sigma(\tau)$, i.e., as a function of averaging time τ. This time domain analysis is often preferred to the frequency domain because it easily shows the long-term behavior of the gravity signal characteristic for the gravimeter performance with sensitivity and long-term stability. In fact, this $\sigma - \tau$ plot highlights particular types of noise distinguishable through their slope: a slope of $\tau^{-1/2}$ is characteristic of white noise and provides the gravimeter sensitivity at $\tau = 1$ s, while a slope of τ^{+1} preceded by a plateau indicates signal drift [13]. Accordingly, a decreasing curve at long averaging time is interpreted as a drift-free signal, implying good long-term stability.

The Allan deviation in Fig. 5 displays a maximum at $\tau = 5$ s which is related to the measurement technique implemented in the AQG. More specifically, the AQG output is servo-locked to the gravity value with a time constant of a few cycles [4]. The servo-lock is also observable in the PSD as a steep decrease within the 0.2 to 1 Hz band. As a result, meaningful gravity data is only to be considered from times >10 s corresponding to frequencies <0.1 Hz. Fitting the Allan deviations in the range 10 to 300 s confirms a white noise behavior of 350 $\mathrm{nm/s^2/\tau^{1/2}}$ with the active vibration isolation ON compared to 1000 $\mathrm{nm/s^2/\tau^{1/2}}$ with the AQG on the ground at Liège (pink). The noise is similar for the two "control on" data segments on 15 September 2023 from 19:30 to 21:30 (brown) and 21:30 to 23:30 (dashed-blue). This is an almost 3-fold noise reduction and demonstrates the efficiency of the isolation platform. The experiment with vibration isolation ON is at the same time the lowest sensitivity ever recorded with an AQG in an urban, noisy environment. This value corresponds to the instrument noise floor set by the intrinsic laser phase noise (dashed-black). This instrumental limit can be independently computed by weighting the measured power spectral density of the laser phase noise with the atom-interferometer transfer function. The laser noise is not a fundamental limit but fixed by the hardware choices [14].

For comparison, we performed another reference measurements with the AQG placed on the ground in the Membach geophysical station (green). The sensitivity obtained in Membach is <450 $\mathrm{nm/s^2/\tau^{1/2}}$ i.e. ~25% bigger than the sensitivity on the isolation platform. The Membach and isolation platform data show that lowering the seismic noise impacts directly the AQG output and leads to an instrument that is more sensitive to gravity fluctuation and operates at its theoretical noise floor.

Conclusion

In any gravimeter, seismic noise affects the measurement of gravity fluctuation. The AQG sensitivity without any external vibration isolation is 1000 $nm/s^2/\tau^{1/2}$ at an inner-city location in Liège, Belgium and less than <450 $nm/s^2/\tau^{1/2}$ in a quiet location in Membach, Belgium. When placed on our active isolation platform, the AQG sensitivity in Liège is 350 $nm/s^2/\tau^{1/2}$. We have thus shown that by lowering the seismic noise within the 0.1 to 10 Hz band by approximately a factor 100, we could reach the technical noise floor of the AQG. This shows that the gravimeter performance is limited by the ground vibrations in a noisy environment. These limitations are not due to the noise of the AQG build-in accelerometer used for the built-in vibration compensation system but are rather coming from potentially unavoidable imperfections in the real time compensation algorithm (time lag, non-linearities, etc.). Improvements to the vibration compensation system will be further investigated in future work. Such work could study the built-in accelerometer, its frequency response and resolution, its position and the feed-back algorithm [15]. Furthermore, active isolation tests could be carried out on other absolute gravimeters for comparison.

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